

Mini Pump Controller (MPC-1)

Technical specifications and design detail

See the separate *User Guide* for an overview of the MPC-1, kit assembly suggestions and test procedure.

MPC-1 block diagram

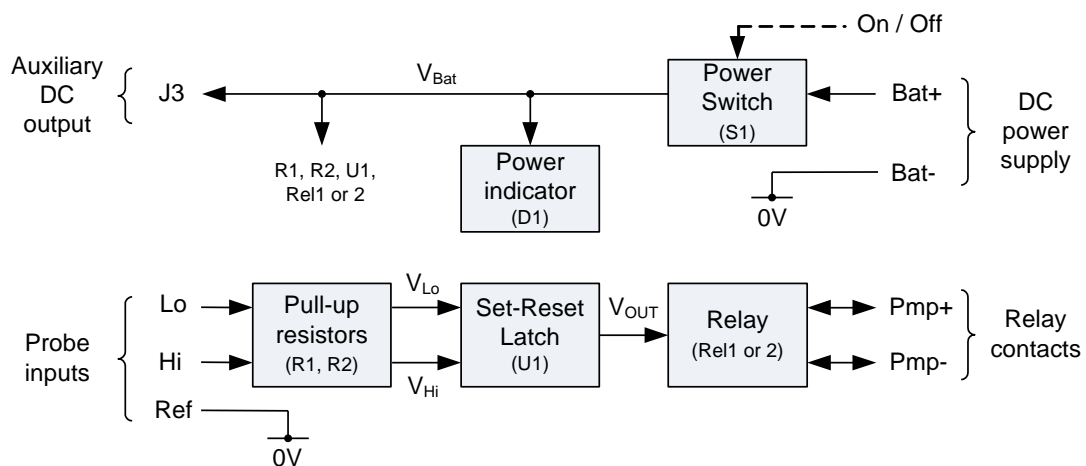
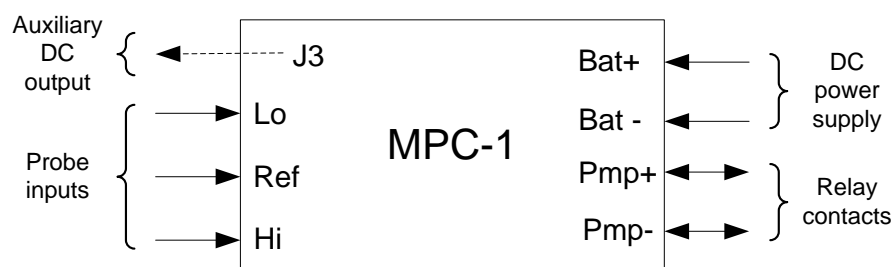


Table of contents

	Topic	Page
1	Specifications	2
2	Circuit design	3
	2.1 Probes and pull-up resistors	3
	2.2 Set-Reset latch	5
	2.3 Relays	6
	2.4 DC power supply voltage range	7
	2.5 Power switch and power indicator	8
3	Suitable power supplies and batteries	9
	3.1 Basic requirements	9
	3.2 Batteries considered	9
	PP3 size: 8.4 V NiMH, and 9V alkaline	10, 12
	AAA size: 8 x 1.2 V NiMH, and 8 x 1.5 V alkaline	13

1 Specifications



Parameter	Typical range or value		
DC power supply Bat+, Bat-			
Voltage	8 V – 15 V		
Current drain	Supply voltage	9 V	12 V
	Standby (relays de-energised)	10 mA	15 mA
	With Zettler relay energised	25 mA	35 mA
	With Goodsky relay energised	35 mA	50 mA
Suggested batteries	8.4 V or 9.6 V NiMH, size PP3 9 V alkaline, size PP3 8 x AAA or AA primary or secondary cells 12 V sealed lead acid		
Probe (water path) resistance			
Lo probe to Ref probe (R_{Lo})	>540 k Ω sensed as Lo probe 'dry' (activates relay) <540 k Ω sensed as Lo probe 'wet'		
Hi probe to Ref probe (R_{Hi})	>140 k Ω sensed as Hi probe 'dry' <140 k Ω sensed as Hi probe 'wet' (de-activates relay)		
Relay contact rating Pmp+, Pmp-			
Standard relay: Zettler AZ951-1C-12DSE	1 A / 30 V		
Optional relay: Goodsky RW-SH-112D	10 A / 24 V		

2 Circuit design

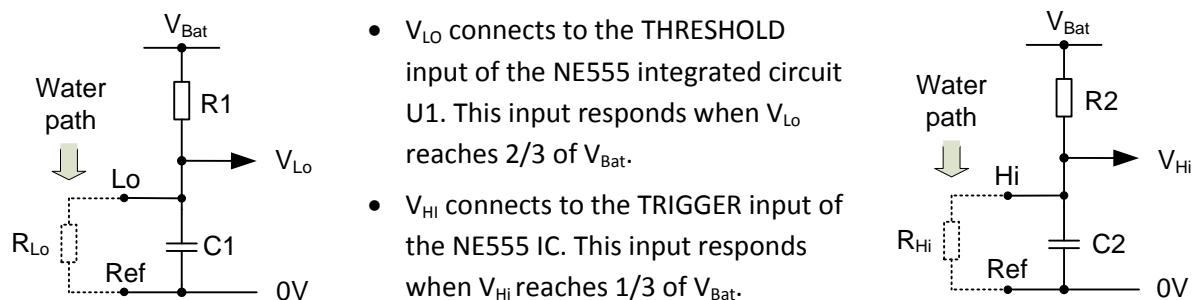
- Refer also to the MPC-1 Block diagram on page 1, and documentation provided with the kit
- In all calculations, circuit components are assumed to be ideal. Manufacturing tolerances and temperature effects are ignored unless they contribute significantly to performance
- Unless otherwise stated, voltages are quoted relative to Gnd (0 V).

2.1 Probes and pull-up resistors

Input voltage dividers

The MPC-1 is controlled by the water path resistances between the Lo and Ref probes (R_{Lo}), and the Hi and Ref probes (R_{Hi}). Pull-up resistors R1 and R2 form voltage dividers with these water path resistances, converting resistance changes to voltage changes. Capacitors C1 and C2 reduce the effects of high-frequency electrical noise induced on the probe assembly and connecting wires.

Figure 2-1 Lo and Hi probe voltage divider circuits



With water path resistance information, R1 and R2 values can be chosen to ensure that V_{Lo} and V_{Hi} fall below these THRESHOLD and TRIGGER voltages when the water surface touches the probe tips.

Water path resistance

A bicycle-spoke probe assembly (as used with model pump stations) was used in the following test circuit to measure water path resistance under various conditions. Table 2-1 presents the results.

Figure 2-2 Water path resistance test circuit and breadboard layout

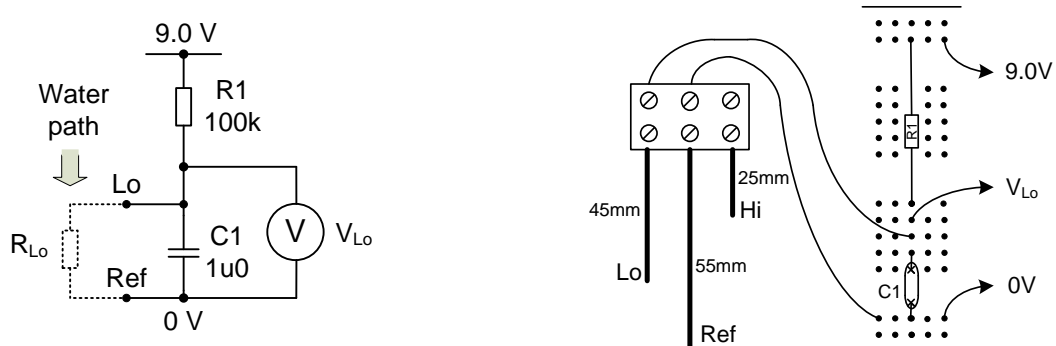


Table 2-1 Water path resistance measurements

Each V_{Lo} voltage recorded here is the average of several measurements with different water samples. These V_{Lo} voltages are used in the formula developed below to calculate the R_{Lo} values in the table.

Calculating R_{Lo} from V_{Lo} and $R1$ (refer to Figure 2-2)	Water quality	Lo probe tip position	Probe voltage V_{Lo}	Path resistance R_{Lo}
$\frac{R1}{R_{Lo}} = \frac{(9.0V - V_{Lo})}{V_{Lo}}$ $so R_{Lo} = \frac{R1 \cdot V_{Lo}}{(9.0V - V_{Lo})}$	Tap water	Just touching water surface	2.1 V	30 k Ω
		5 mm below water surface	1.8 V	25 k Ω
	Rain water (tank)	Just touching water surface	5.2 V	140 k Ω
		5 mm below water surface	4.1 V	84 k Ω

Figure 2-3 Resistor R2 selection

Assuming the worst-case water path resistance of 140 k Ω (Table 2-1), a value of 280 k Ω for R2 will bring the Hi probe voltage down to 1/3 of V_{Bat} (e.g. 3 V with a 9 V supply) when the water surface touches the probe tip.

Use the nearest preferred E12 value of 270 k Ω (250 mW) for R2

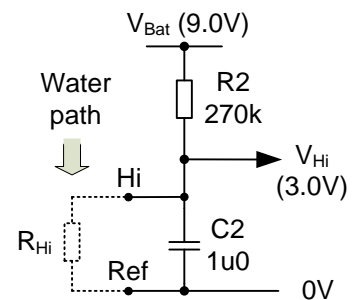
$$\frac{R2}{R_{Hi}} = \frac{V_{R2}}{V_{Hi}} = \frac{6.0V}{3.0V} = 2$$

$$so R2 = 2 \cdot R_{Hi}$$

$$= 2(140k\Omega)$$

$$= 280k\Omega$$

(use 270 k Ω)

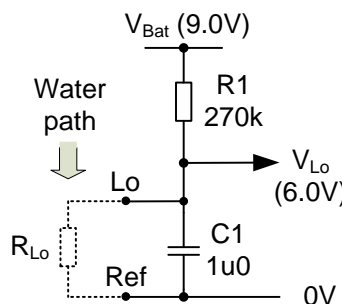


By using 270 k Ω instead of 280 k Ω , the water path resistance needed to trigger the NE555 is slightly lower than 140 k Ω . This is not an issue because the path resistance falls as the water level rises above the probe tip, as shown in Table 2-1 (at 5 mm below the water surface, the resistance is 84 k Ω).

Figure 2-4 Resistor R1 selection

The Lo probe voltage must fall below 2/3 of V_{Bat} (e.g. 6 V with a 9 V supply) to indicate the presence of water. R1 can therefore be lower in value than R2, but for simplicity is made the same value as R2.

Use $R1 = R2 = 270 k\Omega$ (250 mW)



$$\frac{R1}{R_{Lo}} = \frac{V_{R1}}{V_{Lo}} = \frac{3.0V}{6.0V} = 0.5$$

$$so R_{Lo} = \frac{R1}{0.5}$$

$$= \frac{270k\Omega}{0.5}$$

$$= 540k\Omega$$

The Lo probe will therefore indicate the presence of water with about 540 k Ω path resistance, which is well above the worst-case value of 140 k Ω with rain water.

2.2 Set-Reset latch (NE555 timer IC)

When the NE555 is used as an astable oscillator, external resistor - capacitor timing components connect to the THRESHOLD and TRIGGER inputs to control the frequency of oscillation.

In a model pump station, a pump (water input) and drain pipe (water output) replace the external resistors (charge input and output), and a header tank (water storage) replaces the external capacitor (charge storage). The probes convert water level to voltage for the NE555 THRESHOLD and TRIGGER inputs, and the Set-Reset latch output (V_{out}) energises the relay to power the pump.

The NE555 still 'oscillates', but the timing components work with water instead of electric charge.

Figure 2-5 NE555 timer IC pinout and internal latch control functions

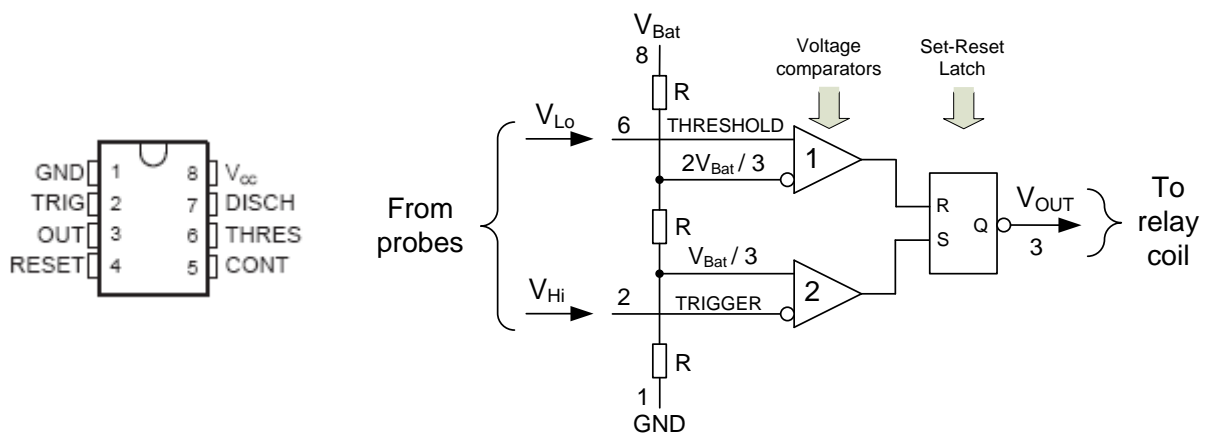


Table 2-2 lists the timing sequence. The pump switches ON when both probes are 'dry' (water level falls below the **Lo** probe), and switches OFF when both probes are 'wet' (water level reaches the **Hi** probe).



Table 2-2 Pump station timing sequence

Tank status	Water level re: probes	Probe voltages	Set-Reset Latch	V_{OUT}	Relay contacts	Pump motor
Almost empty	Below Hi Below Lo	$V_{Hi} > 3.0V$ $V_{Lo} > 6.0V$	Resets	LOW	Close	ON
Filling	Below Hi Above Lo	$V_{Hi} > 3.0V$ $V_{Lo} < 6.0V$	No change	LOW	Remain closed	ON
Almost full	Above Hi Above Lo	$V_{Hi} < 3.0V$ $V_{Lo} < 6.0V$	Sets	HIGH	Open	OFF
Emptying	Below Hi Above Lo	$V_{Hi} > 3.0V$ $V_{Lo} < 6.0V$	No change	HIGH	Remain open	OFF
Almost empty	Below Hi Below Lo	Refilling sequence repeats from the top of the table				

2.3 Relays

Electrical characteristics

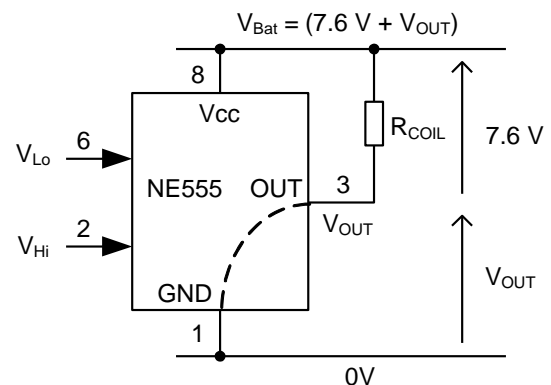
The MPC-1 kit is supplied with a Zettler relay having contacts rated to 1 A – which is more than adequate for controlling small pumps like the PUMP-1 and PUMP-2 designs. Relays with higher rated contacts can also be fitted to the MPC-1. One such example is the Goodsky relay detailed here.

		
Manufacturer	Zettler	Goodsky
Model number	AZ951-1C-12DSE	RW-SH-112D
Current rating of contacts	1 A	10 A
Nominal coil voltage	12 V	12 V
Maximum coil voltage	20.5 V	15.6 V
Coil resistance	700 Ω	400 Ω
Several relays were tested with a variable DC power supply across the coils. As the coil voltage was varied, measurements were made of the voltages at which the contacts closed (pull-in voltage) and opened again (drop-out voltage). The following voltages are typical of the measurements made. These are used later.		
Typical pull-in voltage	7.6 V	7.6 V
Typical drop-out voltage	3.0 V	4.5 V

Driving the relay coils from the NE555

From the above measurements, at least 7.6 V is required across the coils to close the relay contacts. The coils have winding resistances of 700 Ω (Zettler) and 400 Ω (Goodsky), so the lowest acceptable energising current is 11 mA for the Zettler relay or 19 mA for the Goodsky.

When the NE555 attempts to energise the coil (switch it to 0 V), there is a small residual voltage V_{OUT} at pin 3. This must be provided by the DC power supply or battery, so must be allowed for in the specification of the DC power supply voltage range.



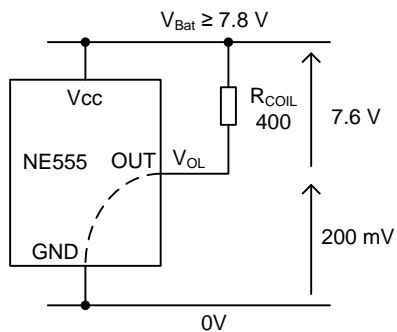
2.4 DC power supply voltage range

The MPC-1 and associated pumps are intended to be powered from regulated DC power supplies or batteries with nominal voltages of 9 V or 12 V. While regulated DC power supplies maintain their nominal voltages at all times and all currents within their specifications, battery voltages vary considerably over the operating life of the battery.

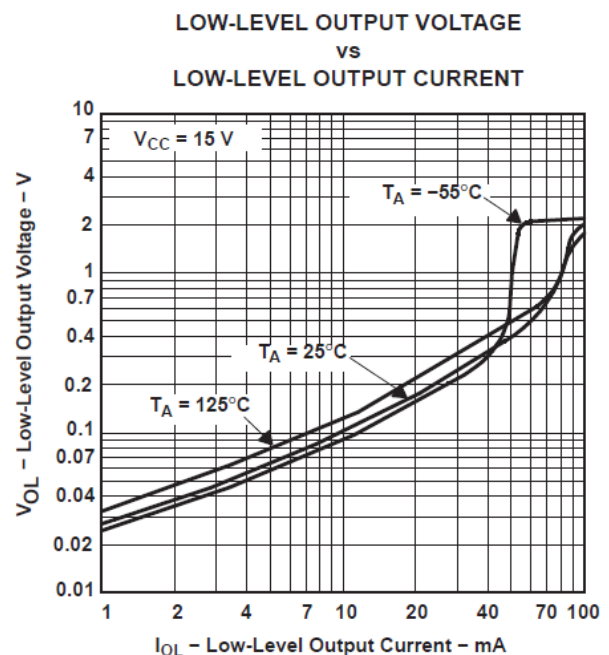
To choose suitable batteries for powering pump stations, the highest and lowest voltages that are acceptable to all components in the MPC-1 must first be determined – and then compared with the voltage variations expected from the batteries.

Lowest power supply voltage (8.0 V)

To energise the relays, the NE555 must sink a maximum of 19 mA (Goodsky). At this current, the residual voltage at the output of the NE55 is about 200 mV (see graph), so V_{Bat} must be at least 7.8 V.



Allowing a margin for manufacturing tolerances, a minimum V_{Bat} of 8.0 V is specified for the MPC-1.



Highest power supply voltage (15 V)

- The maximum operating voltage for the filter capacitors is 50 V
- The maximum coil voltage for the Zettler relay is 20.5 V
- The maximum coil voltage for the Goodsky relay is 15.6 V
- The maximum power supply voltage for the NE555 is 16 V (some manufacturers quote higher values, but this is the lowest value encountered)

Allowing a margin for manufacturing tolerances, a maximum V_{Bat} of 15 V is specified for the MPC-1.

2.5 Power switch and power indicator

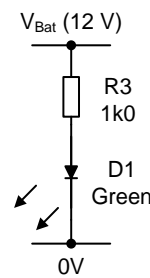
Switch S1 connects the DC power source to the MPC-1 circuit and also to connector J3, which can be used to power auxiliary devices like pump station lighting, alarm circuits, etc

To indicate that DC power is present, green indicator LED D1 illuminates with bias current limited by resistor R3. The bias current chosen is a compromise between brilliance (20 mA) and battery life (5 mA), with allowance for the expected variation in power supply voltage from 8.0 V to 15 V.

Figure 2-2 LED bias resistor R3 calculation

- Assume $V_{Bat} = 12\text{ V}$ (between 8.0 V and 15 V)
- Assume $I_{D1} = 10\text{ mA}$ (between 5 mA and 20 mA)
- Assume $V_{D1} = 2.0\text{ V}$ (typical for green LEDs)
- R3 calculates to 1.0 k Ω

Use 1.0 k Ω (250 mW) for R3.

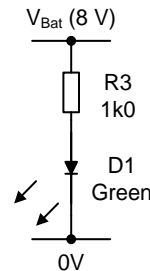


$$\begin{aligned}
 R3 &= \frac{(V_{Bat} - V_{D1})}{I_{D1}} \\
 &= \frac{(12\text{ V} - 2.0\text{ V})}{10\text{ mA}} \\
 &= 1.0\text{ k}\Omega
 \end{aligned}$$

Figure 2-3 Minimum LED bias current check

A minimum bias current of 5 mA is desired for the green power indicator LED in the MPC-1. This is quite visible indoors.

Assuming the lowest power supply voltage of 8.0 V, and the calculated R3 value of 1.0 k Ω , the bias current is 6 mA – which is acceptable.



$$\begin{aligned}
 I_{D1} &= \frac{(V_{Bat} - V_{D1})}{R3} \\
 &= \frac{(8\text{ V} - 2.0\text{ V})}{1.0\text{ k}\Omega} \\
 &= 6.0\text{ mA}
 \end{aligned}$$

3 Suitable power supplies and batteries

3.1 Basic requirements

To power the MPC-1 and a PUMP-1 (or PUMP-2) in a model pump station, a DC power supply or battery must provide:

- A terminal voltage between 8.0 V and 15 V
- A maximum current of 300 mA at 9 V or 400 mA at 12 V when the pump is running
- Sufficient capacity (if a battery) to power the pump station for the required time.

Many suitable 9 V and 12 V regulated power supplies with at least 500 mA current rating are available. These maintain their nominated output voltages at any current within their specified range.

Many 9 V and 12 V batteries are also available, but the wide range of current and capacity ratings, and the variation in terminal voltage over the operating life of a battery, requires that manufacturers' data be consulted to assess suitability for powering a pump station.

Several suitable batteries are considered here, with manufacturers' data presented and used to justify their selection. Where manufacturers' data is limited, batteries are tested under pump-station load conditions. These techniques can be applied to any other batteries.

3.2 Batteries considered

Small batteries like the 9 V PP3 style are popular because they are convenient to mount on small pump stations. Unfortunately they only have enough capacity to power a pump station for a few hours, so they are considered in some detail here to illustrate a method for predicting the effects on operating time of changes in battery chemistry, pump type, header tank size, water draining rate, etc.

One secondary (rechargeable) battery, and one primary (single-use) battery is considered:

- 8.4 V NiMH (size PP3, IEC name 6HR61)
- 9 V alkaline (size PP3, IEC name 6LR61)



Batteries made from larger cells than those in the 9 V PP3 battery will operate pump stations for many hours, so the effects on operating time of pump station design are less of an issue in education. Only AAA NiMH and alkaline cells are considered here, but the method applies to other cell sizes and chemistries.

- 8 x 1.2 V NiMH (size AAA, IEC name HR03)
- 8 x 1.5 V alkaline (size AAA, IEC name E92)



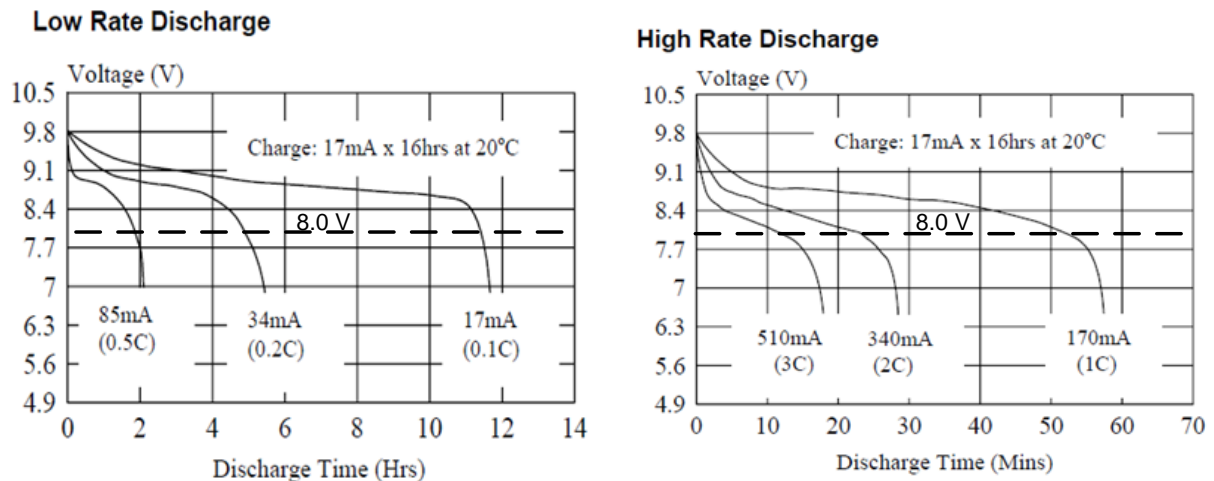
3.2.1 8.4 V NiMH, size PP3 (IEC name 6HR61)

Specifications (GP Batteries, Model GP17R8H)

Nominal voltage 8.4 V

Recommended discharge current 17 mA to 510 mA

Typical capacity 175 mAh (to 8.0 V at 35 mA, 20°C)



This battery is well suited to the MPC-1 and model pump stations. The recommended maximum discharge current of 510 mA is above the combined MPC-1 and PUMP-1 (or PUMP-2) load of 275 mA, and the battery maintains a terminal voltage of least 8.0 V over most of its capacity.

Available battery capacity

With a typical model pump station the MPC-1 activates the pump for about 20% of the time, and the MPC-1 is on standby for the remaining 80% of the time. The current drain is about 275 mA while pumping (25 mA to the MPC-1, 250 mA to the pump), and about 10 mA while on standby.

While the pump is running (275 mA):

Interpolating between the 170 mA and 340 mA 'High Rate Discharge' curves, the discharge time to 8.0 V is about 30 minutes, which equates to a battery capacity near 140 mAh.

$$\begin{aligned} Q(\text{mAh}) &= I(\text{mA}) \cdot t(\text{h}) \\ &= (275 \text{ mA})(0.5 \text{ h}) \\ &\approx 140 \text{ mAh} \end{aligned}$$

While the MPC-1 is on standby (10 mA):

Extrapolating from the 17 mA 'Low Rate Discharge' curve is difficult (maybe 18 hours – giving a capacity of 180 mAh?), but fortunately the manufacturer has specified the capacity at low rate discharge to be 175 mAh, which can be used with more confidence.

$$\begin{aligned} Q(\text{mAh}) &= I(\text{mA}) \cdot t(\text{h}) \\ &= (10 \text{ mA})(18 \text{ h}) \\ &\approx 180 \text{ mAh} \end{aligned}$$

The lower capacity figure can be used to estimate a worst-case (minimum) operating time, or an average capacity figure can be used for a closer estimate.

A worst-case estimate of operating time

With 275 mA flowing for 20% of the time, and 10 mA for the remaining 80% of the time, the average current is about 63 mA. When the lower capacity of 140 mAh is divided by this average current, an operating time of about 2.2 hours results:

Average current, I_{ave}	Operating time, t_{op}
$I_{ave} = \frac{1 \cdot (275mA) + 4 \cdot (10mA)}{5}$ $= \frac{315mA}{5}$ $= 63mA$	$t_{op} = \frac{Q(Ah)}{I_{ave}}$ $= \frac{140mAh}{63mA}$ $\approx 2.2 \text{ hours}$

A better estimate of operating time

The available capacity of the battery is higher than 140 mAh because the average discharge current is lower than 275 mA (the current on which 140 mAh figure is based). A better estimate of operating time is found by dividing the average capacity by the average current – with a result of 2.7 hours:

Average capacity, Q_{ave}	Operating time, t_{op}
$Q_{ave} = \frac{1 \cdot (140mAh) + 4 \cdot (175mAh)}{5}$ $= \frac{840mAh}{5}$ $= 170mAh$	$t_{op} = \frac{Q(Ah)}{I_{ave}}$ $= \frac{170mAh}{63mA}$ $\approx 2.7 \text{ hours}$

Conclusion

These are estimates only, based on several assumptions:

- 20% : 80% pump ON : OFF ratio (every pump station will be different)
- One manufacturer's data (not all such batteries will behave the same)
- new batteries (battery performance changes with age, number of charge cycles, abuse ...)
- moderate temperature (chemical reactions are temperature sensitive – see alkaline cell data on page 13 for discharge curves at three temperatures))
- averaging of capacity and current (current-induced energy loss is not necessarily a linear process)

This battery should operate a pump station for between 2 and 3 hours on one charge.

3.2.2 9 V alkaline, size PP3 (IEC name 6LR61)

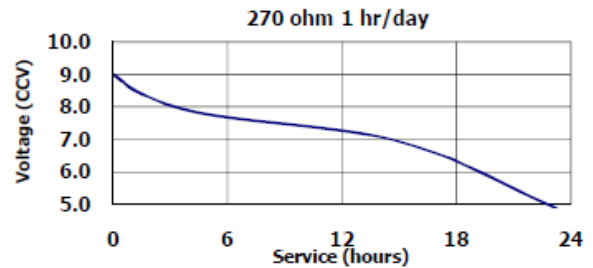
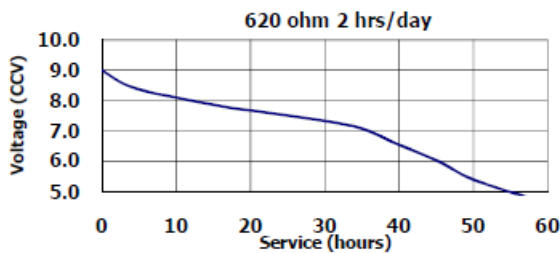
Specifications (Energizer 522)

Nominal voltage 9 V

Maximum discharge current 500 mA

Typical capacity 600 mAh (to 4.8 V at 25 mA, 21°C)

250 mAh (to 4.8 V at 500 mA, 21°C)



Notes:

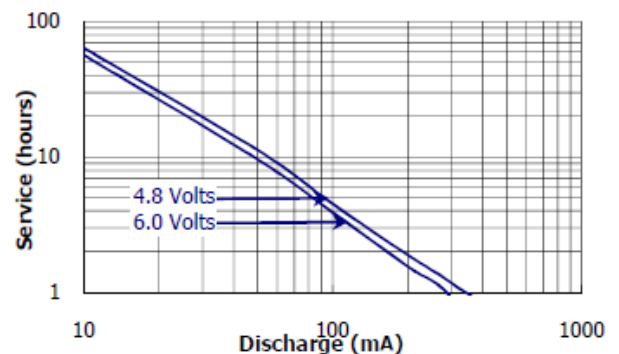
1. At the two test currents of 15 mA (9 V across 620 Ω) and 33 mA (9 V across 270 Ω), the terminal voltage drops below 8.0 V well before the battery is fully discharged. Much of the quoted battery capacity is therefore not available for use in a pump station – even at low currents
2. Little detailed information is available on the performance of the battery above 8.0 V at higher discharge current, so load tests are used to confirm operating time estimates.

Available battery capacity

- Extrapolating from the above data, the service hours to 8.0 V will probably be about one tenth of those to 4.8 V at 275 mA, so capacities to 8.0 V are probably about one tenth of those quoted to 4.8 V. Assume 60 mAh at low rate discharge, and 25 mAh at high rate discharge.
- These capacities produce an average capacity of about 160 mAh, which can be divided by the average current of 63 mA to give a rough estimate of operating time.

Result: an operating time of about 2.5 hours.
(Very approximate – but confirmed later by testing)

Constant Current Performance Typical Characteristics (21°C)



Fortunately the relay has a lower drop-out voltage than pull-in voltage (see Table 2-3), and this prevents the relay from dropping-out when the battery voltage falls below 8.0 V under 275 mA load. Provided the battery voltage rises to at least 8.0 V while the standby current of 10 mA flows, the relay will pull-in when next switched by the NE555. This extends the operating time of the pump station.

Tests results: several 9 V alkaline batteries from different manufacturers were tested, and all operated a pump station for at least 2 hours.

3.2.3 8 x 1.2 V NiMH cells (size AAA, IEC name HR03)

Cell specifications (GP Batteries, model GP80AAAHC)

Nominal voltage 1.2 V
 Recommended discharge current 80 mA to 2.4 A
 Typical capacity 800 mAh (to 1.0 V at 80 mA, 20°C)

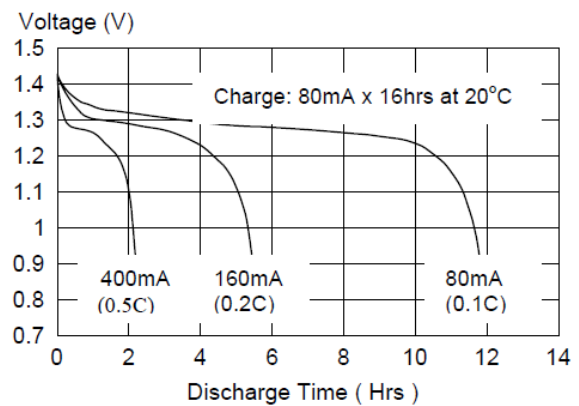


These cells, in packs of 8, are well suited to the MPC-1 and model pump stations. The maximum discharge current of 2.4 A is well above the required 275 mA, and the cells maintain a terminal voltage of at least 1.0 V over most of their capacity.

To estimate operating time, divide the typical capacity (800 mAh) by the average discharge current (63 mA).

Result: This battery should power a pump station for at least 10 hours.

Low rate discharge



3.2.4 8 x 1.5 V alkaline cells (size AAA, IEC name E92)

Cell specifications (Energizer E92)

Nominal voltage 1.5 V
 Maximum discharge current 400 mA
 Typical capacity 600 mAh (to 1.0 V at 250 mA, 21°C)



These cells, in packs of 8, are also well suited to the MPC-1 and model pump stations. These discharge curves are to 1.0 V at a current of 250 mA which is close to the requirements of a pump station.

To estimate operating time, divide the typical capacity (600 mAh) by the average discharge current (63 mA).

Result: This battery should power a pump station for at least 9.5 hours.

