

# Development of High Power Energy Storage for the CIVIC Hybrid

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## ABSTRACT

An attempt was made to improve the power density of a conventional nickel metal-hydride battery for installation of a hybrid system in the limited space available in a heavier vehicle. The plates were extended by 12%, the negative collector tab was eliminated, and the number of welds joining plate and collector was increased. These measures reduced the internal resistance by 19%. As a result, the power density during regeneration improved by 27%, making it possible to deal with increased regeneration energy without increasing the cubic volume of energy storage installed.

## 1. Introduction

Today, with an ever growing awareness of environmental issues such as global warming, etc., the demand for automobiles with reduced exhaust emissions, starting with carbon dioxide, has become stronger. Honda, in response to this demand, has made modifications to its gasoline engines, focusing on VTEC (Variable Valve Timing and Lift Electrical Control)<sup>(1)</sup>. In addition, Honda has developed a hybrid vehicle, leading to further possibilities, refining Honda's proprietary technology, the IMA (Integrated Motor Assist) system<sup>(2)</sup>, and fitting it to the INSIGHT in 1999 with which it entered the market.

Now, in order to promote wider dissemination of the hybrid vehicle, Honda has developed the CIVIC Hybrid, based on the concept of fitting the IMA system to a mass produced vehicle without major changes to the vehicle body. Due to an increase in vehicle weight in comparison with the INSIGHT and the addition of a cylinder idling system<sup>(3)</sup>, there is an increase in input and output electricity to and from the energy storage, and a demand for performance improvements.

This report explains the aims of the development of a new energy storage system (referred to as D2 hereafter) for the CIVIC Hybrid, and the performance it has achieved.

## 2. Aims of Development

In developing D2, a nickel metal-hydride battery (referred to as Ni-MH battery hereafter) was used, similar to that used for energy storage in the INSIGHT (referred to as D1 hereafter). As shown in Table 1, some reasons for the use of a Ni-MH battery are that Ni-MH batteries, in comparison with lead batteries used in conventional automobiles, have a higher power output density per unit of weight<sup>(4)</sup>, have high energy density and a long life, among other features.

Table 1 Constitution and power density of secondary batteries

|         | Positive electrode | Negative electrode | Electrolyte                    | Power density  |
|---------|--------------------|--------------------|--------------------------------|----------------|
| Ni-MH   | NiOOH              | MH                 | KOH                            | Over 500W/kg   |
| Li-ion  | LiMnO <sub>4</sub> | C                  | Organic electrolyte            | Over 1 000W/kg |
| Ni-Cd   | NiOOH              | Cd                 | KOH                            | 170W/kg        |
| Pb-acid | PbO <sub>2</sub>   | Pb                 | H <sub>2</sub> SO <sub>4</sub> | 300W/kg        |

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With the CIVIC Hybrid, due to the increase in vehicle weight and the cylinder idling system, there is a marked increase in input to the energy storage system, particularly during regeneration, over that of the INSIGHT, by approximately 80%. (See Fig. 1.) If D1 were used in the CIVIC Hybrid, there would be the possibility that not all of the regeneration energy could be recovered, reducing the fuel economy benefits of the IMA.

There are two ways the problem with D1 could be addressed in the CIVIC Hybrid.

- (1) Increase the number of batteries installed in the vehicle.
- (2) Improve the maximum charge energy for each cell in the battery.

If the first option were selected, with the increase in the number of cells installed, it leads to the increase in weight and installation volume, which is in direct conflict with the basic concept. In addition, voltage would rise and it would become necessary to change the set voltage for other components included in the IMA system. For these reasons, the second option was selected.

Specifically, the target for maximum charge energy was set at 27%, carrying out a simulation of regenerated energy increase due to increased vehicle weight and the cylinder idling system.

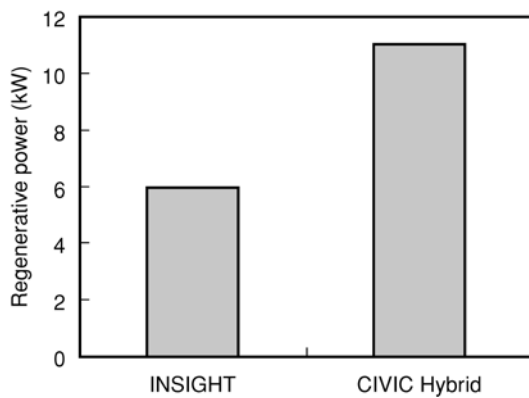
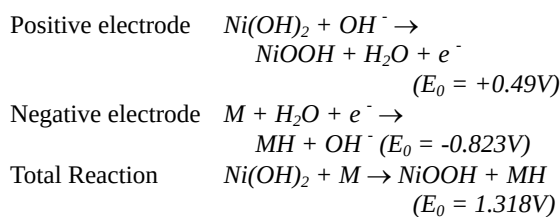


Fig. 1 Regenerative power

### 3. The Battery

The Ni-MH negative electrode is metal-hydride, and when charging and discharging the hydrogen is absorbed or released respectively. As for metal-hydrides, many are based on rare earth metals  $\text{LaNi}_5$ , and there are also those based on the Laves  $\text{TiMn}_{1.5}$  or  $\text{ZrMn}_2$ . At present, considering the service life of the product, the use of rare earth metals is most common, and so the Ni-MH battery for the IMA, uses rare earth metals as well.

The reactions when charging the Ni-MH battery are shown below.



$E_0$  = Equilibrium potential

In this way, with Ni-MH batteries, consumption of electrolyte is restricted because there is no water directly applied in the charge or discharge reactions. Therefore, the battery service life is longer than with a lead battery or nickel cadmium battery. In addition, unlike Li-ion batteries, no organic solvents are used in the electrolyte, so even when the electrodes are excessively charged or excessively discharged, there is no possibility of spontaneous combustion, and therefore safety is not compromised.

## 4. Power Output Improvements

### 4.1. Causes of Power Output Reduction

When the battery is charged or discharged, the electrodes shift from the equilibrium state to the transient state, and so cell voltage is a different voltage from that of the equilibrium state. This phenomenon is called polarization, and when an electrical current flows, the size of the resulting polarization is called overvoltage. There are two major factors in overvoltage – one is called the activation overvoltage, which is the overvoltage needed for the material relating to electrode reaction (hydrogen ions in the case of Ni-MH) to move to the electrode across the solvent absorbing layer called the electrical double layer of the plate surface (see Fig. 2) and, the other is called the concentration overvoltage, which is generated according to the concentration gradient that occurs in the reaction of adjoining electrode surfaces.

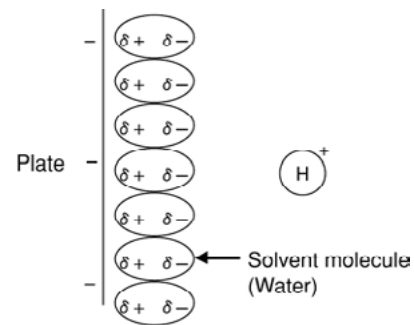


Fig. 2 Electrical double layer

The relationship between these overvoltages, and cell voltage at the time of charge and discharge (cell closed circuit voltage)  $E$  are as shown in Eq. (1).

$$E = E_0 - [(\eta_{ct})_a + (\eta_c)_a] - [(\eta_{ct})_c + (\eta_c)_c] - I \cdot R_i \quad (1)$$

$E_0$  : Cell open circuit voltage  
 $\eta_{ct}$  : Activation overvoltage  
 $\eta_c$  : Concentration overvoltage  
 $a$  : Negative electrode (anode)  
 $c$  : Positive electrode (cathode)  
 $I$  : Cell load current  
 $R_i$  : Cell internal resistance

The overvoltage  $\eta$  which is a total of  $\eta_{ct}$  and  $\eta_c$  is determined, in an ordinary battery, according to the Butler-Volmer formula, as shown below.

$$i = i_0 \left[ -\exp(-\alpha \cdot n \cdot F / (R \cdot T) \cdot \eta) + \exp((1 - \alpha) n \cdot F / (R \cdot T) \cdot \eta) \right]$$

$R$  : Gas constant  
 $T$  : Absolute temperature  
 $n$  : Number of electrons involved in the electrode reaction  
 $\alpha$  : Mobility coefficient  
 $F$  : Faraday constant  
 $i_0$  : Exchange current density  
 $i$  : Current density

When overvoltage is low, developing the above index, items from the third can be ignored. So, looking at the first two items, it becomes as follows.

$$\eta = R \cdot T / (i_0 \cdot F) \cdot i \quad (2)$$

Then Eq. (1) can be simplified.

$$E = E_0 - (R_\eta + R_i) \cdot I \quad (3)$$

This  $R_\eta$  is known as polarization resistance, and is expressed as follows.

$$R_\eta = R \cdot T / (i_0 \cdot F \cdot A) \quad (4)$$

$A$  : Electrode surface area

In the case of the Ni-MH battery actually used in the IMA, cell voltage against current in the use range, as shown in Eq. (3), is confirmed to change linearly. Figures 3 and 4 give examples.

Because the cell voltage when the electrical current is flowing is determined according to Eq. (3), Power output  $P$  at that time is expressed as below.

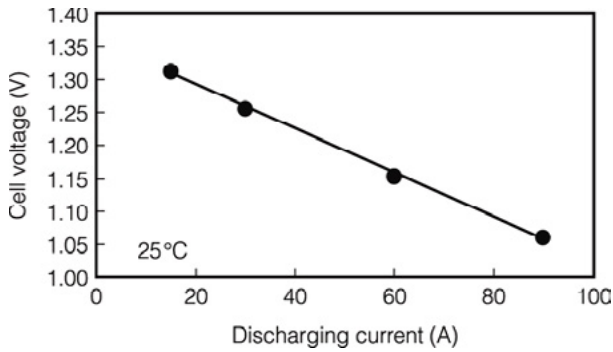


Fig. 3 Cell voltage and discharging current

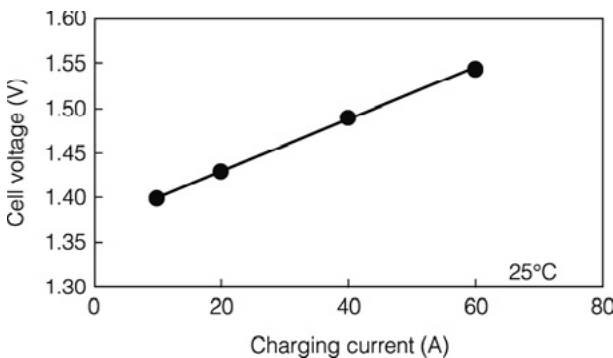


Fig. 4 Cell voltage and charging current

$$P = E \cdot I = E_0 \cdot I - R_T \cdot I \cdot I \quad (5)$$

$$R_T : R_\eta + R_i$$

From the above, by reducing the battery direct current resistant components  $R_\eta$  and  $R_i$ , battery output can be improved.

#### 4.2. Battery Power Output Calculation Method

Equation (5) shows the relationships between  $P$ ,  $E$  and  $I$  when a particular power is being charged or discharged. Using Eq. (3),  $P$  and  $E$  are as follows.

$$P = E \cdot I = E \cdot (E_0 - E) / R_T \quad (6)$$

This relationship between  $P$  and  $E$  can be expressed as a schematic diagram, and is shown in Fig. 5. However, this relationship is only feasible when overvoltage is low and is in the range where Eq. (2) applies.

In addition, when Ni-MH battery is used, if the battery is over-charged and/or excessively discharged, there are secondary reactions, such as water decomposition and additive material reactions, leading to deterioration in the Ni-MH battery. Therefore, an upper limit voltage  $E_U$  is established in order to prevent over-charging, and a lower limit voltage  $E_L$  is established in order to prevent excessive discharge. Because generally these values are set in the overvoltage range where Eq. (2) is feasible, it is possible to apply Eq. (6).

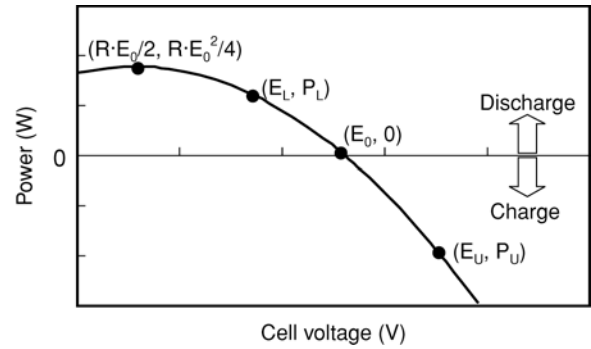


Fig. 5 Change of the electric power by cell voltage

Establishing the upper and lower limit voltage in this way, the maximum absolute values of the discharge power and charge energy can clearly be seen from Fig. 5, and is the  $P_L$  value at the time of  $E_L$ , and is  $|P_U|$  at the time of  $E_U$ . Expressing charging as usual and  $P_U$  as an  $R_T$  function gives the following.

$$E_U = E_0 - R_T \cdot I_U \quad (7)$$

$I_U$  : Current when it becomes  $E_U$

$$\therefore I_U = (E_0 - E_U) / R_T \quad (8)$$

$$|P_U| = |E_U \cdot I_U| = |E_U \cdot (E_0 - E_U) / R_T| \quad (9)$$

Maximum charging power is determined using Eq. (9). In order to determine the  $R_T$  reduction target necessary to improve  $P_U$  by 27%,  $E_U$  is upper limit voltage sub-reaction constraint and  $E_0$  is a unique value for the battery system,

using Eq. (9) as a fixed value,  $|P_U|$  varying rate against the  $R_T$  reduction rate is determined. Here, taking D1's  $R_T$  and  $P_U$  as  $R_{T0}$  and  $P_{U0}$  respectively, and D2's  $R_T$  and  $P_U$  as  $R_{T1}$ ,  $P_{U1}$  respectively, the relationship between  $R_{T1}/R_{T0}$  and  $|P_{U1}/P_{U0}|$  is shown in Fig. 6.

From the above, the  $R_{T1}$  reduction target was set at 19% or above in order to improve maximum charge power by 27%.

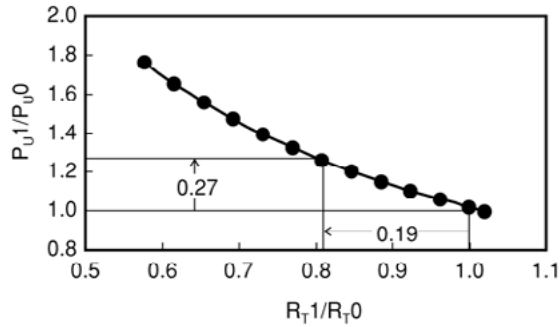


Fig. 6 Relation of regenerative electric power and cell resistance

#### 4.3. Specific Means of $R_{T1}$ Reduction

The two elements that make up  $R_{T1}$  are, as noted earlier, cell internal resistance  $R_i$  and polarization resistance  $R_\eta$  due to overvoltage.  $R_i$  is the resistance in the case of electrical flow through the conductive parts inside the cell, and as shown in Fig. 7, is composed of conduction resistance of the positive and negative plates, conduction resistance of positive and negative collectors, and connection resistance, etc. On the other hand,  $R_\eta$  is expressed in Eq. (4), and the elements that can be changed are exchange current density  $i_0$  and electrode surface area  $A$ . Here,  $i_0$  can be expressed as the following.

$$i_0 = n \cdot F \cdot A \cdot k \cdot C_o^{(1-\alpha)} \cdot C_R^\alpha \quad (10)$$

$k$  : Speed constant

$C_o$  : Oxidant density

$C_R$  : Reductant density

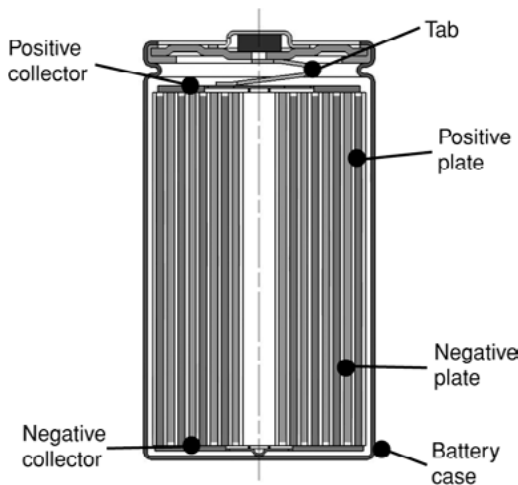


Fig. 7 Structure of cell

As it is dependent on electrode surface area  $A$ , it is clear that an increase in  $A$  will lead to a drop in  $R_\eta$ .

In this project, a study was carried out, looking at two means of improving maximum charge power.

- 1)  $R_i$  reduction
- 2) Expansion of electrode surface area.

As means of reducing  $R_i$ , in order to reduce current flow part resistance, the following are possibilities.

- i) Positive and negative collector current flow resistance reduction
  - Increase thickness of collectors
  - Revise shape
- ii) Positive and negative plate current flow resistance reduction
  - Increase thickness of plates
  - Increase length of plate
- iii) Collector and plate connection resistance reduction
  - Increase spot surface area for weld bonded parts
  - Increase number of weld points
- iv) Tab current flow resistance reduction
  - Increase thickness of tabs
  - Increase tab length

As it is well known that item iv) concerning tab current flow resistance reduction gives little contribution, items i) through iii) were studied.

First, shape of collectors were changed for item i) positive and negative collector current flow resistance reduction, simultaneously for item iii) collector and plate connection resistance reduction. Concerning the collector thickness increase, because the gap between the positive collector and the battery case was insufficient, there was the danger of a short between positive and negative electrodes, so those items were set aside.

The shape change details are shown in Fig. 8.

The main points of the changes were first that by lengthening the positive and negative collector slits, the number of weld points were increased by 27% and 55% respectively, thereby increasing the contacting area between plate and collector; and secondly that by eliminating the negative collector tab, current running is eliminated, and a current density drop is achieved. From the above measures, cell internal resistance could be reduced by 14%.

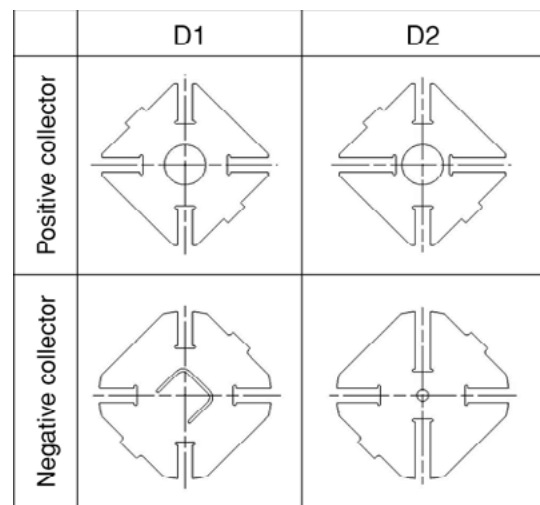


Fig. 8 Form of collector

Next, was an examination of item ii) – the plate current flow resistance reduction. With an increase in thickness, there was a marked reduction in volume of the reaction substances – the nickel hydroxide and the hydrogen storage alloys – which led to a drop in capacity. On the other hand, changing the length of the plates led to an improvement in electrode surface area in (2), and because it also led to a reduction in  $R_{\eta}$ , further study was made of extending the length of the plates.

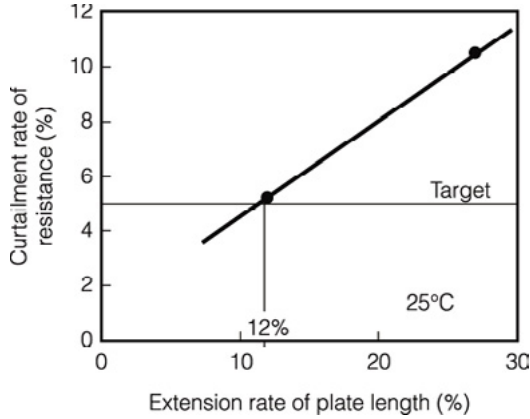


Fig. 9 Effect of plate length on resistance

Figure 9 shows the effect of plate length on resistance reduction. Against the ultimate resistance reduction target of 19%, a resistance reduction of 14% was possible by changing the shape of the collector, so the target for resistance reduction by lengthening the plate is the remaining 5%. From Fig. 9 it can be seen that the plate should be extended 12% in order to achieve the resistance reduction target.

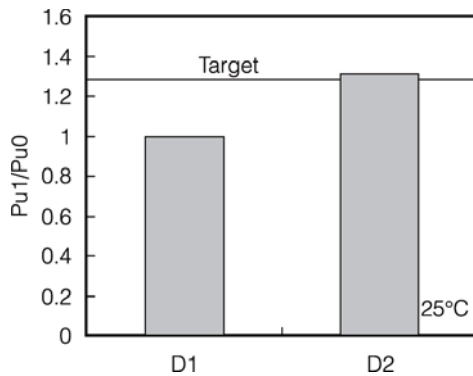


Fig. 10 Ratio of charging power

#### 4.4. Effect of the Countermeasures

The effect of the countermeasures outlined above is shown in Fig. 10.

As intended, it was possible to reduce internal resistance by 19%, giving a 27% improvement in maximum charging power, and so achieving the target.

In addition, because there is a reduction in resistance, discharge power, too, was improved by approximately 10%, as shown in Fig. 11.

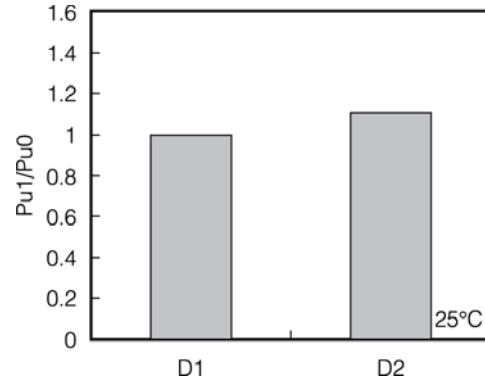


Fig. 11 Rate of discharging power

#### 4.5. The Effect of Temperature

This report has outlined the principles of improving battery power output, measures taken, and their effect. These methods are effective at normal operating temperatures, where cell internal resistance greatly influences output power. However, when the temperature drops, Exchange current density's speed constant, as shown in Eq. (11), drops exponentially.

$$k = C_o^{\alpha} / C_R^{\alpha} \cdot k_f^0 \cdot \exp((- \alpha n F E_e) / (R \cdot T)) \quad (11)$$

$k_f^0$  : Standard speed constant

$E_e$  : Equilibrium potential

As can be seen from Eq. (4) and Eq. (10), accompanying the above temperature drop, there is a dramatic rise in polarization resistance, so that it occupies the major portion of  $R_T$ , and becomes a dominant factor in power output drop. Therefore, at low temperatures, the resistance reducing effect of extending plate length, increasing the number of weld points, and changing the collector shape all drop relatively. As a result, at  $-25^{\circ}\text{C}$ , there is almost no improvement in maximum charging POWER, as shown in Fig. 12.

The contemplated means in this project have almost no effect on power output improvements at low ambient temperatures, so using a temperature control fan, as in a conventional system, to warm the battery leads to power output recovery. In order to improve low ambient temperature power output, it is necessary to increase electrode surface area to a level where it supplements the speed constant drop. The means of accomplishing this are as follows.

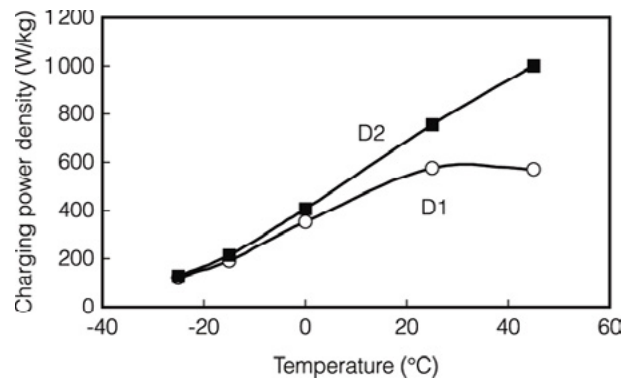


Fig. 12 Characteristic of charging power density by temperature

- a. Change the type of electrode from a sinter type to a foam nickel.
- b. Make the grain diameter of the hydrogen storage alloy smaller, or make the surface rougher.

## 5. Summary

For use in the CIVIC Hybrid's IMA System, a battery was developed that has a 27% improvement in maximum charging power during regeneration. This was done by reducing resistance by 19%, through the measures of dropping current density by eliminating the negative collector tab, by extending plate length by 12%, and by increasing the number of weld points between positive and negative collectors and plates.

At the same time, through this research the following was learned.

- (1) Reduction in cell internal resistance is of great benefit in improving maximum charging power at normal operating temperatures.
- (2) However, at low ambient temperatures, because polarization resistance is high, a drop in upper limit energy becomes dominant, and the benefits are lost.

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