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Comparatively assessing different shapes of lithium-ion battery cells

Robert Schröder*, Muhammed Aydemir, Günther Seliger

Technical University Berlin, Institute for Machine Tools and Factory Management, Chair of Assembly Technology and Factory Managament. Pascalstrasse 8-9, 10587 Berlin, Germany

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Abstract

Different shapes of lithium-ion batteries (LIB) are competing as energy storages for the automobile application. The shapes can be divided into cylindrical and prismatic, whereas the prismatic shape can be further divided in regard to the housing stability in Hard-Case and Pouch. Within this paper, the differences in manufacturing costs and efforts as well as the shape related advantages and disadvantages for an automobile application are discussed. Additionally, the process steps for manufacturing the prismatic hard-case and the pouch cell are analyzed in terms of their individual value contribution to the manufacturing costs. Within the analysis, manufacturing errors can be allocated to specific process steps and economically quantified.

Keywords: battery production, manufacturing costs, sustainable production technology

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1. Introduction

Driven by the scarcity of non-renewable resources and the ecological effects of CO2-emissions, the automobile industry is focusing on sustainable mobility solutions, such as the electrical drive technology. However, uncertainties regarding the developments of demanded quantities, battery price and diversity of variants constitute major challenges for electro mobility. Crowding the conventional combustion engine out of the current portfolio of original equipment manufacturers within the next ten years is considered to be a possible conclusion of electrifying the power train [1]. With an increasing demand of Electric Vehicles, the relevance of lithium-ion battery (LIB) systems

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* Corresponding author. Tel.: +49 (0)30 314 25117; fax: +49 (0)30 22759.
E-mail address: schroeder@mf.tu-berlin.de

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as the main element of the power train increases as well [2,3]. Since the battery takes up around 30-40% of the value creation during the production of electric vehicles and around 60-80% of those costs are accounted for by the battery cell itself [4], a focus of the powertrain electrification is the cost efficient battery production [5]. This paper emphasizes the impact different shapes of LIB have on the manufacturing costs, effort and an automotive applicability.

2. Lithium-Ion Batteries

A galvanic cell can be divided into a primary, a secondary and a tertiary cell, whereas only the secondary cell is rechargeable. The secondary cell is an electrochemical element consisting of a positive (cathode) and negative (anode) electrode, a separator to physically separate the electrodes in order to prevent a short circuit, an electrolyte and a battery housing. The electrolyte realizes the charge transport between cathode and anode. A battery cell consists of at least one, usually more bundled secondary cells which are electrically connected with a tab to increase either the overall voltage or capacity. Several electrically connected battery cells are considered to be a battery system, which requires a battery management system to level the electrical properties of the different battery cells and a cooling system for the battery to be operated safely during different temperatures. Battery cells appear in different outer shapes. The shapes can be divided into a cylindrical and prismatic geometry, whereas the prismatic shape can be further divided according to the housing stability into the prismatic hard-case cell and the prismatic pouch cell [6]. The inner structure, the electrode-separator-compound, is different in terms of the material dimensions and the manufacturing processes used, see Fig. 1.

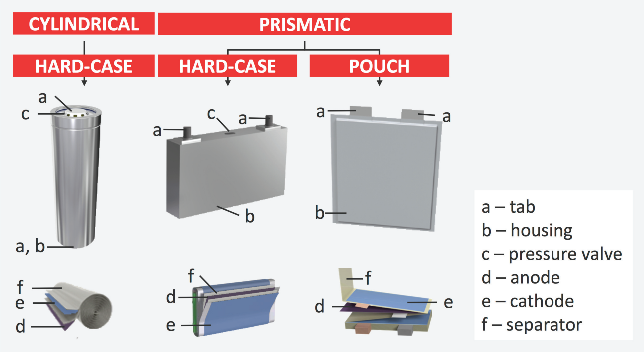

Fig. 1. Shapes of LIB. According to [7]

The classification according to Fig. 1 is chosen since the prismatic shape of a pouch cell is most commonly used. However, this classification might be misleading since pouch cells can be manufactured in a variety of geometrical shapes e.g. round or triangular [8]. The manufacturing process of LIB comprises the electrode, the cell and the battery system manufacturing, see Fig. 2.

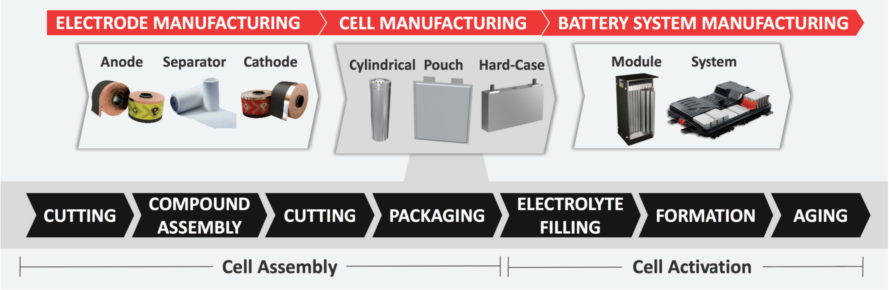

Fig. 2. Manufacturing of LIB

The electrode manufacturing provides the anode, cathode and separator material for the subsequent cell manufacturing. Within the cell manufacturing, the battery cells are assembled and electrically activated. The battery system manufacturing electrically connects the battery cells and implements a battery management system.

2.1. Manufacturing different shapes of LIB

The variety in the cell manufacturing process is characterized through the cell shape and the inner cell structure. The cell assembly comprises of cutting processes, the compound assembly and the packaging.

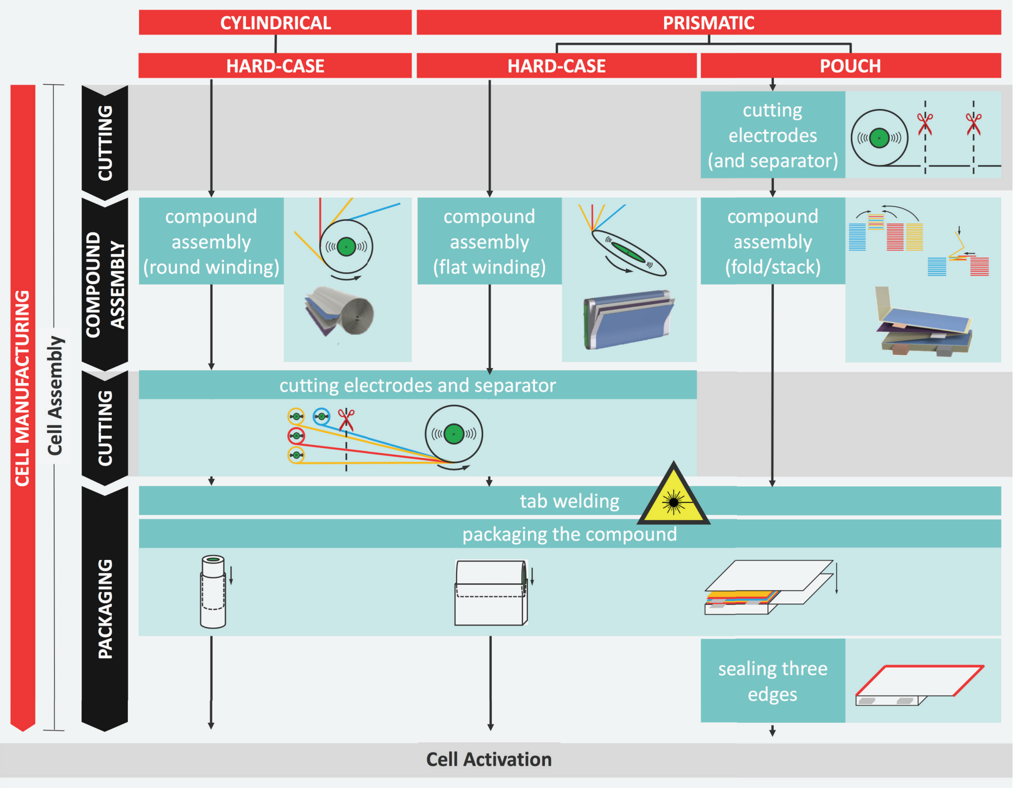

Fig. 3. Assembling different shapes of LIB

Whereas the compound for the cylindrical and the prismatic hard-case cell consists of uncoiled strip electrodes, the compound for the prismatic pouch cell consist of single sheets of electrodes. The materials for the cylindrical and the prismatic hard-case compound are wound, whereas the materials for the prismatic pouch cell are stacked onto each other. This fact explains the initial process step of cutting single sheets of electrodes required for manufacturing the pouch cell, as displayed in Fig. 3. Subsequently to the cutting process, the compound for the pouch cell can either be created by stacking single sheets of electrodes and separator onto each other or by creating a z-folded separator structure, in whose pockets the electrodes are placed [9]. The compound for the cylindrical and prismatic hard-case cell uses uncoiled strip electrodes and separator material, which are assembled using a winding procedure. The materials are cut subsequently.

The tab welding electrically connects the assembled electrodes using ultrasonic or laser welding and is required for all cell shapes and inner structures. The housings for cylindrical cells are made of an either rolled and subsequently welded steel plate or made of a deep-drawn aluminum plate, as is the housing for the hard-case cell. The housing for the pouch cell is a foil made of a deep-drawn aluminum-polymer-compound, a so called pouch foil. The housings are usually purchased parts.

Whereas the wound compounds need to be carefully joined with the rigid housing in order to prevent damages to the compound, the stacked or folded compound is simply inserted onto the lower half of a deep-drawn pouch foil, covered with the upper half and sealed at three edges. This process is comparatively less complex than packaging a wound compound. The remaining edge of the pouch foil is left open for the electrolyte filling process.

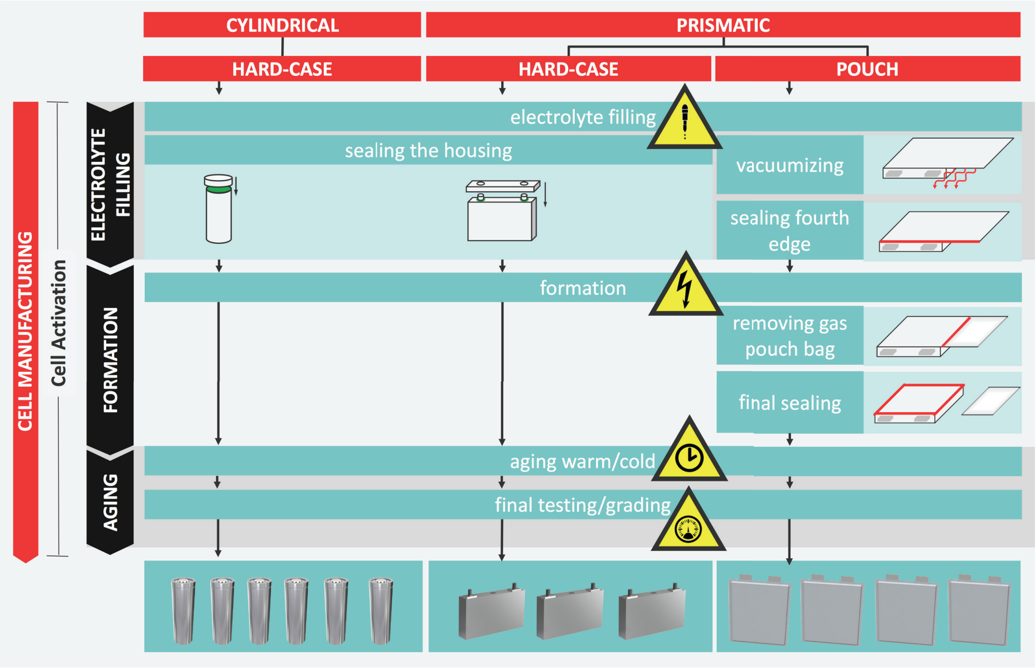

Fig. 4. Activating different shapes of LIB

The cell activation comprises of electrolyte filling, the formation as well as the aging, see Fig. 4. For all cell shapes the electrolyte filling is realized using an injection lance in order to meter the correct amount of electrolyte required. The housing for the pouch cell is subsequently vacuumed in order to force the electrolyte to percolate through the layers of the stacked or folded compound and the fourth edge is sealed. The housings for the hard-case and the cylindrical cell are ultimately sealed subsequently to the electrolyte filling process.

The formation is the initial charging and discharging process for the battery cell and is quite similar for the cylindrical, the hard-case and the pouch cell. During the formation process, gas formations and builds up within the housing. The DIN SPEC 91252 classifies the three shapes according to their housing design and format, the pole arrangement as well as the existence and absence of a pressure valve [10]. The pressure valve is required to release gas pressure and is existent with the cylindrical and the hard-case housing. The pouch cell relies on an additional attached pouch bag, designed to absorb the gas formation. The gas filled pouch bag is removed subsequently to the gas formation and the pouch cell is sealed.

The aging process takes place at different temperatures for up to 30 days and is the final process step of the cell manufacturing. It is designed to detect short circuits within the battery cell and to measure the performance and the properties of the battery cells. The cells are ultimately graded according to their performance and properties.

2.2. Comparative assessment

Following, the impact of the shape related manufacturing costs and efforts as well as application properties need to be considered. The assessment takes place under the following conditions:

- Battery cell characteristics
  - 3.7V, 50Ah, 0.185kWh
  - anode: graphene, cathode: nickel-manganese-cobalt (NMC)
  - cathode load capacity: 2.6mAh/cm^2
  - z-folded compound for pouch cell, wound compound for prismatic hard-case cell
- Production facility
  - production capacity: 0.6GWh per annum and 75% yield

The manufacturing costs comprise of material and production costs. The manufacturing efforts are structured into the process steps of the cell manufacturing and the application properties are structured into the energy and packing density as well as the cell safety, see Fig. 5.

The manufacturing costs for the cylindrical cell are characterized by established and robust processes and machinery. The manufacturing costs for the hard-case cell are characterized by complex processes and a variety of machinery due to the various compound designs. The compound designs vary in terms of their dimensions as well as the positions and design of the tabs. The manufacturing costs for the pouch cell are characterized by simple processes due to fewer components to be assembled in comparison to the hard-case and the cylindrical cell, which require additional insulation and pressure valves. Since fewer components are required for manufacturing the pouch cell, the material costs are considerably lower.

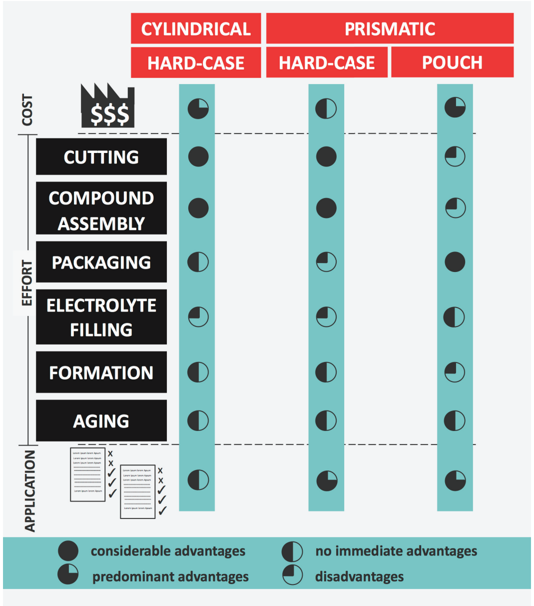

Fig. 5. Comparative assessment of different shapes of LIB

The process variety for manufacturing different shapes of LIB is reflected in the necessary manufacturing effort. The number of electrodes to be tailored for manufacturing a pouch cell is considerably higher in comparison to the cylindrical and the hard-case cell. Maintaining a high cutting edge quality without contamination is a challenging process step for manufacturing any cell shape. However, since fewer cuts reduce the risk of manufacturing errors, the pouch cell manufacturing process of cutting displays a disadvantage.

The compound assembly is a function of the effort required for tailoring the electrodes and the separator material. The amount of electrodes to be assembled significantly increases the cycle time for assembling a stacked or folded compound. The industrially used procedure is a pick-and-place operation, which is considerably less efficient than a high throughput winding procedure. Subsequently to the winding procedure, the wound strips of anode, cathode and separator material are cut altogether. Even though fewer cuts are necessary in comparison to the pouch cell cutting process, the error impact is higher for the wound compounds since more material is lost, if an error occurs.

Joining the round or prismatic wound compound with the deep-drawn housing is considerably more complex due to the high requirements on the dimensional accuracy of the compound and the housing as well as the accompanying risk of damaging the compound during the joining. The packaging of the pouch cell is considerably less complex since the compound is simply positioned onto the lower half of the pouch foil and subsequently covered with the upper half. The sealing of the pouch foil is a robust and simple process step. The electrolyte filling process requires more effort for the wound compounds since the percolation of the electrolyte into the compound and the wetting of the layers requires considerably more time due to the firmly wound structure. The forming process is required for each shape and represents an identical effort. However, the removal of the pouch bag due to gas formation represents an additional process step, which is not required for the cylindrical and the hard-case cell. The aging process represents an identical effort for each shape of LIB.

The energy density is the amount of energy stored in a given system per liter or per kilogram. In comparison to the pouch cell, the housings for the cylindrical and hard-case cell are heavier. This leads to a reduced energy density. Additionally, the stacked or folded compound design, as used for the pouch cell, manifest a higher volumetric and gravimetric energy density, which represent attractive attributes for an automotive application. Due to the round shape, the packing density of electrically connected cylindrical LIB is lower than the packing density of prismatic LIB. In terms of safety, the housing stability of the cylindrical and the hard-case cell is considerably higher than the pouch cell housing, which requires additional housing stability as part of a battery system. Although being an additional component to buy and to assemble, the pressure valve displays a crucial advantage in terms of operational reliability for the hard-case and the cylindrical cell.

3. Value contribution of manufacturing processes

This value creation analysis compares the prismatic wound hard-case cell with the folded pouch cell and is structured into the production and the material costs. In order to quantify the value creation of the process steps according to Fig. 2, the failure costs are declared separately. Failure costs represent manufacturing errors within each process step. The economic influence of an error is quantified by accumulating the material and the production costs to the process step under examination.

In order to quantify the failure costs, the manufacturing errors, respectively the error rates for each production step, are defined according to a six-sigma scale [11]. The basis for the error rates is a sigma level of three, which is equal to 6.7% and adapted for each production step according to the findings of the comparative assessment.

3.1. Comparing the pouch cell with the prismatic hard-case cell

Fig. 5 displays the value contribution within the process steps according to Fig. 2 of the prismatic wound hard-case cell and the folded pouch cell. Each process step comprises of an individual amount of production, material and error costs. The value contribution during cutting is higher for the hard-case cell because the separator material is allocated with the cutting process, since electrodes and separator are wound simultaneously. In contrast, the cutting process for the pouch cell comprises of cutting single sheets of electrodes which reasons the allocation of the separator material to the compound assembly process. Differentiations in error rates originate from the amount and the impact of cuts carried out. Even though the number of cuts necessary for the pouch cell is significantly higher in comparison to the hard-case, the impact of manufacturing errors is significantly higher with the hard-case cell due to a higher material loss, if an error occurs.

The difference between the value contributions of the hard-case compound assembly and the pouch cell is due to the aspects mentioned above as well as the discrepancy in process efficiency. The continuous winding procedures are industrially established and significantly more efficient than the folding procedures, which rely on sequential pick-and-place operations. The packaging process for the hard-case cell is more complex due to the high joining requirements and the electrolyte filling and the accompanying higher risk of manufacturing errors. Forming and aging differ only marginal. Fig. 6a displays the manufacturing cost break down for material, production and error costs.

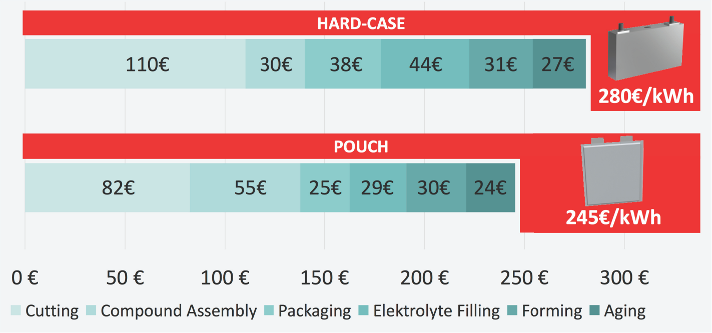

Fig. 5. Comparing the value contribution within the process steps of cell manufacturing

Considering differences in the manufacturing process and shape related advantages and disadvantages, the manufacturing costs are 245€/kWh for the pouch cell and 280€/kWh for the hard-case cell. These values are consistent with prognosis of the M+W GROUP, which state current manufacturing costs of 265€/kWh [12]. The error costs represent about 26% of the total manufacturing costs, which equals to 64€/kWh for the pouch cell to 78€/kWh for the hard-case cell. The error costs display the amount of production and material costs for each process step, which are lost due to manufacturing errors within the individual process step. In general, the later the error in the process chain occurs, the more its economic influence on the manufacturing costs. Since the error costs represent lost material during the manufacturing process and the production yield is set to 75% of 0.6GWh/a, additional material has to be calculated for in order to compensate for lost material.

Assuming a quality rate of a sigma-level three, the error costs accumulate to 26-28% of the overall manufacturing costs. Changes to the production environment can significantly influence the manufacturing costs. Assuming an increased maximum production capacity of 1GWh/a, 85% yield and a sigma level of four, economies of scale, quality improvements and an increased efficiency of manufacturing processes will come into effect and reduce the manufacturing costs by more than 30%, see Fig. 6b. This value is consistent with current market price prognosis of LIB [12].

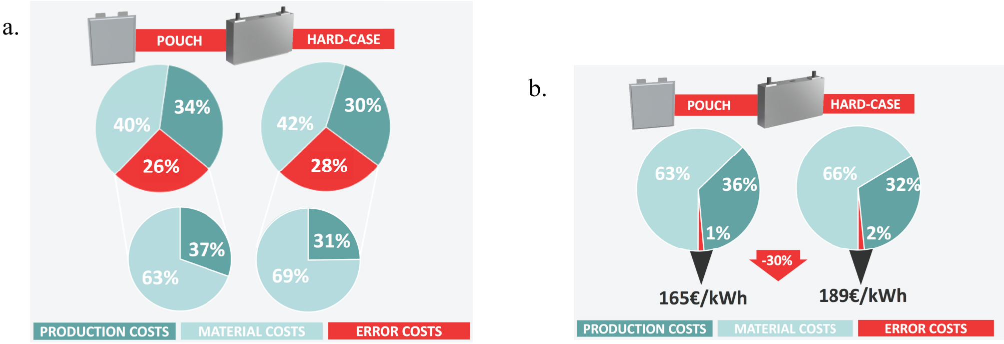

Fig.6: (a) Manufacturing cost break down with separately declared error costs, (b) Significantly reduced manufacturing costs through changing the production environment

The increase in production capacity and yield leads to an increased ration of material costs to production costs. The production becomes more efficient due to process and quality improvements. Economies of scale can be traced back to e.g. reduced overhead costs per kWh and a stronger negotiating power for the purchasing department, since more material is purchased.

4. Summary and conclusion

This paper gave a detailed overview on the advantages and disadvantages of different shapes of lithium-ion batteries. It was shown, that the outer shape and inner cell structure highly influence the manufacturing process and its costs. The three shapes of cylindrical, prismatic hard-case and prismatic pouch were comparatively assessed according to their manufacturing costs and effort as well as their industrial potential in terms of an automobile application. Especially the pouch cell has distinctive advantages in terms of energy and packing density as well as manufacturing costs. However, current manufacturing processes for assembling the folded and stacked compound structure are inefficient due to their sequential pick-and-place operations. The subsequent value creation analysis emphasized the economic impact of inefficient manufacturing processes as well as the significant influence of manufacturing errors on the overall manufacturing costs. Changes to the production environment, such as increasing the maximum production capacity, improving process efficiency and quality can significantly lower the manufacturing costs.

Process stability in terms of minimizing manufacturing errors has to become the primary objective when realizing a competitive production facility for LIB. Manufacturing processes need to increase productivity in order to meet the market demands on high quality and competitive LIB. Especially the pouch cell manufacturing has weaknesses in terms of high-speed cutting and increasing the throughput of assembling a stacked or folded compound. Turning away from time consuming sequential pick-and-place operations through the development of a continuous separating and quality assuring of electrodes as well as a continuous folding of separator material are promising approaches for significantly increasing process efficiency and simultaneously decreasing manufacturing costs [7].

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