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Development of advanced nickel/metal hydride batteries for electric and hybrid vehicles

Paul Gifford [a,*], John Adams [a], Dennis Corrigan [b], Srinivasan Venkatesan [b]

[a] *GM Ovonic L.L.C., 1334 Maplelawn Drive, Troy, MI 48084, USA*
[b] *Ovonic Battery, 1707 Northwood Drive, Troy, MI 48084, USA*

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Abstract

Nickel/metal hydride (Ni/MH) batteries have emerged as the battery technology of choice for electric vehicles. GM Ovonic L.L.C., a joint venture between General Motors and Ovonic Battery was established in 1994 to manufacture and commercialize Ovonic's proprietary Ni/MH batteries for electric and hybrid vehicle applications. GM Ovonic is developing a 'family of batteries' aimed at product improvement and cost reduction. Current performance of these new battery designs is described, as well as projections for future improvements. In addition, advances in cell and battery power have allowed further product diversification into cells and batteries specifically designed for a range of hybrid electric vehicles (HEVs).

Keywords: Nickel/metal hydride batteries; Applications/electric vehicles

1. Introduction

Society's concerns over air pollution and depletion of natural petroleum reserves have spurred renewed interest in electric vehicles. In 1996, the electric vehicle (EV) moved from engineering development to the commercial marketplace with the introduction of General Motor's EV1, the modern world's first ground-up design of a production EV. Other companies quickly followed suit. While recent changes in Californian mandates regarding zero emission vehicles (ZEVs) relaxed the requirements for 1998, mandated volumes of ZEV sales up to 10% remain in effect for 2003. Incentives exist for ZEV sales prior to 2003, particularly for EVs employing advanced batteries. Limited range, due to the current use of lead-acid batteries, has limited market acceptability for battery EVs, so prompting active development of higher-specific energy batteries.

Nickel/metal hydride (Ni/MH) batteries are rapidly becoming the battery technology of choice for the emerging electric vehicle market. Major automotive companies including Daimler Chrysler, Ford, General Motors, Honda and Toyota, are currently introducing EVs with Ni/MH batteries into the marketplace. Toyota recently introduced the world's first commercial hybrid electric vehicle (HEV), the Prius, in Japan, also powered with a special Ni/MH battery pack. GM has introduced for fleet vehicle leasing its electric conversion S-10 pick-up truck equipped with GM Ovonic Ni/MH batteries.

Due to the high specific energy of these batteries, GM was able to preserve full truck payload capacity, while offering a range of over 145 km (90 miles).

In December 1998, GM announced that they would be introducing the EV1 with Ni/MH batteries beginning in 1999, providing a driving range of up to 225 km (140 miles) on a single charge. Several concept vehicles employing advanced GM Ovonic Ni/MH batteries were displayed by General Motors at the 1998 North American Auto Show in Detroit, including advanced hybrid electric vehicles and a fuel cell HEV.

GM Ovonic was established in 1994 as a joint venture between General Motors and Ovonic Battery (OBC), a subsidiary of Energy Conversion Devices (ECD), to commercialize ECD's proprietary Ovonic Ni/MH battery technology for electric and hybrid vehicle applications. This joint venture brings together Ovonic's recognized leadership in the development of Ni/MH batteries with GM's expertise in manufacturing as well as its technical leadership in the area of electric vehicle technology. GM Ovonic is a worldwide supplier of Ni/MH batteries for

* Corresponding author

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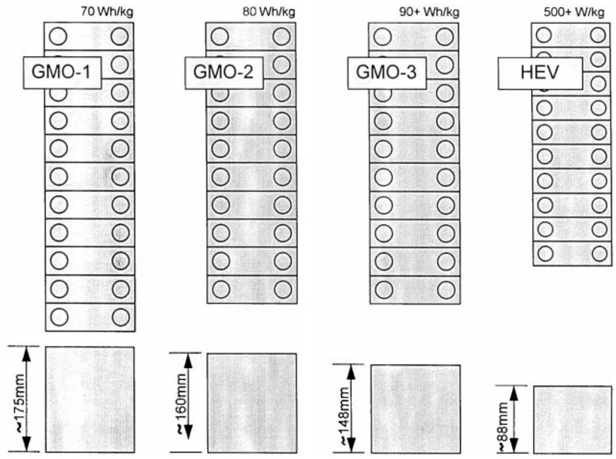

Fig. 1. The GM Ovonic family of batteries for EV and HEV product development.

EVs to all automotive companies and is currently in low-volume production of Ni/MH batteries to meet current customer demand.

In 1997, GM Ovonic introduced its product development strategy for creating a 'family of batteries' that would progressively offer the vehicle engineer higher performance in a smaller, lighter, and lower-cost battery design [1]. These evolutionary products, termed GM01, GM02, and GM03 are shown in Fig. 1. Phased introduction of these product advances is planned as technology matures and volume requirements for EV batteries increase.

Change control and timed introduction of new products is critical to allow for orderly introduction of change and product validation prior to commercial sale. Design changes are bundled into a new product design to minimize validation requirements and frequency of model changes (Fig. 2). GM01 is currently in production. GM Ovonic's product plan calls for introduction of GM02 in time for Model Year 2000, with GM03 introduced at a later date as advanced materials technologies are optimized and scaled up.

Concurrently, special high-power designs were incorporated into this family of product designs to meet the growing interest in, and demand for, high-power batteries for hybrid electric vehicles (HEVs). Prototype HEV batteries are currently available for vehicle level testing from GM Ovonic and its partner OBC in a variety of HEV platforms.

2. EV battery development

2.1. GM01 product status

The current GM01 battery product utilizes 11 cells of 90 A h capacity in a series string, providing a 13.2 V, 1.2 kW h battery. In this configuration, the battery has a specific energy of 70 W h kg^{-1} and an energy density of 170 W h dm^{-3}. Peak power levels are 220 and 200 W kg^{-1} at 50% and 80% depth of discharge (DOD), respectively. Other battery voltages can readily be provided by varying the number of individual cells in series connection, an advantage of a single cell design over a monoblock design.

This battery design has been in low-volume production since 1996, but has undergone a number of product changes for improved manufacturability, product performance, and lower manufacturing cost. Particular attention was paid to those operations that were critical in moving from proto-

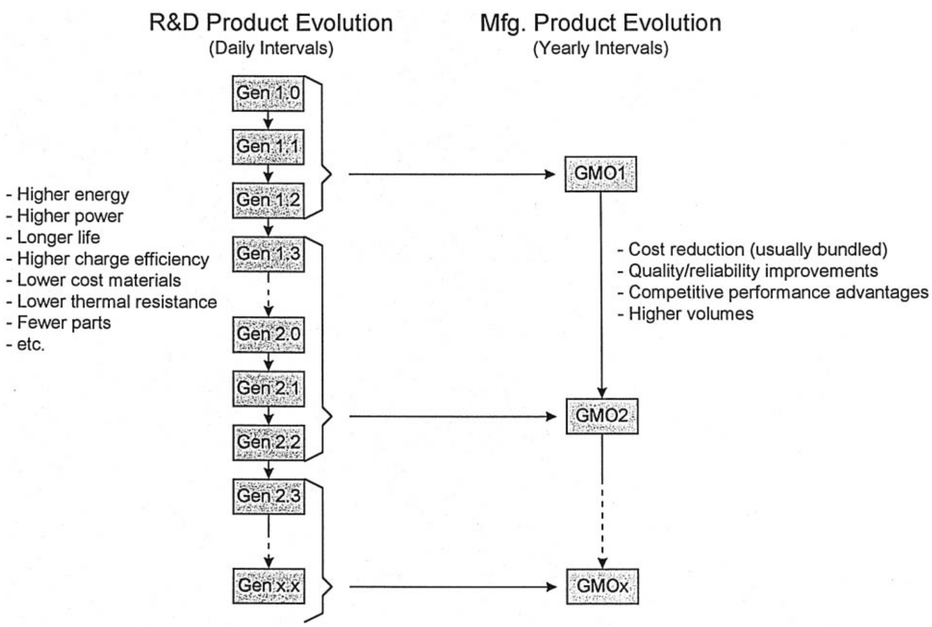

Fig. 2. The GM Ovonic product evolution and product introduction strategy.

type production that was hand-labour intensive, to processes intended for production employing automated assembly operations. Other product developments were introduced to address failure modes that were identified during validation testing of early product samples.

The following are examples of key product improvements to the GM01 design.

(a) Introduction of an advanced welding technique for connecting the electrode tabs to cell terminals, for improved durability, manufacturability and decreased cell impedance

(b) Improved isolation and corrosion protection of the metal can and cell interconnects for life and durability

(c) A continuous, automated, line for producing positive (NiOOH) electrodes, giving reduced manufacturing cost and reduced variability

(d) Mechanization of key manufacturing operations

(e) Significantly simplified formation procedure for finished batteries for improved product performance and reduced manufacturing costs

In addition to these up-grades already introduced into production, GM Ovonic is continuing to introduce product improvements for durability, ease of manufacturing, and, most critically, to lower the cost at the current low production rates.

Supported in part by the United States Advanced Battery Consortium (USABC), GM Ovonic, in collaboration with OBC, recently completed a development programme aimed specifically at reducing Ni/MH battery costs when in low-volume production. Initiatives covered all areas of battery design, including cell and battery hardware, also negative and positive electrode costs. Since GM Ovonic's cost analysis has shown that at mature volumes, over 60% of the battery manufacturing costs are materials-based, this programme focused predominately on reducing material costs. While active material costs strongly drive the total battery material cost, at low purchase volumes, cost of many key electrode materials used in manufacturing EV Ni/MH batteries can benefit from the existing supplier base of these electrode materials for other Ni/MH battery applications. For example, Ni foam and high-density $Ni(OH)_2$ are also used in the Ni/MH and Ni/Cd cylindrical wound cells found in many consumer electronic devices. It was also recognized that at low production volumes, hardware costs can be particularly skewed from vendor cost projections at high manufacturing volumes, and therefore offers an additional opportunity to bring forward cost reductions.

During this programme, several significant opportunities for cost reduction were investigated and proven successful and the programme goals for cost reduction were exceeded. The following are specific initiatives currently being implemented by GM Ovonic.

(a) Simplified battery formation procedure

(b) Replacement of machined components with low-cost stamped components

(c) Improved processing of hydride material for improved consistency, quality and capacity

These improvements are currently being introduced into production with minimum validation requirements, while introduction of other additional cost savings identified under this programme will be bundled into the GM02 product design.

2.2. GM02 product status

Vehicle demonstrations with Ni/MH batteries show that excellent range and performance can be achieved by using current technology. However, GM Ovonic recognizes the critical need to reduce battery cost to achieve a wider market acceptance of EVs. Therefore, our product development activities are strongly focused towards reducing battery cost by improving the utilization of expensive battery materials. It is our belief that the key to reducing battery cost is to improve the battery's specific energy. This is the approach that is being pursued in the GM02 and GM03 product designs.

The design direction for our first significant product up-grade has been to provide the customer with equivalent battery energy and power, but to do so in a smaller (and therefore less costly) package. This has been achieved with the same basic battery active materials to minimize product validation requirements, but with improvements in cell design to achieve higher specific energy and power.

A key feature for the GM02 design is the move from an 11-cell battery to a 10-cell battery, while maintaining the same total delivered energy and power. Since of course the battery nominal voltage is lower, this necessitated an increase in specific power. A detailed analysis of the cell impedance showed the following as the main contributors to cell internal resistance.

(a) Negative electrode resistance (40%)

(b) Positive electrode resistance (30%)

(c) Electrolyte resistance (20%)

(d) Miscellaneous electrical resistances in tabs, terminals, etc. (10%)

Having identified where the greatest opportunities for improved cell impedance were, a systematic effort on improving battery power was successfully carried out. Modifications to the negative electrode design and manufacturing process provided significant improvement in battery power. When coupled with an advanced separator material, battery peak powers of 260/230 W kg^{-1} at 50%/80% DOD were obtained, compared to controls at 200/170 W kg^{-1}.

This improvement in specific power allowed OBC and GM Ovonic cell designers to develop a battery module with power and energy equivalent to the current battery, while reducing the cell hardware requirements by 10%. Equally significant, advances in internal cell stack design result in a total reduction of 18% in the number of plates per battery. The cost advantages of these design advances are obvious.

The GM02 battery has intentionally been designed to give the same 1.2 kW h capacity as the present production battery. By implementing the design changes described above, the GM02 battery is a 12-V design of 100 A h nominal capacity, with a specific energy of 78 W h kg^{-1} in early prototypes, with 80 W h kg^{-1} projected for the final production intent design.

Field testing of Ni/MH batteries indicated that full performance from some battery pack designs could not be achieved under the extreme conditions associated with vehicle charging at elevated temperatures. Although active thermal management is incorporated into battery pack designs with input from GM Ovonic applications engineers, some performance trade-off was encountered at high temperatures such as one might experience in southern California or Arizona where thermal control of the battery pack was not optimum. Therefore, improved high-temperature charge acceptance has been incorporated into the GM02 design.

Diminished discharge capacity associated with high-temperature performance of nickel hydroxide-positive electrodes has been well-documented for systems such as Ni/Cd, Ni/Zn, and Ni/MH [2]. This phenomenon is due to lower charging efficiency of the nickel-positive electrode as the temperature increases. Due to the kinetics of the two competing charge reactions (charging the active mass and oxygen evolution), as the temperature increases, oxygen evolution occurs at lower potentials. Hence, at higher temperatures, the charge efficiency is decreased, causing a decrease in available cell capacity.

By careful selection of the composition of the active material and additives to the positive electrode, it is possible to favorably shift the oxygen overvoltage, thereby improving charge efficiency at elevated temperatures. While the electrode reactant for the positive electrode is $Ni(OH)_2$, actual active materials used in high-performance batteries typically incorporate co-precipitated additives such as Co, Cd, or Zn. Cd is generally not employed in Ni/MH batteries for environmental reasons, and other additives have replaced Cd. GM Ovonic has optimized the metal cation and atomic percentage of co-precipitated additives to provide optimum high-temperature charging.

In addition to the co-precipitated active material, other additives are traditionally added to the active material paste for the positive electrode. Various cobalt compounds have been shown to improve active material utilization, as well as charging efficiency and life [3,4]. Recent findings show that various transition metal cations when added to the paste can improve the high-temperature charging efficiency of the nickel oxyhydroxide electrode [5,6].

Researchers at OBC carefully screened various metal oxides and salts for the effect on hydrogen overvoltage. Through this screening, several additives were selected for testing in sealed EV cells. A final optimization of the type of metal oxide additive and its concentration was chosen from this matrix of EV cells and tested in modules at both room temperature and elevated temperatures. The impact on delivered capacity is shown in Fig. 3. This design feature will be incorporated into the GM02 product to offer the customer-improved vehicle range even when charged under severe temperature conditions.

2.3. GM03 product status

While the GM02 design achieves higher energy and power densities using essentially the same negative and positive active materials, but with advances in cell design, further increases in energy and power density are achieved in the GM03 product by improving the specific capacity of the active materials themselves [7].

The Zr–Ti–Ni-based metal hydride alloy employed in today's product stores typically 380–400 mA h g^{-1} of

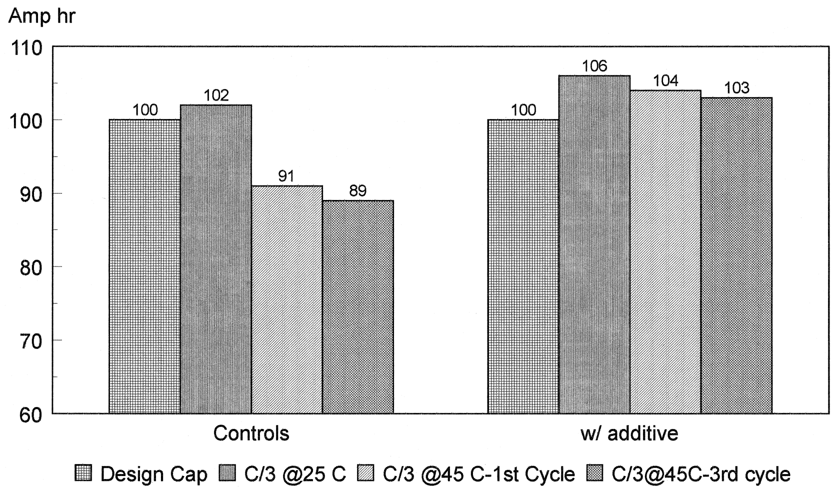

Fig. 3. The effect of metal hydroxide additive on the high-temperature charging efficiency. C/3 discharge capacities at 45°C during first and third cycles, compared with the designed capacity and that measured at 25°C.

alloy [8]. Researchers at ECD have determined that considerably higher specific capacities can be obtained for alloy compositions of this same family by careful control of the local order in these multi-phase alloys and minimizing formation of undesirable minor phases. Control of local phase order is particularly influenced by the induction melting conditions and the quench rate during cooling of the melt. Impurities can also reduce hydride capacity by preferentially occupying active sites. Therefore, control of purity during melting and cooling is critical to obtaining maximum capacity. By optimizing melting and processing parameters, improvements of up to 8% in storage capacity can be obtained for the same chemical composition.

Still further advances in specific capacity can be obtained by proper compositional modification of the base Zr–Ti–Ni alloy. Minor modification of additives and stoichiometric ratios of additives can have a strong impact on isotherm pressure and hydrogen storage capacity of the metal hydride (Fig. 4). This increased hydrogen storage translates to higher electrochemical-specific capacity in the cell. Current alloys based on such compositional modification demonstrate capacities of >450 mA h g^{-1}. Still higher specific capacity will be obtained when these advances in composition are combined with optimized processing. Similarly, the same approach of compositional modification that ECD and OBC pioneered in development of high-capacity metal hydride alloys [9] can be applied to advanced $Ni(OH)_2$ materials to produce active materials of higher specific capacity. While the nickel hydroxide to nickel oxyhydroxide reaction is typically expressed as one electron transfer per Ni atom, it is well-known that the reaction is much more complex than this simple equation and that, in fact, the theoretical upper limit for Ni(II) oxidation is in the order of 3.5, or 1.5 electrons per Ni atom due to the formation of both β- and γ-NiOOH [10]. While traditionally, battery manufacturers have tried to minimise the formation of γ-NiOOH which is typically nonreversible, recent workers have attempted to stabilise a

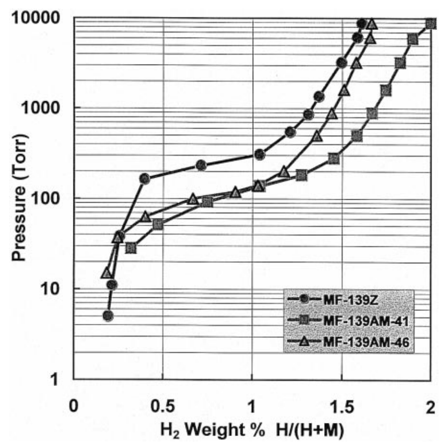

Fig. 4. Pressure-composition isotherm for standard (MF-139Z) and advanced hydride alloys.

reversible γ-NiOOH to obtain reversible multi-electron transfer and hence higher-specific capacity active materials [11,12].

ECD and OBC have been leaders in this effort to develop multi-electron transfer '$Ni(OH)_2$' materials [13]. By proper compositional modification of the base $Ni(OH)_2$ material to obtain stabilised reversible γ-NiOOH phases, OBC has demonstrated, using bulk spherical powders, specific capacities of up to 250 mA h g^{-1} in sealed cells —an improvement of >15% over conventional commercial battery-grade spherical $Ni(OH)_2$ powders. OBC has established a pilot line in Troy to produce these high-capacity powders, demonstrating that these materials can be produced in a low-cost, continuous process.

By combining these advanced negative and positive materials in a sealed, cylindrically wound cell, a specific energy of >95 W h kg^{-1} was achieved. OBC and GM Ovonic are now evaluating these advanced materials in EV cells and modules. It is anticipated that optimized EV cell designs employing these active materials will achieve specific energies of ~ 90 W h kg^{-1} with no trade-off in power, life, or other performance characteristics.

3. HEV battery status

While energy density is perhaps the most critical performance characteristic for EV batteries, power density is the design benchmark for HEV batteries. GM Ovonic and OBC have developed several HEV cell designs to meet a variety of HEV applications ranging from the range-extender concept to dual-ode or power-assist vehicles [14,15]. These cells range in capacity from 60 A h down to 12 A h capacity, providing a wide range of options for pack energy requirements. Specific powers for these cell designs range from 550 to over 600 W kg^{-1}, while demonstrated power densities are 1.2 to 1.4 kW dm^{-3}.The deliverable discharge power remains high from the fully charged state down to 70% DOD. Additionally, the regen power exceeds 500 W kg^{-1} from a 10% DOD down to the fully discharged state, providing operation in the HEV mode over a wide range of state-of-charge. Modelling experiments have shown that with further development, peak power levels over 1 kW kg^{-1} can be obtained, and recent laboratory prototypes have approached this level.

These high-power levels are achieved with little trade-off in specific energy. While there is some decrease in specific energy as the cell capacity is reduced due to a higher contribution from cell and module hardware, energy densities of 70–50 W h kg^{-1} are maintained in modules of 60–20 A h capacity.

Cycle-life testing of these modules is continuing under a simulated HEV driving cycle which simulates a power-assist type of application which subjects the battery to a 2% state-of-charge swing with aggressive discharge and regen power levels. In an on-going test, modules have exceeded over 90,000 of these cycles, corresponding to over 160,000 km driven, with no degradation in delivered power. Even under these aggressive HEV driving schedules, energy efficiencies of 80–90% are maintained at temperatures up to 60°C [16].

The HEV cell construction is similar to that employed for EV cells with certain proprietary improvements in internal cell stack design to provide for lower cell resistance. Common hardware and manufacturing technology helps minimize tooling and capital costs, as well as allowing GM Ovonic to take advantage of higher volume requirements for common hardware, helping drive down battery cost. OBC and GM Ovonic are currently producing HEV batteries and packs at the prototype level for test and evaluation by several automotive customers.

4. GM Ovonic production status

Immediately following the formation of the joint venture, a plan was implemented to establish a pre-production prototype facility for product and process development of the Ni/MH EV battery. This facility was located in Troy, Michigan, in conjunction with OBC to facilitate technology transfer and engineering assistance. The intent of the facility was to maintain the key design and performance features of the current OBC cell design, but also to further develop the product for ease of manufacturing at high volumes and low cost. Concurrently, the electrode and cell assembly processes and equipment were developed and validated for the high-volume production-intent processing of the Ni/MH battery.

Installation of capital equipment was completed in 1997 and this development facility is now producing at its intended capacity of 26 battery modules per day (equivalent to one vehicle pack per day for many vehicle applications). This level of production allows for validation of production-intent processes and provides battery packs to meet early customer demands.

We are now moving ahead to our first level of low-volume production. GM Ovonic has established a wholly owned manufacturing subsidiary, Ovonic Energy Products (OEP) for manufacturing the Ovonic Ni/MH battery. A facility has been established in Kettering, OH, and production of the current GM01 product is commencing at OEP. To maintain manufacturing design flexibility, OEP is being tooled to accommodate both the current design as well as future product designs, including HEV cells.

Product and process development on the GM02 product continues at our Troy pre-production facility for implementation at OEP starting in 1999. Further product development will continue at Troy to bring forward the GM03 product as well as future product and process improvements for both EV and HEV battery designs.

5. Summary

GM Ovonic has moved forward with the its planned product development strategy for improved performance and reduced battery cost. The GM02 product design has moved from laboratory prototype to a pre-production design slated for introduction for Model Year 2000.

Development of advanced negative and positive electrode active materials continues to show advances in specific capacity over materials used in current Ni/MH batteries. Current EV cell prototypes with next-generation advanced materials demonstrate over 85 W h kg^{-1}, while cylindrical cells employing newer advanced materials have achieved 95 W h kg^{-1}. New product designs for HEV applications are under development and demonstrate high specific power with high energy density and prototype batteries are available for evaluation for a range of HEV applications.

Validation of production-intent processes has been completed at GM Ovonic and current pre-production levels of one vehicle pack per day provide for customer samples and meet initial low volume requirements. We have established a new manufacturing subsidiary, Ovonic Energy Products for our next level of production. Field testing of GM Ovonic Ni/MH batteries in such programmes as the GM S-10 electric truck has demonstrated the high performance of these batteries. GM has announced that starting in 1999, the EV1 will be offered with GM Ovonic Ni/MH batteries, providing a practical driving range of over 225 km (140 miles). Continued product development is focused on reducing battery cost through improvements in specific energy achieved through advances in cell design and new active materials.

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