BESS Frequency of Failure Research Topic

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This article is an introduction to the current state of failure frequency research for Battery Energy Storage Systems (BESS). This is the second article in a six-part series. To read other articles in this series, click here.

BESS is a subset of Energy Storage Systems (ESS), which is a system of devices intended to store energy and then release for use. BESS is specifically the type of ESS that uses a rechargeable battery for energy storage, a component to convert/release the electrical energy into motive force or to feed an electric grid/device(s), often with a Battery Management System (BMS) to control its performance and ensure safety. BESS is utilized in a multitude of applications, but the most attention is paid to the growing field of vehicular batteries for hybrid or fully electric vehicles, and stationary battery systems for electrical grids or facilities. In article one of this series, battery failures and the mechanisms of how they occur, and techniques used to evaluate them were discussed. This article discusses the frequency of such failures, which can in turn be helpful in determining the risk from such systems. Failure rate predictions of BESS are conducted with a variety of methods and with differing amounts of success. Review of literature on this topic shows that there are numerous factors that limit the accuracy and usefulness of these prediction methodologies. The primary factors are:

- **BESS has many failure modes, and they are not uniformly defined.** There are many different failure modes for different batteries, or under different configurations. Even among the Lithium-ion batteries (by far the most used in the market), each type has widely different characteristics with regards to fire resistance, fire and explosion propagation, and resilience to ambient conditions. This is not including factors such as manufacturing flaws, the wide range of operating conditions that BESS are subjected to, and effectiveness of the BMS. There are also non-Lithium-ion batteries with different chemical characteristics or mode of operations, such as flow batteries, which have different failure modes and risks.
- **BESS reliability data is scarce**. The publicly available data is limited and non-uniform. Additionally, data recorded is often in the range of fixed temperatures and with fixed cycling conditions. These conditions do not reflect the variability of real-world use.
- **BESS design changes are 'fast paced'**. The drive to develop BESS with more energy density, efficiency, and higher integrity results in changes in BESS design at a high pace. This changes the potential failure modes and frequencies of BESS being modeled, and gathering potentially obsolete failure rate data from older designs.

Standard "simple" equations of component failures

A BESS consists of not only the battery cell but multiple components that can fail and cause the chain of events that result in hazards. Failure rates for BESS can be roughly estimated by conducting failure mode analysis (fault tree, FMEA, etc.) and evaluating the failure rates of each component in its system to determine the overall failure rate. Because failure rates for electronic instrumentation and components are extensively studied, there are simplified equations to estimate failure rates that are commonly used for electronic systems. The IEC TR62308-2004[1] provided calculation equations that were used in a large body of work assessing BESS failures of electric vehicles. The usefulness of these equations is uncertain as the failure rates were not specified for types of failure, and the failure of the battery module is too generic to account for the wide (widening) range of battery systems in the market today. It follows that IEC TR62308-2004 was withdrawn by IEC, and in its place a new IEC TR62308-2006 was re-issued for reliability testing methodology. While there is ongoing research and studies of electric vehicles that use those equations from IEC TR62308-2004, an accurate estimation of battery failure rates will require a new approach, as described below.

Physics based model of prediction

Physics of Failure (PoF) methodology was developed to determine the reliability of early generation electronic parts and systems. It is the use of degradation algorithms that describe how physical, chemical, mechanical, thermal, or electrical mechanisms evolve over time and eventually induce failure. This approach takes the understanding of battery chemistry, material of construction, component failure modes, degradation mechanisms, test experience, etc. to develop first-order equations that allow the design or reliability engineer to predict the time to failure behavior based on information on the design architecture, materials, and environment.

This methodology is already utilized in virtual simulations in industries like aircraft design. However, significant testing is necessary to develop the understanding of battery failure for each type of battery, and proper assumptions are needed to ensure the models developed are accurate. Ultimately, PoF development requires highly knowledgeable experts to perform the analysis, and in developing technologies like BESS, such expertise is not widely available. PoF is not the only type of physics-based approach to model battery failure modes, performance, and degradation process. Other physics-based models have similar issues in development as PoF, and as such they work best with support of empirical data to verify assumptions and tune the results.

Empirical model of prediction

Assessment of instrumentation failures are often performed using failure distribution models to combine time failure data and simplified equations to estimate failure. For example, distribute major types of failures for electronic components such as early failures, random failures, and wear out failures into a 'bathtub' curve. Figure 1 shows an example of how failures are combined to generate a 'bathtub' curve.

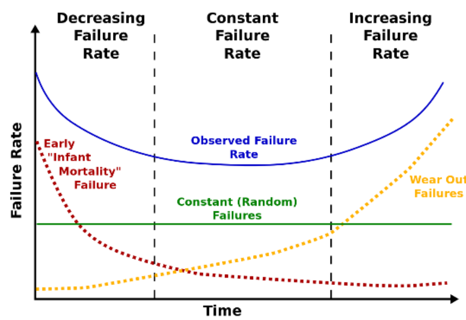

Figure 1. Generic Examples of Bathtub Curves[2]

[1] IEC TR62308-2004, Reliability data handbook - Universal model for reliability prediction of electronics components, PCBs and equipment, International Electro technical Commission, Geneva, 2004

[2] Wyrwas, Edward & Condra, Lloyd & Hava, Avshalom. (2011). Accurate Quantitative Physics-of-Failure Approach to Integrated Circuit Reliability. IPC APEX EXPO Technical Conference 2011.

Standard “simplified equations” used for instrumentation systems generally use the ‘constant’ failure rate value in the ‘useful life’ section of the curve. This is due to the tendency of the random failures being representative of the majority of the instrument’s life-cycle of use. While this approach is widely used for electronic components, it is not appropriate for hazardous evaluation of battery cell failure where significant failure modes of interest tend to be caused by flawed construction (early failures) or degradation (wear out).

BESS will require different distribution models and significant data sets for each type of BESS and configuration. Currently, the most popular type of batteries (Lithium-ion) is receiving the largest share of attention from researchers; however, testing is performed only for a small number of battery cells. For example, investigation of cycling data from the beginning to the end of a battery’s life requires a significant investment of time and resources spanning many months or years. Several organizations have made their testing data for battery cycling public, as listed in Table 1:

Table *1*. Publicly Available Battery Overcycle Data Sets[3]

Source	URL
National Aeronautic and Space Administration (NASA)	https://ti.arc.nasa.gov/tech/dash/groups/pcoe/prognostic-data-repository/
Centre for Advanced Life Cycle Engineering (CALCE)	https://web.calce.umd.edu/batteries/data.htm
Toyota research institute (TRI)	https://data.matr.io/1/
Sandia National Laboratory	https://www.batteryarchive.org/snl_study.html
Battery intelligence lab at Oxford	https://howey.eng.ox.ac.uk/data-and-code/
Hawaii Natural Energy Institute (HNEI)	https://www.batteryarchive.org/study_summaries.html
EVERLASTING Project funded by European Commission	https://data.4tu.nl/articles/dataset/ Lifecycle_ageing_tests_on_commercial_18650_Li_ion _cell_10_C_and_0_C/1437729
Karlsruhe Institute of Technology (KIT)	https://rdr.ucl.ac.uk/articles/dataset/Lithium-ion_Battery_INR18650_MJ1_Data_400_Electrochemical_Cycles_EIL-015_/12159462/1
University College London (UCL)	https://publikationen.bibliothek.kit.edu/1000094469
UC Berkeley	https://data.mendeley.com/datasets/c5dxwn6w92/1
Xi’an Jiaotong University	https://datadryad.org/stash/dataset/doi:10.6078/D1MS3X
Diao et al. (paper)	https://data.mendeley.com/datasets/c35zbmn7j8/1
Poznan University of Technology	https://data.mendeley.com/datasets/k6v83s2xdm/1

However, most have less than 50 battery cells tested, and none have more than 240 cells tested. Fortunately, research is proceeding at a significant pace, and public data storage platforms are providing common and easily navigable locations to find and (possibly) share data. They also promote standardization in data format and descriptions. Some well-known platforms are listed in Table 2:

[3] Dos Reis, Gonçalo & Strange, Calum & Yadav, Mohit & Li, Shawn. (2021). Lithium-ion battery data and where to find it. Energy and AI. 5. 100081. 10.1016/j.egyai.2021.100081.

Table 2. Platforms with Freely Accessible Battery Data Sets

Source	URL
Battery archive, developed at the City University of New York Energy Institute	https://www.batteryarchive.org/
U.S. Department of Energy's Office of Electricity (DOE OE)	https://www.sandia.gov/energystoragesafety-ssl/research-development/research-data-repository/
National Renewable Energy Laboratory (NREL)	https://www.nrel.gov/research/data-tools.html

Additionally, some battery testing data have been deposited at publicly accessible data repositories (see Table 3). These repositories provide users with a storage medium for their open-source data, i.e., generate a Digital Object Identifier (DOI), to make them citable and trackable, and in some cases provide data review and quality assurance.

Table *3*. Curated Public Data Repositories with Battery Data Sets3

Source	URL
Dryad	https://datadryad.org/stash
Zenodo	https://zenodo.org/
European federation of data driven innovation hubs	https://euhubs4data.eu/datasets/
Mendeley data center	https://data.mendeley.com/
4TU.ResearchData	https://data.4tu.nl/

<u>Summary of the state of Failure Rate Research</u>

Currently, the communication of data between end-users, manufacturers, distributors, and providers is poor. There are not many instances of 1) field data shared publicly for battery failures, 2) second-life battery failure data, 3) abuse testing data, and 4) data containing mechanical measurements. Furthermore, there is a general lack of consensus on the way to present data, making efforts difficult to combine or evaluate dataset together. There is considerable room for further research, particularly testing and collection of field observations to generate failure rate models that are accurate and applicable to a greater number of BESS.

BakerRisk is currently working on performing statistical analysis on the failure rate data available, as well as setting up tests to simulate failure; and invites participants in this effort. Once the failure modes and frequency are established, it is important to understand what the consequences of failure may be expected. This is the topic of the third article in this six-part series.