Investigation of the process of thermal runaway in nickel–cadmium accumulators

D.N. Galushkin *, N.N. Yazvinskaya, N.E. Galushkin

*The South-Russia State University of Economics and Services, 147 Shevchenko Street,
Town of Shakhty, Rostov Province, Russia*

Abstract

It has been established experimentally that during thermal runaway a great amount of hydrogen is given off from nickel–cadmium accumulator KSX-25. Through the thermal decomposition of nickel–cadmium accumulator electrodes, it has been shown that hydrogen had been present in the electrodes before the onset of thermal runaway. Through an analysis of the energy balance of thermal runaway, it has been shown that it is not an external source of current that causes thermal runaway, but rather a powerful internal exothermic reaction.
© 2007 Elsevier B.V. All rights reserved.

Keywords: Thermal runaway; Accumulator; Nickel–cadmium; Hydrogen accumulation

1. Introduction

In charging some types of nickel–cadmium (NC) accumulators at constant voltage or their floating charge, the effect known as thermal runaway may be observed. In this case, the charging current in the accumulator begins to increase abruptly; the electrolyte rapidly boils and is converted into vapour. Fusion and breakage of the accumulator case, the expulsion of safety plugs under the action of steam, abundant smoke generation, and even ignition are also possible.

This effect is very unusual and has been little investigated. A review of the literature covering about the last 20 years concerning the investigation of various types of accumulators and the processes taking place in them has revealed that there have been very few papers dealing with the study of thermal runaway. However, this process is mentioned and discussed in quite a number of papers [1–6].

The lack of attention paid to this effect cannot be justified, as, for example, the KSX-25 accumulator, the operation of which may result in thermal runaway, is mounted in an airborne system present in many types of planes. This accumulator is used in the airborne system of a plane as a part of the 20KSX-25 battery.

Since thermal runaway takes place spontaneously and the cause of it presently remains little understood, there is a possibility of it occurring during flight. A plane is an intrinsically rather unsafe means of transport and the occurrence of such an uncontrollable rapid process during a flight, which would be accompanied by steam and smoke generation and probably lead to a short-circuiting of an airborne system of the plane, etc., would inevitably lead to an emergency situation.

This effect is also of great interest from a purely theoretical point of view. Thermal runaway is perhaps the only self-accelerating effect in accumulators that proceeds so rapidly and is accompanied by a great number of visual and thermal effects, yet is practically uncontrollable by the personnel operating the battery.

2. Experimental study of the process of thermal runaway in nickel–cadmium accumulators of KSX-25 type

The main aims of the present study were to experimentally define the change in the charging current and voltage on the accumulator terminals, the change in the accumulator tempera-

* Corresponding author at: Flat 27, 21 Tekstilnaya Street, Town of Shakhty, Rostov Province, Russia. Tel.: +7 86362 22037; fax: +7 86362 25491.
E-mail address: dmitrigal@rambler.ru (D.N. Galushkin).

ture, and the change in the dynamics of gas release during the process of thermal runaway.

Preliminary investigations showed that the possibility of thermal runaway increases with increasing period of operation of the accumulator. It is especially great after very long terms of accumulator operation. Taking this fact into account, 30 accumulators of KSX-25 type that had been in use for more than 5 years were chosen for the experimental study.

First of all, the influence of charger voltage on the possibility of thermal runaway was studied. For this purpose, all of the accumulators were charged in consecutive order at constant voltages of 1.45, 1.67, 1.87, and 2.2 V. The lower value of the range of charging voltages under study corresponds to the accumulator floating charge, which is part of the 20KSX-25 battery.

Each of the accumulators under study was charged and discharged ten times at each charging voltage. Charging was carried out for 8 h. Each accumulator was discharged according to the service instructions for the 20KSX-25 battery at a current of 10 A until the voltage on the accumulator terminals reached 1 V.

To exclude interaction between charging–discharging cycles during the study (through residual phenomena of all types, the "memory effect", etc.), after every cycle studied one to three checking cycles were made.

Charging during the checking cycle was performed in two steps according to the service instructions for the 20KSX-25 battery. The first step at a current of 10 A was for a duration of 3 h, and the second one at a current of 5 A was for a duration of 2 h.

A step-down transformer with a diode bridge capable of ensuring the required voltage and current up to 150 A, and up to 500 A for a short term, was used as a charger.

The released gas was collected in a flexible reservoir capable of storing 1060 l.

3. Results

Firstly, in the course of more than 1100 charging–discharging cycles performed, the effect of thermal runaway was only observed in two cases. Thus, it can be stated that thermal runaway is rather a rare effect.

Secondly, in both of these cases of thermal runaway, the time of operation of the accumulator was more than 5 years (5.5 and 6 years, respectively), with only a 3-year guarantee. Thus, these experimental results directly confirm the preliminary conclusion that the possibility of thermal runaway increases with increasing time of battery operation.

Thirdly, in both instances when thermal runaway occurred, the accumulators were charged at a voltage of 2.2 V, which is significantly greater than the average voltage applied for the operation of these accumulators (1.35–1.5 V). Thus, it can be concluded that the probability of thermal runaway increases with increasing accumulator charging voltage.

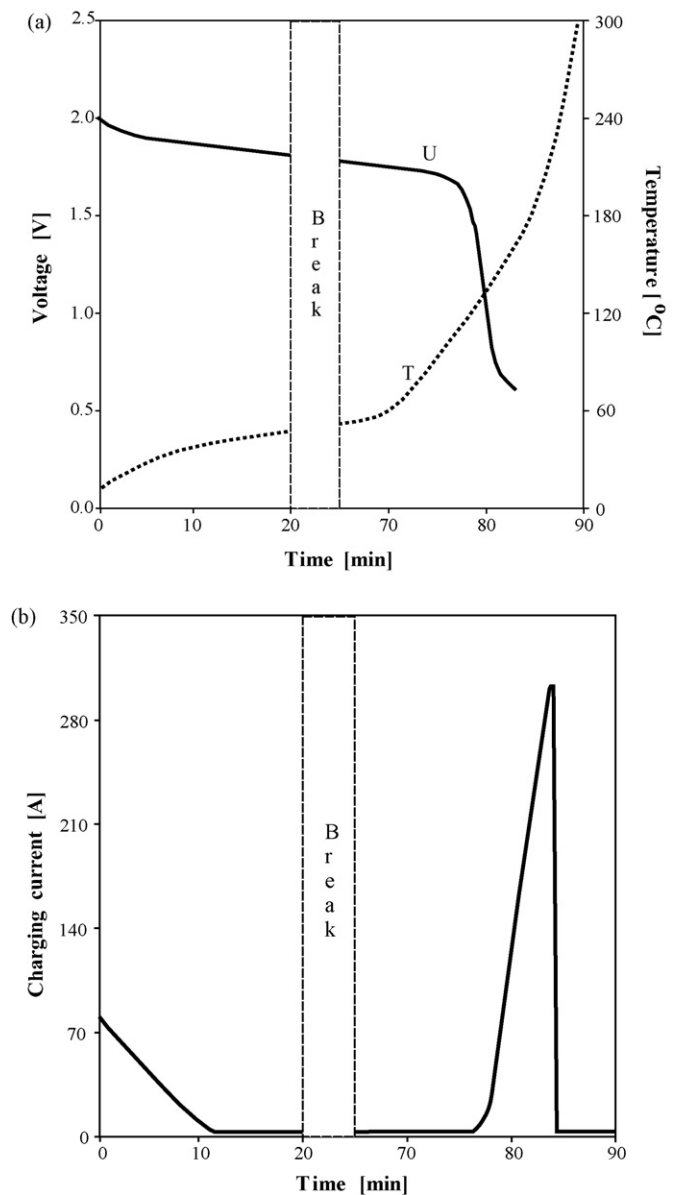Changes in the KSX-25 accumulator parameters during thermal runaway are shown in Figs. 1 and 2. The change of the

Fig. 1. Parameter changes of the KSX-25 accumulator (No. 1) during thermal runaway: I is the charging current of the accumulator, U is the voltage on the accumulator terminals and T is the temperature of the accumulator positive terminal.

charging current in the KSX-25 accumulator shown in Fig. 2 is interesting. Such an uneven change indicates that thermal runaway can appear and die down in the accumulators more than once and spontaneously.

In the final analysis for this accumulator, the electrodes were most probably short-circuited because of separator burn-through, as indicated by the zero voltage on the accumulator terminals at the moment of the installation turning off and by a very great value of the charging current in Fig. 2.

The compositions of the gas mixtures given off as a result of the two thermal runaway events are shown in Table 1.

The total amount of gas mixture was determined as the original amount of gas that was given off. The storage device for the
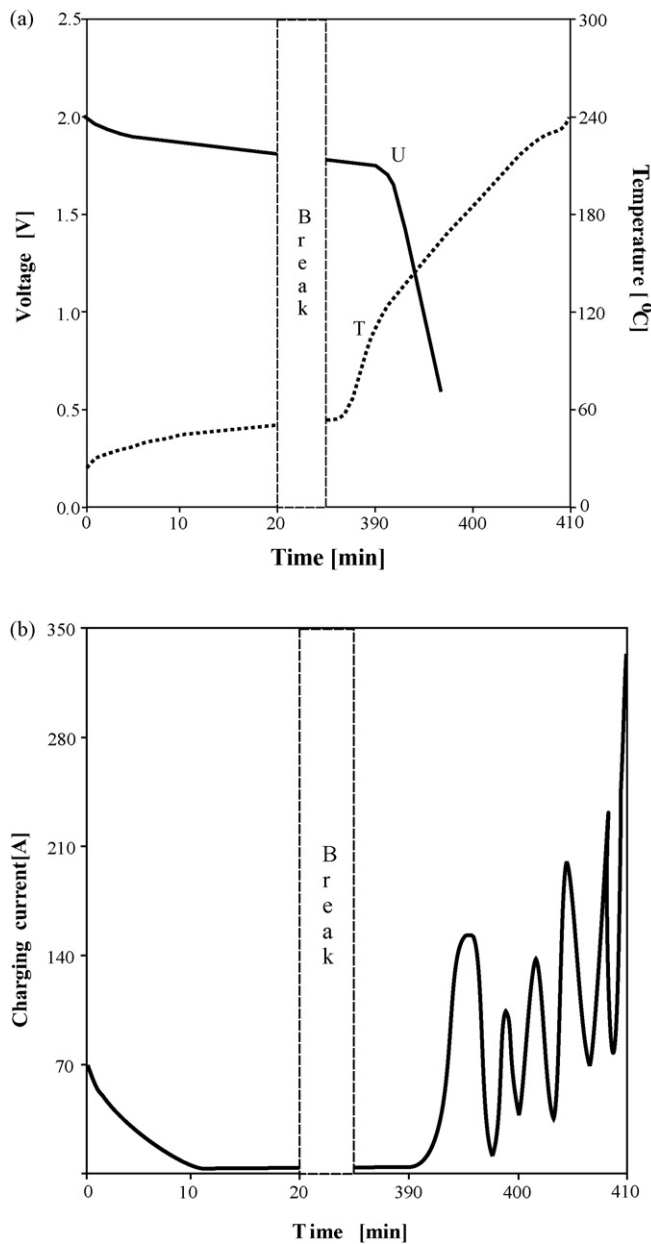
Fig. 2. Parameter changes of the KSX-25 accumulator (No. 2) during thermal runaway: *I* is the charging current of the accumulator, *U* is the voltage on the accumulator terminals and *T* is the temperature of the accumulator positive terminal.

gas mixture was then cooled to room temperature. Thereafter, the amount of released gas was determined for a second time. The difference between these amounts gave the amount of steam that had been given off.

Thus, thermal runaway results in a very intense release of gas that lasts for 4 min (Fig. 1), the amount of gas and steam being about 350 l.

4. Analysis of the gas resulting from thermal runaway

Purely theoretically, the following substances may result from thermal runaway: water vapour, hydrogen and oxygen because of decomposition of water and oxides in the electrodes, and separator combustion products.

Water vapour was separated when the released gas mixture was cooled. Thus, the aim of this section is to study the qualitative and quantitative composition of the rest of the gas.

To test the gas, a VOGA-2M volumetric and optical gas analyser was used. This device can determine the percentage composition of a gas mixture consisting of carbon dioxide, oxygen, carbon monoxide, hydrogen, and methane, a gas volumetric method being used to determine carbon dioxide, oxygen, and carbon monoxide, and an optical method reliant upon a built-in interferometer being used to determine methane and hydrogen.

The results of the analyses of the gas mixtures obtained from the two different accumulators after thermal runaway events are shown in Table 2.

4.1. Discussion

The results obtained are somewhat unexpected, as if we assume that thermal runaway results only in electrochemical or thermal deposition of water, then the hydrogen:oxygen ratio would be oxygen: 33.3%; hydrogen: 66.7%, that is, 1:2.

If we assume that thermal runaway results in hydroxide decomposition because of the high temperature, then the proportion of oxygen in the gas mixture would increase rather than the proportion of hydrogen.

The results obtained can only be explained if we assume that hydrogen had already existed in the electrodes in some form before the thermal runaway and as a result of this process, probably because of high temperature, it was given off in great quantities.

Table 1
Compositions of the gas mixtures evolved in two instances of thermal runaway[a]

Composition of the released gas mixture	Accumulators	
	No. 1	No. 2
Total amount of the *steam–gas* mixture evolved as a result of thermal runaway (l)	351	342
Amount of steam released (l)	63	60
Amount of gas released (l)	288	282

[a] The relative error in measuring these amounts is no more than 10%.

Table 2
Compositions of the gas mixtures after thermal runaway in two KSX-25 accumulators[a]

Gas nature	Accumulator	
	No. 1	No. 2
Gas concentration (%)		
H_2	94	95
O_2	5.2	4.5
Other gases	0.8	0.5

[a] The absolute error in the percentage concentrations in Table 2 is 0.3–0.5.
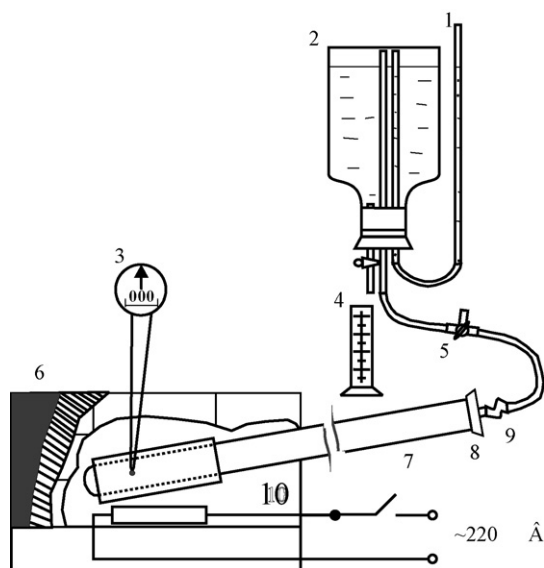
Fig. 3. The experimental set-up to study the process of gas release from the heated accumulator electrodes. (1) Manometer, (2) intake chamber accumulating gas, (3) thermocouple, (4) retort, (5) tap, (6) muffle furnace, (7) metal thermal chamber, (8) rubber plug with a tube for gas extraction, (9) standard coil and (10) heater.

5. Study of the accumulation of gas in alkaline accumulator electrodes

These experiments were carried out to test the assumption of the existence of hydrogen in nickel–cadmium accumulator electrodes prior to thermal runaway and the possibility of its subsequent thermal release.

The experimental set-up to study the process of gas release from the heated accumulator electrodes (Fig. 3) consisted of a metal thermal chamber (7) in the form of a tube 1.8 m long and 2 cm in diameter, the sealed end of which was placed in a muffle furnace, while a rubber plug with a tube for gas extraction was inserted into the other end of the tube.

As under the action of high temperature the electrode under study partially melted and typically adhered to the walls of the thermal chamber, to facilitate its more convenient withdrawal and recovery after the experiment, it was placed into a "cartridge". To reduce heat exchange in the thermal chamber, a round porous ceramic plug, 20 cm long, was placed above the cartridge.

The intake chamber for collecting the gas (2) was a hermetically sealed glass reservoir filled with water. Its capacity was 5 l. At the bottom of this reservoir, a number of tubes were inserted through a rubber plug: a long tube to supply gas from the thermal chamber to the top of the reservoir, a tube to remove excess water, and a leg of a manometer tube (1) to control the pressure of the gas accumulated above the water.

Heating the electrode in the thermal chamber resulted in a release of gas from it. This gas was partially cooled by passage through the standard coil (9) prior to entry into the gas intake chamber. As the gas entered the chamber, the pressure above the water increased, and this was registered by the manometer. To balance the internal pressure in the intake chamber and atmospheric pressure, part of the water was removed from the intake chamber into the retort (4). The water level in the retort gave an indication of the amount of gas that had entered the intake chamber during the period studied.

6. Analysis of the released gas

The released gas was quantitatively analysed with a VOGA-2M gas analyser.

To carry out the experiment, four KSX-25 accumulators were chosen at random. One cadmium and one nickel electrode were taken from each accumulator. These electrodes were then thermally decomposed in the apparatus described above.

Each electrode was decomposed at 800 °C. The reasons for choosing this temperature were as follows. In preliminary experiments, it was determined that visible release of gas starts at about 340 °C for the cadmium electrodes and at about 660 °C for the oxide–nickel electrodes. Big release of the gas starts at temperatures in excess of 740 °C for both the oxide–nickel and cadmium electrodes. The rate of gas release increases with increasing temperature; however, when the temperature exceeds 800 °C, this increase becomes negligible. Thus, the temperature of 800 °C was chosen as an optimum value for thermal decomposition of both the cadmium and oxide–nickel electrodes.

Each cadmium electrode was decomposed over an average period of 7 days, while each oxide–nickel electrode was decomposed over an average period of 13 days, each for 11 h of every 24 h. The amount of gas released from each electrode per day decreased from 4 l during the first days to 100–120 ml during the last days for each cadmium electrode, and from 6 l per day to 100–150 ml per day for each oxide–nickel electrode. The process of thermal decomposition was stopped when the amount of gas released during a 24 h period was less than 100 ml. The results of this experiment are shown in Table 3.

Analysis of the gas released from both electrodes by means of the VOGA-2M gas analyser showed that it consisted of at least 99% hydrogen.

Table 3
Hydrogen content in oxide–nickel and cadmium electrodes of KSX-25 accumulators[a]

No. of the accumulator	1		2		3		4	
Period of operation (years)	4		5		5.2		4.5	
Type of electrode	Ni	Cd	Ni	Cd	Ni	Cd	Ni	Cd
Amount of gas released (l)	31	15	35	18	35.5	19	33	16

[a] The relative error in the data in Table 3 is 5–7%.

6.1. Discussion

According to the results of the experiment (Table 3), prior to thermal runaway, the KSX-25 accumulator electrodes have a very high hydrogen content. The data in the table relate to one accumulator electrode. In a KSX-25 accumulator there are 14 cadmium and 15 nickel electrodes. Therefore, in one KSX-25 accumulator there are approximately $18 \times 14 + 35 \times 15 = 252 + 525 = 777 l$ of hydrogen.

Thus, in total, in a 20KSX-25 aircraft battery there are about $777 \times 20 = 15,540 l$ of hydrogen. The release of such a large amount of hydrogen during thermal runaway from the accumulator to the plane cabin could potentially cause a very powerful explosion. The consequences of such an explosion would be catastrophic.

It is interesting to mention one more fact. The KSX-25 accumulator floating charge results in decomposition of water and release of hydrogen and oxygen in the ratio 33.3% oxygen to 66.7% hydrogen. Nevertheless, experiments carried out to quantitatively and qualitatively determine the composition of the gas released from electrodes showed that in each of the electrodes (oxide–nickel and cadmium) it is only hydrogen that is accumulated.

7. Analysis of the energy balance during thermal runaway

According to the classical mechanistic explanation of thermal runaway, it results from sustained overcharging, which can lead to warming of the accumulator and, as a consequence, to a decrease in its internal resistance and an increase in the recharging current, which, in turn, increases the warming, and so on [1–6].

Thus, this mechanism supposes that all of the energy that results from thermal runaway is supplied by the battery charger. However, it can be proved that the energy received by the accumulator from the battery charger during the thermal runaway is not sufficient even for decomposition of all of the electrolyte. Therefore, thermal runaway must be accompanied by some internal process compensating this shortage.

Indeed, the energy, Q_Z, received by the accumulator from the battery charger during thermal runaway is given by

$$Q_z = \int_{t_1}^{t_2} U(t) I(t) \, dt \tag{1}$$

where $U(t)$ is the voltage change on the accumulator terminals during thermal runaway, $I(t)$ is the change of the charging current during thermal runaway, and t_1 and t_2 are the start and end times of the thermal runaway, respectively.

To calculate the value of Q_Z, let us use the experimental data from Fig. 1. In this figure, it can be seen that during the thermal runaway (4 min) the charging current increased practically linearly from 0.1 to 300 A, while the voltage on the accumulator terminals dropped from 1.8 to 0.5 V. For convenience, let us take the start of the thermal runaway as zero time, so that for the current change during the course of thermal runaway we will have

the equation:

$$I(t) = 1.25t \tag{2}$$

and for the voltage change on the accumulator terminals we have the equation:

$$U(t) = 1.8 - 0.0054t \tag{3}$$

Substituting Eqs. (2) and (3) into the integral (1), one obtains $Q_Z = 33.7$ kJ.

On the other hand, let us estimate the energy that resulted from the thermal runaway on the basis of the external thermal effects. An average KSX-25 accumulator has 60 ml of electrolyte, which evaporates completely during the thermal runaway.

The energy required for this is defined as

$$Q_i = r \times m = 135.6 \, \text{kJ}$$

In addition, the energy to heat the electrolyte from $30 \,^{\circ}\text{C}$ (operating temperature of the accumulator in charge) to $100 \,^{\circ}\text{C}$ is also required.

$$Q_n = c \times m \times (t_2 - t_1) = 17.6 \, \text{kJ}$$

Vapour resulting from the thermal runaway was expelled from the accumulator at a temperature of at least $350 \,^{\circ}\text{C}$. To heat it to this level required:

$$Q_p = cm(t_2 - t_1) = 27.3 \, \text{kJ}$$

In the experiment under consideration, the plastic case of the accumulator together with the electrodes themselves were also heated to a temperature of at least $150 \,^{\circ}\text{C}$; the casing was rapidly fused at the sides. If the mass of the accumulator was about 1 kg, then this heating would have required at least $Q_b = 38$ kJ.

Thus, the total amount of heat:

$$Q = Q_i + Q_n + Q_p + Q_b$$

that results from thermal runaway, as indicated in Fig. 1, must be at least 218 kJ, which is considerably greater than the energy received by the accumulator from the battery charger (4).

In a private conversation that took place in the laboratory of "Non-Steady Electrolysis" (South-Russia State Technical University of t. Novocherkassk), an assumption was made that as a result of thermal runaway the electrochemical energy accumulated by the charged accumulator is a source of the emission of heat. The accumulator used in the experiment had been in operation for 5.5 years, giving an average charge of 14.5–15.5 Ah. That is to say, it had an energy of at most 67 kJ, which is clearly not sufficient. However, at the very beginning of the thermal runaway, the capacity of this accumulator was no more than 7 Ah, which is easily calculated by integrating the curve of the change in the charging current over the interval before the thermal runaway in Fig. 1. Therefore, it had electrochemical energy of no more than 30 kJ, which is again significantly lower than the required value.

This assumption was also tested experimentally. Rapid release of the accumulated electrochemical energy is only possible through a process such as short-circuiting of the accumulator electrodes.

In the course of experiments involving a series of internal short circuits of the plates of KSX-25 accumulators, which had been in use for 5 or 6 years, it was found that internal short circuits increased the temperature of the electrolyte and electrodes to 72–84 °C, with the generation of a small amount of steam. This corresponds to a release of heat of no more than 27 kJ, which is significantly less than the energy released during thermal runaway.

Thus, the results of the estimation of the thermal runaway energy balance unambiguously show that thermal runaway is accompanied by a powerful exothermic reaction with the release of a great amount of heat.

8. Discussion

Of prime concern is the origin of such large quantities of hydrogen evolved from the electrodes of KSX-25 batteries.

Theoretically, one can envisage two sources of hydrogen in the electrodes of the batteries in question:

1. Hydrogen enters the electrodes of these batteries as a result of certain technological processes during their manufacture. If this were the case, new batteries should contain the same amount of hydrogen as batteries that have completed their service life.
2. Hydrogen accumulates in the electrodes of Ni–Cd batteries during their use.

To check these hypotheses, the electrodes of new (never used) KSX-25 batteries were fragmented and analysed. The experiment demonstrated that no hydrogen is present in the electrodes of new batteries.

Hence, this experiment expressly shows that hydrogen accumulates in the electrodes of Ni–Cd batteries during their use.

According to the operation manual of the 20KSX-25 battery, it is charged in two stages: firstly by a current of 10 A over a period of 3 h, and secondly by a current of 5 A over a period of 2 h. Consequently, these batteries overcharge by a factor of 1.6 as compared to their nominal capacity. Overcharge is required for complete charging of the batteries. Thus, in the course of charging, almost 15 Ah are used for electrolyte decomposition with the evolution of hydrogen and oxygen.

Consequently, one charging of a KSX-25 battery produces 6 l of hydrogen and 3 l of oxygen. Thus, the discovered 777 l of hydrogen may have been accumulated during 130 charging–discharging cycles. By the end of its life span, a KSX-25 battery is likely to have gone through ten times as many charging–discharging cycles. Therefore, it can, in principle, accumulate the discovered amount of hydrogen.

In our opinion, hydrogen accumulates inside electrodes in the form of metal hydrides. Transition metals such as nickel and cadmium are capable of accumulating hydrogen [7–12]. The accumulation of hydrogen in transition metals commences with hydrogen adsorption at the metal surface. The adsorbed molecules dissociate into atoms, which can then migrate into the crystal lattice of the metal. At low concentrations, these hydrogen atoms can move freely within the crystal lattice of the metal. However, as their concentration increases, they begin to form chemical bonds with the metal atoms.

Hydrogen is characterised by a very high diffusion permeability. The diffusion coefficient of hydrogen atoms is many times higher than those of all other atoms, including oxygen atoms. For example, at the temperature 20 °C the diffusivity of hydrogen in nickel is approximately 10^{10} times higher than diffusivity of nitrogen or oxygen [7]. The high diffusion permeability of hydrogen is determined by the small size of its atom, its low mass, and the structural peculiarities of metal–hydrogen systems [7,9,10]. These features explain why upon dissociation of an electrolyte into hydrogen and oxygen in a battery, only hydrogen accumulates in the electrodes, while oxygen escapes to the atmosphere.

The amount of hydrogen that may be accumulated in transition metals is determined by many factors. First, there is the particular nature of the hydrogen accumulation process; the amount of accumulated hydrogen increases as the hydrogen pressure is increased. Second, one needs to consider the state of the crystal lattice of the metal. In the case of nickel, less hydrogen will be accumulated by cast nickel than by porous Raney nickel. The more finely divided the nickel and the more collapsed its crystal structure (that is, the more dislocations there are in the crystal lattice), the more capable it is of accumulating hydrogen [11,12].

The amount of hydrogen that we have recovered from KSX-25 battery electrodes is almost tenfold higher than the amount that is typically accumulated by these metals by more conventional means of hydrogen uptake. It would seem that this is related to certain specific features of hydrogen accumulation in the electrodes of alkaline batteries. First, due to the tight packing of the electrodes, hydrogen emitted at the cadmium electrode can penetrate into the pores of both the nickel oxide and cadmium electrodes, and produces very high capillary pressure inside the pores. According to works [13,14] the amount of hydrogen C accumulated in metal is related to external pressure of hydrogen P by the formula:

$$C = K\sqrt{P}$$

Capillary pressure in the electrode pores is inversely proportional to pore radius R, i.e.

$$P = \frac{A}{R} \tag{4}$$

$A = 0.2 \, \mu m \, MPa$—proportionality constant for the given electrolyte.

In porous electrode the main pores have the average radius of the order of several dozens of microns. However the finely divided powder, used for manufacturing of metal–ceramic matrix of the electrodes, have the micro fissures with dimensions from several hundreds of angstrom to the size of crystalline lattice of the metal [15]. Thus, hydrogen accumulating in the micro fissures as the result of electrolyte decomposition may have the pressure of (4) up to 100 MPa.

Second, the process of hydrogen uptake by the electrodes proceeds during their entire lifespan, in the present case for over 5 years.

Third, the nickel oxide electrode in a KSX-25 battery is metal–ceramic, made from finely divided nickel powder with strongly collapsed crystalline structure. Any imperfections of metal crystalline structure (particularly dislocations) are traps for hydrogen, as they decrease the energy of hydrogen atom as compared to their location in normal interstice. Besides they are the centers of hydrogen absorption, and also contribute to hydrogen penetration into the metal depth. Hence, imperfections of the metal crystalline structure cause sharp rise of hydrogen miscibility in it [14,16].

In direct methods the metal hydrides are obtained by metal powder heating in the hydrogen atmosphere to the temperatures, as a rule, lower than 1000 °C. At this the external pressure of hydrogen is either not used or is small [7,17]. However in several experiments it may be up to 20 MPa, for example, during obtaining magnesium hydride. At this the process of hydride obtaining lasts from several minutes to several hours. Analysis of hydrides' research works for approximately last 20 years showed, that most probably there were no experiments for obtaining transition metals hydrides at high external hydrogen pressures lasting for extremely long time periods. However exposure to external pressure is a significant factor at any processes of penetration of one substance into another. Especially when the penetration process is extremely slow as in our case.

Thus, as it seems, it is the high hydrogen capillary pressure, acting during extremely long time on the strongly collapsed crystalline structure of electrode metals, allowed to accumulate in them ten times more hydrogen, as compared to traditional methods of obtaining hydrides.

The above suppositions concerning the nature of hydrogen accumulation in the electrodes of alkaline batteries are largely hypothetical, and hence there is a need for further research, both electrochemical and structural.

Within this hypothesis, the hydrogen evolved upon heating the electrodes can be explained in terms of thermal decomposition of the hydrides. Metal hydrides obtained by direct hydrogenation methods have the temperatures of thermal decomposition comparable to obtained by us in Section 6 [17,18].

Thermal runaway in nickel–cadmium batteries can occur at any point between the opposite electrodes. At this location, the separator between the electrodes burns through in a circular fashion. Temperature evaluation at the point of thermal runaway, judging by thermal marks on the electrodes, demonstrates that at this point the temperature was not less than 700–800 °C. The energy evolved at the point of thermal runaway is used to evaporate the electrolyte and to heat up the battery casing and the electrodes. However, we consider that temperature is not the only reason for the emission of such a large amount of hydrogen from the electrodes in the process of thermal runaway. In our opinion, the hydrogen accumulated in the electrodes actively reacts in the powerful exothermic reaction that accompanies thermal runaway. Indeed, we believe that it is particularly this reaction that contributes to the mass escape of hydrogen from the electrodes during thermal runaway. Indeed at thermal runway in Table 1 (Experiment No. 1) in 4 min 288 l of hydrogen evolved. At thermal decomposition of electrodes at the temperature of 800 °C in 11 h out of nickel oxide electrode 6 l of hydrogen evolved, and from the cadmium electrode – 4 l. KSX-25 accumulators comprise 14 cadmium and 15 nickel oxide electrodes. Consequently, at thermal decomposition of all the electrodes of accumulators within 11 h $4 \times 14 + 6 \times 15 = 146$ l of hydrogen shall evolve. Thus, it takes about 22 h to obtain 288 l of hydrogen from the battery only at the sake of hydrides' thermal decomposition. Hence, at thermal runway there is some other process promoting the mass hydrogen discharge from the electrodes. To our mind, this process is a powerful exothermic reaction, accompanying thermal runway is such a process.

However, this hypothesis has to be checked experimentally. Since the complex electrochemical mechanism of thermal runaway remains relatively unexplored, the resolution of this problem requires further research, both experimental and theoretical.

References

[1] V.V. Tenkovtsev, B.I. Tsenter, Foundations of the Theory of Operation of Hermetically Sealed NC Accumulators, Energoatomizdat, Leningrad, 1985, pp. 50–53.
[2] V.V. Tenkovtsev, M.J-N. Levi, Hermetically Sealed General Purpose NC Accumulators, Informstandartelectro, Moscow, 1968, pp. 51–59.
[3] B.S. Hobbs, T. Keily, A.G. Palmer, J. Appl. Electrochem. 9 (1979) 501.
[4] S.Y. Kan, S. Silvester, J. Sustain. Prod. Design 3 (2004) 29.
[5] R.L. Wickham, Wireless Rev. 15 (1998) 3.
[6] B. Dick, R.W. Wittemann, Telephony 235 (1998) 22.
[7] B.A. Kolachev, A.A. Ilyin, V.A. Lavrenenko, Yu.V. Levinsky, Hydride Systems (Reference Book), Metallurgiya, Moscow, 1992, pp. 37–157.
[8] Proceedings of the Second International Congress, Paris, 1977; Hydrogen in Metals, Oxford Educational Academy, 1978.
[9] B. Hohler, H. Kronmuller, Phil. Mag. A 43 (1981) 5.
[10] Y. Fukai, Y. Sugimoto, Adv. Phys. 2 (1985) 34.
[11] R. Kirchheim, Acta Metall. 2 (1982) 30.
[12] Yu.S. Nechaev, G.A. Filippov, Hydride-like Segregation at Dislocations in Fe and Steels, Defect & Diffusion Forum 194–199 (2001) 1099–1104.
[13] R.H. Fowler, J.S. Smithels, Proc. R. Soc. A 160 (1937) 37.
[14] International Symposium on Hydrogen Systems, CAB Beijing, Beijing, China, May 1985; Hydrogen Systems, vol. 1, Pergamon Press, Oxford, 1986, p. 550; Hydrogen Systems, vol. 2, Pergamon Press, Oxford, 1986, p. 533.
[15] Yu.A. Chizmadjev, V.S. Markin, M.R. Tarasevich, Yu.G. Chirkov, Macrokinetics of Processes in Porous Media, Nauka, Moscow, 1971, pp. 287–318.
[16] Ed.G. Alefeld, J. Volkl, Hydrogen in Metals, vol. 2, Application-oriented Properties, Springer-Verlag, Berlin/Heidelberg/New York, 1978, p. 387.
[17] M.M. Atomova, Metal Hydride's Properties, Reference Book, Naukova Dumka, Kiev, 1975, p. 98.
[18] Ed.G. Alefeld, J. Volkl, Hydrogen in Metals, vol. 1, Basic Properties, Springer-Verlag, Berlin/Heidelberg/New York, 1978, p. 427.