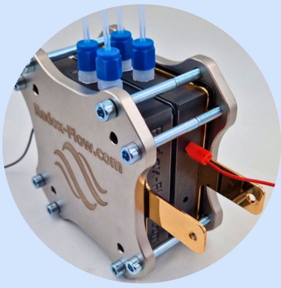 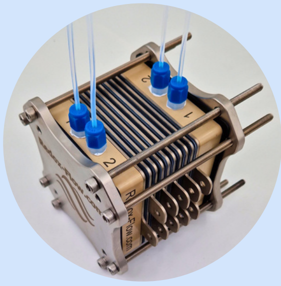 

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**Whitepaper**

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# Minimum Discharge Voltage of Battery Testers

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Carried out by the Redox-Flow team


**Contact person**
Mikkel Kongsfelt
CEO and Co-Owner
sales@redox-flow.com
+45-3126-2040

## Context

The 8 channel battery testers sold by [Redox-Flow.com](Redox-Flow.com) have specs where minimum discharge voltages are in the range 1 V to 1.6 V depending on the specific model. For flow batteries it often desired to be able to discharge below 0.5 V and for this reason we are often asked by our costumers if the 8 channel battery testers can discharge below e.g. 1 V. The short answer is yes, but the minimum voltage is not fixed and it depends on many factors, including experimental factors that can be optimised. This white paper is related to explaining this phenomenon.

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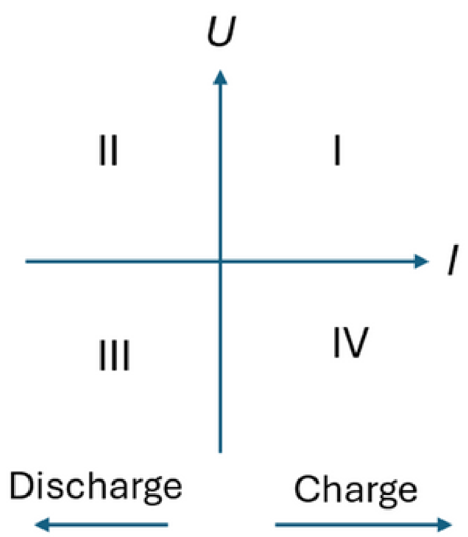
## Introduction

Modern (programmable) power sources and loads are typically referred to how many quadrants in the U-I curve (see Figure below). As an example a power source (e.g. for electrolysers) that can only deliver electrical current will only be able to operate in quadrant I, an electronic load will only operate in quadrant II, while high-end and costly electrochemical workstations/potentiostats are able to operate in all four quadrants and can be used for full characterisation of any electrochemical device.

Battery tester (as the 8 channel battery testers sold by [Redox-Flow.com](Redox-Flow.com)) are very cost-effective alternatives to costly potentiostats. They can be considered as a combined programmable power source and load can operate in both quadrant I and II. i.e. during charging it is controlled by the power source and during discharge it is controlled by the load. Here it is important to understand that an electronic load is a passive device where the electrical current supplied to the load from the battery is driven by the internal voltage of the battery.

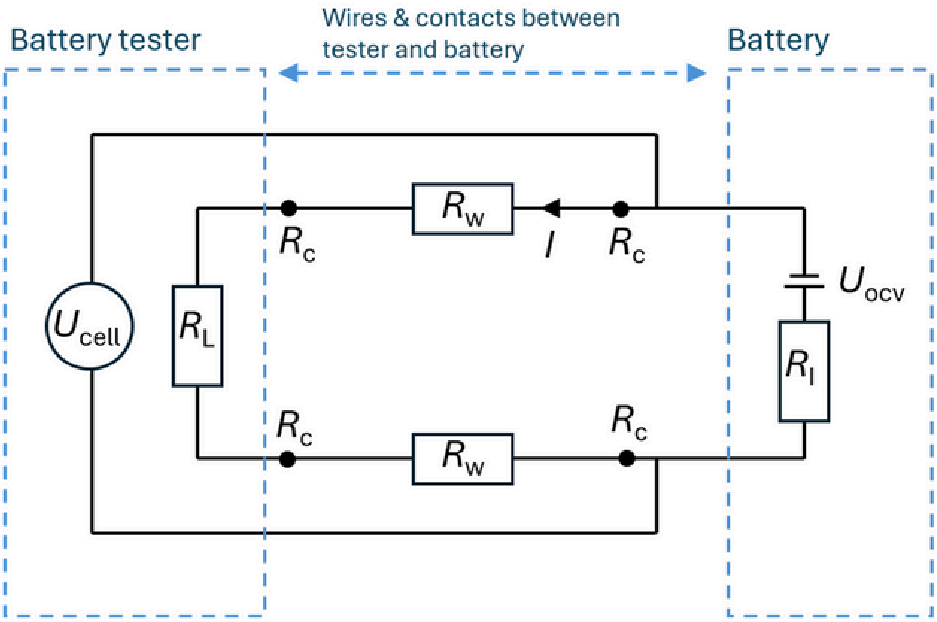


# Equivalent electric circuit of battery and tester

To make quantitative predictions on the minimum discharge voltage it is helpful to make an equivalent electrical circuit of the battery tester and battery and is shown below, where only discharge is considered.

The battery has an internal resistance ($R_I$) and an internal open circuit voltage ($U_{OCV}$). On the left side the battery tester measures the 'external' cell voltage on the battery ($U_{cell}$) through two voltage wires connected to the current collectors on the battery. $U_{cell}$ is the voltage is reported in the 'performance' of the battery. The control of the battery tester can be imagined as being a variable load resistance inside the battery tester ($R_L$). I.e. if $R_L$ is low the electrical current (I) in the circuit increases, while if $R_L$ is high I will decrease. For simplicity a positive electrical current corresponds in the following to discharge (and not discharge as shown in the four-quadrant picture above)

In addition to the two units, there are also electrical wires for carrying the electrical current between the two units. The wires comes with a resistance ($R_w$), while the contact points between tester/wire/battery comes with contact resistances ($R_c$).




From the equivalent circuit above, it is seen that the total voltage loss ($U_{OCV}$) across the circuit is given by Ohms law. i.e. the electrical current multiplied with the sum of all the resistances in the circuit. For simplicity all the wire and contact resistances are replaced by $R_{ex} = 2R_W + 4R_c$ and subscript *ex* refers to *external*.

$$U_{OCV} = (R_L + R_{ex} + R_I) \cdot I \tag{1a}$$

By rearrangement

$$I = \frac{U_{OCV}}{R_L + R_{ex} + R_I} \tag{1b}$$

It can be seen that the discharge current can be varied by changing the load resistance inside the battery tester. Also it is seen that the maximum discharge current ($I_{max}$) is obtained when $R_L = 0\Omega$ and is given by

$$I_{max} = \frac{U_{OCV}}{R_{ex} + R_1} \tag{2}$$

Again, if the wire/contact resistance are zero $(R_{ex} = 0\Omega)$ the maximum electrical current is only given by the internal resistance of the battery.

The voltage measured on the battery ($U_{cell}$) can also be found by circuit analysis and is given by

$$U_{cell} = U_{OCV} - R_I \cdot I \tag{3}$$

And is the 'polarisation curve' obtained when measuring the voltage-current relation in a battery. The slope of the curve gives the internal resistance of the battery. By inserting eq. 1b into eq. 3, the following relation is obtained

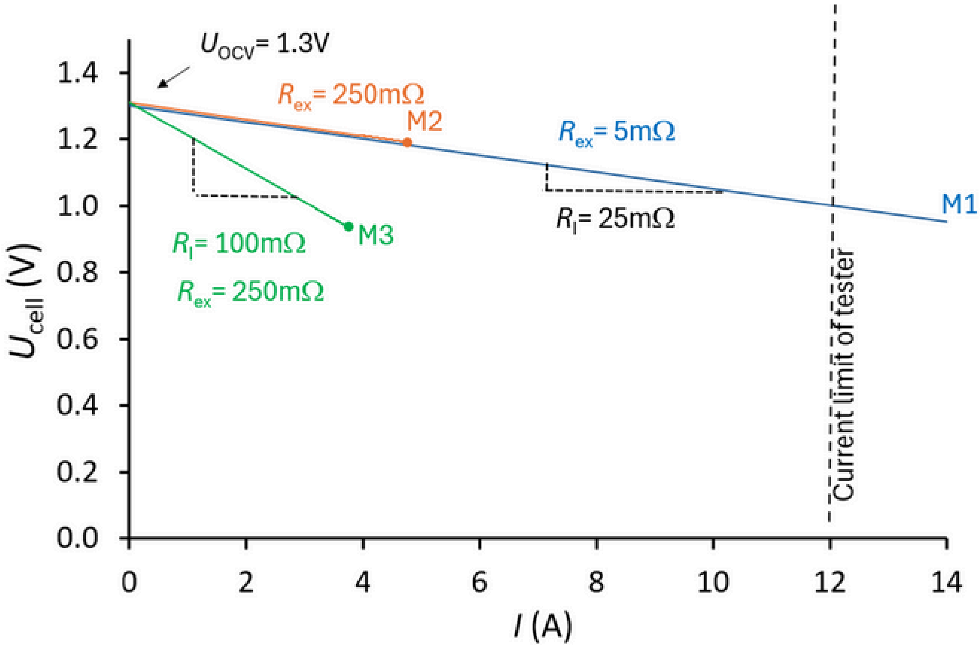
$$U_{cell} = U_{OCV}\left(1 - \frac{R_1}{R_L + R_{ex} + R_I}\right) \tag{4}$$

This equation can be used for analysing the effect of the load and external resistance on the 'minimum discharge voltage' $(U_{cell,min})$. The maximum discharge current is obtained when $R_L = 0\Omega$ and

$$U_{cell,min} = U_{OCV}\left(1 - \frac{R_1}{R_{ex} + R_I}\right) = U_{OCV}\left(1 - \frac{1}{R_{ex}/R_1 + 1}\right) \tag{5}$$

From this equation, it is readily seen that the minimum discharge voltage scales with the internal voltage of the battery. I.e. Li-ion batteries typically has around 3 V, while flow batteries are around 1.3 V, thus for low voltage batteries it is per se easier to discharge to lower voltages than for high voltages batteries.

To go into more details, figure below shows three calculated polarisation curves for batteries with different internal resistance (25 mΩ and 100 mΩ) and different wire/contact resistance (5 mΩ and 250 mΩ ). Here it is assumed that the battery tester has a maximum current of 12 A. The points (M1-M3) shows the maximum discharge currents and minimum discharge voltages for the three cases. In case 1 (blue), the internal resistance of the battery is 25 mΩ while the contact/wire resistance is 5 mΩ. Here the maximum discharge current is beyond the limit of the tester and there is no effect of the wire/contact resistance of the setup. Case 2 (orange) has the battery has the same internal resistance, but a much higher contact/resistance (250 mΩ). Here maximum current is only about 5 A (eq 2) and the minimum discharge voltage is very high (about 1.2V – eq. 5). In case 3, the internal battery resistance is now 100 mΩ and this results in a slightly lower maximum current (appr. 4A), but more interesting the minimum discharge voltage decreases to about 0.9 V.




The voltage measured by the battery tester ($U_{test}$) is given by the second equation and is simply the internal OCV – $R_{batt} \cdot I$. If you combine the two (eq. 3) then you can see that $U_{test}$ will go to zero if $R_{test}$ = $R_{wire/contact}$ = 0 Ohm. However, both have minimum values that are not zero (but close to). In the case of the specs, I guess the reason why they have used the minimum discharge voltage to around 1.0 V, could be that the specs are made with Li pouch cells in mind. I think the internal resistance ($R_{batt}$) of these are very very low (for comparison the lowest you will see with vanadium flow battery chemistry is about 20 mOhm for a 25 $cm^2$ cell). If the internal resistance of the battery is very very low, the relative effect to the $R_{test}$ and $R_{wire/contact}$ becomes larger and it can become difficult to measure down to 0 V.

**So in conclusion, the battery tester will go close to 0 V, but depending on the internal resistance of the battery. Also, to the best of my knowledge any of the other multi-channel battery testers that are on the market are also passive when discharging. Alternatively you will have to go with a much more expensive potentiostatic.**

To explain a little on the discrepancy of the specs and 'reality' I have also included the equivalent electrical diagram for a 'passive' battery tester connected to the battery. Here 'passive' means that on discharge it is the voltage of the battery that drives the discharge. The battery tester has some internal resistance ($R_{test}$) that can be varied and almost go to zero Ohm, when it is drawing maximum current. Then there is wire/contact resistance and finally the internal resistance of the battery ($R_{batt}$). The battery also have some internal OCV (that is dependent on the SOC).

So the current that runs in the circuit (out of battery) is given by the first equation (i.e. simply the internal OCV divided by the total circuit resistance). Here it is obvious that if you want high currents then Rtest has be close to zero, and you need to use thick wires with very good electrical contacts to the cell. But as you can see the internal resistance of the battery plays a major role and is in practice the one that determines the maximum current.

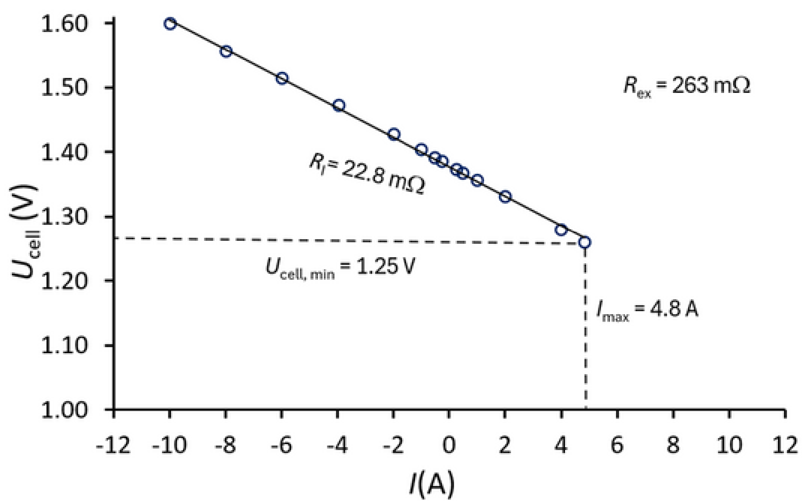
## Will the battery tester be able to discharge below 1V?

Yes, it will discharge below 1 V. Below I have included data for a vanadium flow battery test where it was discharged down to 0.1 V (one cycle). The sequence was constant current charge/discharge 2500 mA with cutoff voltage of 1.6 V (charged) and 0.1 V (discharged), between the charge/discharge there is a pause of about 1 h. Also I have included the corresponding capacity voltage plot. I could not find any data where discharged down to 0.0 V, however, they will not differ much. As you can see, the tester works fine below 1.0 V, below I have in more details explained how this is possible even when datasheet state that it will 'only' discharge down to 1.0 V.

## Experimental data

Figure below shows the polarisation curve for a vanadium flow battery in a 25 $cm^2$ on a 5V/12A tester. The setup has not been optimised with short wires and good electrical connections.

From the slope the internal resistance of the cell is found to be 22.8 mOhm, upon discharge, it is seen that the maximum current is about 4.8 A and the minimum discharge voltage is about 1.25 V. From these values and with either eq. 2 or eq. 5, $R_{ex}$= 263 mOhm is found. This is significantly higher than the internal resistance of the battery and the main reason why the battery cannot be discharged to higher currents (and lower voltages).




**Interested? We'd like to hear from you!**
Don't hesitate to contact us with any kind of inquiries at sales@redox-flow.com or call Mikkel Kongsfelt at +45-3126-2040