

Materials Cost Evaluation Report for High-Power Li-Ion HEV Batteries

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Electrochemical Technology Program
Chemical Technology Division

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MATERIALS COST EVALUATION REPORT FOR HIGH-POWER LI-ION HEV BATTERIES

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EXECUTIVE SUMMARY

The U.S. Department of Energy (DOE) is the lead federal agency in the partnership between the U.S. automobile industry and the federal government to develop fuel cell electric vehicles (FCEVs) and hybrid electric vehicles (HEVs) as part of the FreedomCAR Partnership. DOE's FreedomCAR and Vehicle Technologies Office sponsors the Advanced Technology Development (ATD) Program—involving 5 of its national laboratories—to assist the industrial developers of high-power lithium-ion batteries to overcome the barriers of cost, calendar life, and abuse tolerance so that this technology can be rendered practical for use in HEV and FCEV applications under the FreedomCAR Partnership. In the area of cost reduction, Argonne National Laboratory (ANL) is working to identify and develop advanced anode, cathode, and electrolyte components that can significantly reduce the cost of the cell chemistry, while simultaneously extending the calendar life and enhancing the inherent safety of this electrochemical system. The material cost savings are quantified and tracked via the use of a cell and battery design model that establishes the quantity of each material needed in the production of batteries that are designed to meet the requirements of a minimum-power-assist HEV battery or a maximum-power-assist HEV battery for the FreedomCAR Partnership. Similar models will be developed for FEV batteries when the requirements for those batteries are finalized. In order to quantify the material costs relative to the FreedomCAR battery cost goals, ANL uses (1) laboratory cell performance data, (2) its battery design model and (3) battery manufacturing process yields to create battery-level material cost models. Using these models and industry-supplied material cost information, ANL assigns battery-level material costs for different cell chemistries. These costs can then be compared with the battery cost goals to determine the probability of meeting the goals with these cell chemistries.

The most recent FreedomCAR cost goals for the 25-kW minimum-power-assist and 40-kW maximum-power-assist HEV batteries are \$500 and \$800, respectively. In FY 2001, ANL developed a high-power ATD Gen 2 cell chemistry that was incorporated into high-power 18650 cells for use in extensive accelerated aging and thermal abuse characterization studies under the ATD Program. Our Gen 2 cell chemistry serves as a baseline chemistry for this materials cost study. It incorporates a $\text{LiNi}_{0.8}\text{Co}_{0.15}\text{Al}_{0.05}\text{O}_2$ cathode, a synthetic graphite anode, and a LiPF_6 in EC:EMC electrolyte. Based on volume production cost estimates for these materials as well as the binders/solvents, cathode conductive additives, separator, and current collectors, the total cell winding material costs for a 25-kW minimum power assist HEV battery is estimated to be \$399 (based on a 48-cell battery design, each cell having a capacity of 15.4 Ah). The goal is to reduce the cell winding material costs of the minimum-power-assist battery to less than half of the battery cost goal (i.e., <\$250) in order to allow \geq \$250 for the remaining costs and profit.

The cathode material cost is a significant portion (25%) of the total material cost for the Gen 2 cell chemistry. Emphasis was placed on the identification and development of stable cathode materials that employ less Ni and Co, as a means of reducing the cost of the cathode active material. In addition to evaluating a variety of industry-supplied materials, we synthesized lab-scale materials of this type. We then worked with industrial suppliers to scale up the most promising of these materials and to conduct production cost analyses on these materials.

For the anode, we focused on low-cost natural graphites. We worked with graphite manufacturers to achieve the particle size and morphology that would allow us to achieve the desired electrode coating thicknesses with better abuse tolerance characteristics than those exhibited by our Gen 2 anode material.

In the area of electrolytes, we worked with the Army Research Laboratory (ARL) on the development of lower-cost electrolytes, some of which employ lower-cost salts. Also, we developed and continue to develop new electrolyte additives that protect natural graphites from exfoliation in low-cost PC-based electrolytes. Some of these additives provide additional benefits such as a more thermally stable SEI layer, reduced gas generation during both the cell formation process and normal operation, and/or some level of overcharge protection.

Over the last year, the FreedomCAR Electrochemical Energy Storage Technical Team awarded several contracts to industrial firms to develop lower-cost separator materials. We will request samples of these materials for evaluation and comparison with commercially available SOA materials. Also, ANL is currently evaluating a new class of commercially available lower-cost separator materials.

Combining the results of our materials screening work (to be published in a separate report) with those of this material cost study, we can recommend materials for two high-power, low-cost cell chemistries. Our cell chemistry recommendations and battery-level material costs are listed in Table ES-1.

Table ES-1. Recommended Materials for High-Power, Low-Cost Cell Chemistries

	Advanced Cell Chemistry A	Advanced Cell Chemistry B
Cathode	$\text{LiNi}_{1/3}\text{Co}_{1/3}\text{Mn}_{1/3}\text{O}_2$	LiMn_2O_4 spinel
Anode	Carbon-coated natural graphite	Carbon-coated natural graphite
Electrolyte	LiPF_6 in EC:PC:DMC	LiPF_6 in EC:PC:DMC
Cell capacity	13.8 Ah	8.5 Ah
Material cost	\$300	\$222

Advanced cell chemistry A uses a layered cathode active material that employs Mn as a major component and is easily synthesized using low-cost processing. We obtained production cost estimates in the range of \$13-15/kg for this material, compared with >\$20/kg for the $\text{LiNi}_{0.8}\text{Co}_{0.2}\text{O}_2$ type cathode materials. The LiMn_2O_4 cathode material is the lowest-cost material, at \$7.40/kg. We worked with a graphite supplier to develop a carbon-coated natural graphite with good capacity density, excellent high-rate capability, and optimal morphology and particle

size. Also, the carbon coating on this material protects it from exfoliation in PC-based electrolytes. The production cost estimate for this material is \$10/kg compared with \$15/kg for the synthetic graphite used in our Gen 2 cell chemistry. Finally, the PC-based electrolyte is estimated to cost \$16/L compared with the \$20/L cost estimated for the electrolyte used in our Gen 2 cell chemistry. Another minor cost savings is associated with the use of an aqueous soft rubber binder in the anode of the two advanced cell chemistries. Also, additional cost savings should be achievable via a change in the electrolyte salt. We are currently developing a new solvent system for use with a low-cost non-fluorine containing salt that is more compatible with the LiMn_2O_4 cathode. This salt does not react with trace amounts of water or alcohol to form HF, thereby stabilizing the LiMn_2O_4 cathode against attack by the HF. Use of this new low-cost salt could render the LiMn_2O_4 cathode ideal for this HEV battery application.

As can be seen from the results of this materials cost study, a cell chemistry based on the use of a LiMn_2O_4 cathode material is lowest-cost and meets our battery-level material cost goal of <\$250 for a 25-kW minimum-power-assist HEV battery. A major contributing factor is the high-rate capability of this material, which allows one to design a lower-capacity cell to meet the battery-level power and energy requirements. This reduces the quantities of the other materials needed to produce a 25-kW minimum-power-assist HEV battery. The same is true for the 40-kW maximum-power-assist HEV battery. Additionally, the LiMn_2O_4 cathode is much more thermally and chemically stable than the $\text{LiNi}_{0.8}\text{Co}_{0.2}\text{O}_2$ type cathode, which should enhance inherent safety and extend calendar life (if the LiMn_2O_4 cathode can be stabilized against dissolution via HF attack). Therefore, we recommend that the FreedomCAR Partnership focus its research and development efforts on developing this type of low-cost high-power lithium-ion cell chemistry. Details supporting this recommendation are provided in the body of this report.

1. INTRODUCTION

High-power lithium-ion batteries are being developed to meet the energy storage goals established for hybrid electric vehicles under the FreedomCAR Partnership. As part of this national program, DOE's FreedomCAR and Vehicle Technologies Office established the Advanced Technology Development Program to help FreedomCAR industrial developers overcome calendar life, abuse tolerance, and cost barriers for high-power lithium-ion batteries in HEV applications. As part of the ATD Program, Argonne National Laboratory is charged with the identification and development of low-cost advanced materials that can simultaneously provide adequate energy, power, life, and inherent safety for use in these high-power battery systems. The most recent version of the FreedomCAR Partnership HEV energy storage goals are provided in Table 1. A similar set of energy storage goals are in the process of being finalized for fuel cell electric vehicles and the ATD program will assist the industrial developers of lithium-ion batteries address those goals, as well.

Table 1. FreedomCAR Partnership Hybrid Electric Vehicle Energy Storage Goals

Characteristic	Power-Assist HEV Battery	
	Minimum	Maximum
Discharge pulse power (10 s)	25 kW	40 kW
Maximum regen pulse power (10 s)	20 kW (50-Wh pulse)	35 kW (97-Wh pulse)
Total available energy	0.3 kWh	0.5 kWh
Round-trip efficiency	>90% (25-Wh cycle)	>88% (100-Wh cycle)
Cycle life for specified SOC increments	300,000 cycles (25-Wh cycle)	300,000 cycles (50-Wh cycles)
Cold cranking power @ -30°C (three 2 s pulses with 10 s rests between)	5 kW	7 kW
Calendar life	15 yr	15 yr
Maximum weight	40 kg	60 kg
Maximum volume	32 L	45 L
Production price @ 100 k units/yr	\$500	\$800
Maximum operating voltage	≤ 400 VDC	≤ 400 VDC
Minimum operation voltage	$\geq 0.55 V_{\max}$ VDC	$\geq 0.55 V_{\max}$ VDC
Maximum self-discharge	50 Wh/d	50 Wh/d
Operating temperature range	-30 to +52 °C	-30 to +52 °C
Survival temperature range	-46 to +66 °C	-46 to +66 °C

At \$20/kWh, the cost goals of \$500 for a 25-kWh battery and \$800 for a 40-kWh battery are extremely challenging. If this goal is to be met, cost reduction efforts must be applied to all elements of the battery. This project focuses on reducing the costs of materials that can be used in manufacturing the cells for the HEV application. It involves a concerted effort to acquire and evaluate the latest and most advanced materials that are being developed by industrial lithium-

ion cell material suppliers worldwide, as well as R&D efforts to develop and scale-up low-cost materials that are tailored to meet the requirements of the HEV application.

In general, lithium-ion battery material suppliers are developing advanced materials for high-energy batteries that are used in consumer electronic applications. Most of these materials can be modified to render them more optimal for use in the high-power HEV application. Therefore, it is reasonable to evaluate these new advanced materials for high-power applications. Efforts to modify these materials and make them more optimal for the HEV application are also conducted as part of the ATD Program. An evaluation report on the characteristics of these advanced materials will be issued separately by ANL. In its dealings with international lithium-ion material suppliers, ANL has established working relationships with a large number of these material suppliers. As part of our interactions with these industrial firms, we provide them with information on market size, through the use of our battery design model, and information on lithium-ion battery manufacturing process yields. In this manner, ANL can establish the quantity of each material that is needed to manufacture a 25-kW or 40-kW power-assist HEV battery. This information has been generated and supplied to the material suppliers. Typically, ANL solicits production cost estimates from the international material suppliers based on an introductory market of 100,000 HEVs (and HEV batteries) per year.

One of the major material costs is associated with the positive electrode (cathode). The industrial battery developers, supported by the FreedomCAR Partnership, have focused on the use of $\text{LiNi}_{1-x-y}\text{Co}_x\text{M}_y\text{O}_2$ type cathode materials, where M is a low-level metal dopant. The idea was to move from a LiCoO_2 cathode, of the type used in commercial cells for consumer electronics, to one that uses nickel to replace a large portion of the cobalt. In the end, the cost savings are marginal, because the price of cobalt metal is currently quite low and the processing costs associated with producing the nickelate materials are quite high relative to those associated with producing the cobaltate materials. Therefore, ANL has developed several potentially lower-cost advanced cathode materials (at the laboratory scale) and worked with industrial firms to conduct production cost analyses, as well as to scale up some of these materials.

In order to quantify the material costs relative to FreedomCAR battery cost goals, ANL uses (1) laboratory cell performance data, (2) its battery design model and (3) battery manufacturing process yields to create battery-level material cost models. Using these models and the industry-supplied material cost information, ANL can assign battery-level material costs for different cell chemistries. These costs can then be compared with battery cost goals to determine the probability of meeting the goals with these cell chemistries.

The remainder of this report provides a brief description of ANL's battery cost model, its assumptions and how it is used; industry-supplied material cost estimates for a large number of viable advanced cell materials; a summary of advanced cathode manufacturing cost analyses that were performed for ANL by Fuji Chemical Company; and a discussion of the status of our efforts to identify viable low-cost cell materials. Based on the information acquired, we offer a recommendation as to the type of cell chemistry that the FreedomCAR Partnership should pursue in order to maximize the probability of achieving its battery cost goals, while simultaneously achieving long life and enhanced inherent safety.

2. BATTERY COST MODEL

A spreadsheet battery design model was developed to assist in studying design features of the cells and their components employed in a battery that meets the FreedomCar performance goals. One set of input information to this model is the composition and delivered capacity density of the electrodes under study. Another set is laboratory data on cell performance, including the area-specific impedance and voltage as a function of time and current as determined in hybrid pulse power characterization (HPPC) tests. The model designs full-scale flat-wound cells and calculates the weight, volume and electrical performance of all components and of the total cell. The model also designs modules (typically containing 12 cells) and a 4-module battery for the FreedomCar hybrid electric vehicle application and calculates its weight, volume, power, available energy, and operating voltage range. We use the model to design the batteries to have 130% of the required power at the beginning of life, to allow for this amount of power degradation over its life. Recently, this program was expanded to estimate other costs associated with producing the battery and to arrive at an approximate cost for the entire battery. The effect of variations in any desired parameter can be studied. All elements of the model are linked so that a change in one parameter, such as the thickness of the cathode coating or the number of wraps in the cell windings, will immediately change all affected parameters, including the operating voltage range, the dimensions of the cells, the weight of the battery, and the cost of materials. A tabular printout of about 30 pages provides results on five different batteries with additional charts to illustrate the effects of key variables.

In an earlier study of a 25-kW battery that employs our Gen 2 cell chemistry, the battery design employed 48 series-connected cells, each having 9.4-Ah capacity. This cell size was selected because HPPC data for 5-C rate discharges were available for 18650 cells with the same electrode thicknesses, indicating that the 9.4-Ah cell would operate in an appropriate voltage range for the HEV battery and all other operating criteria appeared to have been met. However, more recent data indicated that these cells could not sustain the low measured area-specific impedance at the high operating current needed for full vehicle acceleration, which requires discharging at the very high current of ~ 27 -C rate. In separate studies, using a similar cell chemistry but a different cathode, we concluded that the deviations at high rates from the area-specific impedances, measured during the HPPC tests at the 5-C rate, were probably caused by the limited rate of solid diffusion in the particles of the positive electrode. One approach to alleviate this situation is to increase the thickness of the electrodes, thereby providing more particle surface area over which to distribute the current.

We employed a much more conservative approach in the present study. The thicknesses of the electrodes were increased over those of the previous study and the maximum current densities, which are based on the electrode area, were also slightly reduced. These changes resulted in a maximum current on discharge of 15 C, which should be readily sustainable for 10 s (the new discharge duration for the FreedomCar power-assist HEV batteries). The resulting cell capacities for 48-cell batteries are 15.4 Ah for the 25-kW battery and 24.7 Ah for the 40-kW battery. The data on materials contained in batteries, as established by the design model, are provided in Table 2.

Because there is some loss of material during cell fabrication, the amounts of materials needed to fabricate the finished cells must be increased to reflect the fabrication yields. Also, the binder solvent, which is sometimes mixed with the binder material by the battery fabricator, is evaporated, collected, and returned to the material manufacturer. These considerations are taken into account in Table 3, which provides the costs of the materials needed to fabricate the cell windings of a 25-kW minimum power-assist HEV battery.

Table 2. Material Quantities Incorporated into Cell Windings of 48-Cell Power-Assist HEV Batteries That Employ the Gen 2 Cell Materials

Type of Material	Material in Cell Windings of Power-Assist Battery	
	25-kW Battery Using 15.4-Ah Cells	40-kW Battery Using 24.7-Ah Cells
Cathode		
Active material (CA1505N)	4.656 kg	7.476 kg
SFG-6	0.222 kg	0.356 kg
Carbon black	0.222 kg	0.356 kg
PVDF binder	0.443 kg	0.712 kg
Anode		
Active Material (MAG-10)	3.008 kg	4.783 kg
PVDF Binder	0.279 kg	0.444 kg
Aluminum foil current collector	20.69 m ²	33.84 m ²
Copper foil current collector	22.33 m ²	36.17 m ²
Separator	45.97 m ²	74.02 m ²
Electrolyte (LiPF ₆ in EC:EMC)	2.57 L	4.11 L

In addition to the costs for the cell winding materials shown in Table 3, the following costs must be added to arrive at a selling price for these batteries: balance of the cell materials (container and terminal assemblies), processing and assembly, module materials and assembly, state-of-charge control and cooling systems, insulated battery enclosure, overhead, and profit. It is not the purpose of this study to estimate those additional costs, but it is apparent that the cost of materials for the windings must be lowered substantially if the overall cost target of \$500 is to be met for the 25-kW minimum power-assist HEV battery.

A similar cost analysis for the 40-kW maximum power-assist HEV battery resulted in a cost of \$641 for the cell winding materials needed to fabricate the 48 cells for this battery (see Appendix A for more detail). Here again, it is apparent that the material costs for the windings must be lowered substantially if the overall cost target of \$800 is to be met for the 40-kW maximum power-assist HEV battery. The cost breakdown is shown in Figure 1, as a percent of the total cost of winding materials in a 25-kW battery. The material cost breakdown for the 40-kW battery is very nearly the same.

Table 3. Cost of Materials Used to Make Cell Windings for a 48-Cell 25-kW Minimum-Power-Assist HEV Battery That Employs the Gen 2 Cell Materials

Type of Material	Finished Amount	Yield, %	Processed Materials	Unit Cost, \$	Cost per Battery, \$
Cathode		97			
Active material (CA1505N)	4.656 kg		4.800 kg	20.52/kg	98.49
SFG-6 graphite	0.222 kg		0.229 kg	15.00/kg	3.44
Carbon black	0.222 kg		0.229kg	6.82/kg	1.56
PVDF binder	0.443 kg		0.457 kg	10.00/kg	4.57
NMP binder solvent	0.000 kg		3.352 kg	3.18/kg	10.66
Anode		93			
Active material (MAG-10)	3.008 kg		3.234 kg	15.00/kg	48.51
PVDF binder	0.279 kg		0.300 kg	10.00/kg	3.00
NMP binder solvent	0.000 kg		2.203 kg	3.18/kg	7.01
Aluminum foil collector	20.69 m ²	99	20.90 m ²	1.00/m ²	20.90
Copper foil collector	22.33 m ²	99	22.55 m ²	2.00/m ²	45.10
Separator	45.97 m ²	99	46.44 m ²	2.00/m ²	92.87
Electrolyte (LiPF ₆ in EC:EMC)	2.570 L	82	3.137 L	20.00/L	62.73
Total material cost					398.84

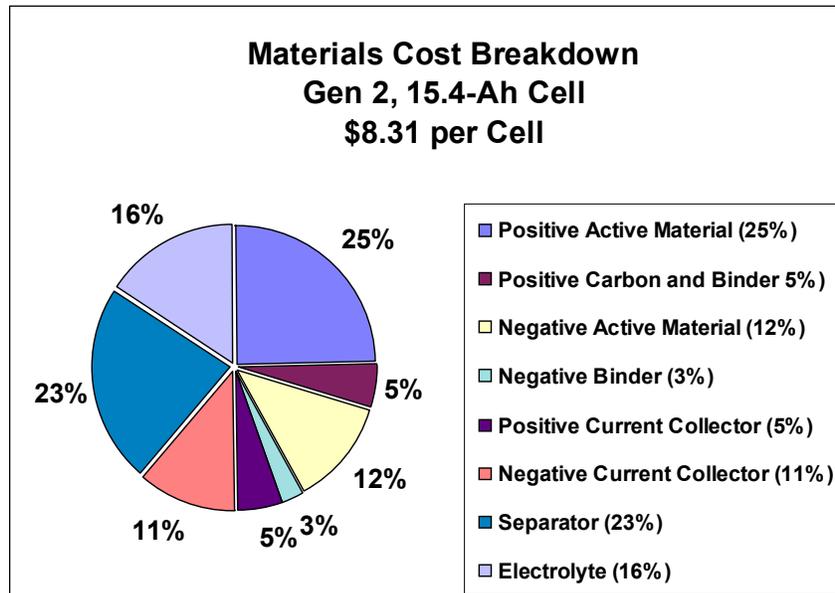


Figure 1. Breakdown of Material Costs in Cell Windings of 15.4-Ah Minimum-Power-Assist HEV Cell that Employs the Gen 2 Cell Chemistry

Figure 1 shows that four materials—the positive and negative active materials, the separator and the electrolyte—account for 76% of the cost. The FreedomCar Partnership has established new industrial efforts to develop lower-cost separators. ANL is hoping to acquire samples of these advanced separator materials for evaluation. ANL’s R&D efforts to reduce material costs are being focused on the positive electrode and the electrolyte as described in the following sections. However, efforts to reduce other material costs are being pursued as well.

3. CATHODE MATERIALS

In the area of advanced cathode materials, we are focusing on materials that have low cobalt and low nickel content to bring down costs. Using battery-level processed material quantities of the type listed in Table 3, ANL provided the international suppliers of advanced cathode materials with “ball park” quantities of their materials needed to produce 100,000 minimum-power-assist HEV batteries per year (as an introductory market). In the case of the positive active material, this amounts to 291,400 kg/yr of lithiated metal oxide material, based on the use of a 9.4-Ah cell. Based on the use of a 15.4-Ah cell, this quantity increases to 480,000 kg/yr. Table 4 summarizes the cost information that was obtained for several types of advanced cathode materials. It should be noted that suppliers of advanced cathode materials informed us (during a February 2002 trip to visit numerous material suppliers in Japan) that the lithiated nickel oxide materials of the type shown for Fuji would be comparable in cost to LiCoO_2 , due to the current low cost of cobalt metal (at \$7-8/kg) and the more expensive processing associated with the lithiated nickel oxide materials.

Table 4. Summary of Industrial Material Supplier Cost Estimates for Advanced Cathode Materials

Industrial Supplier	Cathode Material	Cost Estimate, \$/kg
Fuji Chemical	$\text{LiNi}_{0.8}\text{Co}_{0.15}\text{Al}_{0.05}\text{O}_2$	20.50-22.50
Japanese company	$\text{LiNi}_{1/3}\text{Co}_{1/3}\text{Mn}_{1/3}\text{O}_2$	15.00
OMG America ^a	$\text{LiNi}_x\text{Mn}_{1-x}\text{O}_2$	13.00
Tosoh	$\text{Li}_{1+x}\text{Mn}_{2-x}\text{O}_4$ (spinel) ^b	7.40

^aOMG has been collaborating in the scale-up of ANL’s advanced cathode materials and this is one of the materials they scaled up for ANL.

^bThis material is partially stabilized to reduce the dissolution of Mn^{+2} .

In order to more thoroughly evaluate methods for reducing the cost of the positive active material, ANL contracted with Fuji Chemical Industry Company, Ltd., to conduct manufacturing cost analyses on several types of advanced cathode materials that ANL had successfully synthesized on the laboratory scale. Fuji is somewhat unique in that it employs a spray drying process to produce its standard $\text{LiNi}_{0.8}\text{Co}_{0.15}\text{Al}_{0.05}\text{O}_2$ type cathode materials. The company’s materials possess a high degree of chemical homogeneity and spherical particle morphology—two important characteristics for quality cathode materials. For these and other reasons, ANL selected Fuji’s $\text{LiNi}_{0.8}\text{Co}_{0.15}\text{Al}_{0.05}\text{O}_2$ cathode material for use in the ATD Gen 2 cell chemistry. In its cost analyses, Fuji conducted comparative studies using its spray drying process and the more conventional solid state process. Additionally, ANL requested that Fuji establish a cost

floor for each material by using low-cost precursors as an alternative in the solid state process. Fuji made the following assumptions in conducting its analyses:

- Annual production of 1,000 metric ton/yr
- Capital equipment depreciated using 7-year straight-line method
- Currency exchange rate of \$1.00 = 135 yen
- Selling price calculated using 5% profit

The results of the cost analyses are shown in Table 5. Fuji's complete cost analysis report is included here as Appendix B.

Table 5. Results of Fuji's Production Cost Analyses on ANL's Low-Cost Advanced Cathode Materials

Cathode Material	Spray Dry	Selling Price, \$/kg	
		Solid State Process, Standard Precursor	Solid State Process, ^a Low-Cost Precursor
LiNi _{0.8} Co _{0.15} Al _{0.05} O ₂	CA-5 = 22.45 CA1505N = 20.52		
LiNi _{0.92} Ti _{0.05} Al _{0.03} O ₂	19.17	22.05 ^b	13.41
LiNi _{0.45} Mn _{0.5} Al _{0.05} O ₂	17.62	20.05 ^b 17.91 ^c	11.96
LiNi _{0.2} Mn _{0.8} O ₂	16.23	19.29 ^b 15.41 ^c	11.06

^a These precursor materials were examined to establish a cost floor, with the understanding that the resultant product would not necessarily perform well.

^{b,c} These two prices reflect two variations on the solid state process when the standard grade of precursor materials is used.

Based on the information presented in Tables 4 and 5, it appears possible to develop cell chemistries that are lower in cost than our Gen 2 cell chemistry by moving to one of these advanced cathode materials. ANL is currently evaluating the electrochemical performance, accelerated aging, and thermal stability characteristics of these advanced cathode materials to determine the most optimal advanced cathode material for this long-life high-power HEV application. The \$7.40/kg cost for the LiMn₂O₄ spinel cathode material (Table 4) is lower than all the other materials, even when low-cost precursors are used for the other materials. Therefore, this material would be particularly attractive if a stable cell chemistry could be developed with it. The other components of the composite positive electrode are relatively insignificant from a cost perspective, but ANL continues to evaluate lower-cost conductive carbons and graphite materials, as well as lower-cost binders. There is a concentrated effort to develop better binders that provide equivalent or better binding properties when used at lower levels than the PVDF binders of the type used in our Gen 2 cathode. We continue to evaluate these binders and will use the costs associated with the best binders as input to our materials cost model.

4. ANODE MATERIALS

In the area of advanced graphite anode materials, ANL is focusing on natural graphite materials with the appropriate particle size distribution and particle morphology. Again, using the battery-level material quantities listed in Table 2, ANL provided the international suppliers of advanced anode materials with “ball park” quantities of their materials needed to produce 100,000 minimum-power-assist HEV batteries per year (as an introductory market). In the case of the negative active material, this amounts to 196,300 kg/yr (based on a 9.4-Ah cell). Based on the use of a 15.4-Ah cell, this quantity increases to 323,400 kg/yr. Table 6 summarizes the cost information that was obtained for a variety of graphite anode materials. Hitachi makes a low-cost synthetic graphite (MAG), while the remaining materials are different forms of natural graphite. For reference, the industry standard MCMB synthetic graphite sells for ~\$40/kg. ANL used the MAG synthetic graphite in its Gen 2 high-power cells, because it offered significant cost savings relative to the MCMB graphite, which was used in our Gen 1 high-power cell chemistry.

Table 6. Summary of Industrial Material Supplier Cost Estimates for Advanced Anode Materials

Industrial Supplier	Anode Material	Cost Estimate, \$/kg
Hitachi	Synthetic graphite (MAG)	15.00
Mitsui Mining	Carbon-coated natural graphite (GDR)	10.00
Superior Graphite	Natural graphite (SLC)	10.00
Diabeck	Natural graphite (DJG)	6.00
Timical	Natural graphite (E-SLP)	6.00
SLC	Natural graphite (SLC)	5.00

All of the natural graphite materials possess the desirable round-edge particle morphology and are capable of operating at high rates. Additionally, they exhibit acceptable capacity densities. The Mitsui Mining GDR material is unique in that it incorporates a soft carbon coating at the particle level. The carbon coating appears to protect the bulk natural graphite particles from exfoliation when used with electrolytes that contain PC as a major component of the electrolyte solvent system. So, this material offers the opportunity to use PC-based solvent systems, which also offers a cost reduction advantage. Superior Graphite indicates that it is developing a similar carbon-coated natural graphite material for evaluation by ANL.

Based on ANL’s evaluation of these natural graphite materials and the cost information presented in Table 6, it is apparent that there are opportunities to reduce the cost of the active material in the anode of high-power lithium-ion cells. As mentioned in Section 3, there is a concentrated effort to develop better binders that provide equivalent or better binding properties when used at lower levels than the PVDF binder of the type used in our Gen 2 anode. ANL continues to evaluate these binders and will use the costs associated with the best binders as input to our materials cost model. However, the use of lower-cost binders in the anode will have a minimal impact on the cell material costs since the binder is only a minor contributor. Of some note, however, is the fact that these non-fluorinated soft rubber binders appear to have a positive impact on the inherent safety of the cell chemistry.

5. ELECTROLYTES

In the area of low-cost electrolyte systems, ANL has been working with the Army Research Laboratory (ARL) and, more recently, with Idaho National Engineering and Environmental Laboratory (INEEL) to develop more-optimal electrolyte solvent systems (systems that employ PC as a significant component) and to evaluate low-cost alternative electrolyte salts (alternatives to LiPF_6).

Table 7 lists the costs of some salts and solvents available for use in making electrolytes for lithium-ion batteries. ANL has evaluated the LiBOB and LiFAP salts as alternatives to LiPF_6 and they both offer promise, although they have lower conductivities than LiPF_6 when used in conventional electrolyte solvents. Due to its lower cost, efforts to develop a more optimal solvent system for the LiBOB are being pursued with ARL and INEEL.

Table 7. Cost of Electrolyte Components for Li-Ion Batteries

Electrolyte Component	Cost, \$/kg	
	Battery Grade	Industrial Grade
Salts		
LiPF_6	50	
LiBOB (Chemetal)	33	
LiFAP (Merck)	>50	
Solvents		
PC	6	2
EC (difficult to purify)	10	2
EMC	20	10
DMC	10-15	6
DEC	12	6

As can be seen from Table 7, PC is the least expensive of the common battery-grade organic carbonate solvents. Therefore, ANL is working with ARL and INEEL to develop PC-based solvent systems for use with both the LiPF_6 and LiBOB salts. Also, the use of PC enhances the low-temperature performance of these electrolytes. However, PC does not work with conventional natural graphite anodes because PC intercalates into the graphite layers and causes the graphite to exfoliate. Therefore, the natural graphite needs to be protected from PC intercalation. The Mitsui Mining carbon-coated GDR natural graphite can be used with PC-based electrolytes. Superior Graphite claims that it is developing a similar material. Also, ANL has developed electrolyte additives that appear to protect natural graphite from PC intercalation. Therefore, it should be possible to develop a new low-cost cell chemistry around a PC-based electrolyte system.

EC has been a component of all electrolyte solvent systems for Li-Ion batteries, because it participates in the SEI layer formation process that occurs on the initial charge cycle. It is a solid at room temperature and this creates some difficulties in terms of its purification. In the future, it may be possible to eliminate EC from the solvent system, because some low-level additives will function in a similar manner to form stable SEI layers.

Electrolyte purity is a very important factor in achieving long life from Li-ion cells. Electrolytes that incorporate even low levels of H₂O and/or alcohols tend to shorten the life of the battery because they react with the LiPF₆ salt to form HF. HF is a bad actor in the cell. Therefore, it is important to use high-purity solvents in the preparation of electrolytes for Li-ion batteries. Post-preparation purification is recommended.

Another key factor is the use of electrolyte additives. Much effort has been applied to the development of additives that will protect the natural graphite anode from exfoliating in PC-based electrolytes, enhance the stability of SEI layers, provide some level of overcharge protection, enhance the inherent safety of the cell chemistry, and/or minimize gas formation during the formation cycle and normal use. Typically, these additives are used at very low concentrations (<5 wt%), so they should not have a significant impact on the cost of the electrolyte.

6. SEPARATORS

Worldwide, there are only a few industrial suppliers of porous separator material for use in lithium-ion batteries and their prices are fairly comparable (\$2.00-3.00/m²). Therefore, in 2002 the FreedomCAR Energy Storage Technical Team decided to initiate industrial research and development contracts to develop low-cost separators. The FreedomCAR cost goal is \$1.00/m². ANL is attempting to acquire samples of these advanced low-cost separators for evaluation and is continuing to seek other low-cost separators. We recently acquired samples of new separator materials from Degussa. The materials are Al₂O₃/SiO₂ polymeric non-woven and Al₂O₃/ZrO₂ glass woven separator materials. They are projected to cost \$1.00-1.50/m² and are currently being evaluated at ANL.

7. STATUS AND RECOMMENDATIONS

The volume pricing information presented in this report can be used as input to ANL's battery design cost model, for the purpose of examining the magnitude of the material cost savings that can be achieved relative to the Gen 2 baseline material costs. The Gen 2 cell chemistry is described in Section 2, "Battery Cost Model." Based on the performance characteristics of this cell chemistry, we conservatively selected a 15.4-Ah cell to provide a 30% power margin at the beginning of life for a full-scale battery that is designed for the 25-kW minimum-power-assist HEV application. Figure 2 shows the conceptual design of ANL's flat-wound cell and the dimensions of a 15.4-Ah high-power cell of this design.

A 25-kW minimum-power-assist HEV battery would incorporate 48 cells of this type. Table 3 provides the quantity of each cell material that would be required to manufacture a battery of this design. Using the volume pricing information obtained for each material, the quantity of each material, and the processing yields, it is possible to calculate the total cost for the cell winding materials in a 48-cell battery. Information of this type was provided in Table 3 for a 25-kW minimum power-assist battery that employs the Gen 2 cell chemistry. In the case of our Gen 2 cell materials, the total material cost is \$399. This allows only \$101 for everything

else—electrode fabrication, cell winding, cell hardware and electrolyte filling, cell sealing, cell forming, module hardware and assembly, battery hardware and assembly (including the thermal management subsystem), the electronic control subsystem, overhead, and profit. Therefore, it is necessary to significantly lower the cost of the materials in order to approach the FreedomCAR cost goal of \$500 for a battery of this type.

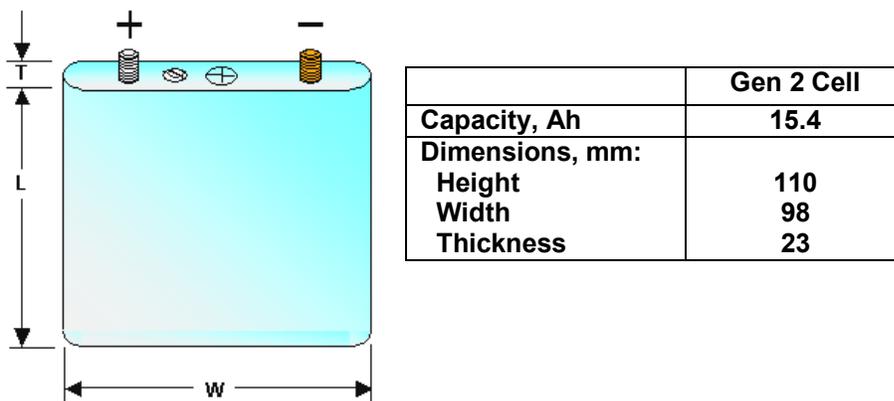


Figure 2. Conceptual Design and Dimensions for 15.4-Ah Flat-Wound High-Power Cell for Use in Minimum-Power-Assist HEV Battery

Using a comparable level of conservatism in our cell and battery designs, we can examine the battery-level material cost impact of using some of the advanced lower-cost materials, discussed earlier in this report. For example, if we employ the cell chemistry (and associated costs) listed in Table 8, in a similarly designed 25-kW battery comprising the same number of slightly smaller cells (13.8 Ah cells) we save \$99 (\$300 vs. \$399) and achieve a 25% reduction material costs. This new cell chemistry employs a lower-cost cathode active material (\$13.00/kg vs. \$20.52/kg), a lower-cost anode active material (\$10.00/kg vs. \$15.00/kg), a lower-cost PC-based electrolyte (\$16.00/L vs. \$20.00/L), a lower-cost anode binder (\$6.00/kg vs. \$10.00/kg) and eliminates the cost associated with the anode binder solvent by switching to a soft rubber (aqueous solvent system) binder. The cell size can be reduced slightly because of a higher OCV vs. DOD profile associated with this cathode material. Although significant, this type of material cost reduction is not adequate in terms of approaching the \$500 FreedomCAR cost goal for a minimum-power-assist HEV battery.

In order to achieve more significant material cost reductions, we need to develop a new cell chemistry that offers a major increase in power characteristics so that the Ah rating and size of cell can be significantly reduced. This would reduce the quantity of all the materials in the cell. In the Gen 2 cell chemistry, it appears that the power of the cell is controlled by the rate capability of the cathode material. Our electrochemical performance evaluation of the new lower-cost cathode materials indicates that only the LiMn_2O_4 spinel type cathode materials possess significantly higher rate capability than the Gen 2 cathode. Our data indicate that cells employing this type of cathode exhibit constant ASI values at discharge rates as high as 29-C (essentially more than double the rate capability of the Gen 2 cathode). Therefore, the Ah capacity of the cell could be reduced to 8.5 Ah for a 25-kW battery. Through more intensive electrode and electrolyte optimization work, it should be possible to reduce the Ah capacity even

further, since significantly higher rate capabilities than 29-C have been reported for spinel. Even using our conservative approach, the impact on the battery-level material costs are quite dramatic. Table 9 provides the material quantities and costs for a 25-kW minimum power-assist battery that is designed with 8.5-Ah high-power cells that employ the LiMn_2O_4 spinel cathode material. With this type of cell chemistry, it appears plausible to reduce the battery-level material cost to \$222 or less. This leaves >\$278 for electrode fabrication, cell winding, cell hardware and electrolyte filling, cell sealing, cell forming, module hardware and assembly, battery hardware and assembly (including the thermal management subsystem), the electronic control subsystem, overhead, and profit.

Table 8. Material Costs for a 25-kW 48-Cell Battery (13.8-Ah cells)
That Employs Lower-Cost Anode and Cathode Materials

Type of Material	25-kW Minimum-Power-Assist Battery		
	Quantity	Unit Cost	Cost, \$
Cathode			
Active material ($\text{LiNi}_{1/3}\text{Co}_{1/3}\text{Mn}_{1/3}\text{O}_2$)	3.643 kg	\$13.00/kg	47.33
SFG-6	0.228 kg	\$15.00/kg	3.42
Carbon black	0.228 kg	\$6.82/kg	1.55
PVDF binder	0.455 kg	\$10.00/kg	4.55
NMP binder solvent	3.337 kg	\$3.18/kg	10.61
Anode			
Active material (GDR)	3.139 kg	\$10.00/kg	31.41
Rubber binder	0.292 kg	\$6.00/kg	1.75
Aqueous solvent	2.141 kg	0.00/kg	0.00
Aluminum foil current collector	20.04 m ²	\$1.00/m ²	20.04
Copper foil current collector	21.65 m ²	\$2.00/m ²	43.33
Separator	44.64 m ²	\$2.00/m ²	89.27
Electrolyte (LiPF_6 in EC:PC:DMC)	2.93 L	\$16.00/L	47.04
Total material cost			300.30

Table 10 summarizes material cost information for the three types of minimum-power-assist and maximum-power-assist batteries. In the table we compare the material costs for batteries that employ the Gen 2 cell chemistry with batteries that would employ advanced cell chemistries based on the use of either a $\text{LiNi}_{1/3}\text{Co}_{1/3}\text{Mn}_{1/3}\text{O}_2$ positive electrode or a LiMn_2O_4 (spinel) positive electrode. For both the minimum and maximum-power-assist HEV batteries, the material cost savings are in excess of 24% and 44%, respectively. Details on the material costs for 40-kW maximum power-assist batteries are provided in Appendix A.

Table 9. Material Costs for a 25-kW 48-Cell battery (8.5-Ah Cells) that Employs LiMn₂O₄ Spinel Cathode Cell Chemistry

Type of Material	25-kW Minimum-Power-Assist Battery		
	Quantity	Unit Cost	Cost, \$
Cathode			
Active material (LiMn ₂ O ₄ spinel)	4.512 kg	\$7.40/kg	33.39
SFG-6	0.282 kg	\$15.00/kg	4.23
Carbon black	0.282 kg	\$6.82/kg	1.92
PVDF binder	0.564 kg	\$10.00/kg	5.64
NMP binder solvent	4.136 kg	\$3.18/kg	13.15
Anode			
Active material (GDR)	2.092 kg	\$10.00/kg	20.92
Rubber binder	0.194 kg	\$6.00/kg	1.17
Aqueous solvent	1.426 kg	0.00/kg	0.00
Aluminum foil current collector	12.81 m ²	\$1.00/m ²	12.81
Copper foil current collector	14.22 m ²	\$2.00/m ²	28.43
Separator	29.68 m ²	\$2.00/m ²	59.39
Electrolyte (LiPF ₆ in EC:PC:DMC)	2.54 L	\$16.00/L	40.56
Total material cost			221.58

Table 10. Cost Estimates for Winding Materials in Power-Assist HEV Batteries that Employ Three Different Positive Electrode Materials

Cell Chemistry	C-Rate Limit	Cell Winding Material Cost, \$		
		25-kW Battery	40-kW Battery	
LiNi _{0.8} Co _{0.15} Mn _{0.05} O ₂	15.4-Ah cells	15	399	--
	24.7-Ah cells	15	--	641
LiNi _{1/3} Co _{1/3} Mn _{1/3} O ₂	13.8-Ah cells	15	300	--
	22.2-Ah cells	15	--	479
Li _{1+x} Mn _{2-x} O ₂	8.5-Ah cells	30	222	--
	13.7-Ah cells	30	--	353

Figure 3 shows that switching to a spinel cathode system significantly modifies the distribution of the material costs. Due to the higher power density (mW/cm²) of the spinel system, the electrode area can be reduced and the significance of the separator is reduced. Although the cost of the positive electrode active material is much lower for the spinel (\$7.40/kg vs. \$13.00), a larger quantity (mass and volume) of spinel is needed because of its lower capacity density. Correspondingly, more positive electrode conductive carbon additive and more binder are needed. So, with other material costs being reduced, the cost of the conductive additive and the binder become significant for the spinel system.

It should be noted that our evaluations indicate that the use of new salts that are more stable than LiPF_6 offer promise for helping to resolve the Mn^{2+} dissolution problem with LiMn_2O_4 spinel cathodes. Also, some of these new more stable salts (e.g., LiBOB) appear to offer some cost reductions relative to the LiPF_6 salt. Therefore, ANL recommends that the FreedomCAR Partnership place a high priority on the development of a low-cost, stable LiMn_2O_4 spinel-cathode-based cell chemistry.

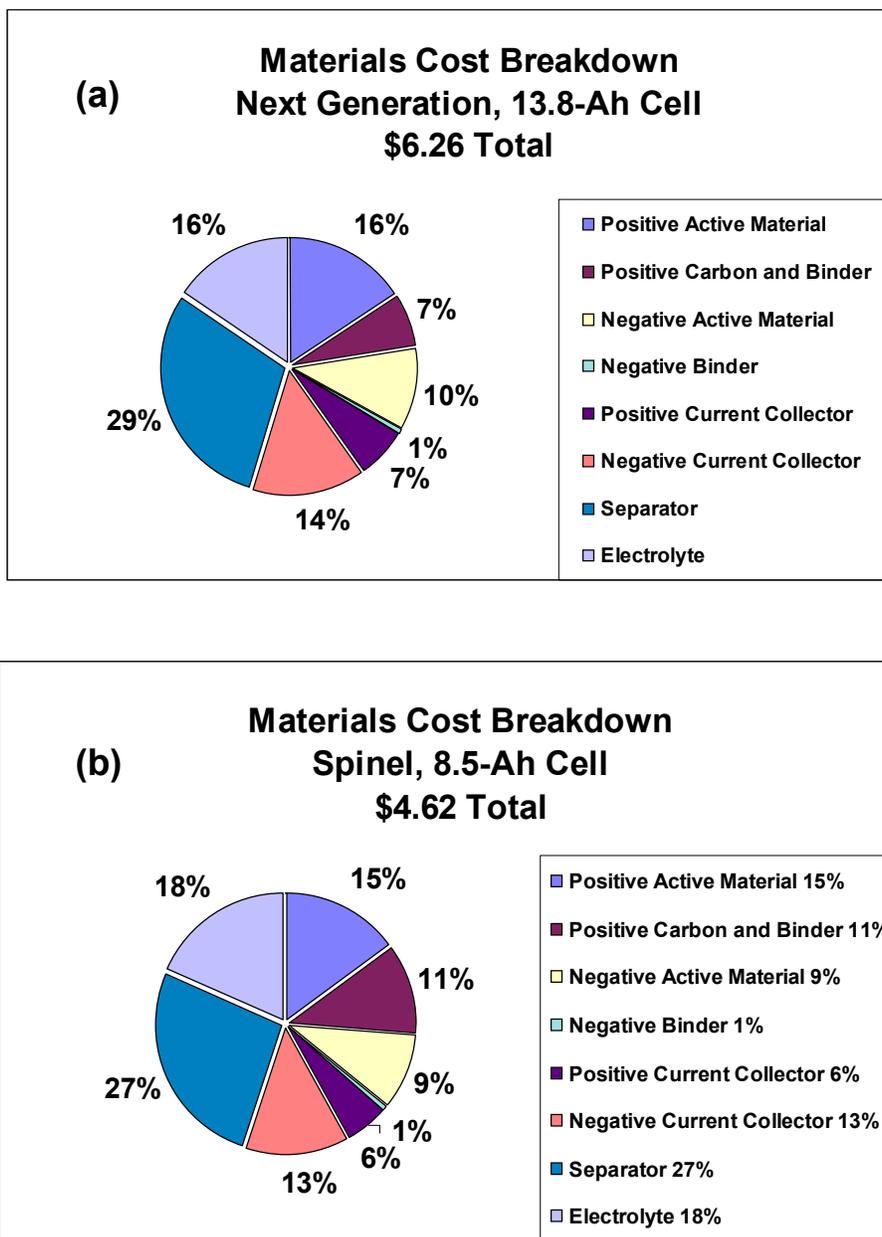


Figure 3. Cost Breakdown for Advanced Cell Chemistries in Cells Sized for the Minimum-Power-Assist HEV Application. Advanced chemistries (a) and (b) incorporate the $\text{LiNi}_{1/3}\text{Co}_{1/3}\text{Mn}_{1/3}\text{O}_2$ cathode and the $\text{Li}_{1+x}\text{Mn}_{2-x}\text{O}_4$ spinel cathode, respectively.

ACKNOWLEDGEMENTS

The authors would like to acknowledge Fuji Chemical Industry Company, Ltd., for the excellent manufacturing cost analysis study that it performed on advanced cathode materials, under contract to ANL. Dr. Dennis Dees provided technical support to this activity via his electrochemical transport model, and assisted in the establishment of the Ah ratings of the cells used in the battery designs. Finally, the authors wish to acknowledge U.S. Department of Energy, FreedomCAR and Vehicle Technologies Office, for sponsoring this work under its Advanced Technology Development Program, and the FreedomCAR Energy Storage Technical Team for its interest and support.

**APPENDIX A. MATERIAL COSTS FOR 48-CELL 40-KW MAXIMUM-
POWER-ASSIST HEV BATTERIES**

Table A-1. Cost of Materials in Cell Windings of a 40-kW 48-Cell Battery (24.7-Ah cells)
That Employs the Gen 2 Cell Materials

Type of Material	40-kW Maximum Power-Assist Battery		
	Quantity	Unit Cost	Cost, \$
Cathode			
Active material (LiNi _{0.8} Co _{0.15} Al _{0.05} O ₂)	7.707 kg	20.52/kg	158.15
SFG-6	0.367 kg	15.00/kg	5.51
Carbon black	0.367 kg	6.82/kg	2.50
PVDF binder	0.734 kg	10.00/kg	7.34
NMP binder solvent	5.383 kg	3.18/kg	17.12
Anode			
Active material	5.143 kg	15.00/kg	77.15
PVDF binder	0.478 kg	10.00/kg	4.78
NMP binder solvent	3.504 kg	3.18/kg	11.14
Aluminum foil current collector	34.18 m ²	1.00/m ²	34.18
Copper foil current collector	36.53 m ²	2.00/m ²	73.07
Separator	74.77 m ²	2.00/m ²	149.54
Electrolyte (LiPF ₆ in EC:EMC)	5.01 liters	20.00/L	100.14
Total material cost			640.61

Table A-2. Cost of Materials in Cell Windings of a 40-kW 48-Cell Battery (22.2-Ah cells)
That Employs Lower-Cost Anode and Cathode Materials

Type of Material	40-kW Maximum-Power-Assist Battery		
	Quantity	Unit Cost	Cost, \$
Cathode			
Active material (LiNi _{1/3} Co _{1/3} Mn _{1/3} O ₂)	5.859 kg	13.00/kg	76.17
SFG-6	0.366 kg	15.00/kg	5.49
Carbon black	0.366 kg	6.82/kg	2.50
PVDF binder	0.732 kg	10.00/kg	7.32
NMP binder solvent	5.371 kg	3.18/kg	17.08
Anode			
Active mMaterial	5.004 kg	10.00/kg	50.04
Rubber binder	0.465 kg	6.00/kg	2.79
Aqueous solvent	3.409 kg	0.00/kg	0.00
Aluminum foil current collector	32.25 m ²	1.00/m ²	32.25
Copper foil current collector	34.51 m ²	2.00/m ²	69.01
Separator	70.67 m ²	2.00/m ²	141.34
Electrolyte (LiPF ₆ in EC:PC:DMC)	4.67 liters	16.00/L	74.79
Total material cost			478.78

Table A-3. Cost of Materials in Cell Windings of a 40-kW 48-Cell Battery (13.7-Ah cells) That Employs Spinel Positive Electrodes and Low-Cost Anode Materials

Type of Material	40-kW Maximum-Power-Assist Battery		
	Quantity	Unit Cost	Cost, \$
Cathode			
Active material (LiMn ₂ O ₄)	7.275kg	7.40/kg	53.83
SFG-6	0.455 kg	15.00/kg	6.82
Carbon black	0.455 kg	6.82/kg	3.10
PVDF binder	0.909 kg	10.00/kg	9.09
NMP binder solvent	6.669 kg	3.18/kg	21.21
Anode			
Active material	3.320 kg	10.00/kg	33.20
Rubber binder	0.308 kg	6.00/kg	1.85
Aqueous solvent	2.261 kg	0.00/kg	0.00
Aluminum foil current collector	20.66 m ²	1.00/m ²	20.66
Copper foil current collector	22.55 m ²	2.00/m ²	45.11
Separator	46.68 m ²	2.00/m ²	93.37
Electrolyte (LiPF ₆ in EC:PC:DMC)	4.03 liters	16.00/L	64.43
Total material cost			352.67

**APPENDIX B. MANUFACTURING COST ANALYSES FOR
LITHIATED METAL OXIDE MATERIALS**

**Cost Analysis of Cathode Materials for
High Power Battery Application**

February 27, 2002

By

Fuji Chemical Industry Co., Ltd.

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1. Assignments

Cost Analysis of Cathode materials for High Power Battery Application

ANL is requesting from Fuji to carry out production cost analysis of a number of potential cathode materials for high power lithium ion batteries. The cost analysis will be carried out using the solid-state reaction process and the spray drying process. This study will help us quantify the cost associated with the process used for the preparation of the materials. Fuji will use the lowest cost precursor materials in order to establish a cost floor. This will be done with the understanding that the final product, obtained when these low-cost precursors are used, may not be acceptable. Additionally, FMC would provide information on how the production cost would increase as a function of using more expensive (and higher purity) precursor materials and optimum process. The materials that ANL is interested to are:

(1) $\text{LiNi}_{0.8}\text{Co}_{0.15}\text{Al}_{0.05}\text{O}_2$

This material is being used in our Gen 2 cells and it has significantly improved the calendar life over the material used in our Gen 1 cells. This will as a baseline or reference point.

Fuji will carry out the production cost analysis of this material using spray dry technique. In the cost analysis, Fuji will use 1) their existing raw material and 2) the lowest possible raw material and simplified process to establish a cost floor.

(2) $\text{LiNi}_{0.92}\text{Ti}_{0.05}\text{Al}_{0.03}\text{O}_2$

Replacing Co with Ti should help bring down the cost of this material. ANL request that Fuji examine the solid-state reaction process for making this material. Also, a floor cost should be given

(3) $\text{LiNi}_{0.45}\text{Mn}_{0.45}\text{Al}_{0.05}\text{O}_2$

This is another potential low-cost cathode material. ANL request that Fuji examine the production cost of making the material using the solid-state reaction and the spray drying process. Also, a floor cost should be given

(4) $\text{LiNi}_{0.2}\text{Mn}_{0.8}\text{O}_2$

This material could be a potential low-cost cathode material. ANL requested that Fuji examine the production cost of making the material using the solid-state reaction and the spray drying process. Also, a floor cost should also be given

2. Assumptions

All analysis in this report were done based on the following assumptions.

(1) Quantity Estimation

The minimum consumption of 1,000 Metric Tons / Year as the total of Cathode Material for each type are used for the estimations. However, those estimations were made that only 1 of 4 products is taken up for the real mass production.

(2) Production Schedule

This cost estimates are prepared assuming that the real mass production shall start in the end of year 2003.

(3) Products Quality

Fuji will not guarantee if the quality of all finished products will satisfy ANL's standard requirements since the estimates were specially prepared for the cheapest Cathode Materials manufactured with any available resources in the world and considerable simplest production processes even though they may not meet current Fuji's quality standards. However, Fuji is quite confident about CA-5 to keep same level of quality as the samples submitted to ANL in the past.

(4) Currency Exchange Rates

Considering the current exchange market situation, \$1.00=¥135 is used for all international transactions such as imports and exports.

(5) Investments and the Depreciations

Assuming the total consumption of the material of 1,000 MT/Year, all investments including the current Buildings, Equipments and Machineries are planned to be depreciated in the next 7 years with Straight-Line Method.

(6) Production Method

- "Spray Drying Process" means "Wet-Mix Method" which is the original production method of Fuji.
- "Solid-State Reaction Process" means "Dry-Mix Method" which is the standard production method most of the other manufacturers are using for Lithium Cobalt Oxide.

3. Material Cost Analysis

Basic price information was collected through one of the biggest Japanese trading companies who is capable of importing natural resources available around the world. Of course, we made the comparison between the price offered by the trading company and those offered to us directly from our current supply sources.

The following price information on the tables are carefully evaluated considering the transportation costs to our factory and exchange rate of \$=¥135 and then listed.

We may be able to expect additional discounts of few percents on each item at the time of materialization of this business. Further discounts may be possible if we made a long-term contract with each manufacturer.

(1) Lithium

Composition	LiOH·H ₂ O	LiOH·H ₂ O
Vender	A (USA)	B (Taiwan)
Unit Cost (¥/kg)	801	669
Purity (%)	99≧	99≧
Impurity (%)		
CO ₂	≦0.35	.
Na	≦0.028	≦0.002
Ca	≦0.021	≦0.002
Fe	≦0.0042	≦0.0005
Si	.	≦0.005
Mg	.	≦0.001
Heavy Metals	≦0.002	≦0.001
SO ₄	≦0.05	≦0.01
Cl	≦0.003	≦0.003

● Unit Cost: DDP Kitakyushu Factory

(2) Nickel

1/NC6

Composition	Ni-metal powder	Ni-metal briquette	NiO	Ni(OH) ₂
Vender	C (Canada)	D (Russia)	E (Japan)	F (Japan)
Unit Cost (¥/kg)	905	894	1,073	1,350
Purity (%)	99.9	99.94	98 \leq	98 \leq
Impurity (%)				
Fe	.	0.0024	.	.
Cu	.	0.0155	.	.
Co	0.091	0.0019	.	.
Zn	.			.

(3) Cobalt

Composition	Co-metal powder	Co-metal briquette
Vender	G (Canada)	H (Congo)
Unit cost (¥/kg)	2,221	2,056
Purity (%)	99.9	94.8 \leq
Impurity (%)		
C	0.0650	0.0219
Fe	0.0023	0.0219
Cu	\leq 0.0005	0.0106
Ni	0.0092	0.1562
Zn	\leq 0.0005	0.8591
SO ₄	0.02	0.6003

(4) Manganese

Composition	CMD·MnO ₂	EMD·MnO ₂	EMD·MnO ₂	Mn-metal Flake	Mn-metal Bar
Vender	I (Belgium)	J (China)	K (China)	L (China)	M (China)
Unit Cost (¥/kg)	338	188	161	145	205
Purity (%)	90 \leq	91 \leq	91 \leq	99.7 \leq	99.9 \leq
Impurity (%)					
Fe	≤ 0.025	≤ 0.02	≤ 0.015	.	0.0025
C	.	.	.	0.016	0.008
Cu	≤ 0.0003	≤ 0.0005	≤ 0.0003	.	.
P	.	.	.	0.0015	0.0003
SO ₄	≤ 1.2	≤ 1.3	≤ 1.0	0.054	0.114
Si	0.002

(5) Aluminum

Composition	Al(NO ₃) ₃	Al(OH) ₃
Vender	N (Japan)	O (Japan)
Unit Cost (¥/kg)	200	80
Purity (%)	98 \leq	99 \leq

(6) Titanium

Composition	TiO ₂	TiO ₂
Vender	P (Japan)	Q (Japan)
Unit Cost (¥/kg)	300	3,000
Purity (%)	98 \leq	90 \leq
Impurity (%)		
Heavy Metals	≤ 0.01	≤ 0.01

(7) Double Hydroxide

Composition	$\text{Ni}_{0.46}\text{Mn}_{0.5}(\text{OH})_2$	$\text{Ni}_{0.2}\text{Mn}_{0.8}(\text{OH})_2$
Vender	R (Japan)	S (Japan)
Unit Cost (¥/kg)	1,228	1,046
Purity (%)	98 \leq	98 \leq

(8) Others and Secondary Raw Materials

Composition	H_3BO_3	HNO_3	NaOH	H_2O_2
Vender	T (Japan)	U (Japan)	V (Japan)	W (Japan)
Unit Cost (¥/kg)	300	30	11	40
Purity (%)	99.5 \leq	67.5 \leq	48.0~49.5	35 \leq

4. Study of Production Process

Following production processes are considered to be most economical and cost effective based on the past studies done by Fuji. However, further experiments should be required for the qualification of each material.

(1) -1. $\text{LiNi}_{0.8}\text{Co}_{0.15}\text{Al}_{0.05}\text{O}_{1.985}$

(BO_3)_{0.01}

(Spray drying process)

(Grade Name: CA-5 & CA-5F)

Dissolving Ni, Co-metal and Al salt with
Nitric acid and H_2O_2

↓

Coprecipitation with NaOH

↓

Filtration

↓

Washing by water

↓

Mixing Coprecipitation, LiOH and H_3BO_3
in water

↓

Spray Dry

↓

Compaction

↓

1st Calcination (below 850°C - 3hr)

↓

Pulverizing

↓

2nd Calcination (below 850°C - 13hr)

↓

Classification

↓

Packing and Labeling

(1)-2. $\text{LiNi}_{0.8}\text{Co}_{0.15}\text{Al}_{0.05}\text{O}_2$

(Spray drying process)

(Grade Name: CA1505N)

Dissolving Ni, Co-metal and Al salt with
Nitric acid and H_2O_2

↓

Coprecipitation with NaOH

↓

Filtration

↓

Washing by water

↓

Mixing Coprecipitation and LiOH
in water

↓

Spray Dry

↓

Calcination (below 850°C - 13hr)

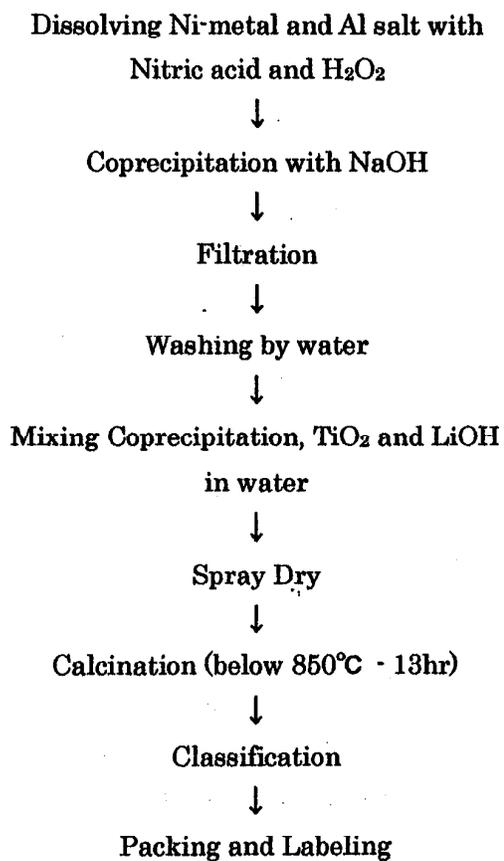
↓

Classification

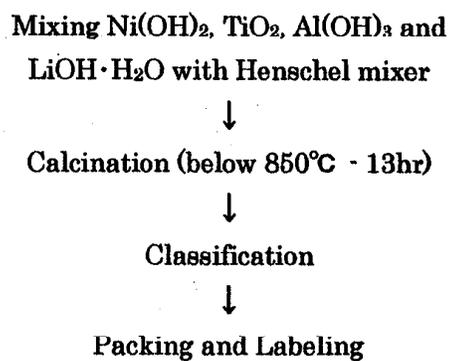
↓

Packing and Labeling

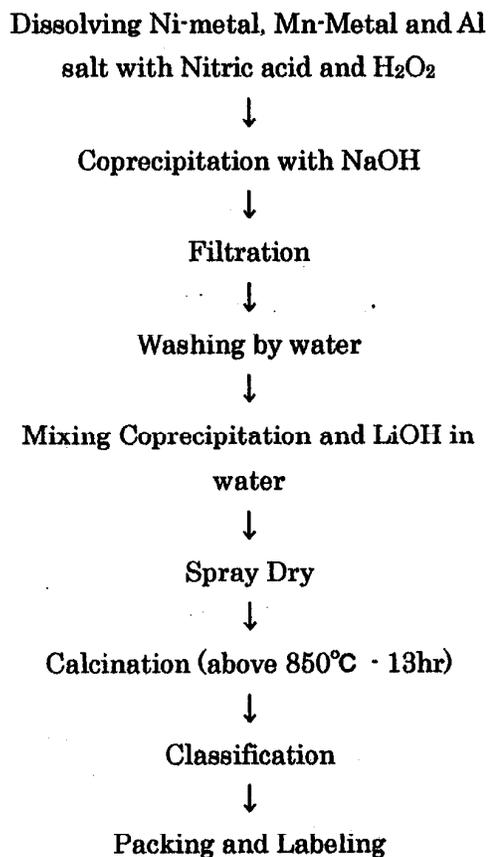
(2)-1. LiNi_{0.92}Ti_{0.05}Al_{0.03}O₂
(Spray drying process)



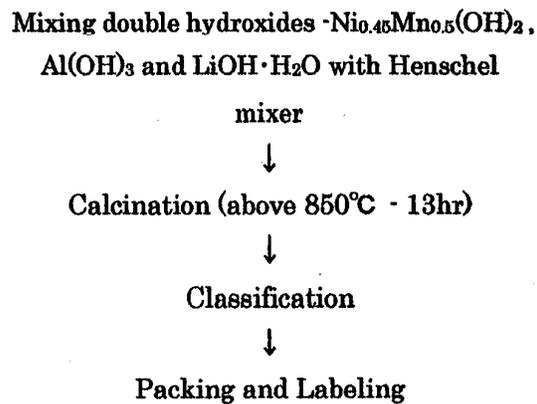
(2)-2. LiNi_{0.92}Ti_{0.05}Al_{0.03}O₂
(Solid-state reaction process)



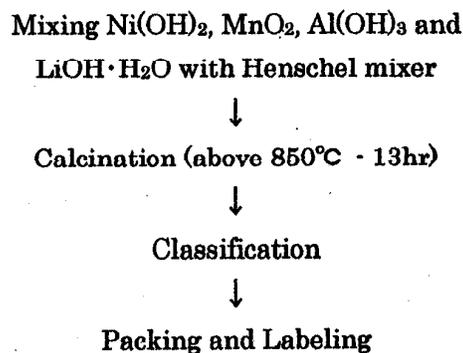
(3)-1. LiNi_{0.45}Mn_{1.05}Al_{0.05}O₂
(Spray drying process)



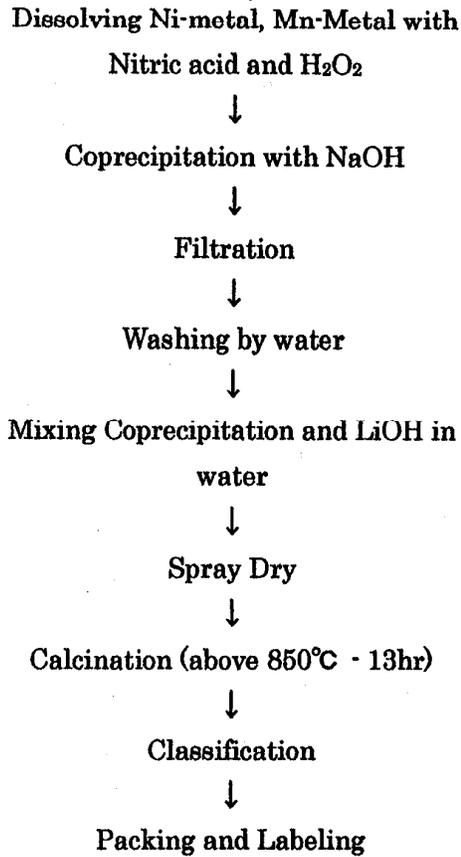
(3)-2-A. LiNi_{0.45}Mn_{1.05}Al_{0.05}O₂
(Solid-state reaction process)



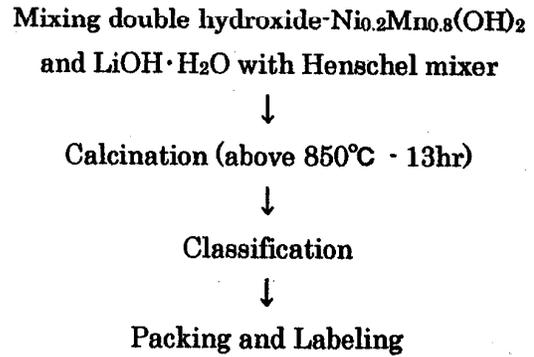
(3)-2-B. LiNi_{0.45}Mn_{0.5}Al_{0.05}O₂
(Solid-state reaction process)



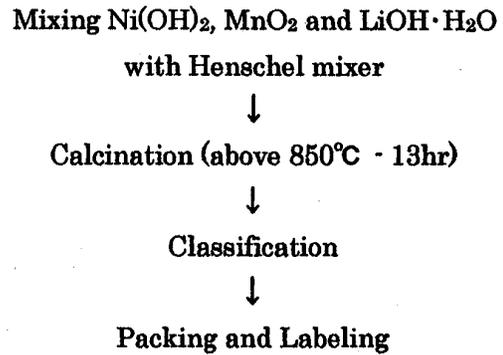
(4)-1. $\text{LiNi}_{0.2}\text{Mn}_{0.8}\text{O}_2$
(Spray drying process)



(4)-2-A. $\text{LiNi}_{0.2}\text{Mn}_{0.8}\text{O}_2$
(Solid-state reaction process)



(4)-2-B. $\text{LiNi}_{0.2}\text{Mn}_{0.8}\text{O}_2$
(Solid-state reaction process)



5. Production Capacity Analysis

Assuming that the total volume of production for each material is 1,000 T/Y (=83.3 T/M), calculation was made based on the factory operation of 25 days/Month, which means that the production volume will be 3.4 T/Day. If the total yield of mass production reached 95%, production volume would be 3.6 T/Day.

(1) -1. LiNi_{0.8}Co_{0.15}Al_{0.05}O_{0.195}(BO₃)_{0.01} (Spray drying process)
(Grade Name: CA-5 & CA-5F)

a. Production Capacity

<u>Current Production Capacity</u>	<u>Production Capacity after Investments</u>
Dissolving of raw materials : 1.2 t / day	Dissolving of raw materials : 3.6 t / day
Reaction process : 4.8 t / day	Reaction process : 4.8 t / day
Heat treatment process : 1.2 t / day	Heat treatment process : 3.6 t / day
Filter press : 4.0 t / day	Filter press : 4.0 t / day
Re-pulp & Addition of LiOH : 4.0 t / day	Re-pulp & Addition of LiOH : 4.0 t / day
Spray Dry : 4.8 t / day	Spray Dry : 4.8 t / day
Compaction : 4.8 t / day	Compaction : 4.8 t / day
1 st Calcination : 1.0t / day	1 st Calcination : 3.6 t / day
Calciner × 2 systems	Calciner × 9 systems
Oxygen generator × 1 system	Oxygen generator × 2 system
Attached facilities × 1 system	Attached facilities × 2 system
Pulverizing : 4.8 t / day	Pulverizing : 4.8 t / day
2 nd Calcination : 1.0 t / day	2 nd Calcination : 3.0 t / day
Calciner × 4 systems	Calciner × 12 systems
Oxygen generator × 1 system	Oxygen generator × 2 systems
Attached facilities × 1 system	Attached facilities × 4 systems
Classification : 3.6 t / day	Classification : 3.6 t / day
Packing and Labeling : 3.6 t / day	Packing and Labeling : 3.6 t / day

b. New Investments of production facilities

I. Reactor	¥20,000,000
II. 1 st . Calciner: three systems plus attached facilities: 1 more system	¥300,000,000
III. 2 nd . Calciner: three systems plus attached facilities: 2 more system	¥960,000,000
IV. Buildings and foundation work for Oxygen generator	¥15,000,000
V. Ceramics trays: eighteen sets	¥126,000,000
VI. Oxygen generator (PSA Lease)	(¥2,200,000/M)
	<u>Total: ¥1,421,000,000</u>

(1) -2. LiNi_{0.8}Co_{0.15}Al_{0.05}O₂ (Spray drying process)
 (Grade Name: CA1505N)

a. Production Capacity

<u>Current Production Capacity</u>	<u>Production Capacity after Investments</u>
Dissolving of raw materials: 2.4 t / day	Dissolving of raw materials: 3.6 t / day
Reaction process : 4.8 t / day	Reaction process : 4.8 t / day
Filter press : 4.0 t / day	Filter press : 4.0 t / day
Re-pulp & Addition of LiOH: 4.0 t / day	Re-pulp & Addition of LiOH: 4.0 t / day
Spray Dry : 3.6 t / day	Spray Dry : 3.6 t / day
Calcination : 1.5 t / day	Calcination : 3.0 t / day
Calciner × 6 systems	Calciner × 12 systems
Oxygen generator × 1 system	Oxygen generator × 2 systems
Attached facilities × 1 system	Attached facilities × 2 systems
Classification : 3.6 t / day	Classification : 3.6 t / day
Packing and Labeling : 3.6 t / day	Packing and Labeling : 3.6 t / day

b. New Investments of production facilities

I. Reactor	¥20,000,000
II. Calciner: six systems plus attached facilities: 1 more system	¥480,000,000
III. Buildings and foundation work for Oxygen generator	¥15,000,000
IV. Ceramics trays: seven sets	¥50,000,000
V. Oxygen generator (PSA Lease)	(¥2,200,000/M)
	<u>Total: ¥565,000,000</u>

(2)-1 LiNi_{0.92}Ti_{0.05}Al_{0.03}O₂ (Spray drying process)

a. Production Capacity

<u>Current Production Capacity</u>	<u>Production Capacity after Investments</u>
Dissolving of raw materials: 2.4 t / day	Dissolving of raw materials: 3.6 t / day
Reaction process : 4.8 t / day	Reaction process : 4.8 t / day
Filter press : 4.0 t / day	Filter press : 4.0 t / day
Re-pulp & Addition of LiOH: 4.0 t/day	Re-pulp & Addition of LiOH: 4.0 t/day
Spray Dry : 3.6 t / day	Spray Dry : 3.6 t / day
Calcination : 1.5 t / day	Calcination : 3.0 t / day
Calciner × 6 systems	Calciner × 12 systems
Oxygen generator × 1 system	Oxygen generator × 2 systems
Attached facilities × 1 system	Attached facilities × 2 systems
Classification : 3.6 t / day	Classification : 3.6 t / day
Packing and Labeling : 3.6 t / day	Packing and Labeling : 3.6 t / day

b. New Investments of production facilities

I. Reactor	¥20,000,000
II. Calciners: six systems plus attached facilities: 1 more system	¥480,000,000
III. Buildings and foundation work for Oxygen generator	¥15,000,000
IV. Ceramic trays: seven sets	¥50,000,000
V. Oxygen generator (PSA Lease)	(¥2,200,000/M)
	Total: ¥565,000,000

(2)-2 LiNi_{0.92}Ti_{0.05}Al_{0.03}O₂ (Solid-state reaction process)

a. Production Capacity

<u>Current Production Capacity</u>	<u>Production Capacity after Investments</u>
Mixing of raw materials : 0.0 t / day	Mixing of raw materials : 3.6 t / day
Calcination : 1.5 t / day Calciner × 6 systems	Calcination : 3.0 t / day Calciner × 12 systems
Oxygen generator × 1 system	Oxygen generator × 2 systems
Attached facilities × 1 system	Attached facilities × 2 systems
Classification : 3.6 t / day	Classification : 3.6 t / day
Packing and Labeling : 3.6 t / day	Packing and Labeling : 3.6 t / day

b. New Investments of production facilities

I. Solid mixing facilities: one system	¥30,000,000
II. Calciners: six systems plus Attached facilities: 1 more system	¥ 480,000,000
III. Buildings and foundation work for Oxygen generator	¥15,000,000
IV. Ceramics trays: seven sets	¥50,000,000
V. Oxygen generator (PSA)	(¥2,200,000 / M)
	<u>Total: ¥575,000,000</u>

(3)-1 LiNi_{0.45}Mn_{0.5}Al_{0.05}O₂ (Spray drying process)

a. Production Capacity

<u>Current Production Capacity</u>	<u>Production Capacity after Investments</u>
Dissolving of raw materials: 2.4 t / day	Dissolving of raw materials: 3.6 t / day
Reaction process : 4.8 t / day	Reaction process : 4.8 t / day
Filter press : 4.0 t / day	Filter press : 4.0 t / day
Re-pulp & Addition of LiOH: 4.0 t/day	Re-pulp & Addition of LiOH:4.0 t/day
Spray Dry : 3.6 t / day	Spray Dry : 3.6 t / day
Calcination(above 850°C) : 0.0 t / day	Calcination(above 850°C) : 3.0 t / day
Calciner (below 850°C) × 6 systems	Calciner (above 850°C) × 12 systems
Oxygen generator × 1 system	Oxygen generator × 2 systems
Attached facilities × 1 system	Attached facilities × 2 systems
Classification : 3.6 t / day	Classification : 3.6 t / day
Packing and Labeling : 3.6 t / day	Packing and Labeling : 3.6 t / day

b. New Investments of production facilities

I. Reactor	¥20,000,000
II. Calciner(above 850°C): six systems and attached facilities	¥ 540,000,000
III. Reconstruction of calciners(bellow 850°C→above 850°C)	¥120,000,000
IV. Buildings and foundation work for Oxygen generator	¥15,000,000
V. Ceramics trays: seven sets	¥50,000,000
VI. Oxygen generator (PSA Lease)	(¥2,200,000 / M)
	<u>Total: ¥745,000,000</u>

(3)-2-A & B. LiNi_{0.45}Mn_{0.5}Al_{0.05}O₂ (Solid-state reaction process)

a. Production Capacity

<u>Current Production Capacity</u>	<u>Investigated Production Capacity</u>
Mixing of raw materials : 0.0 t / day	Mixing of raw materials : 3.6 t / day
Calcination(above 850°C) : 0.0 t / day	Calcination(above 850°C) : 3.0 t / day
Calciner (bellow 850°C) × 6 systems	Calciner (above 850°C) × 12 systems
Oxygen generator × 1 system	Oxygen generator × 2 systems
Attached facilities × 1 system	Attached facilities × 2 systems
Classification : 3.6 t / day	Classification : 3.6 t / day
Packing and Labeling : 3.6 t / day	Packing and Labeling : 3.6 t / day

b. New Investments of production facilities

I . Solid mixing facilities: one system	¥30,000,000
II .Calciner(above 850°C): six systems and Attached facilities:	¥ 540,000,000
III. Reconstruction of calciners(bellow 850°C→above 850°C)	¥120,000,000
IV. Buildings and foundation work for Oxygen generator	¥15,000,000
V. Ceramics trays: seven sets	¥50,000,000
VI. Oxygen generator (PSA Lease)	(¥2,200,000 / M)
	<u>Total: ¥755,000,000</u>

(4)-1 LiNi_{0.2}Mn_{0.8}O₂ (Spray drying process)

a. Production Capacity

<u>Current Production Capacity</u>	<u>Investigated Production Capacity</u>
Dissolving of raw materials: 2.4 t / day	Dissolving of raw materials : 3.6 t / day
Reaction process : 4.8 t / day	Reaction process : 4.8 t / day
Filter press : 4.0 t / day	Filter press : 4.0 t / day
Re-pulp & Addition of LiOH: 4.0 t/day	Re-pulp & Addition of LiOH: 4.0 t/day
Spray Dry : 3.6 t / day	Spray Dry : 3.6 t / day
Calcination(above 850°C) : 0.0 t / day	Calcination(above 850°C) : 3.0 t / day
Calciner (below 850°C) × 6 systems	Calciner (above 850°C) × 12 systems
Oxygen generator × 1 system	Oxygen generator × 2 systems
Attached facilities × 1 system	Attached facilities × 2 systems
Classification : 3.6 t / day	Classification : 3.6 t / day
Packing and Labeling : 3.6 t / day	Packing and Labeling : 3.6 t / day

b. New Investments of production facilities

I. Reactor	¥20,000,000
II. Calciner (above 850°C) : six systems and attached facilities: one system	¥540,000,000
III. Reconstruction of calciner(below 850°C→above 850°C)	¥120,000,000
IV. Buildings and foundation work for Oxygen generator	¥15,000,000
V. Ceramics trays: seven sets	¥50,000,000
VI. Oxygen generator (PSA Lease)	(¥2,200,000 / M)
	<u>Total: ¥745,000,000</u>

(4)-2 -A & B. LiNi_{0.2}Mn_{0.8}O₂ (Solid-state reaction process)

a. Production Capacity

<u>Current Production Capacity</u>	<u>Investigated Production Capacity</u>
Mixing of raw materials : 0.0 t / day	Mixing of raw materials : 3.6 t / day
Calcination (above 850°C) : 0.0 t / day	Calcination (above 850°C) : 3.0 t / day
Calciner (below 850°C) × 6 systems	Calciner (above 850°C) × 12 systems
Oxygen generator × 1 system	Oxygen generator × 2 systems
Attached facilities × 1 system	Attached facilities × 2 systems
Classification : 3.6 t / day	Classification : 3.6 t / day
Packing and Labeling : 3.6 t / day	Packing and Labeling : 3.6 t / day

b. New Investments of production facilities

I . Solid mixing facilities: one system	¥30,000,000
II .Calciner(above 850°C): six systems and Attached facilities: one system	¥540,000,000
III. Reconstruction of calciners(bellow 850°C→above 850°C)	¥120,000,000
IV. Buildings and foundation work for Oxygen generator	¥15,000,000
V . Ceramics trays: seven sets	¥50,000,000
VI. Oxygen generator (PSA)	(¥2,200,000 / M)
	<u>Total: ¥755,000,000</u>

6. Production Cost Analysis

Spray Drying Process

Applied Compositions:

- (1)-1. $\text{LiNi}_{0.8}\text{Co}_{0.15}\text{Al}_{0.05}\text{O}_{1.985}(\text{BO}_3)_{0.01}$
- (1)-2. $\text{LiNi}_{0.8}\text{Co}_{0.15}\text{Al}_{0.05}\text{O}_2$
- (2)-1. $\text{LiNi}_{0.92}\text{Ti}_{0.05}\text{Al}_{0.03}\text{O}_2$
- (3)-1. $\text{LiNi}_{0.45}\text{Mn}_{0.5}\text{Al}_{0.05}\text{O}_2$
- (4)-1. $\text{LiNi}_{0.2}\text{Mn}_{0.8}\text{O}_2$

1. Human Resources and Personnel Expenses

The total number of people required for production is 53. The projected number of individuals for full operation is listed in the following tables:

Individuals Directly Related to Production

Process	No. of Persons	No. of Shifts	Total	Grand Total
Synthesis Spray Drying Calcination	7 per shift	3 (Full Operation)	21 per day	41 per day (40 + 1 extra)
Compacting Pre-calcination Crushing	2 per shift	3 per day	6 per day	
Packing	3 per shift	1 per day	3 per day	
Maintenance	1 per shift	3 per day	3 per day	

Remarks: 25 working days a month will be operative for production.
 28 working days a month will be operative for calcination.
 $33 \text{ workers} \times 25 \text{ days} + 9 \text{ workers for calcination} / 21 \text{ days} = 39.7$
 $\approx 40 \text{ workers}$
 One extra worker for an assistant = 41 needed for full-operated production.

Individuals Indirectly Related to Production

Job Description	No. of Persons	No. of Shifts	Total	Grand Total
Managing Administration Engineering Shipping	3	N/A	3	3

Quality Control

Job Description	No. of Persons	No. of Shifts	Total	Actual No. Needed
Quality Control & Related Work	3	1 (Shift 1) *	3	6 (5 x 25days/21days)**
Same as Above	1	1 (Shift 2 & 3) *	2	

Remarks: *Shift 1: 8:00 – 17:00, Shift 2: 17:00 – 1:00, Shift 3: 1:00 – 8:00
 **5 workers x 25 days / 21 days = 5.9 ≈ 6 workers

General Administration – Factory

Job Description	No. of Persons	No. of Shifts	Total	Grand Total
Factory Chief Administration Reception Cleaning Washing	3	N/A	3	3

Unit Cost for Human Resources

Departments	Unit Price
Production & Factory Administrative	JPY20,000 / cap.
Quality Control	JPY20,000 / cap.

2. Power and Electric Expenses

For full-operated production, the site needs 1280kw/mo of power. The estimated monthly basic charge is JPY1,895.5/kw and the estimated monthly rate is JPY8.75/kwh. Necessary power for each utility is figured according to each process, but for PSA, it is stated in the utility expenses separately.

3. Fuel Expenses (LNG)

Item	Amount Used	Unit Cost	Remarks
Fuel Use	198,000m ³ / mo	JPY45 / m ³	JPY 1 M / mo Basis

Item	Avg. Cost for LNG	Unit Cost for Boilers	Remarks
Reflux Boilers	JPY 27,000 / mo (6,000m ³ x JPY 45)	JPY112,500 / mo (JPY270,000 x 5 mo's / 12 mo's)	Operation for 5 mo's

4. Collection of NaNO₃

The contracted unit cost for collection of NaNO₃ is JPY18/kg (Nitrate Acid).

5. Other Expenses for Production

The primary expenses are miscellaneous expendables, repair, lease and rental expenses. They are figured to be JPY 40 M per annum.

6. Other Expenses

Department	Annual Expenses	Items
Quality Control	JPY10,408 K	<ul style="list-style-type: none">■ Yearly Lease■ Rental Fees■ Expendables
Factory Administration	JPY3,100 K	<ul style="list-style-type: none">■ Miscellaneous
Administration & Production	JPY41,694 K	<ul style="list-style-type: none">■ Taxes and Other Public Charges■ Fire Insurance■ Miscellaneous Expenses Related to Factory Operation■ Communication

Remarks: Quality Control and Factory Administration expenses are figured without Personnel Expenditures.

Solid-State Reaction Process

Applied Compositions:

- (2)-2. $\text{LiNi}_{0.92}\text{Ti}_{0.05}\text{Al}_{0.03}\text{O}_2$
(3)-2-A & -B. $\text{LiNi}_{0.45}\text{Mn}_{0.5}\text{Al}_{0.05}\text{O}_2$
(4)-2-A & -B. $\text{LiNi}_{0.2}\text{Mn}_{0.8}\text{O}_2$

1. Human Resources and Personnel Expenses

The total number of people required for production is 32. The projected number of individuals for full operation is listed in the following tables:

Individuals Directly Related to Production

Process	No. of Persons	No. of Shifts	Total	Grand Total
Mixing	3 per shift	3 (continuous)	9 per day	20 per day (19 + 1 extra)
Calcination	3 per shift	1 per day	3 per day	
Packing	1 per shift	3 per day	3 per day	

Remarks: 25 working days a month will be operative for production.
28 working days a month will be operative for calcination.
 $15 \text{ workers} \times 25 \text{ days} + 9 \text{ workers for calcination} / 21 \text{ days} = 18.2$
 $\approx 19 \text{ workers}$
One extra worker for an assistant = 20 needed for full-operated production.

Individuals Indirectly Related to Production

Job Description	No. of Persons	No. of Shifts	Total	Grand Total
Managing Administration	3	N/A	3	3
Engineering				
Shipping				

Quality Control

Job Description	No. of Persons	No. of Shifts	Total	Actual No. Needed
Quality Control & Related Work	3	1 (Shift 1) *	3	6 (5 + 1 extra) **
Same as Above	1	1 (Shift 2 & 3) *	2	

Remarks: *Shift 1: 8:00 – 17:00, Shift 2: 17:00 – 1:00, Shift 3: 1:00 – 8:00

** $(5 \text{ workers} \times 25 \text{ days}) / 21 \text{ days} = 5.9 \approx 6 \text{ workers}$

General Administration – Factory

Job Description	No. of Persons	No. of Shifts	Total	Grand Total
Factory Chief Administrative Reception Cleaning Washing	3	N/A	3	3

Unit Cost for Human Resources

Departments	Unit Price
Production & Factory Administrative	JPY20,000 / cap.
Quality Control	JPY20,000 / cap.

2. Power and Electric Expenses

For full-operated production, the site needs 1280kw/mo of power. The estimated monthly basic charge is JPY1,895.5/kw and the estimated monthly rate is JPY8.75/kwh. Necessary power for each utility is figured according to each process, but for PSA, it is stated in the utility expenses separately.

3. Fuel Expenses (LNG)

Item	Amount Used	Unit Cost	Remarks
Fuel Use	198,000m ³ / mo	JPY45 / m ³	JPY 1 M / mo Basis

Item	Avg. Cost for LNG	Unit Cost for Boilers	Remarks
Reflux Boilers	JPY 27,000 / mo (6,000m ³ x JPY 45)	JPY112,500 / mo (JPY270,000 x 5 mo's / 12 mo's)	Operation for 5 mo's

4. Other Expenses for Production

The primary expenses are miscellaneous expendables, repair, lease and rental expenses. They are figured to be JPY 40 M per annum.

5. Other Expenses

Department	Annual Expenses	Item
Quality Control	JPY10,408 K	<ul style="list-style-type: none"> ■ Yearly Lease ■ Rental Fees ■ Expendables
Factory Administration	JPY3,100 K	<ul style="list-style-type: none"> ■ Miscellaneous
Administration & Production	JPY41,694 K	<ul style="list-style-type: none"> ■ Taxes and Other Public Charges ■ Fire Insurance ■ Miscellaneous Expenses Related to Factory Operation ■ Communication

Remarks: Quality Control and Factory Administration expenses are figured without Personnel Expenditures.

7. Total Material Cost Analysis

Please refer to the following estimated price idea for each material. The price includes all necessary costs such as Labor/Utility Costs, General Administration Costs, Depreciation and Fuji's profit:

Total Material Cost Break Down

February 20, 2002

Item	(1) - 1	(1) - 2	(2) - 1	(2) - 2
Product Grades	CA-5	CA1505N	TA0503	TA0503
Process Methods	SD	SD	SD	SSR
Production Cost Item				
Raw Materials				
Ni-metal	465	466	536	
Powdered Ni-Hydroxide				1,286
TiO2			13	13
Co-metal	215	215		
Al Hydroxide				2
Aluminum Nitrate	42	42	25	
35% Hydrogen peroxide	75	75	73	
67.5% Nitric Acid	63	63	61	
49% Sodium Hydroxide	21	21	20	
Li-HydroxideMonohydrate	313	310	310	310
H3BO3	2			
Total (Raw Materials) / kg	1,195	1,192	1,038	1,612
Secondary Materials	10	10	10	10
Personnel Expenses for Production	212	184	184	114
Power Expenses	114	94	94	56
Fuel	156	108	108	46
Utilities	172	172	172	97
Other Expenses for Production	40	40	40	40
Quality Control Expenses	39	39	39	39
Indirect Expenses for Factory Operation	55	55	55	55
Production Cost	1,994	1,895	1,740	2,070
*Investment for Facility Reinforcement	*1,421 Mil.	*565 Mil.	*565 Mil.	*575 Mil.
*Initial Investment	*2,660 Mil.	*2,660 Mil.	*2,660 Mil.	*2,660 Mil.
Depreciation Expense (7 Yrs / Straight Line)	583	461	461	462
General Administration Expenses (12%)	309	283	264	304
Total / kg	2,886	2,638	2,465	2,835
Gross Profit (5%)	144	132	123	142
Selling Price in JPY / kg	3,031	2,770	2,588	2,977
Selling Price in USD / kg	22.45	20.52	19.17	22.05

REMARKS:

SD: Spray Drying Process
 SSR: Solid-State Reaction Process
 USD 1.00: 135.00

Total Material Costs Break Down

February 20, 2002

Item	(3) - 1	(3) - 2 - A	(3) - 2 - B	(4) - 1	(4) - 2 - A	(4) - 2 - B
Product Grades	MA5005	MA5005	MA5005	M80	M80	M80
Process Methods	SD	SSR	SSR	SD	SSR	SSR
Production Cost Item						
Raw Materials						
Ni-metal	268			118		
Powdered Ni-Hydroxide			608			267
Powdered Ni0.45Mn0.5 Hydroxide		1,036				
Powdered Ni0.2Mn0.8 Hydroxide					953	
MnO2 (EMD)			182			250
Al Hydroxide		4	4			
Mn-Metal	45			71		
Aluminum Nitrate Nonohydrate	43					
85% Hydrogen peroxide	77			81		
67.5% Nitric Acid	64			67		
49% Sodium Hydroxide	21			21		
Li-Hydroxide Monohydrate	317	317	317	315	315	307
Total (Raw Materials) / kg	834	1,356	1,110	673	1,268	824
Secondary Materials	10	10	10	10	10	10
Personnel expenses for Production	184	114	114	184	114	114
Power Expenses	94	56	56	94	56	56
Fuel	108	46	46	108	46	46
Utilities	172	97	97	172	97	97
Other Expenses for Production	40	40	40	40	40	40
Quality Control Expenses	39	39	39	39	39	39
Indirect Expenses for Factory Operation	55	55	55	55	55	55
Production Cost	1,536	1,814	1,568	1,376	1,726	1,281
*Investment for Facility Reinforcement	*745 Mil.	*755 Mil.	*755 Mil.	*745 Mil.	*755 Mil.	*755 Mil.
*Investment for Maintenance	*2,660 Mil					
Depreciation Expense (7 Yrs / Straight Line)	487	488	488	487	488	488
General Administration Expenses (12%)	243	276	247	224	266	212
Total / kg	2,266	2,578	2,303	2,086	2,480	1,982
Gross Profit (5%)	113	129	115	104	124	99
Selling Price in JPY / kg	2,379	2,707	2,418	2,190	2,604	2,081
Selling Price in USD / kg	17.62	20.05	17.91	16.23	19.29	15.41

REMARKS:

SD: Spray Drying Process
 SSR: Solid-State Reaction Process
 USD 1.00: 185.00

8. Patent Analysis

(1) Objectives

To check the possibilities of infringing any U.S./Japanese patents relating to the 4 types of cathode materials of Lithium-Ion Secondary batteries planned to be produced by Fuji for the U.S. market.

(2) Area of Research

- A. Japanese Patent Office H.P. (1982-2002/2/15)
- B. PATOLIS DABA BASE (1982-2002/02/15)
- C. U.S. Patent Office H.P. (1790-2002/02/15)

(3) Results of Research

A. LiNi_{0.8}Co_{0.15}Al_{0.05}O_{1.985}(BO₃)_{0.01} (CA-5/CA-5F)

1. Identification of Li-Ni-Co Al-B complex oxide:

- (1) COMPOSITION: LiNi_{0.8}Co_{0.15}Al_{0.05}O_{1.985}(BO₃)_{0.01}
- (2) CAS REGISTRY No.: 207803-51
- (3) CA INDEX NAME: Aluminum boron cobalt lithium nickel oxide

2. FUJI PATENT AND PATENT APPLICATION:

Substance and Preparation

- (1) WO98/06670(Priority date 1996.Aug.12)
- (2) US SN. 09/242,308

3. Related Patent:

There might be possible infringement of the Patent owned by SEIKO ELECTRONIC COMPONENTS LTD. and MATSUSHITA ELECTRIC IND. Negotiation of the Royalty Payment might be required before the mass production of this product.

● Patent of SEIKO ELECTRONIC COMPONENTS LTD.:

(1) JP 3162437

LiNiCoAlB Oxide was eliminated from the claim area of original Pat. Application No. 5-54889

(2) US. PAT. 5,286,582

This patent has granted the claim of cathode material for secondary batteries.

● Patent of MATSUSHITA ELECTRIC IND CO., LTD. (A)

- (1) JP Application No. 08-031408 which includes the claim of LiNiCoAlB

Oxide.

(2) US. PAT. 5,609,975 (Filed: May 11, 1995)

Claim 1. A positive electrode for a non-aqueous electrolyte lithium secondary battery, which comprises a positive electrode active material represented by the general formula $\text{Li}_x\text{Al}_1-y\text{MyO}_2$ (A: Mn, Co, and Ni), (M: B, Mg, Ca, Sr, Ba, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Al, In, Nb, Mo, W, Y and Rh).

- Patent of MATSUSHITA ELECTRONIC IND. CO., LTD. (B)
JP 9-199127 A (Priority Applications Date: 19960119)

JP Application only

Claim: Positive electrode:

$\text{Li}_x\text{Ni}_{1-y}\text{MyO}_2$ ($0 \leq x \leq 1.2$, $0 < y \leq 0.5$, M: Ti, V, Cr, Mn, Fe, Co, Cu, Zn, Al, B, etc.),

The lithium compound oxide is composed of only a single crystal phase assigned to R-3m or C2/m in a charged condition single crystal phase.

B. $\text{LiNi}_{0.80}\text{Co}_{0.15}\text{Al}_{0.05}\text{O}_2$ (CA1505N)

1. Identification of Li-Ni-Co Al complex oxide:

(1) FORMULA: $\text{LiNi}_{0.80}\text{Co}_{0.15}\text{Al}_{0.05}\text{O}_2$

(2) CAS REGISTRY No.: 177997-13-6

(3) CA INDEX NAME: Aluminum cobalt lithium nickel oxide

2. FUJI PATENT AND PATENT APPLICATION:

Substance and Preparation

JP 3130813 B2 (Priority Applications Date 1995.11.24),

US SN.09/242,308

3. Related Patent:

There would be strong possibility of infringing the Patent of ASAHI KASEI. Negotiation of the Royalty Payment would be required before the mass production of this product.

- Patent of ASAHI KASEI:

US 4668595 A, US 34991 E (JP 92-024831 B2)

Secondary battery in a nonaqueous type:

A composite oxide possessing a layer structure.

General formula: Ax My Nz O_2 wherein A(alkali metal), M(transition metal), N(Al, In, Sn).

C. LiNi_{0.92}Ti_{0.05}Al_{0.03}O₂

1. Identification of complex oxide:

(1) FORMULA:

(2) CAS REGISTRY

(3) CA INDEX NAME: Aluminum cobalt lithium nickel titanium oxide

2. FUJI PATENT AND PATENT APPLICATION:

Substance and Preparation

(1) No patent application

3. Related Patent:

There would be possibility to infringe the Patent of MATSUSHITA ELECTRIC IND. Negotiation of the Royalty Payment would be required before the mass production of this product.

● Patent of MATSUSHITA ELECTRIC IND., CO., LTD. (A)

(1) JP Application No. 08-031408 which includes the claim of LiNiCoAlTi Oxide.

(2) US. PAT. 5,609,975 (Filed: May 11, 1995)

Claim 1. A positive electrode for a non-aqueous electrolyte lithium secondary battery, which comprises a positive electrode active material represented by the general formula $Li_xAl_{1-y}MyO_2$ (A: Mn, Co, and Ni), (M: B, Mg, Ca, Sr, Ba, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Al, In, Nb, Mo, W, Y and Rh).

● Patent of MATSUSHITA ELECTRIC IND., CO., LTD. (B)

JP 9-199127 A (Priority Applications Date: 19960119)

Application JP only

Claim: Positive electrode:

$Li_xNi_{(1-y)}MyO_2$ ($0 \leq x \leq 1.2$, $0 < y \leq 0.5$, M: Ti, V, Cr, Mn, Fe, Co, Cu, Zn, Al, B, etc.), The lithium compound oxide is composed of only a single crystal phase assigned to R-3m or C2/m in a charged condition single crystal phase.

D. LiNi_{0.45}Mn_{0.5}Al_{0.05}O₂ / LiNi_{0.20}Mn_{0.80}O₂

1. Identification of complex oxide:

(1) FORMULA:

(2) CAS REGISTRY No.:

(3) CA INDEX NAME:

a. Lithium manganese nickel oxide

b. Aluminum lithium manganese nickel oxide

2. FUJI PATENT AND PATENT APPLICATION:

Substance and Preparation

(1) WO97/19023(Priority Applications Date 1995.Nov 24),

(2) WO98/06670(Priority Applications Date 1996.Aug 12)

3. Related Patent:

There would not be any infringements to the patents of any third parties related to these products.

(4) Attachments

All patents related information included in the attached CD-ROM is listed in the next page.

PATENT LIST

Folder No.	FILE NAME	PAT No.	FILE	Assignee
1	<u>US 4668595</u>	US 4668595	rdf	ASAHI KASEI KOGYO KK
	<u>US 5631100</u>	US 5631100	tif	ASAHI KASEI KOGYO KK
	<u>US 5925482</u>	US 5925482	tif	ASAHI KASEI KOGYO KK
	<u>US 5989743</u>	US 5989743	tif	ASAHI KASEI KOGYO KK
	<u>US RE34991</u>	US RE34991	tif	ASAHI KASEI KOGYO KK
	<u>US 4668595</u>	US 4668595	tif	ASAHI KASEI KOGYO KK
2.3	<u>US 5169736</u>	US 5169736	pdf	VARTA BATTERIE AG
4	<u>US 5393622</u>	US 5393622	pdf	MATSUSHITA ELECTRIC INDUSTRIAL Co., Ltd.
	<u>EP 0554906</u>	EP 0554906	pdf	MATSUSHITA ELECTRIC INDUSTRIAL Co., Ltd.
	<u>JP 09-199127</u> ABSTRACT Eng.	-	txt	MATSUSHITA ELECTRIC INDUSTRIAL Co., Ltd.
FCI	<u>US 5648057</u>	US 5648057	pdf	FUJI CHEMICAL INDUSTRY Co., Ltd.
	<u>US 6045771</u>	US 6045771	pdf	FUJI CHEMICAL INDUSTRY Co., Ltd.
	<u>US 6325988</u>	US 6325988	pdf	FUJI CHEMICAL INDUSTRY Co., Ltd.
	<u>EP 0646546</u>	EP 0646546	pdf	FUJI CHEMICAL INDUSTRY Co., Ltd.
	<u>EP 0918041</u>	EP 0918041	pdf	FUJI CHEMICAL INDUSTRY Co., Ltd.
	<u>EP 1035075</u>	EP 1035075	pdf	FUJI CHEMICAL INDUSTRY Co., Ltd.
	<u>JP 2000149923 A</u>	2000-149923 A	lzh	FUJI CHEMICAL INDUSTRY Co., Ltd.
	<u>JP 2000302451 A</u>	2000-302451 A	lzh	FUJI CHEMICAL INDUSTRY Co., Ltd.
	<u>JP 96130013 A</u>	08-130013 A	lzh	FUJI CHEMICAL INDUSTRY Co., Ltd.
	<u>JP 97190818 A</u>	09-190818 A	lzh	FUJI CHEMICAL INDUSTRY Co., Ltd.
	<u>JP 98069910 A</u>	10-069910 A	lzh	FUJI CHEMICAL INDUSTRY Co., Ltd.
	<u>JP 98316431 A</u>	10-316431 A	lzh	FUJI CHEMICAL INDUSTRY Co., Ltd.
	<u>JP 99240721 A</u>	11-40721 A	lzh	FUJI CHEMICAL INDUSTRY Co., Ltd.
	<u>PAT 02729176 B2</u>	PAT 02729176 B2	lzh	FUJI CHEMICAL INDUSTRY Co., Ltd.
	<u>PAT 03130813 B2</u>	PAT 03130813 B2	lzh	FUJI CHEMICAL INDUSTRY Co., Ltd.

9. Summary

- 1 Comparing with "Solid State Reaction Process (Dry-Mix Method)", "Spray Drying Production Process (Wet-Mix Method)" superior in terms of total material cost if certain level of quality was required by the market.
- 2 Ideal total material cost as finished products shall be between \$11 - 23 depending on the quality, the composition, the cost of raw materials, the production process and the exchange rate.
- 3 There would be great potential to reduce the production costs of the cathode materials further by:
 - A. Making the long-term contract with raw materials' suppliers.
 - B. Utilizing cheaper materials available from China or Africa.
 - C. Simplifying the production process. (needs further experiments)
 - D. Increasing the production quantity.

10. Recommendations

Based on this study, Fuji strongly recommends to start the trial production of approx. 200 tons of cathode materials for the U.S. automobile industries with either CA-5 or CA-5F by the following reasons.

- 1 These 2 materials have been well-researched for a long time and recognized by the major battery manufacturers all over the world.
- 2 They have remarkable characteristics both in the capacity and the cycle performance.
- 3 Fuji has the immediate production capacity of 360 tons per annum, which will cover the consumption of approx.168,000 cars (2.14kg of cathode material in 1 car) in the market.
- 4 By utilizing "Wet-Mix Method", Fuji has capability of developing further improved products requiring further more dope of rare metals with nominal additional production cost.
- 5 Fuji has the capability of licensing its own products to the other manufactures of Nickel-base cathode materials to cover future necessity of the materials required by the market.

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