NIST Advanced Manufacturing Series
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Reference model for lithium-based traction battery recovery

NIST TLB-R Model

Matthew J. Triebe
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Abstract

Traction batteries, or electric-drive battery pack systems, rely on critical minerals and materials vulnerable to supply chain disruptions. Recovery strategies, including recycling, reduce reliance on virgin materials and bolster domestic inventories. Therefore, stakeholders across the traction battery supply chain are coordinating to transform existing material flow systems. NIST developed the Traction Lithium Battery Recovery (TLB-R) model to support these efforts. This baseline, open-source reference model can be used as a common framework for understanding the technical processes and potential data requirements of battery recovery. By providing an abstract, unified point of reference, the TLB-R model enables stakeholders to identify new opportunities, inform strategic decision-making, and support innovation and communication within the emerging lithium battery recovery industry.

Keywords

Critical minerals; Critical materials; Traction lithium batteries; IDEF0; Recovery; Reference model.

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Acknowledgments

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Author Contributions

Matthew J. Triebe: Conceptualization, original draft preparation, editing, model development, and software validation.

Jamie L. Weaver: Conceptualization, draft preparation, editing, reference collection, and model development.

KC Morris: Conceptualization, draft preparation, editing, and model development.

1. Introduction

Materials such as cobalt (Co), lithium (Li), nickel (Ni), graphite, copper (Cu), and manganese (Mn) are important to emerging technologies and have a risk of supply chain disruption [1]. Because of this, these materials are on the USGS's list of critical minerals and the DOE's list of critical materials [2]. These two lists and their combined tabulated materials will herein be described as critical minerals and materials (CMMs). The extensive use of these materials in U.S. industries, including Electric Vehicle Batteries (EVBs), creates an opportunity to recover CMMs from end-of-life (EOL) products to supplement the domestic supply [3, 4].

EVBs have reached broad commercialization over the last several decades. Their technology is rapidly evolving, and currently includes a range of predominantly lithium-based (e.g., Li-ion) battery chemistries [5–8] that contain at least one or more CMM. The newness of EVB technology and its relatively long use lifespan (> 15 years) has resulted in slow, but increasing, development of an EVB recovery and recycling industry in the U.S. [9]. In recent years, the U.S. has scaled up efforts to build lithium-ion battery recycling centers. However, domestic recycling remains relatively small-scale, with literature estimating that only 5% to 10% of U.S.-based EV batteries are currently recycled [10–13]. Additionally, replacing old electric vehicle (EV) lithium batteries with remanufactured ones instead of new batteries in vehicles has become more common among original equipment manufacturers [14]. Similarly, there have been examples of EVBs being repurposed for energy storage [15, 16], an application that is forecasted to expand in the near future [17].

The Traction Lithium Battery Recovery (TLB-R) model presented in this report is an abstraction of the technical processes that may be used to recover, extend the life of, or facilitate the recycling of EOL traction batteries. SAE J2289 [18] defines a traction battery as a "rechargeable energy storage device consisting of battery modules or cells, designed to supply power to propel electric drive systems in vehicles." EVBs are covered by the TLB-R model. This model provides a common point of reference that collates new technologies and research surrounding the emerging lithium battery recovery/recycling industry. It may facilitate coordination of battery recovery research. Businesses may use and adapt this model for decision-making activities. Standards development organizations may use the model to build consensus, discover new stakeholder communities, and map technical standards development activities.

This model was developed using the Integration Definition 0 (IDEF0) language, which is defined by ISO/IEC/IEEE 31320 [19]. This modeling language is used to illustrate functions within a system or subject area and represents activities in terms of inputs, outputs, controls, and mechanisms. This form of modeling also supports abstraction, where each activity can be decomposed into a subset of activities, enabling users to consider activities and their interactions at differing levels of detail. The IDEF0 model is browsable online at NIST [20] and for individual use [21].

This report is outlined as follows. Related work is reviewed, followed by a description of the IDEF0 modeling language. An overview of the model is then provided. The activities within the model are described. The report concludes with a summary and identifies future directions. An annotated bibliography and terms can be found in Appendix A; more descriptions of IDEF0 models developed by NIST can be found in Appendix B; a decomposition table of activities within the model is in Appendix C; and a list of acronyms is in Appendix D.

2. Related Work

Other publicly available efforts map out the recovery of EVBs, but most do not provide a detailed literature-based, multi-level resolution presented here. This model builds upon prior studies that detailed distinct stages of the battery lifecycle. For example, Chen et al. [15] and Neumann et al. [22] informed the collection stage, Zhu et al. [23] and Montes et al. [24] informed the test and sort activity, and Foster et al. [25] and Garole et al. [26] informed the recover materials/devices activity. For the broader recovery activities of repurpose, remanufacture, and recycle [27], this work built upon Werner et al. [28], Zhu et al. [23] and Chen et al. [15] for repurpose, Canals Casals et al. [29] and Foster et al. [25] for remanufacture, and Chen et al. [15], and Gaines [30] for recycling.

Additional model parameters were researched through consultations with industrial trade organizations and U.S.-based stakeholders, an analysis of the 2023 Argonne National Laboratory EverBatt supply chain model [31] (the baseline mechanisms of which are described in Dai et al. [32]), the SAE J3327 Electric Vehicle (EV) Battery Traceability Record [33], and a review of NIST lithium battery research activities over the last decade [34]. A detailed breakdown of the literature supporting this multi-level model is provided in the annotated bibliography in Appendix A.

The IDEF0 modeling language used to develop the TLB-R model is part of a broader suite of languages called IDEF and was developed under funding from the U.S. Air Force. It has been widely used by the military and other U.S. Department of Defense agencies [35] as well as in international standards specifications [36]. IDEF0 is applied for systems engineering, business process engineering, manufacturing planning and modeling, project management, and other areas [37]. The IDEF0 modeling language was chosen for this application because it provides a standardized method for illustrating functions within a system or subject area in terms of inputs, outputs, controls, and mechanisms. The IDEF0 modeling language supports activity abstraction, where each activity can be composed of a subset of activities. This feature allows others to build upon this model for their own purposes.

NIST has developed several IDEF0 models that provide the foundation for the TLB-R model. More details on these models can be found in Appendix B. These IDEF0 models include the *Systems Integration of Manufacturing Applications* (SIMA) Reference Architecture [38], the GreenSIMA model [39], and the *Smart Manufacturing Reference Architecture* (SMRA) [40]. The SIMA model focused on manufacturing activities, and the GreenSIMA and SMRA models were built on SIMA. Recently, NIST developed the *Production in a Circular Economy* (PCE) model [41–44] to describe the activities and flows of materials and information in a Circular Economy (CE). The PCE model was expanded to include more detail for design [43] and EOL [44]. The TLB-R model presented in this report focuses on treatment at EOL, corresponding to the *Treat at End of Life* (A5) activity in the PCE model. The TLB-R model presented in this report was first proposed in Triebe et al. [45] and has been adapted from the PCE model.

3. IDEF0 Modeling Language

IDEF0 is a functional modeling language that represents the activities and decision points within a system. The format of the modeling language is shown in Fig. 1, where boxes represent functions or activities, and inputs, outputs, controls, and mechanisms are depicted by arrows, as defined by ISO/IEC/IEEE 31320 [19]. Note that arrows can be tunneled, meaning they feed into an activity but are left undrawn in the activity's decomposition, so as not to provide further information on that arrow. Each function has a function name in the middle of the box and a function number at the bottom right. Functions with shadows can be decomposed into sub-activities to provide more detail on that function. The function transforms the inputs into output flows. The controls define conditions to ensure the correct outputs are generated, and the mechanisms are the methods and means to complete the function.

One key feature of IDEF0 modeling is its support of abstraction. Users can decompose each function into a subset of functions to provide more detail on the activities that comprise that function. The function number allows for tracing functions throughout decompositions within the model. For example, from the model described in this report, A31: Repurpose is an activity within A3: Recover, and A313: Send for New Application is an activity within A31: Repurpose.

The model described in the report can be found on the model website [20][1].

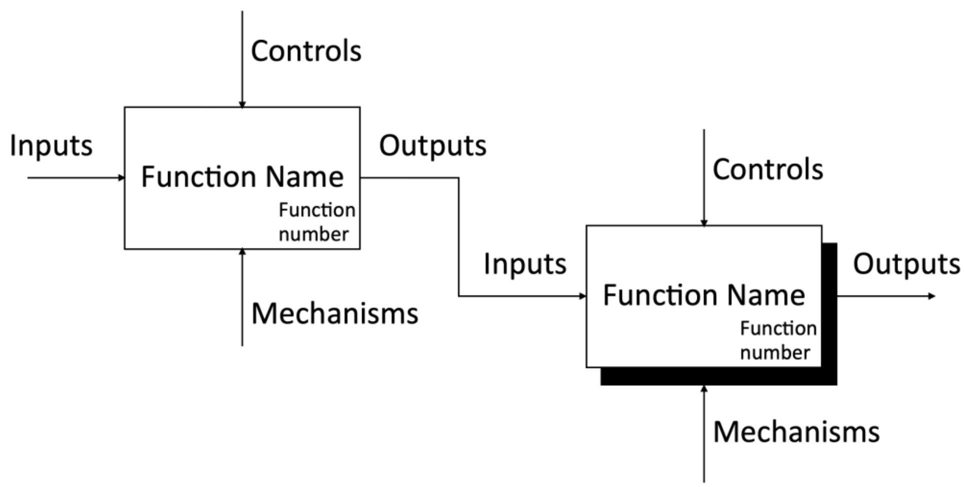

Fig. 1. IDEF0 guide

[1] It may be helpful to consult the online model while reading through this report. To open the model, select the "Treat Traction Lithium Batteries at End-of-life" link in the sidebar on the left side of the screen. This opens the model's top level. Then, clicking on an activity opens the description. Scrolling down provides a link to the activity decomposition, where more details about the sub-activities are available. Further instructions can be found using the "How to Navigate" link in the sidebar on the left side of the screen

4. Overview of the TLB-R Model

The reference model presented outlines general, abstracted activities involved in recovering value from EOL traction lithium batteries (TLBs) or associated manufacturing scrap. In this context, recovery includes either repurposing or remanufacturing TLBs to extend their lifespan or utility or recycling them or scrap to recover materials of value (e.g., CMMs). This reference model aims to clarify key recovery activities and suggest potentially useful information required to carry them out. While the model acts as a stylized abstraction of complex, real-world processes, its multi-level architecture is designed to be modular; users can add, remove, or redirect activities to reflect specific operational requirements.

An example of a traction lithium-ion battery construction is shown in Fig. 2, where the basic building block is an electrochemical cell. This figure shows a prismatic cell; however, cells may also be cylindrical or pouch geometries. Several cells are assembled into a module, and multiple modules may be used to make up a pack. Some battery designs do not have modules; this type of design is called a cell-to-pack battery. The battery system consists of a pack and other components that control or assist in operating the battery. These include the battery management system (BMS), thermal management system, and battery housing.

As TLB recovery and recycling is a relatively new and evolving industry in the U.S., it involves a diverse array of stakeholders with various areas of expertise and perspectives [46]. The TLB-R model aims to facilitate the coordination of research and recovery initiatives by providing a common point of reference for these stakeholders. This section guides interested parties through the model and provides descriptions for each activity. A decomposition table of the activities is in Appendix C, and an annotated bibliography with brief descriptions, key term definitions, and references to consensus-developed standards and peer-reviewed articles on each activity is in Appendix A. Acronyms used throughout the report are listed in Appendix D.

To assist users in navigating the framework, individual activities within the TLB-R are supplemented with contextual references and clarifying annotations where applicable. These supplemental materials include consensus standards, harmonized definitions, and relevant literature intersecting with the designated activity. Of note, not all activities include this additional content.

Potentially applicable standards were identified through a combination of stakeholder consultations, including both industry and other federal agency technical experts, and targeted keyword queries across the digital repositories of several large standards-developing organizations, including ISO, SAE, UL, ASTM, IEC, IEEE, ASE (Automotive Service Excellence), FMVSS (Federal Motor Vehicle Safety Standards). Database and registry searches utilized combinations of the following technical terms: lithium battery, Li-ion battery, electric vehicle, traction battery, recycling, refurbishment, repurposing, remanufacturing, recovery, hydrometallurgy, pyrometallurgy, circular economy, and second life. These standards database searches were conducted between April 2025 and September 2025. To ensure broad coverage of the rapidly shifting regulatory landscape, a complementary scoping review of gray literature and U.S. federal regulations was executed via structured web-based search engines using the same keyword matrix prior to publication of this document.

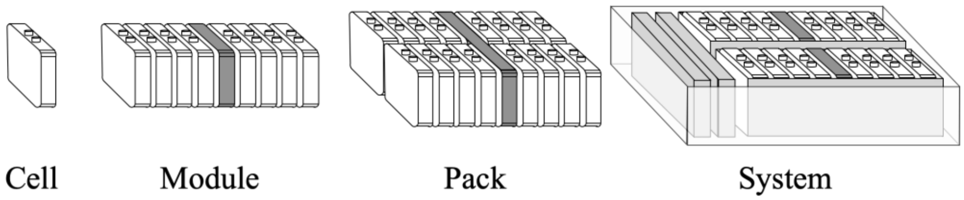

Fig. 2. Example of a traction battery construction

A0: Treat Batteries and Battery Materials

The initial steps of recovery are found in the top level of the model (see Fig. 3, starting at **A0**) and include the sub-activities of feedstock collection, including EOL batteries, battery manufacturing scrap (material left over from product production [47]), battery data, etc., (**A1**), the testing and sorting of the feedstock (**A2**), and the recovery step (**A3**). These sub-activities are summarized in Fig. 4. The main purpose of this level is to collect and sort feedstock for the recovery activities identified in activity **A3** (Repurpose (**A31**), Remanufacture (**A32**), and Recycle (**A33**)). Outputs of the model include Battery Materials, Waste, Data, Other Byproducts, and Recovered Batteries. Battery Materials consist of materials recovered during recycling that can be used in new batteries. Waste consists of recycling waste (e.g., wastewater organic waste) and rejected batteries and components that cannot be safely recycled. Data can include end-of-life treatment data that can inform recovery process improvement and design. Other Byproducts include unusable battery components (e.g., battery housing, wires, fasteners) that cannot be recycled into battery materials but can be recycled or reused using other processes. Recovered Batteries include batteries that can be redeployed as traction batteries or deployed in other applications such as energy storage. The controls for the model include Capital/Operating Expenditure, Governmental or Documentary Controls, Supply Chain and Materials Availability, Technology, and Safety Constraints. The control Technology includes Technology Availability, Product Design, Battery Chemistry, and Equipment Overhead. The mechanisms for the model include Infrastructure, Expertise, and Transportation.

A1 and A2: Collect, Test, and Sort

The **A0** activity comprises three sub-activities. Collection (**A1**) includes the process of gathering and transporting feedstock to a sorting facility for further processing [48]. Testing and sorting (**A2**) may include screening, classification, and performance diagnostics of feedstock by chemistry, degradation level, or electrochemical state (batteries). This step is important for identifying feedstock that meets requirements for refurbishment or repurpose activities or should be diverted to recycling for material recovery (**A33**). While screening is often exploratory, technicians conduct testing on individual batteries for safety and performance evaluations, such as electrochemical tests, ultrasound, or direct observation, to determine if a unit is suitable for the Repurpose (**A31**) or Remanufacture (**A32**) activities. Finally, **A3** covers the recovery of materials and devices from these input streams, as described in more detail below.

A3: Recover Materials/Devices

Following the testing and sorting activity (**A2)**, batteries enter the **A3** stage and proceed through one of three recovery avenues: Repurpose (**A31**), Remanufacture (**A32**), or Recycle (**A33**) (see Fig. 5). In some cases, the battery will be found unusable for all three follow-on activities and will be sent for disposal (labeled Waste in Fig. 4).

A31: Repurpose

This activity outlines the steps to repurpose a TLB for another application (see Fig. 6). In this context, repurposing is defined as adapting a product or its components for a function other than that originally intended, without implementing major modifications to its physical, chemical, or mechanical structure [36]. This pathway is designated for batteries that retain remaining useful life (RUL) but no longer meet the high-performance requirements of an EV. Instead, these units are transitioned to applications better suited to their as-accepted functionality, such as stationary energy storage. The process is divided into three core activities: Preparation (**A311**), Repurposing (**A312**), and Sending for a New Application (**A313**).

A311: Prepare Battery for Repurposing

Preparing the battery (see Fig. 7) for repurposing often begins with battery performance testing, which may include a safety check and electrochemical discharging (**A3111**) or placing the battery into a safe state and then assessing its functionality (**A3112**). Discharging (**A3111**) is the controlled depletion of stored energy to a pre-defined amount in an electrochemical cell/battery. Under this context (which can be different from the contextual use of the word under the recycling activity described below), the discharge is completed electrochemically, via a load connection. This pre-defined amount is sometimes described as a deep depth-of-discharge (DOD) and is a complement (or additive inverse relative to 100%) to a battery's state of charge (SOC).

A312: Repurpose Battery

Mechanical and electrical repair and testing of recovered lithium traction batteries are covered in this step of the Repurposing activity (**A312**). The battery repurposing activity (see Fig. 8) consists of repairing (**A3121**) and testing with a BMS or an interfaced control system (**A3122**). Compliance with standards, regulations, and industry's best practices is important to verify that safety and repurposing benefits are fully realized.

A3121: Repair Battery

This activity outlines the steps to repair, reconfigure, and reintegrate a recovered battery into a TLB (see Fig. 9). Following a safe discharge (**A3111**), the battery is disassembled (**A31211**) to identify, replace, or repair (**A31212**) faulty and worn components [49]. Technicians recondition (**A31213**) parts of the battery and test them, then reassemble (**A31214**) them into the product and test it again. Reconditioning (**A31213**) the battery refers to an industrial process that returns a used product or component to a satisfactory performance level when made available on the market as a used product [49]. According to the cited ISO definition for reconditioning, reconditioning is synonymous with refurbishing, and this generally involves more extensive processes than for repair. In this case, reconditioning/refurbishing is utilized to describe the process required to bring a part or component (e.g., cell) back to marketable utility, and that will be used to repair a full battery. Reconfiguring, e.g., changing the physical connections of cells within a battery, may occur at this step to further optimize the device's performance. If the product passes predefined tests, it is recharged to a defined level for storage, transportation, or other desired application(s).

A3122: Test Battery with Battery Management System

After the battery is repaired and reconfigured, reconnection and testing are completed on the battery management system (BMS) (see Fig. 10). The BMS is the electronic device that controls or manages the electric and thermal functions of the battery system [50]. It also provides communication between the battery system and other vehicle controllers. Evaluating the BMS, which can also occur during battery repair, may include testing the thermal behavior of the system (**A31221**), testing the BMS itself for faults or defects (**A31222**), and then evaluating the safety and compliance of the BMS (**A31223**). The thermal test (**A31221**) evaluates a system's performance and safety under various temperature conditions, including extreme heat, cold, or rapid temperature changes, to ensure its reliability, longevity, and suitability for its intended use [51–53]. Safety and performance tests (**A31223**) may be conducted to meet business or industry standards, or regulatory requirements relating to the batteries' new application. See A31223 in Appendix A for more information on standards related to safety and performance testing.

A313: Send for New Application

Sending the battery for a new application (see Fig. 11) starts with reconfiguring the battery (**A3131**) [54], following the methods and using electronics or devices that make the repurposed device fit for the new application. The activity may conclude with a final certification phase (**A3132**); this may utilize the same advanced methods identified in **A2**—such as electrochemical analysis, observation, and ultrasound—to verify the safety and integrity of the repurposed unit [55].

A32: Remanufacture

This activity details the steps to remanufacture a TLB (see Fig. 12), which is an industrial process by which an item is returned to a like-new condition from both a quality and performance perspective [36]. While similar to repurposing in its use of repairs, remanufacturing specifically restores batteries for use in electric vehicles rather than secondary applications. Remanufactured batteries must retain a high RUL to satisfy EV performance requirements. The process is divided into three core activities: Preparation (**A321**), Remanufacturing (**A322**), and Installation (**A323**).

A321: Prepare Battery for Remanufacturing

This activity is the first of three involved in remanufacturing TLBs (see Fig. 13). Preparing the battery consists of discharging (**A3211**), assessing (**A3212**), and disassembling (**A3213**). During this step, assessing (**A3212**) entails a targeted evaluation of individual cells, modules, or packs, or a mixture thereof, to determine their specific remanufacturing needs. While the overall feasibility of this pathway is established during the initial Test and Sort (**A2**) activity, this targeted assessment confirms which components are suitable for EV reuse.

A322: Remanufacture Battery

During this step, damaged components are replaced or repaired (**A3221**), and the battery unit is made into a "like-new" state (see Fig. 14). The process concludes with battery reassembly and validation (**A3224**). To ensure the battery meets the requirements for EV reintegration, the validation follows the safety and screening protocols outlined in Activity **A2**, utilizing diagnostic methods such as electrochemical analysis and (on a rare basis) ultrasound.

A323: Install Battery

The final stage of remanufacturing involves the physical and digital reintegration of the battery into the vehicle (see Fig. 15). The unit is secured to the frame (**A3231**)—the structural component used to mount battery modules/packs and removable elements like the BMS [56]—and connected to the software interface(s) (**A3232**) to enable diagnostic communication between vehicle systems [57]. Final reconditioning (**A3233**) and reconfiguration (**A3234**) (such as integrating the BMS) ensure the battery is optimized for its specific EV application. The process concludes with a final certification/testing phase (**A3235**) to verify that the fully integrated system meets all safety and performance technical requirements.

A33: Recycle

This activity outlines the recovery of materials from TLBs as illustrated in Fig. 16. Recycling is defined as the transformation of waste or scrap into reusable materials, whether or not they retain their original form [58]. TLB recycling may consist of a pretreatment step (**A331**), Pyrometallurgy (**A332**), and Hydrometallurgy (**A333**) [59]. However, some recycling processes, specifically pyrometallurgical processes, may not have a pretreatment step. There are also recycling processes in which battery materials undergo both pyrometallurgical and hydrometallurgical steps [59]. Beyond these methods, direct recycling offers a specialized alternative by retaining the chemical structure of select battery materials. Direct recycling is still in the research and development phase and not yet commercialized. Therefore, it is not included in this model, but, while not detailed here, this approach is explored in Gaines et al. [60].

A331: Pretreat Battery

The first step in recycling a TLB is pretreatment of the battery (see Fig. 17). Pretreatment may occur before hydrometallurgy, pyrometallurgy, or other chemical separation and purification activities. This activity consists of discharging the battery (**A3311**), disassembling (**A3312**), or mechanically or chemically pretreating the battery material (**A3313**). Pretreatment (**A331**) may include additional disassembly activities, electrolyte removal, cryogenic treatment, shredding, sieving, heating, milling, washing, etc., and may include additional sorting and separation steps. The disassembly step (**A3312**) may include a chemical neutralization step. Discharging a cell or battery is a reversible process (e.g., the chemical potential transfer mechanism remains intact, and the device can be recharged at a later time), whereas neutralization is a non-reversible process where the chemical potential of the cell or battery is rendered inert. Neutralization can also be referred to as deactivation or discharging in literature. The mechanical or chemical pretreat step (**A3313**) is completed to reduce the size and heterogeneity of materials, further sort battery materials and cells, and/or improve the materials' state-of-safety. This activity may also include a neutralizing step. Pretreatment (**A3313**) may result in the formation of black mass (also known as black powder, black sand, etc.), which is material that can undergo hydro- or pyrometallurgical activities [61].

A3313: Mechanically/Chemically Pretreat Material

This activity focuses on reducing material size and heterogeneity to enhance safe handling and facilitate effective sorting (see Fig. 18). The process may begin with size reduction and stabilization techniques such as shredding (**A33131**)—which uses wet, dry, or vacuum environments to tear and downsize materials into smaller fragments or pieces [49]—and crushing or grinding to fracture solids into finer particles (**A33133**) [62, 63]. This stage may also include calcination (**A33132**), a high-temperature heating process designed to remove carbon dioxide and moisture without fusing the solid mass [64]. This process may be called "binder burnout", pyrolysis, or thermal binder decomposition if conducted under inert conditions with the goal to remove binders or organic solvents. The process then moves to material separation (**A33134**), which can include: froth flotation (utilizes chemical reagents and air bubbles to float specific fine materials) [65]; electromagnetic separation (employs permanent magnets or eddy currents to isolate ferrous and non-ferrous metals) [66]; sieving/screening (partitions particles by size via vibratory or rotary action) [67]; and air classifying (sorts components by density using directed air streams). The final phase of this activity (**A33135**) involves the treatment of off-gases and waste streams generated during these mechanical and chemical operations.

A332: Pyrometallurgy

Pyrometallurgy is centered around high-temperature extractive techniques—including roasting, smelting, and refining, with the goal of isolating metals from waste/recovered material streams (see Fig. 19) [68]. The process begins with thermal conditioning (**A3321**) to enhance recovery rates; this includes roasting to produce oxides [69], calcination to drive off volatile organics and moisture [64], and sintering, which bonds particles below their melting point to increase structural strength [70]. The core extraction occurs through pyrolysis (**A3322**), the thermal decomposition of materials [59], or smelting (**A3322**), which applies intense heat to produce molten metal [64]. Following these high-heat stages, the process integrates chemical recovery steps, including leaching (**A3324**) to treat the material with liquid solvents, biological agents, or microbial species to extract metals [71], while final oxidation (**A3325**) or sintering/screening (**A3326**) phases refine the output into high-purity materials. This process recovers metals (Co, Ni, Cu) in metallic alloy phase(s), while Li and Mn will partition to the slag [68].

A3323: Treat Gas for Pyrometallurgy

Pyrometallurgical operations generate gases that may need to be treated prior to waste release (see Fig. 20). The process entails filtering the gas stream (**A33231**), leaching the captured solids (particulates, **A33232**), and precipitating specific elements for recovery (**A33233**). In the context of EV battery recycling, this process is particularly significant as it serves as a potential pathway for recovering Li in the form of lithium carbonate from the particulates.

A333: Hydrometallurgy

Hydrometallurgy serves as another method for material recovery from TLBs, utilizing aqueous solutions and water-based chemical reactions to extract and purify metals (see Fig. 21). Often used in tandem with pyrometallurgy to maximize recovery rates, this process involves several specialized steps: it begins with leaching (**A3331**), where liquid solvents treat the battery material to dissolve minerals [71], followed by solvent extraction (**A3332**), which separates constituents based on their varying solubilities [72]. To ensure purity, solvent scrubbing (**A3333**) is employed to remove unwanted contaminants (e.g., co-extracted impurities) from an loaded organic phase, while stripping (**A3334**) uses an aqueous medium to reverse the extraction, transferring the target metal back into a concentrated aqueous phase [73]. Electrowinning (**A3335**) can then be employed to recover the final pure metals via electrolysis to deposit metals onto an electrode [74]. Alternatively, precipitation (**A3335**), a chemical reaction that forms solid products from the solution, can also be utilized [75].

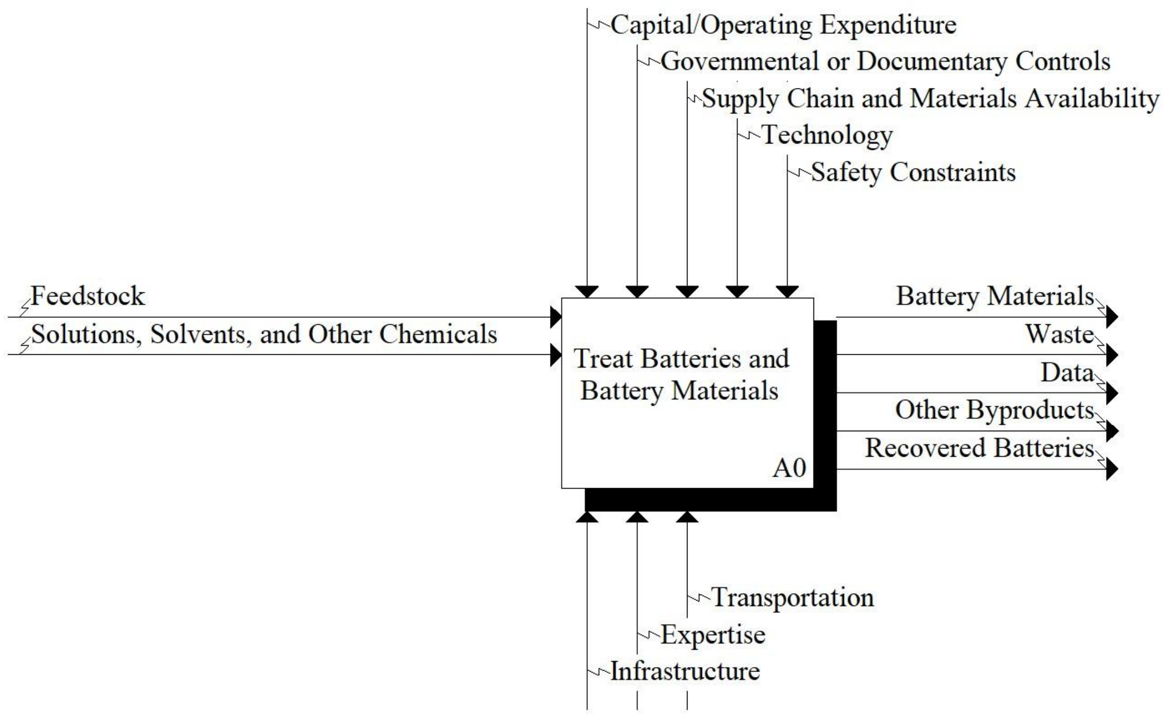

Fig. 3. Top level of the Traction Lithium Battery Recovery (TLB-R) model

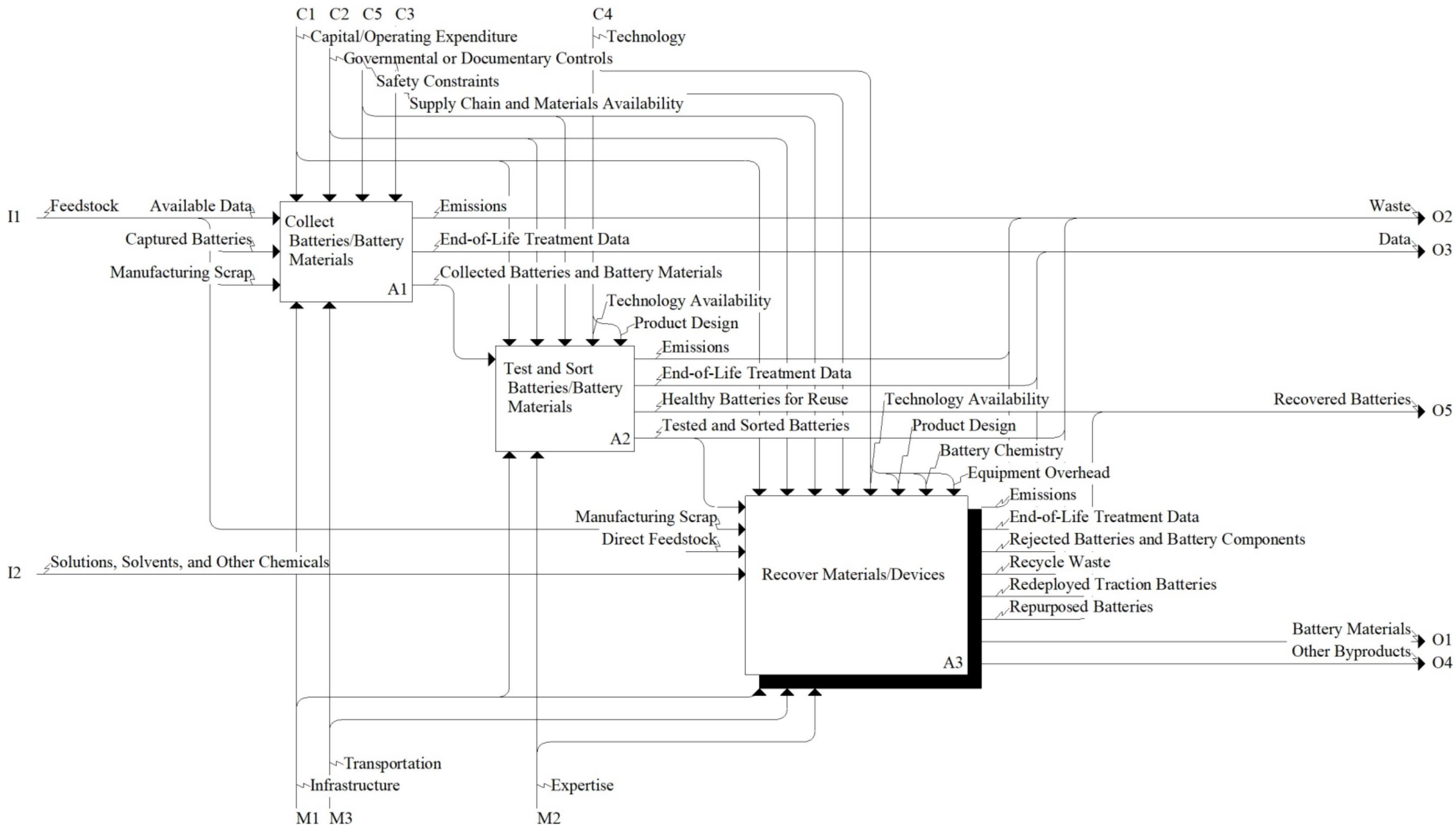

Fig. 4. Decomposition of A0: Treat Batteries and Battery Materials

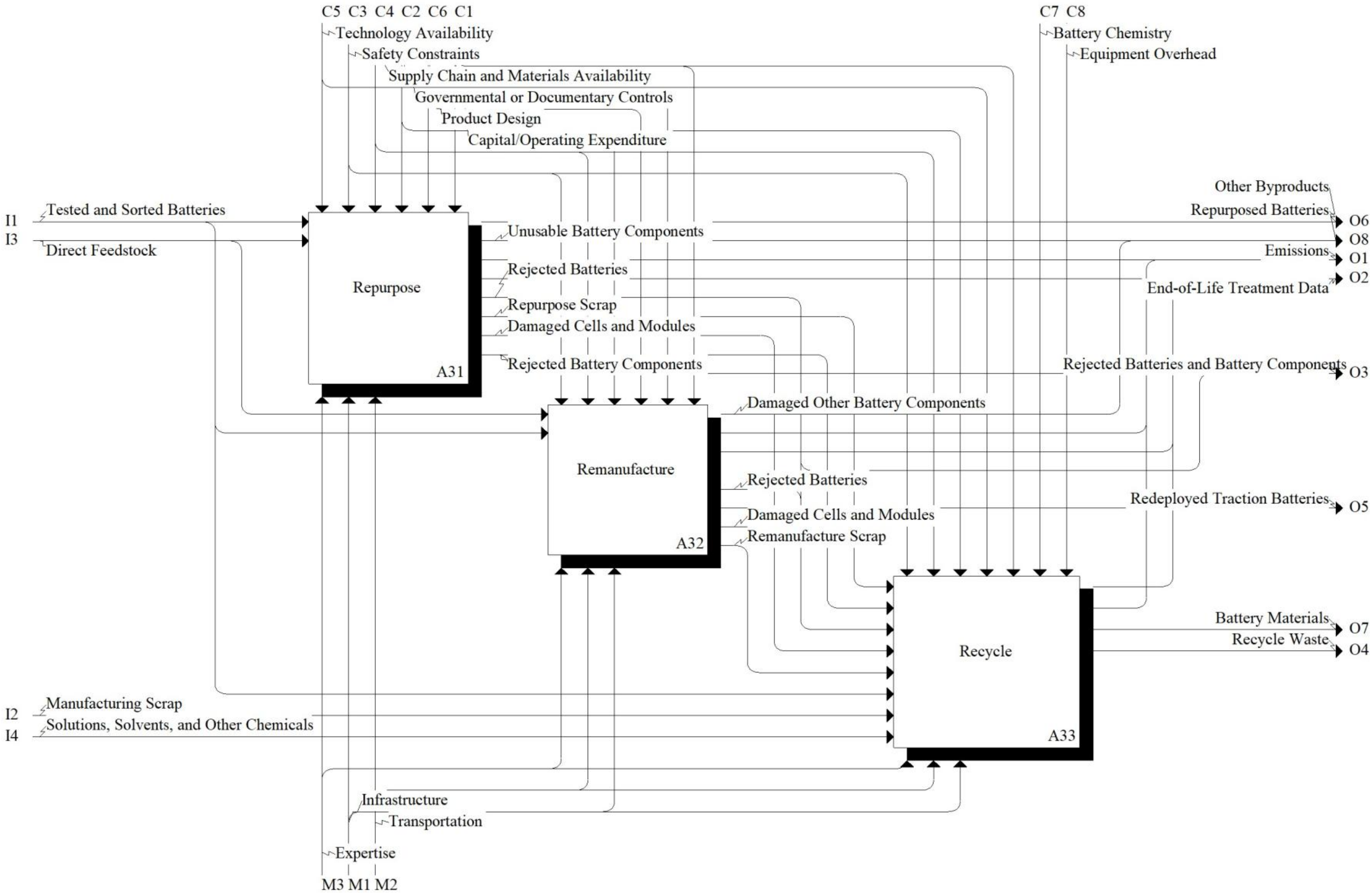

Fig. 5. Decomposition of A3: Recover Materials/Devices

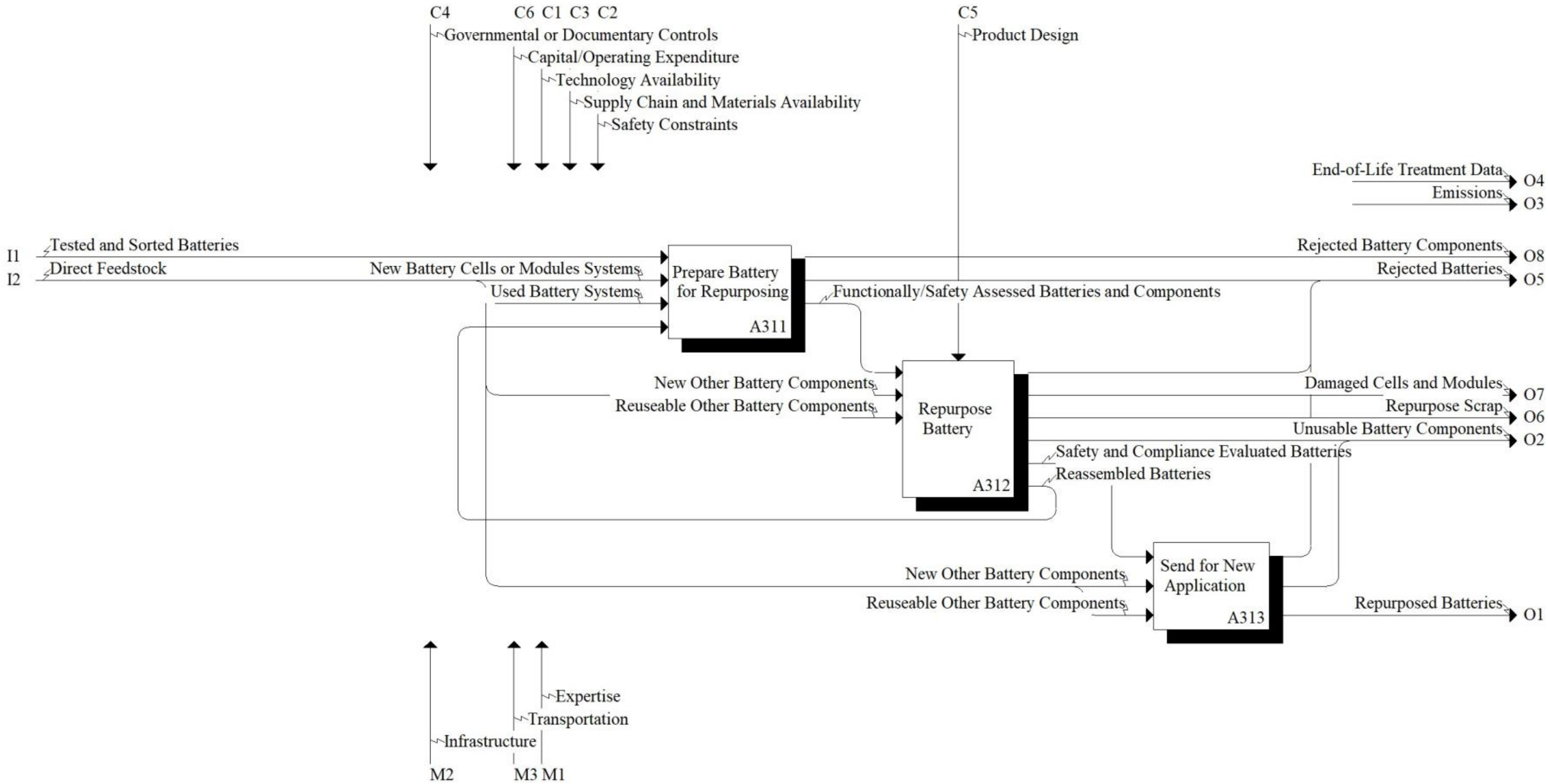

Fig. 6. Decomposition of A31: Repurpose

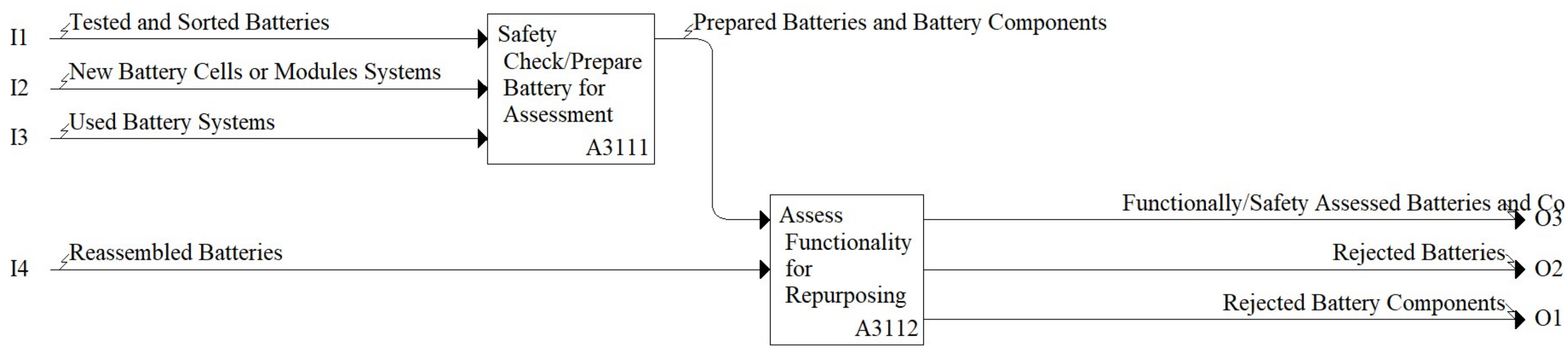

Fig. 7. Decomposition of A311: Prepare Battery for Repurposing

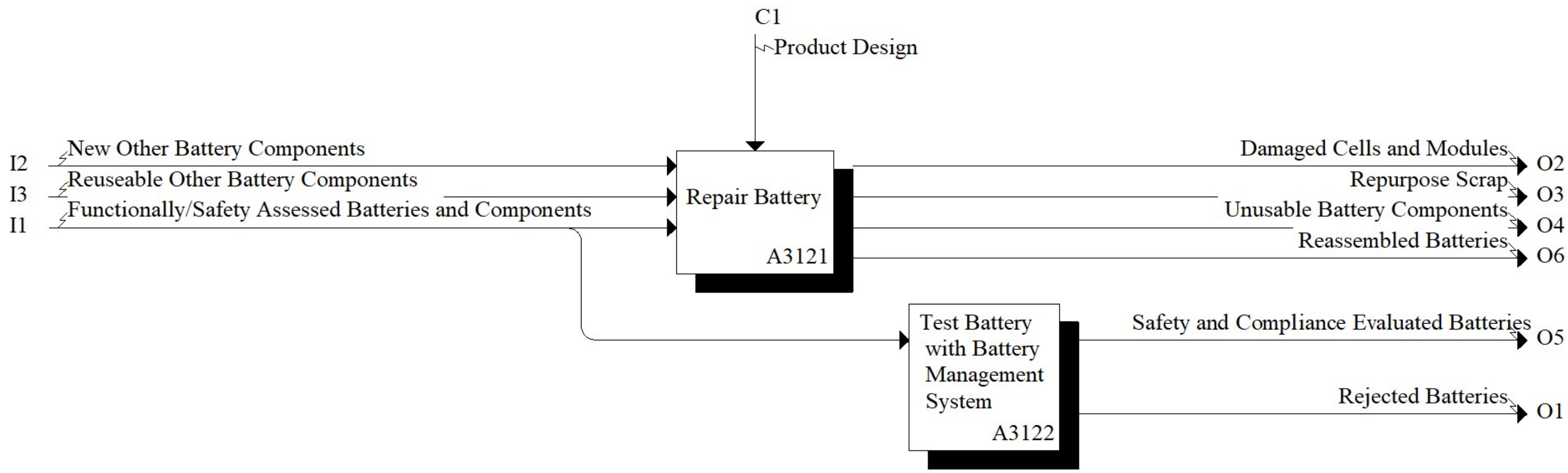

Fig. 8. Decomposition of A312: Repurpose Battery

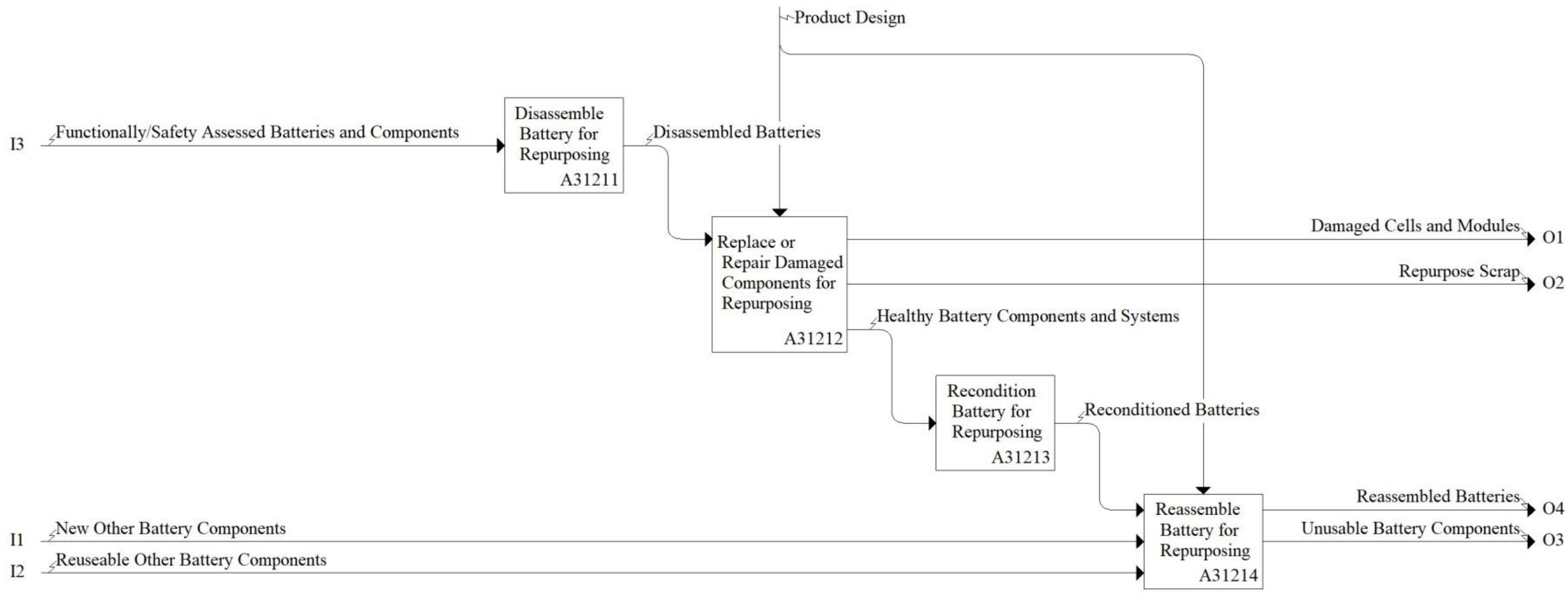

Fig. 9. Decomposition of A3121: Repair Battery

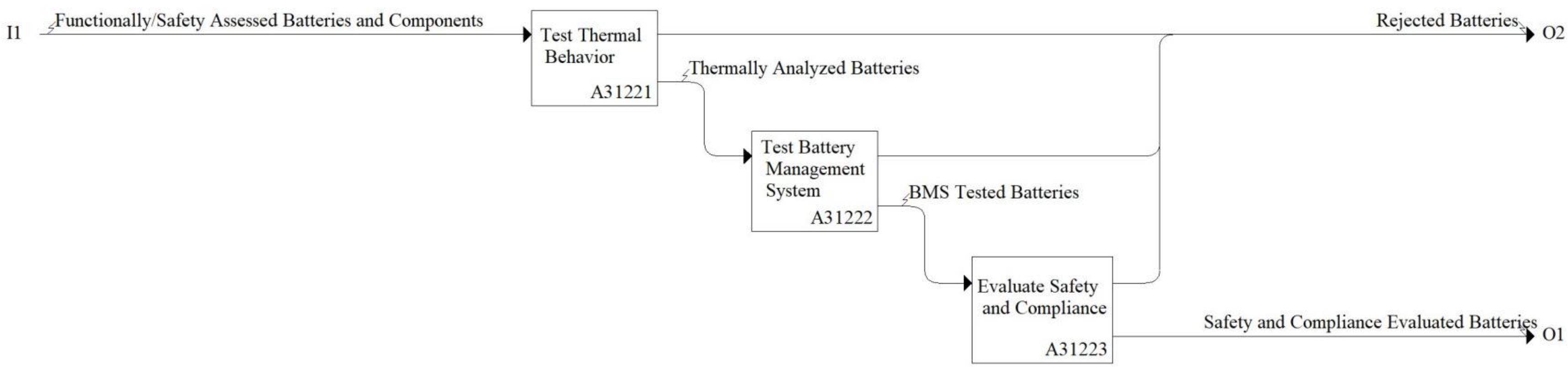

Fig. 10. Decomposition of A3122: Test Battery with Battery Management System

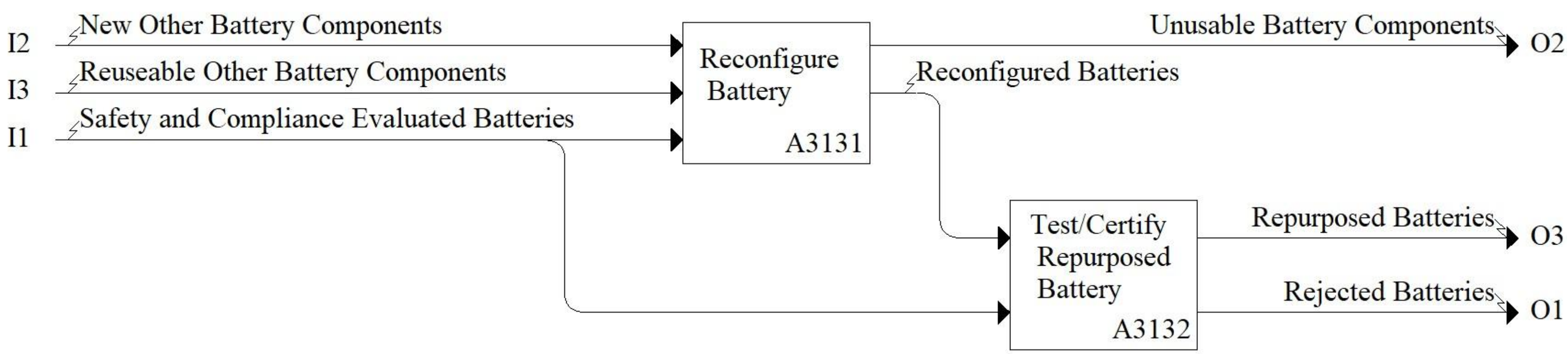

Fig. 11. Decomposition of A313: Send for New Application

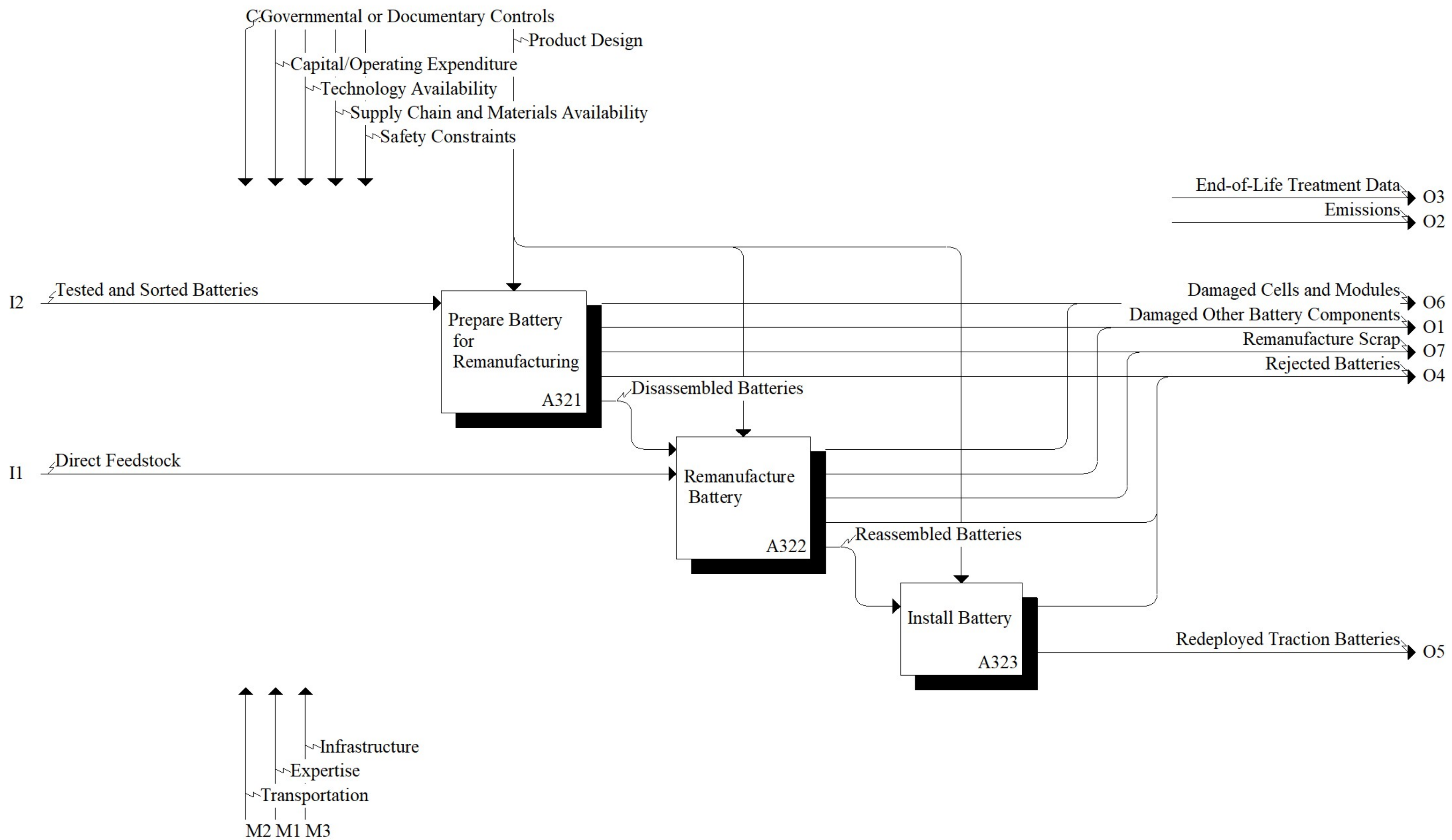

Fig. 12. Decomposition of A32: Remanufacture

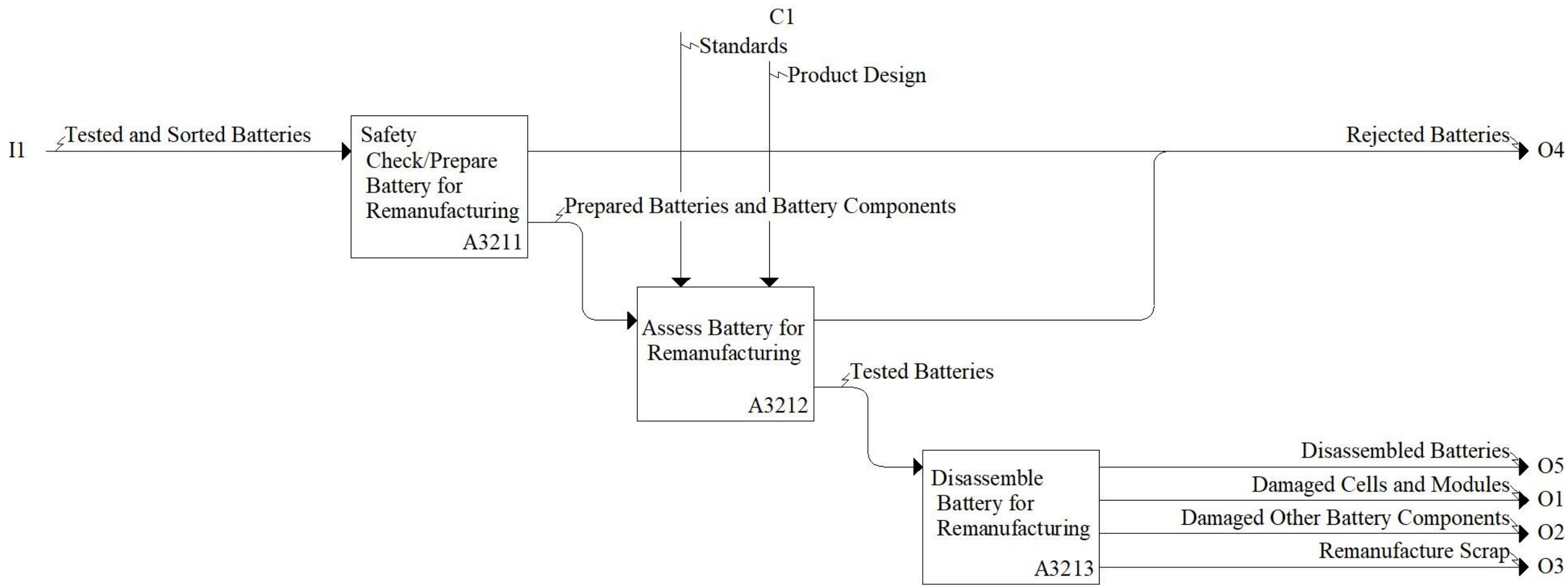

Fig. 13. Decomposition of A321: Prepare Battery for Remanufacturing

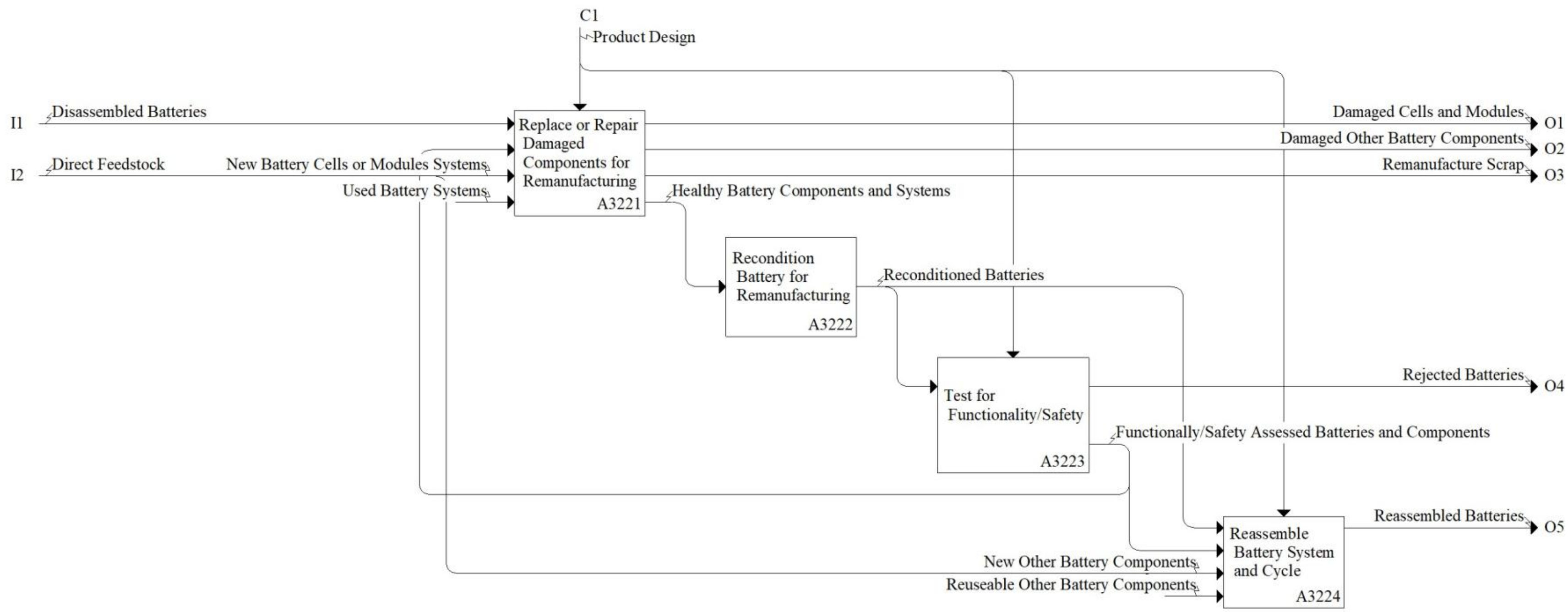

Fig. 14. Decomposition of A322: Remanufacture Battery

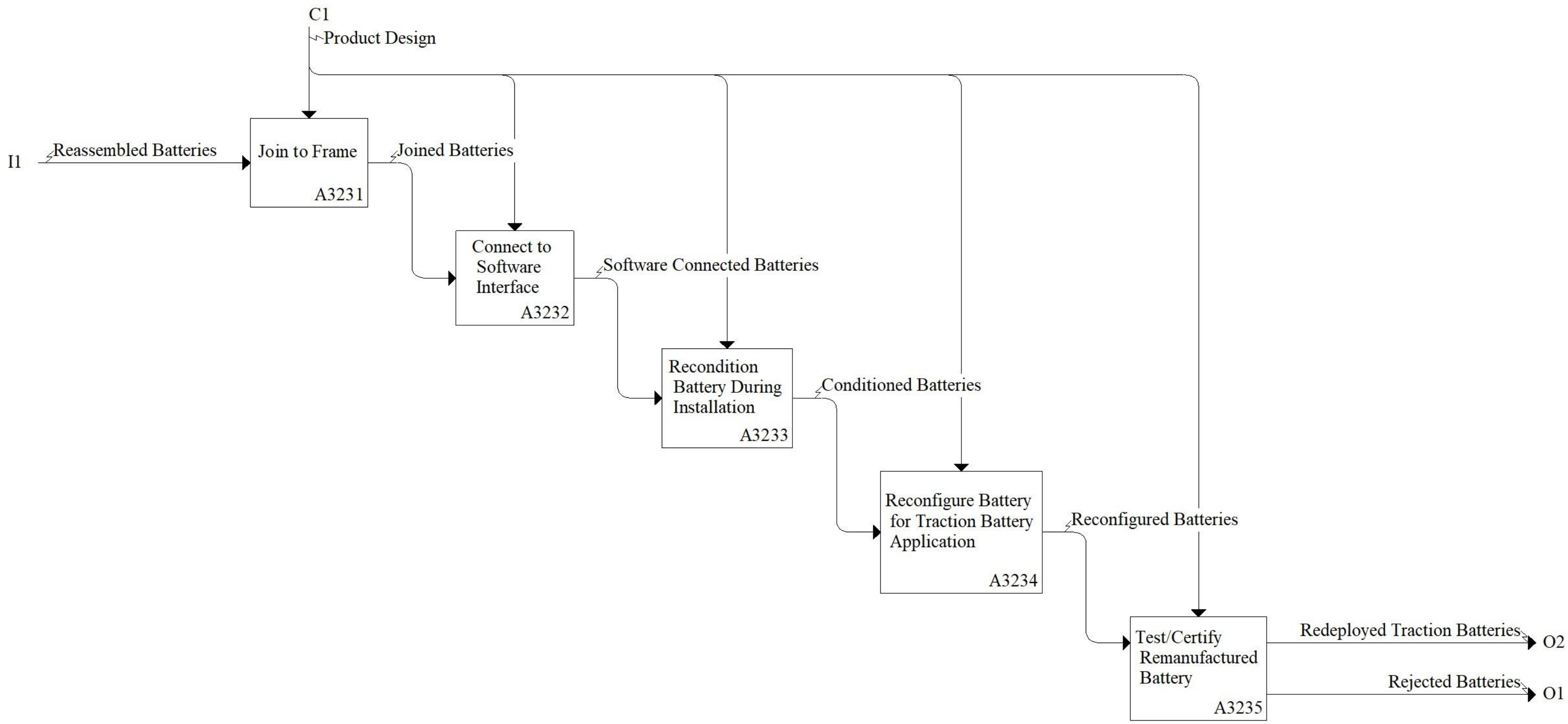

Fig. 15. Decomposition of A323: Install Battery

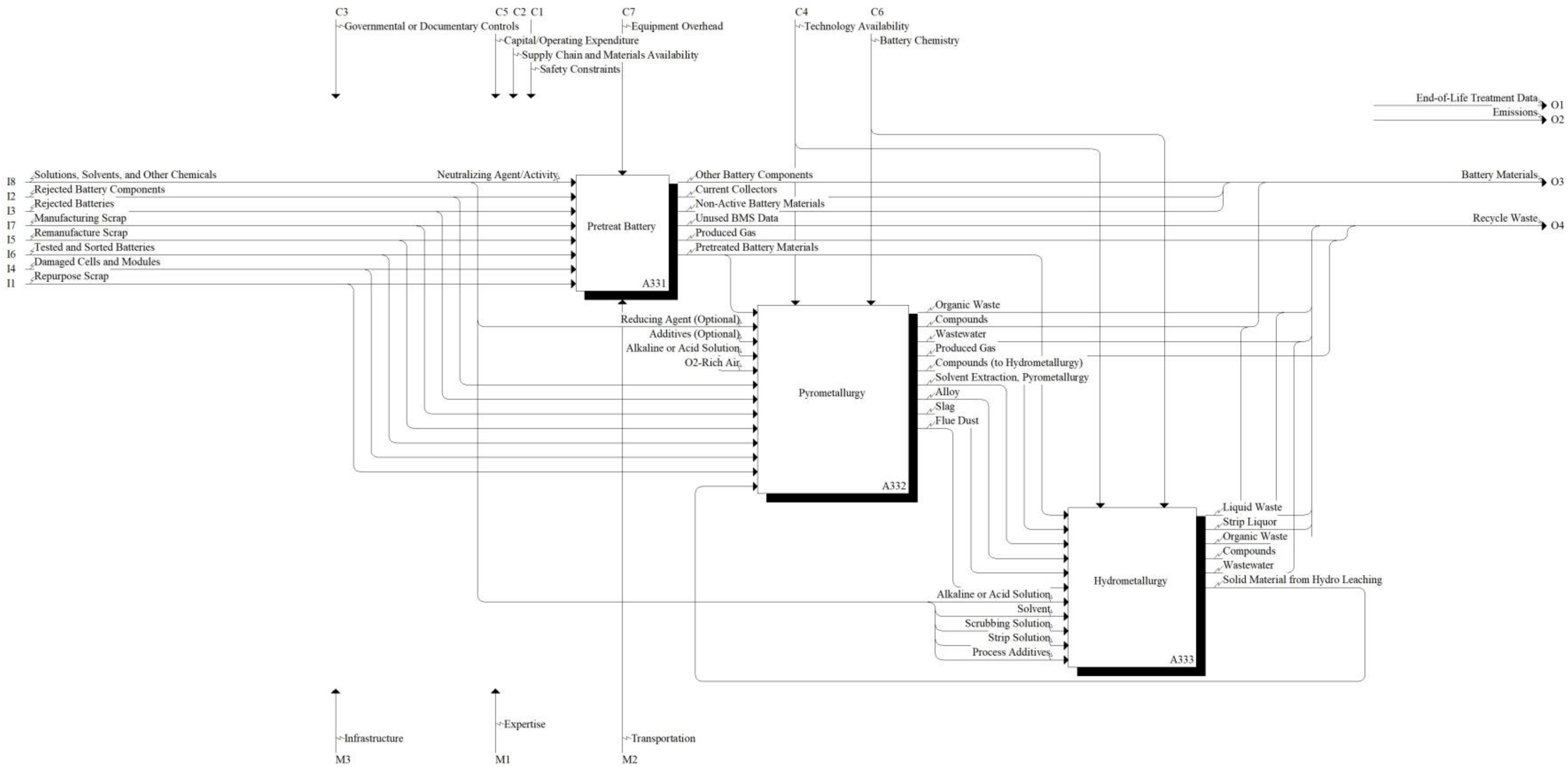

Fig. 16. Decomposition of A33: Recycle

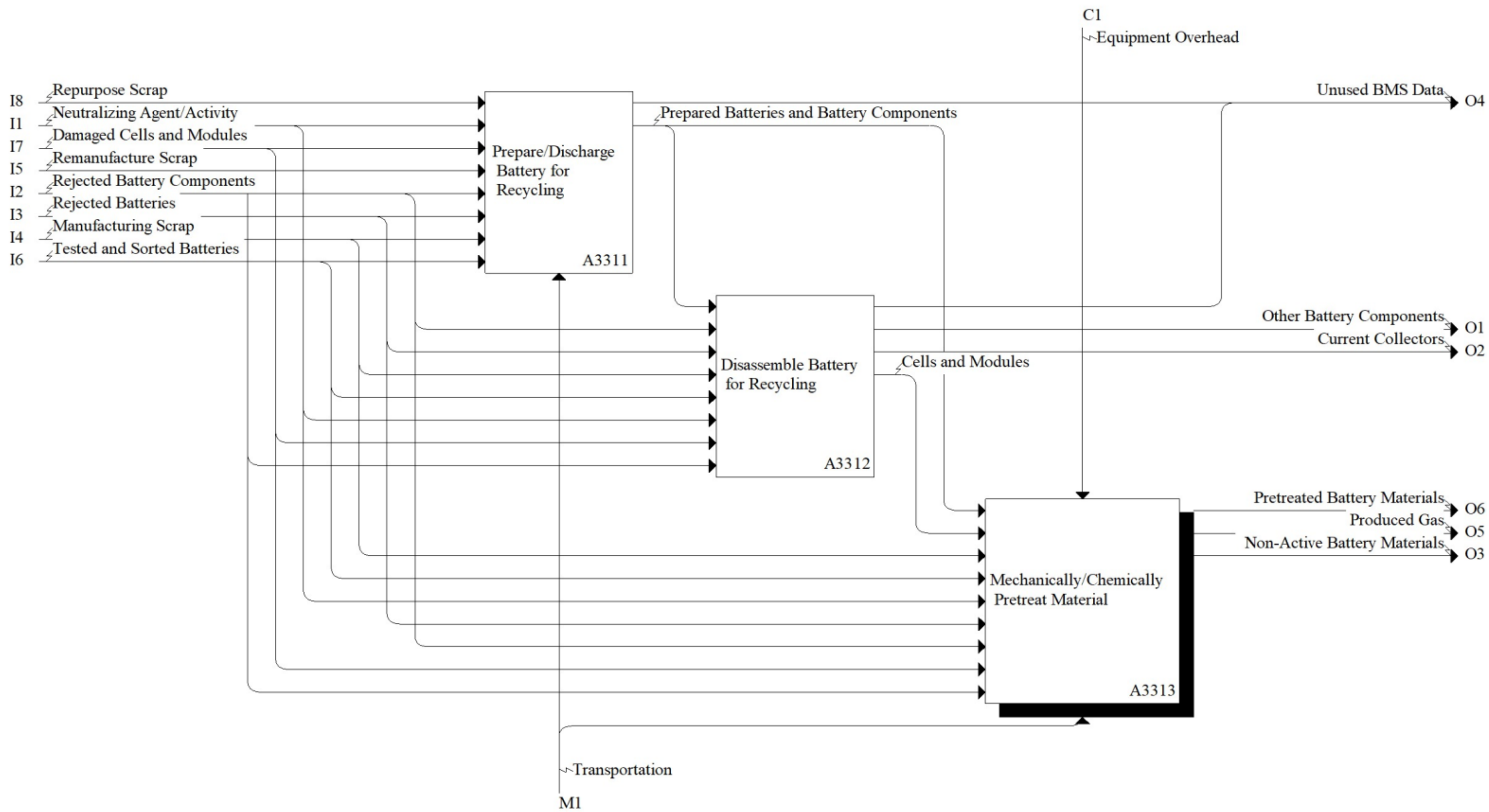

Fig. 17. Decomposition of A331: Pretreat Battery

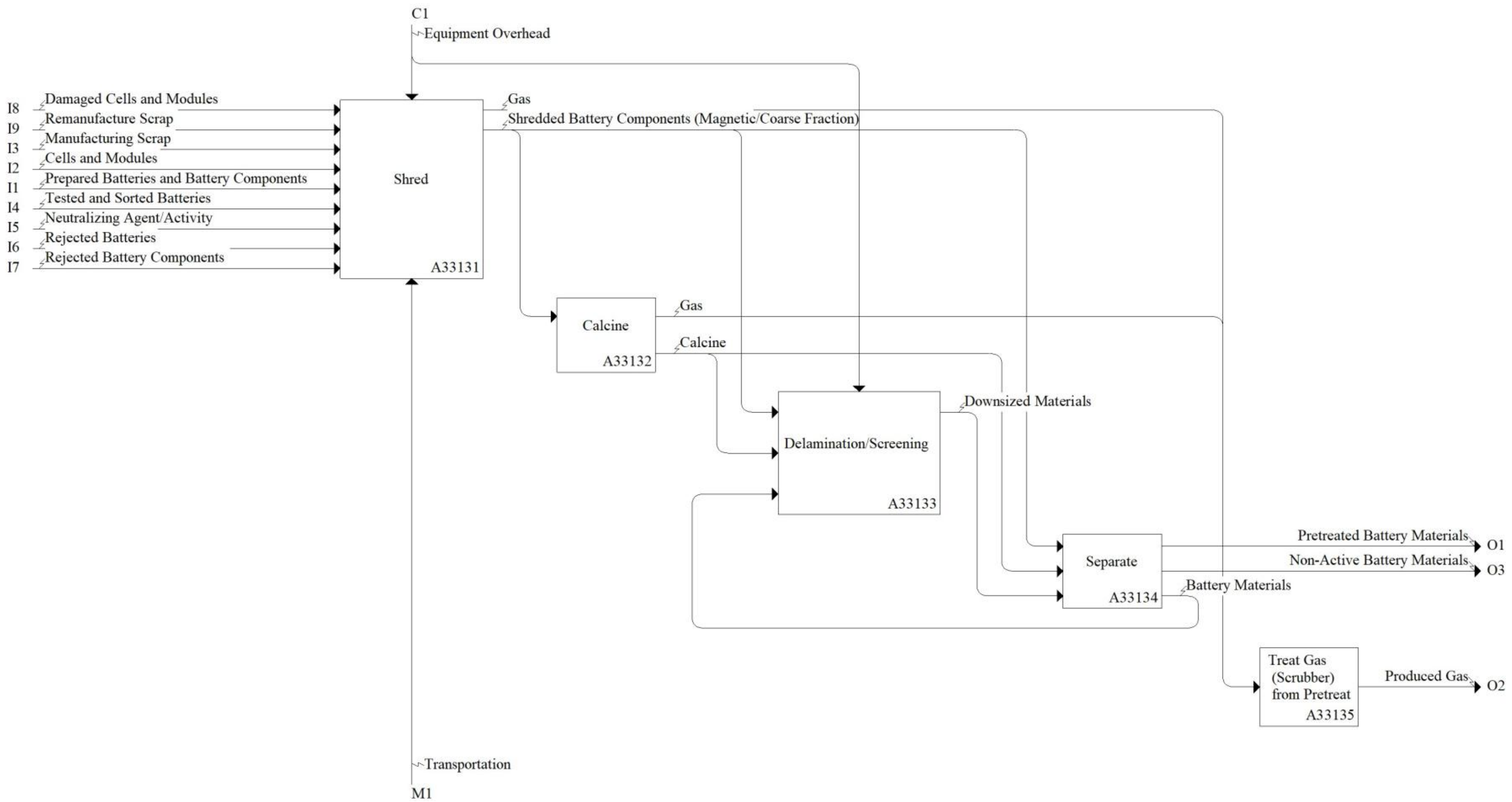

Fig. 18. Decomposition of A3313: Mechanically/Chemically Pretreat Material

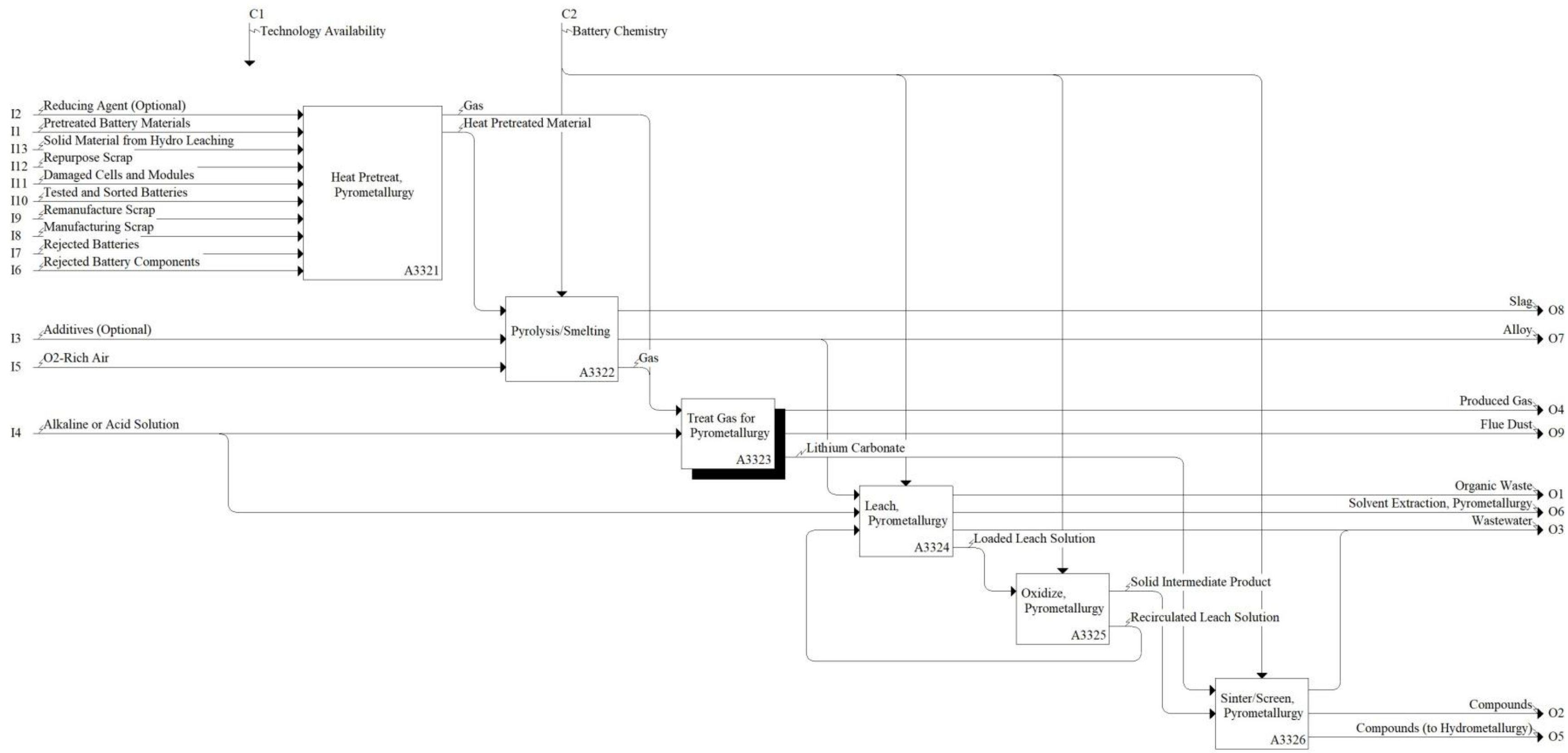

Fig. 19. Decomposition of A332: Pyrometallurgy

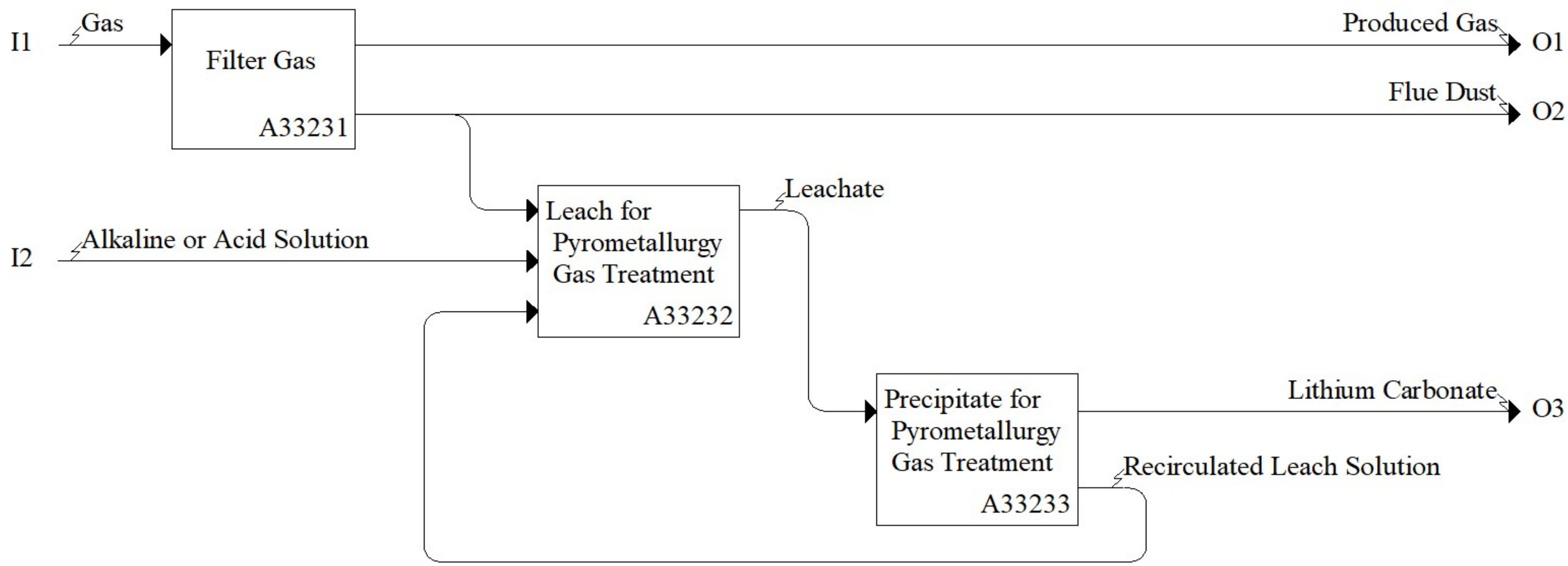

Fig. 20. Decomposition of A3323: Treat Gas for Pyrometallurgy

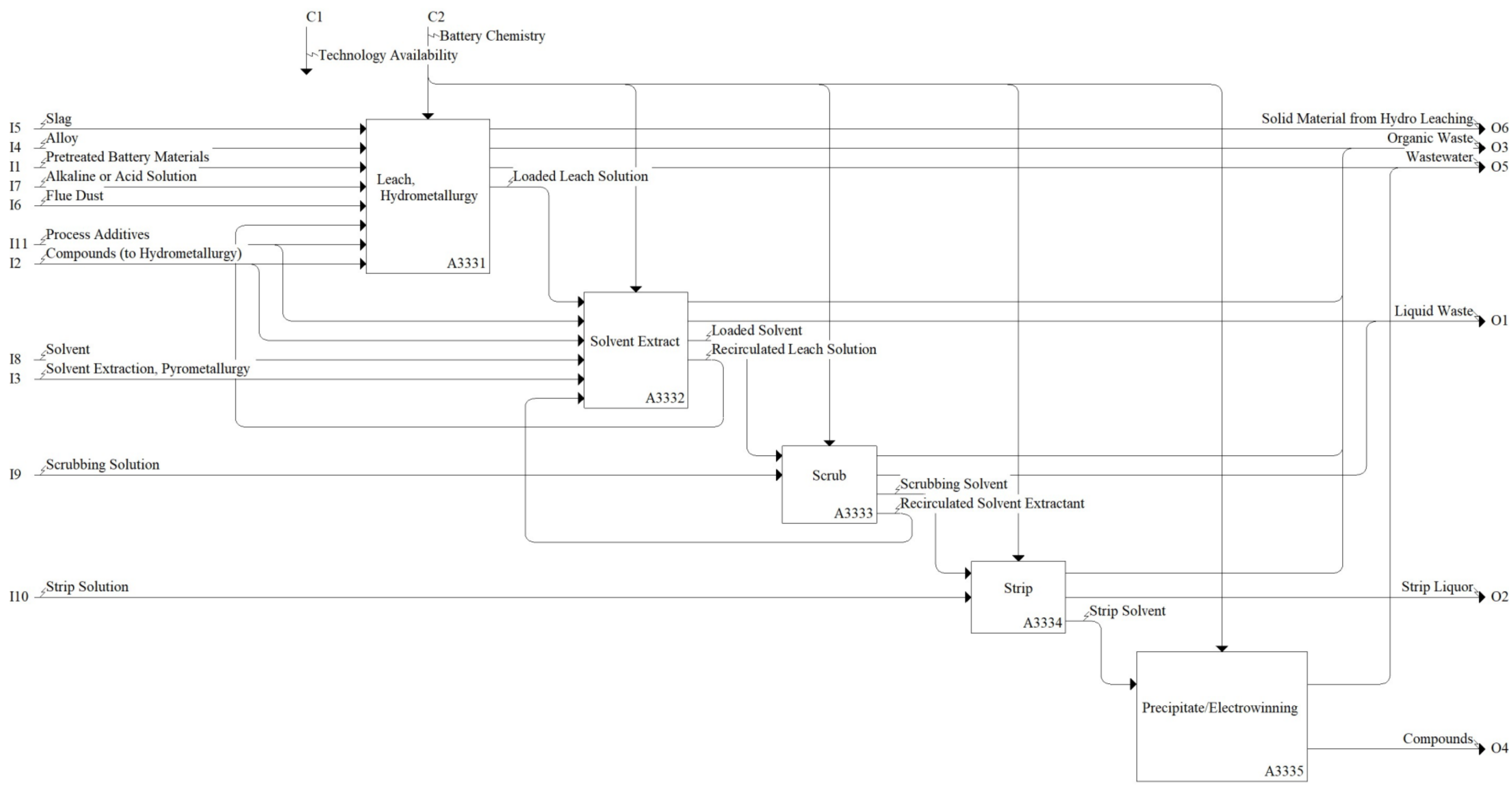

Fig. 21. Decomposition of A333: Hydrometallurgy

5. Summary & Future Opportunities

This report details a baseline open-source model for Traction Lithium Battery Recovery (TLB-R). By synthesizing emerging capabilities into a unified resource, the model supports the recovery, life extension, and recycling of end-of-life (EOL) lithium-ion batteries. The model is accessible via [20] and downloadable from [21], allowing organizations to customize the framework for their specific planning needs. While detailed, the current model presents several opportunities for expansion:

Technical Readiness: Future iterations could incorporate pilot-scale and low-Technology Readiness Level activities to augment existing material, information, and data flows to scale recovery capabilities for large-format lithium-ion batteries.

Direct Recycling: As direct recycling gains traction in the U.S.—following established precedents in other markets —incorporating these pathways will be essential.

Enhanced Design for Circularity: The model can be restructured to support Design for Disassembly, a key circular strategy, by reflecting simplified cell collection and the potential elimination of select processing steps.

By integrating knowledge from across the spectrum of complex activities involved in battery recovery, this resource establishes a common reference point for the cross-sector collaboration required to scale battery recovery operations [76]. As the industry matures, the model may continue to provide the strategic architecture needed to transition from linear production to a fully integrated circular economy.

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Appendix A. Annotated Bibliography and Terms

This section includes information associated with each activity within the model, when applicable. Information sections included with each activity may include notes, definitions, standards/best practices/regulations, or references.

Notes: Notes are included to provide context to the activity being described or to direct the user to additional related resources.

Definitions: Definitions are provided for the terms used to describe most activities within the model. When possible, definitions were sourced or adapted from existing standards or dictionaries.

Standards/Best Practices/Regulations: Standards, best practice documents, or regulations that may interact with the listed activity are recorded here. This does not confirm the use of these standards for the listed purpose. Most standards identified in this report and the model are cross-listed in the NIST Circular Economy Standards Registry [77].

References: References that were utilized to identify and scope the listed activity are provided here.

A0: Treat Batteries and Battery Materials

Notes:
For information about IDEF0 model representation systems-level engineering, please see: Reslan M, Last N, Mathur N, Morris KC, Ferrero V (2022) Circular economy: a product life cycle perspective on engineering and manufacturing practices. *Procedia CIRP*, 105, 851-858. https://doi.org/10.1016/j.jclepro.2023.139017

Definitions:
End-of-life – the point at which a product or component is taken out of use. From ISO 8887-1:2017.

Standards:

- SAE J2974_201902, Technical Information Report on Automotive Battery Recycling
- SAE J1715/2_202108 - Battery Terminology
- UL 3601, Measuring and Reporting Circularity of Li-ion and Other Secondary Batteries
- UL 1974, Evaluation for Repurposing or Remanufacturing Batteries
- ISO 8887-1:2017, Technical product documentation - Design for manufacturing, assembling, disassembling and end-of-life processing - Part 1: General concepts and requirements

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A1: Collect Batteries/Battery Materials

Notes:
The process of gathering and transporting all input materials—including end-of-life (EOL) batteries, battery manufacturing scrap, and associated battery data—to a sorting facility for further processing.

Definitions:
Collection - process of gathering and transporting used products or waste materials to a sorting facility for further processing such as reuse, repair, remanufacturing, or recycling. Adapted from ISO 5157:2023(en).

Scrap - recyclable materials left over from product manufacturing. May include whole, part, or parts of lithium batteries. Adapted from ISO 22450:2020(en).

Standards/Best Practices/Regulations:

- U.S. Environmental Protection Agency, Battery Collection Best Practices
- U.S. Environmental Protection Agency, Voluntary Battery Labeling Guidelines
- US Department of Transportation, Transporting Lithium Batteries

References:

Chen M, Ma X, Chen B, Arsenault R, Karlson P, Simon N, Wang Y (2019) Recycling end-of-life electric vehicle lithium-ion batteries. *Joule*, 3(11), 2622-2646. https://doi.org/10.1016/j.joule.2019.09.014

Ma X, Meng Z, Bellonia MV, Spangenberger J, Harper G, Gratz E, Olivetti E, Arsenault R, Wang Y (2025) The evolution of lithium-ion battery recycling. *Nature Reviews Clean Technology*, 1(1), 75-94. https://doi.org/10.1038/s44359-024-00010-4

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Pipeline and Hazardous Materials Safety Administration (2024) Lithium Battery Guide for Shippers. Available at https://www.phmsa.dot.gov/lithiumbatteries

US Environmental Protection Agency (2025) Voluntary Battery Labeling Guidelines. Available at https://www.epa.gov/electronics-batteries-management/voluntary-battery-labeling-guidelines

US Environmental Protection Agency (2026) Battery Collection Best Practices Report to Congress. Available at https://www.epa.gov/system/files/documents/2026-05/battery-collection-best-practices-report-to-congress_508.pdf

A2: Test and Sort Batteries/Battery Materials

Notes:

Comprises of screening and classification to group feedstock by chemistry, electrochemical performance and degradation. This step can be used to determine if cells meet requirements for repurposing or must be diverted to recycling. Screening typically involves exploratory sample analysis, whereas testing provides individual safety and performance verification using electrochemical, observational, or ultrasound methods.

Definitions:

Sorting - physical separation or grouping according to defined attributes (i.e., classes). Sorting can be based on electrical chemical parameters, chemistry, and physical appearance (Rehman, et al., (2024) (see references below). Adapted from ISO 59014:2024(en), 3.20.

Screening (testing) - application of any analytical semi-quantitative method for exploratory analysis. Adapted from ISO 12404:2021(en).

Standards:

- UL 1974, Evaluation for Repurposing or Remanufacturing Batteries
- UL 1973 (ANSI/CAN/UL) Batteries for Use in Stationary and Motive Auxiliary Power Applications

References:

Chung HC (2021) Charge and discharge profiles of repurposed $LiFePO_4$ batteries based on the UL 1974 standard. *Scientific Data*, 8(1), 165. https://doi.org/10.1038/s41597-021-00954-3

Montes T, Etxandi-Santolaya M, Eichman J, Ferreira VJ, Trilla L, Corchero C (2022) Procedure for Assessing the Suitability of Battery Second Life Applications After EV First Life. *Batteries*, 8(9), 122. https://doi.org/10.3390/batteries8090122

Rehman S, Short M, Savage R, Cui X, Al-Greer M, Emandi B, Burn A (2024, August) A Review of the EoL EV Batteries Sorting and Disassembly Challenges. In 2024 *29th International Conference on Automation and Computing,* pp 1-6 IEEE. https://doi.org/10.1109/ICAC61394.2024.10718731

Zhu J, Mathews I, Ren D, Li W, Cogswell D, Xing B, Sedlatschek T, Kantareddy SNR, Yi M, Gao T, Xia Y, Zhou Q, Wierzbicki T, Bazant MZ (2021) End-of-life or second-life options for retired electric vehicle batteries. *Cell Reports Physical Science*, 2(8). https://doi.org/10.1016/j.xcrp.2021.100537

A3: Recover Materials/Devices

Notes:
Following the testing and sorting process, feedstock is routed into one of three recovery streams based on their (battery) health and state: repurposing for secondary use, remanufacturing for restoration to original specs, or recycling for material recovery. Feedstock that fails to meet the minimum requirements for any of these three pathways are diverted to disposal (Waste).

Definitions:
See daughter activities.

Standards:

- UL 3601, Measuring and Reporting Circularity of Li-ion and Other Secondary Batteries
- UL 1974, Evaluation for Repurposing or Remanufacturing Batteries

References:

DeRousseau M, Gully B, Taylor C, Apelian D, Wang Y (2017) Repurposing used electric car batteries: a review of options. *JOM*, 69(9), 1575-1582. https://doi.org/10.1007/s11837-017-2368-9

Foster M, Isely P, Standridge CR, Hasan MM (2014) Feasibility assessment of remanufacturing, repurposing, and recycling of end of vehicle application lithium-ion batteries. *Journal of Industrial Engineering and Management*, 7(3), 698-715. https://doi.org/10.3926/jiem.939

Garole DJ, Hossain R, Garole VJ, Sahajwalla V, Nerkar J, Dubal DP (2020) Recycle, recover and repurpose strategy of spent Li-ion batteries and catalysts: Current status and future opportunities. *Chemistry-Sustainability-Energy-Materials*, 13(12), 3079-3100. https://doi.org/10.1002/cssc.201903213

Standridge CR, Hasan MM (2015) Post-vehicle-application lithium-ion battery remanufacturing, repurposing and recycling capacity: Modeling and analysis. *Journal of Industrial Engineering and Management*, 8(3), 823-839. https://doi.org/10.3926/jiem.1418

A31: Repurpose

Notes:
None

Definitions:
Repurpose - (to) adapt a product or its component parts for use in a different function than it was originally intended for, without making major modifications to its physical, chemical or mechanical structure. From ISO 59004:2024.

Repair - returning a faulty, worn or broken product or component back to a usable state. From ISO 8887-2:2023.

Standards:

- UL 1974, Evaluation for Repurposing or Remanufacturing Batteries
- UL 1973, Standard for Batteries for Use in Stationary, Vehicle Auxiliary Power and Light Electric Rail Applications
- ISO 8887-2:2023, Technical product documentation - Design for manufacturing, assembling, disassembling and end-of-life processing - Part 2: Vocabulary
- IEEE 2993-2025, Recommended Practice for Energy Storage System Design using Second-Life Electric Vehicle Batteries

References:
Bobba S, Mathieux F, Ardente F, Blengini GA, Cusenza MA, Podias A, Pfrang A (2018) Life Cycle Assessment of repurposed electric vehicle batteries: an adapted method based on modelling energy flows. *Journal of Energy Storage*, 19, 213-225. https://doi.org/10.1016/j.est.2018.07.008

Chen M, Ma X, Chen B, Arsenault R, Karlson P, Simon N, Wang Y (2019) Recycling end-of-life electric vehicle lithium-ion batteries. *Joule*, 3(11), 2622-2646. https://doi.org/10.1016/j.joule.2019.09.014

DeRousseau M, Gully B, Taylor C, Apelian D, Wang Y (2017) Repurposing used electric car batteries: a review of options. *JOM*, 69(9), 1575-1582. https://doi.org/10.1007/s11837-017-2368-9

Illa Font CH, Siqueira HV, Machado Neto JE, Santos JLF, Stevan SL Jr, Converti A, Corrêa FC (2023) Second life of lithium-ion batteries of electric vehicles: a short review and perspectives. Energies, 16, 953. https://doi.org/10.3390/en16020953

Martinez-Laserna E, Sarasketa-Zabala E, Villarreal Sarria I, Stroe DI, Swierczynski M, Warnecke A, Timmermans JM, Goutam S, Omar N, Rodriguez P (2018) Technical viability of battery second life: a study from the ageing perspective. IEEE Transactions on Industry Applications, 54, 2703-2713. https://doi.org/10.1109/TIA.2018.2801262

Montes T, Etxandi-Santolaya M, Eichman J, Ferreira VJ, Trilla L, Corchero C (2022) Procedure for Assessing the Suitability of Battery Second Life Applications After EV First Life. *Batteries*, 8(9), 122. https://doi.org/10.3390/batteries8090122

Rufino Júnior CA, Riva Sanseverino E, Gallo P, Koch D, Diel S, Walter G, Trilla L, Ferreira VJ, Pérez GB, Kotak Y, Eichman J, Schweiger HG, Zanin H (2024) Towards to battery digital passport: reviewing regulations and standards for second-life batteries. *Batteries*, 10(4), 115. https://doi.org/10.3390/batteries10040115

Zhu J, Mathews I, Ren D, Li W, Cogswell D, Xing B, Sedlatschek T, Kantareddy SNR, Yi M, Gao T, Xia Y, Zhou Q, Wierzbicki T, Bazant MZ (2021) End-of-life or second-life options for retired electric vehicle batteries. *Cell Reports Physical Science*, 2(8). https://doi.org/10.1016/j.xcrp.2021.100537

A311: Prepare Battery for Repurposing

Notes:
See A31.

Definitions:
None

Standards:
None

References:
Chung HC (2021) Charge and discharge profiles of repurposed LiFePO4 batteries based on the UL 1974 standard. Scientific Data, 8(1), 165. https://doi.org/10.1038/s41597-021-00954-3

Roy JJ, Verma V, Srinivasan M (2026) Second-life application of electric vehicle batteries: electrode deterioration, automated disassembly, second-life extension, and applications. ChemSusChem, 19, e202500845. https://doi.org/10.1002/cssc.202500845

Nazim MS, Elavarasan RM (2026) Extending battery lifecycles: a holistic review of second-life lithium-ion technology in sustainable energy systems from assessment to emerging trends. Renewable and Sustainable Energy Reviews, 233, 116848. https://doi.org/10.1016/j.rser.2026.116848

A3111: Safety Check/Prepare Battery for Assessment

Notes:
None

Definitions:
Discharge - controlled depletion of stored energy to a pre-defined amount in an electrochemical cell/battery. Sometimes described as a deep depth of discharge.

Depth of Discharge (DOD) - percentage of a rechargeable battery's capacity that has been used or cycled out of the battery during a discharge cycle. This is a complement (or additive inverse relative to 100%) to a batteries state of charge (SOC). Adapted from Park et al., (2023) (see references below).

Standards:

- SAE J1634_202104, Battery Electric Vehicle Energy Consumption and Range Test Procedure.

References:

Park SJ, Song YW, Kang BS, Kim WJ, Choi YJ, Kim C, Hong YS (2023) Depth of discharge characteristics and control strategy to optimize electric vehicle battery life. *Journal of Energy Storage*, 59, 106477. https://doi.org/10.1016/j.est.2022.106477

Ramoni MO, Zhang HC (2013) End-of-life (EOL) issues and options for electric vehicle batteries. Clean Technologies and Environmental Policy, 15(6), 881-891. https://doi.org/10.1007/s10098-013-0588-4

Rehman S, Short M, Savage R, Cui X, Al-Greer M, Emandi B, Burn A (2024, August) A Review of the EoL EV Batteries Sorting and Disassembly Challenges. In 2024 29th *International Conference on Automation and Computing*, pp 1-6 IEEE. https://doi.org/10.1109/ICAC61394.2024.10718731

A3112: Assess Functionality for Repurposing

Notes:
None

Definitions:
None

Standards:

- UL 1974, Evaluation for Repurposing or Remanufacturing Batteries

References:

Chung HC (2021) Charge and discharge profiles of repurposed LiFePO4 batteries based on the UL 1974 standard. *Scientific Data*, 8(1), 165. https://doi.org/10.1038/s41597-021-00954-3

Kehl D, Jennert T, Lienesch F, Kurrat M (2021) Electrical characterization of Li-ion battery modules for second-life applications. *Batteries*, 7(2), 32. https://doi.org/10.3390/batteries7020032

Michelini E, Höschele P, Abbas SM, Ellersdorfer C, Moser J (2023) Assessment of health indicators to detect the aging state of commercial second-life lithium-ion battery cells through basic electrochemical cycling. *Batteries*, 9(11), 542. https://doi.org/10.3390/batteries9110542

Murphy L, Crawford C (2025) Data-driven classification of lithium-ion batteries for second-life applications. *Journal of Energy Storage*, 133, 117994. https://doi.org/10.1016/j.est.2025.117994

Svensson D, Särnevång A (2024) Inspection and Evaluation Method to Repurpose Used Batteries. http://hdl.handle.net/20.500.12380/308820

A312: Repurpose Battery

See A31.

A3121: Repair Battery

Notes:
None

Definitions:
Repair - returning a faulty, worn or broken product or component back to a usable state. From ISO 8887-2:2023.

Standards:

- ISO 8887-2:2023, Technical product documentation - Design for manufacturing, assembling, disassembling and end-of-life processing - Part 2: Vocabulary
- ISO 12405-4:2018, Electrically propelled road vehicles - Test specification for lithium-ion traction battery packs and systems
- ISO 6469-1, Electrically Propelled Road Vehicles - Safety Specifications - Part 1: Rechargeable Energy Storage System (RESS)
- IEC 62660-3, Secondary Lithium-ion Cells for the Propulsion of Electric Road Vehicles - Part 3: Safety Requirements
- IEC 63057, Secondary Cells and Batteries Containing Alkaline or Other Non-acid Electrolytes - Safety Requirements for Secondary Lithium Batteries for Use in Road Vehicles Not for the Propulsion
- UL 2580, Standard for Batteries for Use in Electric Vehicles
- UL 1974, Evaluation for Repurposing or Remanufacturing Batteries
- SAE J2929, Safety Standard for Electric and Hybrid Vehicle Propulsion Battery Systems
- Utilizing Lithium-based Rechargeable Cells
- SAE J1798, Performance Rating of Electric Vehicle Battery Module
- SAE J2380, Vibration Testing of Electric Vehicle Batteries
- FMVSS, Federal Motor Vehicle Safety Standard
- CMVSS, Canadian Motor Vehicle Safety Standards

References:
None

A31211: Disassemble Battery for Repurposing

Notes:
None

Definitions:
Disassembling - taking apart of an assembled product into constituent materials and/or components. From ISO 8887-1:2017.

Standards:
- ISO 8887-1:2017, Technical product documentation - Design for manufacturing, assembling, disassembling and end-of-life processing - Part 1: General concepts and requirements

References:
Ramoni MO, Zhang HC (2013) End-of-life (EOL) issues and options for electric vehicle batteries. Clean Technologies and Environmental Policy, 15(6), 881-891. https://doi.org/10.1007/s10098-013-0588-4

Rehman S, Short M, Savage R, Cui X, Al-Greer M, Emandi B, Burn A (2024, August) A Review of the EoL EV Batteries Sorting and Disassembly Challenges. In 2024 *29th International Conference on Automation and Computing*, pp 1-6 IEEE. https://doi.org/10.1109/ICAC61394.2024.10718731

Rettenmeier M, Möller M, Sauer A (2024) Disassembly technologies of end-of-life automotive battery packs as the cornerstone for a circular battery value chain: A process-oriented analysis. *Resources, Conservation and Recycling*, *209*, 107786. https://doi.org/10.1016/j.resconrec.2024.107786

Zang Y, Wang Y (2022, September) Robotic disassembly of electric vehicle batteries: an overview. *2022 27th International Conference on Automation and Computing (ICAC)*, pp 1-6. https://doi.org/10.1109/ICAC55051.2022.9911109

A31212: Replace or Repair Damaged Components for Repurposing

Notes:
None

Definitions:
Repair - returning a faulty, worn or broken product or component back to a usable state. From ISO 8887-2:2023.

Replace - remove a part or component and mount a new or checked part or component with the same characteristics. Adapted from ISO 9879:2024.

Standards/Guidance/Regulations:
- ASE Electrified Propulsion Vehicles (xEV) High-Voltage Electrical Safety Standards Level ONE - Electrically Aware Person

- ASE Electrified Propulsion Vehicles (xEV) High-Voltage Electrical Safety Standards Level TWO - High-Voltage Vehicle Technician
- Federal Motor Vehicle Safety Standard (FMVSS) No. 305a
- National Highway Traffic Safety Administration Interim Guidance for Electric and Hybrid-Electric Vehicles Equipped With High-Voltage Batteries

References:

Fechtner H, Saes KH, Fechtner E, Braun, T, Schmülling, B (2016) Clarification of the Training Requirements for Working on Electric Vehicles. *International Journal of Advanced Corporate Learning*, 9(1). https://doi.org/10.3991/ijac.v9i1.5635

Linja-Aho V (2024) Assessing the Electrical Risks in Electric Vehicle Repair: Results for use in developing safe working practices and regulations. *IEEE Industry Applications Magazine*, 30(5), 32-41. https://doi.org/10.1109/MIAS.2024.3387142

A31213: Recondition Battery for Repurposing

Notes:
None

Definitions:
Reconditioning - industrial process which returns a used product, or component to a satisfactory performance level when made available on the market as a used product. From ISO 8887-2:2023.

Standards:

- UL 1974, Evaluation for Repurposing or Remanufacturing Batteries

References:

Rasheed M, Hassan R, Kamel M, Wang H, Zane R, Tong S, Smith K (2023) Active reconditioning of retired lithium-ion battery packs from electric vehicles for second-life applications. *IEEE Journal of Emerging and Selected Topics in Power Electronics*, 12(1), 388-404. https://doi.org/10.1109/JESTPE.2023.3325251

Rasheed M, Kamel M, Wang H, Zane R, Smith K (2020, November) Investigation of Active Life Balancing to Recondition Li-ion Battery Packs for 2nd Life. *2020 IEEE 21st Workshop on Control and Modeling for Power Electronics (COMPEL)*, pp 1–7. https://doi.org/10.1109/COMPEL49091.2020.9265808

A31214: Reassemble Battery for Repurposing

Notes:
None

Definitions:
Reassembling **-** to bring or put together the parts of (something) again (Merriam-Webster)

Standards:
None

References:
None

A3122: Test Battery with Battery Management System

Notes:
None

Definitions:
See A31222.

Standards:

- IEC 62133-2:2017, Secondary cells and batteries containing alkaline or other non-acid electrolytes - Safety requirements for portable sealed secondary cells, and for batteries made from them, for use in portable applications - Part 2: Lithium systems
- UL 1974, Evaluation for Repurposing or Remanufacturing Batteries
- UL 1642, Certification of Lithium-ion Battery
- ISO 12405-1:2011, Electrically propelled road vehicles - Test specification for lithium-ion traction battery packs and systems - Part 1: High-power applications

References:
Chung HC (2021) Charge and discharge profiles of repurposed LiFePO4 batteries based on the UL 1974 standard. *Scientific Data*, 8(1), 165. https://doi.org/10.1038/s41597-021-00954-3

Kehl D, Jennert T, Lienesch F, Kurrat M (2021) Electrical characterization of Li-ion battery modules for second-life applications. *Batteries*, 7(2), 32. https://doi.org/10.3390/batteries7020032

Michelini E, Höschele P, Abbas SM, Ellersdorfer C, Moser J (2023) Assessment of health indicators to detect the aging state of commercial second-life lithium-ion battery cells through basic electrochemical cycling. *Batteries*, 9(11), 542. https://doi.org/10.3390/batteries9110542

Murphy L, Crawford C (2025) Data-driven classification of lithium-ion batteries for second-life applications. *Journal of Energy Storage*, 133, 117994. https://doi.org/10.1016/j.est.2025.117994

Svensson D, Särnevång A (2024) Inspection and Evaluation Method to Repurpose Used Batteries. http://hdl.handle.net/20.500.12380/308820

A31221: Test Thermal Behavior

Notes:
None

Definitions:
Thermal test - evaluates a battery's performance and safety under various temperature conditions, including extreme heat, cold, or rapid temperature changes, to ensure its reliability, longevity, and suitability for its intended use. Adapted from IEC 62133, UL 2054, and SAE J2464.

Thermal runaway - uncontrollable condition whereby a cell or a battery overheats and reaches very high temperatures in very short periods (seconds) through internal heat generation caused due to an internal short or due to an abusive condition. From ISO 17546:2024.

Standards:
See parent description (A3122).

References:
Bandhauer TM, Garimella S, Fuller TF (2011) A critical review of thermal issues in lithium-ion batteries. *Journal of the electrochemical society*, *158*(3), R1. https://doi.org/10.1149/1.3515880

Chen SC, Wan CC, Wang YY (2005) Thermal analysis of lithium-ion batteries. *Journal of power sources*, 140(1), 111-124. https://doi.org/10.1016/j.jpowsour.2004.05.064

Feng X, Sun J, Ouyang M, He X, Lu L, Han X, Fang M, Peng H (2014) Characterization of large format lithium ion battery exposed to extremely high temperature. *Journal of Power Sources*, *272*, 457-467. https://doi.org/10.1016/j.jpowsour.2014.08.094

Jaguemont J, Bardé F (2023) A critical review of lithium-ion battery safety testing and standards. *Applied Thermal Engineering*, 231, 121014. https://doi.org/10.1016/j.applthermaleng.2023.121014

Maleki H, Al Hallaj S, Selman JR, Dinwiddie RB, Wang H (1999) Thermal properties of lithium-ion battery and components. *Journal of The Electrochemical Society*, 146(3), 947. https://doi.org/10.1149/1.1391704

Wu MS, Chiang PCJ, Lin JC, Jan YS (2004) Correlation between electrochemical characteristics and thermal stability of advanced lithium-ion batteries in abuse tests—short-circuit tests. *Electrochimica acta*, 49(11), 1803-1812. https://doi.org/10.1016/j.electacta.2003.12.012

A31222: Test Battery Management System

Notes:
None

Definitions:
Battery Management System (BMS) - electronic device that controls or manages the electric and thermal functions of the battery system and that provides communication between the battery system and other vehicle/device controllers. Adapted from ISO/IEC 15118-1:2013.

Standards:
- IEC 61508-1:2010, Functional safety of electrical/electronic/programmable electronic safety-related systems - Part 1: General requirements (see Functional Safety and IEC 61508)

- IEC 62933-1:2024, Electrical energy storage (EES) systems - Part 1: Vocabulary
- IEC 62619:2022, Secondary cells and batteries containing alkaline or other non-acid electrolytes - Safety requirements for secondary lithium cells and batteries, for use in industrial applications.
- ISO 26262-1:2018, Road vehicles — Functional safety Part 1: Vocabulary
- ISO 50001:2018, Energy management systems — Requirements with guidance for use
- UL 1741, Inverters, Converters, Controllers and Interconnection System Equipment for Use with Distributed Energy Resources
- UL 1973, ANSI/CAN/UL Batteries for Use in Stationary and Motive Auxiliary Power Applications
- IEEE 1547-2018, Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces
- IEEE 2686-2024, Recommended Practice for Battery Management Systems in Stationary Energy Storage Applications
- NERC PRC-005-2, Protection System Maintenance

References:

Brandl M, Gall H, Wenger M, Lorentz V, Giegerich M, Baronti F, Fantechi G, Fanucci L, Roncella R, Saletti R, Saponara S, Thaler A, Cifrain M, Prochazka W (2012) Batteries and battery management systems for electric vehicles. *2012 Design, Automation & Test in Europe Conference & Exhibition (DATE)*, pp 971-976. https://doi.org/10.1109/DATE.2012.6176637

Gabbar HA, Othman AM, Abdussami MR (2021) Review of battery management systems (BMS) development and industrial standards. *Technologies*, 9(2), 28. https://doi.org/10.3390/technologies9020028

Lelie M, Braun T, Knips M, Nordmann H, Ringbeck F, Zappen H, Sauer DU (2018) Battery management system hardware concepts: An overview. *Applied Sciences*, 8(4), 534. https://doi.org/10.3390/app8040534

Rahimi-Eichi H, Ojha U, Baronti F, Chow M-Y (2013) Battery Management System: An Overview of Its Application in the Smart Grid and Electric Vehicles. *IEEE Industrial Electronics Magazine*, 7(2):4-16. https://doi.org/10.1109/MIE.2013.2250351

Rahmawatie B, Sutopo W, Fahma F, Purwanto A, Nizam M, Louhenapessy BB, Mulyono AB (2017) Designing framework for standardization and testing requirements of battery management system for electric vehicle application. *2017 4th International Conference on Electric Vehicular Technology (ICEVT)*, pp 7-12. https://doi.org/10.1109/ICEVT.2017.8323525

A31223: Evaluate Safety and Compliance

Notes:
None

Definitions:
Compliance - fulfillment of specified requirements. From ISO 2394:2015.

Standards:

- ISO 6469-1, Electrically Propelled Road Vehicles - Safety Specifications - Part 1: Rechargeable Energy Storage System (RESS)
- IEC 62660-3, Secondary Lithium-ion Cells for the Propulsion of Electric Road Vehicles - Part 3: Safety Requirements
- IEC 63057, Secondary Cells and Batteries Containing Alkaline or Other Non-acid Electrolytes - Safety Requirements for Secondary Lithium Batteries for Use in Road Vehicles Not for the Propulsion
- SAE J2929, Safety Standard for Electric and Hybrid Vehicle Propulsion Battery Systems Utilizing Lithium-based Rechargeable Cells
- SAE J2380, Vibration Testing of Electric Vehicle Batteries
- FMVSS, Federal Motor Vehicle Safety Standards
- CMVSS, Canadian Motor Vehicle Safety Standards

References:
Catton J, Walker SB, McInnis P, Fowler M, Fraser R, Young SB, Gaffney B (2017) Comparative safety risk and the use of repurposed EV batteries for stationary energy storage. *2017 IEEE International Conference on Smart Energy Grid Engineering (SEGE)*, pp 200-209. https://doi.org/10.1109/SEGE.2017.8052799

Zhao J, Feng X, Tran MK, Fowler M, Ouyang M, Burke AF (2024) Battery safety: Fault diagnosis from laboratory to real world. *J. Power Sources*, *598*(234111), 10-1016. https://doi.org/10.1016/j.jpowsour.2024.234111

A313: Send for New Application

See A31.

A3131: Reconfigure Battery

Notes:
Reconfiguration involves modifying a battery pack's structure/design to accommodate new components, chemistries, or applications.

Definitions:
Reconfigure - to rearrange (something) into an altered form, figure, shape, or layout (Merriam-Webster).

Standards:
See parent description (A31).

References:

Ci S, Lin N, Wu D (2016) Reconfigurable battery techniques and systems: A survey. IEEE Access, 4, 1175-1189. https://doi.org/10.1109/ACCESS.2016.2545338

A3132: Test/Certify Repurposed Battery

Notes:

Includes safety and performance testing. Also referred to as screening. May include electrochemical, observation, and other advanced testing methods (ultrasound).

Standards:

- ISO 8887-2:2023, Technical product documentation - Design for manufacturing, assembling, disassembling and end-of-life processing - Part 2: Vocabulary
- ISO 12405-4:2018, Electrically propelled road vehicles - Test specification for lithium-ion traction battery packs and systems
- ISO 6469-1, Electrically Propelled Road Vehicles - Safety Specifications - Part 1: Rechargeable Energy Storage System (RESS)
- IEC 62660-3, Secondary Lithium-ion Cells for the Propulsion of Electric Road Vehicles - Part 3: Safety Requirements
- IEC 63057, Secondary Cells and Batteries Containing Alkaline or Other Non-acid Electrolytes - Safety Requirements for Secondary Lithium Batteries for Use in Road Vehicles Not for the Propulsion
- UL 2580, Standard for Batteries for Use in Electric Vehicles
- SAE J2929, Safety Standard for Electric and Hybrid Vehicle Propulsion Battery Systems Utilizing Lithium-based Rechargeable Cells
- SAE J1798, Performance Rating of Electric Vehicle Battery Modules
- SAE J2380, Vibration Testing of Electric Vehicle Batteries
- FMVSS, Federal Motor Vehicle Safety Standards
- CMVSS, Canadian Motor Vehicle Safety Standards

References:

See A31223

A32: Remanufacture

Notes:

None

Definitions:

Remanufacturing: industrial process by which an item is returned to a like-new condition from both a quality and performance perspective. From ISO 59004:2024

Standards/Best Practices/Regulations:

- UL 1974, Evaluation for Repurposing or Remanufacturing Batteries
- ISO 59004:2024, Circular economy - Vocabulary, principles and guidance for implementation
- FMVSS No. 305a (Electric-Powered Vehicles)

References:

Casals LC, García BA, Cremades LV (2017) Electric vehicle battery reuse: Preparing for a second life. *Journal of Industrial Engineering and Management*, 10(2), 266-285. https://doi.org/10.3926/jiem.2009

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Montes T, Etxandi-Santolaya M, Eichman J, Ferreira VJ, Trilla L, Corchero C (2022) Procedure for Assessing the Suitability of Battery Second Life Applications After EV First Life. *Batteries*, 8(9), 122. https://doi.org/10.3390/batteries8090122

A321: Prepare Battery for Remanufacturing

See parent description (A32).

A3211: Safety Check/Prepare Battery for Remanufacturing

See A3111

A3212: Assess Battery for Remanufacturing

Notes:
This activity involves targeted evaluation of cells, modules, or packs for remanufacturing purposes. It is assumed that the validity of remanufacturing the unit was determined in step A2.

Definitions:
See A32

Standards:
See A32

References:
See A32

A3213: Disassemble Battery for Remanufacturing

See A31211

A322: Remanufacture Battery

Notes:
None

Definitions:
See A32

Standards:
See A32

References:
Graner M, Heieck F, Fill A, Birke P, Hammami W, Litty K (2022, November) Requirements for a process to remanufacture EV battery packs down to cell level and necessary design modifications. *In Stuttgart Conference on Automotive Production* (pp 376-386). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-031-27933-1_35

A3221: Replace or Repair Damaged Components for Remanufacturing

See A31212

A3222: Recondition Battery for Remanufacturing

See A31213

A3223: Test for Functionality/Safety

Notes:
Includes safety and performance testing. Also referred to as screening. May include electrochemical, observation, and other advanced testing methods (e.g., ultrasound).

Definitions:
None

Standards:

- ISO 8887-2:2023, Technical product documentation - Design for manufacturing, assembling, disassembling and end-of-life processing - Part 2: Vocabulary
- ISO 12405-4:2018, Electrically propelled road vehicles - Test specification for lithium-ion traction battery packs and systems

- ISO 6469-1, Electrically Propelled Road Vehicles - Safety Specifications - Part 1: Rechargeable Energy Storage System (RESS)
- IEC 62660-3, Secondary Lithium-ion Cells for the Propulsion of Electric Road Vehicles - Part 3: Safety Requirements
- IEC 63057, Secondary Cells and Batteries Containing Alkaline or Other Non-acid Electrolytes - Safety Requirements for Secondary Lithium Batteries for Use in Road Vehicles Not for the Propulsion
- UL 2580, Standard for Batteries for Use in Electric Vehicles
- SAE J2929, Safety Standard for Electric and Hybrid Vehicle Propulsion Battery Systems Utilizing Lithium-based Rechargeable Cells
- SAE J1798, Performance Rating of Electric Vehicle Battery Modules
- SAE J2380, Vibration Testing of Electric Vehicle Batteries
- FMVSS, Federal Motor Vehicle Safety Standards
- CMVSS, Canadian Motor Vehicle Safety Standards

References:
None

A3224: Reassemble Battery System and Cycle

No further information provided

A323: Install Battery

No further information provided.

A3231: Join to Frame

Notes:
None

Definitions:
Frame (EV) - any part of the frame, chassis or cradle of the vehicle to which the engine and/or transmission unit and/or the engine and transmission unit itself are attached. From ISO 9021:2020

Or
- a metal component of specified shape constituting both the device for mounting the modules and the removable elements and the device for fixing the assembly. From ISO 8668-1:1986.

Standards:
None

References:
None

A3232: Connect to Software Interface

Notes:
None

Definitions:
Interface - set of functions to provide communication between vehicle systems and a software application for diagnostics or reprogramming according to the technical requirements specified in this document. From ISO 18541-6:2018.

Standards:

- ISO 11898, Road Vehicles Controller Area Network (CAN) Package:
- ISO 17987-1:2016, Road vehicles – Local Interconnect Network (LIN)
- ISO 26262, road vehicles functional safety
- SAE 2018-08-20, Serial Control and Communications Heavy Duty Vehicle Network - Top Level Document
- SAE 2022-11-02, High-Speed CAN (HSC) for Vehicle Applications at 500 kbps with CAN FD Data at 5 Mbps J2284/5_202211
- SAE J 2602-1-2021, LIN Network for Vehicle Applications
- UL 1973, ANSI/CAN/UL Standard for Batteries for Use in Stationary, Vehicle Auxiliary Power and Light Electric Rail (LER) Applications
- UL 9540, Energy Storage Systems and Equipment

References:
None

A3233: Recondition Battery During Installation

See A31213

A3234: Reconfigure Battery for Traction Battery Application

Notes:
This includes adding a new battery management system. The application depends on the health of the battery.

See A3131

Definitions:
None

Standards:
None

References:
None

A3235: Test/Certify Remanufactured Battery

See A3132

A33: Recycle

Notes:
None

Definitions:
Recycling - process of transforming waste materials into a reusable form which may be similar to the original product or not. Adapted from ISO 24161:2022, 3.1.3.10.

Standards:

- SAE J2974_201902, Technical Information Report on Automotive Battery Recycling
- SAE J3071_201604, Automotive Battery Recycling Identification and Cross Contamination Prevention
- SAE J2984_202109, Chemical Identification of Transportation Batteries for Recycling
- SERI R2 Standard, Responsible Recycling ("R2") Standard for Electronics Recyclers
- e-Stewards Standard, Responsible Recycling and Reuse of Electronic Equipment
- ISO 8887-1:2017, Technical product documentation - Design for manufacturing, assembling, disassembling and end-of-life processing - Part 1: General concepts and requirements

References:
Baum ZJ, Bird RE, Yu X, Ma J (2022) Lithium-ion battery recycling- overview of techniques and trends. *ACS Energy* Letters, 7(2):712-719. https://doi.org/10.1021/acsenergylett.1c02602

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A331: Pretreat Battery

Notes:
None

Definitions:
Pretreat - occurs before hydro-, pyro-, or other chemical separation and purification activities. This step may include additional disassembly activities, electrolyte removal, shredding, sieving, heating, milling, washing, etc... May include additional sorting and separation steps.

Standards:

- UL 1974, Evaluation for Repurposing or Remanufacturing Batteries

References:
Amalia D, Singh P, Zhang W, Nikoloski AN (2025) A review of pretreatment methods for spent lithium-ion batteries to produce black mass–comparison of processes of Asia Pacific recyclers. *Mineral processing and extractive metallurgy review*, 46(5), 626-643. https://doi.org/10.1080/08827508.2024.2367420

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A3311: Prepare/Discharge Battery for Recycling

Notes:
None.

Definitions:
Discharge - controlled depletion of stored energy to a pre-defined amount in an electrochemical cell/battery. Sometimes described as a deep depth of discharge .

Depth of Discharge (DOD) - percentage of a rechargeable battery's capacity that has been used or cycled out of the battery during a discharge cycle. This is a complement (or additive inverse relative to 100%) to a batteries state of charge (SOC). Adapted from Park et al., (2023) (see references below).

Standards:
- SAE J1634_202104, Battery Electric Vehicle Energy Consumption and Range Test Procedure.

References:
Park SJ, Song YW, Kang BS, Kim WJ, Choi YJ, Kim C, Hong YS (2023) Depth of discharge characteristics and control strategy to optimize electric vehicle battery life. *Journal of Energy Storage*, 59, 106477. https://doi.org/10.1016/j.est.2022.106477

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https://doi.org/10.1109/ICAC61394.2024.10718731

A3312: Disassemble Battery for Recycling

Notes:
May include neutralization step.

Definitions:
Disassembling - taking apart of an assembled product into constituent materials and/or components. From ISO 8887-1:2017.

Standards:
- ISO 8887-1:2017, Technical product documentation - Design for manufacturing, assembling, disassembling and end-of-life processing - Part 1: General concepts and requirements

References:
Ramoni MO, Zhang HC (2013) End-of-life (EOL) issues and options for electric vehicle batteries. *Clean Technologies and Environmental Policy*, 15(6), 881-891. https://doi.org/10.1007/s10098-013-0588-4

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A3313: Mechanically/Chemically Pretreat Material

Notes:
This activity is completed to reduce the size and heterogeneity of materials, further sort battery material and cells, or improve the state of safety of the material. May include a neutralizing step.

This often results in the formation of black mass (aka black powder, black sand, etc.), which is material that can undergo hydro- or pyrometallurgical activities.

Definitions:
Feed (stock) - material being supplied to a processing machine.

Black Mass - shredded battery material.

Pre-treatment - activity (e.g., drying, grinding, grading) applied to a material before it enters the main treatment process. Adapted from ISO 11074:2025, 3.343.

Standards:
None

References:
Mousa E, Hu X, Ånnhagen L, Ye G, Cornelio A, Fahimi A, Bontempi E, Frontera P, Badenhorst C, Santos AC, Moreira K, Guedes A, Valentim B (2022) Characterization and thermal treatment of the black mass from spent lithium-ion batteries. *Sustainability*, 15(1), 15. https://doi.org/10.3390/su15010015

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Wang H, Liu C, Qu G, Zhou S, Li B, Wei Y (2023) Study on pyrolysis pretreatment characteristics of spent lithium-ion batteries. *Separations*, 10(4), 259. https://doi.org/10.3390/separations10040259

A33131: Shred

Notes:
Activity can be completed "wet", "dry", or under vacuum. Goal is to reduce the size of incoming material.

Definitions:
Shredding - process of cutting or tearing which reduces products (3.47) and/or materials to smaller pieces. From ISO 8887-2:2023.

Standards/Regulations/Guidelines:
- U.S. Government, 42 U.S.C. CH. 85 (§§ 7401-7671q), Clean Air Act
- OSHA (U.S.) 1910, General Industry Standards (29 CFR Part 1910)
- OSHA (U.S.) 3348-05, Guidance for the Identification and Control of Safety and Health Hazards in Metal Scrap Recycling
- Construction Industry Standards (29 CFR 1926)

References:

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Bertuol DA, Toniasso C, Jiménez BM, Meili L, Dotto GL, Tanabe EH, Aguiar ML (2015) Application of spouted bed elutriation in the recycling of lithium ion batteries. *Journal of Power Sources*, *275*, 627-632. https://doi.org/10.1016/j.jpowsour.2014.11.036

Costa H (2025) Shredding of Lithium-Ion Batteries: Overview and Industrial. *Waste Management for a Sustainable Future-Technologies, Strategies and Global Perspectives: Technologies, Strategies and Global Perspectives*, 77.

Khodadadmahmoudi G, Javdan Tabar K, Homayouni AH, Chehreh Chelgani S (2023) Recycling spent lithium batteries–an overview of pretreatment flowsheet development based on metallurgical factors. *Environmental Technology Reviews*, *12*(1), 2248559. https://doi.org/10.1080/21622515.2023.2248559

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A33132: Calcine

Notes:
Calcination results in removal of the electrolyte.

Definitions:
Calcining - to heat (as inorganic materials) to a high temperature but without fusing to drive off volatile matter or to effect changes (as oxidation or pulverization). This process is typically used for the removal of organic material, combining water and/or volatile material from a material. Adapted from ISO 13574:2015.

Standards:
None

References:
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A33133: Delamination/Screening

Notes:
None

Definitions:
Crushing - mechanical reduction of the particle size of a material by fracturing large pieces into multiple smaller pieces. From ISO 14284:2022.

Particle size reduction - process of crushing or grinding the sample to reduce the particle size. From ISO 1213-2:2024.

Standards:
None

References:
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A33134: Separate

Notes:
None

Definitions:
Froth flotation - process for cleaning fine (material) in which the (parent material), with the aid of a reagent or reagents, becomes attached to air bubbles in a liquid medium and floats as a froth. Adapted from ISO 1213-1:2020.

Electromagnetic separation - separation of metals by inducing temporary magnetic forces. Adapted from ISO 21637:2020. It can be completed using powerful magnets (ferrous materials) or rotating magnetic fields (aka Eddy Current Separators, non-ferrous materials).

Sieving/Screening (process) - A process of separating a mixture of particles according to their sizes with one or more sieves. From ISO 4551:1987. May include rotation of vibratory actions.

Air classifying (sieving) - passing a stream of air through a mixture of materials and sorting material by density.

Standards:
- ASTM E703, Eddy-Current Sorting of Non-ferrous Metals
- ASTM D5158-98(2019), Standard Test Method for Determination of Particle Size of Powdered Activated Carbon by Air-Jet Sieving
- ASTM C136 / AASHTO T 27, (Aggregates)
- AASHTO T 11, (Fine aggregates and soils)

References:
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Rinne T, Araya-Gómez N, Serna-Guerrero R (2023) A study on the effect of particle size on li-ion battery recycling via flotation and perspectives on selective flocculation. *Batteries*, *9*(2), 68. https://doi.org/10.3390/batteries9020068

Vanderbruggen A, Salces A, Ferreira A, Rudolph M, Serna-Guerrero R (2022) Improving separation efficiency in end-of-life lithium-ion batteries flotation using attrition pre-treatment. *Minerals*, *12*(1), 72. https://doi.org/10.3390/min12010072

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A33135: Treat Gas (Scrubber) from Pretreat

Notes:
None

Definitions:
Off-gassing – the evolution of gaseous products from a liquid or solid material into an atmosphere. From ISO 14624-3:2023.

Standards:

- ISO 7504:201, Gas analysis — Vocabulary
- ISO 19230:2020, Gas analysis — Sampling guidelines

References:

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A332: Pyrometallurgy

Notes:
None

Definitions:

Pyrometallurgy - a branch of extractive metallurgy that involves using high temperatures to extract and purify metals from ores or waste streams through processes such as roasting, smelting, and refining. Adapted from Zhang et al. (2022) (see references below).

Standards Subcommittees:

- ASTM B02 on Nonferrous Metals and Alloys
- ASTM B07 on Light Metals and Alloys
- ASTM E01 on Analytical Chemistry for Metals, Ores, and Related Materials
- ISO/TC 119/SC 2, Powder metallurgy
- ISO/TC 155: Nickel and nickel alloys
- ISO/TC 183: Copper, lead, zinc, and nickel ores and concentrates
- ISO/TC 345: Materials for specialty technologies
- ISO/TC 132: Ferroalloys
- ISO/TC 102: Iron ore and direct reduced iron

References:

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A3321: Heat Pretreat, Pyrometallurgy

Notes:
This process may involve roasting, calcination, and sintering. It also includes applying controlled heat and/or specific atmospheric conditions to a material before the main high-temperature extraction process. This approach removes impurities and alters the chemical and physical composition of the feed material, ultimately enhancing the recovery rates of the desired materials.

Definitions:
Roasting – processing of treating (feedstock) at elevated temperatures to obtain oxides. Adapted from ISO 22444-1:2020.

Calcination – See A33132

Sintering – thermal treatment of a powder or (material), at a temperature below the melting point of the main constituent, for the purpose of increasing its strength by the metallurgical bonding of its particles. Adapted from ISO 3252:2023.

Standards/Subcommittees:
- See A332

References:
Hu X, Mousa E, Ye G (2025, February) Opportunities and Challenges in Lithium-Ion Battery Recycling: Emphasis on Pretreatment and Pyrometallurgical Processing. In *TMS Annual Meeting & Exhibition* (pp 23-31). Cham: Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-80892-0_3

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Wang H, Liu C, Qu G, Zhou S, Li B, Wei Y (2023) Study on pyrolysis pretreatment characteristics of spent lithium-ion batteries. *Separations*, *10*(4), 259. https://doi.org/10.3390/separations10040259

A3322: Pyrolysis/Smelting

Notes:
None

Definitions:
Pyrolysis - decomposition brought about by high temperatures (Merriam Webster).

Smelting – production of metal through a process where energy is applied to feed material. Adapted from ISO 13574:2015.

Standards/Regulations:

- U.S. EPA, National Emission Standards for Hazardous Air Pollutants
- U.S. EPA, New Source Performance Standards
- U.S. EPA, Effluent Limitation Guidelines

References:

Cornelio A, Zanoletti A, Bontempi E (2024) Recent progress in pyrometallurgy for the recovery of spent lithium-ion batteries: A review of state-of-the-art developments. *Current Opinion in Green and Sustainable Chemistry*, 46, 100881. https://doi.org/10.1016/j.cogsc.2024.100881

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A3323: Treat Gas for Pyrometallurgy

See A33135 and A3322.

A33231: Filter Gas

See A33135 and A3322.

A33232: Leach for Pyrometallurgy Gas Treatment

No further information provided

A33233: Precipitate for Pyrometallurgy Gas Treatment

No further information provided

A3324: Leach, Pyrometallurgy

Notes:
Completed on alloy or slag material produced from pyrolysis/smelting step. Can be followed by hydrometallurgy steps (A333).

Definitions:
Leaching – a process that treats (material) with liquid solvents for the recovery of minerals. Adapted from ISO 22932-8:2025. *Bioleaching* involves the use of bio-organisms as the leaching agent.

Standards:

- ISO 22932-8:2025, Mining — Vocabulary — Part 8: Extraction
- U.S. Test Methods for Evaluating Solid Waste, Physical/Chemical Methods (SW-846)
- U.S. EPA, Effluent Limitation Guidelines
- U.S. EPA, New Source Performance Standards

References:
Gao W, Liu C, Cao H, Zheng X, Lin X, Wang H, Zhang Y, Sun Z (2018) Comprehensive evaluation on effective leaching of critical metals from spent lithium-ion batteries. *Waste Management*, 75, 477-485. https://doi.org/10.1016/j.wasman.2018.02.023

Holzer A, Windisch-Kern S, Ponak C, Raupenstrauch H (2021) A novel pyrometallurgical recycling process for lithium-ion batteries and its application to the recycling of LCO and LFP. *Metals*, 11(1), 149. https://doi.org/10.3390/met11010149

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A3325: Oxidize, Pyrometallurgy

Notes:
Can be completed on leached (from A3324) or further refined (via hydrometallurgy, A333) produced materials.

Definitions:
None

Standards:
None

References:
None

A3326: Sinter/Screen, Pyrometallurgy

See A3321 and A33134.

A333: Hydrometallurgy

Notes:
None

Definitions:
Hydrometallurgy - branch of extractive metallurgy that uses aqueous solutions, or water-based chemical processes to extract and purify metals from ores or waste streams through processes such as leaching, solvent extraction, and ion exchange.

Standards:

- ISO 77.120, Non-ferrous metals: Including classification, designation, sampling, chemical analysis, etc.
- ISO/IEC 17025:2017, General requirements for the competence of testing and calibration laboratories
- ISO 4907-1:2023 Plastics - Ion exchange resin - Part 1: Determination of exchange capacity of acrylic anion exchange resins
- ASTM E2941-21, Standard Practices for Extraction of Elements from Ores and Related Metallurgical Materials by Acid Digestion

References:
Brückner L, Frank J, Elwert T (2020) Industrial recycling of lithium-ion batteries—a critical review of metallurgical process routes. *Metals*, 10(8), 1107. https://doi.org/10.3390/met10081107

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Larouche F, Tedjar F, Amouzegar K, Houlachi G, Bouchard P, Demopoulos GP, Zaghib K (2020) Progress and status of hydrometallurgical and direct recycling of Li-ion batteries and beyond. *Materials*, 13(3), 801. https://doi.org/10.3390/ma13030801

Lee C, Arby DS, Kim C, Lim J, Kwon K, Chung E (2025) Hydrometallurgical process of spent lithium-ion battery recycling Part. 1 Chemical leaching of valuable metals from cathode active materials: Review and case study. *Hydrometallurgy*, 106494. https://doi.org/10.1016/j.hydromet.2025.106494

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Swain B, Jeong J, Lee JC, Lee GH, Sohn JS (2007) Hydrometallurgical process for recovery of cobalt from waste cathodic active material generated during manufacturing of lithium ion batteries. *Journal of Power Sources*, *167*(2), 536-544. https://doi.org/10.1016/j.jpowsour.2007.02.046

Tedjar F, Foudraz JC (2013) Method for the mixed recycling of lithium-based anode batteries and cells (Canadian Patent No. CA 2559928 C). Canadian Intellectual Property Office (as cited in Pinegar et al., (2019)).

Zhang P, Yokoyama T, Itabashi O, Suzuki TM, Inoue K (1998) Hydrometallurgical process for recovery of metal values from spent lithium-ion secondary batteries. *Hydrometallurgy*, 47(2-3), 259-271. https://doi.org/10.1016/S0304-386X(97)00050-9

A3331: Leach, Hydrometallurgy

Notes:
None

Definitions:
Leaching – See A3324.

Standards:
None

References:
Chagnes A, Pospiech B (2013) A brief review on hydrometallurgical technologies for recycling spent lithium-ion batteries. *Journal of Chemical Technology & Biotechnology*, *88*(7), 1191-1199. https://doi.org/10.1002/jctb.4053

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Vieceli N, Nogueira CA, Guimarães C, Pereira MF, Durão FO, Margarido F (2018) Hydrometallurgical recycling of lithium-ion batteries by reductive leaching with sodium metabisulphite. *Waste Management*, *71*, 350-361. https://doi.org/10.1016/j.wasman.2017.09.032

A3332: Solvent Extract

Notes:
None

Definitions:
Solvent extraction – a fractionation process based upon the difference in solubility, in a given solvent of the various constituents of the mixture to be fractionated. From ISO 1998-4:1998.

Standards:

- U.S. EPA Method 3570 (SW-846), Microscale Solvent Extraction (MSE)
- ASTM E2941-21, Standard Practices for Extraction of Elements from Ores and Related Metallurgical Materials by Acid Digestion

References:

Granata G, Pagnanelli F, Moscardini E, Takacova Z, Havlik T, Toro L (2012) Simultaneous recycling of nickel metal hydride, lithium ion and primary lithium batteries: Accomplishment of European Guidelines by optimizing mechanical pre-treatment and solvent extraction operations. *Journal of Power Sources*, *212*, 205-211. https://doi.org/10.1016/j.jpowsour.2012.04.016

Lei S, Sun W, Yang Y (2022) Solvent extraction for recycling of spent lithium-ion batteries. *Journal of Hazardous Materials*, *424*, 127654. https://doi.org/10.1016/j.jhazmat.2021.127654

Nguyen TH, Lee MS (2018) A review on the separation of lithium ion from leach liquors of primary and secondary resources by solvent extraction with commercial extractants. *Processes*, *6*(5), 55. https://doi.org/10.3390/pr6050055

Tang YC, Wang JZ, Shen YH (2023) Separation of valuable metals in the recycling of lithium batteries via solvent extraction. *Minerals*, *13*(2), 285. https://doi.org/10.3390/min13020285

Vieceli N, Vonderstein C, Swiontekc T, Stopić S, Dertmann C, Sojka R, Reinhardt N, Ekberg C, Friedrich B, Petranikova M (2023) Recycling of Li-ion batteries from industrial processing: Upscaled hydrometallurgical treatment and recovery of high purity manganese by solvent extraction. *Solvent Extraction and Ion Exchange*, *41*(2), 205-220. https://doi.org/10.1080/07366299.2023.2165405

Wesselborg T, Virolainen S, Sainio T (2021) Recovery of lithium from leach solutions of battery waste using direct solvent extraction with TBP and FeCl3. *Hydrometallurgy*, *202*, 105593. https://doi.org/10.1016/j.hydromet.2021.105593

A3333: Scrub

Notes:
None

Definitions:
Scrubbing – a purification step that removes unwanted impurities from the organic solvent containing the desired product after an extraction cycle.

Standards:
See A333.

References:

Nguyen VNH, Lee MS (2020) Separation of Co (II), Cu (II), Ni (II) and Mn (II) from synthetic hydrochloric acid leaching solution of spent lithium ion batteries by solvent extraction. *Physicochemical Problems of Mineral Processing*, *56*(4), 599-610. https://doi.org/10.37190/ppmp/122784

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Vieceli N, Vonderstein C, Swiontekc T, Stopić S, Dertmann C, Sojka R, Reinhardt N, Ekberg C, Friedrich B, Petranikova M (2023) Recycling of Li-ion batteries from industrial processing: Upscaled hydrometallurgical treatment and recovery of high purity manganese by solvent extraction. *Solvent Extraction and Ion Exchange*, *41*(2), 205-220. https://doi.org/10.1080/07366299.2023.2165405

A3334: Strip

Notes:
See A3333 and A333.

Definitions:
Stripping - an aqueous solution or other medium used to reverse the extraction process, transferring a target metal from the organic phase back into the aqueous phase in a purified and concentrated form. Adapted from US5228903A (see references).

Standards:
None

References:
See A3333 and A333.

O'Keefe TJ (1993) Method for stripping metals in solvent extraction (U.S. Patent No. 5228903 A). U.S. Patent and Trademark Office.

A3335: Precipitate/Electrowinning

Notes:
None

Definitions:
Electrowinning- process of recovering metals from solutions, such as dissolved ores, by using electrolysis to deposit the pure metal onto an electrode (Merriam-Webster).

Precipitation – a chemical reaction in solution resulting in the formation of a solid product. From ISO 23044:2020.

Standards:
None

References:
Chagnes A, Pospiech B (2013) A brief review on hydrometallurgical technologies for recycling spent lithium-ion batteries. *Journal of Chemical Technology & Biotechnology*, *88*(7), 1191-1199. https://doi.org/10.1002/jctb.4053

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Nickel and Cobalt (pp 99-110). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-030-65647-8_7

Xing P, Wang C, Wang L, Ma B, Chen Y (2019) Hydrometallurgical recovery of lead from spent lead-acid battery paste via leaching and electrowinning in chloride solution. *Hydrometallurgy*, *189*, 105134. https://doi.org/10.1016/j.hydromet.2019.105134

Appendix B. NIST IDEF0 Models

NIST has developed several IDEF0 models in the past that have influenced the TLB-R model described in this report. The *Systems Integration of Manufacturing Applications* (SIMA) Reference Architecture [38] is a foundational model focused on manufacturing activities. Both the GreenSIMA model [39] and the *Smart Manufacturing Reference Architecture* (SMRA) [40] build upon the SIMA model to provide a focus that was missing in the original model. The GreenSIMA model focuses on sustainable manufacturing activities and the SMRA focuses on facility design. Following the release of these models, the *Production in a Circular Economy* (PCE) model [41–44] was developed to provide the activities and the flow of materials and information in a Circular Economy (CE).

The SIMA model describes the functions utilized to develop a product from the point of conception to production. The model provides a reference architecture that defines the functions of software systems in the product creation process, their relationships, and the necessary information interfaces between them. The SIMA model describes the general activities common to manufacturing and illustrates the flow of information that allows those activities to function. This frame of reference provides a structure for defining and scoping interfaces by helping projects name and locate them based on the functions they support.

In 2014, NIST developed an extension to the SIMA model to consider efficient and sustainable manufacturing activities. This model is referred to as the GreenSIMA model [39]. The GreenSIMA model identified key factors to consider, including water and material consumption, energy use, emissions, and waste. The model identifies existing items in the SIMA model and adds efficiency-related information, along with associated calculations. The model also incorporates new information necessary to perform these calculations.

Building on the GreenSIMA model, NIST further developed the SIMA model with the SMRA [40], which provides a list of engineering and operational functions involved in producing discrete products, along with the information flows among them. The reference architecture models the integration of manufacturing software for the fabrication and assembly of electromechanical parts. The SIMA model provided a reference architecture that described how a manufacturing facility made a product. The SMRA model builds upon this architecture but focuses on how a manufacturing facility is designed to produce a product.

Recently, NIST developed the PCE model [41], which expands upon these three models by providing a manufacturing-focused activity diagram that incorporates recovery, materials, and waste into the activities and flows. The goal of the PCE model was to provide a preliminary framework for discussing CE and its impact across life cycle phases. CE is a “systemic approach to maintain a circular flow of resources by recovering, retaining or adding to their value” [27] and addresses the challenges of material sourcing and supply chain vulnerability by prioritizing recovery and product life extension. The PCE model includes the five activities of design product, acquire materials, produce product, use and consume, and treat at end of life. The model was first proposed in Reslan et al. [42], where the authors defined the model’s top level. The PCE model was later expanded to include more detail for design [43] and EOL [44]. Ferrero et al. [43] expanded the *Design Product* (A1) activity, and Mathur et al. [44] expanded the *Treat* *at End of Life* (A5) activity. The TLB-R model presented in this report focuses on treatment at EOL, corresponding to A5 in the PCE model. The TLB-R model presented in this report was first proposed in Triebe et al. [45] and has been adapted from the PCE model.

Appendix C. Decomposition Table of Activities

Activity ID	Description
A0	Treat Batteries and Battery Materials
A1	Collect Batteries/Battery Materials
A2	Test and Sort Batteries/Battery Materials
A3	Recover Materials/Devices
A31	Repurpose
A311	Prepare Battery for Repurposing
A3111	Safety Check/Prepare Battery for Assessment
A3112	Assess Functionality for Repurposing
A312	Repurpose Battery
A3121	Repair Battery
A31211	Disassemble Battery for Repurposing
A31212	Replace or Repair Damaged Components for Repurposing
A31213	Recondition Battery for Repurposing
A31214	Reassemble Battery for Repurposing
A3122	Test Battery with Battery Management System
A31221	Test Thermal Behavior
A31222	Test Battery Management System
A31223	Evaluate Safety and Compliance
A313	Send for New Application
A3131	Reconfigure Battery
A3132	Test/Certify Repurposed Battery
A32	Remanufacture
A321	Prepare Battery for Remanufacturing
A3211	Safety Check/Prepare Battery for Remanufacturing
A3212	Assess Battery for Remanufacturing
A3213	Disassemble Battery for Remanufacturing
A322	Remanufacture Battery
A3221	Replace or Repair Damaged Components for Remanufacturing
A3222	Recondition Battery for Remanufacturing
A3223	Test for Functionality/Safety
A3224	Reassemble Battery System and Cycle
A323	Install Battery
A3231	Join to Frame
A3232	Connect to Software Interface
A3233	Recondition Battery During Installation
A3234	Reconfigure Battery for Traction Battery Application
A3235	Test/Certify Remanufactured Battery
A33	Recycle

A331	Pretreat Battery
A3311	Prepare/Discharge Battery for Recycling
A3312	Disassemble Battery for Recycling
A3313	Mechanically/Chemically Pretreat Material
A33131	Shred
A33132	Calcine
A33133	Delamination/Screening
A33134	Separate
A33135	Treat Gas (Scrubber) from Pretreat
A332	Pyrometallurgy
A3321	Heat Pretreatment, Pyrometallurgy
A3322	Pyrolysis/Smelting
A3323	Treat Gas for Pyrometallurgy
A33231	Filter Gas
A33232	Leach for Pyrometallurgy Gas Treatment
A33233	Precipitate for Pyrometallurgy Gas Treatment
A3324	Leaching, Pyrometallurgy
A3325	Oxidize, Pyrometallurgy
A3326	Sinter/Screen, Pyrometallurgy
A333	Hydrometallurgy
A3331	Leaching, Hydrometallurgy
A3332	Solvent Extract
A3333	Scrub
A3334	Strip
A3335	Precipitate/Electrowinning

Appendix D. Acronyms

BMS
Battery Management System

CE
Circular Economy

EOL
End-of-Life

EV
Electric Vehicle

EVB
Electric Vehicle Battery

FDI
Factory Design and Improvement

IDEF0
Integration Definition 0

NIST
National Institute of Standards and Technology

PCE
Production in a Circular Economy

RUL
Remaining Useful Life

SIMA
Systems Integration for Manufacturing Applications

SMRA
Smart Manufacturing Reference Architecture

TLB
Traction Lithium Battery

TLB-R
Traction Lithium Battery Recovery

USGS
U.S. Geological Survey