Maceration Technology Landscape

Tri-EHI and Plitzie

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EXECUTIVE SUMMARY

Maceration technology is commonly used within the wastewater treatment industry, as it reduces the size of the solid waste material present in the wastewater, reducing the risk of clogging or damaging downstream components and increasing the surface area of solid waste to improve processing efficiency. Consequently, many projects funded through “Reinvent the Toilet” — a program in novel wastewater treatment technologies run by the Bill & Melinda Gates Foundation’s (BMGF) Water, Sanitation, and Hygiene (WSH) team — utilize maceration and grinding technologies to process waste before feeding into different processing systems.

While a variety of macerator products are available commercially, some of the WSH projects have stringent performance, power, size, and operability constraints that limit the viability of commercial macerators for use in these systems. The objective of this study, then, is to assess the requirements for macerators within each WSH system and to identify commercial products that can meet those requirements. In cases where the requirements are not met by commercial offerings, we identify those gaps and offer recommendations for further investment in the technology and supply chain.

This study was performed using a combination of “top down” and “bottom up” perspectives. In our “top down” analysis, we solicited information on maceration use and needs from each WSH project and, based on the responses, derived requirements for macerator subsystems. For the “bottom up” analysis, commercially available macerator technologies were surveyed and categorized based on a number of metrics, including capacity, size, power consumption, and application from the US, EU, China and India. Requirements from the “top down” approach were matched to the capabilities defined in the “bottom up” approach to determine if current macerator systems meet the needs of the WSH projects.

As shown in Figure 1, the results of this study show that many of the WSH projects can use commercially available macerators to meet most of their needs. However, at least 10 projects have requirements that are not met by commercial products or haven’t yet implemented maceration but are considering it. Three critical gaps were identified that indicate a need for the development of new systems to meet all of the requirements of the WSH teams.

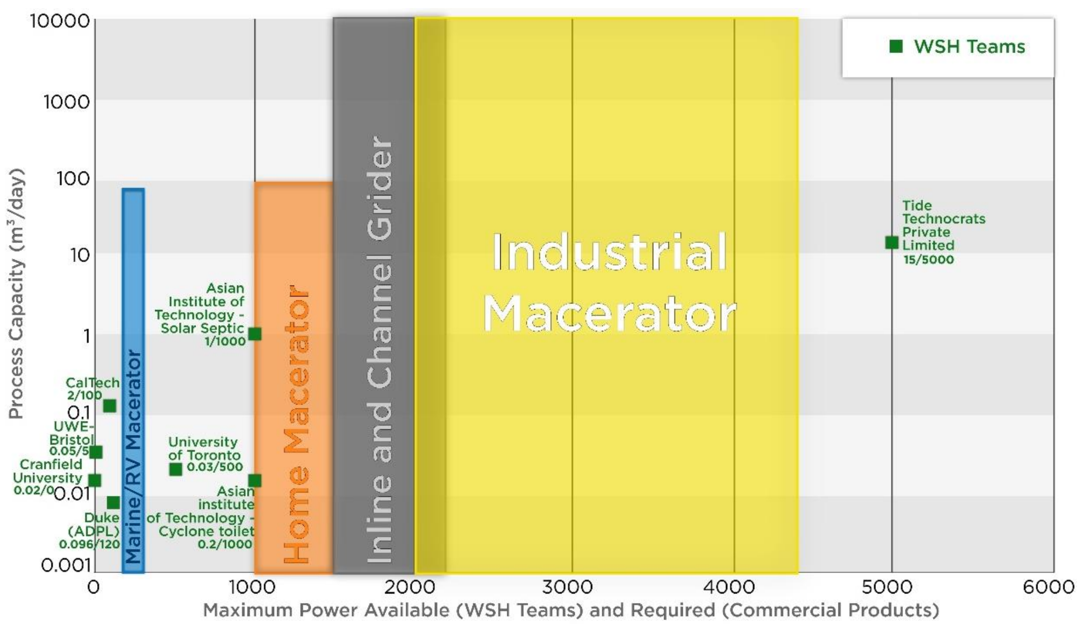

Figure 1 Summary of Commercial Macerator Capabilities with WSH Team Capacity

RECOMMENDATION 1

DEVELOP MACERATORS THAT CAN HANDLE FEMININE HYGIENE PRODUCTS.

While there are some maceration products that fit the need to handle feminine hygiene requirements, many products cannot easily macerate disposable feminine hygiene products. The combined requirements of low power and maceration of feminine hygiene products cannot be accomplished with current, off the shelf products. Four of the surveyed projects expected to regularly process feminine hygiene products and ten projects noted some limited or occasional processing. This universal need could be addressed and given global attention through a partnership or open source contest approach with an interested partner.

RECOMMENDATION 2

DEVELOP ULTRA-LOW POWER MACERATION PRODUCTS.

Three WSH teams require power consumption below the lowest power commercial options. To meet the needs of these teams, a dedicated effort would be needed to focus on low-power or hand-powered approaches. If possible, this product could also meet Recommendation 1. It is also important for teams to differentiate between peak power and energy to determine how systems may need to be setup considering distributed or off-grid use.

RECOMMENDATION 3

INVEST IN LOCAL SUPPLY-CHAINS FOR MACERATOR PRODUCTS OR CREATE SUPPORT SYSTEMS WITH LOCALLY REPLACEABLE PARTS.

Macerator repair parts are not typically available through local supply chains, which can hamper widespread implementation and maintenance. Given the wide geographic distribution of projects and target areas (Figure 2), locally produced systems are a good potential option. If supporting the creation of a new, local supply chain is not an option, another option would be to support the creation of a system that has more universal parts (e.g. DoD's attempt with Humvee's Universal Parts System). Products that can be serviced locally or manufactured in country (e.g. open source design or additive manufacturing of replacement parts) using traditional supply chains or widely available parts, without the need for specialty parts, would be of greatest long-term benefit.

CURRENT WSH TEAMS

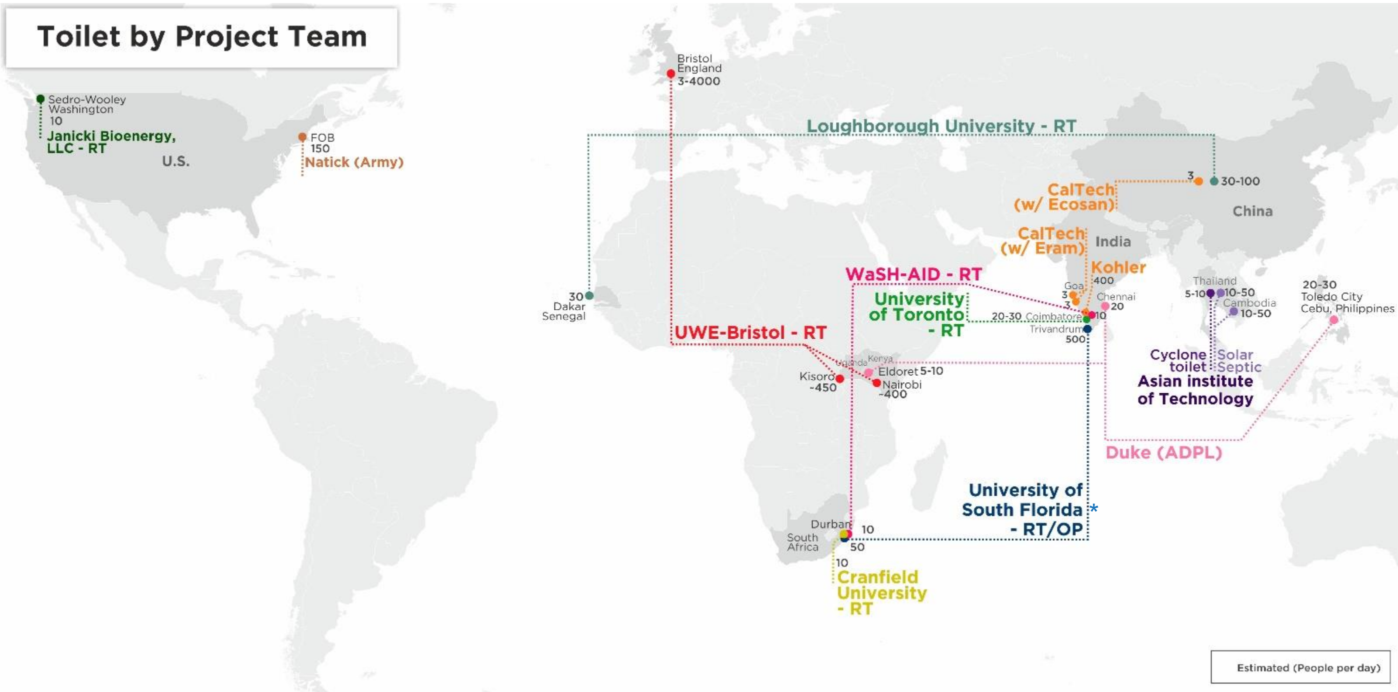

Figure 2 Global Map of Current Reinvent the Toilet Teams Locations

*Note: University of South Florida would like to be considered RT only and not RT and OP.

INTRODUCTION

The Gates Foundation has invested in R&D projects seeking to "Reinvent the Toilet," focusing on the needs of underserved communities around the world. The goal of the "Reinvent the Toilet" challenge is to develop a novel toilet technology solution that:

- Removes germs from human waste and recovers valuable resources such as energy, clean water, and nutrients.
- Operates "off the grid" without connections to water, sewer, or electrical lines.
- Costs less than US $0.05 per user per day.
- Promotes sustainable and financially profitable sanitation services and businesses that operate in poor, urban settings.
- Is a truly aspirational next-generation product that everyone will want to use—in developed as well as developing nations.

A component of many of the projects working under the "Reinvent the Toilet" challenge was maceration — the use of physical force to break apart solid materials. This increases surface area, improves flow and results in a more consistent product, leading to increased efficiencies and reduced maintenance.

Because so many of the projects rely on maceration technology, it is possible that synergistic or shared solutions may exist, reducing program cost and speeding up timelines. Therefore, the leadership within the Bill & Melinda Gates Foundation's Water, Sanitation, and Hygiene program commissioned an analysis of maceration products, with the explicit intent being to identify technological gaps, shared solutions, and appropriate off-the-shelf technologies that may be applied to the teams within the "Reinvent the Toilet" program. The current location of team projects is shown in Figure 2, and an image of the Omni-Ingestor and Omni-Processor programs are presented in Appendix 1.

We performed the overall analysis using a combination of "top down" and "bottom up" perspectives. In our "top down" analysis, survey responses gathered by Tri-EHI were used to derive a set of requirements that any macerator equipment would need to meet if added to the process for each of the BMGF "Reinvent the Toilet" projects.

For the "bottom up" analysis, we surveyed commercially available macerator technologies and then categorized them in terms of capacity, size, power consumption, application, etc. The nexus of these two approaches involved matching the requirements from the "top down" approach to the capabilities defined in the "bottom up" approach to determine if current macerator systems meet the needs of the BMGF "Reinvent the Toilet" projects. Additional groups and potential stakeholders were also approached to determine existing technologies that may not be commercially available but relevant may exist (United States Marine Corps, National Guard, and NASA). In cases where the requirements are not met, we have identified these gaps and provided recommendations for further study or research toward satisfying unmet macerator needs.

TERMINOLOGY NOTE

Within the industry, the terms macerator and grinder are used to refer to distinct categories of technologies. Both reduce the size of solid waste material. A macerator depends on the solid waste being entrained in a moving fluid stream. The moving fluid stream is passed through a mechanical chopping element. A macerator cannot operate on dry material. A grinder uses interlocking chopping elements to grind and homogenize solid waste. A grinder can operate either dry or wet. Grinders are applied outside of sewage treatment, in industrial food processing, recycling, and elsewhere. This report uses the term "macerator" without regard to the technological approach.

THE "BOTTOM UP" APPROACH: MACERATION SURVEY DESIGN

In order to understand the capabilities, needs, and gaps present in the current "Reinvent the Toilet" portfolio of projects, Tri-EHI undertook a detailed survey of each individual project. Representatives from each of the "Reinvent the Toilet" projects, as well as representatives from the Omni-Processor projects, were surveyed on the topic of solids processing (i.e., maceration) to determine the following:

1. What are the expected inputs for each system?
2. What are current or planned maceration methods?
3. What requirements for a maceration system?

A detailed list of all questions is provided in Appendix 2. The surveys asked detailed technical questions related to the volume and constituency of the waste stream processed by each technology, along with characteristics of the maceration system (if used) or requirements for a maceration system (if needed or considered). Respondents also ranked the importance of certain maceration parameters (e.g., tolerance to inputs, particle size, homogenization, energy efficiency, etc.) and how a macerator fits into the overall system componentry.

Based on the survey responses, the overall need for maceration technology across the portfolio of projects was assessed. In this "top down" approach, the requirements for maceration performance and operability were summarized for each project in preparation for a comparison against a variety of existing maceration systems to see if the need is met (or mostly met) by commercial products.

SURVEY RESULTS

A high-level overview of the survey responses is provided in Table 1 and summarized in Figure 3. A total of 19 survey responses (out of 25 organizations considered) were collected and analyzed. Of the 19 respondents, six indicated that their system currently uses some form of maceration, and one of these six indicated that the macerator does not meet performance specifications. Of the 13 responses that do not use maceration, four indicated they do not need maceration, and nine stated that they are considering adding a maceration capability or that maceration would provide a benefit to their system's operation. Therefore, a total of 10 projects have identified interest in adding or enhancing maceration. These are emphasized via orange boxes in Figure 3.

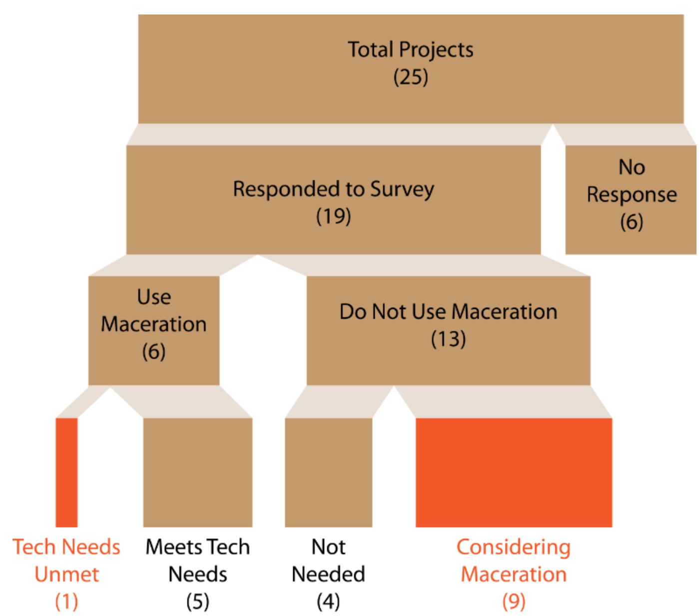

Figure 3 Top-level Survey Responses

Table 1 Summary of Responses to Survey on the Need for Maceration for Solid Waste Processing

Organization	Is maceration currently used?	If used, does macerator meet project needs?	If not used, has maceration been considered or assessed to provide benefit?
Duke WaSH-AID	Y	Y	
Loughborough University	Y	Y	
Biomass Controls, LLC	Y	Y	
Janicki Bioenergy, LLC [Toilet]	Y	Y	
Duke (SCWO)	Y	Y	
CalTech	Y	N	
Cranfield University	N		Y
University of South Florida	N		Y
University of Toronto	N		Y
UWE-Bristol	N		Y
Tide Technocrats Private Limited	N		Y
Duke (ADPL)	N		Y
Asian institute of Technology - Solar Septic	N		Y
Asian institute of Technology - Cyclone toilet	N		Y
University of Missouri - Kansas City	N		Y
Kohler	N		N
Ankur Scientific Energy Technologies Pvt. Ltd.	N		N
Idee e Prodotti Srl	N		N
NC State	N		N

For these 10 projects, we assessed the key requirements that a macerator sub-system would need to meet to be considered for use in the future. In order to compare these requirements to specifications associated with specific commercial products that are currently on the market, we identified the following key parameters. These parameters are summarized in Table 2 for each project that indicated a need for implementing or enhancing maceration.

- Nature of waste stream processed (total, solids only)
- Expected daily volume of waste processed (m^3/day)
- Power consumption constraints (W)
- Desired particle size of processed solids (mm)
- Size of macerator unit (dm^3)
- Acquisition cost constraint (USD)

Table 2 Summary of Macerator Requirements by Project

Organization	Waste Stream	Max. Waste Volume (m^3/day)	Max. Power (W)	Power Source	Particle Size of Processed Solids (mm)	Macerator Size (dm^3)	Acquisition cost (USD)
CalTech	Total	2	100	24 VDC	NS	NS	NS
Cranfield University	Solids	0.02	0	Mechanical	4	0.5	NS
University of South Florida	Total	10	NC	12 or 24 VDC	NC	NC	$400
University of Toronto	Solids	0.03	500	NC	12.5	1.6	NS
UWE-Bristol	Total	0.05	5	5 VDC	30	NS	NS
Tide Technocrats Private Limited	Total	15	5000	220, 415 VAC	1	28	$200
Duke (ADPL)	Total	0.096	120	12 VDC	NS	5	$300
Asian institute of Technology - Solar Septic	Total	1	1000	12-24 VDC	1	50	NS
Asian institute of Technology - Cyclone toilet	Solids	0.2	1000	220 VAC	1	4	NS
University of Missouri - Kansas City	Total	1	NS	220 VAC	6	1000	NS

Cells shaded red indicate requirements that are not met with commercially available Marine/RV Macerator systems.
NC = Not Critical
NS = Not Specified

In addition to the performance requirements listed in Table 2, a variety of operational requirements as they may relate to available maceration technologies were also assessed. These requirements are summarized in Table 3.

Table 3 Summary of Maceration Operations Requirements by Project

Organization	Maintenance (months)	Lifespan (years)	Availability	Tolerance to inputs
CalTech	NS	1.5	Local source, few weeks lead time	TP, condoms
Cranfield University	3	NS	Likely custom build	Food, seeds, corn
University of South Florida	6 to 12	5	NS	TP, feminine hygiene products
University of Toronto	6	NS	NS	TP, feminine hygiene products
UWE-Bristol	NS	5	Local replacement parts	TP
Tide Technocrats Private Limited	3	5	NS	TP, feminine hygiene products, plastics
Duke (ADPL)	6	NS	NS	TP
Asian institute of Technology - Solar Septic	12	NS	Readily available parts	TP
Asian institute of Technology - Cyclone toilet	12	NS	Readily available parts	TP
University of Missouri - Kansas City	12	NS	NS	TP, wires

Cells shaded yellow indicate requirements that are only partially met with commercially available Marine/RV Macerator systems.
NC = Not Critical, NS = Not Specified, TP = Toilet Paper

Based on the requirements listed in Table 2 and Table 3, we assessed whether existing commercial products could meet maceration needs. For 6 out of the 10 projects, existing commercial macerator technology is available to meet most, if not all, of the surveyed requirements. Specifically, the various **Marine/RV Macerators** (details below) match the capacity, power consumption, size, and cost specifications. The performance caveats are that the waste stream inputs are sufficiently "wet" to enable use of these macerators, and that these macerators cannot, and are not intended to, grind plastics or feminine hygiene products. The implementation caveats are that the systems and parts are distributed internationally but may not be available in every region, and repair parts are proprietary to the original vendor.

For the other four projects, the limitations are power related, with the macerator power consumption too high or a mismatch in operational voltage. The operational voltage is something that may be resolvable with a custom system, but further power reductions are unlikely without changing the underlying technology.

THE "TOP-DOWN" APPROACH: MARKET ASSESSMENT

We completed a market survey aimed of available macerators and grinders, with the objective of defining the space of available technologies in order to compare with maceration requirements of the BMGF "Reinvent the Toilet" projects. This was done via web searches, review of industry trade publications, searches of patents and research journals, phone calls and referrals. Some of the WSH survey responses provided information on commercial solutions that were investigated further. Representatives from some WSH teams and from identified companies were interviewed.

We then grouped the commercial technologies according to the scale of their application. Scale is best quantified by the maximum flow rate a system can process, is indicative of the manufacturer's intended applications, and correlates to power consumption. These groupings form the organizational structure of the survey results as discussed below.

In addition to scale, our survey documented the electrical requirements (operating power, operating voltage, power cycling), acceptable inputs (specifically fibrous material such as feminine hygiene products), and physical characteristics. Finally, we recorded a few properties that arise from concerns raised by the WSH team due to the particular use case: the availability of the products internationally, the operational noise of the systems, and the maintenance and reliability of the systems.

We further investigated other household products that may serve the intended purpose. Finally, we examined current research and development activities that may prospectively meet the demands of the program.

Our survey was limited to companies that used English as their primary language and published detailed information online. Surveys and interviews were also conducted in Mandarin, Hindi and Gujarati. Appendix 3 notes where information was given from contacts rather than publicly available sources.

SURVEY RESULTS

GROUPINGS BASED ON THROUGHPUT

Through our grouping exercise, we identified four broad categories of macerators:

Marine/RV (Recreational Vehicle) Macerators process 2 to 6 m^3/hour, are designed to only operate periodically, and consume the least power	**Home Macerators** process about 7 m^3/hour, are designed to operate periodically, and consume more power during operation than the Marine/RV Macerators
Inline and Channel Grinders start at 15 m^3/hour, but include models designed for hundreds of m^3/hour. These are designed for facility or waste treatment plant applications, are intended to operate 24/7, and require more power than Marine/RV and Home macerators	**Industrial Macerators** handle 80 to 100 m^3/hour and are also designed for facility or waste treatment plant applications. Because of their size and process volume, they require the most power

POWER, INPUTS, THROUGHPUT, AND PHYSICAL CHARACTERISTICS

Table 4 lists the commercially available systems according to these categories.

Table 4 Commercially Available Macerator Systems and Their Key Performance Characteristics

Category	Vendor / Model	Operating Power (W)	Operating Voltage(s)	Operate continuously?	Fibrous materials?	Max throughput (m^3 / day)	Envelope volume (dm^3)	Weight (kg)
Marine / RV Macerator	Oberdorfer / 209M	216	12, 24, 32 VDC	No	No	24	1.8	1
	Oberdorfer / 214M	200	120 VAC	No	No	34	14.2	1
	Oberdorfer / 406M	200	120 VAC	No	No	68	ND	3
	Raritan / Macerator 53	192	12, 24 VDC	No	No	30	3.6	2
	Sanipro / SFA 260	300	120 VAC	No	No	72	31.7	7
	Life SRC/ MP4500	300	12, 24 VDC	No	No	ND	4.1	2.3
	Xylem / JABSCO 18555	200	12 VDC	No	No	24	13.2	3
	Xylem / JABSCO 18590	200	12, 24 VDC	No	No	34	2.9	2
	Xylem / JABSCO 22130	180	110, 220 VAC	No	No	34	10.9	10
Home Macerator	JETS / Vacuumarator	1500	24 VDC, 230 VAC	No	Yes	83	38.4	36
	Zoeller / Quik Jon Ultima	1150	115 VAC	No	No	4.5	37	11.3
	Saniflo / Sanibest Pro	1080	120 VAC	No	Yes	ND	28	12
Inline and Channel Grinder	Börger / HAL 50	1500	VAC	Yes	Yes	360	77.9	87
	Grundfos / SEG A15	1500	230 VAC	Yes	Yes	432	12.0	46
	Grundfos / Sewer Chewer 7671	2200	VAC	Yes	Yes	1752	89.5	113
	Sulzer-JWCE / Muffin Monster 10000	1500	230, 460 VAC	Yes	Yes	1488	105.3	137
	Sulzer-JWCE / Muffin Monster 10002	1500	230, 460 VAC	Yes	Yes	994	54.8	153
	Wilo / MTS 40 / 95	1500	230, 460 VAC	No	Yes	434	41.6	30
Industrial Macerator	Börger / Multichopper 150 plus	2200	VAC	Yes	Yes	1920	306.2	130
	Börger / Multichopper 150 pure	2200	VAC	Yes	Yes	1920	221.4	110

We gave limited attention to **Industrial Macerators**, as the power, size, and maintenance requirements for these systems are not in line with the WSH team needs.

Inline and Channel Grinders all have high power requirements (1500 to 2200 W during operation) but are offered in a range of sizes including those appropriate to the larger scale WSH teams. They can be operated periodically (for example, once per day), saving power without any detriment to their performance, can operate dry without risk of damage, and process fibrous materials such as feminine hygiene products. Several of them are designed for end-user maintenance to clear any problematic materials and replace any damaged grinding blades.

In cases with high process volume or that prioritize handling complex waste streams, systems in this category are the best commercially available option. For example, the Biomass Controls team has incorporated one model in this category, the Sulzer-JWCE Muffin Monster, in their system. The Muffin Monster team was very interested in the new potential application space but would need more information on the potential market[1].

The Jets Vacuumarator pump — and toilets or sewage treatment systems built around it — is unique and was fit into the category of "Home Macerator". The Jets Vacuumarator pump (Figure 4) combines a macerator with a relatively powerful pump that pulls a vacuum. This allows for more rapid throughput with limited fluid. They can grind fibrous materials including feminine hygiene products. The Jets systems are marketed for marine applications, for homeowners with houses or cabins that are not connected to a municipal sewage system, and for temporary needs such as trailers at music festivals or disasters responses. The systems require operational power comparable to Inline and Channel Grinders, but only draw power periodically, during waste disposal. The systems are compact and marketed for integration directly with a toilet or to support several toilets plumbed together.

[1] Interview with JWC Municipal Sales, 9-14-18

Figure 4 Jets Vacuumarator™ 15 MB Pump[2]

The Jets Vacuumarator pump was selected by Loughborough University for testing in their prototype system. A Jets toilet was part of their first two prototype systems. They selected this toilet because of its limited water consumption. The maceration it provides was an advantage but not their primary concern. They did not permit feminine hygiene products in their toilets because the subsequent stages would not digest plastics, so they did not test how effective this feature of the Vacuumarator was with these materials. They report that the Jets toilets operated well, were well constructed, and had a reasonable power consumption because it only draws power during a flush. They also report that the Jets toilet was "very expensive" and not something they intend to use in produced systems. Their group attempted to contact the Jets Group to propose collaborative research and development, but never received any response to these proposals[3]. Similar "vacuum macerators" exist (e.g. H2O Inc) but are truly marine systems as they do have similar voltages, but do not operate at similar vacuum, and cannot handle feminine hygiene products. The Sanibest system also uses a grinder and can handle a variety of fibrous materials and could be another avenue of development.

Marine/RV Macerators all use impeller pumps (Figure 5 and Figure 6) to drive fluid flow and a macerating blade to reduce solid waste in that fluid stream. These systems require only 10 to 20% of the power that the other categories require. The systems are designed to be relatively portable, easy to use, and straight forward to maintain. These systems are sold in either DC or AC power models and are widely available from global manufacturers.

Figure 5 Raritan Model 53 Impeller Macerator[4]

[2] "The Heart of Our System," Retrieved 2018-09-30. https://jetsgroup.com/jets-group/the-highest-standards/the-heart-of-our-system
[3] Interview with Professor M. Sohail, technical lead for the Loughborough University team, on 2018-09-27.
[4] "Macerator Pump." Retrieved 2018-09-30. http://raritaneng.com/raritan-product-line/sanitation-accessories/macerator-pump/

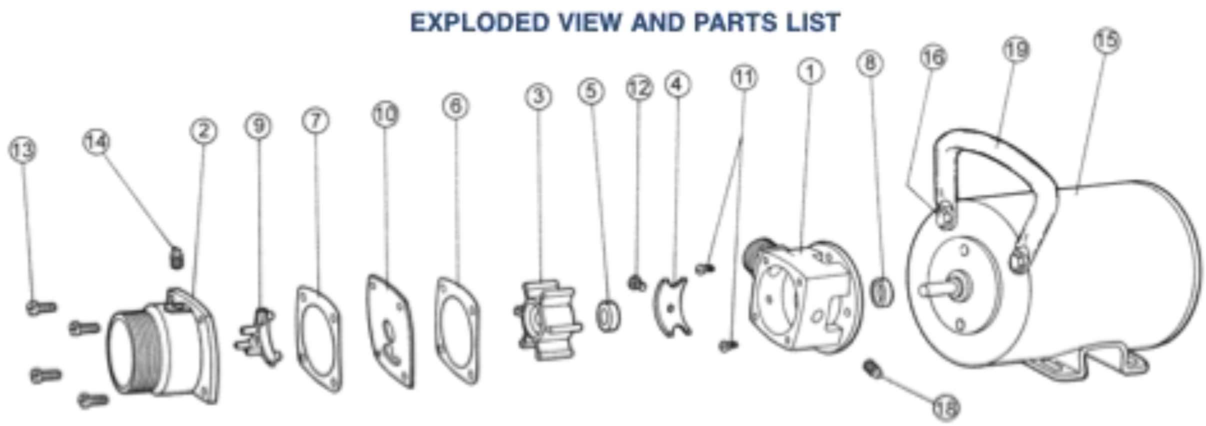

Figure 6 Assembly View of Oberdorfer 209M[5]

In Figure 6, Component 3 is the rubber impeller that spins to drive fluid flow. The rubber impeller pump experiences the fastest wear in the system and requires replacement as preventative maintenance and would be a key failure point or part that would be best supplied locally if available.

These systems have two major downsides relative to the WSH teams' needs. First, they are the most restrictive on the types of solid waste that can be in the fluid stream. In particular, feminine hygiene products cannot be macerated. A Raritan sales engineer said that this is "an age-old problem" they have worked to overcome without success.[6] The low power motors used in these macerators are not capable of processing tough, fibrous solids. Second, most of these systems are designed with limited duty cycles in mind. Several models cannot operate for more than 30 minutes continuously without overheating and risking damage. These systems will require preventative maintenance, replacing impeller pump blades (Figure 6), more rapidly than other systems assessed (in comparable use scenarios).

INDIAN & CHINESE SUPPLY CHAIN

There are a variety of systems available in China, from RV/Marine type to industrial/municipal uses. Generally, their product portfolios appear to follow the EU/US systems. Beyond traditional macerator systems, five shredder and grinder companies were contacted to gauge their interest and potential to create feminine hygiene capable, low-power sewage sludge systems. Most providers attested that their products would able to process feminine hygiene products (their systems appear overdesigned for sewage sludge and feminine hygiene maceration) and all providers demonstrated an interest in deploying their technologies in developing countries but do not currently have systems designed to do so. Supply chain capacity from these providers demonstrated an ability for rapid scale-up, however, short range ceilings for full production capacity was indeterminable. Given China's very strong general logistical infrastructure for global delivery, supply chains for small macerators should be fundamentally stable once a need established. Performance parameters would need to be specified to have the manufacturers make a better assessment of their supply chain integrity for a new or unique market.

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[5] "209M Spec Sheet". Retrieved 2018-09-30. https://www.gardnerdenver.com/-/media/files/oberdorfer/pdf/flexible-impeller/209m.ashx?la=en

[6] Interview with Vinod Mehta, Vice President of Engineering for Raritan Engineering, on 2018-09-18.

India has recently undertaken a program entitled Swacch Bharat Abhiyan, or the Clean India Movement. Consequently, sanitization and hygiene is a popular priority but has limited supply chain translation. Macerating toilets and Maceration pumps have been introduced in India by both local (Sharp Pumps Private Ltd) and foreign manufacturers (e.g. Saniflo) for domestic and industrial sewage treatment plants. Local hospital macerator demand is often supplied by local manufacturers. Macerating toilet systems (e.g. Ascent II) are also available by multiple distributors with external macerators. However, the Clean India Movement focuses on creating Shauchalaya (toilets) at every corner so that people from rural parts of the country do not have to use open public spaces, fields and farm lands as toilets (especially women and children). The Indian government is offering schemes to low-income families to build free toilets. Under this program, many innovative ideas are being tested to create better sewage systems at a local level that are also socially accepted, eco-friendly and strategic for long-term waste management (e.g. e-Toilet by ERAM Scientific). In terms of supply chain, industrial macerators are more common than domestic macerators. It is unclear whether macerators for domestic toilets with sanitary napkins can be a rapidly growing market, but low-cost options certainly show an upward growth amongst domestic consumers. Tampons are less popular than sanitary napkins for economic and social reasons in India, and gender marketed sanitary wipes for middle class users are available for both men and women. Consequently, sanitary napkin incinerators have certainly gained some attention.

ADDITIONAL CONCERNS

In the course of our survey, also we found the following generalizations with respect to the aforementioned specific concerns raised by the WSH team:

INTERNATIONAL AVAILABILITY

All of the vendors of these systems market and sell their products in multiple countries. Many of them are produced by multinational conglomerates. Even the Marine/RV Macerators are marketed and sold internationally because the marine applications take their users across the globe. This includes manufacturing in the EU/US with international resale and Asian manufacturing with EU/US resale.

NOISE

None of the vendors provide noise level information in their marketing material. Two Marine/RV Macerator manufacturers responded to inquiries that the noise level was “moderate,” and the system could be operated in an enclosed space. The Home Macerator is also marketed to be operated in a bathroom, as an integrated part of a toilet. Loughborough University did not receive any feedback about the noise level from this being a significant concern.

MAINTENANCE AND RELIABILITY

The manufacturers of the Industrial Macerators and Inline and Channel Grinders emphasize the reliability and robustness of their systems. However, they do not advertise quantitative specifications for reliability. Because they are marketed for large-scale facilities, they are designed to be maintained on-site by personnel with some mechanical training and expertise. Estimated performance limits were not explicitly listed on most products, from the US, EU and Asian producers.

ENGINEERING METRICS

The macerators reviewed have application metrics precisely defined (e.g. Max throughput) whereas projects may need non-traditional metrics (e.g. Min throughput). These different metrics may need to be redefined by interested manufacturers to support the “Reinvent the Toilet” projects.

SIMILAR PRODUCTS

After researching these commercial maceration products, we considered if any other categories of consumer/household products could meet the needs of the WSH teams. Household products are more likely to meet the target characteristics of low power consumption, local production/service, low cost, and low noise. The two categories of household products we considered were garbage disposals and kitchen blenders/grinders.

A **garbage disposal** operates on a similar principal to a Marine/RV Macerator but without an integrated pump. Like a Marine/RV Macerator, a garbage disposal uses a spinning impeller to draw a mixture of liquid and solids against a spinning blade. The blade macerates the solid materials until they are small enough to pass through. The resultant solid particulates are small enough to pass through household plumbing and into municipal waste streams. A garbage disposal depends on liquid being present to carry the solids and particulates and it cannot grind highly fibrous materials (such as feminine hygiene products). While a garbage disposal suffers from the same impeller-related problems as a Marine/RV Macerator, it is inferior to it because a garbage disposal depends on gravity to move the fluid.

Food blenders and grinders are designed to macerate solids or mixtures of solids and liquids. They are similar to Inline and Channel Grinders in their operation, and they require comparable amounts of power (1500 to 2200 W) during operation but are relatively inexpensive and widely available. However, they have faster wear and shorter design lifetimes than Inline and Channel Grinders. Blenders are also not designed to be integrated into either a flowing or highly automated process. Finally, the blade design of food blenders and grinders is less effective at grinding fibrous materials such as feminine hygiene products. There are specialty food grinder projects that are focused on maceration of food waste for anaerobic digestion and use systems that use very little water, are robust, and able to handle significant amounts of waste and debris. However, many of these teams have never been approached with sewage or low power applications; they have displayed interest in sharing their learnings[7].

RESEARCH AND DEVELOPMENT

We researched patent databases, scholarly literature databases, and trade publications for evidence of research and development in macerator and grinder technology. The only areas of research and development we found emphasized in trade publications was handling large and dense fibrous materials. In developed countries, wet wipes have proven to be a problem at municipal treatment plans, and several vendors now market systems as capable of macerating these. They achieved this by redesigning the grinder teeth and/or increasing the power of the motors. Also, in developed countries, prison waste treatment facilities present a challenge because inmates will flush large objects (jeans, bed sheets, towels) down toilets in an attempt to disrupt the systems. Several vendors market systems as capable of macerating these large objects using specialized grinders and higher power motors.

In particular, we searched for evidence of research into macerator power reduction since that was a widespread concern in the WSH survey response. We found no evidence of research in this direction, nor did vendors emphasize this in their marketing. An assessment by Zhou[8] analyzed power usage at municipal treatment facilities, and the maceration process was not found to be a high-power consumption process. Therefore, even for municipal facilities focusing on power usage, macerators are not their focus.

[7] Interview with Emerson Grind2Energy Program Lead, on 10-22-18

[8] Zhou, Y. et al. "Energy utilization in sewage treatment – a review with comparisons." **Journal of Water and Climate Change**, volume 4 (2013).

RECOMMENDATIONS & PATHS FORWARD

GAPS IDENTIFIED

Three critical gaps were identified that, when combined, indicate a need for the development of a new system to meet all of the requirements of the WSH teams:

1. **Maceration of feminine hygiene products is possible only with high power macerators.** Disposable feminine hygiene products share the common feature of incorporating highly fibrous materials as absorbents. These materials can be cotton, plastic, paper, or mixtures. When macerated with a relatively low power motor, these will tend to separate into long strands that then catch and bind the motor instead of being macerated further. Macerators with higher power motors or a high-power grinder overcome this problem and macerate feminine hygiene products effectively.

   One third of the WSH teams responded that macerating feminine hygiene products would be a desirable goal for a macerator. Because most of the WSH teams require very low power consumption, small size, and low cost, the requirement to macerate feminine hygiene products within the human waste stream will be difficult to accomplish with current, off the shelf products. It should be noted that the final waste stream from the products developed by these teams will likely be sent directly to the environment and could result in local environment plastic contamination.

2. **Several WSH projects require lower power consumption than can be provided by commercial macerator products.** All of the commercial macerators operate with electrical power and have a peak power consumption of at least several hundred watts. One WSH team responded that they would require a macerator that did not require any electrical power (e.g. manual systems). We did not identify any commercial options that meet this requirement.

   Three WSH teams responded with power limitations below the lowest power commercial options. It is critical to clarify if the WSH teams were providing their peak power restriction or average power restriction. If the latter, then the Marine/RV Macerators may be acceptable. Macerating feminine hygiene products requires no less than 1500 W peak power for the commercial options, and this exceeds the majority of the power restrictions.

3. **Macerator products and replacement parts are not typically available through local supply chains.** Several WSH teams specified a requirement that a macerator system be produced and/or maintained “locally,” yet while the vendors and manufacturers identified distribute their products internationally, they have centralized manufacturing facilities. These would not meet the local production criteria. The components required to maintain the Marine/RV Macerator are relatively simple and could possibly be produced locally, though testing may be required to verify this in various countries and regions. The other categories of commercial macerators are more complex in design and contain more proprietary components. It is less likely, though not infeasible, that they could be maintained locally.

An alternative approach for WSH teams that seek to develop new macerator systems and designs would be to constrain systems to work with few specialized components, create open source designs capable of distributed manufacturing or design with ease of replacement in mind. The Department of Defense Humvee program provides a valuable precedent for these types of approaches. Initially, they tried to simplify their in field maintenance of Humvees by limiting the number and type of parts to allow for easier repair and scavenging, and now they are transitioning to a program aimed at creating qualified metal replacement parts for motors that are additively manufactured in field with little training by soldiers[9].

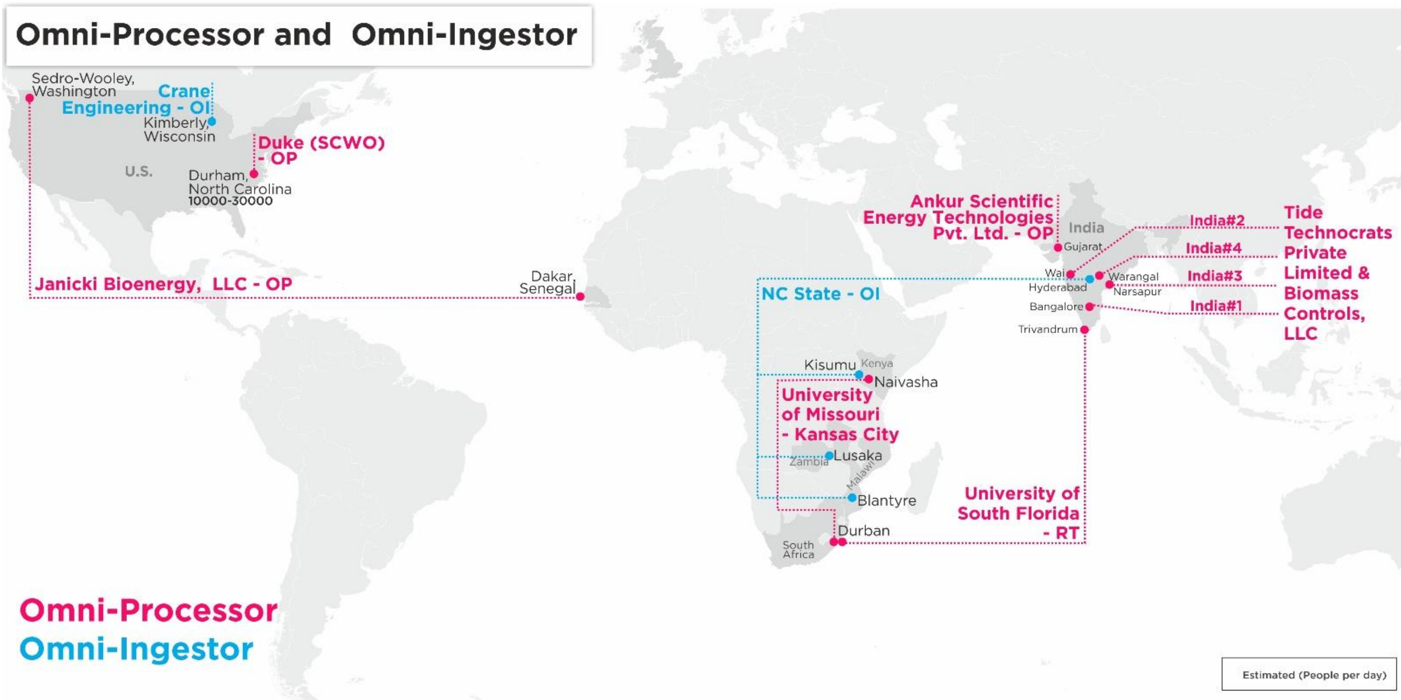
POTENTIAL SOLUTIONS AND NEXT STEPS

Based on the findings of this analysis, we provide several possible solutions that can help facilitate the use of macerator technologies within the WSH team's toilet processes.

- **Work with WSH teams to operationally assess Marine/RV Macerators in their systems.** These are the commercial systems that satisfy the majority of the team's requirements, primarily because of their relatively low power consumption. There appear to be multiple options, with similar performance characteristics. A field test would assess the strengths and weaknesses of these options.
- **Work with the Jets or Saniflo Group to miniaturize their Home Macerator.** The Jets and Saniflo products have the potential to meet many of the requirements of the WSH teams through reduction in operating power and cost as well as ensuring local maintainability. Jets Group has not previously responded to inquiries from an individual team along these lines, but an approach from BMGF or a dedicated team may generate greater interest.
- **Invest in research to develop a competitor product in the Home Macerator category.** The Jets Group has demonstrated that a compact, moderate power macerator is possible. The absence of any competitors in this space may be a function of lack of market demand. A BMGF development effort could ensure that the design is not proprietary and, therefore, lower cost and more likely to be producible and maintainable locally.
- **Host a conference and/or competition that invites ideas for a low cost, low power macerator for low-volume applications.** The absence of commercially available solutions may be a product of limited market demand rather than technological infeasibility. Drawing attention and interest could lead to the discovery of an existing or readily available solution, and interest in the topic has been expressed by multiple commercial and government groups. A key part of this conference would be outlining the potential business case for interested companies to invest in this area of development while maintaining their current differentiation in their higher margin markets. Another approach would be to develop an open source design and allow companies to commercialize the design at will.
- **Invest in research for alternative methods for fibrous material degradation.** This could include novel physical methods, but also enzymatic, chemical, or thermal approaches, as well as separations technologies. This, too, may be a proper venue for a challenge or convening.

[9] Interview with United States Marine Corps NexLog (Next Generation Logistics) Program, 10-04-18

APPENDIX 1 OMNI-PROCESSOR AND OMNI-INGESTOR LOCATIONS



APPENDIX 2 MACERATION QUESTIONS

QUESTION 1 EXPECTED INPUTS

Volume (L/d), Scale (p/d), Current testing locations, %TS, COD (mg/L), Contents, Wash/Wipe, Trash & debris, Other

QUESTION 2 CURRENT MACERATION

Equipment (macerator type, make, model), Waste stream (total stream, wet only, dry only, other), Daily operation time (hr.), Daily volume macerated (L), Size & Capacity, Operating voltage (AC, DC), Power demand (W), Maintenance req'd, Prefiltration required

Max particle size (mm), Is pumping required for input/output from macerator or is it gravity fed? What are the macerator treatment chamber measurements? (length before blades, diameter of blades, diameter of chamber, length of chamber after maceration), Issues/barriers w/ equipment, Is there a picture of maceration system and chamber that can be shared? Desired improvements

QUESTION 3 CONSTRAINTS FROM MACERATING & LIMITS

Cost (Y/N; $ limit), Size (Y/N; limit), Energy req'd (Y/N, W), Remote site (Y/N; how?)

QUESTION 4 DOES LACK OF MACERATION HINDER YOUR SYSTEM'S PERFORMANCE?

Yes, how? / No, why not?

QUESTION 5 HOW WOULD MACERATION IMPROVE YOUR SYSTEM?

QUESTION 6 EQUIPMENT FAILURE

Lifespan (months), What would happen if equipment failed?

QUESTION 7 WHICH PARAMETERS ARE YOU MOST INTERESTED IN?

(Rate high to low), Higher tolerance to inputs, Particle size distribution, Mixing or homogenization, Protection of downstream components, Energy efficiency

QUESTION 8 STEPS BEFORE MACERATOR?

QUESTION 9 RATE POTENTIAL IMPROVEMENT?

APPENDIX 3 SOURCES OF VENDOR DATA

Data on commercial macerator systems was, with the exceptions noted below, acquired from product data sheets posted on vendor and distributor websites. Information was obtained through email and conversations from:

Name	Organization	Email	Phone
Peter Knauerhase	Gardner Denver Oberdorfer Pumps	pete.knauerhase@gradnerdenver.com	800–448–1668x236
M. Sohail (Khan)	Professor of Sustainable Infrastructure	m.sohail@lboro.ac.uk	+44–(0)1509–222890
Bjarte Hauge	Jets Group	bjh@jets.no	
Vinod Mehta	Raritan Engineering Company	vinod@raritaneng.com	856–825–4900x214
Keith McManus	Wilo USA	Keith.McManus@wilo-usa.com	888-945-6872
Product Tech Support	Zoeller Pumps		502-778-2731