

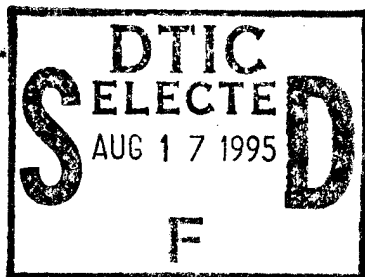
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STUDY ON THERMAL PROPERTIES OF Cd-Ni BATTERIES FOR SATELLITES

by

Hu Jingang



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# STUDY ON THERMAL PROPERTIES OF Cd-Ni BATTERIES FOR SATELLITES

Hu Jingang

## ABSTRACT

Empirical research was carried out on thermal properties associated with the use of Cd-Ni storage cells in satellite engineering. Introduction is made of measured cell thermal capacities as well as amounts of heat put out by systems. The systems in question possess the advantages of being simple and reliable. Measured results are given, and, in conjunction with that, comparisons are carried out with data from abroad.

SUBJECT TERMS Cd-Ni Storage Cells, Spaceflight Power Sources, Calorimetry, Specific Heat Meter, Research

## I. INTRODUCTION

Energy source systems are one important satellite subsystem. The quality of their operation is directly related to satellite tactics, technological performance, as well as satellite operating life. Energy source system design includes the electrical, mechanical, and thermal design of systems. In the last more than twenty years, from energy source systems composed of a combining of silicon solar energy and Cd-Ni storage cells, adequate development and broad applications have been obtained, satisfying the electric supply requirements of full time satellites. Following along with the development of spaceflight technology, requirements for power supplied by energy source systems have grown larger and larger. Cd-Ni cell capacities have developed from a few amp-hours to several tens of amp-hours. Powers supplied have also risen from a few watts to a few tens of watts, a few hundreds of watts, and even up to the level of thousands of watts. Cd-Ni cells possess a large number of iterations of charging and discharging cycles, long life, as well as reliable and stable performance. However, there is a close relationship between electrical properties of this type of cell

and the temperature of cell bodies themselves. At low temperatures, cell discharge properties are bad. At high temperatures, cell charging efficiencies are low. Because of this, creating a good operating temperature environment guarantees normal cell operation, extends useful cell life, and is one important task of thermal design.

If one wants to accurately and rationally carry out cell thermal design, it is necessary to understand thermal properties of cell bodies. This includes the two key parameters of cell thermal capacity and amount of heat put out. At the present time, with regard to cell thermal property research, it is primarily based on experimental methods. Abroad, work in this area has already developed for several decades. Different researchers utilize different systems, and all arrive at extremely similar results (1~8). The focal points of research are utilizing calorimetric methods to measure the amounts of heat put out during periods of cell charging and discharging; again, on the basis of cell output electric power, to solve for changes in enthalpy value  $\overline{\Delta H}$ , during cell charging and discharging; to analyze cell interior chemical reactions; and, to find ways of increasing cell performance. The overall status of research abroad is seen in detail in Table 1.

Table 1 Overall Status of Cd-Ni Cell Research Abroad

1 研究者	2 年代	3 量热计型式	4 电池容量 Ah	5 电池热容kJ/K 或比热 J/(g·K)	$\overline{\Delta H}$ (kJ/mol)	6 备注
Salkind A J. <sup>[1]</sup>	1962	7 恒温器			133.9	测电池温度系数求 $\Delta H$ 8
Milson L. <sup>[2]</sup>	1963	9 杜瓦瓶内装硅油	10 20 (梭诺通公司)	0.979J/(g·K)	133.9	$\overline{\Delta H}$ 为放电时值 11
Gillibrand M I. <sup>[3]</sup>	1964	12 空气加热式绝热量热计	35/75	1.34kJ/K/ 4.81kJ/K	137.6	$\overline{\Delta H}$ 为充、放电平均值 13
Metzger W H. <sup>[4]</sup>	1964	14 杜瓦瓶装硅油	4~6	3.18kJ/K	138.0	$\overline{\Delta H}$ 为放电时值 15
Bruins P F. <sup>[5]</sup>	1966	16 空气加热式绝热量热计	5	0.22~0.33kJ/K	138.6	$\overline{\Delta H}$ 为放电时值 17
Webster W H. <sup>[6]</sup>	1967	18 等温流动型量热计	6 19 塑料壳		138.6	模拟电池工作状态 20
Gross S. <sup>[7]</sup>	1969	21 半绝热法	12 22 (不锈钢壳)	0.92J/(g·K)		研究电池发热状况 23
Liebert L H. <sup>[8]</sup>	1971	24 绝热包扎	34	1.129J/(g·K)		研究电池内部温度分布 25

Key: (1) Researcher (2) Year (3) Calorimeter Type (4) Cell Capacity (5) Cell Heat Capacity kJ/K or Specific Heat J/(g·K) (6) Remarks (7) Thermostat (8) Measures Cell Temperature Coefficients Solving for  $\overline{\Delta H}$  (9) Silicon Oil Loaded into Dewar Flask (10) Suonotong (phonetic) Company (11)  $\overline{\Delta H}$  is value at discharge time (12) Air Heating Type Adiabatic Calorimeter (13)  $\overline{\Delta H}$  is average charging and discharging value (14) Silicon Oil Loaded into Dewar Flask (15)  $\overline{\Delta H}$  is discharge time value (16) Air Heating Type Adiabatic Calorimeter (17)  $\overline{\Delta H}$  is discharge time value (18) Isothermal Flow Type Calorimeter (19) Plastic Casing (20) Simulated Cell Operating Configuration (21) Semiadiabatic Method (22) (Stainless Steel Casing) (23) Studies Cell Heat Output Configuration (24) Adiabatic Packing (25) Studies Cell Interior Temperature Distributions

## II. CELL INTERIOR ENERGY EQUILIBRIUM

On the basis of the first law of thermodynamics, if one takes cells and sees them as forming a single system, the system in question has work and heat exchanges with the outside. Assuming that the cell work done on the outside is  $A$  and the amount of heat the cell discharges toward the outside is  $Q$ , then, the amount of reduction associated with cell interior energy  $U$  should be

$$-\Delta U = A - Q \quad (1)$$

Generally speaking, the work done by cells includes two parts. One part is the electrical work  $W$ . The other part is mechanical work, that is, due to changes in cell volume and pressure, the  $PV$  form of work  $A'$  is done. Because of this, one has

$$\begin{aligned} A &= W + A' \\ \Delta U &= Q - W - A' \end{aligned} \quad (2)$$

If cells are sealed, then volume  $V$  is constant. At the same time, selecting appropriate charging and discharging periods, causing cell interior pressures to be invariable (or basically invariable). Then, pressure  $P$  is a constant. As a result,

$$A' = \Delta(PV) = P \cdot \Delta V + V \cdot \Delta P = 0$$

Consequently,

$$\Delta U = Q - W \quad (3)$$

From thermodynamic function relationships, it is possible to know that system enthalpy  $H$  and internal energy  $U$  have the relationship described below

$$\begin{aligned} H &= U + PV \\ \text{that is,} \quad \Delta H &= \Delta U + \Delta(PV) = \Delta U \\ \text{Therefore,} \quad \Delta H &= Q - W \end{aligned} \quad (4)$$

Equation (4) takes changes in cell enthalpy values during discharge and relates them to cell electrical work done to the outside as well as the heat cells discharge to the outside.

/65

The conditions for setting it up are cell interior pressures and cell volumes are invariable. The equation in question does not explain reductions in cell enthalpy values ( $\Delta H$  is negative) being equal to the amount of heat discharged by cells ( $Q$  is negative) or differences in the electrical work ( $W$  is positive) done on the outside. The symbol  $\Delta H$  is determined by the sum of the numbers represented by  $Q$  and  $W$ . The symbols  $Q$  and  $W$  stipulate the same first law of thermodynamics, that is, with regard to cell work done on the outside and cell heat transferred to the outside-- $W$  and  $Q$ --are positive. Otherwise, they are negative. In accordance with this rule, during discharge processes, cell enthalpy values are reduced. In that case,  $\Delta H$  should be a negative value.

If the current  $I$  flows through the cell, and cell discharge time is  $S$ , then, on the basis of Farraday's Law, at this time, the amount of material participating in cell interior chemical reactions is

$$n = I \cdot S / F \quad (5)$$

The electrical work  $W$  which cells output to the outside is

$$W = \int_0^S I \cdot V dt = I \cdot \bar{V} \cdot S \quad (6)$$

The heat  $Q$  which cells discharge to the outside is

$$Q = G \cdot C_p \cdot \Delta t \quad (7)$$

During cell discharge, unit molar enthalpy change  $\overline{\Delta H}$  is

$$\overline{\Delta H} = \frac{\Delta H}{n} = (Q - W) \cdot F / I \cdot S \quad (8)$$

During cell discharge, the average amount of heat put out  $\bar{q}$  is

$$\bar{q} = Q/S = G \cdot C_p \cdot \Delta t / S \quad (9)$$

In the equations above,

I--current strength during discharge (A);

V--cell terminal voltage during discharge (V);

$\bar{V}$ --cell average terminal voltage during discharge (V);

S--discharge time (min);

G--cell mass (kg);

$C_p$ --cell specific heat (kJ/kg);

$\Delta t$ --temperature rises at times of cell discharge start and stop (K);

F--Farraday constant 1610 A • min/mol.

From Table 1, it is possible to see that no matter what the cell capacity is, what type of material casings are, what type of model calorimetric systems are, cell average enthalpy changes  $\bar{\Delta H}$  gotten from tests are all basically the same. Because of this, it is possible to use them in order to check the reliability of thermal property research carried out on cells. Among the research techniques discussed below and their results, calculations were also done of  $\bar{\Delta H}$ , and they agreed entirely with values from abroad (Table 1). With this being the case, it proves that these methods and systems are accurate and reliable.

### III. CELL THERMAL PROPERTY RESEARCH

#### 1. SPECIFIC HEAT CONTENT

Cd-Ni cells used in satellites are all metal casing sealed type cells. This type of cell is a composite body composed of a number of types of metallic and nonmetallic materials. Besides solid materials, there are also liquid electrolytes. With regard

to this type of composite body, there is no way to opt for the use of conventional specific heat measurement methods--for example, calorimeter methods and copper calorimeter methods to carry out test measurements. To this end, specialized designs were done for a set of calorimeters using water equivalent methods in order to complete cell heat capacity measurements.

Water equivalent method measurement principles are as follows: take cells which have gone through adequate constant temperature ( $t_2$ ) heating and rapidly introduce into them /66 calorimeters with water temperatures of  $t_1$ . At the same time, record liquid temperature rises in calorimeters. Wait until after systems reach thermal stability, and measure equilibrium temperatures  $t$  associated with cells, calorimetric tubes, and liquid water. After that, in accordance with the formula below solve for average heat capacity within cell temperature ranges  $t_2$  and  $t$

$$C_1 = \frac{t-t_1}{t_2-t} (C_{\text{水}} + C_{\text{量}}) \quad (10)$$

Key to eq. (10): (1) water (2) calorimeter

In the equation,  $C_1$  --cell heat capacity (kJ/K);  
 $C_{\text{water}}$  --heat capacity of water in calorimeter tube (kJ/K);  
 $C_{\text{calorimeter}}$  --heat capacity of calorimeter tube itself (kJ/K);  
 $t_1$  --initial water temperature (K);  
 $t_2$  --initial cell temperature (K);  
 $t$  --water temperature after reaching thermal stability (K).

If cell mass is  $m_1$ , then, cell specific heat capacity is

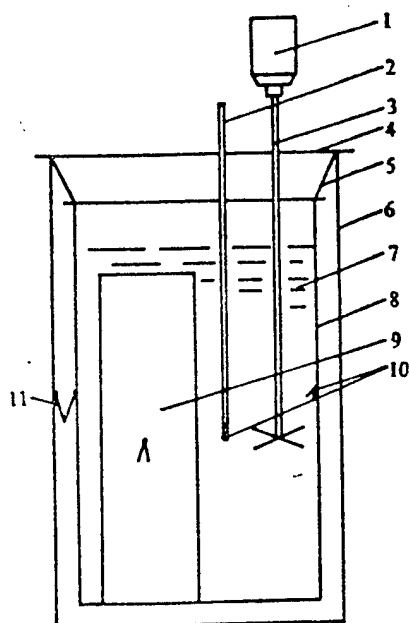


Fig.1 Specific Heat Calorimeter Structure Schematic

Key: 1-Variable Speed Electrical Machinery 2-Glass Rod  
 3-Stirring Rod 4-Foam Plastic Cover 5-Nylon Suspension Rope  
 6-Protective Tube 7- Distilled Water 8-Calorimetric Tube  
 9-Cell 10-Thermocouple 11-Temperature Differential Thermocouple

Specific heat capacity measurement systems are as shown in Fig.1. The magnitude of their dimensions is determined by the dimensions of the cells being measured. Generally speaking, when designing calorimeter tubes, one should consider the interior storage of adequate distilled water and submergence of cells. At the same time, one should make the water temperature increase value  $t-t_0$  larger than 10K in order to reduce measurement errors. On the outside surface of tubes, there is attached a layer of aluminum plated polyester film. In conjunction with this, use is made of fine nylon rope for suspension in protective tubes.

Protective tubes outside calorimetric tubes also use 1mm thick red copper plate for manufacture. The interval between them is as small as possible. On interior surfaces of protective tubes, there is attached a layer of aluminum plated polyester film. Exterior surfaces are covered over with constantan heating plates, used to add heat when tracking temperature. At the gap on the top end of protective tubes and calorimetric tubes, use is made of a low density foam plastic ring added as a seal.

Temperature tracking systems are composed of DW-702 precision temperature control devices, temperature differential thermocouples, as well as heaters. During tests, one should insure that the temperature differential between calorimetric tube outer walls and protective tube inner walls is smaller than  $\pm 0.2\text{K}$ . Requirements for temperature measuring instruments are temperature measurement errors not larger than  $\pm 0.2\text{K}$ .

In order to specify the degree of accuracy of specific heat measuring systems, measurements were carried out on specific heat capacities associated with several types of common metallic and nonmetallic materials. The results were as shown in Table 2.

From Table 2, it is possible to know that the maximum relative error between measurement results and values set out in tables does not exceed  $\pm 3\%$ . On the same type of material, two or more iterations of repeated test measurements were carried out in all cases. Replicability was within  $\pm 5\%$ .

After calibration of completed specific heat capacity measurement systems, four iterations of measurements were carried out on the specific heat capacities of two single 13.6 Ah Cd-Ni cells used in satellites. The results were as shown in Table 3. Besides this, cell specific heat capacities were also solved for using calculations methods based on cell structural components and in accordance with mass percentage ratios. In conjunction with this, comparisons were made with measurement values. From Table 3, it can be seen that deviations between experimentally measured values and calculated values is within 3.3%. From another angle, this proves that measurement results are reliable.

Table 4 gives cell specific heat capacity calculation results associated with two experimental uses.

Finally, the average value associated with four iterations of measurement values act as specific heat capacity values for the models of cell in question. The value is 0.912J/(g•K).

Cd-Ni cells are composite structures of many types of materials. This then determines cell specific heat capacity dependence on their structural components. Because of this, for different structures and different models of cells, the specific heat capacities all apply experimental methods to carry out measurements. /67

Table 2 Test Measurement Results for Specific Heat Capacities of Several Types of Materials

1 材 料	2 比热容 (J/g•K)	
	3 实 验 值 (平均温度℃)	4 表列值 <sup>[7]</sup> (温度范围℃)
LY12CZ	0.858 (52)	0.858~0.891 (26.8~76.8)
LC4CS	0.870 (52)	0.849~0.887 (26.8~76.8)
紫铜 5	0.382 (52)	0.377~0.393 (26.8~76.8)
3025酚醛布板 <sup>6</sup>	1.527 (52)	1.493 <sup>*</sup> (164.8)

7 \* 沈阳金属所铜卡计法测试结果

Key: (1) Material (2) Specific Heat Capacity (3) Experimental Values (Average Temperature °C) (4) Value Set Out in Tables (Temperature Range °C) (5) Red Copper (6) 3025 Phenolic Panels (7) Shenyang Metals Institute Copper Calorimetric Method Test Measurement Results

## 2. AMOUNTS OF HEAT PUT OUT DURING DISCHARGE

In order to simplify experimental equipment, under atmospheric conditions, option is made for the use of temperature tracking methods to complete measurements of amounts of heat put out during discharge. Equilibrium amounts of heat put out during cell discharge are

$$Q = G \cdot C_p \cdot \Delta t + Q' \quad (12)$$

In the equation,  $Q'$  is heat leakage term.

Due to option for the use of temperature tracking techniques,  $GC_p\Delta t$  terms are far larger than  $Q'$  terms. Because of this, as long as measurements are made of cell mass  $G$ , specific heat capacity  $C_p$  as well as cell temperature rises  $\Delta t$  during discharge, it is possible to solve for cell amounts of heat put out.

Measurements were done of the main body components of adiabatic calorimeters associated with amounts of cell heat put out--calorimetric tubes as shown in Fig.2. On protective tube inner surfaces was attached low emission rate aluminum plated thin film. Protective tube outer surfaces had attached constantan heating plates. By DWT-702 temperature control device controls, tracking was done of cell temperature changes, making

Fig.2 Calorimetric Tube Structure Schematic

Key: 1-Nylon Suspension Rope  
2-Protective Tube  
3-Temperature Measurement Thermocouple  
4-Cell  
5-Temperature Differential Thermocouple

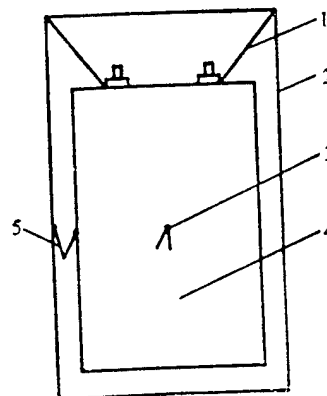


Table 3 Single Unit Cell Specific Heat Capacity Values

1 序号	2 电池代号	3 电池质量 (g)	4 比热容值 (J/g·K)	
			5 实验值	6 计算值
1	75-2	597.0	0.924	0.936
2			0.912	
3	75-11	586.0	0.916	0.928
4			0.899	

Key: (1) Sequence No. (2) Cell Code (3) Cell Mass  
 (4) Specific Heat Capacity Value (5) Experimental Value  
 (6) Calculated Value

Table 4 Single Unit Cell Specific Heat Capacity Calculated Values

1 部件	2 材料	3 比热 J/(g·K)	4 75-2 电池		4 75-11 电池	
			5 质量 (g)	6 热容 (J/K)	7 质量 (g)	8 热容 (J/K)
9 盖	13 密封陶瓷	1.08	5	5.40	5	5.40
	08F 钢 14	0.46	26	11.96	25.9	12.86
10 壳	08F 钢 14	0.46	131.5	60.49	129.2	59.43
11 隔膜	尼龙毡 15	1.88	13.1	24.62	10.9	20.49
12 电解液	密度为 1.28g/cm <sup>3</sup> , 每升含 8~10gLiOH 的 KOH 液 16	3.34	76.7	256.1	75.4	251.8

Key: (1) Part (2) Material (3) Specific Heat (4) Cell  
 (5) Mass (6) Heat Capacity (7) Mass (8) Heat Capacity  
 (9) Cover (10) Casing (11) Separator (12) Electrolyte  
 (13) Sealed Ceramic (14) Steel (15) Nylon Felt (16)  
 Density is 1.28 g/cm<sup>2</sup>. Each litre contains 8-10g LiOH  
 associated with KOH liquid.

续 表 1

2	活性物质	NiOH	0.46	60.5	27.83	59.4	27.32
		Cd(OH) <sub>2</sub>	0.84	82.7	69.46	72.0	60.48
3	基本骨架	镍 7	0.50	196.3	98.15	203.8	101.9
4	隔板	硬聚氯乙烯 8	1.00	5	5	5	5
5	合计			596.9	559.01	586.6	544.68
6	比热容			0.936J/ (g·K)		0.928J/ (g·K)	

Key: (1) Continued Table (2) Active Substance (3) Basic Frame (4) Isolation Panels (5) Total (6) Specific Heat Capacity (7) Nickel (8) Hardened Polyvinylchloride

temperature differentials between the two not exceed  $\pm 0.2^{\circ}\text{C}$ .

Using this system, measurements were carried out on four individual unit cells associated with two production batches. The four cells, respectively, were coded 1-1, 1-2, 2-1, and 2-2. Nominal capacity was 13Ah. Cell structural forms were entirely the same. The second batch used different nickel powder. The outer casing was changed from the original 08F steel to stainless steel. The second batch production techniques were slightly different. Looking from the point of view of experimental results, this type of tiny difference did not greatly influence cell thermal properties. During experiments, discharge currents varied from 4.5A - 8A. Discharge terminal voltage was 1.0V. All together, 14 iterations of discharge tests were carried out on the four cells. Measurement results are seen in Table 5.

Table 5 Measurement Results for Amounts of Heat Produced in Association with Cd-Ni Cell Discharge

9 电 池	1 项 目	2 热 容 (kJ/K)	3 放电电流 I(A)	4 平均电压 V(V)	5 放出热量 Q(kJ)	6 电 功 W(kJ)	7 焓 值 变 化 $\Delta H$ (kJ/mol)	8 平均发热量 $\bar{q}$ (W)
1-1	0.5288	4.5	1.225	10.20	65.14	136.8	0.865	
		5.5	1.220	10.33	64.05	136.8	1.082	
		6.5	1.218	10.04	60.83	136.8	1.308	
		8.0	1.210	10.25	58.78	137.2	1.690	
1-2	0.5296	4.5	1.232	10.04	61.75	138.4	0.904	
		5.5	1.229	10.71	62.76	138.0	1.148	
		6.5	1.222	10.79	61.58	138.4	1.394	
		8.0	1.212	10.87	58.78	138.4	1.798	
2-1	0.5255	5.5	1.223	11.00	74.09	135.5	0.996	
		6.5	1.210	10.50	68.32	135.1	1.210	
		7.5	1.199	11.04	68.19	134.7	1.456	
2-2	0.5363	5.5	1.224	10.29	68.19	135.9	1.017	
		6.5	1.215	10.50	68.40	135.5	1.219	
		7.5	1.210	10.50	66.60	135.1	1.434	
10 平均值						136.6		
11 方差						1.33		

Key: (1) Item (2) Thermal Capacity (3) Discharge Current  
 (4) Average Voltage (5) Discharge Heat (6) Electrical Work  
 (7) Enthalpy Value Variations (8) Average Amounts of Heat Put  
 Out (9) Cell (10) Average Value (11) Variance

$\overline{\Delta H}$  values associated with Table 5 and Table 1 are extremely close, thus proving that measurement results are reliable.

Fig.'s 3, 4, and 5 are voltage, casing temperature, and instantaneous heat production curves over time during cell discharge processes. From Fig.3, it can be seen that--in association with initial and final periods of discharge--voltages drop rapidly. However, in the middle, there is a section which is a relatively gentle phase. In contrast with this, the instantaneous amount of heat put out  $q$  during discharge periods rises relatively fast during initial and end periods. In the middle, there is also a section of an almost level and smooth phase. This clearly shows that, following along with changes in terminal voltage during cell discharge processes, amounts of heat put out from cells also varies incessantly.

Fig.4 gives a cell casing temperature rise curve. It explains--under adiabatic conditions--that amounts of heat put out during cell discharge are entirely used in raising its own temperature and the maximum temperature increases it is capable of reaching. If the cell and the surrounding environment exchange heat (nonadiabatic conditions), then, cell temperature rises should be smaller than this value.

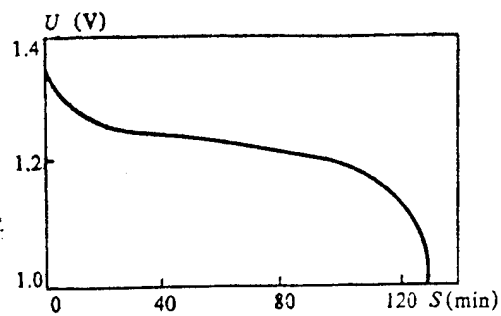


Fig.3 Classical Voltage Variation Curve

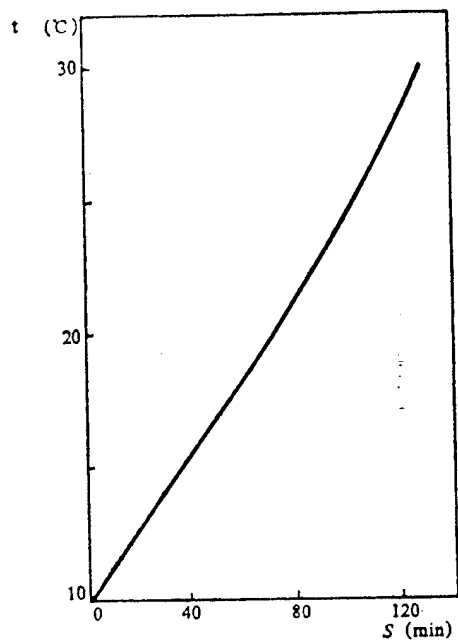


Fig.4 Temperature Variation Curve During Cell Discharge

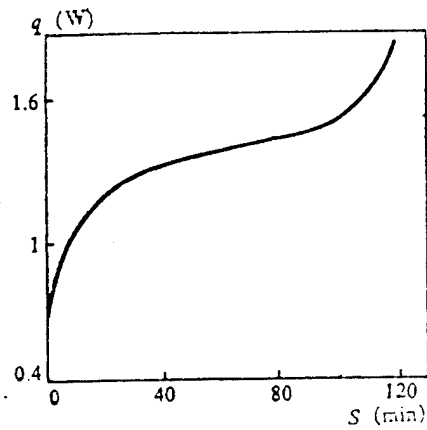


Fig.5 Relationship Between Instantaneous Amount of Heat Put Out  $q$  and Time  $S$

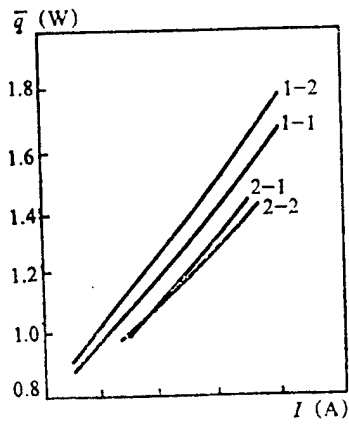


Fig.6 Relationship Between Average Amount of Heat Put Out  $\bar{q}$  and Discharge Current  $I$

Fig.6 gives the relationship between the average amount of heat put out  $\bar{q}$  and discharge current I during cell discharge processes. The larger discharge currents are, the higher average amounts of heat put out  $\bar{q}$  also are. The relationship between the two almost becomes linear. As far as the curve corresponding to each cell is concerned, each curve is certainly not coincident. Analyzing the causes, it is possible that it is given rise to by differences in cell interior properties (internal resistance). If the match up between cell properties is relatively good, then, curves should basically coincide. If one takes the two cells in the second batch 2-1 and 2-2, they have curves that coincide better than the first batch cells. /70

### 3. SPECIFIC HEAT CAPACITY MEASUREMENTS

On the basis of equation (10), the main measurement parameter during experimental processes is temperature. Because of this, errors, which come along due to temperature measurement errors, are random errors. However, specific heat amounts associated with calorimetric tube specific heat quantities and distilled water specific heat quantities are measured before experiments. The errors they cause are systemic errors.

Errors which are given rise to by temperature measurements are

$$\begin{aligned} \frac{\Delta C_1}{C_1} &= \sqrt{\left(\left|\frac{\partial C_1}{\partial \bar{t}}\right| \cdot \frac{\Delta \bar{t}}{|C_1|}\right)^2 + \left(\left|\frac{\partial C_1}{\partial t_1}\right| \cdot \frac{\Delta t_1}{|C_1|}\right)^2 + \left(\left|\frac{\partial C_1}{\partial t_2}\right| \cdot \frac{\Delta t_2}{|C_1|}\right)^2} \\ &= \sqrt{\left(\frac{t_2 - t_1}{(t_2 - \bar{t})(t_1 - \bar{t})} \cdot \Delta \bar{t}\right)^2 + \left(\frac{\Delta t_1}{\bar{t} - t_1}\right)^2 + \left(\frac{\Delta t_2}{t_2 - \bar{t}}\right)^2} \end{aligned}$$

In tests, the single sections  $t_2 = 100^\circ\text{C}$ ;  $t_1 = 20^\circ\text{C}$ ;  $\Delta \bar{t} = 30^\circ\text{C}$  have measurement errors taking  $\Delta \bar{t} = \Delta t_1 = \Delta t_2 = 0.2^\circ\text{C}$  to do calculations obtaining

$$\frac{\Delta C_1}{C_1} = \pm 3.1\%$$

As far as the errors caused by calorimetric tube heat capacities and water capacities are concerned, they are estimated at less than 1%. Therefore, the total error for the systems in question is smaller than  $\pm 4.1\%$ .

#### 4. MEASUREMENTS OF AMOUNTS OF HEAT PUT OUT

Measurements of amounts of heat put out are completed under atmospheric conditions. Due to small amounts of air existing between cells and measurement tubes, at the same time, there is a temperature differential of  $\pm 0.2^\circ\text{C}$  between cells and measurement tubes. Because of this, a certain amount of heat loss exists overall. After considering the nonadiabatic factors discussed above, energy equilibrium during cell discharge is

$$Q = Q_{\text{elec}} + Q_{\text{air}} + Q_{\text{convec}} + Q_{\text{rad}}$$

In the equation,  $Q_{\text{elec}}$  --amount of heat associated with cell discharge

$Q_{\text{air}}$  --amount of heat absorbed by air

$Q_{\text{convec}}$  --amount of heat carried away by air convection

$Q_{\text{rad}}$  --radiation heat transfer between cell outer surfaces and measurement tubes

When cell temperatures are higher than measurement tubes, cells transfer heat to measurement tubes.  $Q_{\text{convec}}$  and  $Q_{\text{rad}}$  are positive. Conversely, when measurement tubes transfer heat to cells,  $Q_{\text{convec}}$  and  $Q_{\text{rad}}$  are negative. Due to opting for the use of automatic temperature tracking techniques, during tests, maximum temperature differentials between cell surfaces and measurement tube surfaces are controlled and do not exceed  $\pm 0.2^\circ\text{C}$ . Speaking in terms of statistical probability, chances for cell

temperatures higher than measurement tubes and chances for those lower than measurement tubes are roughly equal. In this way, within narrow ranges of temperature differentials, overall effects of  $Q_{convec}$  and  $Q_{rad}$  approach zero. Besides this,  $Q_{air}$  is assumed to be an amount of heat associated with air absorption which comes entirely from cell heating of it. In reality, air also absorbs amounts of heat coming from measurement tubes. Moreover, the interior surface area of measurement tubes is far larger than cell exterior surface area. With regard to air heating effects, measurement tubes should play an important role. Summarizing the analysis discussed above, under extreme conditions, that is, recognizing that measurement tube temperatures are always lower than cell temperatures ( $-0.2^{\circ}\text{C}$ ), amounts of heat associated with air absorption come entirely from cells. Calculation analysis arrives at the result below

$$\frac{Q_{air} + Q_{convec} + Q_{rad}}{Q_{elec}} \approx \pm 1.99\% \leq \pm 2\%$$

that is, systemic errors induced by heat leakage quantities are not larger than  $\pm 2\%$ . Analysis clearly shows that  $Q_{convec}$  and  $Q_{rad}$  are far larger than  $Q_{air}$ . Because of this, during tests, temperature tracking precision should be guaranteed at better than  $\pm 0.2^{\circ}\text{C}$ . Temperature differentials between measurement tubes and cells are key factors influencing the accuracy of measured values.

In measurements, errors induced by measured temperatures are smaller than  $\pm 1.5\%$ . Errors induced by cell heat capacities are  $\pm 4.1\%$ . Summarizing the analysis above, overall errors in measurements of heat put out during cell discharge are smaller than  $\pm 7.6\%$ .

## IV. CONCLUSIONS

(1) Making use of water equivalent methods, cell specific heat determination problems were resolved. The accuracy of test measurement results was better than 95%, satisfying the requirements of engineering use.

(2) At normal pressure, opting for the use of temperature tracking techniques, test measurements were completed of amounts of heat put out during single unit Cd-Ni cell discharge. Good results were obtained, getting a large amount of useful data. From test data, calculations of  $\bar{\Delta H}$  values and values reported abroad matched up extremely well, proving that results of test measurements of amounts of heat put out are reliable. Overall errors in amounts of heat put out are smaller than  $\pm 7.6\%$ .

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