# Nitrile cup seal robustness in the India Mark II/III hand pump system

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### A B S T R A C T

Accessing clean water is a persistent and life-threatening challenge for millions of people in the world. Each hour, 400 children under the age of five die because of the lack of clean water. To help people get access to clean ground water, mechanical hand pumps are often used. Among the most ubiquitous is the India Mark II/III hand pump system, of which there are more than 4 million installed across the world. These are estimated to serve between 600 million and 1 billion people. But as with most mechanical systems, they degrade over time–leading to pumps becoming dysfunctional due to lack of required service. The pump's nitrile cup seals are the most common cause of dysfunctionality. The purpose of this paper is to analyze the robustness of the cup seals in the India Mark II/III hand pump system. In this paper, 110 off-the-shelf nitrile cup seals purchased by the authors in Uganda were tested and characterized. Leak and pump performance tests were performed in both static and dynamic settings and the correlations between performance and geometry and material properties of the cup seals were determined. This important baseline evaluation for the seals supports our future work to improve the longevity and robustness of the India Mark II/III hand pump system, with a focus on the cup seals. We believe that by finding the baseline of a product, engineers and designers will be able to improve its performance.

## 1. Introduction

The world's need for clean drinking water cannot be overstated, as diarrhea kills more children than malaria, measles, and AIDS combined (see Fig. 1) (Liu et al., 2012). Each hour, 400 children under the age of five die due to the lack of access to clean water (Gadgil, 1998). The lack of clean water also causes 19.5 million people per year to be infected with roundworm and whipworm (UNICEF, 2003). These parasites retard children's physical development and prevent education. If they had access to clean water, poverty would be reduced, suffering would decrease, and more children would be able to go to school (Fagan et al., 2015).

Mechanical hand pumps have a long history of helping people access clean ground water for drinking and daily use. Ground water is a good source of clean water since it is naturally filtered through layers of soil (Gadgil, 1998; International Water and Sanitation Centre, 1988). It is estimated that at least 1 billion people get their drinking and daily usage water from hand pumps across the world (Carter and Lockwood, 2011) and that at over 4 million hand pumps have been installed in Africa, Asia, and India over the last 20 years (Carter et al., 2010; Mudgal, 1997). Although ownership models vary across these continents, mechanical hand pumps are often community owned and maintained in countries

such as Uganda. A hand pump is often within 500 m of one's dwelling, and is shared by approximately 150–250 people (known through interviews by the authors with water officials in Uganda and through literature) (Mudgal, 1997). One of the most commonly manufactured mechanical hand pump systems is the India Mark II hand pump, shown in Fig. 2. It was developed by UNICEF in 1978 (Arlosoroff et al., 1987). The India Mark II hand pump is now used across the globe. In India alone, it is estimated that over 2.6 million India Mark hand pump systems are operating (Mudgal, 1997).

As expected, it is common for mechanical hand pumps to become dysfunctional over time, owing largely to the degradation of items such as seals, bushings, and bearings. Not uncommon is the dysfunction stemming from theft and vandalism (Klug et al., 2018). Other times hand pumps fail after aid agencies and donors turn over their projects to local villages, leaving them without resources for upkeep and repairs (Thomas, 2016). This is a reoccurring problem with many aid-based projects due to culture, lack of training, infrastructure, finance, public consultation, political backing, and other related challenges (Hernandez et al., 2019; Mac Mahon and Gill, 2018). Also, some pumps remain functional but fail to support local communities when water tables change or become contaminated (Klug et al., 2018; Koehler et al., 2015). It is estimated that 15% of India Mark II hand pumps are currently
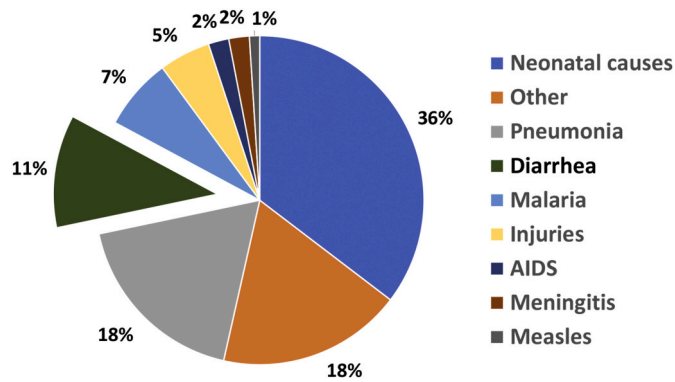
Fig. 1. Cause of death for children under 5 (worldwide) (Liu et al., 2012).



Fig. 3. Percent of hand pump water sources non-functional by age (Banks and Furey, 2016).

dysfunctional or otherwise not supporting the needs of local communities (Mudgal, 1997). Of those, approximately 70% are dysfunctional due to hardware problems that could be repaired (Klug et al., 2018). Additionally, as a pump system ages, its functionality goes down due to lack of maintenance, leaving more people without direct access to clean water (see Fig. 3) (Banks and Furey, 2016; Mattson et al., 2017). One reason for lack of maintenance is often the associated cost (Koehler et al., 2015; Ottosson et al., 2018). Another reason for infrequent service visits in Uganda was because the service personnel were overwhelmed with the number of pumps they needed to service (Ottosson et al., 2018). Unfortunately, repair times can be expected to be between 1 and 5 weeks for any type of failure (Mudgal, 1997). As a pump becomes dysfunctional, the people relying on its water are often forced to use unimproved water sources (Klug et al., 2018). It was found in a study by Hunter et al. that even a few days of using unimproved water sources can be sufficient to offset the benefits from normally having clean water, leading to serious sickness and/or death (Hunter et al., 2009). For the 1 billion people using hand pumps for daily access to clean water, their health is directly related to the reliability of the pump system they use (Thomas, 2016).
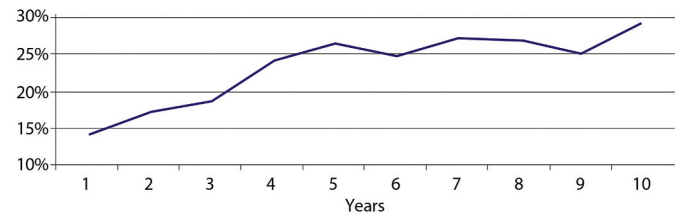
The social impact of loosing access to clean water is significant: When a local water source becomes non-functional, users walk to another more distant source, preventing them from performing other tasks and activities such as work, school, tending to the family, etc.

The gender impacts of loosing a water source are also significant as the burden of collecting water is typically borne by women and girls (Mudgal, 1997; Whittington et al., 1990). Having a nearby functional hand pump has a greater impact on women than men since they are principally responsible for taking care of the family in terms of health, food, and water (Hyder et al., 2005). Women also bear the extra burden of water-related diseases (diarrhea, dysentery, typhoid, giardiasis, dracunculiasis, shigellosis, etc) as they more often care for the sick (Mudgal, 1997). Another impact of a mechanical pump with poor reliability is that communities loose confidence and patience with the water source and ultimately abandon it (Carter and Ross, 2015).

Research shows that pump malfunction is most often due to hardware problems (Klug et al., 2018) and that the cup seals degrade and cause the pump efficiency to go down (Mudgal, 1997; Klug et al., 2018). Fig. 4 shows common points of failures for the India Mark II/III pump system with the cup seal as the biggest point of failure (Erpf, 2004).

**The purpose of this paper** is to quantify baseline performance for the nitrile cup seal used in the India Mark hand pump system and to create the foundation for the next step in a larger study to understand – mechanically and socially – how hand pumps perform, degrade, get repaired, and ultimately meet human needs. The findings presented here
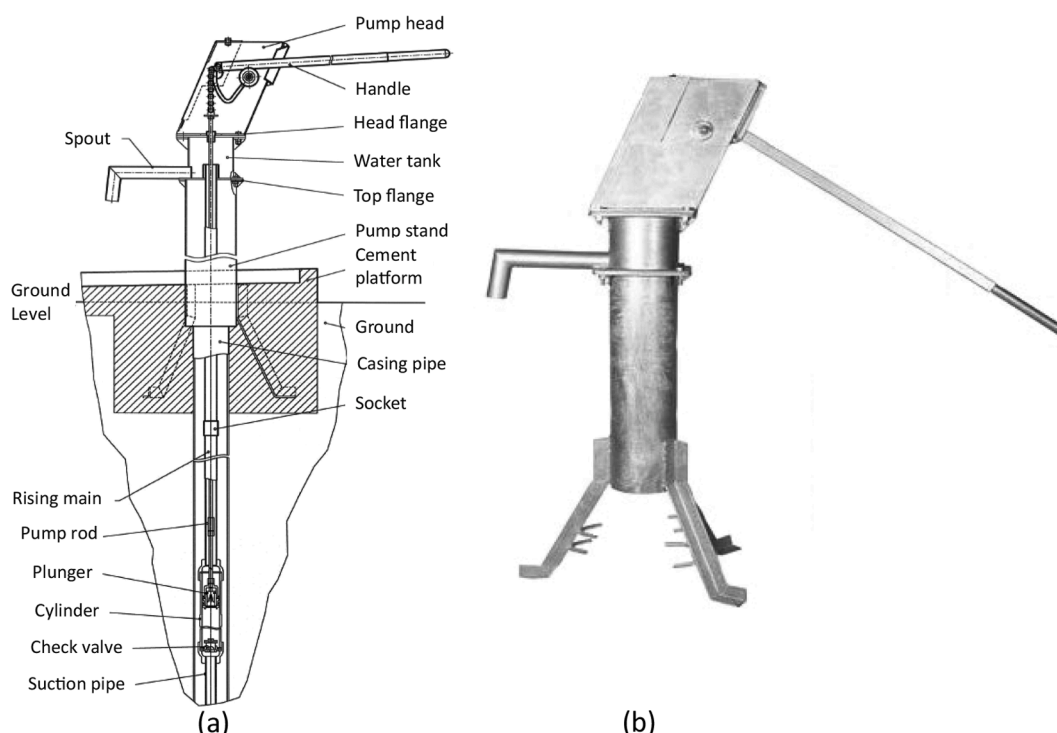


Fig. 2. (a) India Mark II hand pump system schematic and (b) image of an India Mark II hand pump (Erpf, 2007).
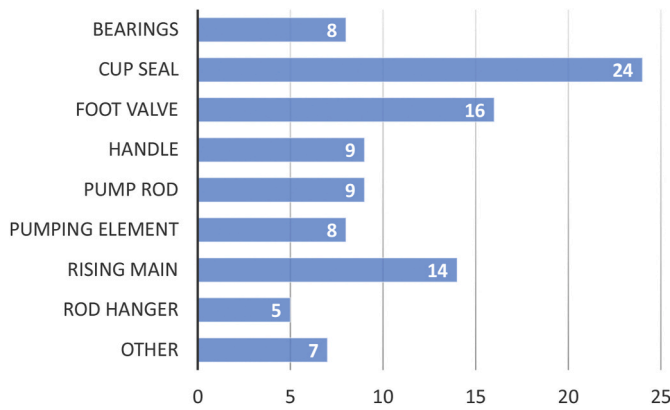
Fig. 4. Points of failure for the India Mark II/III hand pump system (percent of total failures) (Erpf, 2004).



Fig. 6. Specified cup seal dimensions (mm) (Erpf, 2007).

will be incorporated into our larger research where we have used field sensor data to capture pump usage scenarios, and machine learning techniques to begin mapping engineering design parameters, such as those presented in this paper, to the social impacts of an engineered product (Ottosson et al., 2018; Stringham et al., 2020).

The remainder of the paper is organized as follows: In Section 2, we present technical preliminaries related to seal configuration and performance. We then present a short synopsis of the approach, limitations of the current study, followed by the methods and results of gathering geometric, material, leak, and pump data. This is followed by a conclusion with suggestions for future work.

## 2. Technical preliminaries

The India Mark II/III hand pump has three sets of seals as shown in Fig. 5. The seals that are the focus of this paper are the cup seals (two in each pump installed in the plunger assembly). The other seals are flat seals that are part of check valves. This configuration is a common setup for reciprocating hand pumps (Arlosoroff et al., 1987). The large majority of cup seals are molded in India according to the dimensioned drawing shown in Fig. 6 (Erpf, 2007; Sansom and Koestler, 2009). Such seals are sold in small and large shops throughout the world in units of
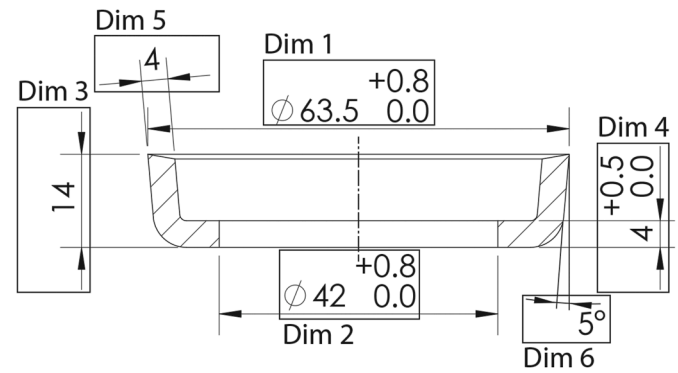
one or thousands. Typically, a pump repair person will purchase one or a few seals at a time depending on the maintenance jobs in the queue. When purchasing in these quantities seals cost the buyer approximately USD 0.5 in Uganda (purchased in Uganda by authors in 2018). Due possibly to the low profit margins, vastly differing environmental conditions (throughout the developing world) and manner in which seals are stored, there are significant variations in new seal geometry and material properties, as will be shown in this paper.

**Basic Functionality:** Conceptually the seal functions at its peak when there is a column of water in the riser pipe that acts downward on the seal causing the seal to flex radially outward thus making greater contact with the surrounding cylinder wall. In east Africa, a common well depth is 42 m (Mattson et al., 2019), producing a hydrostatic pressure of 412 kPa acting on the first seal in the seal set. The cup seal performance, together with stroke length, determines how much of the column of water is lifted during each pump stroke and exits the spigot at the surface.

Seals for machinery in general have been well-studied and are well-documented in the literature. Earlier works include fundamental principles of seal performance (Mayer, 1969; Martini, 1984), while new research continues to seek for improvements in seals (Pinedo et al., 2018; Valentini et al., 2019). It is important to recognize that while the nature of seals are relatively well known as a whole, no work has been published on characterizing the seal performance of the India Mark II/III
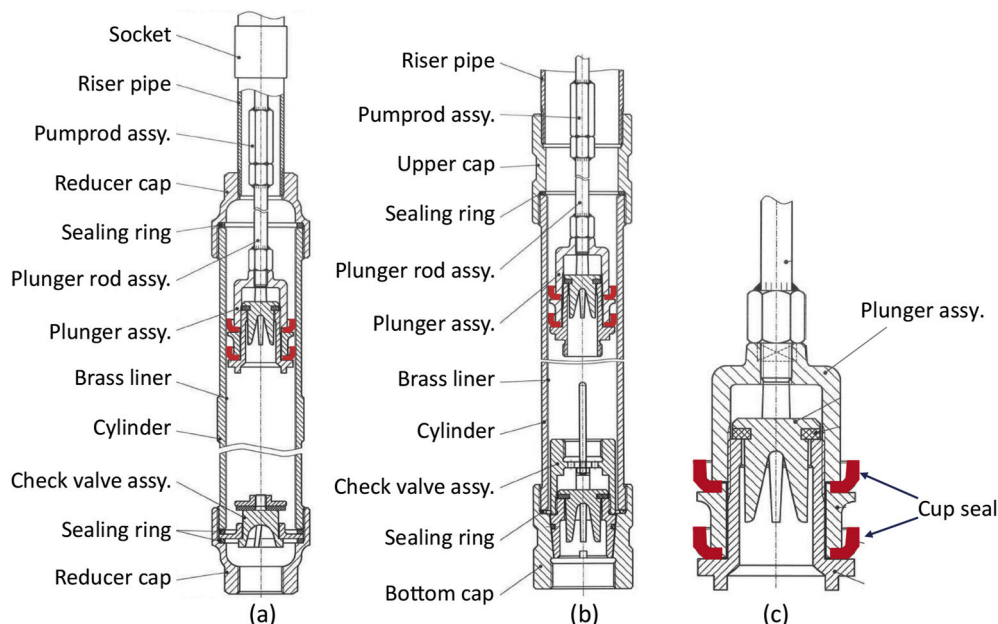


Fig. 5. (a) Schematics of the India Mark II and (b) India Mark III pump cylinders, together with (c) the plunger assembly (cup seals highlighted).

cup seals, possibly due to the harsh realistic operating conditions, and how these seals are made, distributed, and sold. Because millions of people are affected by the performance of the cup seals in the India Mark II/III, we are motivated to present findings that lay the ground work for engineering an improved seal and pump that could increase access to clean water.

With a better understanding of the cup seal mechanics and its performance sensitivity to real geometric and material variations, we can examine the potential to engineer a more robust, longer lasting, and possibly more easily maintained seal.

**Installation and Maintenance:** In order to better help governments and NGO's install and manage hand pumps and to provide clean water to more people (159 million people still collect their drinking water directly from surface water sources (WaterAid, 1981)), an initiative to create a set of guidelines for hand pumps was created in the early 1980's. It was called the *Village Level Operation and Management of maintenance project* (VLOM) (Colin and Woodfield, 1999). See below for VLOM project guidelines. With this came a need to have a hand pump system suitable for the VLOM directives. After the introduction of the VLOM initiative and the India Mark II hand pump, the hand pump failure rates in India went from about 70% in the 1970's to about 20% in the 1980's (Arlosoroff et al., 1987).

The Village Level Operation and Management of maintenance (VLOM) project guidelines (Mudgal, 1997; Arlosoroff et al., 1987; Colin and Woodfield, 1999):

- Easily maintained by a villager caretaker, requiring minimal skills and few tools;
- Manufactured in-country, primarily to ensure the availability of spare parts;
- Robust and reliable under field conditions;
- Cost effective;
- Community choice of when to service pumps;
- Community choice of who will service pump; and
- Direct payment to repairers by the community.

In order to better comply with the VLOM guidelines, the India Mark II hand pump system was improved. The main objectives for the redesign was to increase the Mean Time Before Failure (MTBF) and to simplify maintenance (Mudgal, 1997). This resulted in the India Mark III hand pump system where the serviceability of the seals was greatly improved. The redesign enabled the seals to be changed without having to remove the riser pipes (which are wider in the India Mark III), making it both easier and faster to service the pump (see Fig. 5(b) for the India Mark III pump cylinder). The cup seal configuration remained the same (RWSN, 2018).

**A Pump Redesign:** A notable non-UNICEF commissioned redesign of the traditional hand pump increased the MTBF significantly by removing the need for cup seals completely. The redesigned pump was developed by Fairwater Foundation together with Oxfam and is called the BluePump (Mcsorley, 2012; Foster and McSorley, 2016). The Blue-Pump has proven to be a more reliable pump than the India Mark II/III hand pump system (Foster and McSorley, 2016) but adoption rates have been very low due to its significantly higher initial price, lack of part standardization, and regulations across Africa (MacArthur, 2015).

## 3. Approach and limitations of the current study

We have taken a multifaceted approach to better understand the nature of the failures of the India Mark II/III hand pump system. While there are many potential points of failure, this paper focuses on just one – the eventual failure of the cup seals. Prioritizing the cup seals is motivated by both literature research (Fagan et al., 2015; Ottosson et al., 2018; Erpf, 2004; Reynolds, 1992) and our interviews with hand pump technicians and suppliers in Uganda. This will then be used as a baseline for a future study where we will develop a wear model for the cup seal to predict degradation over time.

For the present paper, we have done the following:

1. Searched literature for understanding of hand pump failures
2. Acquired multiple India Mark hand pumps for use in the laboratory
3. Visited multiple pumps sites, observing pump usage at each site
4. Interviewed water district officials in multiple locations
5. Acquired district managers' water reports
6. Interviewed pump mechanics and water source caretakers
7. Purchased 110 seals from local markets in multiple locations (see Fig. 7)
8. Tested seals in field and laboratory settings
9. Analyzed the findings

The primary limitation of this study is that the dynamic performance test of the cup seal is limited to a laboratory setting with a pump depth of 0.6 m instead of using the well depth of 42 m commonly found in east Africa (greater borehole depth increases the hydrostatic pressure on the cup seal caused by the water column in the rising main, causing a potential performance difference for the cup seal). This is not a limitation for the static performance test, which used increased water pressure to simulate actual well-depths. Another limitation of the study is that our field work was performed in one country. But after reading other research on hand pumps across many developing countries throughout the world (Arlosoroff et al., 1987; MacArthur, 2015; Reynolds, 1992; Furey, 2013; Arlosoroff et al., 1984), we conclude that the findings in this paper can also be meaningful for someone researching hand pumps in other developing countries with similar conditions to those in Uganda (such as humidity and temperature). It is also important to note that the India Mark hand pump systems and their spare parts are almost exclusively manufactured in India due to price and quality (Sansom and Koestler, 2009). Despite these limitations, this paper will characterize:

1. Geometric variation of off-the-shelf seals
2. Material variation of off-the-shelf seals
3. Static zero-cycle leak performance of off-the-shelf seals
4. Dynamic zero-cycle pump performance of off-the-shelf seals
5. Statistical correlations between Geometric and Material variation to zero-cycle performance

## 4. Quantification of geometric and material variation of off-the-shelf seals

In order to better understand the workings of the India Mark hand

**Fig. 7.** The different locations in Uganda where seals were purchased.

pump system and how seal degradation occurs, the authors traveled to Uganda and interviewed local pump users, caretakers, technicians, part store owners, and water officials. Uganda was chosen for two reasons: first, through our existing relationship with WHOlives (WHOlives) we could utilize their network of contacts. Second, the Ugandan government has regulations in place, limiting the number of hand pump systems across the country (India Mark II being the most prevalent system) (MacArthur, 2015). Data on pump usage, spare part availability, and interviews were collected. New and used seals (see Fig. 8) and other spare parts were also purchased for evaluation. It was found during the field visits and interviews that the cup seal was indeed a significant point of failure.

To find cup seals and other spare parts, we went to three different towns across Uganda: Kampala, Jinja, and Gulu (see Fig. 7). For each town, we visited multiple local markets and stores. It was found that of the stores visited, all had only a small supply of cup seals except for one store in Kampala. To not interrupt the local supply of seals, only a small number of seals were purchased from each store. There was no indication to how long the cup seals had been in the stores before we purchased them. This resulted in a total of 110 cup seals purchased. No set price was found in any of the stores we visited. This always led to a discussion between our local team members and the shop owners. The cost of a seal did not vary much between each store (approximately USD 0.5 per cup seal).

Multiple methods were used to assess the geometric and material variations in the seals. The weight, volume, density, hardness, and geometry of each seal were measured and recorded. These measurements were performed in Uganda directly after purchase to ensure that the measurements reflected the local environment and weren't changed due to changes in climate or prolonged storage. The same procedures and testing equipment were used to measure all seals. These measurements were performed to evaluate whether the seals met the manufacturing specifications (see Fig. 6).

A test fixture was used to simultaneously take a top, right and left side photo of each seal. These images were then processed with Matlab image processing software (The MathWorks Inc.) for dimensions 1, 2, and 6 (see Fig. 9). For dimensions 3, 4, and 5, a digimatic indicator with an accuracy of 0.02 mm, (Mitotoyo 575-123) was used. The Sartorius AY303 scale was used to measure seal weight, with 0.001 g readability, repeatability 0.005 g, and linearity 0.005 g. The water displacement method was used to measure seal volume. To measure volume, the seal was held by a steadying rod and a seal basket to keep the seal from touching the side and bottom of the vessel. The Sartorius scale was also used for this test. Density was then calculated by using the weight and volume results. The hardness of each seal were measured by using a Starrett Handheld Digital Durometer (H, Shore A Scale). This durometer is capable of a resolution of 0.5 H, deviation <1% in the 20–90 HSA range.

All data was gathered and Matlab was used to calculate statistical significance and variations. The average values and variations can be seen in Table 1.

It was found that the mean for three of the six dimensions and the seal hardness fell outside the specified tolerance. Since the material was only specified as "*Nitrile-Butadien Rubber (NBR) conforming to BS 2751*" (Erpf, 2007) without mentioning a specific density interval, the specification for weight and density are left blank (Erpf, 2007). The volume was calculated from a 3D CAD file of the cup seal downloaded from the
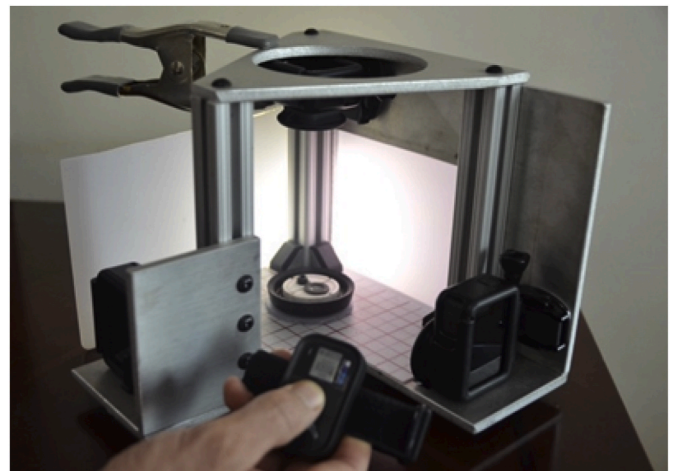


**Fig. 9.** Test rig used for recording pictures of each seal.

Rural Water Supply Network (Miller, 2012). These results create the baseline for the seal performance in our study.

### 4.1. Error analysis for the geometric and material measurement system

An error analysis was done on the measuring system. The purpose of this analysis is to characterize the uncertainty associated with the measurement methods themselves. We are interested in this uncertainty because it cannot be attributed to part variation, and therefore must be discovered in order to more fully characterize a part's actual variation. There is potential error in the measurements of geometry, weight, volume, and hardness.

The geometry, weight, volume, and hardness of a single seal was measured at least 30 times. In all cases except the hardness tests and the wall angle test (Dim 6), the percent error was less than 1%. For these two tests, a larger uncertainty is expected because they were not fully automated.

Note that the units for the amount shown for Stdev are the native units for the item being evaluated. E.g., for weight it is *grams*, for volume it is $g/cm^3$, etc. The result of the analysis can be seen in Table 2.

### 5. Static zero-cycle leak performance of off-the-shelf seals

To find the leak rate of each purchased seal, a static seal leak-rate test rig was built at Brigham Young University (see Fig. 10). It consisted of a pump cylinder from an India Mark III hand pump system complete with a plunger. Attached to the pump cylinder was a high pressure water source, an adjustable regulator, and a gauge. Different well depths could be simulated by adjusting the pressure of the water entering the pump cylinder. Each seal was tested individually and the data collected and evaluated. The seal being tested was placed in the lower seal position of the plunger (see Fig. 5(c)).

The 110 seals that were tested came from seven different stores in Uganda. Out of those, five seals leaked (4.5%). The results can be seen in Table 3. Interesting to note is the information in the last row of Table 3, showing the number of seals outside specifications. To ensure that leakage was not due to improper installation, each seal that leaked was removed, re-installed, and tested five times.

The data suggest that installation could have been a factor in seal leakage since only one out of five seals leaked again (see Table 4). The seal that leaked multiple times was then tested further to study the variation of seal performance due to installation. After testing the seal ten times and comparing the leak rates, it can be seen that the installation did affect the seal's leak performance (see Table 5).

A two-level full factorial design of experiments was generated with angle and insertion position as the parameters to further quantify the



**Fig. 8.** New cup seal (left) and a used cup seal (right) for the India Mark II/III hand pump system.

**Table 1**
Measurement results from the 110 seals acquired in Uganda, shaded cells indicate where mean is outside tolerance (see Fig. 6 for drawing of cup seal with dimensions).

| | Dim 1 (mm) | Dim 2 (mm) | Dim 3 (mm) | Dim 4 (mm) | Dim 5 (mm) | Dim 6 (degrees) | Weight (g) | Volume (cm³) | Density (g/cm³) | Hardness (ShoreA) |
|---|---|---|---|---|---|---|---|---|---|---|
| **Spec** | 63.5 | 42 | 14 | 4 | 4 | 5 | - | 12.91 | - | 75-85 |
| **Spec Min** | 63.5 | 42 | 13.5 | 4 | 3.5 | 4.5 | - | - | - | 75 |
| **Spec Max** | 64.3 | 42.8 | 14.5 | 4.5 | 4.5 | 5.5 | - | - | - | 85 |
| **Mean** | 64.27 | 41.87 | 12.40 | 4.23 | 4.17 | 7.53 | 17.589 | 12.410 | 1.417 | 86.05 |
| **Stdev** | 0.53 | 0.23 | 0.43 | 0.18 | 0.18 | 2.22 | 1.333 | 0.450 | 0.0842 | 3.44 |
| **Min** | 62.86 | 41.42 | 11.36 | 3.75 | 3.76 | 1.57 | 14.685 | 11.718 | 1.250 | 75.75 |
| **Max** | 65.68 | 42.71 | 13.15 | 4.77 | 4.62 | 12.50 | 23.142 | 13.812 | 1.677 | 96.75 |
| **Range** | 2.82 | 1.29 | 1.79 | 1.02 | 0.86 | 10.93 | 8.457 | 2.094 | 0.427 | 21 |
| **Median** | 64.26 | 41.85 | 12.46 | 4.24 | 4.16 | 7.48 | 17.541 | 12.386 | 1.392 | 85.63 |

**Table 2**
Coefficient of variation (CV), the % error, mean, standard deviation, 3*standard deviation, min, max, range, and median (110 seals).

| Test | Dim 1 (mm) | Dim 2 (mm) | Dim 3 (mm) | Dim 4 (mm) | Dim 5 (mm) | Dim 6 (degrees) | Weight (g) | Volume (cm³) | Hardness (ShoreA) |
|---|---|---|---|---|---|---|---|---|---|
| CV | 0.0049 | 0.0025 | 0.0025 | 0.0030 | 0.0088 | 0.0165 | 0.0002 | 0.0011 | 0.0337 |
| % error | 0.49% | 0.25% | 0.25% | 0.30% | 0.88% | 1.65% | 0.02% | 0.11% | 3.37% |
| Mean | 64.1069 | 41.7731 | 11.8606 | 4.1809 | 4.0973 | 10.7038 | 16.7579 | 12.0292 | 86.1743 |
| Stdev | 0.3146 | 0.1029 | 0.0296 | 0.0124 | 0.0359 | 0.1770 | 0.0028 | 0.0130 | 2.9058 |
| 3*Stdev | 0.9438 | 0.3087 | 0.0888 | 0.0372 | 0.1077 | 0.531 | 0.0084 | 0.039 | 8.7174 |
| Min | 63.4890 | 41.4879 | 11.79 | 4.1625 | 4.0800 | 10.3048 | 16.7500 | 12.0040 | 79.625 |
| Max | 64.7374 | 41.9869 | 11.9150 | 4.2050 | 4.2950 | 11.0035 | 16.7640 | 12.0560 | 91.00 |
| Range | 1.2484 | 0.4990 | 0.1250 | 0.0425 | 0.2150 | 0.6987 | 0.0140 | 0.0520 | 11.375 |
| Median | 64.0707 | 41.7781 | 11.8650 | 4.1800 | 4.0925 | 10.7073 | 16.7580 | 12.0260 | 86.125 |



**Fig. 10.** Test setup for determining cup seal leak rate.

effect of installation on seal performance. The two angles were 0° and 1.51° (the maximum angle that can be imposed before the connecting rod impinges on the surrounding cylinder) and the two positions were related by a 90° axial rotation from each other. The process parameters for the experiment can be seen in Table 6. Each experimental condition was replicated five times. To ensure that leak would occur, the seal that leaked multiple times was used.

The results from the design of experiments can be seen in Table 7. The change in position had a greater influence on leak rate than the change in angle (see Fig. 11). This can also be seen in Fig. 12 where the second box plot is taller than the other box plots.

To quantify what an acceptable leak rate for a new seal is, old seals that had been removed during pump maintenance visits in both Uganda and Haiti were installed in the leak-rate test rig (see right seal in Fig. 8 for an example of an old seal). The logic behind this approach is that if the seal had been replaced during a maintenance visit, its performance was likely to be unacceptable. Consequently, the leak rate for these decommissioned seals provides an estimate of what is an unacceptable leak rate.

The used seals from Uganda were purchased by the authors and the seals from Haiti were acquired by WHOlives (WHOlives). The average measured leak rate for the decommissioned seals were 35,000 mL/min, many times higher than the leak rates measured during the tests with new seals (see Tables 3–5, and 7, and Fig. 12).

Based on the leak rate of the decommissioned seals, we conclude that none of the 110 new seals violates the leak rate acceptable limit. This suggests that the observed geometric and material variations, together with the variability introduced by installation, have a negligible impact on static zero-cycle pump performance.

### 5.1. Error analysis for the leak test

The seal leak test was analyzed by performing three different self studies with one seal randomly selected from the 110 seals. The first self study was to find variations due to the test-rig. The second was to find variations due to the mating between the pump cylinder and the plunger assembly. And the third was to find variations due to disassembly and

**Table 3**
Leak test results (shaded cells indicate where the value is outside of tolerance).

| Seal number | Leak rate (*mL/min*) | Dim 1 (*mm*) | Dim 2 (*mm*) | Dim 3 (*mm*) | Dim 4 (*mm*) | Dim 5 (*mm*) | Dim 6 (*degrees*) | Hardness (*ShoreA*) |
|---|---|---|---|---|---|---|---|---|
| 1B-027 | 10.27 | 64.13 | 41.75 | 12.90 | 3.99 | 4.19 | 11.31 | 92.38 |
| 5B-017 | 0.30 | 64.12 | 42.08 | 11.81 | 4.16 | 4.03 | 7.40 | 80 |
| 5B-018 | 0.01 | 65.46 | 41.81 | 11.76 | 4.33 | 4.00 | 9.72 | 85.63 |
| 5B-023 | 1.39 | 64.44 | 41.66 | 11.93 | 4.06 | 3.89 | 8.50 | 86.38 |
| 6-019 | 0.69 | 64.18 | 42.31 | 12.83 | 4.13 | 4.09 | 8.13 | 96.75 |
| Number of seals that fall outside the tolerance | - | 58/110 | 81/110 | 110/110 | 13/110 | 3/110 | 95/110 | 67/110 |

**Table 4**
Additional tests of seals that failed during initial testing.

| Seal | Leak test (*mL/min*) | | | | |
|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 |
| 1B-027 | 10.27 | 140.69 | No leak | 60.11 | 120.86 |
| 5B-017 | 0.30 | No leak | No leak | No leak | No leak |
| 5B-018 | 0.01 | No leak | No leak | No leak | No leak |
| 5B-023 | 1.39 | No leak | No leak | No leak | No leak |
| 6–016 | 0.69 | No leak | No leak | No leak | No leak |

**Table 5**
Variation of seal performance due to installation.

| Seal 1B-027 | |
|---|---|
| Test | Leak rate (*mL/min*) |
| 1 | 10.27 |
| 2 | 140.69 |
| 3 | No leak |
| 4 | 60.11 |
| 5 | 120.86 |
| 6 | No leak |
| 7 | 6.53 |
| 8 | 70.36 |
| 9 | 42.60 |
| 10 | No leak |

**Table 6**
Process parameters for the design of experiment.

| Process parameters | Labels | Low level | High level |
|---|---|---|---|
| Angle | A | 0° | 1.51° |
| Insertion position | P | 1 | 2 |

assembly of the plunger assembly. Each self study was repeated 30 times for the single seal.

No leaks were found in the first self study. For the second self study (variation due to the mating between the pump cylinder and the plunger assembly), one test out of thirty produced a measurable leak rate. This corresponds to a probability of 3.3% of leaks happening due to installation of the plunger assembly into the cylinder. No leaks were found in the third self study.

## 6. Dynamic zero-cycle pump performance of off-the-shelf seals

To find how each seal performed off-the-shelf, a dynamic test-rig was built at Brigham Young University (see Fig. 13). An India Mark II pump cylinder complete with a plunger assembly was connected to a water tank (see schematic on the left side in Fig. 2) from an India Mark III. A water tank from the India Mark III was used in order to enable the removal of the plunger assembly without dismantling the rising main. Then a motor-powered crank-slider mechanism was built to simulate the movement of the pump handle. The pump cylinder was immersed in a barrel of water. A National Instruments controller and LabView (National Instruments) were used to start and stop the motor to ensure a cycle time of 1 min. The crank-slider mechanism pumped 42 full strokes per minute. Each seal was tested individually by being placed in the lower seal position of the plunger assembly, leaving the upper position empty (see Fig. 5(c)). A scale was used to measure the water output (Mango Spot portable scale). The test setup was created to match the discharge test performed in the field at the time of cup seal/pump cylinder installation (see below). This is done to ensure that the pump cylinder is tight and that the cup seals are functioning properly.

**Discharge Test** (Erpf, 2007):
The cylinder shall be primed and testing shall start after a continuous flow of water through the spout has been obtained. The water shall then be collected in a container for 40 continuous full strokes of the plunger. This test shall be completed in 1 min and the discharge thus measured
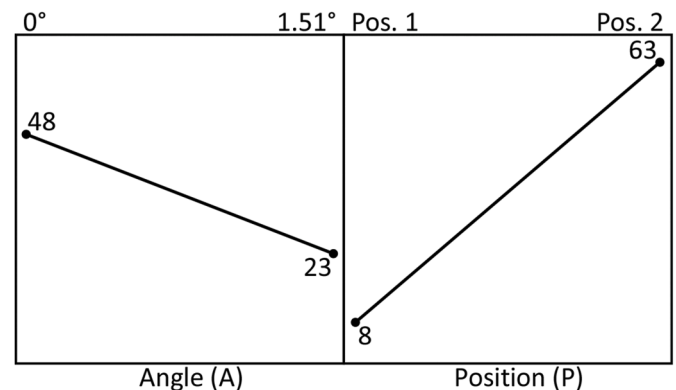


**Fig. 11.** Main effects plot for the design of experiment.

**Table 7**
Design layout of the experiment with response values and averages.

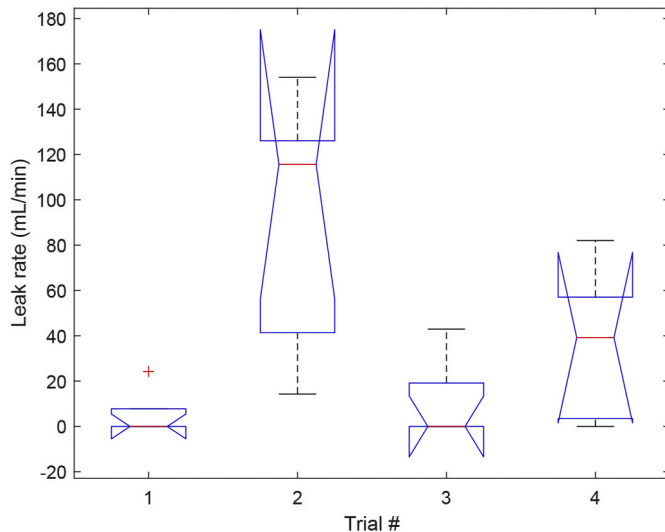| DOE trial # | Angle | Insertion position | Leak rate (mL/min) | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | Test 1 | Test 2 | Test 3 | Test 4 | Test 5 | Average |
| 1 | 0° | 1 | 0.003 | 24.247 | 0 | 0 | 2.310 | 5.312 |
| 2 | 0° | 2 | 50.382 | 154.059 | 115.649 | 116.739 | 14.312 | 90.228 |
| 3 | 1.51° | 1 | 0 | 0 | 0 | 11.230 | 42.951 | 10.836 |
| 4 | 1.51° | 2 | 39.188 | 0 | 4.601 | 48.709 | 82.056 | 34.911 |

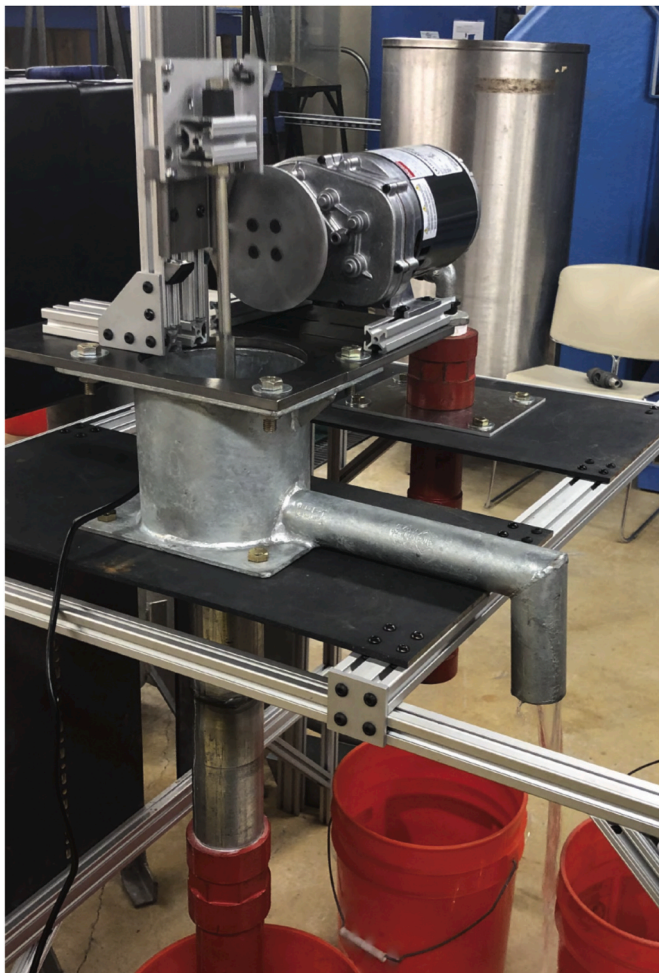**Fig. 12.** Box plots showing the different trials for the design of experiment.



**Fig. 13.** Dynamic test rig for determining cup seal performance.

shall not be less than 15 L.

Because the in-field discharge test is done with two cup seals and the in-lab pump performance test setup employed only one cup seal, it was necessary to determine the equivalent acceptable output for a single-seal pump configuration. To determine the acceptable level of output, two

seals were placed in the plunger assembly and the test was performed. The same test was then repeated with only one seal to compare the output. The discharge test was repeated with several different seal configurations and a model was created to calculate the output of one seal that would corresponding to the output using two seals. The output was reduced by 4.24%. Therefore, an output of 14.36 L/min was deemed acceptable (95.76% of 15 L/min).

The dynamic test was then performed for all 110 seals. The range of the output was 6.425–16.36 L/min with an average of 14.188 L/min, $\sigma$ = 2.2477. 60 of the 110 seals had an output above 14.36 L/min (55%). It was noted that the seals from store 4 and 5 performed better overall compared to seals from the other stores (see Fig. 14).

Based on the pump performance test, we can conclude that 45% of the seals would have failed a field discharge test. This suggests that the observed geometric and material variations and how the seals were stored before purchase affected the dynamic pump performance to the degree that one in four seals would not perform satisfactory at time of installation.

### 6.1. Error analysis for the pump performance test

The dynamic test setup was analyzed by performing two self studies with one seal randomly selected from the 110 seals. The first self study was to find the variation in output due to the mechanical pump system and the second was to find the variation in measuring the weight of the water output. Each self study was repeated 30 times for the single seal.

In the first self study, the results of the output ranged from 15.90 to 16.03 L/min with an average of 16.00 L/min, $\sigma$ = 0.02331. For the second self study, a 13.66 kg weight was used to find the variation of measurements for the scale. No variation was found for the scale.

## 7. Statistical correlations between geometric and material variations to zero-cycle performance

Principal component analyzes were done to determine if there were correlations between geometric and material parameters and leak and pump performance that could not be observed naturally. This type of analysis is helpful for researchers and engineers to aid in determining which parameters should be prioritized throughout the design process. Principal component analysis (PCA) is a dimensionality reduction technique used to identify a small number of mutually orthogonal composite variables (principal components), that are linear combinations of the original variables, and which better explain the variance in the observed data (Vidal et al., 2016; Larose, 2006; Jackson, 1991).

It was found that many of the parameters were highly correlated with each other, meaning that they are partially redundant (see Sections 7.1 and 7.2). These findings will guide us in our future work to improve the seal.

### 7.1. Geometric variations

The variables included in the PCA for the geometric variations were the six different dimensions seen in Fig. 6. The PCA showed that much of the geometric variability in both the static leak and dynamic pump performance tests could be accounted for by height (Dim 3) and base thickness (Dim 4) as seen in column PC 1 of Table 8, (even though all six geometric parameters would have to be included to fully represent the total system variability due to geometry). This agrees with the results found when evaluating a free body diagram of the seal, where it can be seen that the height and base thickness affected the seal performance. From Table 8 we can also see that four parameters account for half of the variance (the two first principal components). Also, see Fig. 15. To verify the results, we analyzed the measurement data for the seal height (Dim 3) in relation to the pump water output and found that there is a linear relationship. We believe that extra focus on these four parameters could lead to improvements of pump performance when considering a
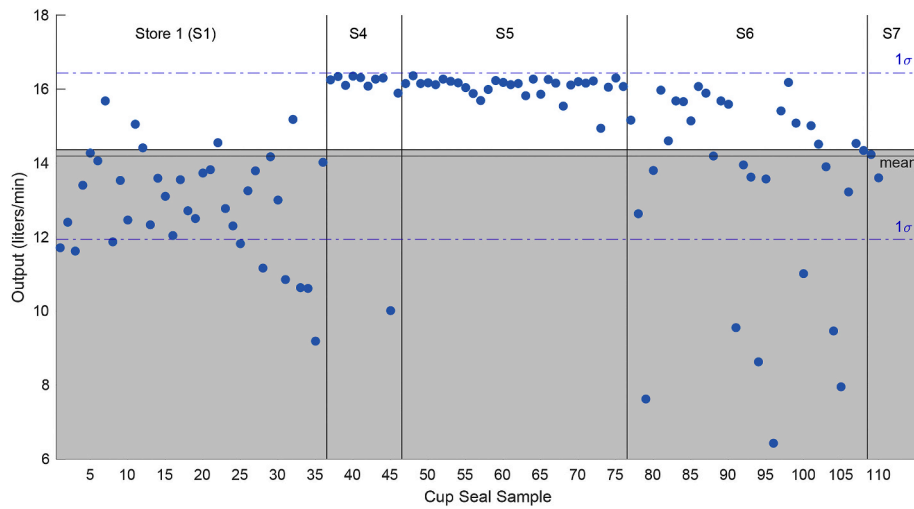
**Fig. 14.** Seal output for the zero-cycle pump performance test, values in the grey area are outside of specification (displayed in same order as tested).

**Table 8**
Geometric parameters affecting each principal component for the zero-cycle performance tests (PC 1–6).

| Parameter | PC 1 | PC 2 | PC 3 | PC 4 | PC 5 | PC 6 |
|---|---|---|---|---|---|---|
| Outer diameter (Dim 1) | −0.134 | **0.696** | 0.129 | 0.036 | **0.613** | −0.323 |
| Inner diameter (Dim 2) | 0.279 | −0.384 | **0.466** | **0.611** | 0.416 | 0.102 |
| Height (Dim 3) | **0.694** | 0.007 | −0.159 | 0.047 | −0.182 | **−0.677** |
| Base thickness (Dim 4) | **0.490** | 0.388 | −0.440 | 0.209 | 0.067 | **0.607** |
| Wall thickness (Dim 5) | 0.427 | −0.016 | **0.465** | **−0.719** | 0.177 | 0.231 |
| Wall angle (Dim 6) | 0.026 | **0.467** | **0.575** | 0.250 | **−0.618** | 0.080 |
| Variance explained by each principal component | 26.9% | 22.9% | 20.1% | 13.1% | 10.9% | 6.1% |



**Fig. 15.** Principal Component Analysis (PCA) plot showing the geometric parameters for the performance tests projected in the first two principal components.

redesign of seal geometry.

### 7.2. Material variations

The variables included in the PCA for the material variations were weight, volume, density, and hardness. The PCA showed that more than half of the material variability in both the static leak and dynamic pump performance tests could be accounted for by weight and density as seen in column PC 1 (first principal component) of Table 9, (even though all four material parameters would have to be included to fully represent the total system variability due to material). Since these two parameters affect how dense the material is, it is in agreement with our physical models. Also, see Fig. 16. We believe that extra focus on weight and density could lead to improvements of pump performance when considering a redesign of seal material.

### 7.3. Cup seal manufacturer

Out of the 110 cup seals purchased in Uganda, seven different manufacturers were identified and their performance analyzed and
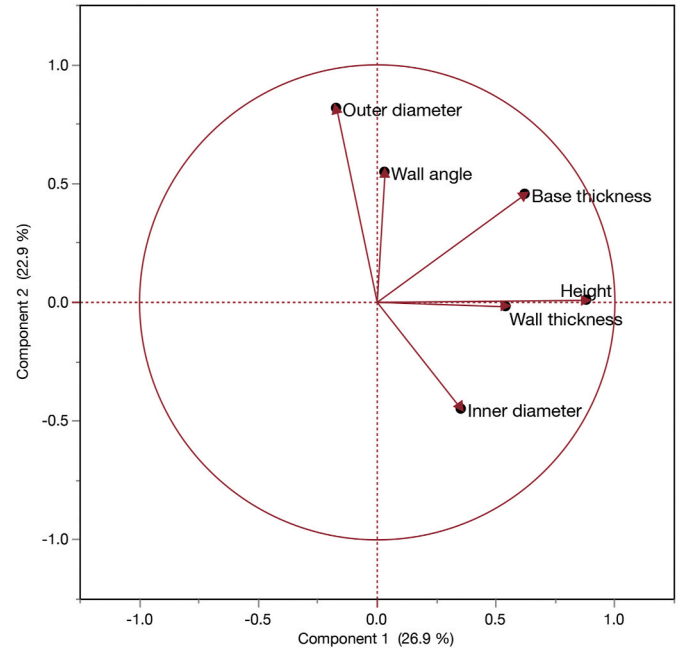
**Table 9**
Material parameters affecting each principal component for the zero-cycle performance tests (PC 1–4).

| Parameter | PC 1 | PC 2 | PC 3 | PC 4 |
|---|---|---|---|---|
| Weight | **0.683** | −0.040 | −0.067 | **−0.726** |
| Volume | 0.422 | −0.545 | 0.622 | 0.370 |
| Density | **0.586** | 0.296 | −0.483 | **0.579** |
| Hardness (durometer) | 0.107 | **0.783** | 0.612 | 0.02 |
| Variance explained by each principal component | 53.3% | 28.8% | 17.9% | 0.003% |

compared.

No difference was found for the static leak performance test, but for the dynamic pump performance test it was found that the output varied greatly between manufacturers (see Fig. 17). This explains in part why
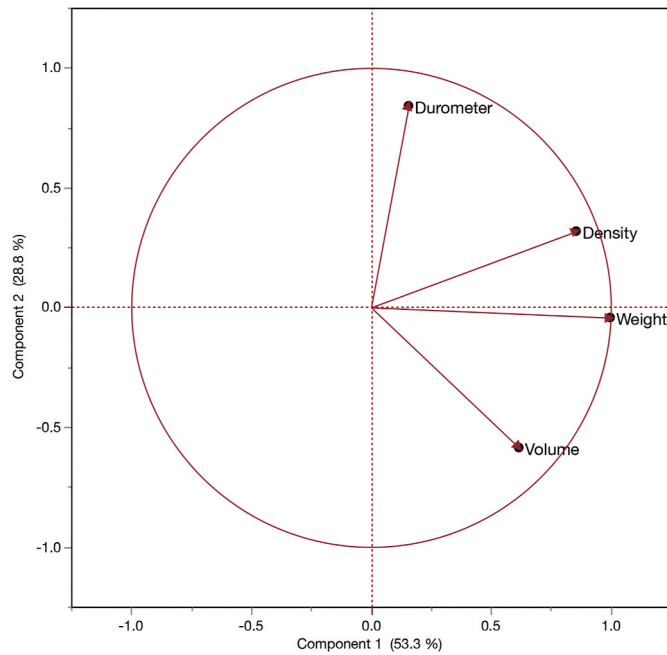
**Fig. 16.** Principal Component Analysis (PCA) plot showing the material parameters for the performance tests projected in the first two principal components.

the seals from store 4 and 5 performed so well (see Fig. 14) since they were principally manufactured by AOV. By comparing the measurements and material properties of the seals from each manufacturer, it was found that the seals from AOV have a higher percent of their seals within specifications for base thickness (Dim 4), wall angle (Dim 6), and hardness compared with the other manufacturers. Different manufacturing processes and material blends can also be factors affecting performance (not part of this research).

### 8. Discussion

This section displays the test results and discusses the robustness of the cup seal. For convenience, a summary of the test results can be found in Table 10. **Characterization of the Robustness of a New Cup Seal in the India Mark II/III Hand Pump System:**

In the static zero-cycle leak performance test (Section 5) we found
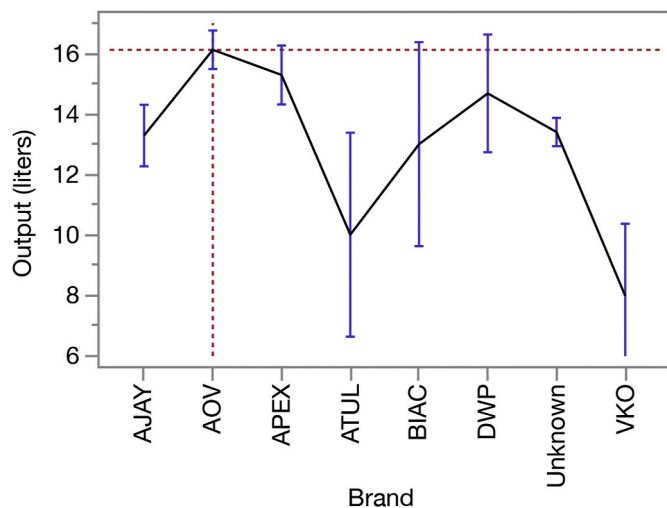


**Fig. 17.** The effect of different manufacturers on water output (best performing seal manufacturer highlighted).

that 95.5% of the seals functioned correctly at a simulated depth of 42 m. Important to note is that for the seals that did leak, the leak rate was 140 mL/min or lower. When considering the fact that there are always two seals installed in the plunger assembly, a leak at this rate will have a negligible impact on pump performance.

The dynamic zero-cycle pump performance test (Section 6) was done in laboratory settings where the pump depth was only 0.6 m instead of the average depth of 42 m. This could have influenced the water output due to a shorter water column above the plunger assembly, causing less pressure between the cup seal and the pump cylinder. The average water output was 14.188 L/min. Out of the 110 seals, 60 had an acceptable output above 14.36 L/min. It was found that for the seals that performed poorly, many of their parameters were out of specification. If the seals had been tested at 42 m, it is probable that the increased pressure would have improved seal performance. Fig. 14 displays the output for the 110 seals.

Variation in how the cup seals were stored by vendors (sometimes hanging on a string, piled in a bucket or on a counter with average temperature 28.9 °C and relative humidity 47.8%), together with variations in geometry and material properties did not affect the static leak performance once seals were installed. For the dynamic pump performance test, 50 seals (45%) performed below specification.

The geometry and material parameters that had the greatest impact on pump performance were height (Dim 3), base thickness (Dim 4), weight, and density. When comparing the different cup seal manufacturers, it was found that AOV and APEX performed better and more consistently over all.

### 9. Conclusions

Our focus for this paper has been on the cup seal of the India Mark II/III hand pump system. This was because the cup seal is the part of the pump system that caused the most dysfunction (Fagan et al., 2015; Ottosson et al., 2018; Erpf, 2004; Reynolds, 1992). In this paper we have examined off-the-shelf nitrile seals for the India Mark II/III mechanical hand pump, which is the most ubiquitous pump for accessing ground water in the developing world. We examined four facets of the cup seals (i) the geometric variation present in the off-the-shelf components, (ii) the material variation present in the off-the-shelf components, (iii) the leak performance in a static test simulating 42 m well depth, and (iv) the pump performance of the cup seals in a dynamic test. Measurement error was evaluated and analyses were performed to extract meaningful relationships and findings. This robustness study was carried out since it can be used to improve a product's design as shown in other research (McComb et al., 2018; Cheng et al., 2015).

The results show wide geometric and material variation to be present in the off-the-shelf cup seals. Surprisingly, the leak performance was shown to be incredibly robust to these geometric and material variations, yielding acceptable performance for the static zero-cycle leak test for all tested seals. However, in the dynamic zero-cycle test, only 55% of the seals yielded an output above the 14.36 L/min threshold, leaving room for improvement.

**Table 10**
Summary of cup seal tests.

| Test | Result |
| --- | --- |
| Geometry variation (Section 4) | 3 out of 6 dimensions had mean and median outside of specifications. See Table 1 for all results. |
| Material variation (Section 4) | Both the mean and median for the hardness were outside of specification. See Table 1 for all results. |
| Static leak test (Section 5) | Geometric and material variations had minimal or no effect on leak at time of cup seal installation. |
| Dynamic pump test (Section 6) | The average output for the zero-cycle test was 14.188 L/min with an output range between 6.425 and 16.36 L/min 60 out of the 110 seals had an output above 14.36 L/min (55%). |

With a track record of over 40 years, the cup seal design has proven to be a robust design that is well suited for low cost production and small sales margins. These characteristics, together with the findings in this paper, make the cup seal well suited for global development, and as such, a candidate for geometry and material updates to become even more robust.

**Why the baseline performance matters:** From a scientific point-of-view, and a design point-of-view, it doesn't matter what the baseline performance is as long as it is known. Knowing the baseline is essential, so that observed performance can be compared to baseline performance and a change in performance can be declared. We believe that this is a method that engineers and designers can use as they work on improving the performance of existing products. In this paper, we have established that wide variations in geometric and material properties produce little to no leakage for off-the-shelf cup seals tested statically but that for the dynamic pump performance test it was found that only 55% of the tested seals passed, leaving room for improvement.

Our future work is to understand how and to what degree seals can be improved in terms of both material and geometry by developing a wear model for the cup seal. We will also link the performance of the India Mark II/III to social impact categories found in literature (Rainock et al., 2018) and to UN's sustainable development goals (United Nations Department, 2018).

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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