Development of a Borehole Chlorinator for Small Communities

by

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INTRODUCTION

Access to a safe drinking-water supply is an important factor in eliminating waterborne diseases in a community. Groundwater sources, particularly boreholes, are used extensively in rural areas, villages and densely populated informal settlements. Owing to seepage from sources such as pit latrines, this groundwater may be polluted with pathogenic micro-organisms, particularly during the rainy season when the water table is near the surface. Polluted groundwater may spread waterborne diseases such as cholera and typhoid.

Rivers, lakes and other surface waters generally require filtration before disinfection, at least during some period of the year, as the chlorination of turbid water does not necessarily guarantee disinfection. Most groundwaters, on the other hand, are clear and may be effectively disinfected by chlorination without pretreatment.

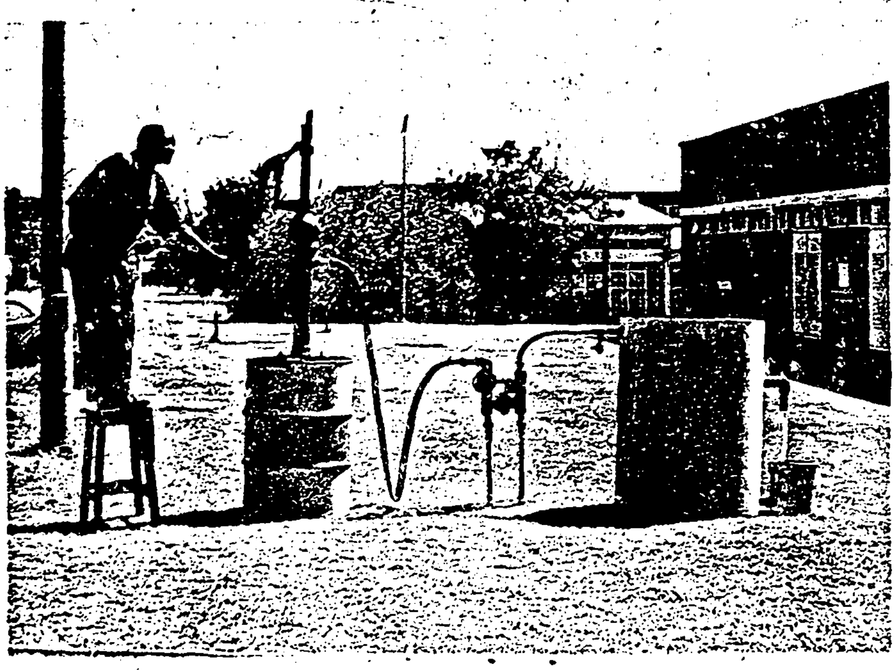
In response to a request from the Government of Bophuthatswana for assistance with the disinfection of groundwater known to be polluted, which is used as a water source for a densely populated informal settlement, the National Institute for Water Research (NIWR) has developed a borehole chlorinator.

The chlorinator uses calcium hypochlorite (trade namd HTH) tablets and can disinfect up to 10 000 ℓ of water per day. It operates without electricity and is suitable for use with mechanically operated pumps discharging up to 40 ℓ/min and with hand pumps. For larger water supplies, other commercially available equipment should be used.

The chlorinator is installed in-line between the pump and a storage tank which provides the retention time required for adequate disinfection. A typical arrangement is shown in Figure 1. For hand-pumped boreholes which do not have a storage tank, a 900 ℓ asbestos cement tank, with a baffle wall to prevent short-circuiting of the flow, is provided. The water is not accessible to the user until it is discharged from the tank, after having been disinfected, as illustrated in the photograph of the laboratory arrangement with the hand pump.

Effective operation of the chlorinator depends on the appointment of a reliable person at each installation to replenish the chlorine tablets daily. This is a simple operation which only takes about two minutes and can be carried out as part of a daily routine, for example when the pump is started each morning. All the individual members of the community must follow good hygienic practices to prevent the water becoming recontaminated after disinfection.

Eighteen of these chlorinators, installed on a trial basis in Bophuthatswana, have been delivering safe, coliform-free water consistently for more than six months, provided the chlorine tablets are replenished daily. The local people have accepted the slight chlorine taste in the water, following education by a local health officer on the benefits of drinking disinfected water. A further 21, optimiz-



Laboratory hand pump, chlorinator and container tank.

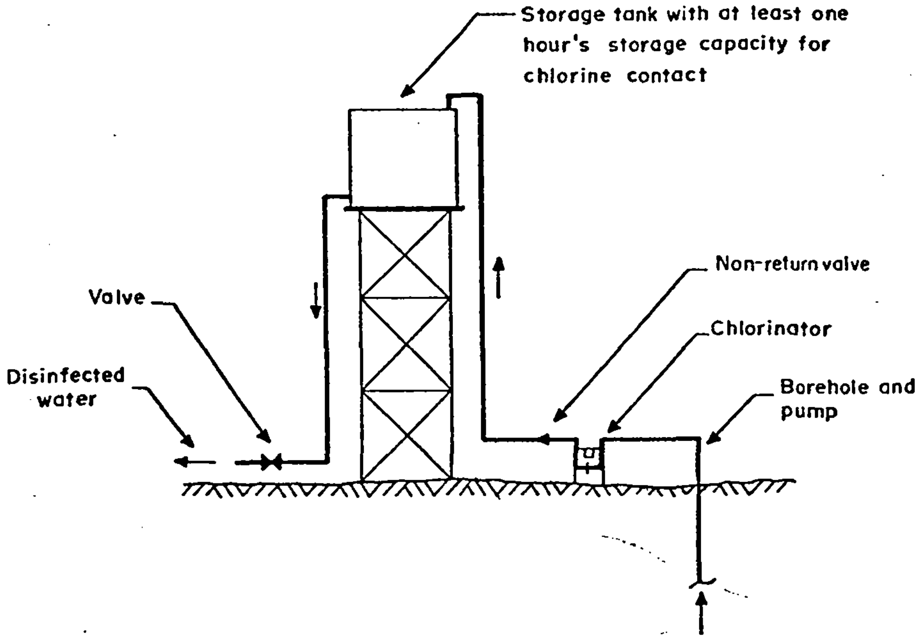


FIGURE 1. TYPICAL ARRANGEMENT OF CHLORINATOR AND EXISTING STORAGE TANK.

ed chlorinators are currently being installed in the same area.

The current cost (1982) of the chlorinator and associated pipework is approximately R300. With a 900 ℓ contact tank plus installation on a concrete slab base, the estimated total cost is R800, excluding transport costs. The average cost to disinfect 1 000 ℓ of water using HTH tablets is about 4 cents.

The chlorine tablets, the tablet containers and the 900 ℓ contact tanks are now being manufactured commercially in accordance with NIWR specifications. The associated pipework comprises standard PVC and steel pipe fittings, which are detailed in a leaflet available from the supplier of the tablet containers. (Refer to advertisement elsewhere in this journal.)

The NIWR has carried out extensive tests on the chlorinator, both in the laboratory and in the field. The final design of the unit and the results of the chlorine dosage and bacteriological tests are reported in this paper.

METHODS OF CHLORINATION

Chlorination is the most commonly used disinfection method for water supplies in South Africa, and is considered to be the most suitable method for small-scale groundwater supplies.

Chlorine is commercially available as a pure gas, a liquid (sodium hypochlorite) and a solid compound (calcium hypochlorite). All these forms are approved by the Directorate of Health for long-term use in drinking-water supplies. The gaseous form is dangerous to use unless the equipment is operated by trained personnel at a water treatment plant. Sodium hypochlorite is supplied as a 15% chlorine solution, but this concentration gradually reduces to less than 10% after a few months' storage. Calcium hypochlorite (HTH) is supplied in granular or tablet form, with 70% available chlorine, and is relatively stable. It is also safe to store and handle, provided the supplier's directions are followed. HTH was adopted as the most suitable form of chlorine for the borehole chlorinator.

HTH chlorinators are commonly used for private swimming-pools, but this type of equipment is not designed for intermittently operated borehole pumps. Other small-scale chlorination equipment requires adjustment of valves and regular maintenance for proper operation or can only be installed at the discharge point into a storage tank rather than at a convenient location near the pump. The NIWR undertook to develop a chlorinator which would overcome these problems and therefore be more suitable for village use.

FACTORS AFFECTING CHLORINE DISINFECTION

The minimum chlorine dosage necessary to ensure effective disinfection depends on the characteristics of the particular water. A sample of water from each borehole should be laboratory tested to determine whether it is bacteriologically polluted and, if so, the chlorine dosage necessary for disinfection. (The local office of the Directorate of Health can advise on sampling methods and arrange for the tests to be carried out.)

Each water has a specific chlorine demand, which is the amount of chlorine required to react with substances in the water to form chlorine compounds. These compounds are either weak or non-disinfectants, and it is only when the demand is satisfied that the remaining chlorine, known as the free residual chlorine, is available for disinfection. The chlorine demand is primarily affected by the presence of ammonia, soluble iron, manganese, sulphur compounds and organic substances in the water. Some of the organic compounds formed can give the water an objectionable taste.

The pH of the water (a measure of its acidity or alkalinity) is another important factor as it governs the forms in which the free residual chlorine occurs. Chlorination is most effective at a pH

Placing a chlorine tablet in the tablet container value of less than 6,5, which decreases to minimum effectiveness at above pH 8,4, owing to the change in the form of the free residual chlorine from the unionized form HOCl, a strong disinfectant, to the ionized form OCl^-, a relatively weak disinfectant. the pH of borehole water is generally less than 7,7, although it is likely to be higher in limestone areas. The required free residual chlorine for effective disinfection at different pH values is discussed in the section on bacteriological tests. The minimum chlorine dosage necessary for disinfection of a particular water is the chlorine demand plus the required free residual chlorine.

The chlorine must be rapidly mixed with the water, followed by a period of time for the chlorine to react before the water is used by the consumer. This contact period should be at least 15 minutes, preferably longer. It is generally provided by a storage or contact tank between the chlorine injection point and the point of supply.

DESIGN AND OPERATION OF THE CHLORINATOR

The borehole chlorinator has been designed to be simple and safe to operate, reliable and relatively inexpensive. It is robust, being made of non-corrodible materials and has no mechanical parts, and therefore should require little maintenance. The unit can be installed at any convenient location in-line between the pump and the storage or contact tank.

The chlorinator and the tablet container are shown schematically in Figures 2 and 3. The principle of operation is that a proportion of the total flow (up to 7%) is bypassed through the chlorine tablet container, which contains 30 to 140 mg/ℓ of chlorine. This concentrated solution is then reintroduced into the main flow, where it is diluted to between 2 and 10 mg/ℓ (normally in the range 3 to 7 mg/ℓ). The proportion of the bypass flow is regulated by the diameter of the opening in the orifice plate in the main flow line. The optimum diameter of the orifice for a particular installation depends on the pumping rate (for a constant flow rate pump) or the type of reciprocating pump, and also on the chlorine demand and pH of the particular water. Once the optimum orifice plate is fitted at a particular installation, there should be no need to change it, unless the type of pump or the water characteristics change significantly. The orifice plate is bolted between flanges so that it cannot easily be tampered with. The head loss through the orifice plate is 1 to 2 kPa (100 to 200 mm water head).

The chlorine tablet container has been specially designed so that the top surface of the upper tablet is eroded by the jets of water impinging on it. The turbulence prevents an insoluble calcium carbonate layer blanketing the tablet and keeps the insoluble material suspended until it flows out of the container. With a constant rate pumped flow, at least 1 ℓ/min bypass flow is necessary to maintain sufficient turbulence in the container, but this is reduced in the case of reciprocating pumps because of the intermittent surge flow on each pump stroke. The inlet jets of water pass through the

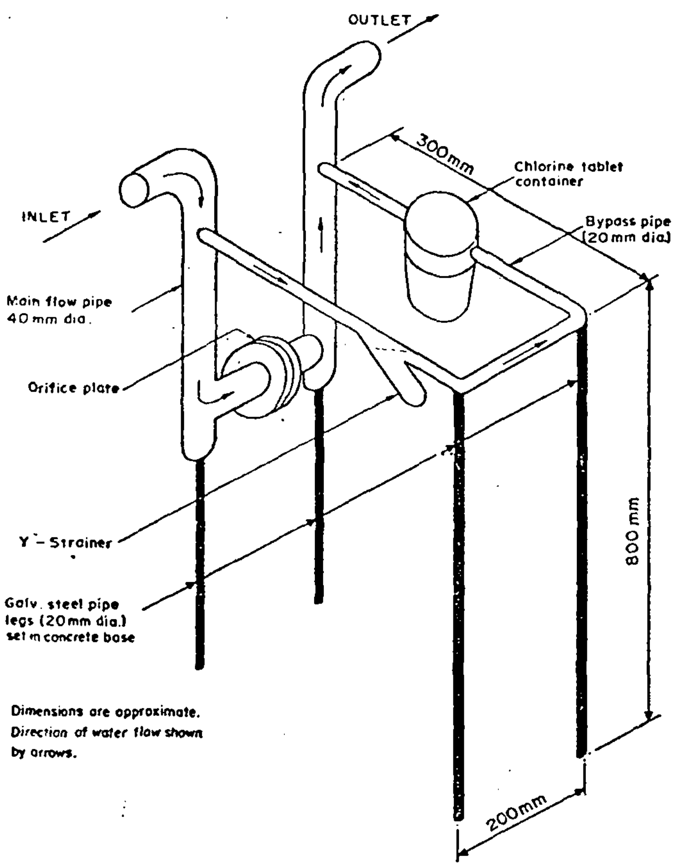


FIGURE 2. **CHLORINATOR**

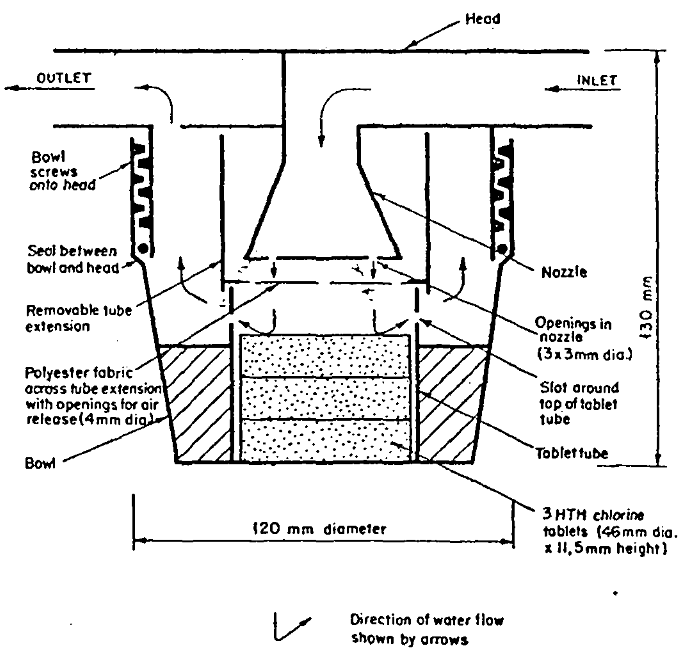


FIGURE 3. **CHLORINE TABLET CONTAINER**

polyester fabric, which reduces the force of the jets so that, during pump operation, the chlorine concentration in the container remains in the range 30 to 140 mg/ℓ. The openings at the edge and centre of the fabric allow air to escape.

When the pump is not operating, the erosion ceases. The tablets continue to dissolve slowly by diffusion, but the rate of dissolution is reduced as the concentration in the container increases. When the pump restarts there is an immediate high chlorine dosage, but this rapidly diminishes to the normal dosage rate within about three minutes. Test results show that the high initial chlorine dosage is diluted in the contact tank, so that the chlorine concentration in the water discharged from the tank is acceptable.

The calcium hypochlorite (HTH) tablets are safe to handle, provided the operator rinses his hands afterwards. The 70% chlorine concentration remains stable for a year or more if the tablets are kept in an air-tight, non-corrodible container and stored in a cool, dry place. The tablets used in the chlorinator are 46 mm in diameter by 11,5 mm in height, with a mass of 34,5 g. The chlorinator has been designed so that swimming-pool 'booster' tablets will not fit into the tablet container. These tablets are unsuitable as they dissolve too quickly for this application. Some of them are made from isocyanurates, which are not approved by the Directorate of Health for the long-term disinfection of drinking-water.

Each tablet can disinfect approximately 4 000 ℓ of water, and the container can hold three tablets. The capacity of the chlorinator is given as 10 000 ℓ of disinfected water, which includes a built-in safety factor. The tablets should be replenished daily, otherwise they are likely to disintegrate partly and to be difficult to remove. Depending on the water consumption from the particular borehole, one, two or three tablets should be inserted. The number of tablets used can readily be established after a few days' operation. The tablets are replenished simply by unscrewing the bowl of the container. The bowl and the polyester fabric should be rinsed clean at the same time.

Rapid mixing of the chlorine with the water takes place in the pipework, as the injection point is in the turbulent zone after the orifice plate. The design of the 900 ℓ asbestos cement contact tank shown in Figure 4 provides the required retention time for sufficient chlorine disinfection. Details are available from the supplier of the chlorine tablet containers. If a galvanized steel tank is used as a storage tank it should be painted internally with a suitable non-toxic, phenol-free paint to prevent corrosion of the tank, which will be accelerated by chlorine in the water. The pipework between the chlorinator and the tank should be made from material resistant to chlorine, such as PVC or polyethylene.

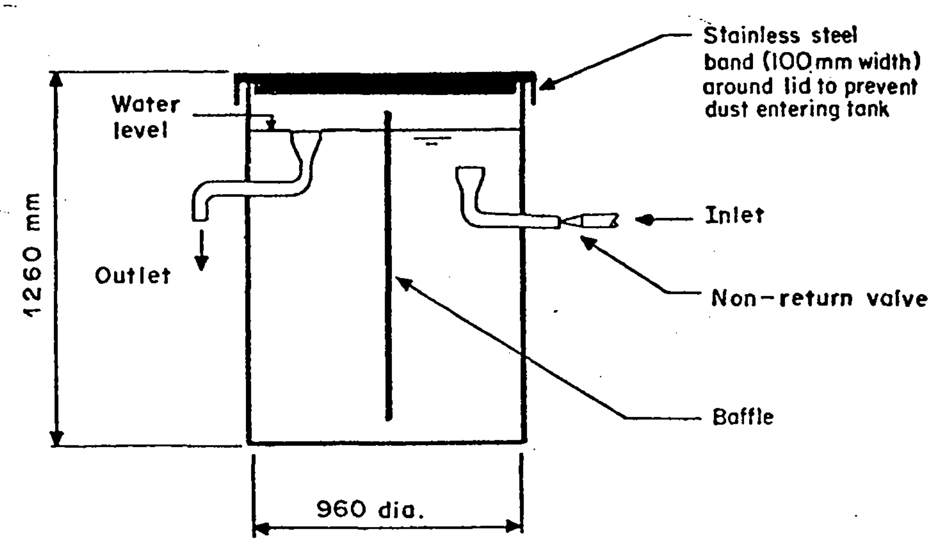


FIGURE 4. CONTACT TANK (900 ℓ)

CHLORINE DOSAGE TESTS

The following tests were carried out by the NIWR to evaluate the chlorinator under various operating conditions:

(a) Continuous, constant flow (as would occur with a centrifugal pump) of 20, 25, 30 and 40 ℓ/min.
(b) Intermittent constant flow (the chlorinator operated intermittently at 40 ℓ/min).
(c) Interrupted flow (the chlorinator filled with tablets and then left overnight to determine the shock chlorine dosage on start-up).
(d) Hand pump operation (the chlorinator was tested with three different types of reciprocating hand pumps, designated A, B and C).
(e) Monitoring of chlorinators have been installed in the field, over a period of six months.

Method

Total chlorine determinations for tests (a) to (d) were made by the DPD titrametric method [1] for chlorine concentrations up to 20 mg/ℓ, the samples above 10 mg/ℓ being diluted first. The thiosulphate titrametric method [1] was used to analyse samples with chlorine concentrations above 20 mg/ℓ. The chlorine determinations for test (e) were made using a Lovibond 100 comparator.

Tests (a), (b), (c) and (d-A) were carried out at the NIWR laboratory, Pretoria, using municipal water which had been passed through an activated carbon column to reduce the total chlorine concentration to 0,4 mg/ℓ or less. This residual chlorine was measured and subtracted from the titration results. The temperature of the water was 16 to 20°C and the pH was 8,0 to 8,8.

For tests (a), (b) and (d-A), the samples were titrated within 3 min of the chlorine being added. A check series of titrations using samples with known chlorine concentrations gave results that were 85% of the known concentration. The titration results have therefore been adjusted by a factor of $\frac{1}{0,85}$.

For test (c) the samples were stored in stoppered glass bottles for at least 1 h before titration. Therefore, on the basis of the breakpoint curve determined for the municipal water (Figure 5), all the titration results have been adjusted by adding 3,1 mg/ℓ chlorine.

Tests (d-B), (d-C) and (e) were carried out in the field at boreholes where trial chlorinators had been installed. DPD analyses showed that the chlorine demand was negligible, and therefore no adjustment was made to the measured results. The temperature of the water was 16 to 22°C and the pH 7,0 to 7,7.

Results

(a) *Continuous constant flow tests*
These results are shown graphically in Figure 6. The recommended orifice plate sizes are:
20 to 25 ℓ/min flow rate – 20 mm diameter orifice
26 to 40 ℓ/5min flow rate – 24 mm diameter orifice.
The chlorine dosages were between 2 and 10 mg/ℓ.

(b) *Intermittent constant flow test*
The chlorinator was filled with three tablets and operated at 40 ℓ/min for intermittent periods during the day, with a 24 mm diameter orifice plate installed. The test results are shown in Figure 7.
The results show that the chlorine dosage was consistently within the range 2 to 10 mg/ℓ. The chlorinator was operating for a period of 5 h, and therefore 12 000 ℓ of water were dosed with chlorine. Approximately 50% of the bottom tablet remained at the end of the test.

(c) *Interrupted flow test*
The chlorinator was filled with tablets, operated for 20 min so that the water in the contact tank was dosed with chlorine, and then left

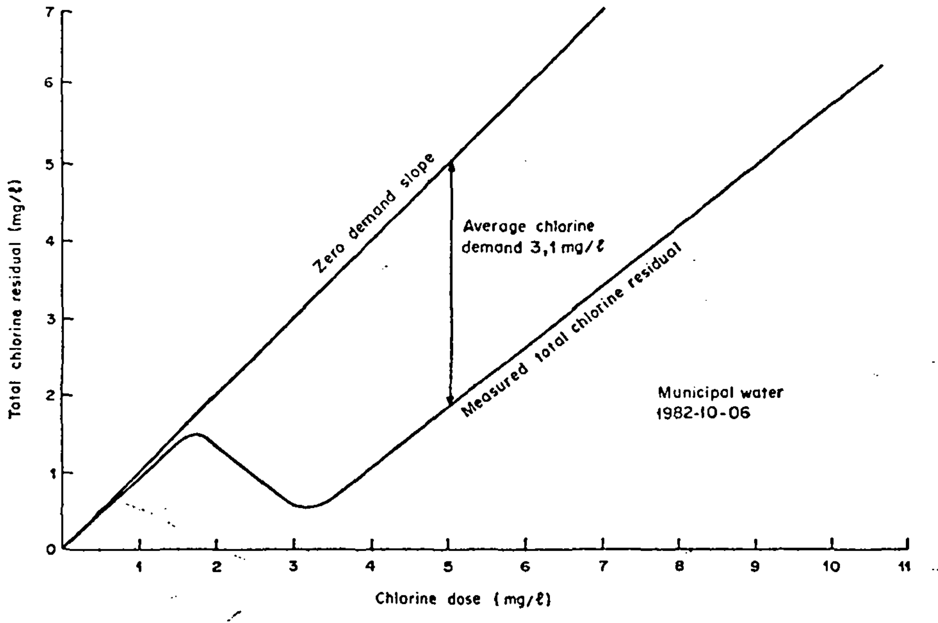


FIGURE 5. **CHLORINE BREAKPOINT CURVE**

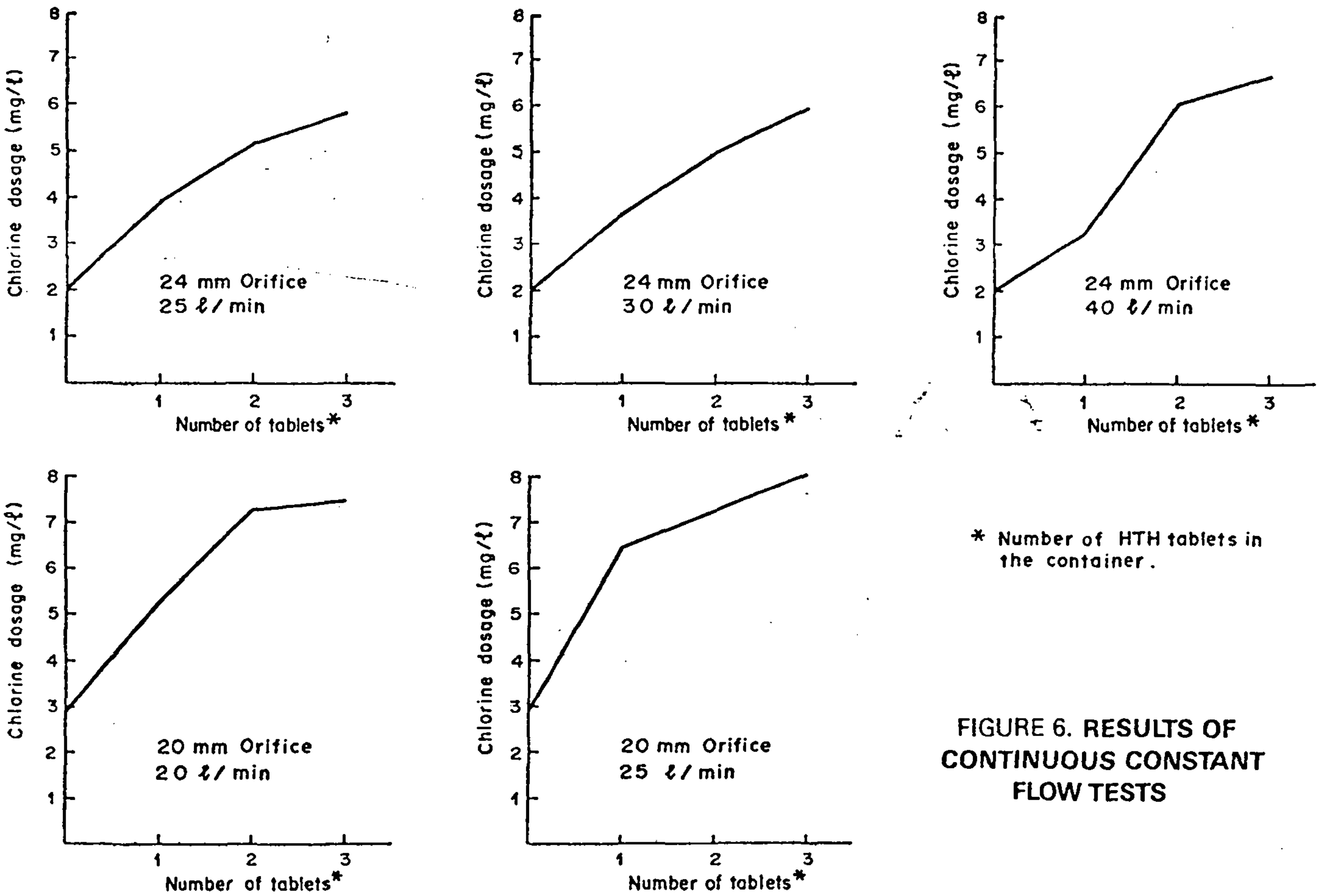


FIGURE 6. **RESULTS OF CONTINUOUS CONSTANT FLOW TESTS**

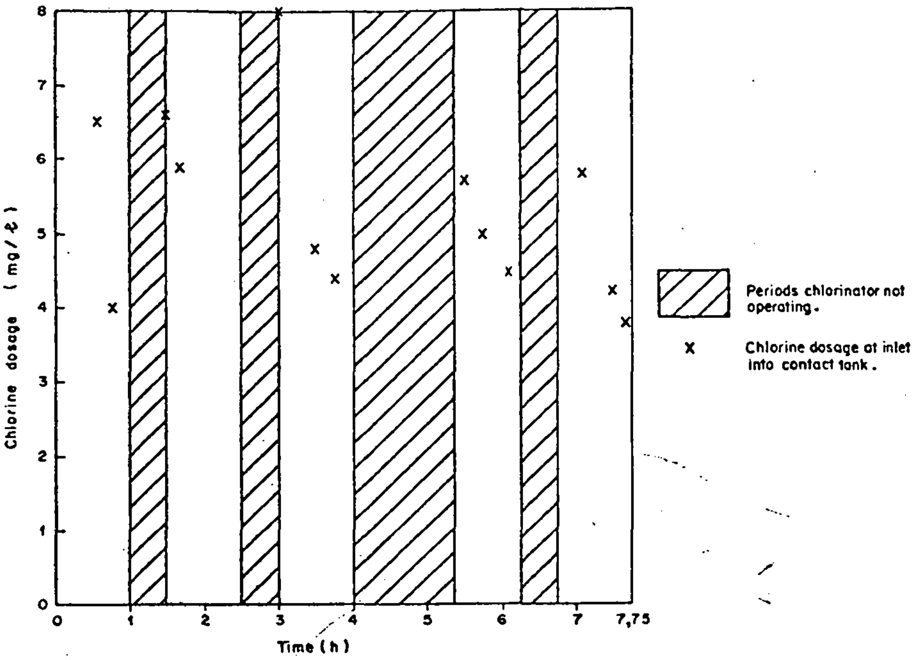


FIGURE 7. **RESULTS OF INTERMITTENT CONSTANT FLOW TESTS**
(Chlorinator filled with 24 mm dia. orifice plate and initially filled with 3 chlorine tablets. Operated intermittently at 40 ℓ/min.)

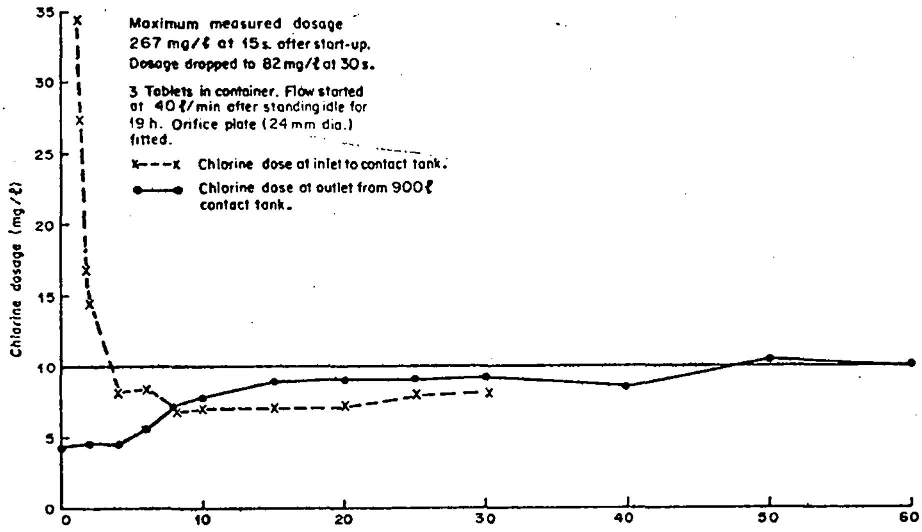


FIGURE 8. **RESULTS OF INTERRUPTED FLOW TESTS.**

idle for 19 h. The flow was then restarted at 40 ℓ/min and frequent samples taken from both the inlet and the outlet of the contact tank. The test results are shown graphically in Figure 8.

The objective of the test was to determine the highest 'shock' chlorine dosage that could occur owing to the chlorine concentration building up in the container over a prolonged period of disuse. The results show that the chlorine dosage at the inlet to the tank was very high (more than 200 mg/ℓ) for a few seconds, but diminished within 3 min to 8 mg/ℓ. However, this high initial dosage was diluted in the contact tank, so that the chlorine concentration at the outlet from the tank only marginally exceeded 10 mg/ℓ.

(d) *Hand pump operation tests*

Tests were carried out with the following types of reciprocating hand pumps:

Type A – lever hand pump (shown in the photograph of the laboratory arrangement).

Type B – rotary hand pump (operated by turning a wheel).

Type C – deep well, manually operated pump. This type of pump is also known as a 'donkey' pump as it can be operated by an animal walking around a central shaft.

The reciprocating pumps have a different effect to the constant flow pumps because of the surge flows which occur once or twice during each pump cycle. The surge flow is much greater than the average pumped flow rate, and therefore erosion of the chlorine tablet takes place mainly during the surge phase of the cycle. Test results showed that the optimum diameter of the orifice plate was different for each type of pump, owing to the different characteristics of the surges.

The chlorine dosage for each pump depended on the rate at which the pump was operated and the number of tablets in the container. The test results are summarized in Table 1. These results show that, for each pump, a single orifice plate gave chlorine dosages that were normally between 2 and 10 mg/ℓ over the range of operating conditions.

(e) *Monitoring of chlorinators in the field*

Samples are taken regularly from

TABLE 1 : Chlorine dosages with reciprocating hand pumps

HAND PUMP DETAILS								CHLORINATOR		
Type of hand pump	Pump flow (ℓ/min)			Pump cycles (surges/min)			Optimum orifice plate dia. (mm)	Total chlorine dosage[a] (mg/ℓ)		
	Slow	Normal	Fast	Slow	Normal	Fast		Minimum	Average	Maximum
A	10	25	30	38	60	90	24	2,5	4	10
B	15	20	30	32	38	43	33	1,30 [b]	5	16 [b]
C [c]	15	30	50	50	60	70	29	2,0	4	9

a) Chlorine dosage measured at inlet into contact tank. Dosages are for continuous operation, not high 'shock' dosages which would occur after interrupted flow.

b) These extreme chlorine dosages occurred only at abnormally slow and fast pumping rates. Chlorine concentrations are diluted to acceptable levels (10 mg/ℓ maximum) in the contact tank.

c) Pump Type C is usually operated at a reasonably constant rate, with only a small variation between the slow and fast cycles/min. However, this type of pump is difficult to operate manually and, therefore, is generally pumped for only a few seconds at a time, resulting in intermittent operation and a wide variation in pumped flows.

TABLE 2 : Test results from borehole with trial chlorinator installed[a]

TEST	TEST RESULTS											SABS LIMITS (3)	
Date 1982	03-30	04-13	04-19	05-03	05-10	05-24	06-28	06-14[b]	07-01	07-19	09-07	Recommended	Maximum allowed
Coliform organisms per 100 mℓ	0	0	0	0	0	0	0	17	0	0	0	0	10
E. coli per 100 mℓ	0	0	0	0	0	0	0	16	0	0	0	0	0
Total viable organisms (colonies per mℓ)	3	1	1	3	1	2	16	290	3	7	14	100	-
Free residual chlorine (mg/ℓ)	3,0	5,0	3,0	3,0	4,0	4,0	2,5	0,0	3,6	4,0	2,0	-	-
Total residual chlorine (mg/ℓ)	4,0	5,0	3,0	3,3	4,5	4,0	2,5	0,0	4,7	4,0	2,5	-	-

a) This borehole has a hand pump Type C (operated manually). The chlorinator has a 29 mm dia. orifice plate and was operated with one or two chlorine tablets in the tablet container.

b) No HTH tablets were in the chlorinator at the time the sample was taken on 14 June.

TABLE 3: Results of chemical analysis of borehole with trial chlorinator installed*

pH	7,5
Total dissolved solids	180 mg/ℓ
Total hardness as $CaCO_3$	54 mg/ℓ
Nitrate as N	0,8 mg/ℓ
Sulphate as SO_4	7 mg/ℓ
Chloride as Cl	18 mg/ℓ
Total alkalinity as $CaCO_3$	115 mg/ℓ
Chemical oxygen demand	15 mg/ℓ
Fluoride as F	880 µg/ℓ
Cadmium as Cd	5 µg/ℓ
Copper as Cu	< 25 µg/ℓ
Iron as Fe	< 45 µg/ℓ
Zinc as Zn	680 µg/ℓ

* Sampling date: 16 June 1982.

These results are within the limits (where applicable) recommended by the S.A. Bureau of Standards for drinking-water[3].

the boreholes having trial chlorinators and tested for micro-organisms and chlorine. The test results over a four-month period for a borehole at which a hand pump type C (donkey pump) is installed, are given in Table 2. This is a public borehole operating for 4 to 5 h/d. The chlorinator has a 29 mm orifice plate and uses two chlorine tablets per day.

The test results show that the raw water from the borehole is polluted (sample taken 14 June), but the chlorinated water consistently meets the bacteriological requirements for drinking-water[3], provided the HTH tablets are replenished daily. The chlorinated water has very little chlorine taste and has been readily accepted by the local population. Results of chemical analysis of the water from this borehole, which meets the requirements for drinking-water[3], are given in Table 3.

Problems revealed during operation of the trial chlorinators in the field for over six months have been overcome in the commercial model, 21 of which are now being installed in the same area.

BACTERIOLOGICAL TESTS

Bacteriological tests were carried out to evaluate the disinfection effectiveness of the chlorinator. These test results are summarized here and reported in detail elsewhere[2].

The tests were carried out by seeding the municipal water with the bacteria *Streptococcus faecalis*, a faecal indicator organism. Of the several different indicators tested initially, including *Escherichia coli, S. faecalis* was the most resistant to inactivation by chlorination. It is well known that cholera and typhoid bacteria are less resistant to chlorine than *E. coli.*

The chlorinator was operated at its maximum design flow rate of 40 ℓ/min, with a 24 mm diameter orifice plate and one chlorine tablet in the container. The samples were taken from the outlet of the 900 ℓ contact tank illustrated in Figure 4. The water flowing into the chlorinator was seeded with more than 2×10^5 *S. faecalis* organisms per 100 mℓ, which far exceed the number of organisms expected to occur in groundwater. Two series of tests were run, the first with the water at a pH value of 7,7 and the second at pH 8,8.

The bacteriological tests were therefore carried out under the most stringent operating conditions, and the inflowing water was seeded with a very high concentration of chlorine-resistant bacteria. The test results showed that a five-log reduction in viable organisms, which is a measure of satisfactory disinfection, was achieved with a free chlorine residual of 0,35 mg/ℓ at a pH value of 7,7 and 1,0 mg/ℓ at pH 8,8.

CONCLUSIONS

The results of the chlorine dosage tests show that the borehole chlorinator can reliably dose a minimum of 2 mg/ℓ chlorine when used with a constant flow pump (between 20 and 40 ℓ/min flow rate) or with a reciprocating pump (at average pump rates). The total chlorine concentration at the outlet of the 900 ℓ contact tank should rarely exceed 10 mg/ℓ. The bacteriological test results show that effective disinfection is achieved with a free chlorine residual of 0,35 mg/ℓ for water with a pH of 7,7 or less, and 1,0 mg/ℓ for a pH of more than 7,7.

The field trials indicate that the chlorinator is robust, can be operated reliably by villagers and that the chlorinated water is accepted by the local people after education by a health officer. The chlorinator is therefore suitable for use within the limitations defined in the introduction to this paper.

ACKNOWLEDGEMENTS

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