THE VALIDITY OF CYCLE LIFE BENCH TEST DATA IN RELATION TO REAL WORLD IN-VEHICLE TESTING

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Summary

In order to fulfill the stringent requirements of EV propulsion with the lead–acid system, careful modification and adaptation with regard to vehicle and vehicle operation is important. Bench tests provide much of the required information. Because of the controlled test conditions the impact of various parameters as well as differently designed battery cells can be compared. Test benches which simulate practical operation sufficiently well usually provide cycle life results which are in good accord with on-the-road results. Even when less carefully adapted, reasonable results can be obtained by the application of correction factors.

Successful EV battery bench tests require the application of dynamic fundamental cycles (instead of low rate constant current) as well as waiving the possibility of accelerated cycling (*e.g.*, increased number of cycles per day or increased current rates). In addition, the thermal behaviour of batteries in practical operation must be considered.

Practical field tests with vehicle fleets continue to be important. These are the only tests which allow the battery to be stressed with the entire spectrum of constructive and operational parameters. The results complement, and in many cases correct, the bench tests.

Why are bench tests important?

When operated in EVs, traction batteries are required to deliver a maximum of energy- and power density. In addition, the conditions of operation can vary significantly. This is especially true for personal cars. The categories of operating conditions are driving-, charging-, maintenance- and climatic conditions. Several parameters belong to each category.

Some examples are:

- Daily driving distance
- Topography
- Initial charge current
- Charge factor

— Equalisation charge
— Watering
— Average discharge temperature
— Temperature variation within battery pack.

For these reasons it is extremely difficult to evaluate the impact of a single parameter on battery life from field test results. If the vehicle fleet is not too small, however, useful information on battery life can be obtained when affected by *all* parameters. Of course, unrepresentative failures of non-battery components can invalidate the results. Another problem is the limitation and reliability of in-vehicle mobile data acquisition.

All the typical field test restrictions do not apply to bench tests. The operating conditions are under close control. Disturbances and faults can be limited in their consequences. Data acquisition is a matter of cost only. Because of the controlled similarity of the operating conditions of several test objects, certain parameters can be compared directly. For example, the effect of a 20 K increase in operating temperature can be determined exactly, all other conditions being equal. Different cells in terms of size and design can be compared directly when operated under similar conditions.

On the other hand, it is rather difficult to draw conclusions from bench tests on cycle life under actual operating conditions. Relevant results presuppose the simulation of realistic operating conditions. It may not be possible to achieve these in entirety. Important steps in this direction have been undertaken, however; for example, in ref. 1 the very important question of a suitable power profile is explained. If, in addition to power performance testing, it is necessary to conduct cycle life tests, the power profile requirements will probably increase.

An additional means of increasing confidence is by the application of a correction factor. With this factor it is possible to correct the cycle life result obtained from bench tests. The correction factor can be derived empirically from the correlation between earlier bench tests and corresponding field tests.

At this point it becomes obvious that both methods — bench and field tests — can be justified.

Test conditions must compare with operating conditions

When planning a bench test the operating parameters must be considered. The discharge and charge profile, as well as the operating temperature range, should equate with field test conditions.

Complex high-power duty cycles, which are typical of EV application, cannot be represented by a sequence of constant current discharges and charges alone: not even when current mean values coincide with practical conditions.

The fundamental unit of the duty cycle is the so-called fundamental cycle, which is derived from the required driving profile (*e.g.*, acceleration and velocity) and the predetermined vehicle data (*e.g.*, curb weight and battery capacity). This results in a power profile which usually consists of the four most important elements of dynamic driving performance; these are periods of acceleration, constant velocity, braking, and standing. A permitted simplification is to apply a current profile instead of a power profile. Examples are given in Figs. 1 and 2. Further simplification can lead to a situation where there is little or no correlation between bench and field test cycle life. For example, the power limit (end of life criteria) will be reached much earlier when eliminating regenerative braking. On the other hand, elimination of the acceleration peak leads to a significantly longer battery life because the power limit can be reduced to much lower values.

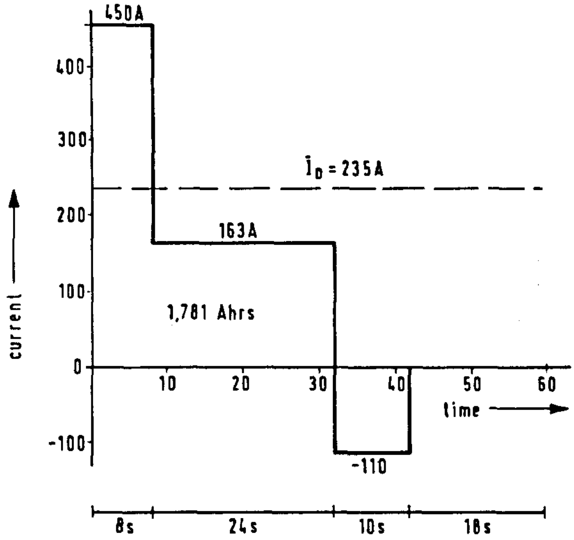

Fig. 1. Fundamental cycle for testing of cycle life of EV-battery 455 A h (C_5).

The charge profile is just as important as the discharge profile. It is determined by the charge characteristic and overcharge control. It is obvious that the practical charge method must be applied. Both the discharge and charge profile are elements of the daily or weekly duty cycle which determines the sequence of discharges and recharges. Examples are indicated in Figs. 3 and 4.

The requirement that, to a large extent, bench test procedures must correspond with actual operation does not allow accelerated cycle life tests. Accelerated endurance tests of electrochemical systems, different from electrical or mechanical components, usually result in failure and wear mechanisms which can deviate significantly from practical experience. The consequences are often incorrect estimation of the investigated parameters and too favourable a cycle life. This becomes noticeable especially when time-dependent operating parameters such as standtime are the subject of an accelerated bench test.

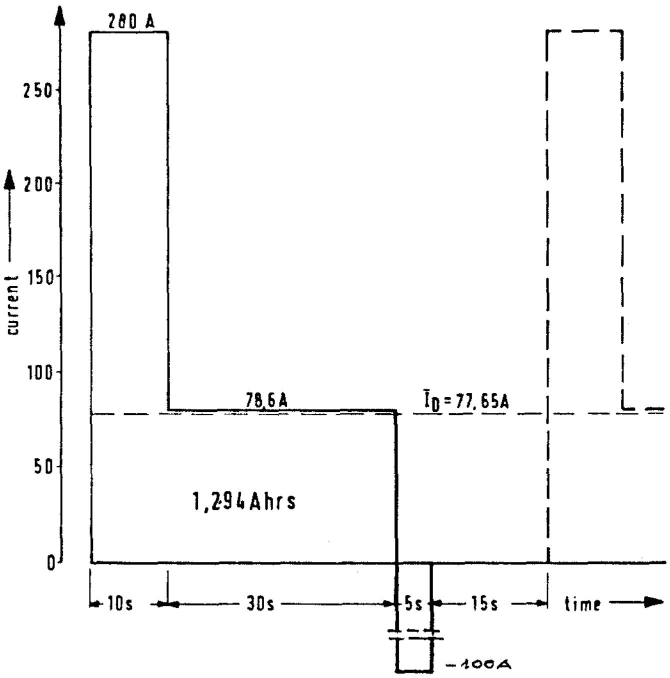

Fig. 2. Fundamental cycle for testing of cycle life of EV-battery 143 A h (C_5).

Are bench-test cycle-life results transferable to practical operation?

Figure 3 indicates the daily duty cycle of a newly developed charge/discharge operation, used by battery-powered electric buses (Fig. 5). Small amounts of discharge, frequent interim recharges and high ampere hour throughput are the characteristics of this operation. The interim recharges remain in the range of minutes at high current rates (4 - 5 times I_5). In practice, the bus is connected to the charge station automatically when approaching the main station (Fig. 3). Before the general introduction of this technology the impact on battery life — which was expected to be critical — was investigated. At this time the average battery life in normal operation was 800 to 900 full cycles. This was achieved with "battery exchange" instead of "interim recharge". The operational conditions of "battery exchange" are characterized by deeper discharges and charging in the average current range (2.5 times I_5).

The duty cycle shown in Fig. 1 based on actual operation, was obtained using programmable test equipment. The average line operation duty cycle (Fig. 2) was also considered. Operational measures such as equalization charge and monthly maintenance have been programmed additionally.

Five test batteries representing various kinds of operation have been cycled, as described, for approximately 2 years. Figure 6 shows the resulting capacity histogram. Curve 1 indicates the cycle life obtained by the test

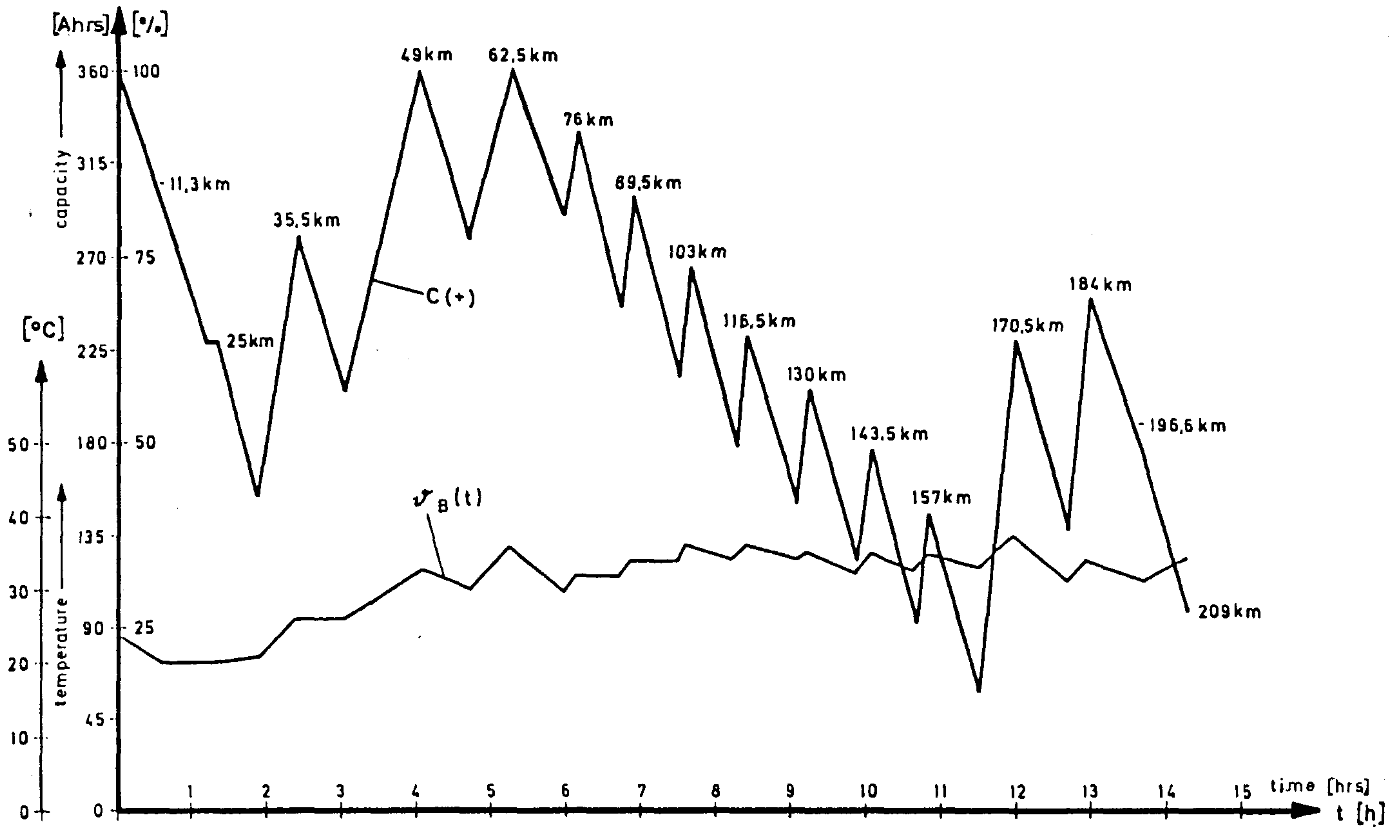

Fig. 3. Daily charge/discharge cycle for testing of cycle life of EV-battery 455 A h (C_5). Simulation of electric bus operation in public transportation.

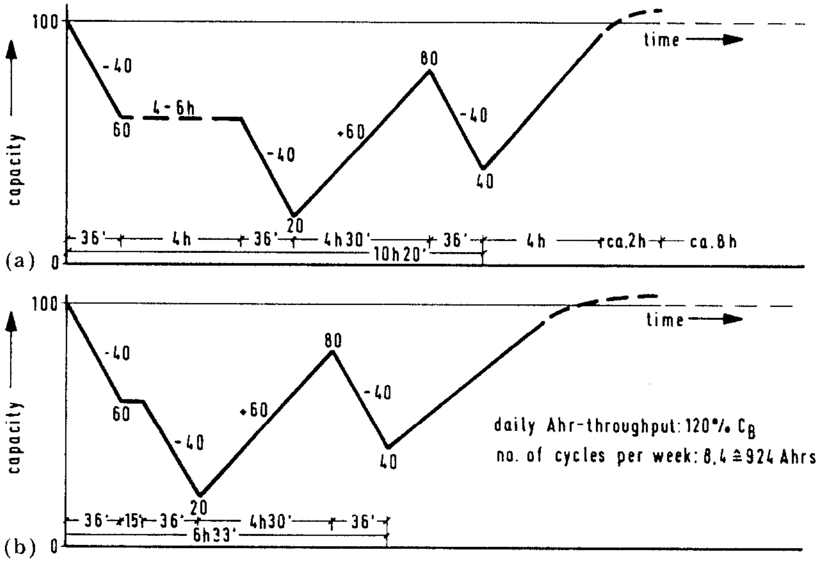

Fig. 4. Daily charge/discharge cycle for testing of cycle life of EV-battery 143 A h (C_5). (a) With, (b) without stand-time under partially discharged condition.

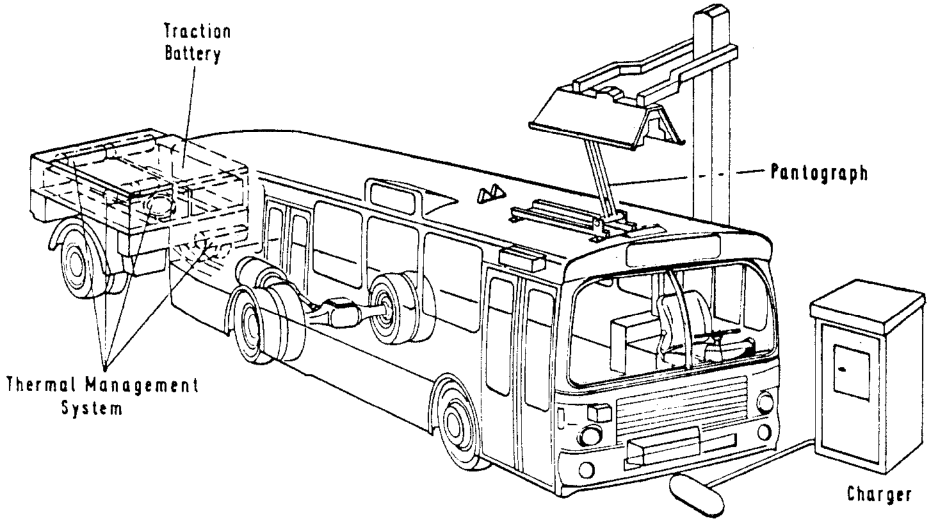

Fig. 5. Battery powered bus (MAN) with pantograph for interim recharge.

battery simulating "battery exchange" operation. The 800 full cycles achieved compare well with practical experience. The 2000 full cycles obtained with "interim recharge" operation, however, were rather surprising (curve 2). Instead of the expected reduction of battery life the results indicated a great improvement. The confidence in bench test results was questioned. Nevertheless, it was decided to operate 20 battery-powered

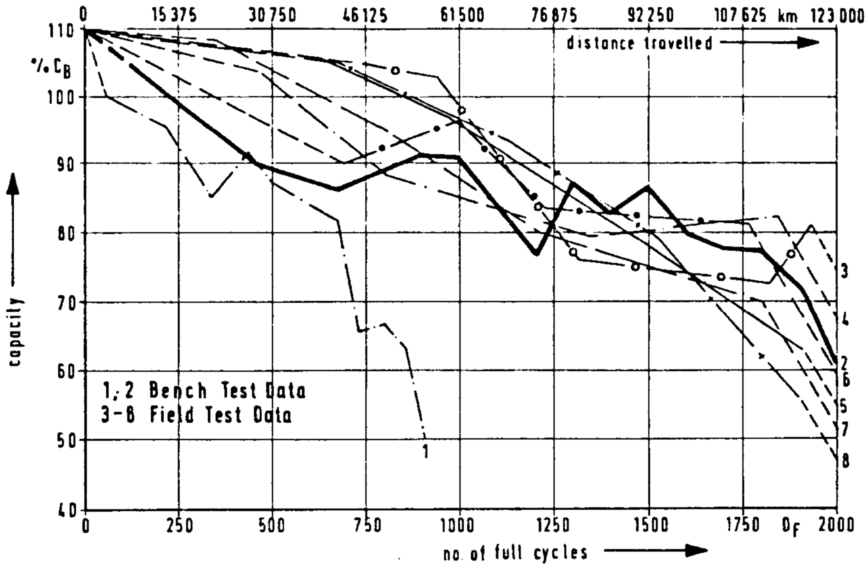

Fig. 6. Capacity *vs.* cycle life, correlation between bench test and field test data.

buses in the described operation mode. After 3 years of "interim recharge" the first 6 batteries have now reached the end of their lives. Curves 3 - 8 show the evaluated results. Again, there was satisfactory correlation between bench and field test results. In consequence, the relevance of carefully conducted cycle life tests has been confirmed.

How do we conduct cycle life tests now?

Battery bench tests are now well established within the development of EVs. By comparing parameters bench tests provide valuable information concerning the effectiveness of constructed features of cells and cell peripherals. Bench tests especially, provide reliable and comparable data on different battery systems.

Currently the impact of operational as well as design parameters on battery life are the subjects of an investigative program within the development of an electric personal car (Fig. 7). Subjects under investigation are stand-time under partially discharged conditions and the electrolyte circulation system, designed for the "CitySTROMer" battery (Fig. 8).

The applied fundamental cycle is derived from the requirements of the SAE J227c driving cycle and the driving characteristics of the "City-STROMer" EV. The resulting mean value equals the 1.5 h discharge current. Different from a scheduled bus operation (Fig. 3), it is difficult to simulate stochastic personal car operation on a test bench. Economical cycle life tests are only possible when applying an average daily duty cycle based on long term observation of practical fleet operation.

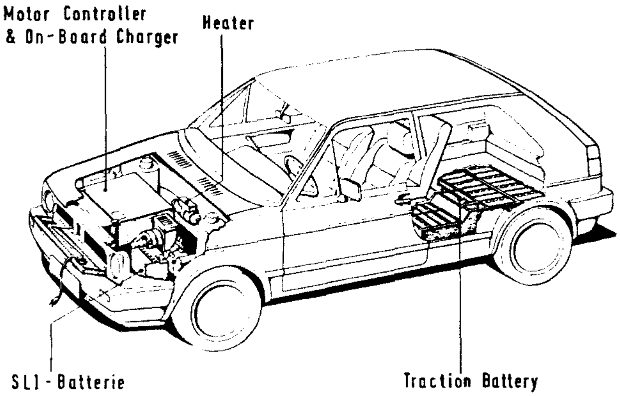

Fig. 7. GES "CitySTROMer" (VW-Golf basis).

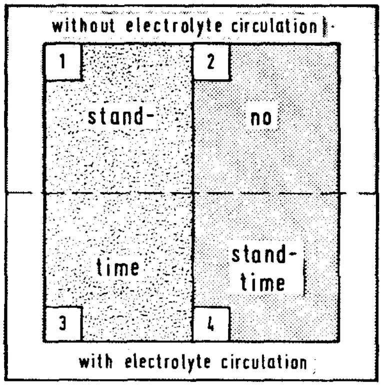

Fig. 8. Objective of current cycle life test: investigate impact of electrolyte circulation and stand-time.

The daily duty cycles, applied in the bench test discussed are described in Fig. 4. They only differ in the stand-time during a partially-discharged condition. The daily A h throughput averages 120% of the operational capacity. A thermal management system, designed for heating and cooling, ensures — individually for each battery on test — an operating temperature between 30 and 50 °C. This complies with today's practical operating conditions, which are based on the experience that battery temperatures below 30 °C result in a sensible power reduction. On the other hand, the upper temperature limit given by the manufacturer (*e.g.*, 50 °C) cannot be exceeded without damage. Temperature peaks, which can occur occasionally in practical operation, lead to cooling-off periods without battery operation.

This is unacceptable for bench testing because all batteries on test should be operated simultaneously along a given duty cycle. This makes an active cooling system necessary, especially at high discharge/charge rates.

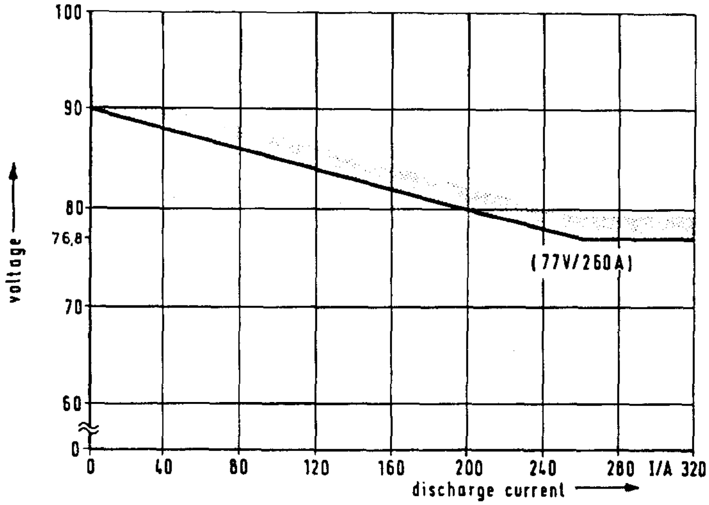

Fig. 9. Current dependent undervoltage control characteristic for EV-battery 143 A h/ 96 V.

An important supplement in relation to earlier bench tests is the current-dependent undervoltage control. As with the driving (discharge) current control, this system originates from the control concept of the "CitySTROMer" drive train. This concept considers the fact that the battery voltage decreases with increasing depth of discharge. Instead of compensating for the loss of power by increasing the discharge current (constant power load) the latter will be reduced, following a defined characteristic (Fig. 9).

In the first case the minimum power requirement, derived from practical driving operation, can no longer be fulfilled after a few days operation. Often the bench test is then discontinued without the best batteries reaching the end of their lives.

In the second case, the test batteries are effectively protected against inadmissible current loads at low voltages by the described undervoltage control. The effect of this measure is illustrated by the sequence of partial discharges in Fig. 10. The particular test has been conducted with aged batteries. It will be recognized that the undervoltage control begins to be effective during the second discharge. The defined power minimum (performance limit = end of life) is nearly approached at the end of the third discharge.

The first results of the cycle life bench test described are expected to be available by the end of next year.

References

1 R. von Courbière and H.-G. Müller, Requirements for EV batteries and consequences for test procedures, *1st International Workshop on Battery Testing, Heidelberg, F.R.G., Sept. 29 - Oct. 2, 1985*; this issue of *J. Power Sources, 17* (1986) 75.

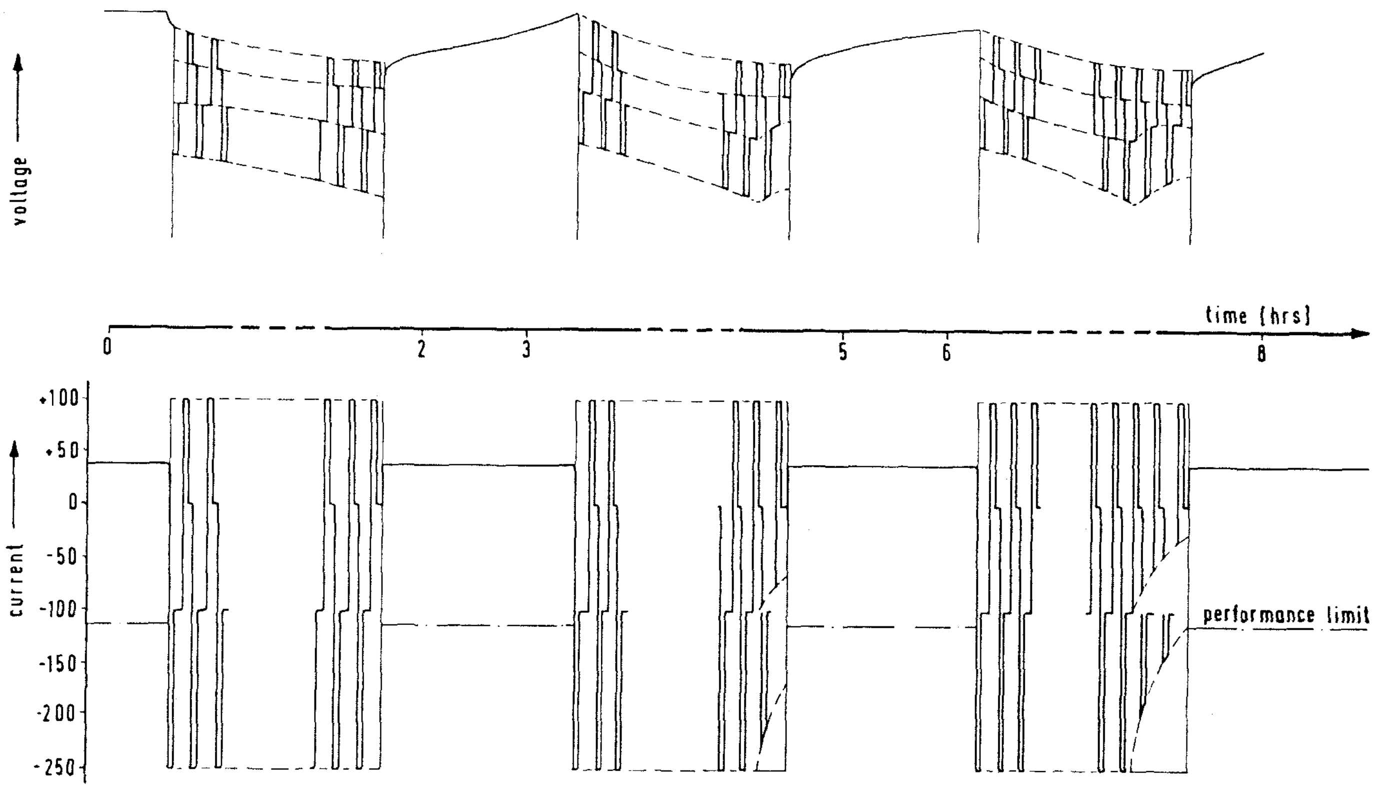

Fig. 10. Performance of current dependent undervoltage control during cycling.