Ridgetop Group Inc
ENGINEERING INNOVATION

# CellSage™ Software User Guide

CellSage™
ridgetopgroup.com

Advanced Battery Health Modeling, Simulation, and Analysis


**Prepared and Distributed by:**

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To maintain the quality of our publications, we need your comments on the accuracy, clarity, organization, and value of this user guide.

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# Revision Record

| Release | Date | Remarks |
|---|---|---|
| 1.0 | December 06, 2021 | First release. |
| 1.1 | February 11, 2022 | Second release. |
| 1.2 | March 1, 2022 | Third release. |
| 1.3 | March 29, 2022 | Fourth release. |
| 1.4 | April 27, 2022 | Fifth release with automatic calculation for duty cycle time breakdown and CSI parameter. |
| 1.5 | June 22, 2022 | Sixth release with new plots & overlay feature. |
| 1.6 | October 21, 2022 | Seventh release with reorganized data output files and new plotting capabilities. |
| 1.7 | November 22, 2023 | Eighth release with New Chemistry Import Feature. |
| 1.8 | November 28, 2023 | Ninth release. |
| 1.9 | April 5, 2024 | Tenth release with new autofit for initial SRE estimation. |

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# 1. Introduction to CellSage™

## 1.1 Introduction

Welcome and congratulations on your purchase of CellSage™! This innovative technology is an advanced battery and cell aging software simulation tool that represents over a decade of research in electrochemistry, physics, and thermodynamics. Under license from the United States Department of Energy's Idaho National Laboratory (INL), Ridgetop Group Inc. (Ridgetop) has significantly enhanced and extended this battery simulation technology to offer customers a unique toolbox for modeling and determining the long-term performance and aging effects of battery packs used in electric vehicles (EV), robotics, power tools, stationary power backup systems, and other battery powered devices and/or systems. CellSage™ allows battery end users to create "what if" scenarios to weigh the impact of operational and environmental stress factors on battery performance and battery health.

In the last decade there has been a massive surge in the adoption and deployment of lithium-ion batteries, and innovative tools like CellSage™ are needed to characterize the performance and behavior of battery-based energy systems throughout the entire product lifecycle. The simulations results and analysis provided by CellSage™ help to select the most appropriate battery for a given mission, and also helps battery researchers determine what secondary applications can make use of the same battery after it has served its initial purpose and mission.

As a standalone software simulation tool, CellSage™ provides the following technology benefits and value proposition:

- Addresses diagnostic and prognostic evaluations of battery-based energy systems, including capacity fade.
- Optimizes battery life and warranty periods by investigating how various battery chemistries age and degrade in response to different usage profiles during a simulated battery life cycle.
- Helps to reduce costs associated with upfront cycle life testing by at least 50%, while also reducing the cost of battery pack designs by at least 5-20%.
- Helps to refine battery management system (BMS) strategies to reduce battery aging by at least 10-25%.

Note that the estimated metrics listed above were identified through the Energy I-Corps program as a joint effort between Ridgetop and INL. According to https://energyicorps.energy.gov/, the Energy I-Corps program is a training program that connects national laboratory researchers with industry mentors and partners like Ridgetop Group to define value propositions, conduct customer discovery exercises, and develop viable market pathways for innovative technologies.

The User Guide presented here encapsulates the latest advancements in the commercialization endeavors conducted by Ridgetop and INL with regard to the CellSage™ Detailed Cycling Conditions (DCC) Simulation Module and the CellSage™ New Chemistry Import Feature. Since 2015, Ridgetop and INL have fostered a robust partnership, both in the business and technology domains. Through collaborative initiatives, they have effectively collaborated with industry peers to ensure that CellSage™ aligns seamlessly with the specific application needs of their customers in the fields of battery life modeling, simulation, and analysis, spanning primary and secondary usage scenarios.

The CellSage™ Battery Health Modeling, Simulation, and Analysis (MS&A) software platform represents one of the earliest scientific software tools available in the market. Additionally, it serves as a prominent illustration of successful collaboration between the U.S. Department of Energy's Office of Technology Transitions and small businesses, facilitating the commercialization of cutting-edge R&D originating from the U.S. National Laboratories. The CellSage™ collection of battery health MS&A software tools is also safeguarded by a series of U.S. Patents and Copyrights, as listed Section 6.1 in the Appendix.

**About INL:** As one of 17 national labs in the U.S. Department of Energy complex, Idaho National Laboratory (INL) is home to more than 5,700 researchers and support staff focused on innovations in nuclear research, renewable energy systems, and security solutions that are changing the world. From discoveries in advanced nuclear energy to carbon-free energy options and to protecting our nation's most critical infrastructure assets, the talented team at INL is constantly pushing the limits to redefine what's possible. To find out more information about INL visit their website at www.inl.gov.

**About Ridgetop Group:** Ridgetop, founded in 2000, is an established engineering and technology company that provides condition-based maintenance (CBM), prognostic health management (PHM), and reliability engineering solutions to government and commercial organizations around the world. CellSage™ is a key component in Ridgetop's technology set which is aimed at helping customers ensure precise identification and isolation of system anomalies, advance notice of impending failure, and the necessary combination of firmware, hardware, and software solutions for mission critical systems. Ridgetop is headquartered in Tucson, Arizona and has a dedicated staff of highly qualified researchers, engineers, and data scientists who support the business development team to develop, deploy, and commercialize the most innovative solutions. Ridgetop is also an AS9100D and ISO9001:2015 certified organization by the Management Certification of North America (MCNA). More information on Ridgetop's complete list of products and services can be reviewed on our website at www.ridgetopgroup.com.

## 1.2 Technology Background

The underlying technology core of CellSage™ represents the culmination of over a decade of research and study into the degradation mechanisms of lithium-ion based energy storage devices. As it became apparent that lithium-ion chemistries were becoming a foundation for electrification, the US National Laboratories, including INL, began investigating the behavior and failure modes of lithium battery cells. Recognizing that these devices would be the cornerstone of the new energy economy, the Department of Energy began funding the research. Under the guidance of Dr. Kevin Gering, principal investigator, several existing research programs were extended, and new research programs were developed to really understand how lithium cells behave during their anticipated lifecycle.

Battery testing has been around for many years. Among the common methodologies were load testing, repeated charge and discharge cycling, as well as electrical impedance spectroscopy (EIS.)

However, Dr. Gering and other researchers weren't satisfied that the functional testing was enough to fully evaluate the life-cycle characteristics. They speculated further that not only does the temperature of cells affect the performance and life-cycle, but that ambient conditions such as the temperature variations of the specific geographical operating region also had an impact on the life-cycle of batteries and their component cells.

The research community began to develop a key concept in order to design experiments and interpret the test results. "Aging path dependence" is a concept that is key to understanding how CellSage™ evaluates battery cells, and how "path dependence" is an important factor for any battery that undergoes prolonged usage in one or more applications. This is especially true if battery usage patterns continue to change during their service life. In the context of lithium-ion cells in arbitrary service (vehicle applications, laptop, and consumer electronics) the extent of aging experienced by a cell at a given point in its life depends on the cumulative stress encountered under aging conditions by the cell at that point.

Path dependence asserts that the sequence of aging conditions (as well as the nature of conditions) has a direct influence on the rate of aging and net aging along the timeline. "(From L. Gering, et. al. (2011). See also "Investigation of path dependence in commercial lithium-ion cells chosen for plug-in hybrid vehicle duty cycle protocols." Journal of Power Sources. 196. 3395-3403. 10.1016/j.jpowsour.2010.05.058.)

- **Aging Path Dependence** asserts that the *sequence* of aging conditions along the timeline (as well as their magnitude) has a direct influence on the irreversible aging trends of battery systems and their operational envelopes. Aging history is unique to the path.
- **Reaction kinetics and thermodynamics** are key to understanding the aging process along the path. A change in aging conditions (stress inputs) can accelerate or decelerate degradation mechanisms and can initiate new ones.
- **Cell aging models** (in use by CellSage™) can simultaneously judge loss of capacity, rise in impedance, loss of power, polarization effects, etc., where each have a standardized basis. (From Gering et. al., "CellSage™ Modeling Tool for Diagnostic and Predictive Evaluations of Battery Life and Mission Readiness"

An illustration of aging path dependence is shown in Figure 1, "wherein an arbitrary relative performance loss (capacity fade and power fade) plotted against aging time, shows four distinct aging regions. This is an idealized plot for illustration purposes. The reference extent of performance loss, (* or star) is shown for the four aging regions or periods being in the …order they are in the figure. Under a true path dependence scenario, a random re-arrangement of the order of aging periods will not necessarily yield the identical loss of relative performance (*) at the end of the fourth period. In fact, based upon the principles of reaction kinetics that proceed from an intermediate state and related thermodynamic constraints, we should expect the cumulative performance loss under a random rearrangement of aging conditions to produce net aging that is different from any other rearrangement." (From L. Gering, et. al. (2011). "Investigation of path dependence in commercial lithium-ion cells chosen for plug-in hybrid vehicle duty cycle protocols." Journal of Power Sources. 196. 3395-3403. 10.1016/j.jpowsour.2010.05.05

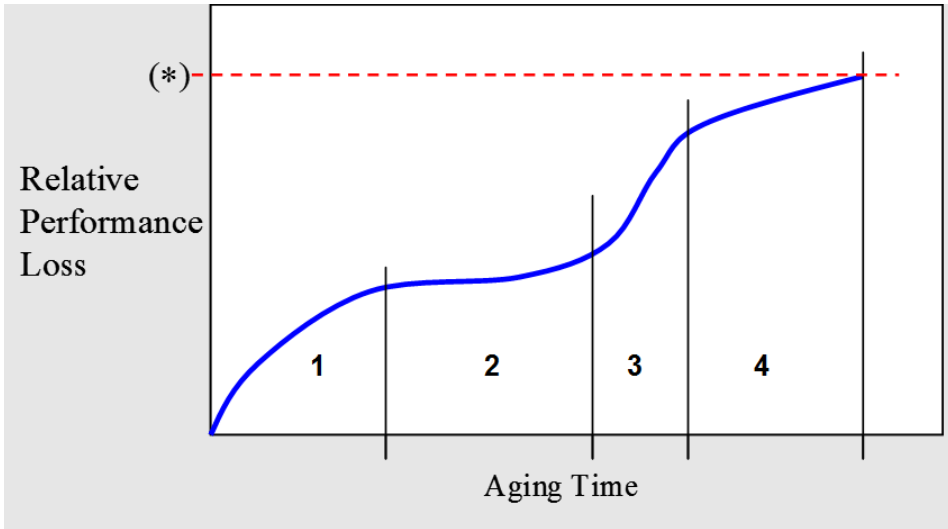



**Figure 1. Shown is an idealized projection of a path dependence.**

An actual cell might encounter many times more unique aging conditions while in service. CellSage™ can help to optimize the path by refining battery management system strategies to minimize the relative performance loss that may occur by the end of the last aging period.

## 1.3 Mechanisms Behind Aging Path Dependence

Before we begin software installation procedure, let's become acquainted with the CellSage™ output files that show a cell's aging path and thermal effects. CellSage™ provides several output files, in both textual table form and in comma-separated value form for easy import into other analysis tools (such as MATLAB, Microsoft Excel, and others.) The first file is a diagnostic file that can be used to explore the science behind cell aging using a baseline test condition. The second set of files are the aging path dependence files. The path dependence files provide the simulation progression at arbitrarily chosen conditions for a given cell chemistry, for both a cell and series string basis.

Two mechanisms that contribute to cell aging path or degradation are loss of lithium inventory (LLI) and loss of active material (LAM). The effects of these degradation modes are capacity fade and power fade. These mechanisms are unavoidable, and, depending on conditions, are partially reversible or, in some cases, irreversible. LLI and LAM can be mitigated with proper selection of duty-cycle requirements, SOC management, and thermal management strategies. These conditions can be experimentally simulated within CellSage™.

The illustration in Figure 2 shows a simplified cross-section of a lithium-ion cell under a charge condition (cathode and separator not shown). Lithium ions are available for "intercalation" or migration into and out of the anode. However, for the lithium to migrate, active material sites must be available to accept the lithium ions. Likewise, at the cathode side there must be viable active sites releasing lithium. As lithium ions migrate through the electrolyte and separator, a solid-electrolyte interphase (SEI) layer builds up on the anode surface impeding the progress of the lithium ions. Over time this complicated interplay across the whole cell (including the cathode) will influence all aspects of cell performance and aging.

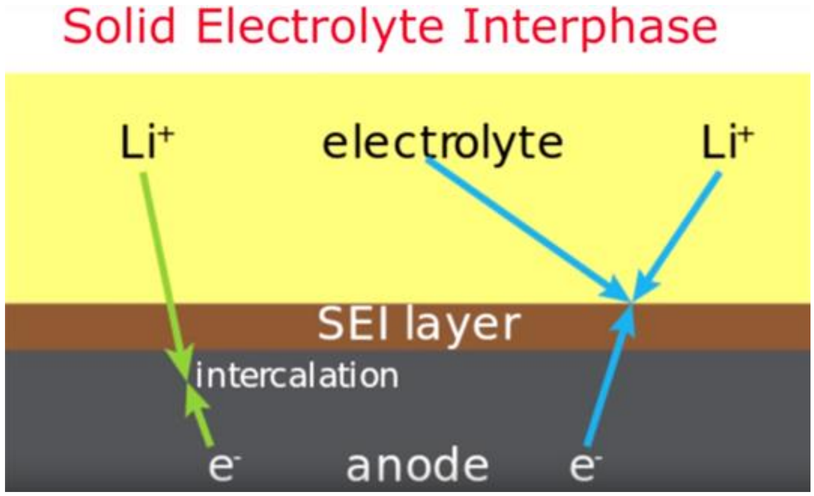



**Figure 2. Simplified cross-section of a lithium-ion cell under a charge condition.**

The figure below summarizes the two aging / degradation mechanisms, wherein Fraction of Available Labile Lithium (FALL) is equivalent to LLI, and Fraction of Active Available Sites (FAAS) represents LAM. Please note that state of charge, charge voltage, and temperature determine whether these effects are reversible or permanent. Some of the effects occur early in the cell's life and CellSage™ provides the means to see these effects throughout the anticipated service life of the cell. One key attribute of CellSage™ is its ability to model different operating characteristics to flush out undesirable aging effects.

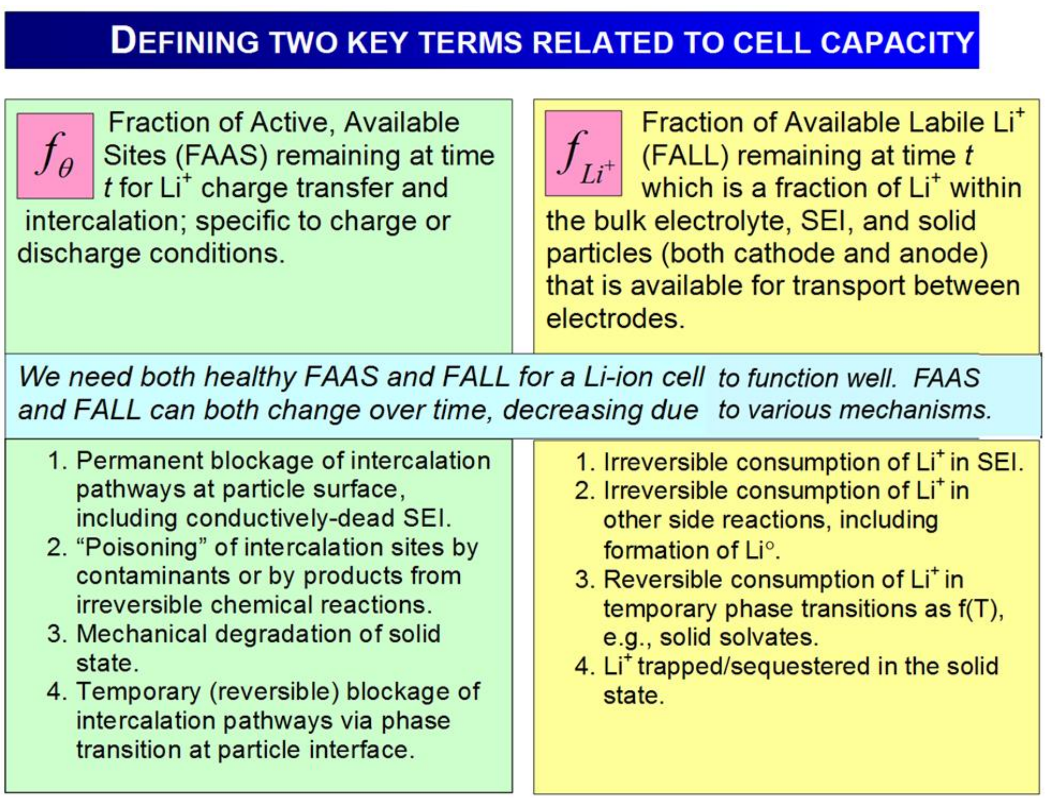



**Figure 3. Aging / degradation mechanisms for common lithium cells.**

The illustration shown in Figure 4 graphically shows bulk aging mechanisms and modes for Gen2 NCA/Graphite cell chemistry. This graph considers LLI and LAM effects for both reversible and irreversible cases of discharge capacity. Irreversible losses are surmised at a slow cycling rate of Capacity (C)/25 (discharging a full cell over a 25-hour period), while the reversible capacity is due to polarization effects as the cell goes from a C/25 basis to C/1. For this cell chemistry, irreversible losses dominate during early testing while reversible losses dominate later (well past the 140-week test period.) Overall, it is the capacity performance tied to active sites that dominate the effective capacity loss over extended time.

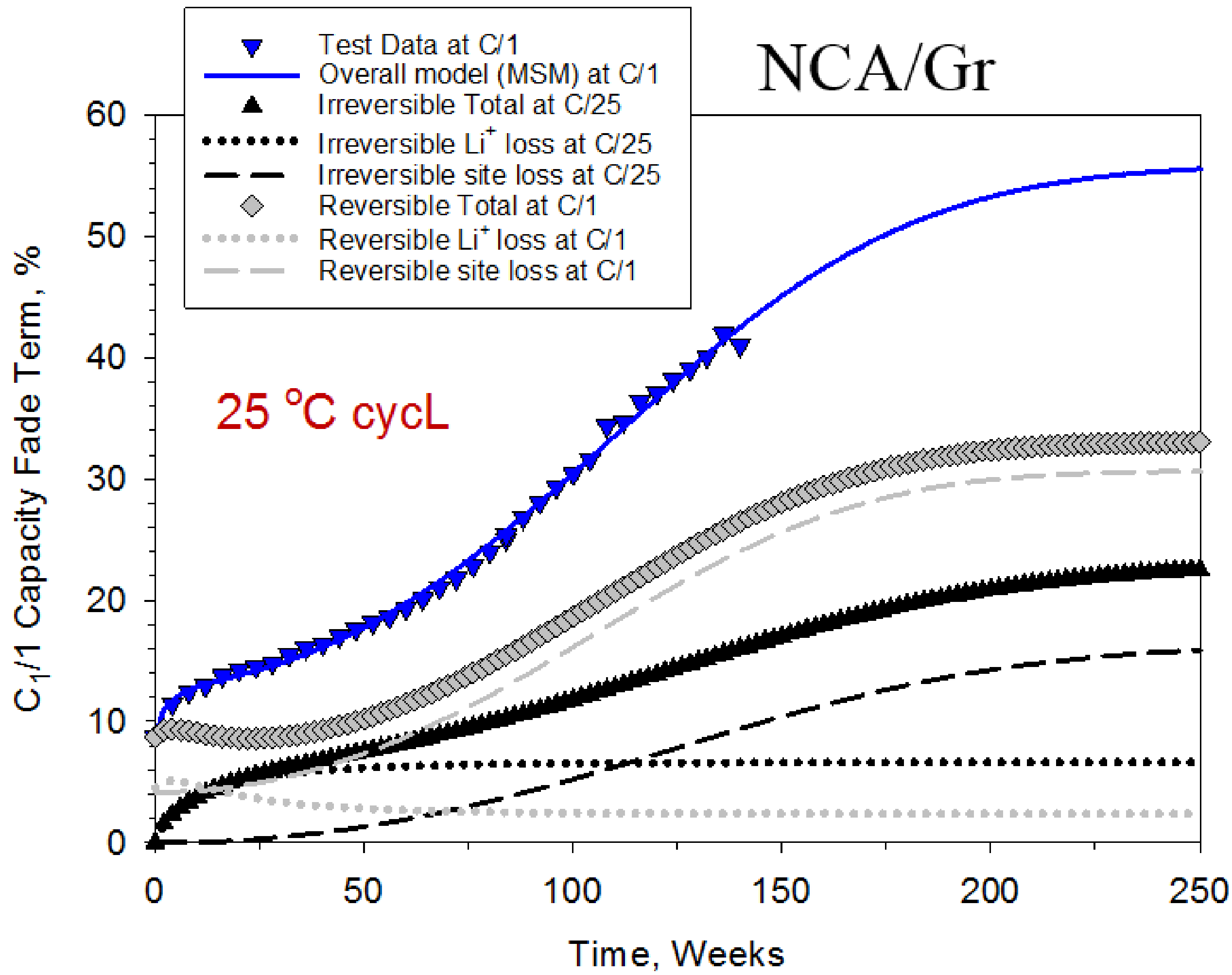



**Figure 4. Bulk aging mechanisms and modes for Gen2 NCA/Graphite cell chemistry.**

## 1.4 Importance of Battery Health Modeling, Simulation, and Analysis Software Tools

Battery health modeling, simulation, and analysis (MS&A) software tools play a crucial role in various industries, particularly in the electric vehicle (EV), renewable energy, consumer electronics, and grid energy storage sectors. These tools provide valuable insights and offer numerous advantages, which are essential for both businesses and researchers. Here are some general market insights and the importance of these tools:

1. **Optimizing Battery Performance**: Battery modeling software allows for the optimization of battery systems to maximize their performance. This is critical for industries relying on battery technology, as it can lead to improved efficiency and extended battery life.
2. **Cost Reduction**: Analyzing battery health helps identify factors that can reduce the cost of battery replacement or maintenance. This is especially important for EV manufacturers and renewable energy providers, where battery costs are a significant portion of the overall system cost.
3. **Predictive Maintenance**: Battery health analysis tools enable predictive maintenance. By monitoring the battery's condition over time, companies can schedule maintenance or replacements proactively, reducing downtime and saving costs.
4. **Enhanced Safety**: Ensuring the health and safety of batteries is crucial, especially when dealing with large battery banks or high-capacity batteries. Simulation tools can predict and prevent potentially dangerous situations, such as thermal runaway.
5. **Environmental Impact**: Battery health analysis can contribute to sustainability efforts. By extending the lifespan of batteries, the need for replacements and disposal is reduced, which has positive environmental implications.
6. **Energy Storage and Grid Integration**: As renewable energy sources become more prevalent, the ability to store and manage energy effectively is essential. Battery modeling and simulation tools assist in integrating energy storage systems into the grid, improving grid stability and reliability.
7. **Research and Development**: For battery manufacturers and researchers, these tools are essential for designing and testing new battery technologies. They can simulate various scenarios to understand how a battery will perform under different conditions, accelerating the development of new and improved batteries.
8. **Regulatory Compliance**: In some industries, there are strict regulations and standards for battery performance and safety. Battery health analysis tools help ensure compliance with these standards.
9. **Consumer Electronics**: In the consumer electronics market, battery health tools are important for maintaining the user experience. They can help optimize battery life and ensure a longer operational period between charges.
10. **EV and Transportation**: For electric vehicle manufacturers and transportation companies, battery health is a critical factor. These tools help maintain the reliability of electric vehicles and can extend the driving range.

11. **Data-Driven Decision Making**: Battery modeling and simulation provide data that can be used for informed decision-making. This includes decisions related to battery sourcing, replacement strategies, and overall system design.
12. **Mitigating Degradation**: Battery degradation is an inherent issue with lithium-ion batteries. Modeling and analysis tools help in understanding and mitigating this degradation, leading to longer-lasting batteries.

In summary, battery health modeling, simulation, and analysis software tools are essential in a wide range of industries. They provide insights and benefits that go beyond improving battery performance to include cost savings, safety enhancements, environmental considerations, and the advancement of battery technology. As the demand for batteries continues to grow in various applications, the importance of these tools is likely to increase further.

## 1.5 Technology Summary

- **What is it?**
  CellSage™ is an advanced battery software simulation tool with a robust foundation in physics, electrochemistry, and thermodynamics to diagnose and predict performance and aging aspects for battery cells and strings.
- **What battery chemistries are in CellSage™?**
  There are representative chemistries from Sanyo, Panasonic, A123 and a DOE NCA/Gr chemistry. Additional chemistries can be easily added once the necessary cycle life testing data has been generated and analyzed to extract model parameters.
- **Typical Input Parameters:**
  Cell chemistry, state of charge (SOC), Temperature (T) and DT, location of use (US or custom annual temperature profiles), uniquely configured duty cycles that allow the user to specify charging/discharging/rest frequencies and rate, thermal management metrics, string attributes, and others.
- **Outputs (see supporting files):**
  Cover mechanistic evaluation of performance change (e.g., capacity loss, power fade) over an arbitrarily chosen aging path input by the user. Multi-year simulations are feasible.
- **Platforms**:
  Can be used as a stand-alone software simulation tool on a PC or embedded into a customized battery management system design for target applications. The embedded version of CellSage™ is feasible with the necessary application and system engineering to develop a BMS design or architecture that compares near real time BMS data to a CellSage™ simulation model.

# 2. CellSage™ Installation

## 2.1 System Requirements

The following system requirements have been tested to ensure proper software installation and operation:

1. PC with Windows 7 or Windows 10 Professional operating system (either 32- or 64-bit).
2. At least 4 GB ram.

**Important Note:** There is no specialized test equipment, hardware, or additional third-party software that needs to be purchased to run the CellSage™ software application.

## 2.2 Installing the Software

1. Download and extract the installation folder **CellSage™_GUI_XXXXXX** from the download source. (Download source could be through Email, USB, Disk, Dropbox, etc.)
   **Important Note:** XXXXXX represents the date of release for the CellSage™ GUI, and your version may be different if it was compiled during a later software release.

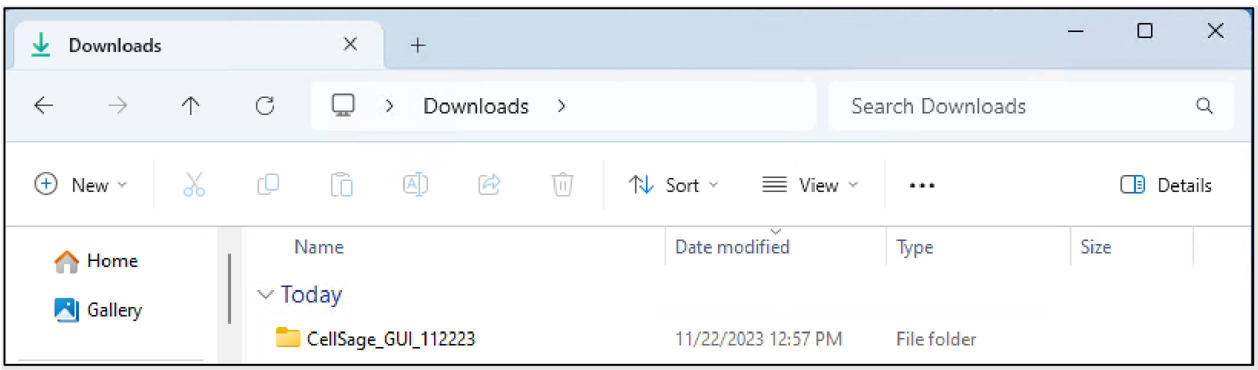



**Figure 5. CellSage™ installation folder saved in This PC > Downloads.**

2. Navigate to the following directory in the Windows File Explorer: **...\Downloads\CellSage™_GUI_XXXXXX**

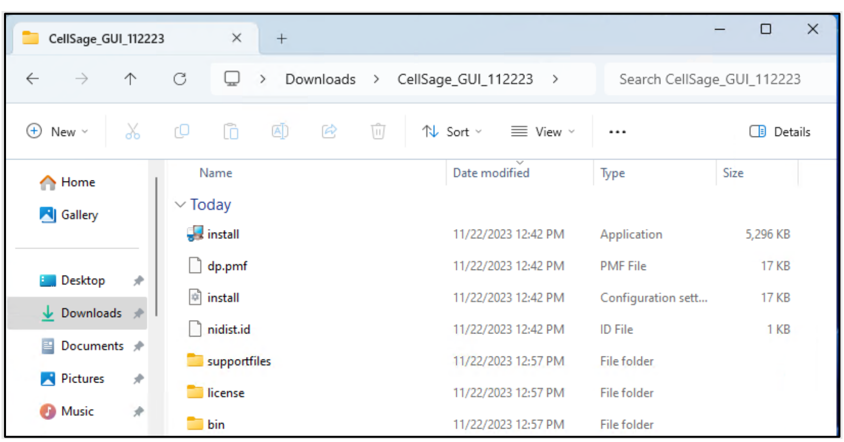



**Figure 6. Folder is located at ...\Downloads\CellSage™_GUI_XXXXXX.**

3. Right click on the **install.exe** and select **Run as Administrator**.
4. Verify that installation wizard initializes as shown in Figure 7.

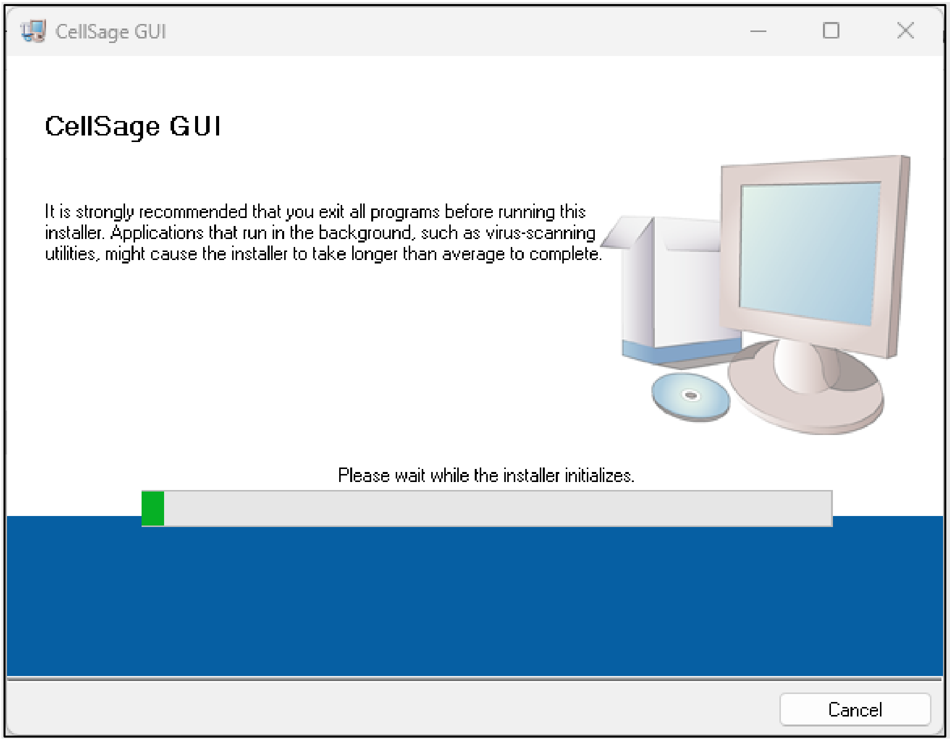



**Figure 7. CellSage™ installation wizard initializing.**

5. Follow the Setup Wizard's installation prompts as shown in Figures 8 – 13:

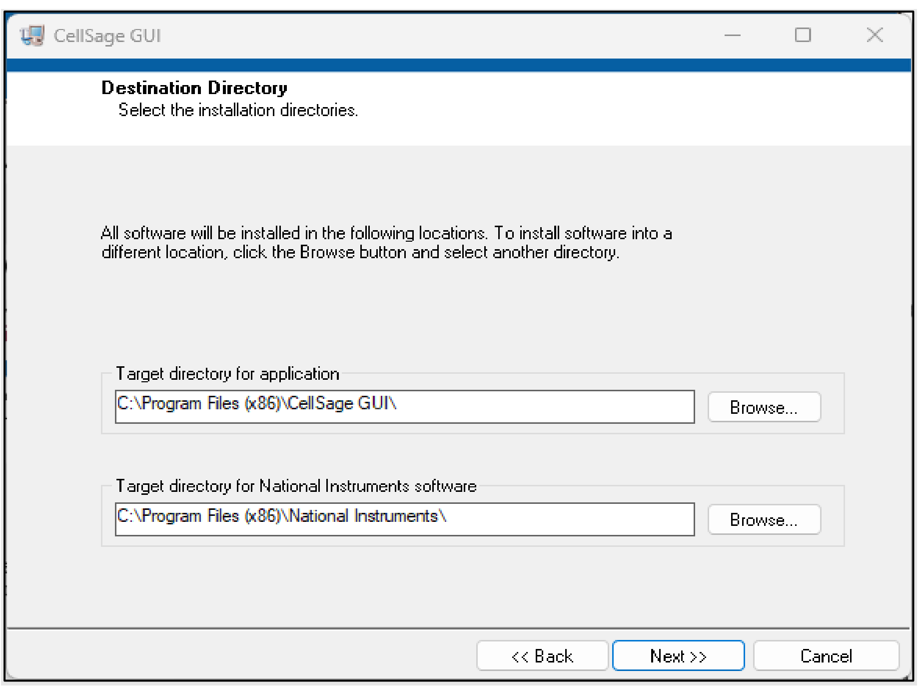



**Figure 8. View of the installation wizard for the CellSage™ installation directory. Click Next>> to continue.**

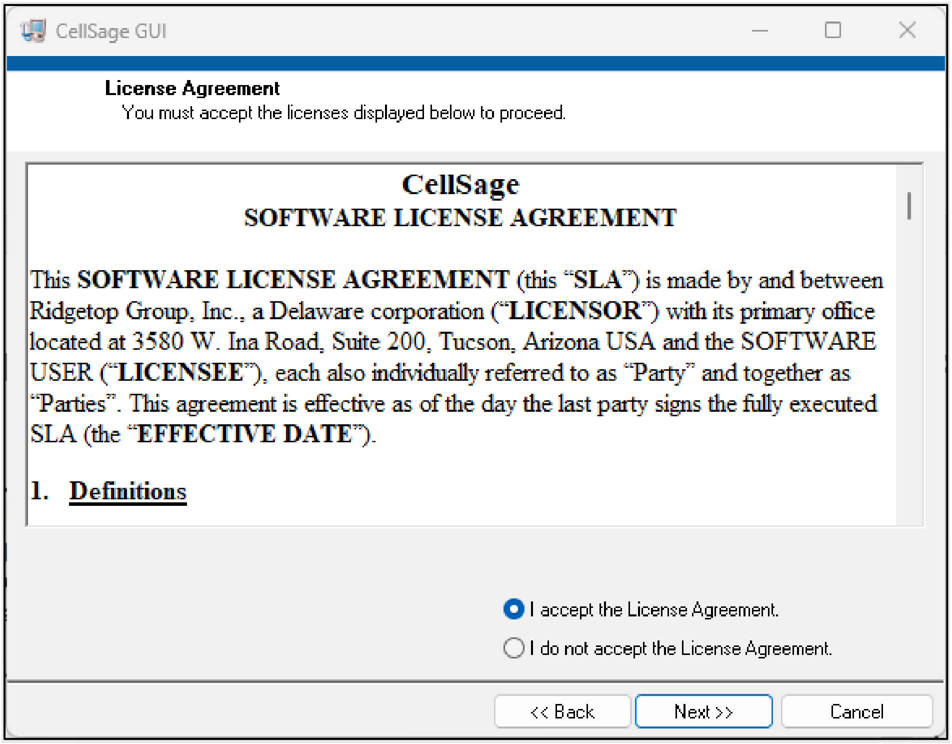



**Figure 9. View of the installation wizard that prompts the user to select the National Instruments Software License Agreement. Click Next>> to continue.**

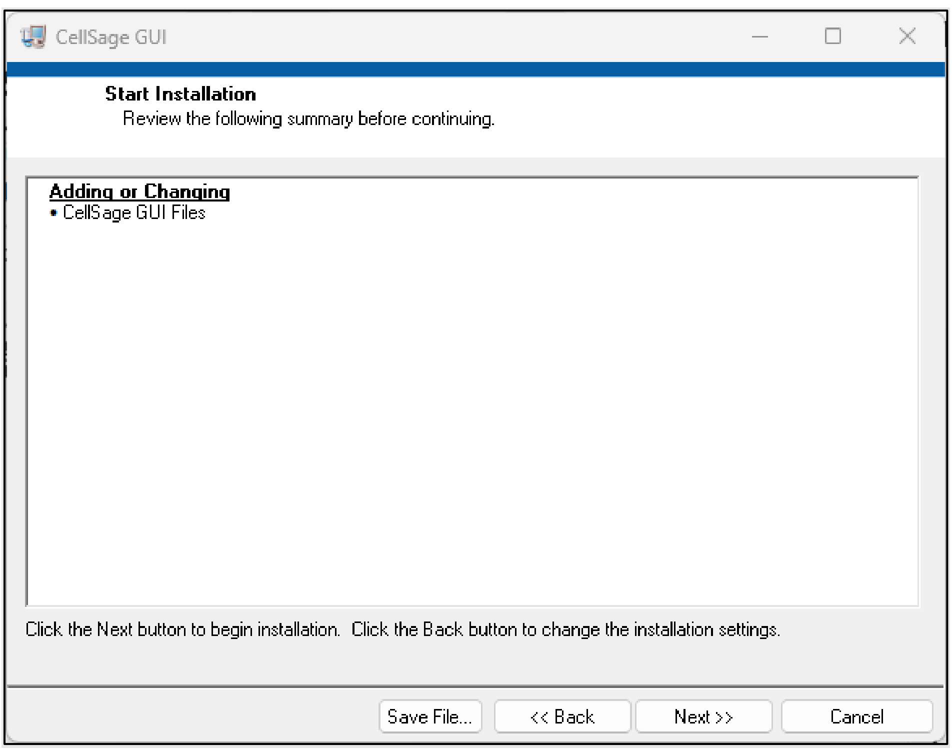



**Figure 10. View of the installation wizard to start the installation. Click Next>> to continue.**

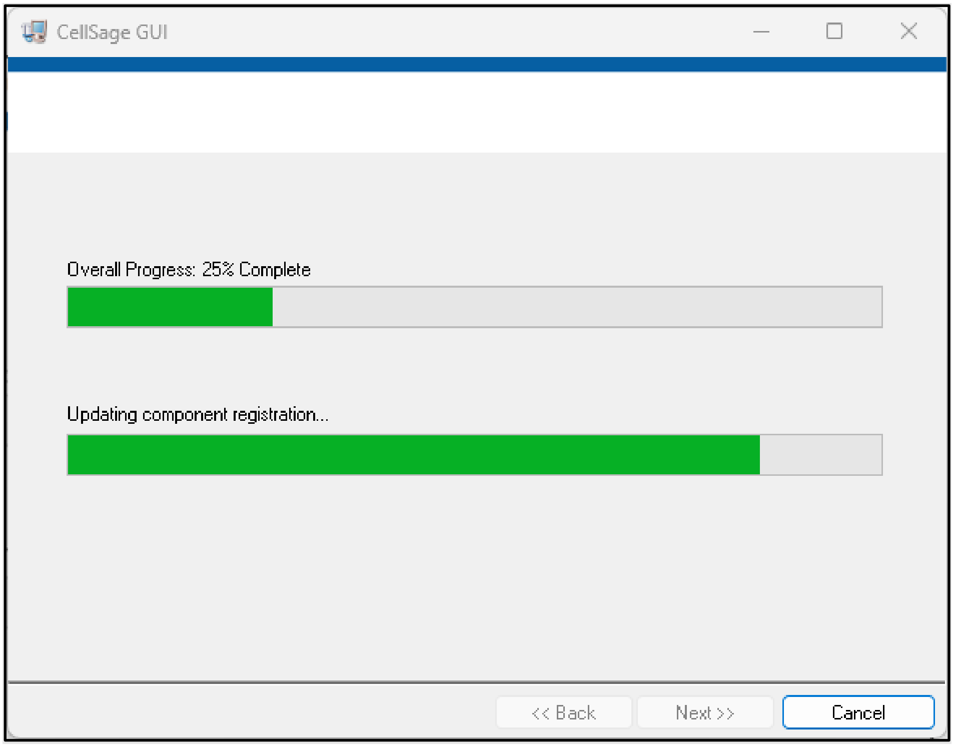



**Figure 11. View of the installation wizard installing the software.**

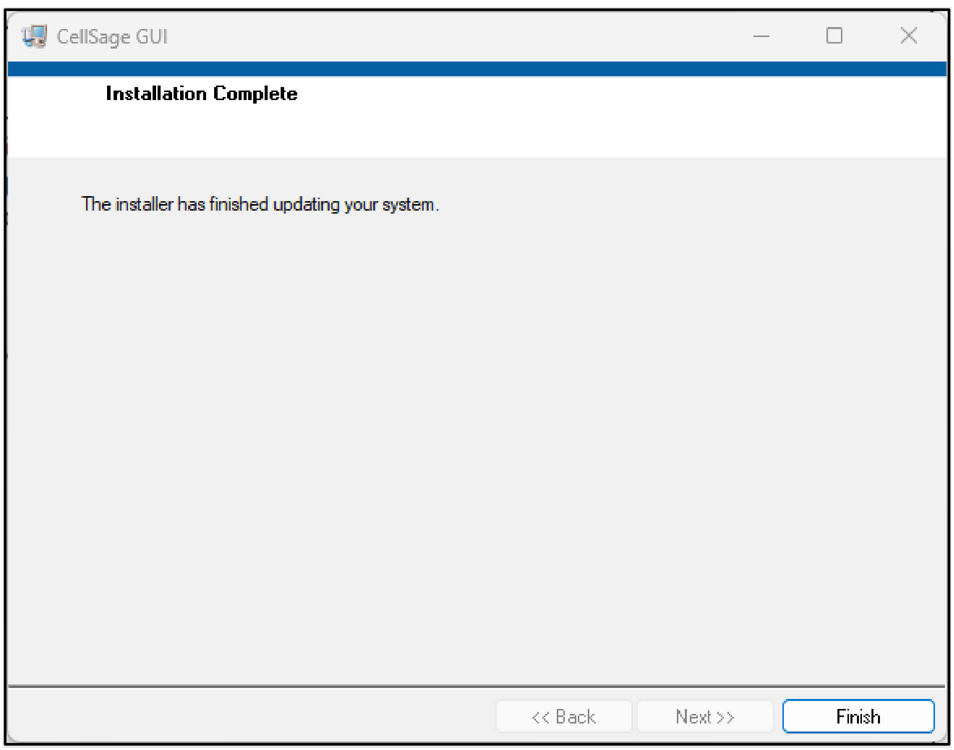



**Figure 12. View of the installation wizard when the installation has completed.**

6. Select **Finish** and exit the installation wizard.
7. Restart your computer to complete the installation procedure.

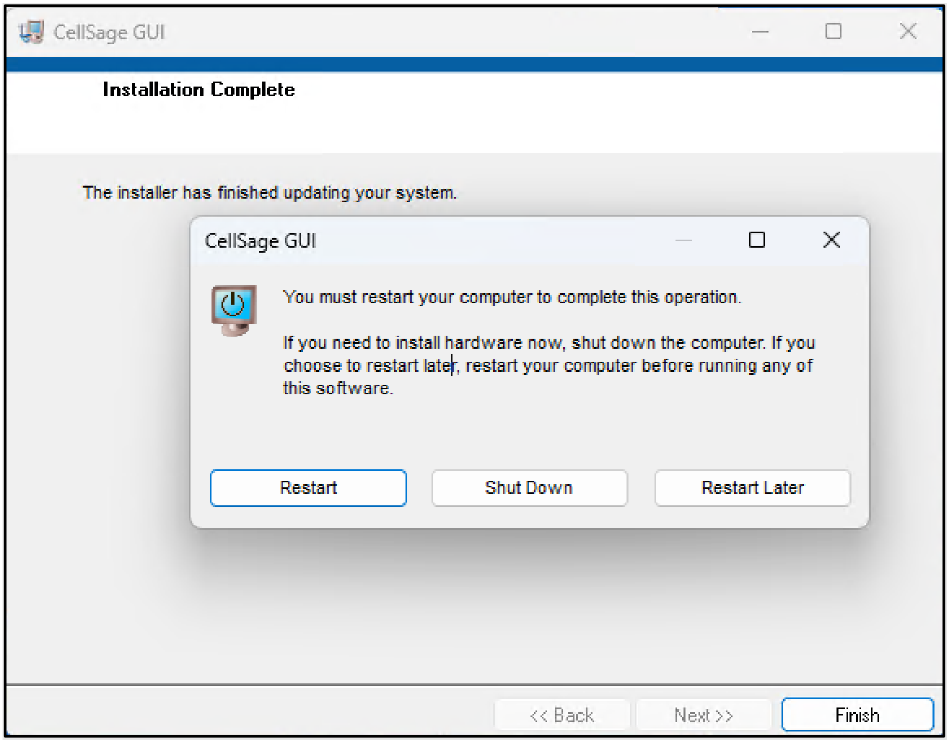



**Figure 13. View of installation wizard prompting the user to restart their computer.**

## 2.3 Activating License and Verifying Software Installation

1. Open the CellSage™ GUI by using the shortcut in the Windows Start Menu or by opening a File Explorer and navigating to the default installation directory. The default directory is located at the following path: **C:\Program Files (x86)\CellSage™_GUI\Dependencies**

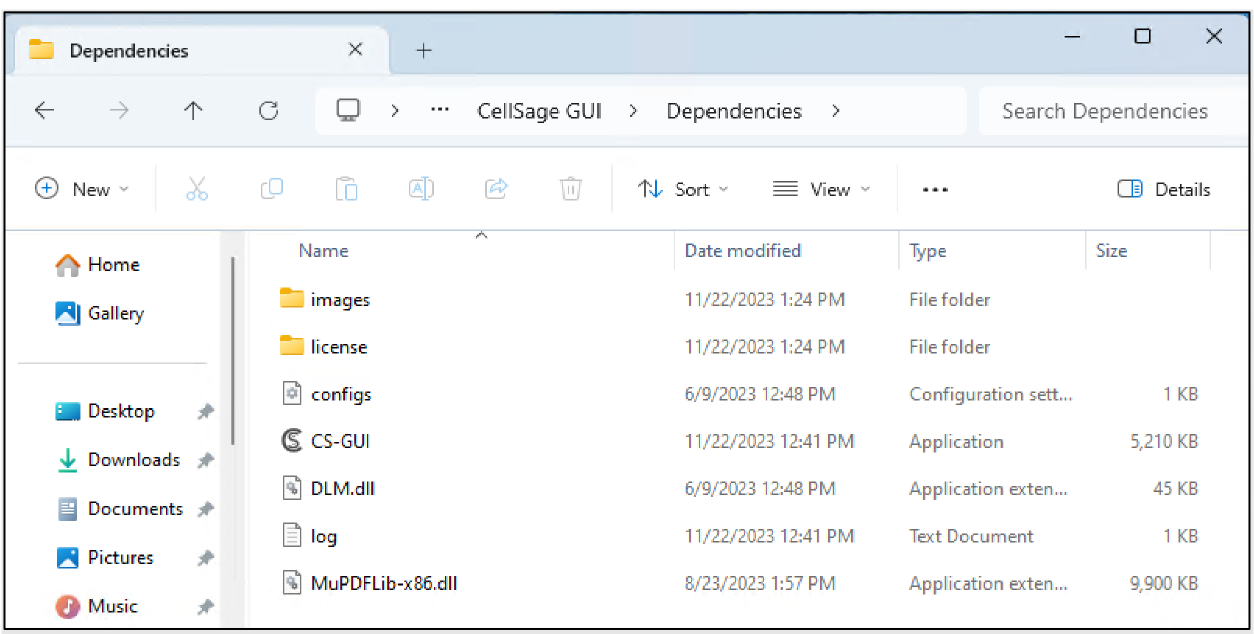



**Figure 14. Installation directory of CellSage™.**

2. Open the **CS-GUI.exe** application by either a double click or right click and select **Run as Administrator**.
3. If an active license is not found the program will prompt the user to retrieve a license from the server. To do this click the **GET NEW LICENSE** button as shown in Figure 15.

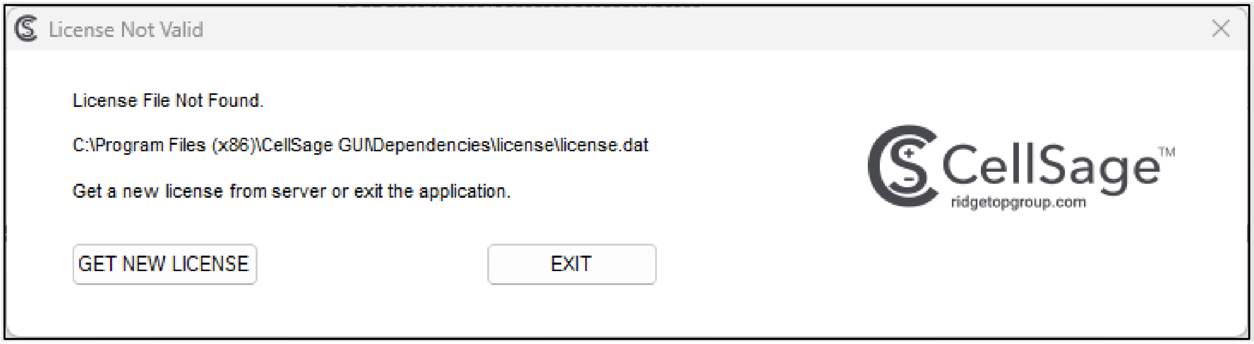



**Figure 15. License verification prompt asking user to retrieve a license from the server.**

4. Login to the license server with the username and password combination that was provided through email. If you do not have a username and password, please contact a Ridgetop Group representative.


**Figure 16. Logging into the license server.**

5. Enter your credentials and click the **Request License** button.
6. Verify that the software license is activated as shown in Figure 17. If the login credentials were not entered correctly or if the license is expired, then the user will be prompted to get a new license.


**Figure 17. Message that software license is activated and installed correctly.**

7. Click **OK** to continue and open the application.

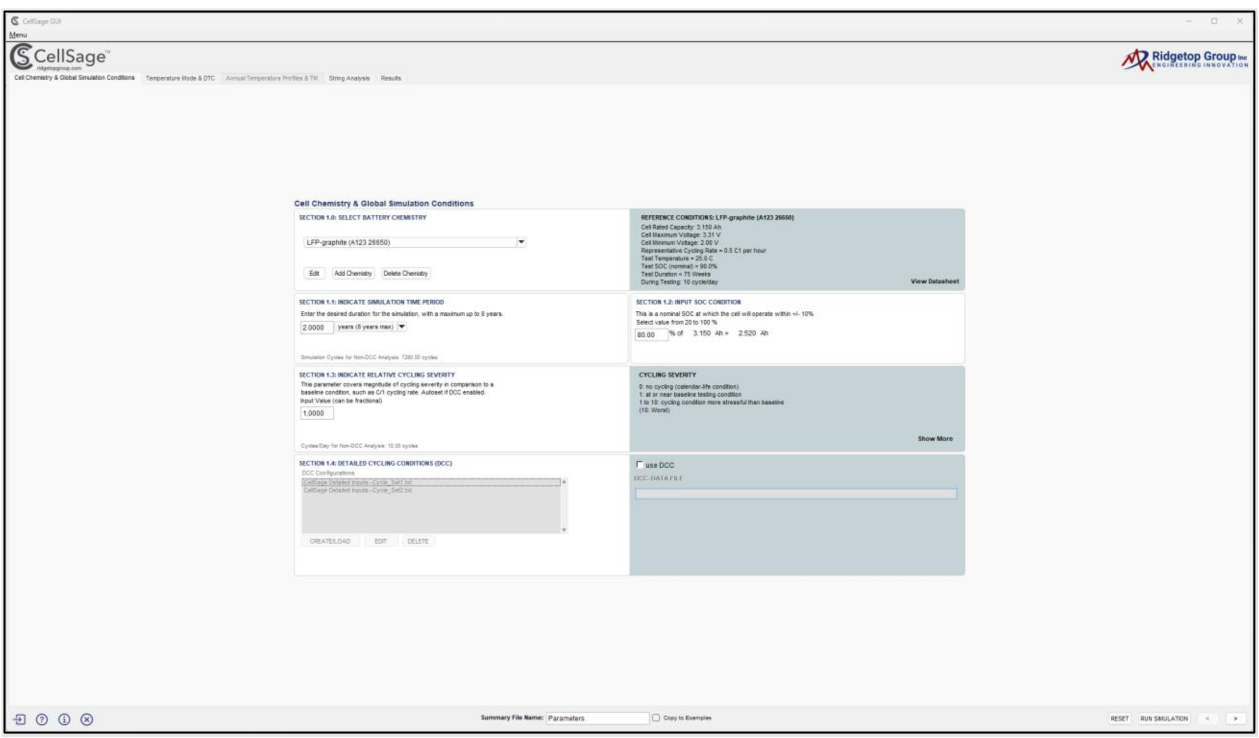



**Figure 18. View of the CellSage™ program being opened after license installation.**

# 3. CellSage™ Graphical User Interface

This User Guide provides details regarding the CellSage™ Battery Health Modeling, Simulation, & Analysis (MS&A) software platform, which is an extended product offering from the CellSage™ Detailed Cycling Conditions (DCC) Simulation Module and the CellSage™ Capacity Power Conductance (CPC) Module.

## 3.1 CellSage™ GUI Tabs

The CellSage™ Battery Health MS&A Software Platform is a Microsoft Windows-based Graphical User Interface (GUI) program for the CellSage™ battery simulation engine. The CellSage™ GUI provides access to existing cell models, selection of baseline aging conditions, and also provides access to detailed charge, rest, and discharge cycling conditions that a battery may experience in arbitrary applications. Finally, the GUI provides access to string power and hot spot simulation options to identify power fade due to hot spots and other string imbalance.

Regression results from sufficient baseline aging conditions are used by CellSage™ to simulate aging conditions at arbitrary use conditions in terms of variables T, SOC, cycling type, etc. over the timeline. This allows investigation of numerous "what-ifs" regarding thermal management of batteries during life, seasonally variant SOC, as well as string aging. Much of the simulations done are based on the Gen2 cell chemistry, but other chemistries can be used if there is adequate upfront information on stress factor response of the cell chemistry.

The CellSage™ GUI produces five main data output files in .txt format as well as multiple .csv data plot files that are used to generate automated data plots for select simulations. A brief overview of each data output file is outlined below:

1. CS_Path-Dependence.txt: A simulation results output file that provides the path dependence aging.
2. CS_Path-Dependence-Dcc.txt: An extended version of the above path dependence file that includes additional data outputs from the DCC simulation module.
3. CS_String_Analysis.txt: A simulation results output file that provides the string analysis.
4. CS_Diagnostics.txt: This file provides information related to the regression models simulation.
5. Parameters.txt: This text file provides information for each of the simulation parameters that were entered for a given simulation.

Each of these data output files and the corresponding *.csv data plot files are logged in a time stamped simulation run folder that is stored in a user specified directory. All data output files can be opened with any Windows application that can open plain ASCII text files such as Notepad, Notepad++, Excel, etc. Please see Section 3.2 for more details pertaining to the contents of each data output file.

There are five main tabs in the CellSage™ GUI and they are identified in the list below:

1. Cell Chemistry & Global Simulation Conditions
2. Temperature Mode & DTC
3. Annual Temperature Profiles & TM
4. String Analysis
5. Results

Each tab offers a variety of check boxes and parameters that a user can specify to run a simulation. The following sub-sections provide an overview of each tab.

### 3.1.1 Cell Chemistry & Global Simulation Conditions

The CellSage™ GUI has the following global simulation conditions as shown in Section 1.0 – 1.4 on the first GUI tab:

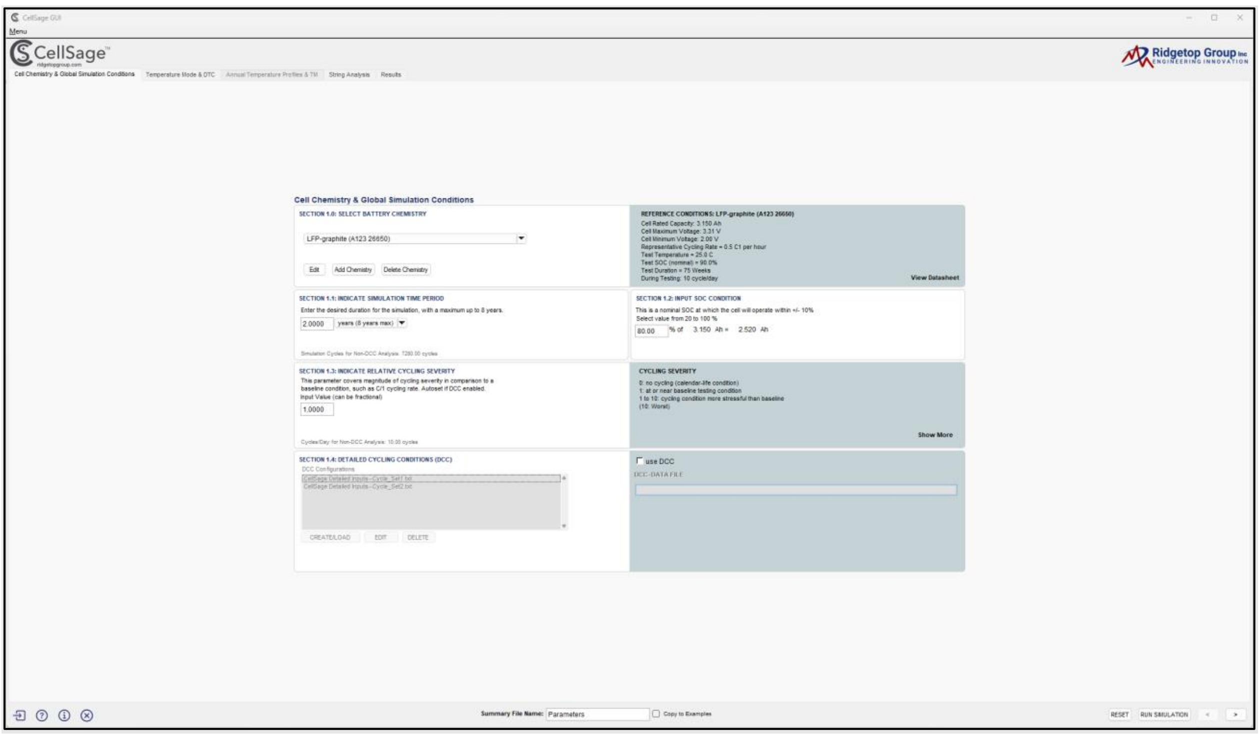



**Figure 19. Tab 1 – Cell Chemistry & Global Simulation Conditions.**

**Section 1.0: Select Battery Chemistry –** There are 5 different chemistries available to run a CellSage™ simulation. When a chemistry is selected, the baseline test and reference conditions are displayed in the text box as shown above. Ridgetop Group is currently working with industry partners and government organizations to expand the list of available chemistries, in addition to building a baseline modeling feature for future cell chemistries and types.

**Section 1.1: Indicate Simulation Time Period (8 years max) –** This setting reflects the capability of CellSage™ to generate simulated data output results for up to 8 years. The simulation time can also be increased for certain applications, but Ridgetop has found that an 8-year max is a good baseline for a majority of lithium-ion cells that are in operation. This parameter can also be set in units of months or weeks by clicking on the drop-down box. The simulation time period is also used to calculate the estimated number of simulation cycles, which is dependent on this parameter as well as the user defined number of cycles per day in the DCC config file. If the DCC config file is not used in the simulation, the total number of cycles referenced in the "CS_String-Analysis.txt" data file is based on the simulation time and the number of cycles per day that was used during baseline testing at INL. The number of cycles per day based on chemistry type is listed below:

1: NCA/graphite (DOE Gen2 18650) – 1 cycle per day
2: NMC/graphite (Sanyo Y 18650) – 10 cycles per day
3: LFP/graphite (A123 Nanophosphate 20Ah) – 10 cycles per day
4: LFP/graphite (A123 26650) – 10 cycles per day
5: NMC/graphite (Panasonic UR 18650) – 5 cycles per day

**Section 1.2: Input SOC Condition –** This is the average or typical State of Charge (SOC) the simulation starts with for testing. If the application charges the cell to 80% and discharges to 20% then the nominal SOC is not the midpoint, but instead it is 80% because that's where the testing starts. The higher SOC is favored here as that is the condition in which more energy is delivered. This simulation condition can be from 20% to 100% of the manufacturer's rated capacity for each cell type. It is assumed that each cell is charged to the rated SOC under constant current and voltage. The manufacturer's rated capacity for each cell type can be found in the Appendix.

**Section 1.3: Indicate Relative Cycling Severity –** This parameter covers magnitude of cycling severity in comparison to a baseline condition such as a C/1 cycling rate used during the initial characterization testing. The relative Cycling Severity Index (CSI) is a parameter that can be entered on a scale from 0-10 or it can be auto calculated based on the inputs from the Detailed Cycling Conditions (DCC) user form. The CSI parameter approximates the relative impact of the cycling conditions on battery aging consequences. It is meant to capture the effects of increased (or decreased) cycling rates/frequency in relation to the baseline. In short, more severe cycling conditions (more frequent duty cycles, greater cycling rates, greater power demands) will cause more stress that accelerates cell aging. In CellSage™, CSI helps to provide initial conditioning of parameters for the physics-based aging rate expressions, considering the charge and discharge cycling conditions en masse. The CellSage™ software program then updates these values to align with particular detailed conditions provided by the user. Table 1 provides guidance for the correspondence of CSI values to cycling conditions. Note that integer and non-integer values are equally valid as inputs. In all cases, a CSI value of unity (=1) relates back to the baseline cycling conditions of the original benchmark data, which is assumed to have some cycling components and not just purely calendar-life conditions. Therefore, variations of CSI should be made in reference to the baseline conditions, as these could very well differ between cell chemistries and benchmark datasets. In general, CSI is scaled in terms of discharge conditions, as this represents the work being done by the battery; additional conditioning is done for charge conditions (e.g., fast charging) within the CellSage™ DCC module. For many typical battery use conditions CSI will have values between 0.5 to 4.0, depending how the baseline was defined. Table 1 provides some additional notes on how to select the appropriate CSI, and this table can also be displayed in the GUI by clicking the "Show More" button.

**Table 1.0 – Relative Cycling Severity Index (CSI) table.**

| Cycling Condition | CSI |
|---|---|
| Calendar-life only; no cycling except periodic diagnostic cycling events. | 0 |
| Mixture of calendar-life and baseline conditions; cycling conditions milder than baseline. | 0.1 to 0.9 |
| Baseline conditions. | 1.0 |
| Cycling conditions that comprise up to twice the cycle frequency per day and/or twice the magnitude of current or power, compared to baseline. | 1.1 to 2 |
| Cycling conditions that comprise between two to three times the cycle frequency per day and/or similar increase in magnitude of current or power, compared to baseline. | 2.1 to 3 |
| Cycling conditions that comprise between three to five times the cycle frequency per day and/or similar increase in magnitude of current or power, compared to baseline. Depending on the cycling schedule and nested rest periods, mild reversible polarization effects might also emerge in addition to the irreversible contributions determined by the model. | 3.1 to 5 |
| Cycling conditions that comprise more than five times the cycle frequency per day and/or similar increase in magnitude of current or power, compared to baseline. Mild-to-moderate reversible polarization effects might also emerge in addition to the irreversible contributions determined by the model. | 5.1 to 7 |
| Harshest conditions comprised of continuous high-power conditions covering the entire voltage range. This is on the border of abuse-type conditions. Moderate-to-severe reversible polarization effects are also likely to emerge in addition to the irreversible contributions determined by the model. | 7.1 to 10 |

**Section 1.4: Detailed Cycling Conditions (DCC) –** This section of Tab 1 gives the user the option to include or not include detailed cycling conditions (DCC) in the CellSage™ simulation. This option is enabled by a checkbox, and if selected the user will have the ability to create a new DCC configuration file or select an existing DCC configuration file from the scroll box. When a DCC file is selected, the path of that DCC file is shown to the right of the scroll box. The default path where DCC files are stored are under the following directory: **C:\Users*user-ID*\Documents\CellSage™ Simulations\DCC**. Note that the ***user-ID*** is unique to the end user and the PC the software is installed on. An example for one of the default DCC input files being selected is shown in Figure 20.

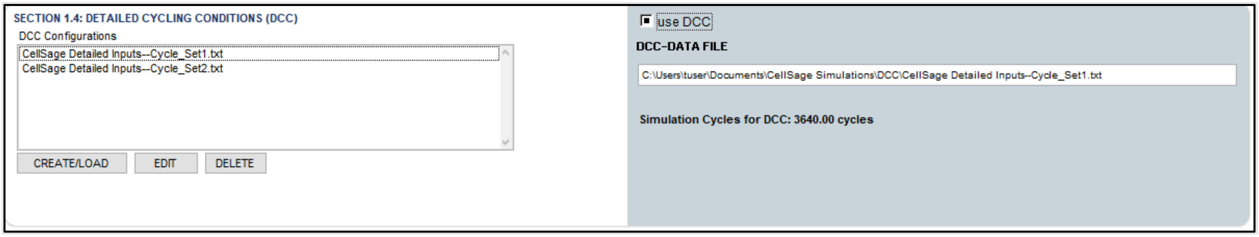



**Figure 20. GUI view where Detailed Cycling Conditions configuration file is specified.**

Whether editing an existing DCC configuration file or creating a new one, the program will display a pop-up that allows the user to edit and/or specify each of the DCC input parameters from a user form. The user form also provides the option to load DCC parameters from an existing DCC configuration file, save any edits, and/or close the user form. The DCC configuration option allows the user to specify detailed charge, rest, and discharge parameters that are specific to battery application or mission. A brief list of each for each of the DCC Configuration parameters is listed below:

- Input Mode
  - Value = 1: Allows the user to define charge and discharge rates on a C-Rate Basis.
  - Value = 2: Allows the user to define charge and discharge rates on a Current Basis.
- Cycles Per Day
  - Values = 1-X Used to specify the number of user defined cycles per day for those days in a week that undergo active duty cycles. Note that there is not an upper limit for X, but the specified number of duty cycles must fit in a 24-hour schedule.
- Charge Steps Per Cycle
  - Values = 1-10: Sets the number of editable fields for Charge Rates per Step and Voltage Values per Step During Charge.
- Charge Rest Steps Per Cycle
  - Values = 0-10: Sets the number of editable fields for Rest Values per Step During Charge.
- Discharge Steps Per Cycle
  - Values 0-10: Sets the number of Discharge Rates Per Step and Voltage Values Per Step During Discharge.
- Discharge Rest Steps Per Cycle
  - Values 0-10: Sets the number of Rest Values Per Step During Discharge.
- Charge Rates Per Step
  - When using C-Rate Basis, the charging rate is defined by assigning a factor to the rated cell capacity ($C_{cell}$). This is done by dividing $C_{cell}$ by the desired charge time that would be required going from Vmin to Vmax while at constant-current (CC) conditions. For example, if a full charge time is defined as two hours, then the rate is specified as $C_{cell}/2$, while a charge that would elapse 20 minutes would be at a $3C_{cell}$ rate.
  - When using Current Basis, the actual charge current per cell is used per a CC basis.
- Discharge Rates Per Step
  - When using C-Rate Basis, the same premise is used as described above for charge conditions, but applied to discharge rates.

    - When using Current Basis, the actual discharge current per cell is used per a CC basis.
- Voltage Values Per Step During Charge
    - User defined voltage values for each step during **charging steps.** The specified voltage values are approximate terms that would be attained by the end of each charge step. Note that the voltage values shall be in between the lower and upper limit that is noted for the selected chemistry.
- Starting Charge [V]
    - User defined Starting Charge voltage. Note that this value should be in the range of Vmin and Vmax for the selected chemistry, and the value must be less than the last Voltage Value Per Step During Charge. For typical applications, this Starting Charge voltage value shall match the last step of the Voltage Value Per Step During Discharge.
- Voltage Values Per Step During Discharge
    - User defined voltage values for each step during **discharge steps.** The specified voltage values are approximate terms that would be attained by the end of each discharge step. Note that the voltage values shall be in between the lower and upper limit that is noted for the selected chemistry.
- Rest Values Per Step During Charge (hr)
    - User defined resting time in **hours** following each **charging step**. Note that the sum of these steps cannot exceed 24 hours in a day. Rest times can have zero values.
- Rest Values Per Step During Discharge (hr)
    - User defined resting time in **hours** following each **discharging step.** Note that the sum of these steps cannot exceed 24 hours in a day. Rest times can have zero values.
- Discharge Mode
    - Value = 1: Allows the user to set the discharge mode to use Constant Current.
    - Value = 2: Allows the user to set the discharge mode to use Constant Power. Note that when this option is chosen the software will automatically convert the input discharge rate and current specifications to render the constant power over all discharge steps. Thus, the user-input discharge current and related cycling rates will likely appear different in the simulation outputs.
- Discharge Power Target
    - User defined discharge power target in units of Watts.
- Cells in Series
    - Values 1-25: Used to specify number of cells in series. Note a value of 5 indicates a 5S1P string configuration.
- Days Per Week on Cyc-Life
    - Defines how many days per week the duty cycle is active.
- Days Per Week on Cal-Life
    - Defines how many days per week when the duty cycle is not active, but instead on calendar life. Note that the sum of Days Per Week on Cyc-Life and Days Per Week on Cal-Life shall = 7 in order to save a valid DCC config file.

- Cell Voltage at Cal-Life
    - User defined voltage value when the cell or string is at Cal-Life. Note that this value shall be in between the lower and upper voltage limits (Vmin and Vmax) for the selected chemistry. If there are no Days Per Week on Cal-Life, then this Cell Voltage at Cal-Life is defaulted to Vmin.
- Breakdown of auto calculated time metrics for cycle-life, cal-life, and the relative CSI parameter based on DCC inputs.

**Important Note:** The CSI from DCC inputs is used to automatically scale the CSI parameter in Section 1.3, so that the simulation results for the DCC outputs have the same cycles per day. Because the CSI calculation is a function of the cycling rate as well as the number of days on cycle life versus calendar life, the calculated CSI for the DCC inputs may be different than the calculated CSI for Section 1.3. The reasoning for this is because the baseline conditions may also be different from the DCC input conditions, and the program allows the user to enter the CSI in section 1.3 independently of DCC if desired.

An example of the DCC configuration user form is shown in Figure 21.

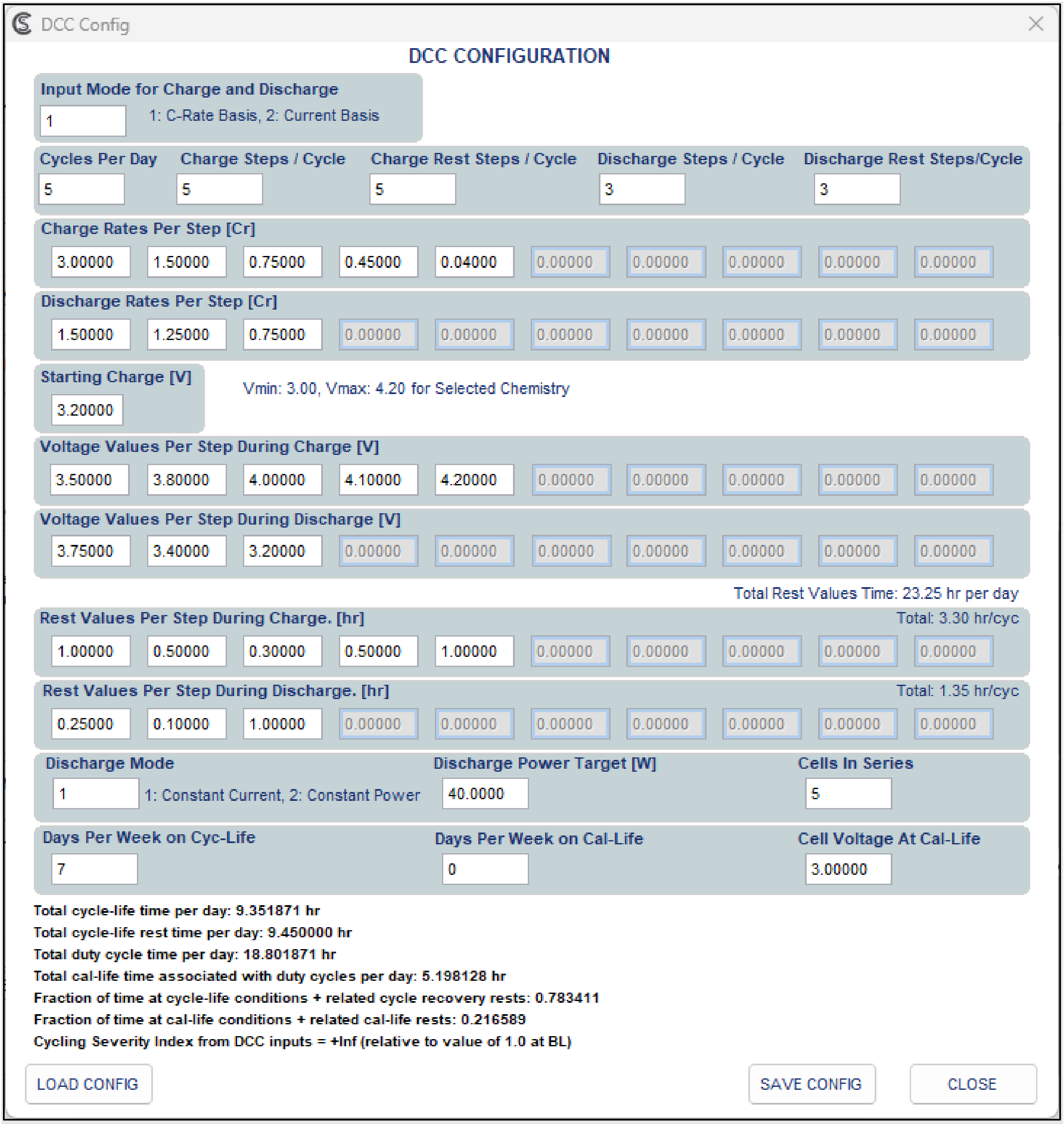



**Figure 21. GUI user form to edit Detailed Cycling Conditions (DCC) Configuration file.**

The example DCC Configuration parameters shown in Figure 21, corresponds to a duty cycle that has the following key elements:

- 5 cycles per day that utilize a C-Rate basis for the charge and discharge rates.
- Each cycle has 5 "Charge Steps Per Cycle" to specify the number of "Charge Rates Per Step" and "Voltage Values Per Step During Charge". Note that the Voltage values ramp up from 3.50 [V] to 4.2 [V], while the Charge Rates ramp down from 3 [Cr] to 0.04 [Cr] during the charge process.

- Each cycle has 5 "Charge Rest Steps Per Cyle" to specify the number of "Rest Values Per Step During Charge". Note that "Rest Values Per Step During Charge" are in time-based units of hours.
- Each cycle has 3 "Discharge Steps Per Cycle" to specify the number of "Discharge Rates Per Step" and "Voltage Values Per Step During Charge". Note that the Voltage values ramp down from 3.75 [V] to 3.2 [V] during the 3-step discharge process.
- Each cycle has 3 "Discharge Rest Steps Per Cycle" to specify the number of "Rest Values Per Step During Discharge". Note that "Rest Values Per Step During Discharge" are in time-based units of hours.
- The "Starting Charge Voltage" is set to 3.2 [V] which matches the last voltage value during the discharge process.
- The "Discharge Mode" is set to 1 for Constant Current, and the "Discharge Power Target" is set to 40 Watts for a 5S1P battery pack configuration.
- The "Days Per Week on Cyc-Life" and the " Days Per Week on Cal-Life" are set to 7 and 0 respectively to reflect that the duty cycle is active 7 days per week.
- The "Cell Voltage at Cal-Life [V]" is set to 3.00 Volts when the duty is not active.
- The specific charge rates, discharge rates, voltage values, and rest values entered in the example DCC configuration form are representative of an example duty cycle that the NMC/graphite (Panasonic UR18650) chemistry may operate under. These values and parameters could be adjusted to match other specific chemistries, missions, and/or applications.

**Important Note:** The DCC Config user form may outline certain fields in red (or issue red text) if a boundary condition or logic check is not met. Any detected errors must be corrected in order to reenable the "Save Config" button. An example of a detected error is shown in Figure 22 where the sum of the "Day Per Week on Cyc-Life" and the "Days Per Week on Cal-Life" should equal 7 days. The cycle and cal-life breakdown will also be hidden until the error is fixed.

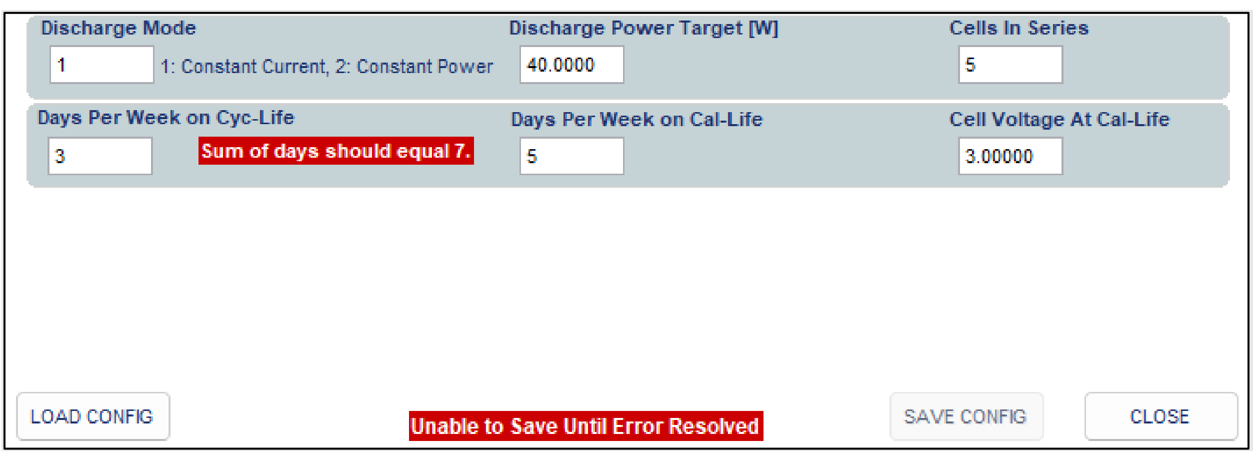



**Figure 22. Example of detected error in DCC Config user form.**

### 3.1.2 Temperature Mode & Daily Thermal Cycling

This GUI tab allows the user to specify the desired temperature mode in Section 2.0, and the effects of battery daily thermal cycling (DTC) as shown in Section 3.0 in Figure 23.

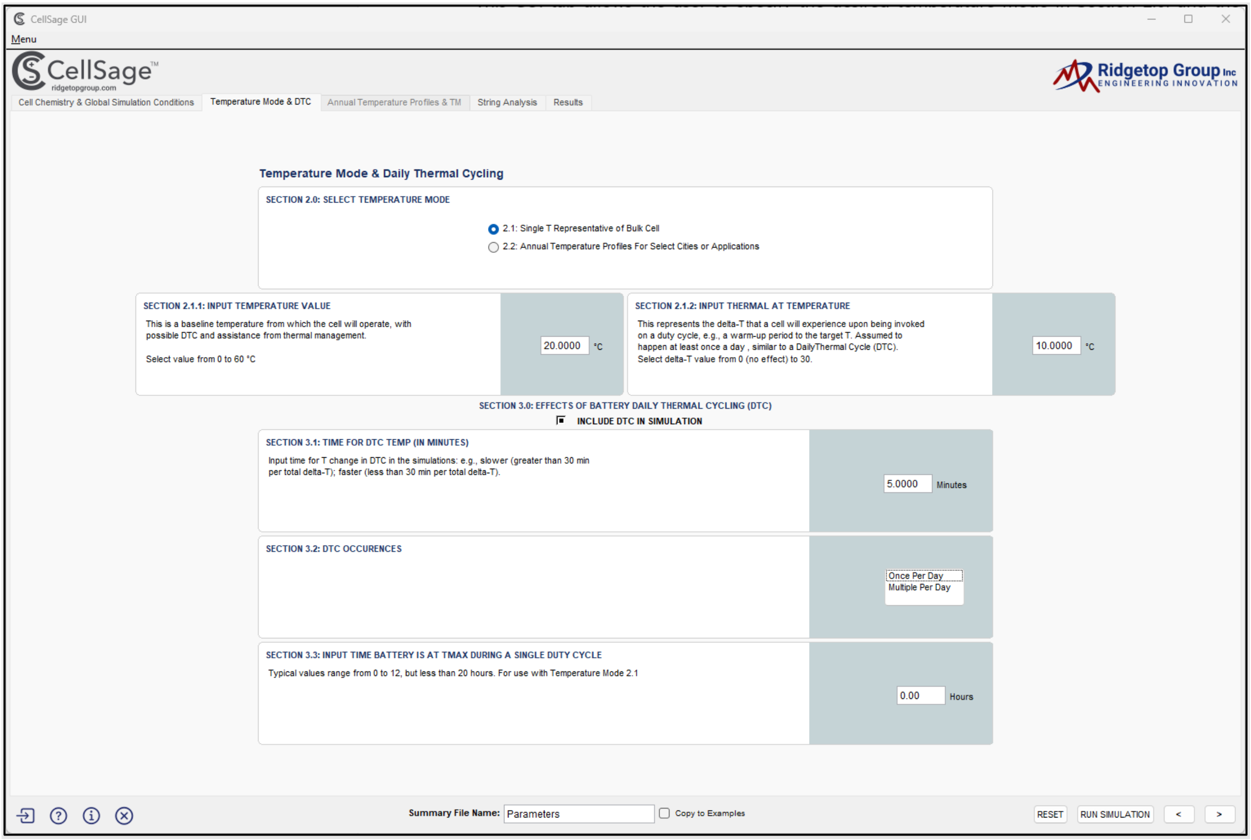



**Figure 23. Tab 2 – Temperature Mode & Daily Thermal Cycling (DTC).**

**Section 2.0: Select Temperature Mode** - This selection provides the means to provide a single nominal operating temperature or fold in the added stress of annual temperature variations by select cities and/or geographic regions. Indoor applications would likely use option **2.1: Single T Representative of Bulk Cell** and outdoor applications may use option **2.2: Annual Temperature Profiles for Select Cities or Applications.**

If the temperature mode is specified to be **2.1: Single T Representative of Bulk Cell**, then the user will be prompted to enter values for the following parameters:

- **Section 2.1.1: Input Temperature Value** - This is the baseline temperature from which the cell will operate. An input value should be from 0 to 60 degrees Celsius (C).
- **Section 2.1.2: Input Thermal Cycle At Temperature** - This parameter is the Delta-T in degrees C that a cell will experience upon being invoked on a particular duty cycle. This value should range from 0 to 30 degrees C.
- It should be noted that this temperature mode disables Tab 3 where annual temperature profiles for select cities and thermal management conditions are set. Those input

simulation conditions are enabled when the temperature modes is set to **2.2: Annual Temperature Profiles for Select Cities or Applications**.

- It should also be noted that temperature mode **2.1: Single T Representative of Bulk Cell**, automatically assumes DTC is enabled in Section 3 and those parameters must be specified if DTC is to be included in the simulation. To not include DTC in the simulation the user can set **2.1.2: Input Thermal Cycle at Temperature** equal to 0, as this this ensures that there is no DTC being observed from the input temperature value and Section 3 becomes disabled.

**Section 3.0: Effects of Battery Daily Thermal Cycling (DTC) –** Daily thermal cycling or DTC is another thermal-driven stress factor that causes battery material degradation and related aging. It is a realistic condition for many battery use cases (especially those with no active thermal management).

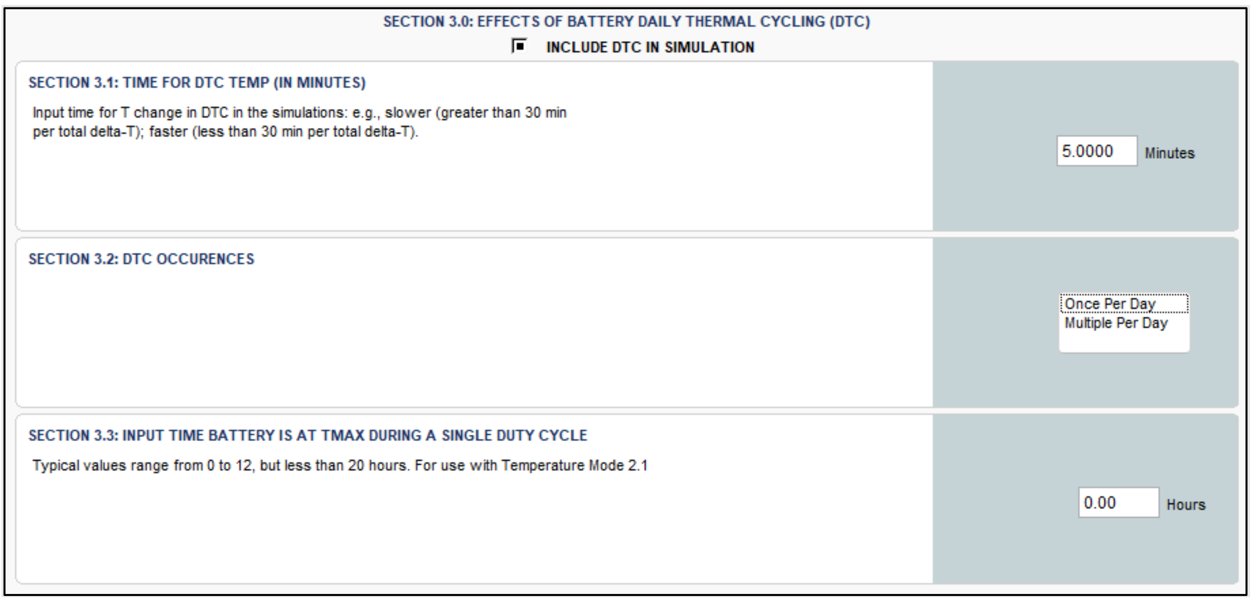



**Figure 24. GUI Section 3.0 for the effects of battery daily thermal cycling conditions.**

A summary for each of the three DTC parameters is shown below:

**Section 3.1: Time for DTC Temp (in minutes):** Sets the warm-up time from idle or "cold start" to fully operating or "warmed up." An input from 5 minutes to 60 minutes can be entered. This parameter represents the estimated time required for the warm-up temperature transition from an initial (cooler) starting value to the final (warmer) value that would ordinarily be seen in the battery application. This should typically track with the duty cycle frequency. One way to look at this is a PHEV service vehicle that has frequent starts and stops, some rest periods, etc. The battery will undergo more than just one round-trip (duty cycle) equivalent of exposure to DTC.

**Section 3.2: DTC Occurrence** - Sets the simulation DTC frequency. It can be set to either once per day or multiple thermal cycles per day. At present the details of a particular duty cycle are specified in the DCC configuration file.

**Section 3.3: Input Time Battery is at Tmax (in hours):** Time duration in hours during a single duty cycle. Typical values range from 0 to 12 hours, but less than 20 hours. This third DTC parameter can only be selected if Temperature Mode 2.1 is selected for the simulation.

### 3.1.3 Annual Temperature Profiles & Thermal Management (TM) Conditions

This tab is enabled when the temperature mode in Tab 2 is set to **2.2: Annual Temperature Profiles for Select Cities or Applications**, and allows the user to specify, view, and edit annual temperature profiles as well as thermal management (TM) conditions.

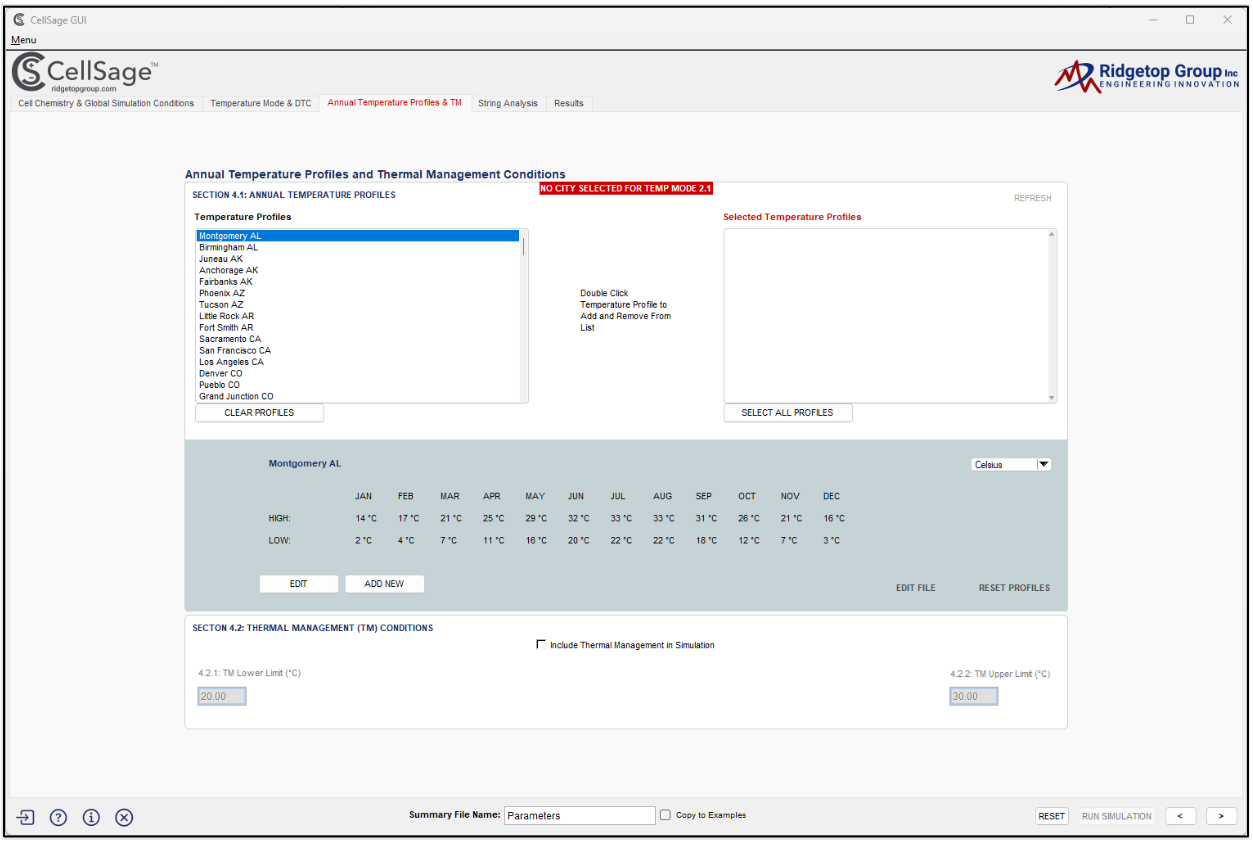



**Figure 25. Tab 3 – Annual Temperature Profiles and Thermal Management (TM) Conditions.**

**Section 4.1: Annual Temperature Profiles** – This section allows the user to view, edit, and create annual temperature profiles related to select cities or geographic regions as well as specific annual temperature profiles for custom applications. By default, all temperature profiles are in units of degrees Celsius, but the user can switch to degrees Fahrenheit if desired by changing the temperature setting in the dropdown box. The annual temperature files are saved in *.csv file format which can be edited with Microsoft Excel by clicking the "EDIT FILE" button. Since temperature profiles can be edited, there is also a "RESET Profiles" button that will restore the default annual temperature profiles for all 130 US cities and discard any changes that have been made or added. The complete list of US cities is shown in Section 5.1 in the Appendix.

The temperature profile for a selected city or application can be added to the simulation by double clicking on the city in the displayed list, and verifying that it shows up in the scroll box for Selected

Temperature Profiles. All temperature profiles can be added to or removed from the simulation by clicking on the "Select All Temperature Profiles" button or the "Clear Temperature Profiles" button respectively.
If the user wishes to edit or add a new annual temperature profile within the program, the user can select the corresponding button and the program will generate a pop-up window that shows monthly high and low temperatures for the selected city or temperature profile ID. The following image provides a visual aid of the pop-up user form, and shows that the user can delete a temperature profile, save temperature profile edits, or cancel making any changes:

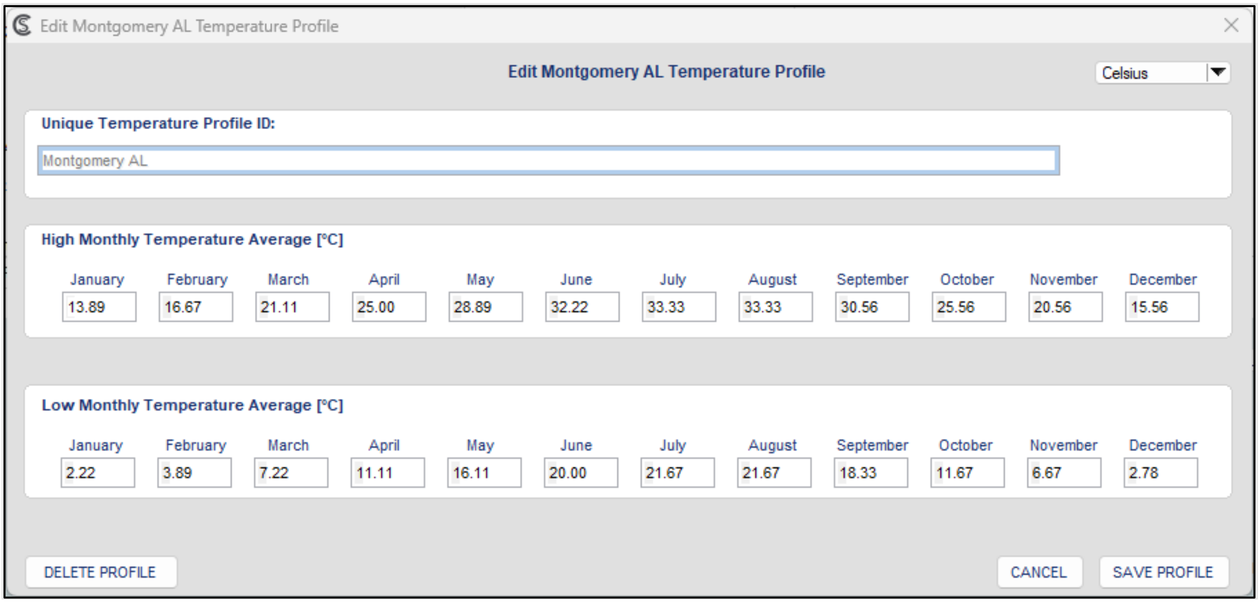



**Figure 26. GUI user form to edit annual temperature profiles.**

The following image shows a visual aid for adding Denver, Tucson, and Phoenix to a simulation run by double clicking on the selected cities. Upon executing the simulation, the data output files will show results that are dependent on the actual temperature profiles for each of the selected cities. The cities can be removed by double clicking on them in the right scroll box window.

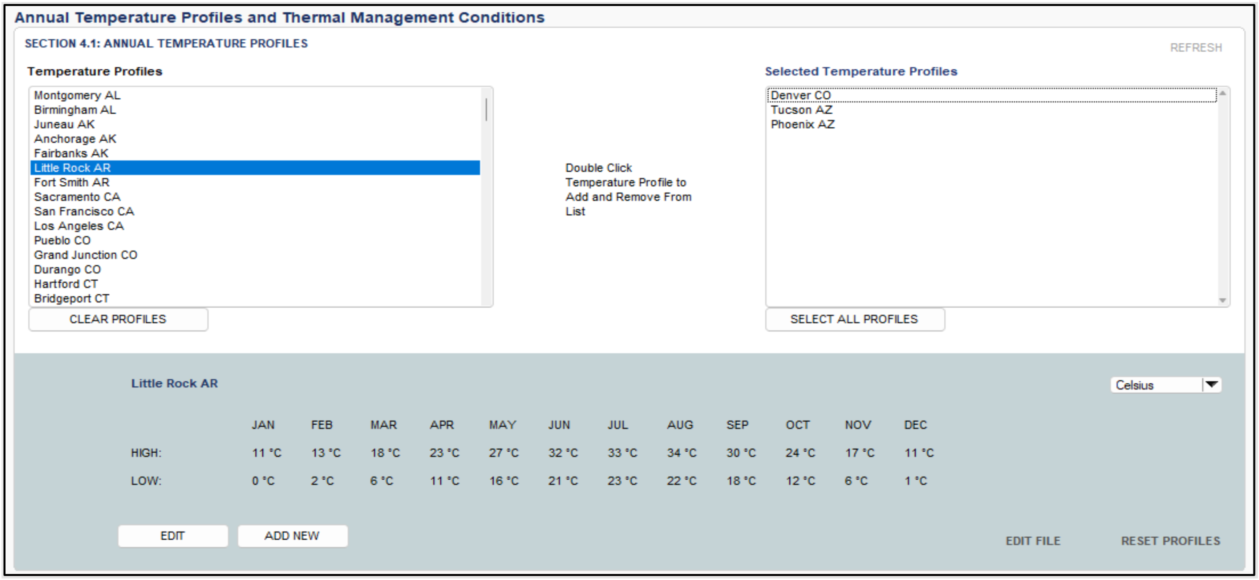



**Figure 27. Example view for adding select city temperature profiles to simulation.**

**Section 4.2: Thermal Management Conditions -** This section in Tab 3 provides the means to limit the cell temperature excursions due to thermal management systems such as liquid or air cooling. This does not impact the cell charging, discharging, or other cycling phenomenon. This is more of an open-loop system capability to reflect there is an external system providing cell level heating and cooling. It is recommended that this option is left disabled if no thermal management resides in your battery powered product or system.

- **4.2.1: TM Lower Limit (deg. C)** - Sets the thermal management low temperature limit.
- **4.2.2: TM Upper Limit (deg. C)** - Sets the thermal management high temperature limit.

### 3.1.4 String Analysis Tab

This tab will allow a user to enter parameters that simulate the effects of thermal hot spots in string aging and then run the simulation as all required input conditions have been entered.

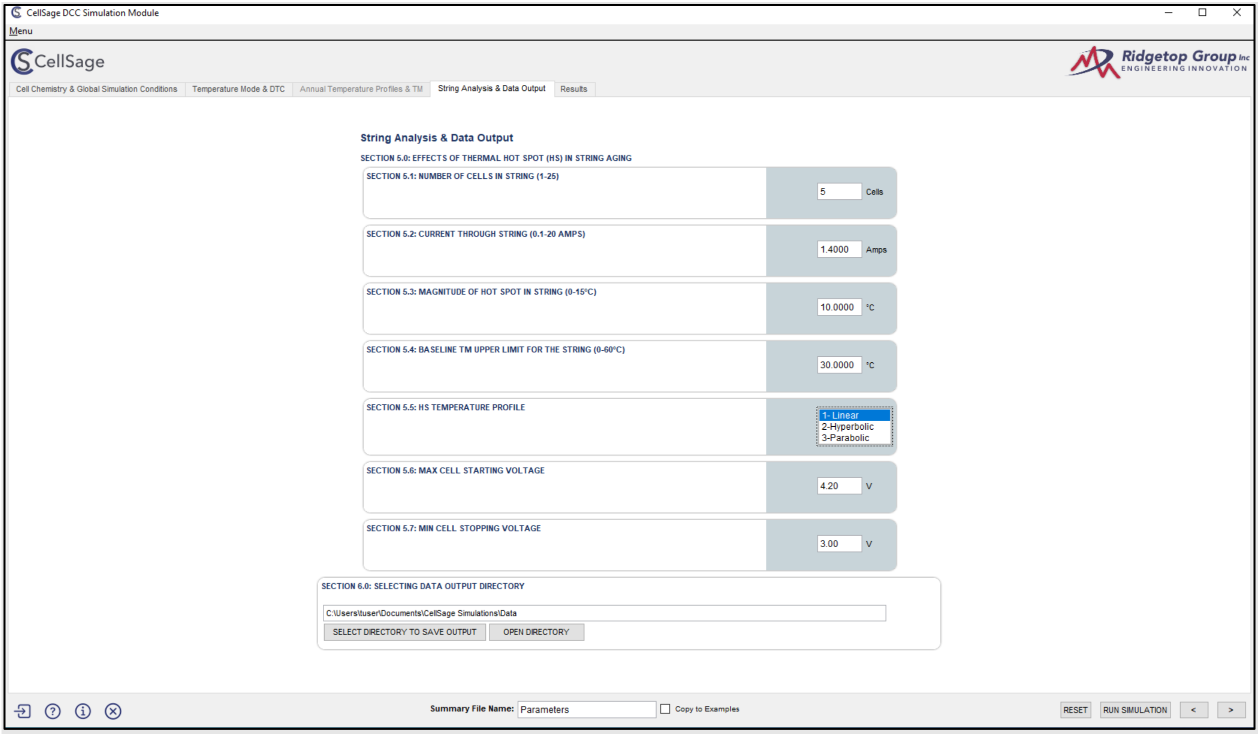



**Figure 28. Tab 4 – String Analysis & Data Output.**

**Section 5.1: Number of Cells in String (Range 1-25) -** The presumption is a single series string having 3 to 25 cells can be used for many applications involving lithium-ion cells. A battery pack that is comprised of only one or two cells is usually not defined as a full string, but it can still be modeled. It's recognized that there are battery packs that have many different combinations of cells; 2 or more in series, 2 or more in parallel, but at this time, CellSage™ only supports cells in configured series. Parallel string analysis is a feature that Ridgetop will release in future versions of the program.

**Section 5.2: Current Through String (Amps) -** This setting is usually the discharge current that would be observed under the 18650 cell basis. What does 18650 cell basis mean? The reference to 18650 (18mm dia. x 65 mm length and circular cross section) cell basis is that the CellSage™ is utilizing a common basis for cells and the electrochemical properties of that specific package type. The cell length, diameter, and electrical contacts all impact the cell models and simulation results. Other package formats would have to be specifically modeled to ensure a faithful representation of cell aging.

**Section 5.3: Magnitude of Hot Spot in String -** This setting is the absolute positive temperature variation from the center cell to end cells of a series string. In practice there could be regional effects on thermal management, but the code could be run to explore what happens when you change the magnitude of the hot spot. This condition can be set to a temperature value from 0 to 15 C.

**Section 5.4: Baseline TM Upper Limit for the String (deg. C) -** This is typically the same setting as max temperature under thermal management. However, thermal management isn't always enabled and this additional setting is used for power fade calculations. This simulation condition is useful if the upper temperature limits differ from that of the string operation.

This parameter must be set even if thermal management is not enabled. If thermal management is enabled then it should be set to the same value as the upper limit for the Thermal Managements Conditions tab. If thermal management is not enabled then it should be set to the value entered in **Section 2.1.1: Input Temperature Value** from the Temperature Mode tab. This will reflect the baseline temperature for which the cell will operate and must be from 0 to 60 degrees C.

**Section 5.5: HS Temperature Profile -** There are 3 choices 1-Linear, 2-Hyperbolic, 3-Parabolic. The type of thermal management (ambient, air-driven, fluid, etc.) and its responsiveness can impact how the hot spot permeates from the center (is the temperature profile concave-up or concave-down, or linear?).  This will have an impact on net aging within the string.

**Section 5.6: Max Cell Starting Voltage (V) -** The maximum cell starting voltage for string power fade calculations is the upper limit of the cell operating voltage.

**Section 5.7 Min Cell Starting Voltage (V) -** The minimum cell stopping voltage for string power fade calculations is the lower cell voltage limit.

### 3.1.5 Results Tab

The fifth and final tab in the CellSage™ GUI is the "Results" section, where the user can preview data output files and plots.

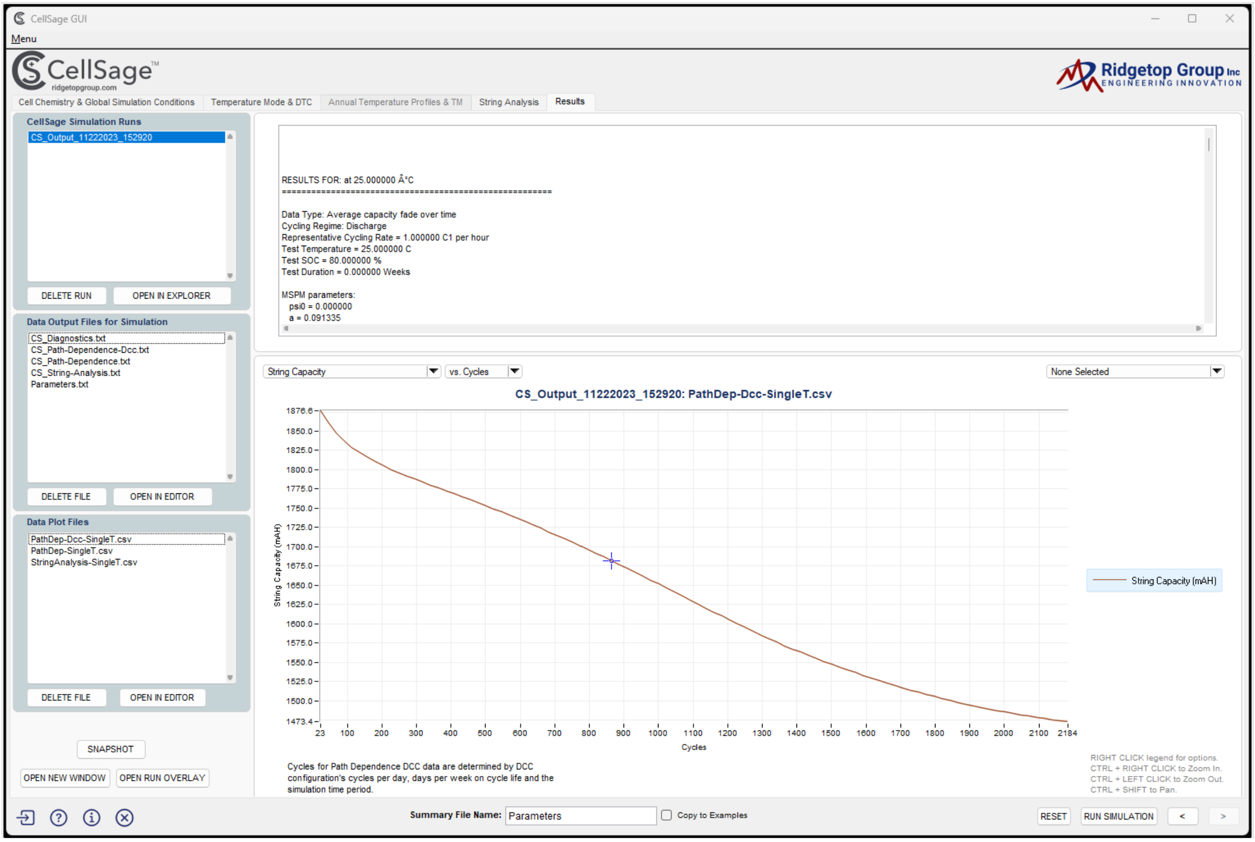


**Figure 29. Tab 5 – Results tab.**

The Results tab is separated into three scroll boxes, a text previewing window, a graphing chart, and a list of available data plots to populate the graphing chart. The first scroll box is a list of available simulation runs that have been logged in the data output directory that was specified in Section 3.1.4. The second scroll box is a list of the 5 main data output files in .txt format that are contained in the selected simulation run folder from the first scroll box. A brief overview on the contents of the 5 main data output files is covered in Section 3.2. When a specific *.txt file is selected in the second scroll box, the user can preview its contents in the large text previewing window above the graphing chart. The third scroll box contains a list of available *.csv data files, and, depending on the type of simulation, there will be a list of available data plots that can be selected via the dropdown box above the chart area. The different data plot types are automatically generated from the *.csv outputs that pertain to either the CS_Path-Dependence-DCC.txt, the CS_Path-Dependence.txt, or the CS_String-Analysis.txt output files. Finally, the graphing chart area also supports the ability to overlay different data plot types as it is useful to see certain combinations of data output such as Estimated Cell Capacity and Temperature vs. Cycles. The OPEN RUN OVERLAY button extends this capability to compare different data outputs from two different simulations as shown in Figure 30.

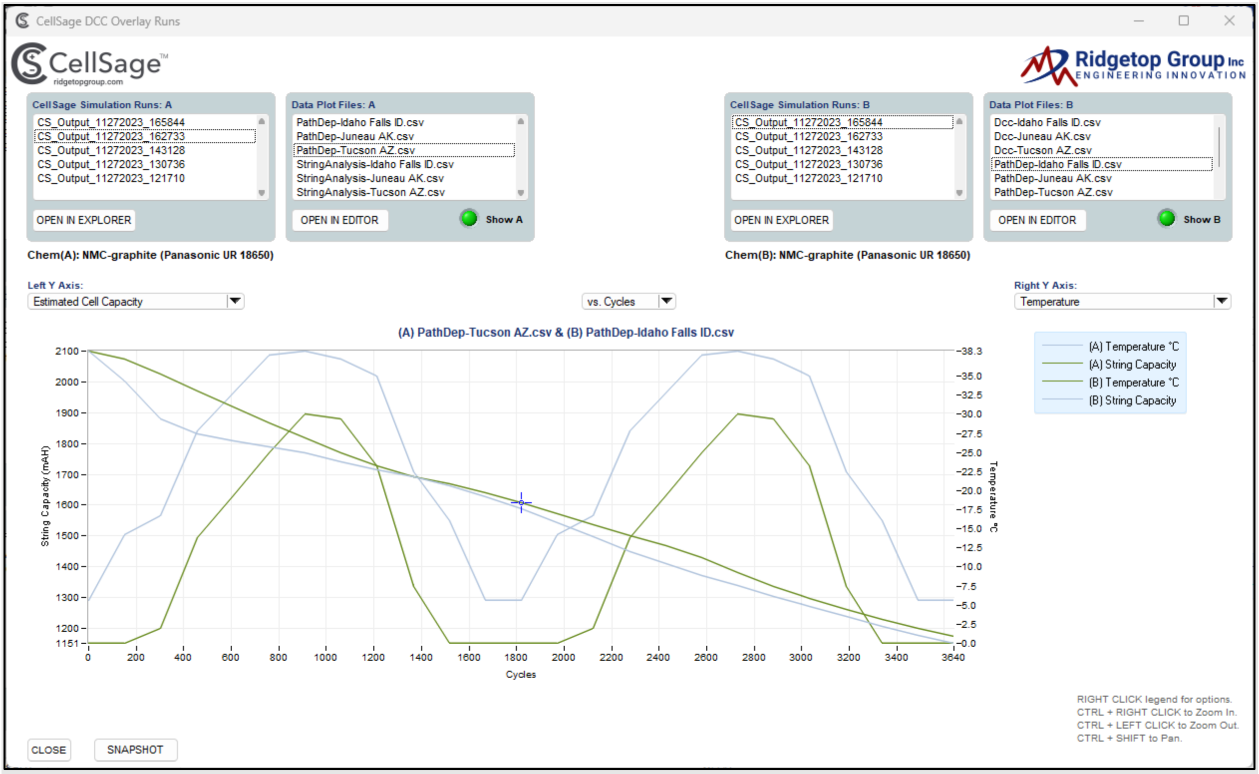



**Figure 30. Example 4 simulation results for Estimated Cell Capacity and Temperature in Tucson, AZ vs. Example 5 simulations Results for Estimated Cell Capacity and Temperature in Idaho Falls, ID. Note: Plots can be toggled on and off by clicking the green radio button for Simulation A vs. Simulation B.**

**List of Data Plots from CS_Path-Dependence-DCC.txt**

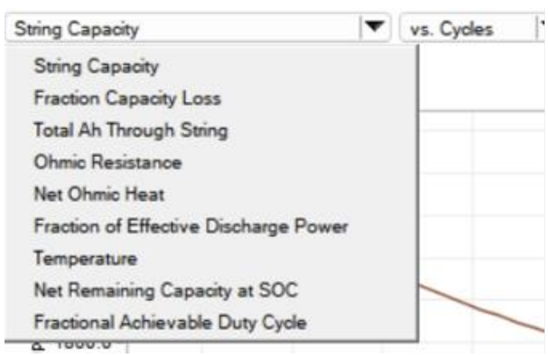



**Figure 31. View of dropdown box for plots based on CS_Path-Dependent-Dcc.txt.**

- String Capacity vs. Weeks or Cycles
  - String Capacity refers to total energy capacity in the modeled string of batteries. This plot shows how string capacity changes as a function of time (in weeks) or number of charge-discharge cycles.
- State of Health vs. Weeks or Cycles

  - State of health (SOH) refers to battery capacity normalized with respect to pristine battery capacity. This plot shows normalized string capacity as a function of time (in weeks) or number of charge-discharge cycles.
  - $SOH = (Remaining\ Capacity)/(Pristine\ Capacity)$
- Fraction Capacity Loss vs. Weeks or Cycles
  - Fraction of Capacity Loss (FCL) refers to remaining battery relative to initial battery capacity.
  - $FCL = 1 - SOH$
- Total AH through String vs. Weeks or Cycles
  - Total AH through String refers to total charge throughput of battery system. This plot shows total charge in amp-hours that has been charged to, discharged from, or both charged to and discharged through the battery string. Total charge throughput can be plotted against time (in weeks) or number of charge-discharge cycles.
- Ohmic Resistance vs. Weeks or Cycles
  - Ohmic Resistance refers to the ionic resistance associated with (charging, or discharging, or both charging, and discharging) of the battery string. This resistance increases with time because of the growth of the solid-electrolyte interphase layer. Ohmic Resistance can be plotted against time (in weeks) or number of charge-discharge cycles.
- Net Ohmic Heat vs. Weeks or Cycles
  - Net Ohmic Heat refers to internal heat generation associated with battery charge and discharge. Net Ohmic Heat can be plotted against time (in weeks) or number of charge-discharge cycles.
- Fraction of Effective Discharge Power vs Weeks or Cycles
  - Fraction of Effective Discharge Power refers to maximum string discharge power output relative to pristine power output. Fraction of Effective Discharge Power decreases with battery use because of energy losses associated with internal ionic resistance. Fraction of Effective Discharge Power can be plotted against time (in weeks) or number of charge-discharge cycles.
- Temperature vs. Weeks or Cycles
  - This plot shows the modeled temperature profile versus weeks or cycles during a CellSage™ simulation. This temperature model can be either a Single T Representation with Temperature Mode 2.1, or it can be an annual temperature profile that is observed in different geographic regions or cities with Temperature Mode 2.2.
- Net Remaining Capacity at SoC vs. Weeks or Cycles
  - This plot shows the Net Remaining Capacity as a function of SOC and Aging Conditions.
  - For some battery applications, it may be desirable to connect remaining or available capacity to the SOC range of interest. While there is an underlying proportionality of battery capacity back to the reference of 100% SOC, it starts to become inaccurate as we operate beneath 100% SOC.  This is due in part to regions of the electrode solid state that determine capacity over SOC can age at different rates, making it unrealistic to assert that since a cell has lost 20% capacity based on a full charge, that there is also 20% relative loss if only charged to 90, 80….50% SOC, for example. Added to this are the non-linear relationship between SOC and voltage, as well as polarization effects from operating at

high cycling rates, both of which have associated aging effects. Such artifacts are readily seen in differential capacity data (dQ/dV), for example.

- To provide a first-order estimate of the remaining/available capacity, the CellSage™ software imposes a simple relationship involving the loss of capacity at 100% SOC converted to the operating range of SOC for the user-defined duty cycle. Note that the code already assesses capacity loss based on the collective charge and discharge steps; this latest development also conditions the available capacity with respect to SOC. With this addition, users can now determine how to manage SOC over time to have both sufficient battery life and storage capacity over the intended lifecycle. For example, some battery applications may call for starting with a modest upper SOC (e.g., 85-90%) to reduce aging, but then carefully increasing this over time to compensate for lost energy storage. Conversely, other applications may benefit from stage-wise reduction of the SOC window, while necessarily reducing the duration of power delivery, to conserve battery life. Please note that this first-order estimate may become less precise as the working SOC maximum is decreased from 100%.

- Fraction of Achievable Duty Cycle vs. Weeks or Cycles
    - This plot shows the Fraction of Achievable Duty Cycle that can be performed as the cells age during the simulation.
        - A value of 1.0 (100%) indicates that a complete duty cycle specified in the DCC User Form (both charging and discharging) can be entirely completed without lacking energy storage.
        - A value less than 1.0 (< 100%) indicates that the cells have suffered some loss of energy storage.
        - A flag has also been added to identify whether the loss of energy storage was due to discharge conditions denoted as 'd', or charge conditions denoted as 'c'. If no loss of energy storage is identified, then the flag is set to 'n' (neutral).

**List of Data Plots from CS_Path-Dependence.txt**

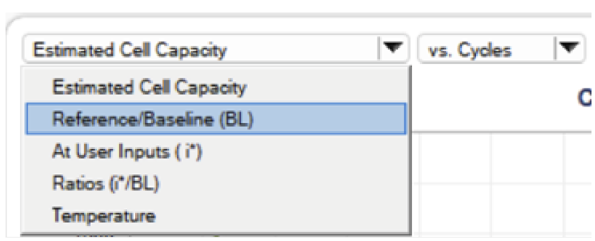



**Figure 32. View of dropdown box for plots based on CS_Path-Dependence.txt.**

- **Estimated Cell Capacity vs. Weeks or Cycles**
    - Estimated Cell Capacity provides an estimate of string capacity calculated according to the "path-dependence" degradation calculation method. The "path-dependence" calculation method determines battery degradation by accounting for accumulated stress factors such as elevated temperature, overcharge, over-discharge, and over-current events. Estimated Cell Capacity can be plotted against time (in weeks) or number of charge-discharge cycles.
- **State of Health vs. Weeks or Cycles**

- State of Health (SoH) is Estimated Cell Capacity relative to pristine cell capacity. State of Health This plot shows how string capacity changes as a function of time (in weeks) or number of charge-discharge cycles.

- **Reference/Baseline (BL) vs. Weeks or Cycles**
  - Reference/Baseline (BL) refers to degradation measured under "Reference Conditions" indicated on the "Cell Chemistry & Global Simulation Conditions" tab (See Figure 19). This plot shows degradation according to the two mechanisms most responsible for capacity loss: (1) loss of lithium inventory (LLI), and (2) loss of active material (LAM). Loss of lithium inventory refers to lithium ions that (a) react with organic compounds in the electrolyte, or (b) become lithium metal and plate the anode, cathode, or separator. Loss of active material refers to loss of anode or cathode due to overcharging, over-discharging, thermal shock, vibration, etc. TOTAL shows loss associated with LLI and LAM. This plot also shows the sum of capacity loss due to these mechanisms. Reference/Baseline plots can be shown as functions of time (in weeks) or number of charge-discharge cycles.
- **At User Inputs (i*) vs. Weeks or Cycles**
  - At User Inputs shows LLI, LAM, and TOTAL loss associated with user-defined battery operating conditions. At User Inputs (i*) plots can be shown as functions of time (in weeks) or number of charge-discharge cycles.
- **Ratios (i*/BL) vs. Weeks or Cycles**
  - Ratios (i*/BL) shows (a) ratio of loss of lithium inventory at user-specified conditions (LLI(i*)) per loss of lithium inventory at baseline conditions (LLI(BL)) (LLI(i*)/LLI(BL)), (b) ratio of loss of active material at user-specified conditions (LAM(i*)) per loss of active material at baseline conditions (LAM(BL)), LAM(i*)/LAM(BL), and (c) ratio of total loss at user-specified conditions (TOTAL(i*)) per total loss at baseline conditions (TOTAL(BL)), TOTAL(i*)/TOTAL(BL). Ratio (i*/BL) plots can be shown as functions of time (in weeks) or number of charge-discharge cycles.
- **Temperature vs. Weeks or Cycles**
  - Temperature shows temperature profiles used by CellSage™ to calculate degradation. Temperature profiles used to calculate degradation plots can be shown as functions of time (in weeks) or number of charge-discharge cycles.

**List of Data Plots from CS_String-Analysis.txt**

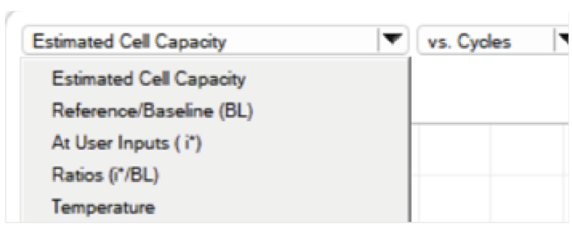



**Figure 33. View of dropdown box for plots based on CS_String-Analysis.txt.**

- **Cell Capacity vs. Weeks or Cycles**
  - Cell Capacity refers to per cell energy capacity in the modeled string of batteries. This plot shows how string capacity changes for the cell that is closest to the string's hot spot (Worst Case), furthest from the string's hot spot (Best Case), and at half-way point between Best

Case and Worst Case (Ave Case) as a function of time (in weeks) or number of charge-discharge cycles.

- **State of Health vs. Weeks or Cycles**
  - State of Health (SOH) refers to Worst Case degradation normalized with respect to pristine capacity. State of Health plots can be shown as functions of time (in weeks) or number of charge-discharge cycles. $SOH = (Cell\ Capacity)/(Pristince\ Cell\ Capacity)$
- **String Capacity Loss vs. Weeks or Cycles**
  - String Capacity Loss refers to loss of SOH for the Best Case, Worst Case, and Ave Case. String Capacity Loss plots can be shown as functions of time (in weeks) or number of charge-discharge cycles. $SOH = 1 - SOH$
- **Power vs. Weeks or Cycles**
  - Power refers to cell discharge power in units of Watts and is determined using cell starting voltage with and without a thermal hot spot (Vstart HS and Vstart No HS). The string discharge power plot also shows calculated outputs over a Voltage range with and without a thermal hot spot (Vrange HS and Vrange No HS). Power plots can be shown as functions of time (in weeks) or number of charge-discharge cycles
- **Temperature vs. Weeks or Cycles**
  - Temperature shows temperature profiles used by CellSage™ to calculate degradation. Temperature profiles used to calculate degradation plots can be shown as functions of time (in weeks) or number of charge-discharge cycles.

Notes About Simulation Type and Data Plots:

- The cycle count in the "CS_String-Analysis.txt" and "CS_Path-Dependence.txt" data files is independent of the cycle count referenced in the "CS_Path-Dependence-Dcc.txt" data files. As outlined in Section 3.1.1, the "CS_String-Analysis.txt" file uses a fixed number of cycles per day dependent on chemistry and CSI, where as the "CS_Path-Dependence-Dcc.txt" file uses a cycle count based on the number of cycles per day defined in the DCC config file. By default the program will auto set the CSI calculations to synchronize the total number of cycles, but these parameters can still be set independently if desired.
- Temperature Mode 2.1 with No DCC – Generates .csv data files titled "StringAnalysis-SingleT.csv".
- Temperature Mode 2.1 with DCC – Generates .csv data files titled "PathDep-SingleT.csv".
- Temperature Mode 2.2 with No DCC – Generates .csv data files titled "PathDep-*Temp_ID*.csv", where *Temp_ID* is replaced with the city name or annual temperature profile ID.
- Temperature Mode 2.2 with DCC – Generates .csv data files titled "Dcc-*Temp_ID*.csv", where *Temp_ID* is replaced with the city name or annual temperature profile ID.

## 3.2 Data Output Files

The CellSage™ Battery Health MS&A Software Platform produces five main data output files in a .txt file format. An overview of what can be reviewed in each data output file is detailed below:

1. **CS_Diagnostics.txt**: This file provides the intermediate simulation results determined by the regression models embedded within CellSage™ software. This file is designed for inspection and validation of the simulation results.
2. **CS_Path-Dependence-Dcc.txt**: This file is an extended version of the above CS_Path-Dependence.txt file that includes additional data outputs that were generated from the DCC module.
3. **CS_Path-Dependence.txt**: This file provides simulated cell/battery aging at any sequence and combination of T, SOC, cycling regime over time, and also accounts for the detrimental effects of daily thermal cycling (DTC), which is dependent on the presumed geographic location of battery usage. Outputs also cover thermal management scenarios of choosing Tmin and Tmax of the battery enclosure. This file covers the arbitrarily-chosen conditions that reflect a battery duty cycle and ambient working conditions of the battery-driven product. "Path dependence" is a crucial consideration since each unique usage path for a battery within a given product will produce a unique aging path and history. One ultimate advantage to CellSage™ is to optimize the usage path to minimize the battery aging to satisfy life and performance requirements.
4. **CS_String-Analysis.txt:** This file provides analysis of available power over aging in terms of a reference voltage context (HEV application) and a power-at-range metric (EV-PHEV application) that incorporates the effect of capacity loss over time. Calculations are done for a series string of cells, with inputs provided by the user (number of cells, maximum and minimum voltages, string hot spot attributes, and others).
5. **Parameters.txt**: This file provides a summary of all input parameters that were selected or entered for a given simulation. The default file name is Parameters.txt, but it can defined by the global "Parameter Summary File Name:" input at the bottom of the GUI. The file can also be copied to Examples subdirectory, so the simulation conditions can be imported and rerun at a later time.

The application allows a user to select the output directory as covered in Section 3.1.4. Once the simulation parameters have been entered, the output directory has been specified, and the user clicks the Run Simulation button, these data output files will be generated and logged in a simulation folder. The default name of the simulation folder is shown below: **C:\Users*user-ID*\Documents\CellSage™ Simulations\Data\ CS_Output_*Timestamp*,** where the ***user-ID*** is unique to the end user and the PC the software is installed on, and the *TIMESTAMP* is appended to the folder name of each simulation run. The timestamp is defined as Month-Day-YYYY-Hour-Minute-Second. An example is shown in Figure 34.

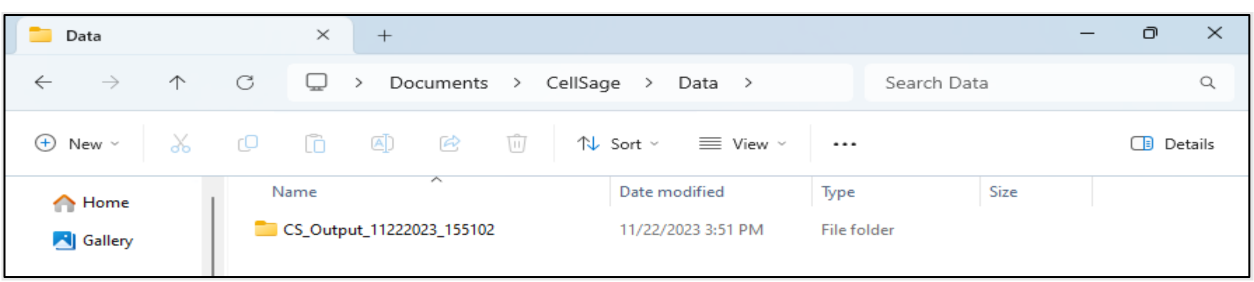



**Figure 34. Example view of timestamped data output folder in default data output directory.**

The following image provides a visual of what is inside this data output directory:

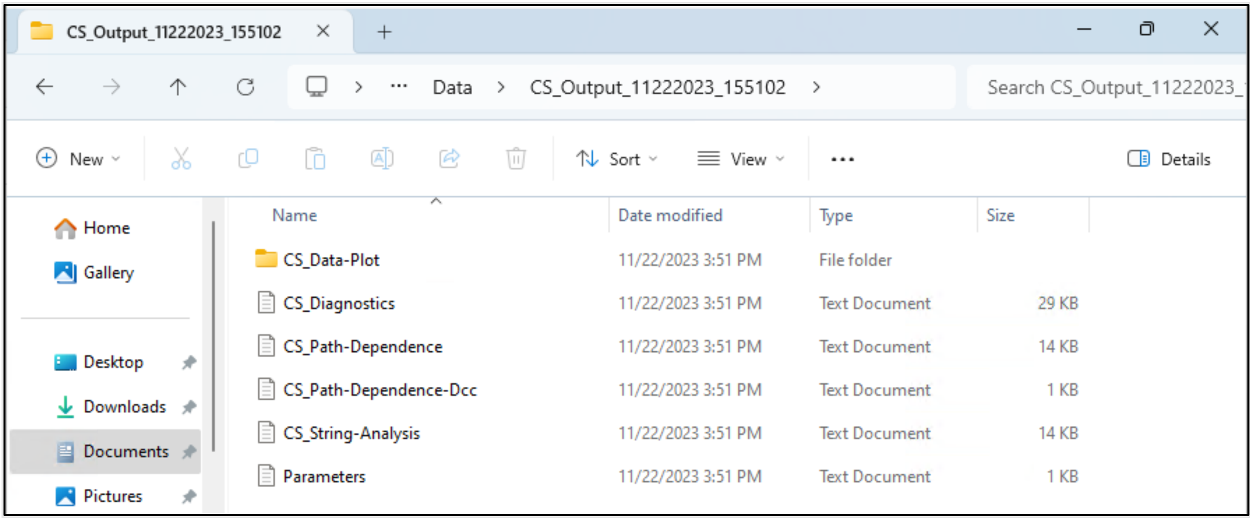



**Figure 35. Example view of simulation folder contents.**

Each output file will appear as a series of tables that show the aging effects by weeks and/or cycles. They are tailored to users with a chemistry background. The last column provides total percentage capacity fade, which may be of high importance to a common battery power system engineer.

As previously covered in Section 3.1.5, the CellSage™ GUI provides automatic plotting capabilities for all simulation runs. This has been made possible by creating additional *.csv files that only contain the key numeric data necessary for generating data plots from the "CS_Path-Dependence.txt", "CS_Path-Dependence-DCC.txt", and "CS_String-Analysis.txt" files. Each of the *.csv data files are stored CS_Data-Plot folder within the simulation run folder. A visual from Example 5 is displayed in Figure 36.

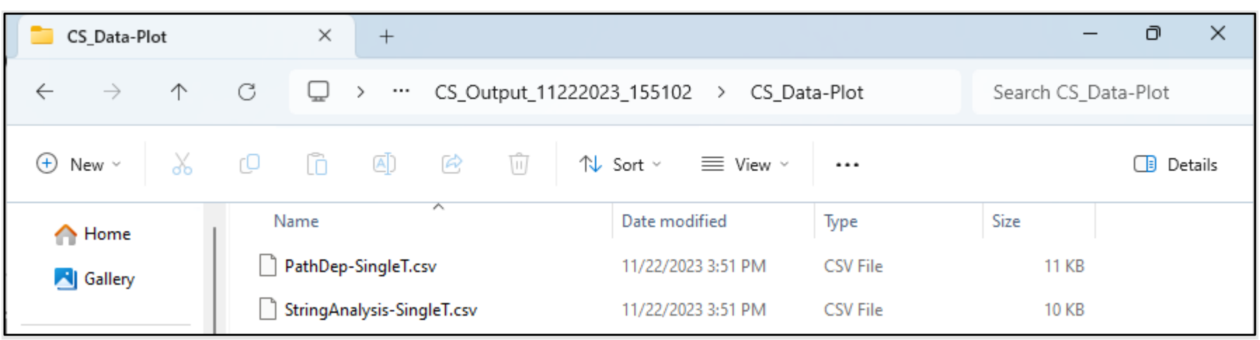



**Figure 36. Example view of CS_Data-Plot folder.**

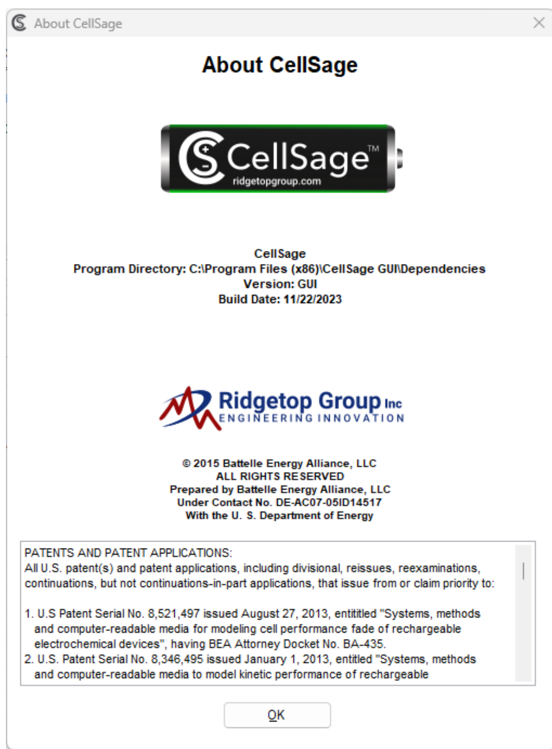
## 3.3 Global Features in CellSage™

### 3.3.1 Operating Buttons

There are nine (9) primary operating buttons that can be considered as global features. The program also supports a global input that is used to save a list of all defined simulation conditions in a unique .txt file name, that can be stored for future use in the Examples subdirectory. A brief overview for each global feature is outlined below:

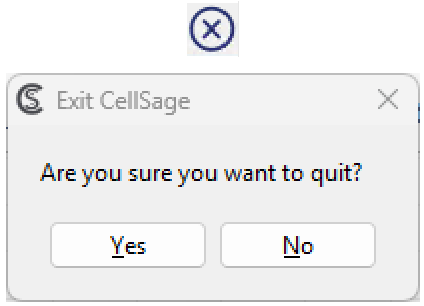
1. **Import Button:** This button allows a user to import a full set of simulation conditions from a parameters.txt file that is stored in the Examples subdirectory. When selected, this button will open up a Windows File Explorer for the user to search for a parameters.txt file or another Parameter Summary File Name as defined by the user. This feature is very useful when trying to rerun previous CellSage™ simulations as well as existing examples covered in the User Guide. After a parameters.txt file is selected for import, the program will prepopulate all simulation conditions to be specified in each tab.

2. **Information Button:** This button will generate a pop-up window and tell the user what version of the GUI they are working with.

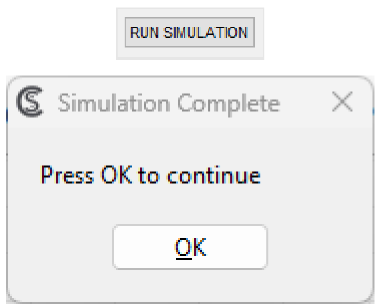



3. **Help Button:** This button will open up a hyperlink to the User Guide.

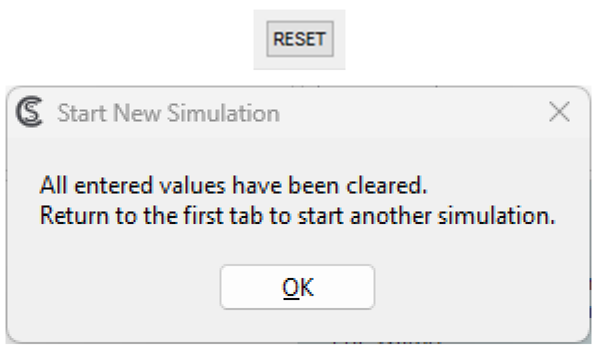
4. **Exit Button:** This button will prompt the user if they would like to close and exit the program. The simulation conditions that have been selected will not be remembered, so a user should only exit the program when they wish to close it.




5. **RUN SIMULATION Button**: This button will run the CellSage™ simulation once all simulation conditions have been satisfied. Once the simulation is complete a message box will appear and take the user to the Results tab to view the data outputs.

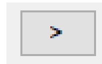



6. **RESET Button**: This button can be pressed to start a new simulation from scratch. It will generate a message box that states the parameters have been cleared and take the user back to the Cell Chemistry & Global Simulation Conditions tab to start over.




7. **Previous Button:** This button will take the user to the previous tab when selecting parameters for a simulation run. Do note that the parameter selection follows a linear programming flow from Tab 1 – Tab 5.


8. **Next Button:** This button will take the user to the next tab when selecting parameters for a simulation run. Do note that the parameter selection follows a linear programming flow from Tab 1 – Tab 5.




9. **Summary File Name:** This global input allows the user to specify a unique file name in .txt format that will list all defined parameters and conditions used in the simulation. This is a useful feature as the user also has option to save the unique file name to be used with the Import function at a later time. The default file name is "Parameters", and is included in the data output folder for CellSage™ Simulation Run.


# 4. CellSage™ New Chemistry Import Feature

The CellSage™ New Chemistry Import Feature represents a significant technological advancement, offering end-users the capability to customize the CellSage™ library for a wide range of battery chemistries and form factors. This is achieved by leveraging existing baseline aging data, and then performing an automated regression analysis to extract key model parameters.

## 4.1 Patented Approach to Modeling Capacity Loss with Sigmoidal Rate Expressions (SREs)

CellSage™ calculates battery degradation and makes predictions based on the idea that loss of capacity is a function of Sigmoidal Rate Expressions (SREs). This idea is expressed mathematically as shown below:

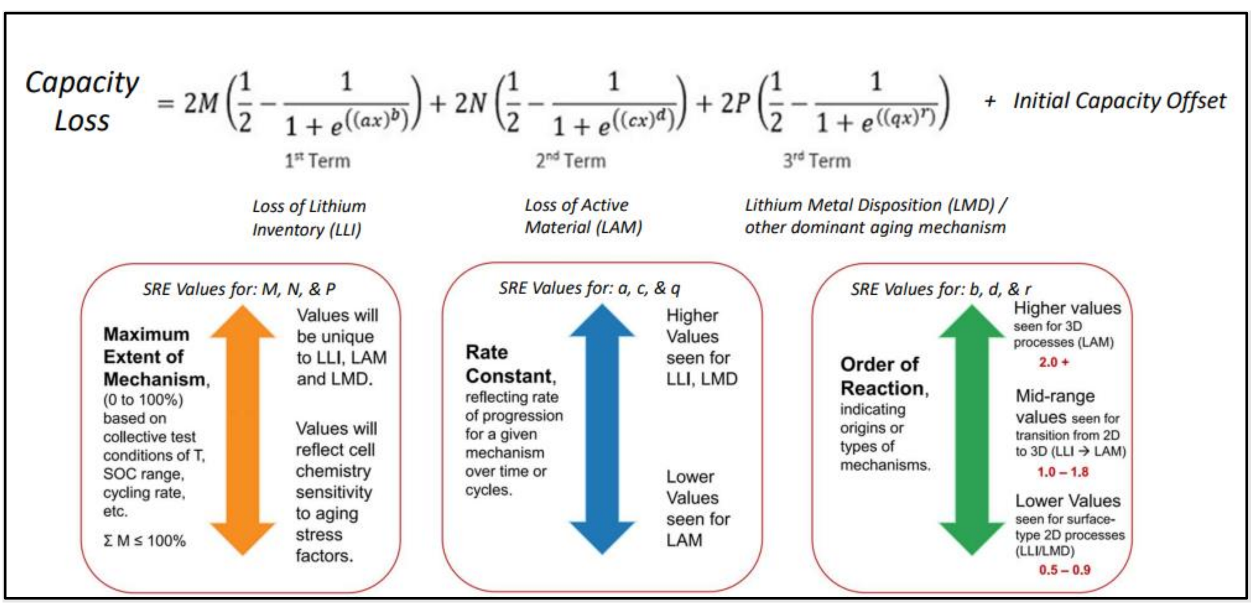



**Figure 37. SRE equations for modeling capacity loss in CellSage™.**

The foundation of CellSage™ lies in its patented approach, which utilizes SRE terms to accurately model the primary aging mechanisms in lithium-ion batteries. In its historical application, CellSage™ utilized two sets of SRE terms to model Loss of Lithium Inventory (LLI) and Loss of Active Material (LAM). However, with this new release package developed in collaboration with Ridgetop and Idaho National Laboratory (INL), a third set of SRE terms has been introduced to model additional dominant aging mechanisms that may be present in a customer's dataset.

SRE modeling is pivotal for comprehending the aging process of lithium-ion batteries. As battery energy storage (BES) gains traction in various sectors like electric vehicles and stationary energy systems, it becomes imperative to implement advanced battery management systems (BMS) that can compare real time degradation data against proven physics-based models like CellSage™. When fully integrated, such BMS designs enable real-time monitoring of battery health, prediction of aging trends, and early detection of potential failures during operation. This proactive approach not only enhances battery longevity but also contributes to safety and sustainability, aligning with the ongoing shift towards electric solutions aimed at achieving zero emissions.

Understanding the root causes of degradation is vital for guiding improvements in battery chemistry and corrective strategies. Battery aging is influenced by factors like path dependence, cell chemistry, and the differentiation between reversible and irreversible performance losses. To address these complexities, Ridgetop and INL researchers have collaborated extensively to test and validate the SRE modeling approach within CellSage™ to allow for the identification and classification of aging modes using electrochemical data.

The SRE modeling approach in CellSage™ is protected by multiple patents and copyrights as outlined in Section 6.1 in the Appendix. This collection of patented IP also plays a crucial role in accurately modeling the aging effects in lithium-ion batteries, particularly concerning LLI and LAM. In summary, our technology not only enhances battery management and monitoring practices, but also extends the lifetime of batteries, contributing to the overall efficiency and sustainability of energy storage solutions.

For more information on the SRE Basis and Background of CellSage™, please review the following publications:

- Accelerated Battery Life Predictions Through Synergistic Combination of Physics-based Models and Machine Learning
- Novel Method for Evaluation and Prediction of Capacity Loss Metrics in Li-Ion Electrochemical Cells

## 4.2 Cell Survey Tab

When adding a new cell chemistry or editing an existing cell chemistry model, the first tab within the New Chemistry Import Feature is the Cell Survey Tab. This tab is where the user enters and saves key model parameters that are obtained from the manufacturer datasheet, or some baseline testing experiments. This tab contains both required model parameters, and optional information that could be used for reference when expanding the CellSage™ library for the local installation. By default, there are eight cell chemistry models within CellSage™ and additional cell chemistry models will be added by Ridgetop Group and INL when they become available. Engineering services can also be quoted on a per project basis to customize the software and adapt the model for proprietary battery chemistries. A brief overview and description for all required model parameters is shown in Table 2, and the same is done for optional parameters in Table 3.

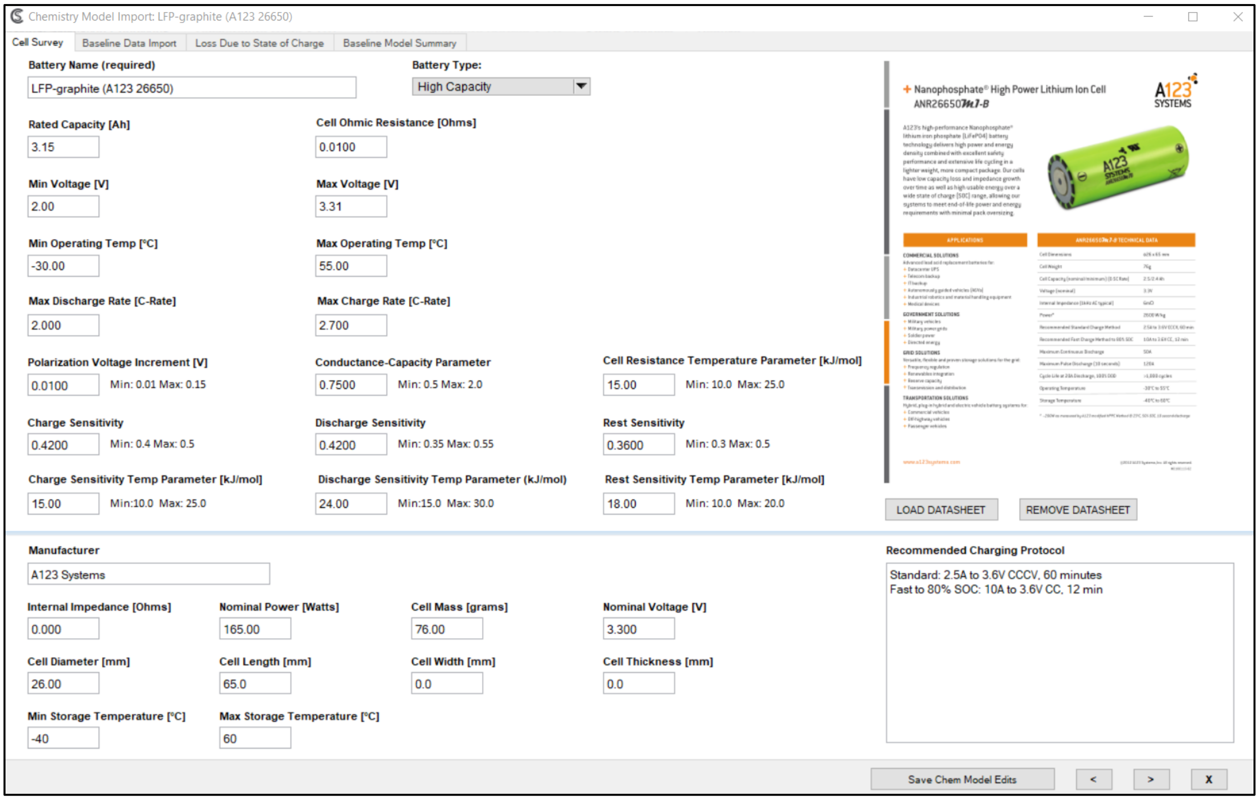



**Figure 38. Cell Survey Tab displayed in the New Chemistry Import Feature.**

**Table 2. Required Parameter Descriptions for Cell Survey Tab.**

| | Parameter | Description | Typical Range |
|---|---|---|---|
| 1 | Battery Name (required) | Unique string / text identifier to be associated with the file name for each battery chemistry model. | N/A |
| 2 | Battery Type | Specifies type of battery from dropdown list where options are (1) fast charge and discharge, (2) balanced, and (3) high capacity. Battery type is used to specify battery material capacity. | N/A |
| 3 | Rated Capacity [Ah] | Maximum charge of battery in Amp-Hours. Typically identified from manufacturer datasheet. | 1.0 - 20.0 [Ah] |

| | | | |
|---|---|---|---|
| 4 | Cell Ohmic Resistance [Ohms] | Measure of DC resistance in the battery, referenced at 298K [Ω]and mid-range SOC. Depends on cell chemistry, dimensions, and overall size (capacity) of cell. Generally, this is standardized as a value equivalent to an 18650-sized cell. | 0.0025 to 0.25 [Ω] |
| 5 | Min Voltage [V] | Minimum operating voltage of cell. Cell operation below this voltage leads to over-discharge and can cause permanent damage. Typically identified from manufacturer datasheet, but could depend on electrode couple. | 1.8 - 3.0 [V] |
| 6 | Max Voltage [V] | Maximum operating voltage of cell. Charging cell beyond maximum operating voltage leads to over-charge and can cause permanent damage. Typically identified from manufacturer datasheet, but could depend on electrode couple. | 2.8 - 4.2 [V] |
| 7 | Min Operating Temp [°C] | Coldest temperature at which cell can be charged or discharged under recommended rates without causing undue aging. Typically identified from manufacturer datasheet. | -20 to 0 [°C] |
| 8 | Max Operating Temp [°C] | Hottest temperature at which cell can be charged or discharged under recommended rates without causing undue aging. Typically identified from manufacturer datasheet. | 60 to 80 [°C] |
| 9 | Max Discharge Rate [C-Rate] | Maximum rate at which battery can be discharged, relative to a standard one-hour (1C) discharge rate. For example, if a battery has a 2 Ah discharge capacity rating at a cycling rate of 1C, then 2A can be sustained for one hour. A 5C rate would entail a 10A current, etc. Higher rates past | 1.0 to 10.0+ [C-Rate] |

| | | | |
|---|---|---|---|
| | | the recommended maximum will incur greater cell polarization and limit performance. Lower values are generally used for higher-energy cells, as opposed to higher-power cells. Exceeding this rate can also lead to permanent cell damage, and thermal runaway. If battery maximum pulse rate and maximum continuous discharge are specified, use maximum continuous discharge rate. Typically identified from manufacturer datasheet, but a conservative default could be 1C. | |
| 10 | Max Charge Rate [C-Rate] | Maximum rate at which battery can be charged, relative to a standard one-hour (1C) charge rate. Higher values past the recommended maximum will incur greater cell polarization and limit performance. Lower values are generally used for higher-energy cells, as opposed to higher-power cells. Exceeding this rate can also lead to permanent cell damage such as lithium plating and thermal runaway. Typically identified from manufacturer datasheet. | 0.5 to 5.0+ [C-Rate] |
| 11 | Polarization Voltage Increment [V] | Voltage margin required to overcome internal resistance, activation and concentration overpotentials, and reverse chemical reactions occurring during discharge.<br>This term is chemistry dependent, and highly dependent on temperature. It should be evaluated at the equivalent 1C discharge current within the SOC range anticipated for the application (typically, a condition between 60-90% SOC) for the cell of interest. | 0.01 to 0.15 [V]<br>default = 0.05 [V] |

| | | | |
|---|---|---|---|
| | | Cited by manufacturer, or often determined as a 1kHz measurement, this term could also be determined experimentally through voltage drop/jump during short constant-current pulses.<br><br>A higher value of this parameter would be used for higher-impedance cells and those intended for high energy applications, since they would employ thicker electrode laminates more prone toward polarization. A conservative default could be set to 0.05 [V]. | |
| 12 | Conductance-Capacity Parameter | Power law exponent relating increase of cell ohmic resistance to capacity loss. It is a general observation that capacity and conductance loss will track with each other as both increase with cell aging. However, their magnitude can differ over time. This parameter sets the magnitude of the conductance loss term relative to capacity loss.<br><br>Values above 1.0 are for cases where cell conductance loss is greater than the capacity loss, while values less than 1.0 are for the opposite case. | 0.5 - 2.0<br><br>default = 1.0 |
| 13 | Cell Resistance Temperature Parameter<br><br>(activation energy) | Chemistry specific activation energy parameter to assign sensitivity of cell resistance to temperature. Cell resistance temperature variation is assumed to vary according to an Arrhenius relationship.<br><br>If cell resistance over temperature is dominated by electrolyte resistivity, then the activation energy of the electrolyte can serve to provide an estimate of this parameter. An example is shown in Figure 39 in the notes section following this table for | 10.0 - 25.0 [kJ/mol]<br><br>default = 12.5 [kJ/mol] |

| | | | | |
|---|---|---|---|---|
| | | a common carbonate-based electrolyte. | | |
| 14 | Charge Sensitivity | Assigns sensitivity of cell capacity loss to charge rate conditions. A higher value increases sensitivity with correspondingly more aging. | 0.4 to 0.5<br>default = 0.4 | In practice, these terms will have lower values for higher-power cell chemistries that are lower impedance and designed to operate at higher rates. |
| 15 | Discharge Sensitivity | Assigns sensitivity of cell capacity loss to discharge rate conditions. A higher value increases sensitivity with correspondingly more aging. | 0.35 to 0.55<br>default = 0.4 | |
| 16 | Rest Sensitivity | Assigns sensitivity of cell capacity loss to SOC at rest conditions. A higher value increases sensitivity with correspondingly more aging. | 0.3 to 0.5<br>default = 0.3 | |
| 17 | Charge Sensitivity Temp Parameter<br>(activation energy) | Chemistry specific activation energy parameter to assign sensitivity of cell aging to charge conditions over temperature. Assumes an Arrhenius-like relationship between temperature and the charge-related aging.<br>This can be evaluated through aging data for cell groups being tested at different isothermal conditions, keeping all other charge test parameters equivalent. | 10.0 to 25.0 [kJ/mol]<br>default = 10.0 [kJ/mol] | |
| 18 | Discharge Sensitivity Temp Parameter<br>(activation energy) | Chemistry specific activation energy parameter to assign sensitivity of cell aging to discharge conditions over temperature. Assumes an Arrhenius-like relationship between temperature and the discharge-related aging.<br>This can be evaluated through aging data for cell groups being tested at different isothermal conditions, | 15.0 to 30.0 [kJ/mol]<br>default = 15.0 [kJ/mol] | |

| | | | |
|---|---|---|---|
| | | keeping all other discharge test parameters equivalent. | |
| 19 | Rest Sensitivity Temp Parameter<br>(activation energy) | Chemistry specific activation energy parameter to assign sensitivity of cell aging to calendar-life rest conditions over temperature.<br>This can be evaluated through aging data for cell groups being tested at different isothermal conditions, keeping all other calendar-life test parameters equivalent. | 10.0 to 20.0 [kJ/mol]<br>default = 10.0 [kJ/mol] |

**Notes:**

1. Parameters 1-19 are required for model operation, and Parameters 20-31 are optional information obtained from the manufacturer's data sheet.
2. Parameters 14-16 help establish the relative cell sensitivity to the given condition of charging, discharging or rest, and help mark the inflection point (for aging versus cycling rate) past which cell aging rates are notably increased for charging or discharging, and the relative impact of rest conditions.
3. The Arrhenius relationship is often used to describe the temperature dependence of chemical reactions and physical processes, including those related to battery cell resistance. The Arrhenius equation is given by:

$$k = A \cdot e^{-\frac{E_a}{RT}}$$

Where:

- $k$ is the rate constant of the reaction or process.
- $A$ is the pre-exponential factor (frequency factor), which is a constant.
- $Ea$ is the activation energy of the reaction or process.
- $R$ is the gas constant (8.314 J/(mol·K)).
- $T$ is the absolute temperature in Kelvin.

In the context of battery cell resistance, this equation can be applied to describe how the resistance ($R$) of the cell changes with temperature. The activation energy ($Ea$) represents the energy barrier that must be overcome for the resistance-related processes to occur.

For battery cells, resistance is influenced by various processes such as ion mobility, electrode kinetics, and electrolyte conductivity. As the temperature increases, these processes tend to occur more rapidly, leading to a decrease in resistance. The Arrhenius relationship helps to quantify this temperature dependence.

Keep in mind that the application of the Arrhenius equation assumes that the temperature range under consideration is not too extreme and that the system behaves according to the principles of the Arrhenius equation. In reality, there may be other factors and complexities that could influence battery behavior at very low or high temperatures. Additionally, different components of a battery cell may have different activation energies, so the overall behavior can be complex and depend on the specific chemistry and design of the battery.

4. An example of using electrolyte resistivity (inverse of conductivity) to estimate the activation energy for cell ohmic resistance. Such electrolyte properties can be accurately modeling and determined with the Advanced Electrolyte Model (AEM) developed by Idaho National Laboratory and exclusively distributed by Ridgetop Group Inc. For more information on AEM, contact a Ridgetop Group representative or visit the website at the following link:
    - [Advanced Electrolyte Model (AEM) – Developed by Idaho National Laboratory - Ridgetop Group]

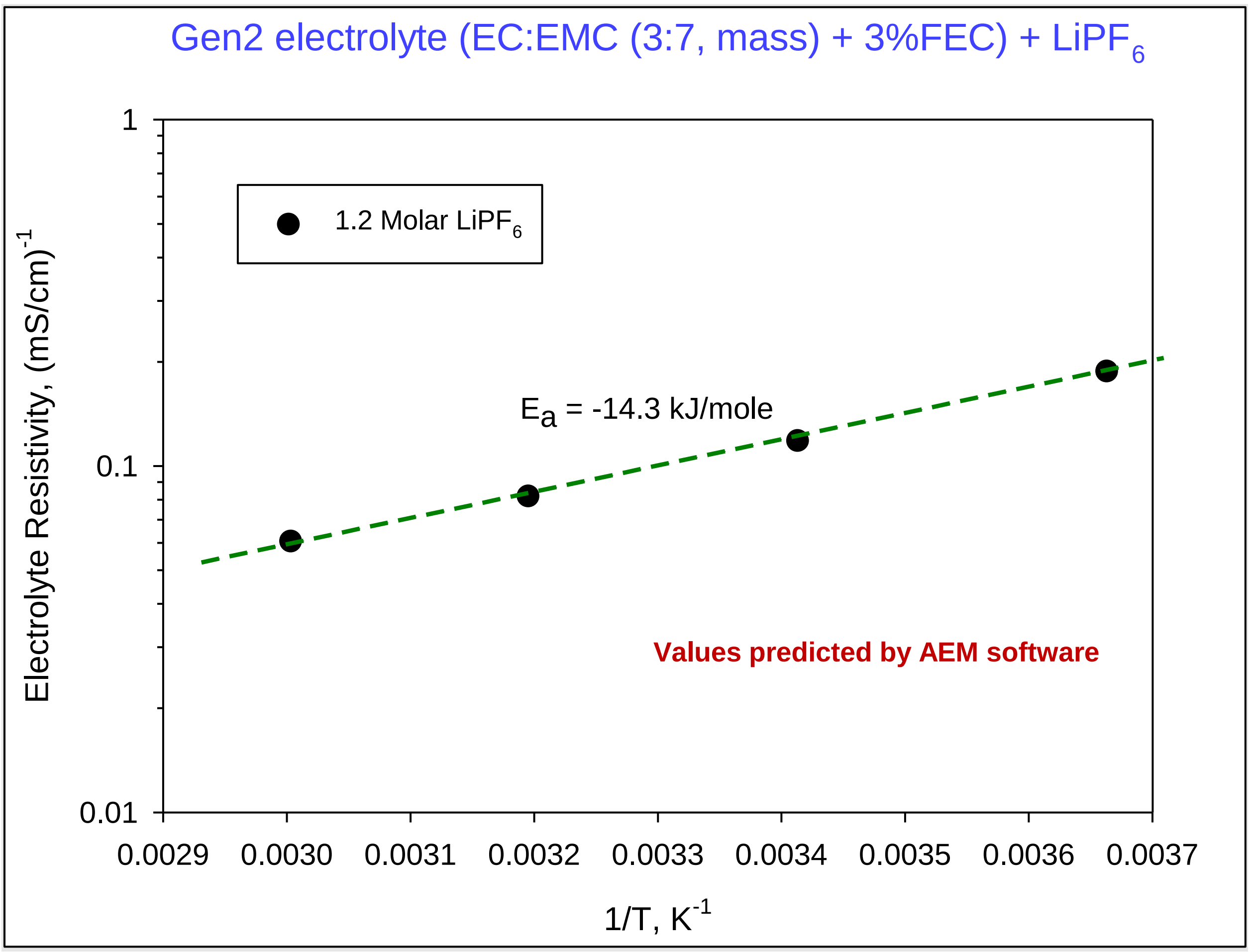



**Figure 39. Example of using electrolyte resistivity to estimate activation energy.**

5. Table 3 shows a list of optional parameters that can be stored inside of CellSage™ and they are separated by a light blue line from required parameters (1-19).

**Table 3. Optional Parameter Descriptions for Cell Survey Tab.**

| | Parameter | Description |
|---|---|---|
| 20 | Manufacturer | Name of battery manufacturer. |
| 21 | Internal Impedance [Ohms] | Sum of resistances including ionic resistance in electrolyte and electrodes, and electronic resistance in electrodes. |
| 22 | Nominal Power [Watts] | Battery power output at voltage where voltage-state of charge curve is relatively flat. |
| 23 | Cell Mass [grams] | Battery mass in grams. |
| 24 | Nominal Voltage [V] | Battery voltage where voltage-state of charge curve is relatively flat |
| 25 | Cell Diameter [mm] | If cell is circular in cross-section, this refers to cross-section diameter |
| 26 | Cell Length [mm] | If cell is circular, or prismatic in cross-section, this refers to dimension of cell perpendicular to cross-section. |
| 27 | Cell Width [mm] | If cell is prismatic, this refers to one dimension perpendicular to length of cell that is not thickness. |
| 28 | Cell Thickness [mm] | If cell is prismatic, this refers to one dimension perpendicular to length of cell that is not width. |
| 29 | Min Storage Temperature [°C] | Coldest temperature at which battery can be safely stored. |
| 30 | Max Storage Temperature [°C] | Hottest temperature at which battery can be safely stored. |
| 31 | Recommended Charging Protocol | Series of recharging steps recommended by manufacturer to charge battery. |

| | | |
|---|---|---|
| 32 | Datasheet | Specification sheet for battery. |

## 4.3 Baseline Data Import Tab

The Baseline Data Import Tab is where a user is prompted to enter the required information and data from four different sets of baseline testing conditions. These baseline testing conditions are identified as Cycle-Life One, Cycle Life Two, Calendar-Life One, and Calendar-Life Two.

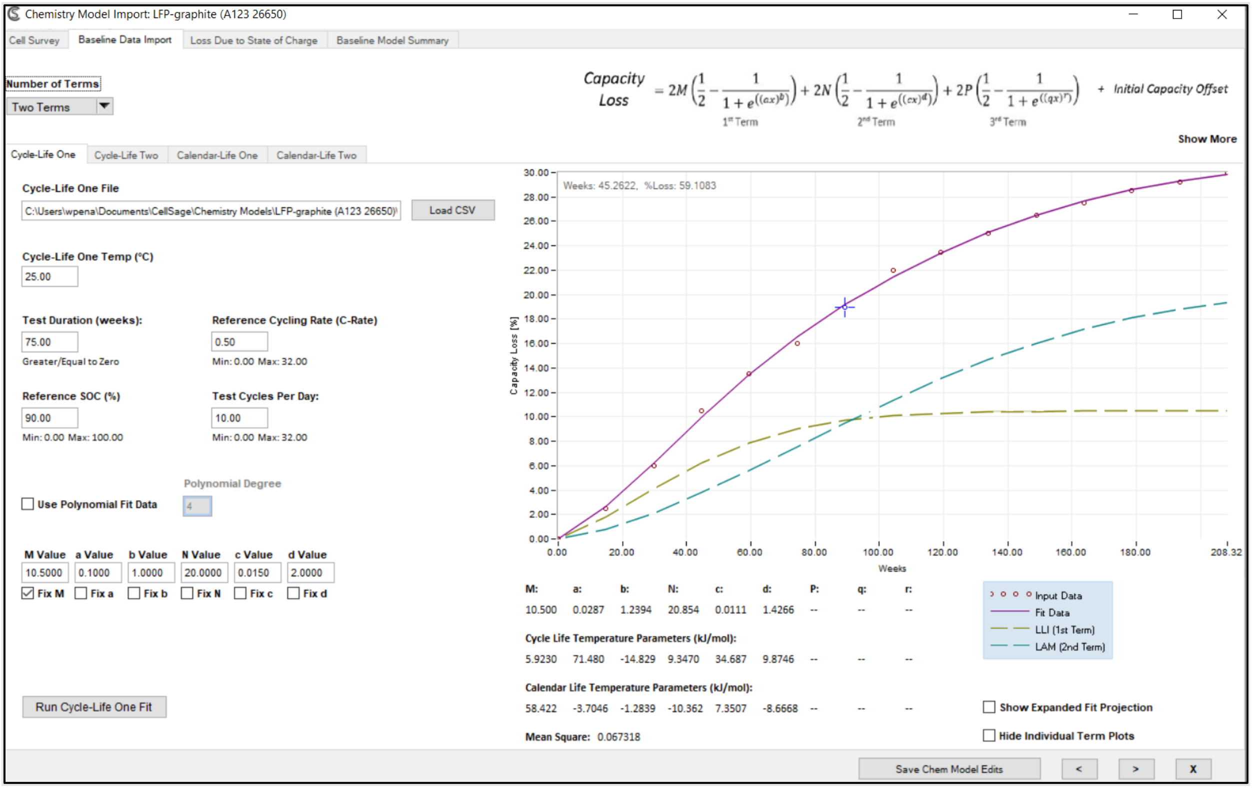



**Figure 40. Baseline Data Import Tab displayed in the New Chemistry Import Feature.**

Each set of baseline testing conditions requires the following information to be entered and/or uploaded into CellSage™:

- Baseline Aging Data contained in a .csv file and formatted as capacity percentage loss vs. weeks.
- Temperature in [°C]
- Test Duration in Weeks
- Reference SOC [%]
- Reference Cycling Rate [C-Rate]

It is important to note that not all testing data is created equal, and in some cases testing data could be noisy, low fidelity, and/or subject to external factors that could prevent the automated regression analysis from being performed within CellSage™. This procedure will be covered in Section 4.6, but it is recommended that all new CellSage™ program users attend at least one training course to develop an understanding for what types of baseline aging data results in a high-fidelity prediction model.

This tab also has a **Show More** button, which will display another pop-up window for how to interpret and set the SRE model parameters within CellSage™.

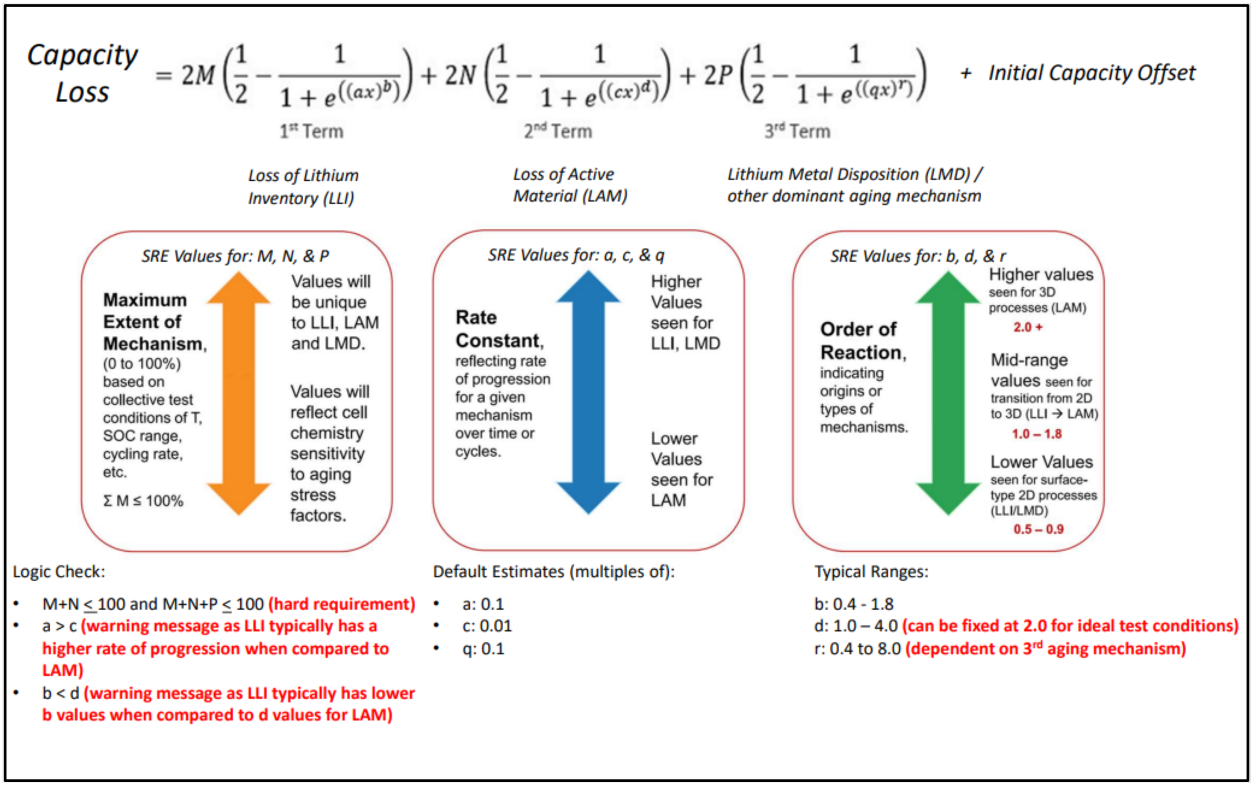



**Figure 41. Pop-up window for how to interpret SRE model parameters when selecting Show More button on Baseline Data Import Tab.**

## 4.4 Loss Due to State of Charge (SOC) Tab

State of charge can be a chief stress factor in lithium-ion batteries, especially when operating at higher SOCs shifts the thermodynamic state of the lithium chemical potential at the anode toward promoting detrimental side reactions which can cause an increase in SEI film thickness, side reactions and possible gas formation. There are chemistry-specific parameters in the CellSage™ architecture that allow a rigorous approach to SOC effects on cell aging. As such, each SRE (M, a, b) and (N, c, d) parameter sets for LLI and LAM, respectively, are adapted to include SOC as a stress factor. In addition, adjustments to SOC parameters based on temperature effects and activation energies are included.

The purpose of physics-based battery aging models is to link aging consequences to physical attributes of the cell and cell environment while under use. As such, key test conditions may be necessary to produce data that isolates model parameters that represent distinct conditions of charging, discharging or resting (calendar-life). These parameters will depend on cell chemistry, since each chemistry will respond to stress factors in meaningful and possibly different ways. Thus, in some cases battery testing is recommended to quantify aging contributions from stress factors like SOC. This could involve a matrix of cells at cycle-life or calendar-life where SOC is the parameter, keeping all other factors constant. Similarly, temperature could be the parameter, but keeping the SOC condition consistent so that activation energies can be obtained. RGI and INL can advise on testing protocols that would assign model parameters to battery applications of interest.

Following such testing (or if the data already exists), these SOC parameters can then be determined by RGI and INL through regression analysis based on data that has SOC and temperature as parameters, such as capacity loss data for cycle-life or calendar-life conditions at a representative SOC. It is suggested that data for more than one SOC be evaluated, if feasible. In lieu of such data, default values have been employed with the software that will allow reasonable initial estimates for the SOC impact on aging.

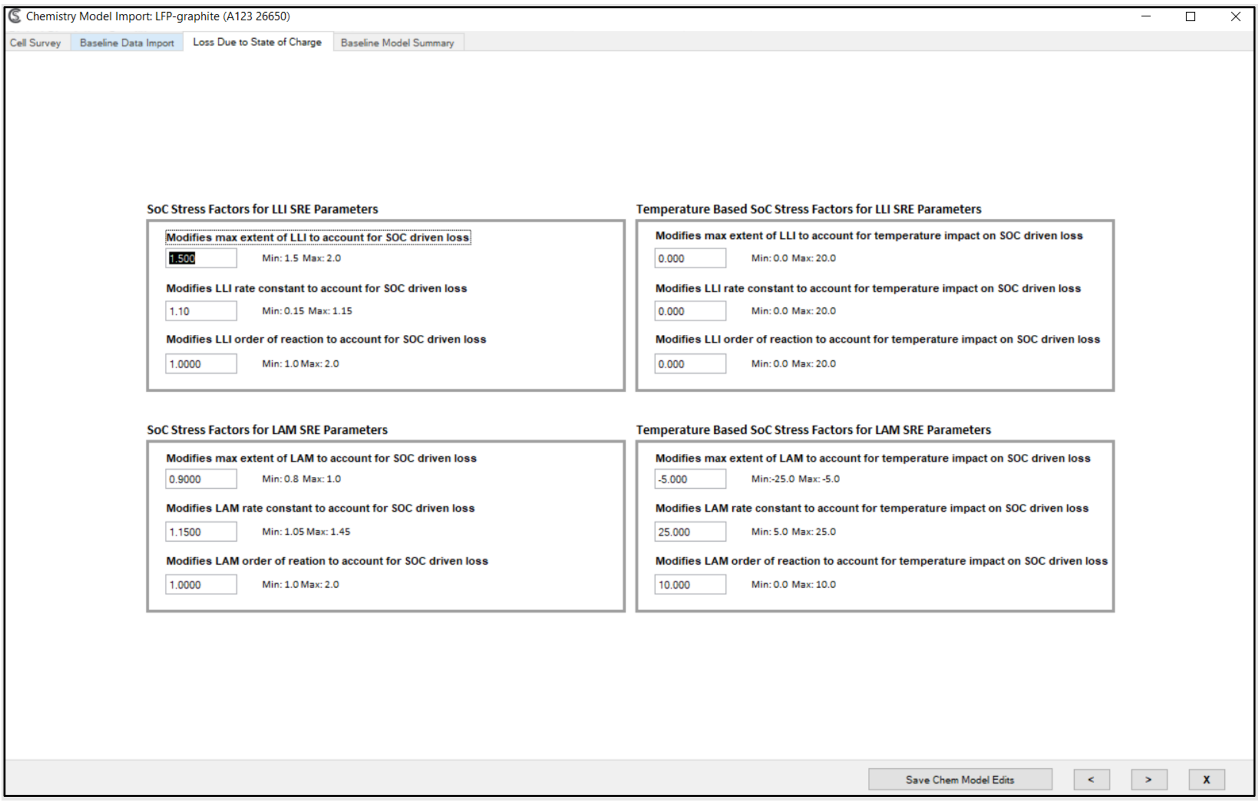



**Figure 42. Loss Due to State of Charge (SoC) Tab displayed in the New Chemistry Import Feature.**

**Table 4. Description of parameters of Loss Due to State of Charge.**

| | Parameter | Description | Typical Range |
|---|---|---|---|
| 1 | Modifies max extent of LLI to account for SOC driven loss | SoC Stress Factor for parameter 'M'. | Min: 0.2, Max: 2.0 |

| | | | |
|---|---|---|---|
| | | Value <1 decreases SOC-related LLI aging extent as SOC is increased.<br>Value >1 increases SOC-related LLI aging extent as SOC is increased.<br>Value of 1.0 cancels SOC dependence | Default: 1.2 |
| 2 | Modifies LLI rate constant to account for SOC driven loss | SoC Stress Factor for parameter 'a'.<br>Value <1 decreases SOC-related LLI aging rate as SOC is increased.<br>Value >1 increases SOC-related LLI aging rate as SOC is increased.<br>Value of 1.0 cancels SOC dependence | Min: 0.15, Max: 1.15<br>Default: 0.5 |
| 3 | Modifies LLI order of reaction to account for SOC driven loss | SoC Stress Factor for parameter 'b'.<br>Given that the 'b' parameter represents the order of reaction (or process) that is immune to SOC if the same LLI mechanism applies, then a default value of 1.0 is recommended. | Min: 1.0, Max: 2.0<br>Default: 1.0 |
| 4 | Modifies max extent of LAM to account SOC driven loss | SoC Stress Factor for parameter 'N'.<br>Value <1 decreases SOC-related LAM aging extent as SOC is increased.<br>Value >1 increases SOC-related LAM aging extent as SOC is increased.<br>Value of 1.0 cancels SOC dependence<br>It has been observed that stress factors that highly accelerate LAM in Li-ion cells, such as SOC, can promote a self-quenching outcome that curtails the overall extent of progression for LAM. Hence, this parameter is generally assigned a value <1. | Min: 0.5, Max: 1.0<br>Default: 0.8 |
| 5 | Modifies LAM rate constant to account for SOC driven loss | SoC Stress Factor for parameter 'c'.<br>Value <1 decreases SOC-related LAM aging rate as SOC is increased.<br>Value >1 increases SOC-related LAM aging rate as SOC is increased.<br>Value of 1.0 cancels SOC dependence | Min: 0.5, Max: 1.5<br>Default: 1.05 |

| | | | |
|---|---|---|---|
| 6 | Modifies LAM order of reaction to account for SOC driven loss | SoC Stress Factor for parameter ‘d’.<br>Given that the ‘d’ parameter represents the order of reaction (or process) that is immune to SOC if the same LAM mechanism applies, then a value of 1.0 is recommended. | Min: 1.0, Max: 2.0<br>Default: 1.0 |
| 7 | Modifies max extent of LLI to account for temperature impact on SOC driven loss | Temperature-based SoC Stress Factor for parameter ‘M’.<br>This yields a shift in activation energy of the affected ‘M’ parameter, if warranted. | Min: 0.0, Max: 20.0<br>Default: 0.0 |
| 8 | Modifies LLI rate constant to account for temperature impact on SOC driven loss | Temperature-based SoC Stress Factor for parameter ‘a’.<br>This yields a shift in activation energy of the LLI rate constant parameter, if warranted. | Min: 0.0, Max: 20.0<br>Default: 0.0 |
| 9 | Modifies LLI order of reaction to account for temperature impact on SOC driven loss | Temperature-based SoC Stress Factor for parameter ‘b’.<br>This yields a shift in activation energy of the LLI order of reaction parameter, if warranted. | Min: 0.0, Max: 20.0<br>Default: 0.0 |
| 10 | Modifies max extent of LAM to account for temperature impact on SOC driven loss | Temperature-based SoC Stress Factor for parameter ‘N’.<br>This yields a shift in activation energy of the LAM max extent parameter, if warranted.<br>See also last comment under item 4 in this table, which would help explain the negative activation energies for this LAM parameter in terms of temperature. | Min: -25.0, Max: -5.0<br>Default: -10.0 |
| 11 | Modifies LAM rate constant to account for temperature impact on SOC driven loss | Temperature-based SoC Stress Factor for parameter ‘c’.<br>This yields a shift in activation energy of the LAM rate constant, if warranted. | Min: 5.0, Max: 25.0<br>Default: 10.0 |
| 12 | Modifies LAM order of reaction to account for temperature impact on SOC driven loss | Temperature-based SoC Stress Factor for parameter ‘d’.<br>This yields a shift in activation energy of the LAM order of reaction, if warranted. | Min: 0.0, Max: 10.0<br>Default: 0.0 |

## 4.5 Baseline Model Summary Tab

The fourth and final tab within the CellSage™ New Chemistry Import Feature, is the Baseline Model Summary Tab. This tab shows a summary for all key baseline testing conditions, a textbox to store any notes associated with a particular model, and four plots for the different baseline aging data in addition to the calculated Mean Square Error. The example below shows, the baseline model summary for the LFP-graphite (A123 26650) cell chemistry within CellSage™:

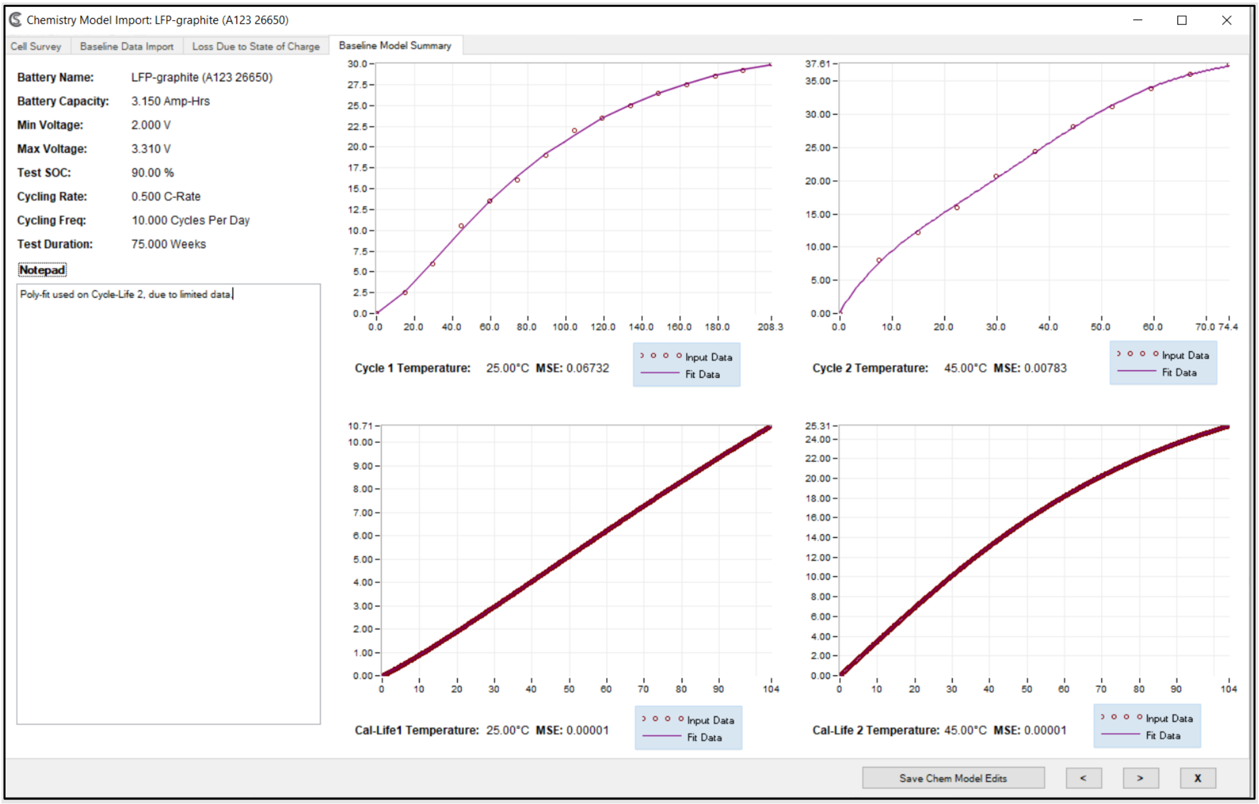



**Figure 43. Baseline Model Summary Tab displayed in the New Chemistry Import Feature.**

## 4.6 SRE Regression Analysis Procedure

In this section, a high-level procedure is outlined for the SRE Regression Analysis within the CellSage™ New Chemistry Import Feature.

**General SRE Regression Analysis Procedure:**

1. Open the CellSage™ New Chemistry Import Feature by selecting the Edit or Add Chemistry button from Section 1.0 on the main Cell Chemistry & Global Simulation Conditions GUI tab. For this example, we will use the Edit button for the LFP-graphite (A123 26650) cell chemistry model.
2. Verify that the Cell Survey Tab pops-up as shown in Figure 44.

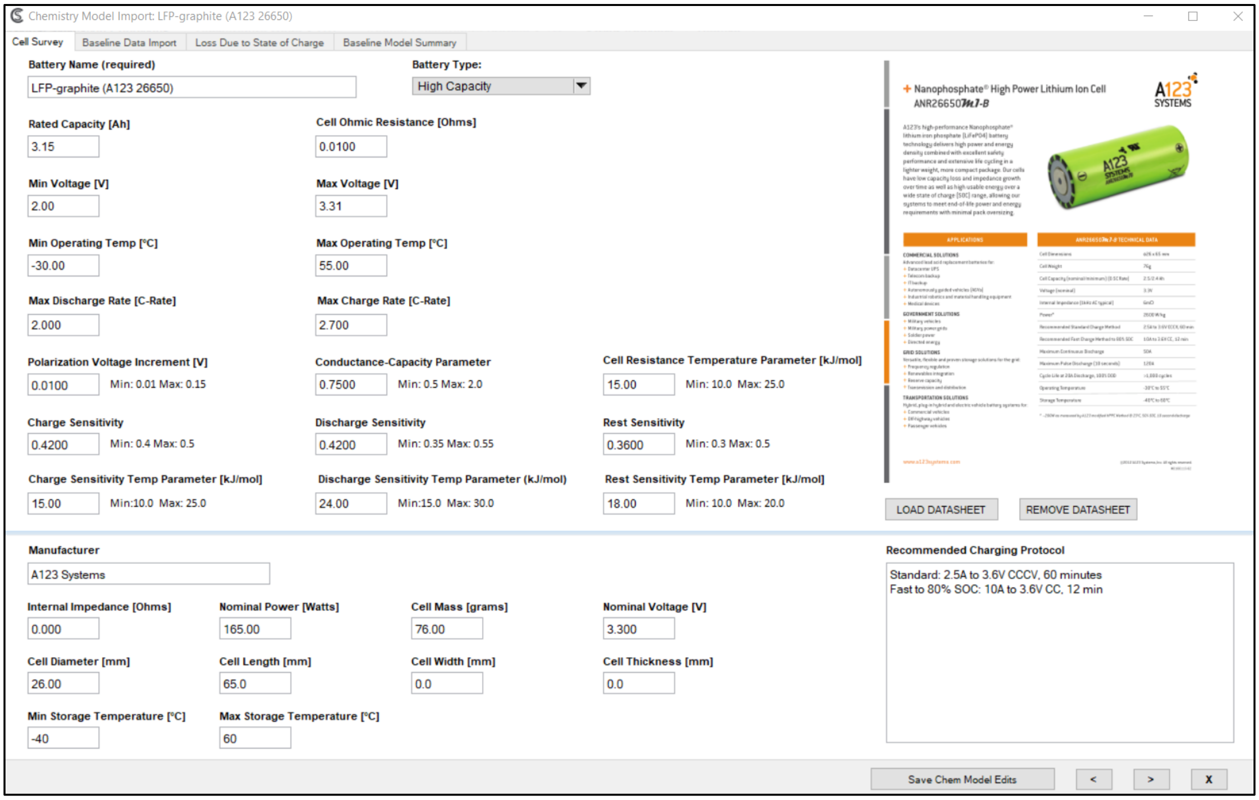



**Figure 44. Cell Survey Tab for high-level procedure on how to use the CellSage™ New Chemistry Import Feature.**

3. Navigate to the Baseline Data Import Tab, and use the "Load CSV" button to upload baseline aging data in a .csv file for Cycle-Life One. Data should be formatted as Capacity Loss % vs. Weeks.
4. Verify that your uploaded data set is displayed in the graph, and zoom out (Ctrl+Left Click) to see the full data set as shown in Figure 45.

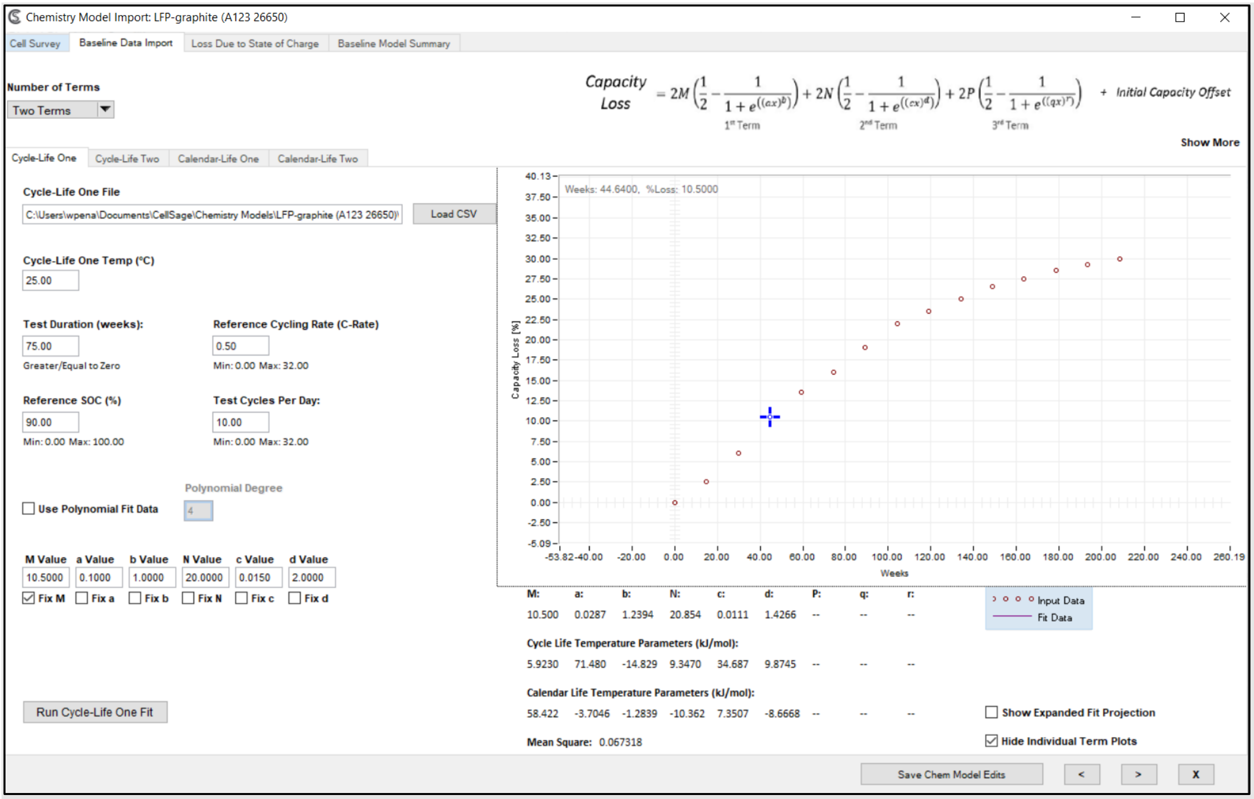



**Figure 45. Baseline Data Import Tab for high-level procedure on how to use the CellSage™ New Chemistry Import Feature.**

5. Select the Number of Terms for the CellSage™ chemistry model which is specified based on number of aging mechanisms present in the data. This could be determined based on number of inflection points, but typically it is based on how much baseline aging data was collected. For small data sets, there might not be an inflection point that shows a clear progression from LLI to LAM as the dominant aging mechanism. Such cases could still be modeled with a single term, but on the contrary the Three Term model can be used for longer duration data sets where LLI, LAM, and some other dominant aging mechanism is observed in the dataset. Figure 46, Figure 47, Figure 48 show example data sets for a single term model, two term model, and three term model respectively. Note that a single term model can be achieved by fixing N, c, d to zero with the two term model drop down selection.

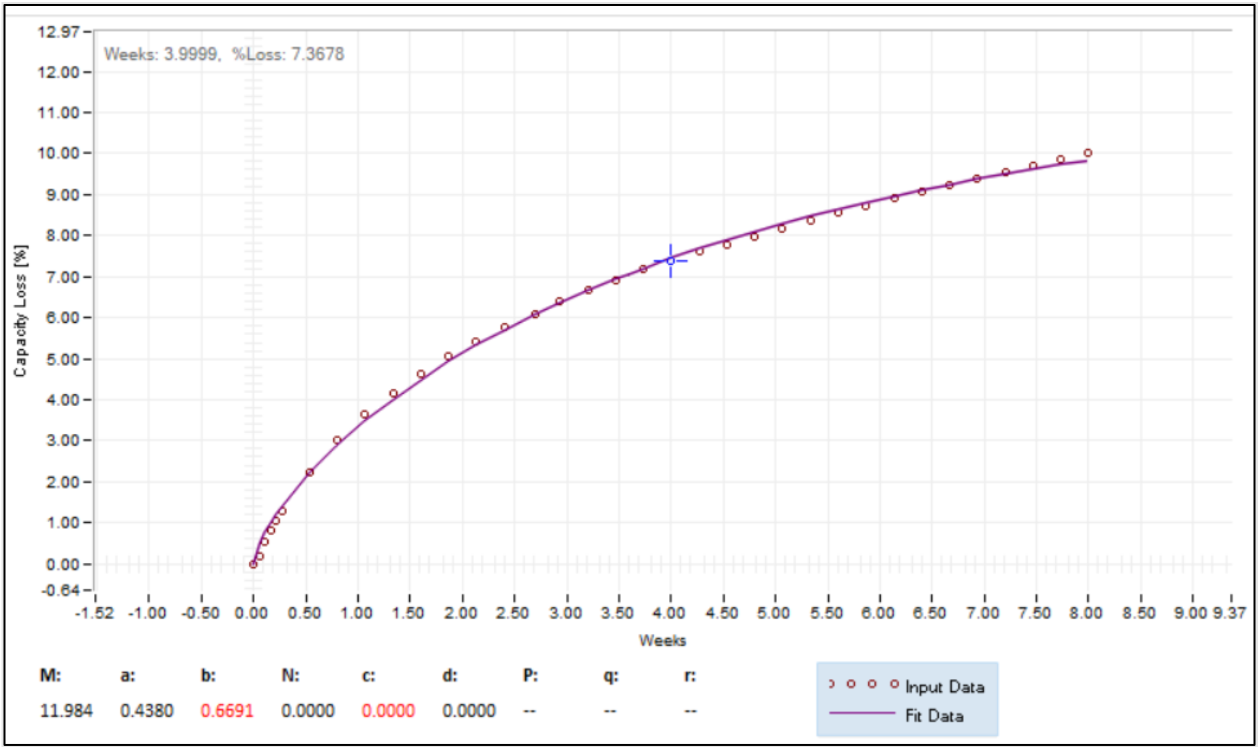



**Figure 46. Example of single term data set being modeled in CellSage™ New Chemistry Import Feature.**

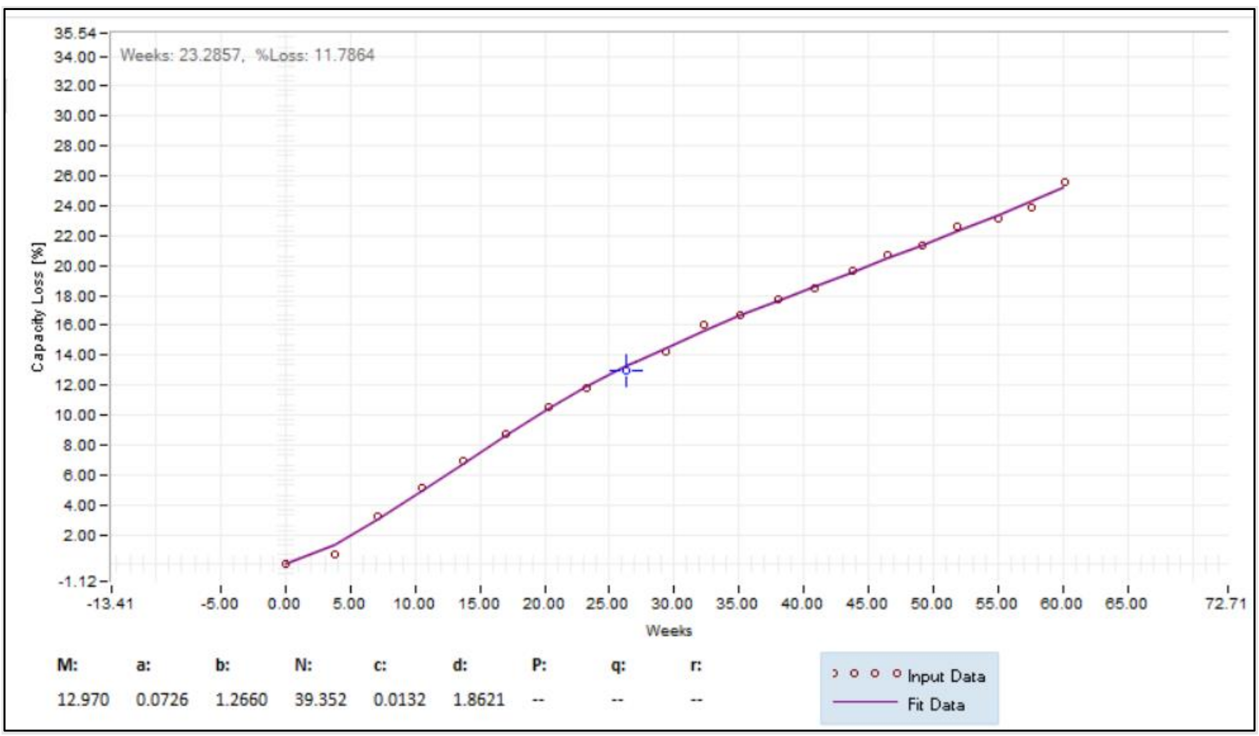



**Figure 47. Example of two term data set being modeled in CellSage™ New Chemistry Import Feature.**

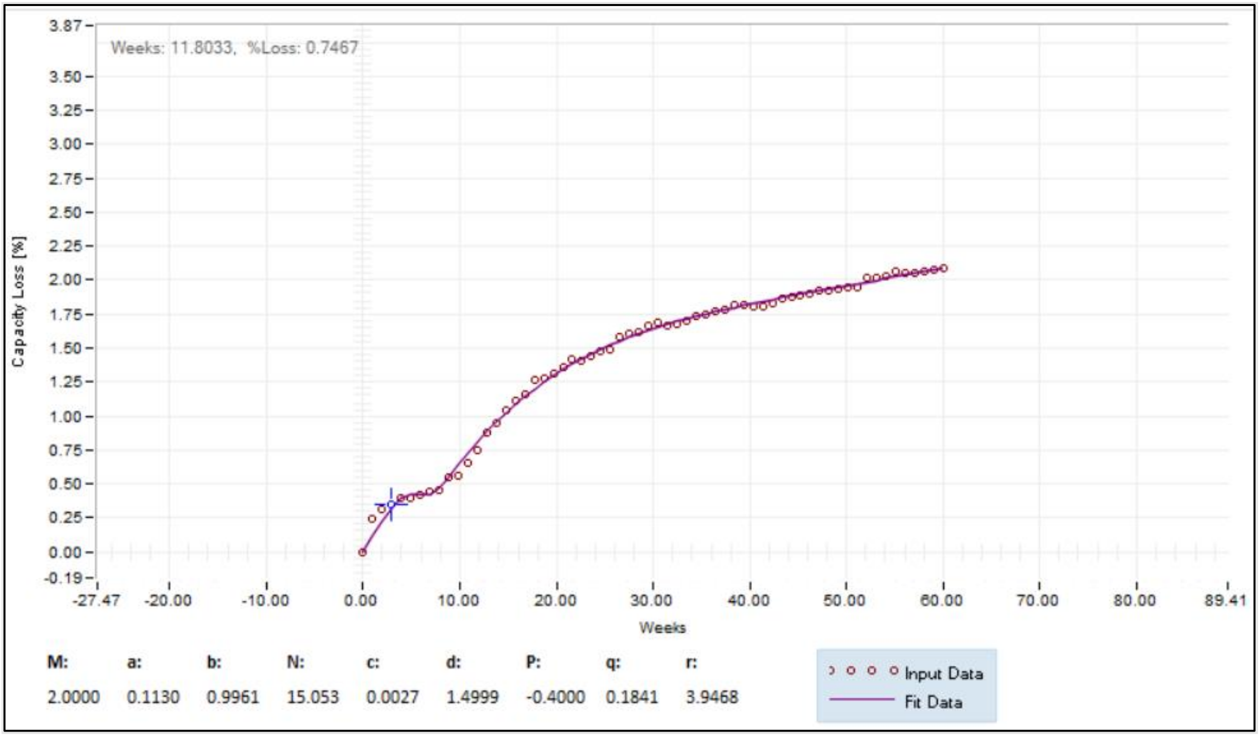



**Figure 48. Example of three term data set being modeled in CellSage™ New Chemistry Import Feature.**

6. Next, we enter the input for Baseline Testing Conditions associated with our two term dataset as shown in Figure 49.
    - Cycle-Life One Temp
    - Test Duration (weeks)
    - Reference Cycling Rate (C-Rate)
    - Reference SoC (%)
    - Test Cycles per Day

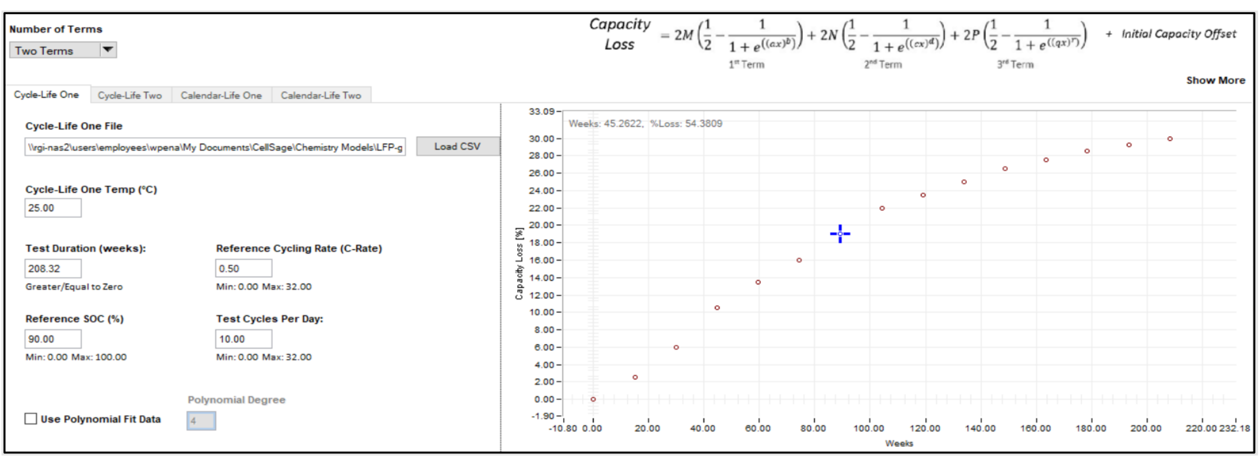



**Figure 49. Cycle-Life One baseline testing conditions.**

7. Determine if the baseline dataset is noisy or only has a limited amount of data points, if so the Polynomial Fit option can be used to help generate a smoother baseline dataset with additional data points. An example of this is shown with Cycle-Life Two for the LFP-graphite (A123 26650) chemistry model as the original data set only had 11 measurements.

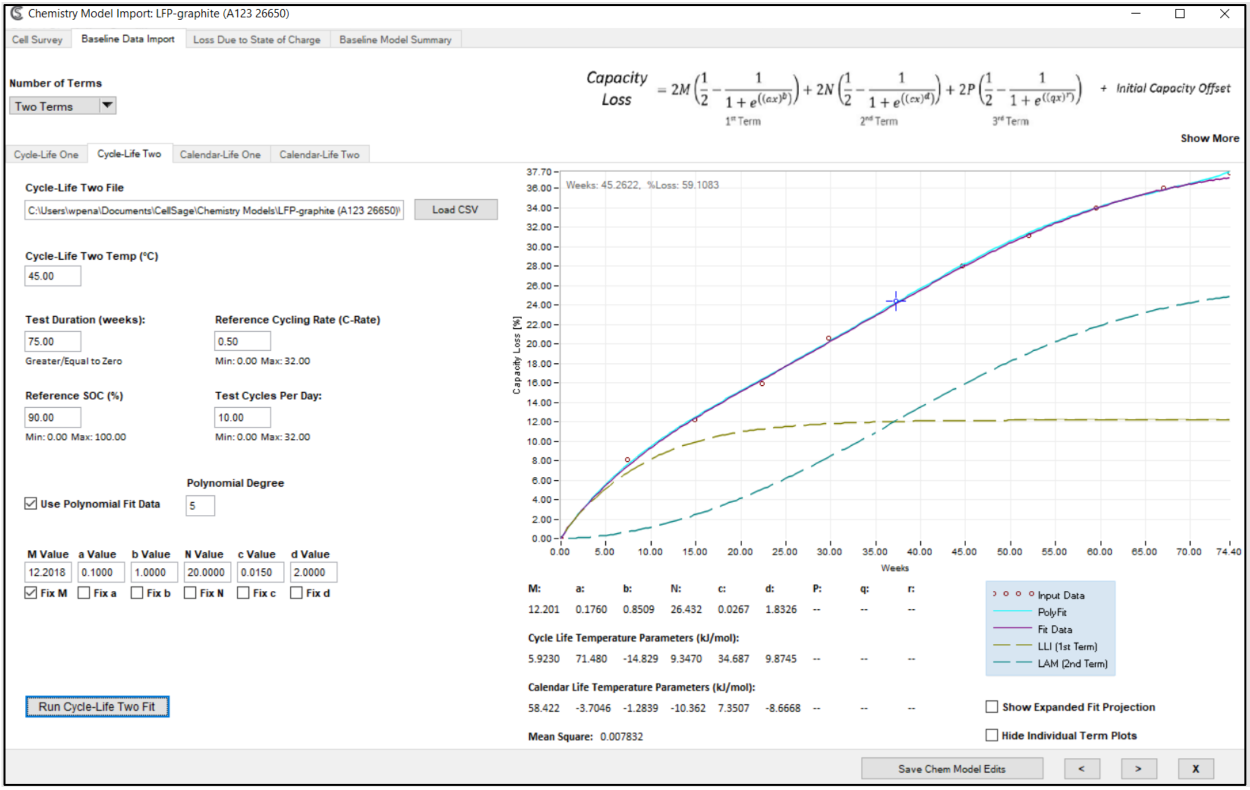


**Figure 50. Example of when to use the Polynomial Fit Data option during the baseline data regression analysis.**

8. Next, we specify each set of initial values for the SRE terms based on the guidelines shown in the "Show More" pop-up window.
   - **'M' Value** – This parameter represents the maximum extent of degradation (as a percentage) from the LLI aging mechanism. In most cases this value can be easily identified by the y-intercept for the first inflection point, as the LLI aging mechanism typically occurs before LAM. Note that this is the case for all default models in CellSage™ with the exception of the LMO/LTO chemistry model. In that case, a third aging mechanism is observed prior to LLI due to excess lithium which resulted in a negative percentage loss for the 'P' SRE parameter.

     **IMPORTANT NOTE:** All Two Term SRE models in CellSage™ utilized a fixed 'M' Value to complete the default regression analysis.

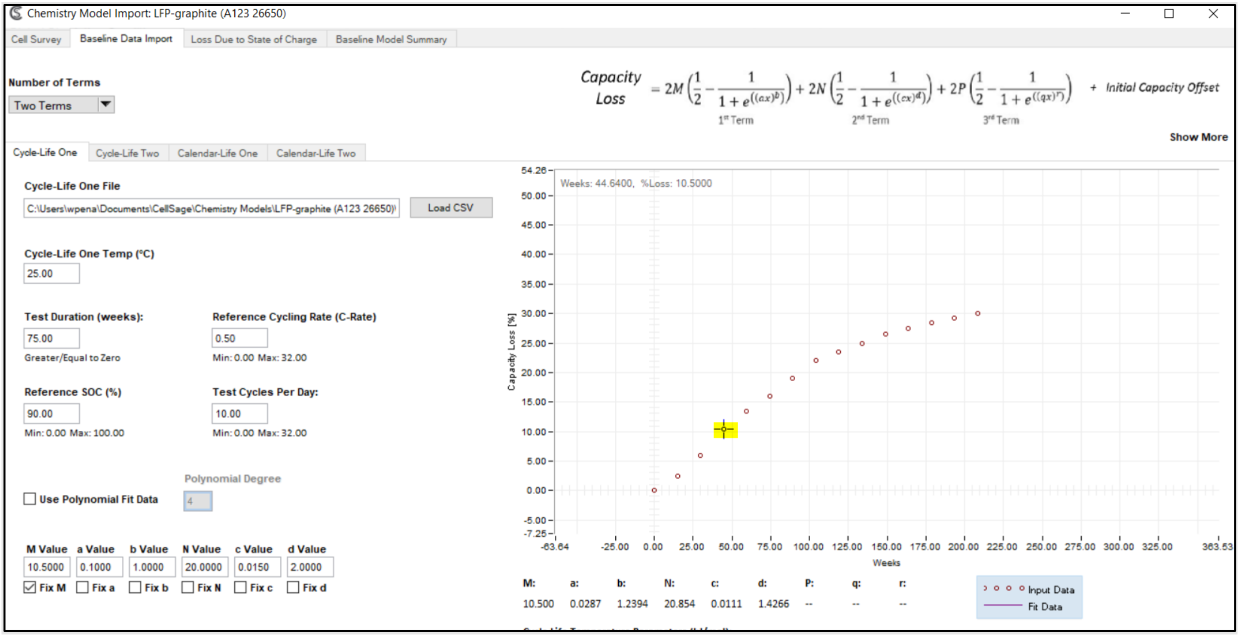


**Figure 51. Example of how to specify 'M' Value for baseline data regression analysis.**

- **'a' Value –** This parameter represents the rate constant for the rate of progression for a given aging mechanism over time or cycles. The initial value should be set to 0.1, but could range from 0.01 to over 1.0. When conducting the default regression analysis, it was observed that a satisfactory fit could be achieved by adjusting this value in increments of ± 0.05. As a general rule of thumb, a steep degradation curve for the LLI aging mechanism will result in a larger '**a' Value** for the rate of progression. An example of this is shown in the following image when comparing the regression analysis results for the LFP-graphite (A123 26650). The left image is for Cycle-Life One data at 25.0 C, and the right image is for Cycle-Life Two data at 45 C.

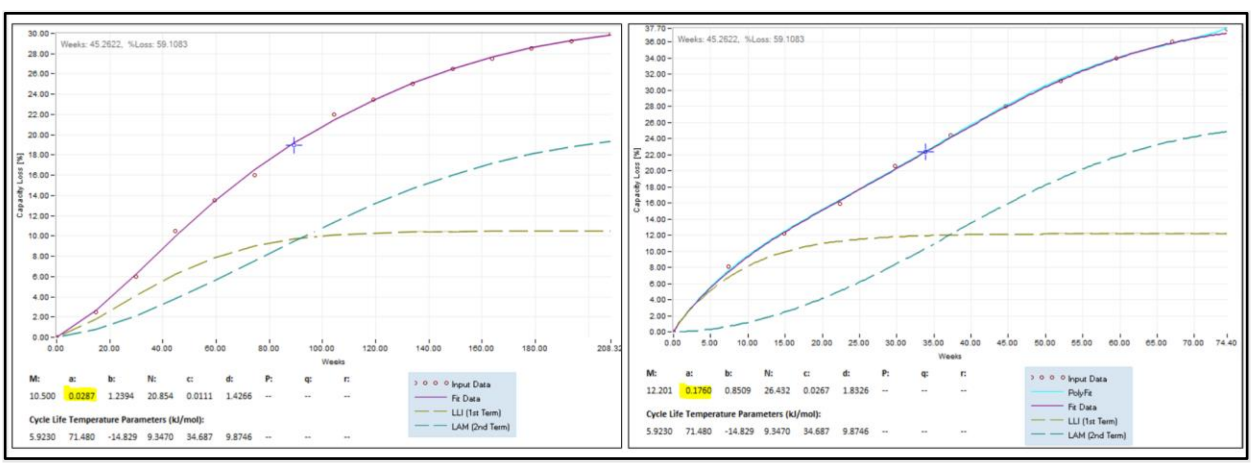


**Figure 52. Example of how to specify the 'a' Value for baseline data regression analysis.**

- **'b' Value –** This parameter represents the order of reaction for the LLI aging mechanism and should have a value from **0.4 to 1.3** with a default initial estimate **0.6 or 1.0**.
- **'N' Value –** This parameter represents the maximum extent of degradation (as a percentage) for the LAM aging mechanism. Because LAM typically occurs after LLI, this maximum extent of degradation may or may not be fully observed in the recorded dataset. For that reason, the regression analysis is performed by identifying a baseline upper limit for the LAM aging mechanism, but it is not fixed as done with the **'M' Value** for LLI. A typical starting point could be the maximum capacity loss minus the **'M' Value.** An example of this for the LFP-graphite (A123 26650) chemistry is shown for the Cycle-Life One dataset:

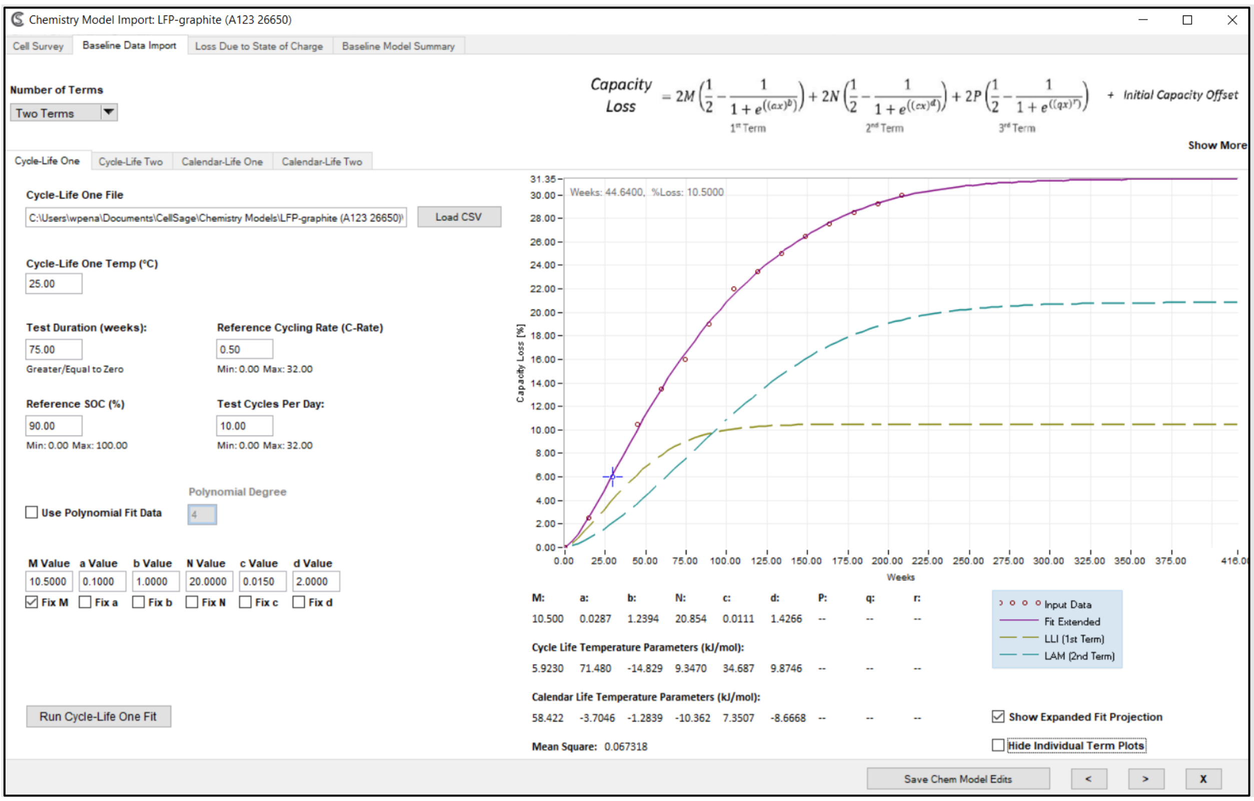



**Figure 53. Example of how to specify the 'N' Value for baseline data regression analysis.**

- **'c' Value –** This parameter represents the rate constant for the rate of progression for the LAM aging mechanism. As previously referenced with the '**a' Value** this parameter corresponds to the slope of the degradation curve, and will typically be smaller than the **'a' Value.** The default estimate should be set to 0.01 with a range of 0.001 to 0.5. When doing the default regression analysis, it was observed that a satisfactory fit could be achieved by adjusting this value in increments of ± 0.005.
- **'d' Value –** Similar to the **'b' Value** for LLI**,** this parameter represents the order of reaction for the LAM aging mechanism. Because LAM typically occurs and after LLI, this value should be higher than the **'b' Value**, with a default estimate of 2.0 and range from 1.2 – 4.8.

**IMPORTANT NOTE:** For this example, we are focused on a Two Term SRE model for the LFP-graphite (A123 26650) cell chemistry. For a Three Term SRE Model, note that the **'P' Value** corresponds the maximum extent of degradation for the third aging mechanism, the **'q' Value** corresponds to the rate constant, and **'r' Value** corresponds the order of reaction.

9. Once the **'M' Value** is Fixed, and a default estimates are entered for the remaining parameters, the "Run Cycle-Life One Fit" button can be used to perform the baseline regression analysis on the imported dataset. Note that this could be an iterative process that will need to be done until an acceptable fit is achieved. Any errors will result in a red highlighted parameter(s) if any of the logic check conditions are violated or if a parameter is outside a typical range.

Logic Check:

- M+N $\leq$ 100 and M+N+P $\leq$ 100 **(hard requirement)**
- a > c **(warning message as LLI typically has a higher rate of progression when compared to LAM)**
- b < d **(warning message as LLI typically has lower b values when compared to d values for LAM)**

Default Estimates:

- a: 0.1 **(increments of $\pm$ 0.05)**
- c: 0.01 **(increments of $\pm$ 0.005)**
- q: 0.1 **(increments of $\pm$ 0.05)**

Typical Ranges:

- b: 0.4 - 1.3
- d: 1.2 – 4.8
- r: 0.4 to 8.0 **(dependent on 3rd aging mechanism)**

**IMPORTANT NOTE:** Model accuracy is typically evaluated based on the calculated Sum of Squared Errors (SSE), Root Mean Square Error (RMSE), Mean Square Error (MSE), and R-Squared Coefficient ($R^2$) highlighted in Figure 54.


**Figure 54. Example calculated accuracy metrics for baseline data regression analysis.**

10. Repeat steps 3-9 for Cycle Life Two, Calendar Life One, and Calendar Life Two.
11. Visualize your automated regression analysis results and Mean Square Error on the Baseline Model Summary tab, and then save your chemistry model using the "Save Chem Model Edits" button.

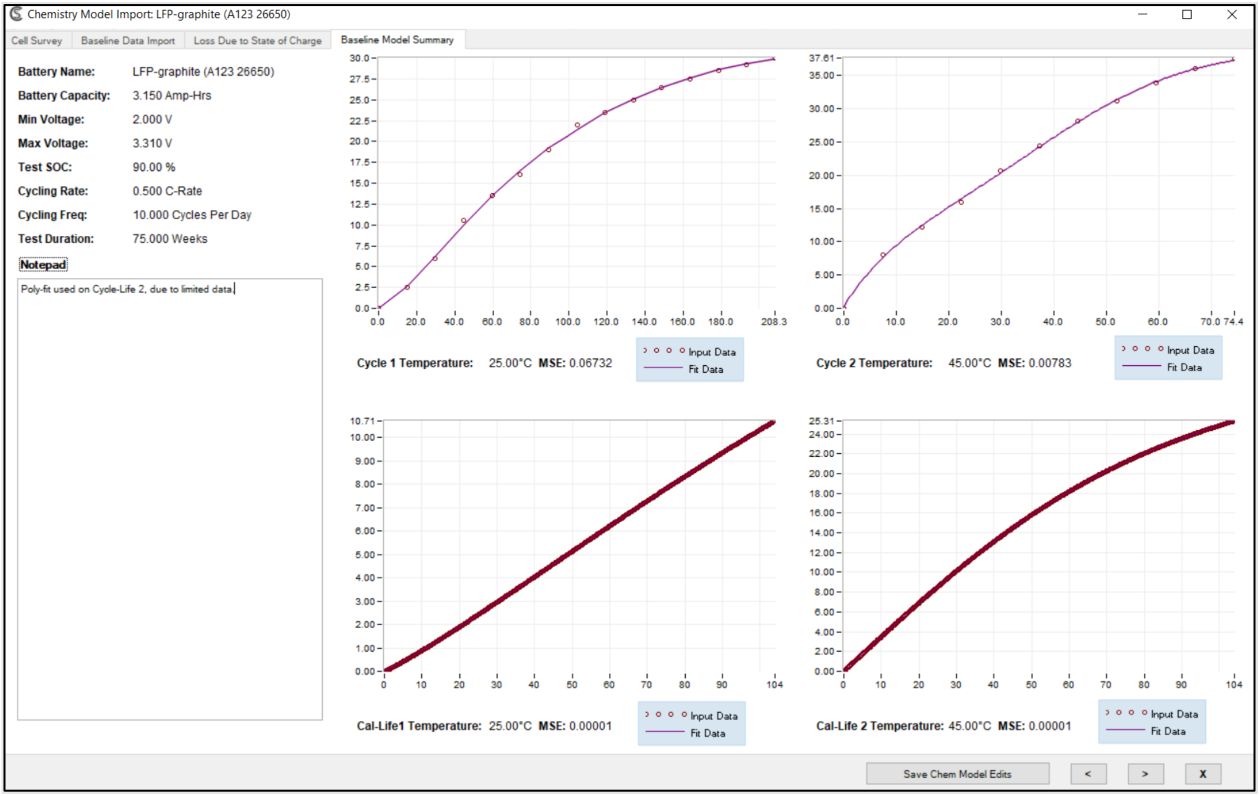



**Figure 55. Example of Baseline Model Summary tab after completing baseline data regression analysis.**

## 4.7 SRE Regression Analysis Results

In this section, we will review a summary table for the calculated Sum of Squared Errors (SSE), Root Mean Square Error (RMSE), Mean Square Error (MSE), and R-Squared Coefficient ($R^2$ ) for each of the default cell chemistry models within CellSage™. The following notes can be used to assess the quality of the fit based on each of the calculated metrics:

- SSE – The smaller the SSE, the better the fit.
- RMSE – The smaller the RMSE, the better the fit.
- MSE – The smaller the SSE, the better the fit.
- $R^2$ - The closer to 1.0, the better the fit.

Figure 56 - Figure 63 show the corresponding Baseline Model Summary tab for all default cell chemistry models. It is important to note that in some cases baseline aging data did not exist for all four testing conditions. For such cases, Ridgetop generated synthetic data in .csv format based on the estimated SRE parameters from Idaho National Laboratory. This data can be easily

identified in the Baseline Model Summary tab, where the **Input Data** appears to be more like a solid red line.

**Table 5. Summary Table for MSE, SSE, R Square, RMSE.**

| | Chemistry Model | SSE | RMSE | MSE | $R^2$ |
|---|---|---|---|---|---|
| 1 | LFP-graphite (A123 26650) | 1.0097 | 0.3349 | 0.0673 | 0.9992 |
| 2 | LFP-graphite (A123 Nanophosphate 20Ah) | 0.2654 | 0.1429 | 0.0139 | 0.9986 |
| 3 | LithiumCobaltOxide (18650) | 0.1251 | 0.0657 | 0.0035 | 0.9996 |
| 4 | LMO-LTO (Toshiba SCiB 20 Ah) | 0.0666 | 0.0354 | 0.0010 | 0.9969 |
| 5 | NCA-graphite (DOE Gen2 18650-Model 1) | 4.0927 | 0.3633 | 0.1106 | 0.9927 |
| 6 | NCA-graphite (DOE Gen2 18650-Model 2) | 3.0844 | 0.3154 | 0.0833 | 0.9909 |
| 7 | NMC-graphite (Panasonic UR 18650) | 1.5267 | 0.3190 | 0.0727 | 0.9987 |
| 8 | NMC-graphite (Sanyo Y 18650) | 0.7012 | 0.2162 | 0.0333 | 0.9976 |

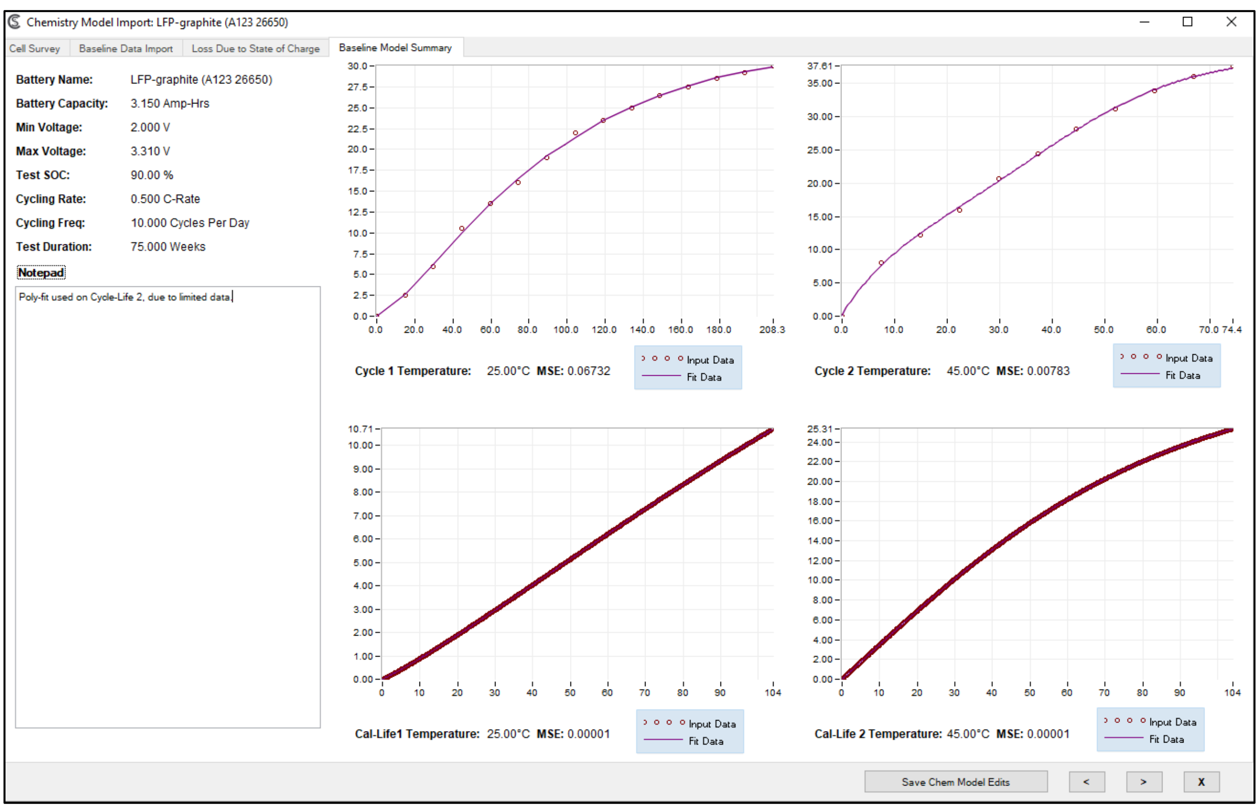



**Figure 56. Example of Baseline Model Summary tab for LFP-graphite(A123 26650).**

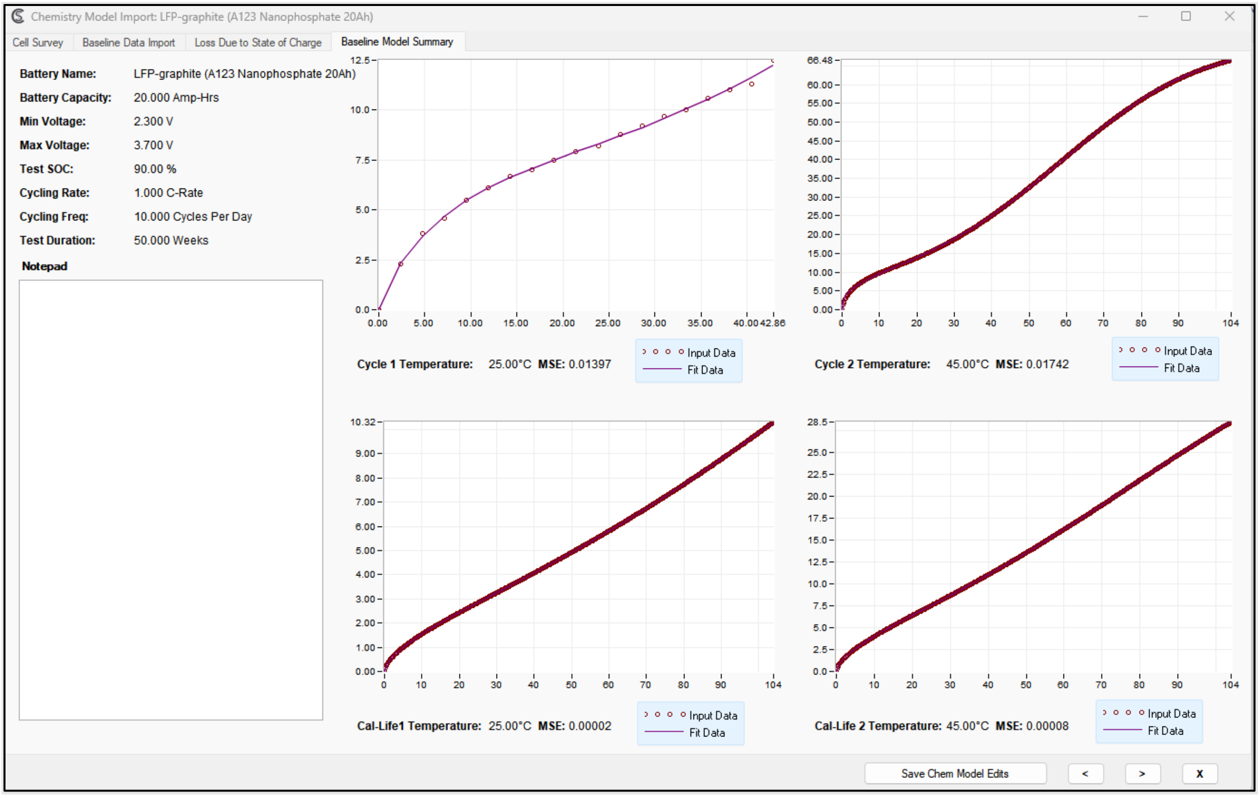



Figure 57. Example of Baseline Model Summary tab for LFP-graphite (A123 Nanophosphate 20Ah).

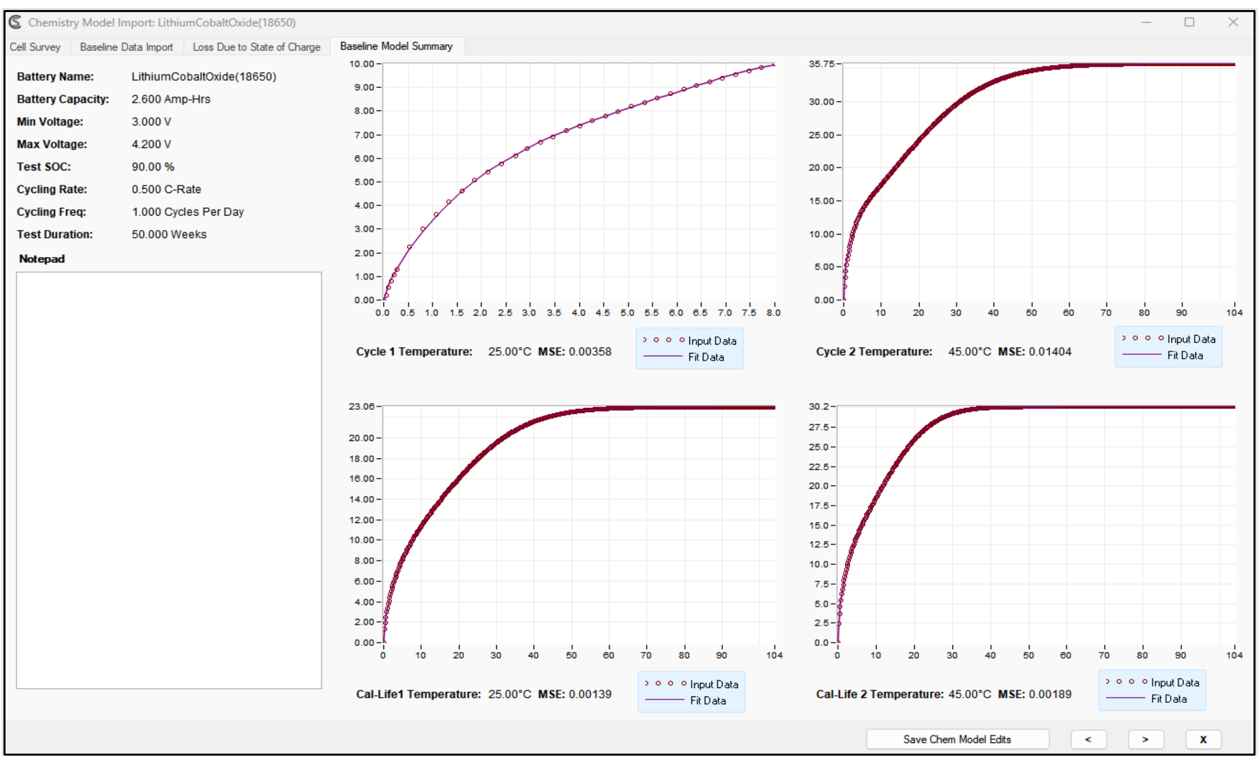



Figure 58. Example of Baseline Model Summary tab for LithiumCobaltOxide(18650).

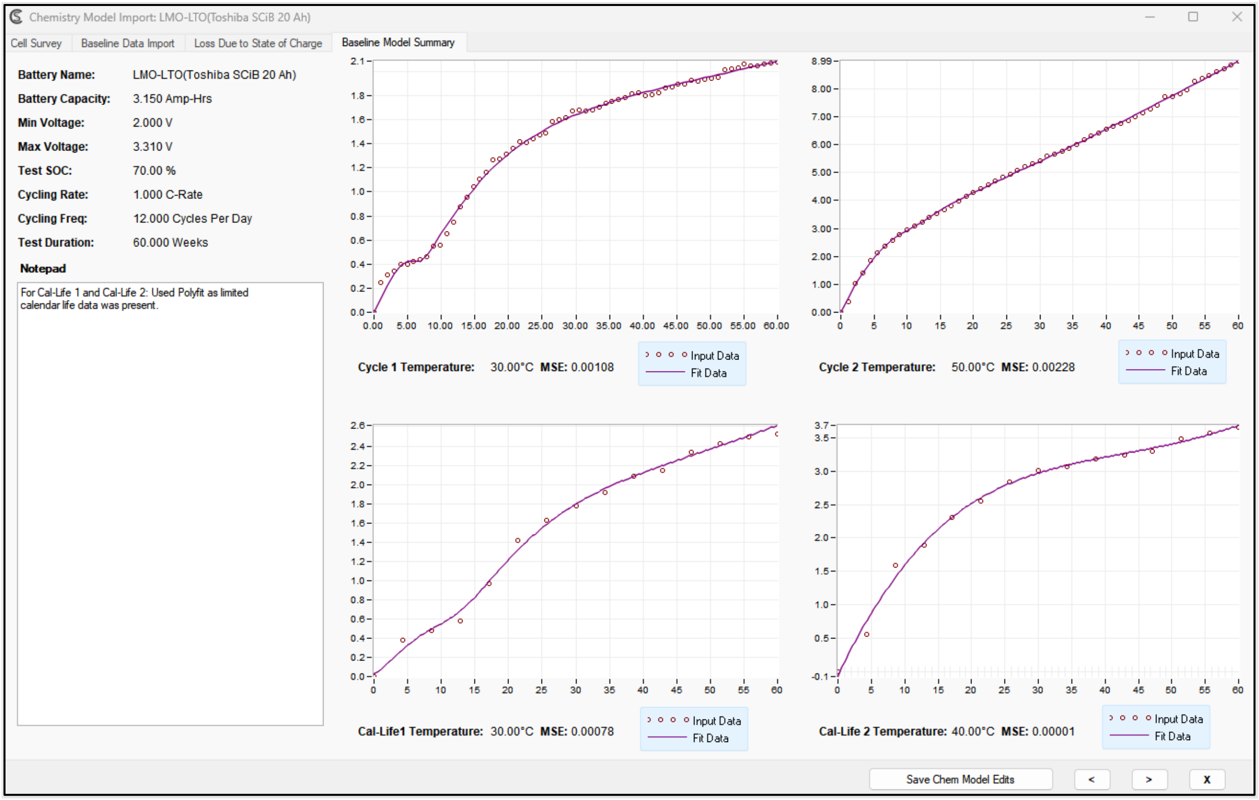



**Figure 59. Example of Baseline Model Summary tab for LMO-LTO (Toshiba (SCiB 20Ah).**

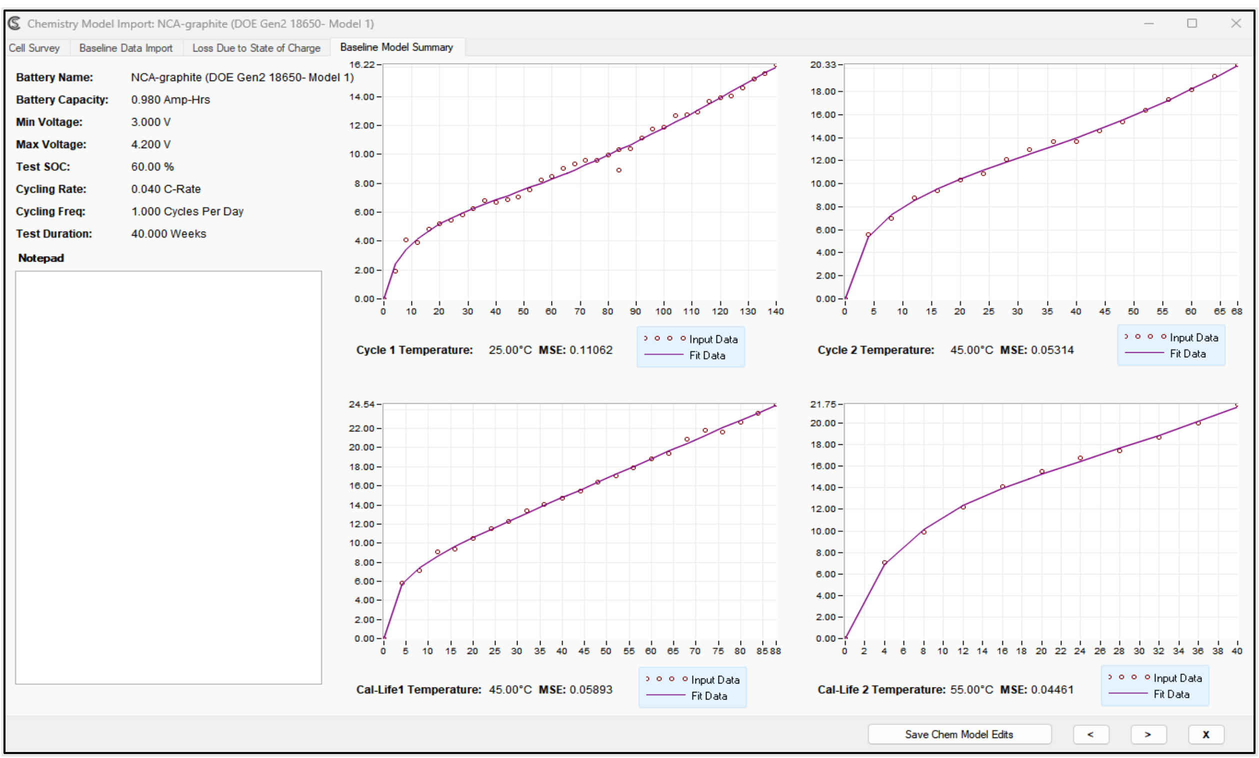



**Figure 60. Example of Baseline Model Summary tab for NCA-graphite (DOE Gen 18650 – Model 1).**

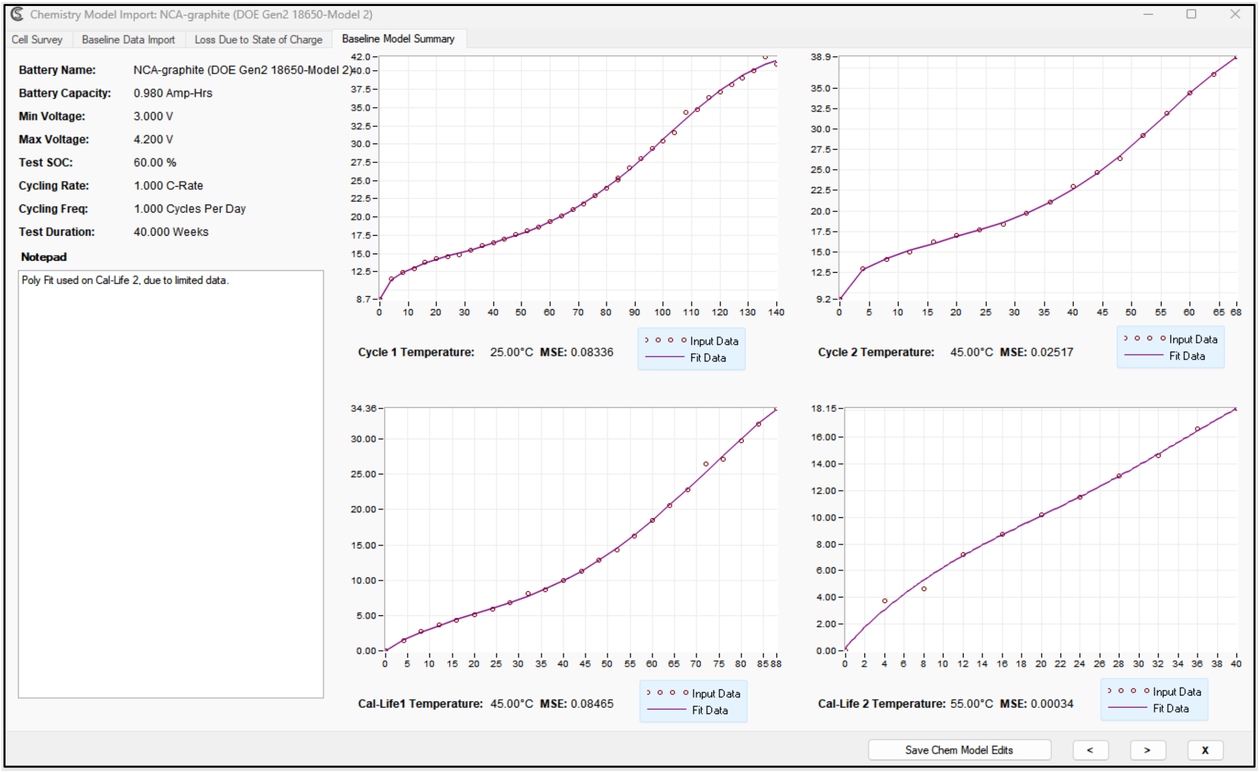



**Figure 61. Example of Baseline Model Summary tab for NCA-graphite (DOE Gen 18650 – Model 2).**

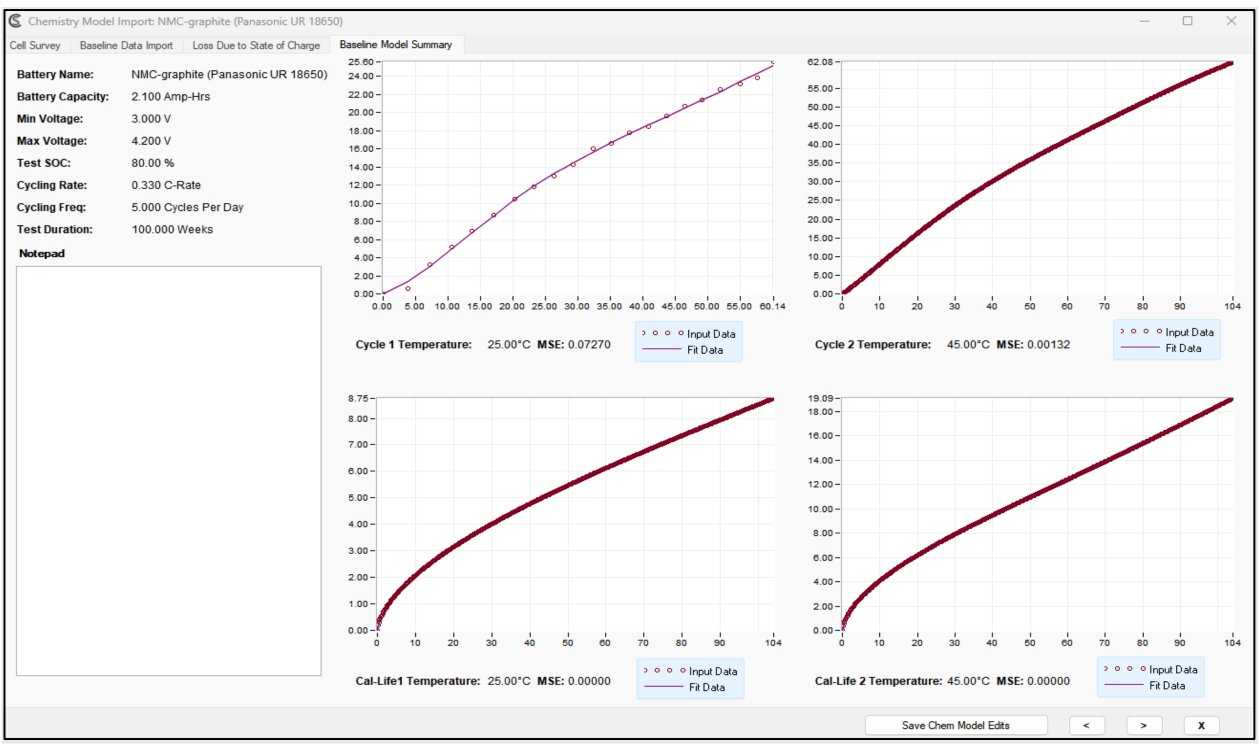



**Figure 62. Example of Baseline Model Summary tab for NMC-graphite(Panasonic UR 18650).**

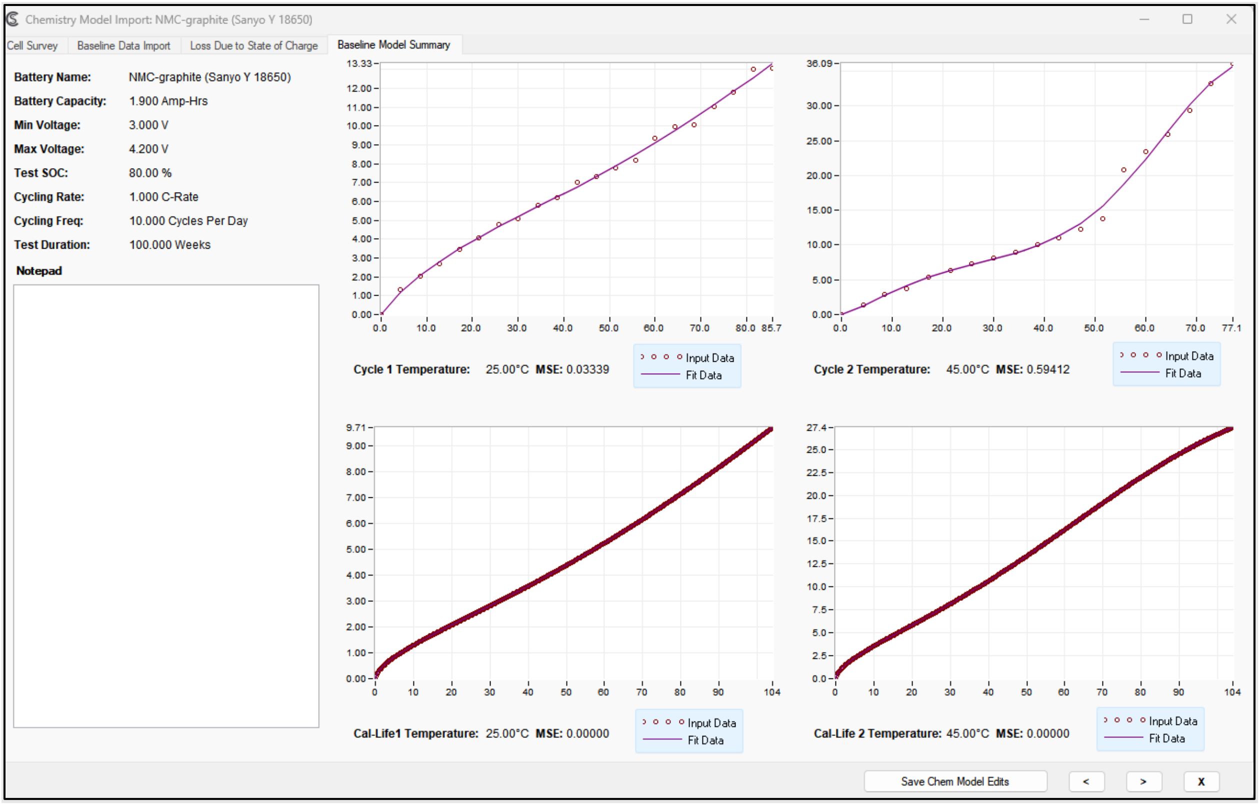



**Figure 63. Example of Baseline Model Summary tab for NMC-graphite(Sanyo Y 18650).**

## 4.8 Autofit Function for Initial Estimate of SRE Parameters

In this section, we will explore how the autofit functionality within the New Chemistry Import Feature can be utilized to obtain initial estimates. This feature complements manual SRE regression analysis effectively, as its results can serve as the starting values for each SRE parameter when building a valid CellSage model. This capability was specifically requested by Ridgetop customers due to the challenges associated with manual SRE regression analysis, particularly when dealing with noisy cycle life testing data.

As demonstrated in preceding sections of this User Guide, the accuracy of CellSage fitting results hinges on the initial estimates of the SRE parameters. Users can either estimate these initial values themselves or utilize the genetic-algorithm fitting scheme discussed herein to provide an initial guess. Conceptually, the genetic algorithm operates as depicted in Figure 3.

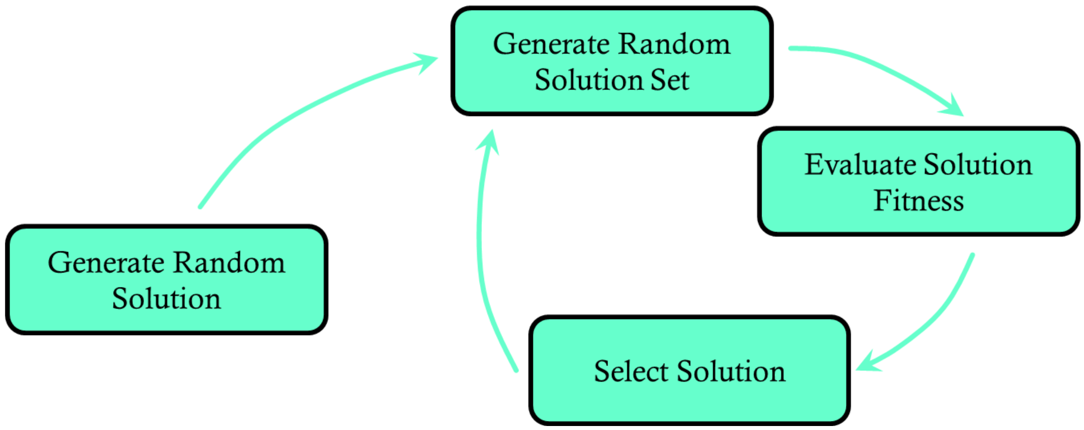



**Figure 64. Conceptual View of the Genetic Algorithm.**

The genetic algorithm employed in CellSage begins by generating a randomized set of three values for each of the six or nine SRE parameters, depending on whether the two or three-term model is chosen for fitting the data. The selected model undergoes evaluation through exhaustive combinations of the randomly generated solutions. Fitness of a solution is determined based on the sum of squares error and the fulfillment of the following criteria:

- the total extent of each reaction must not exceed 100%;
- the reaction rate of LLI must surpass that of LAM;
- the order of reaction for LLI must be lower than that of LAM;
- the ratio of LLI extent to LAM extent must fall between 0.325 and 3.0;
- the LLI rate magnitude should be near 0.1; the LAM reaction rate value should approach 0.005;
- the LLI reaction order should approach 0.65;
- the LAM reaction order should approach 3.0.

When a proposed solution passes these logic checks and has a lower sum of squares error than the previous best solution, it becomes the new best solution and is used to generate a new set of solutions. This iterative process continues until a solution meets predetermined criteria.

When utilizing the Autofit Function, a window will appear displaying Runtime, Number of Iterations, and Fit Results when the genetic algorithm converges to a valid solution. Once finished, the user can either accept the values as initial estimates for manual SRE regression analysis or cancel and disregard the results provided. It's important to note that there can be multiple valid sets of initial SRE parameters, and results may vary due to the stochastic nature of the genetic algorithm. Hence, the autofit functionality serves as a starting point for generating initial SRE parameter estimates, particularly useful for analyzing noisy or limited cycle life testing data.

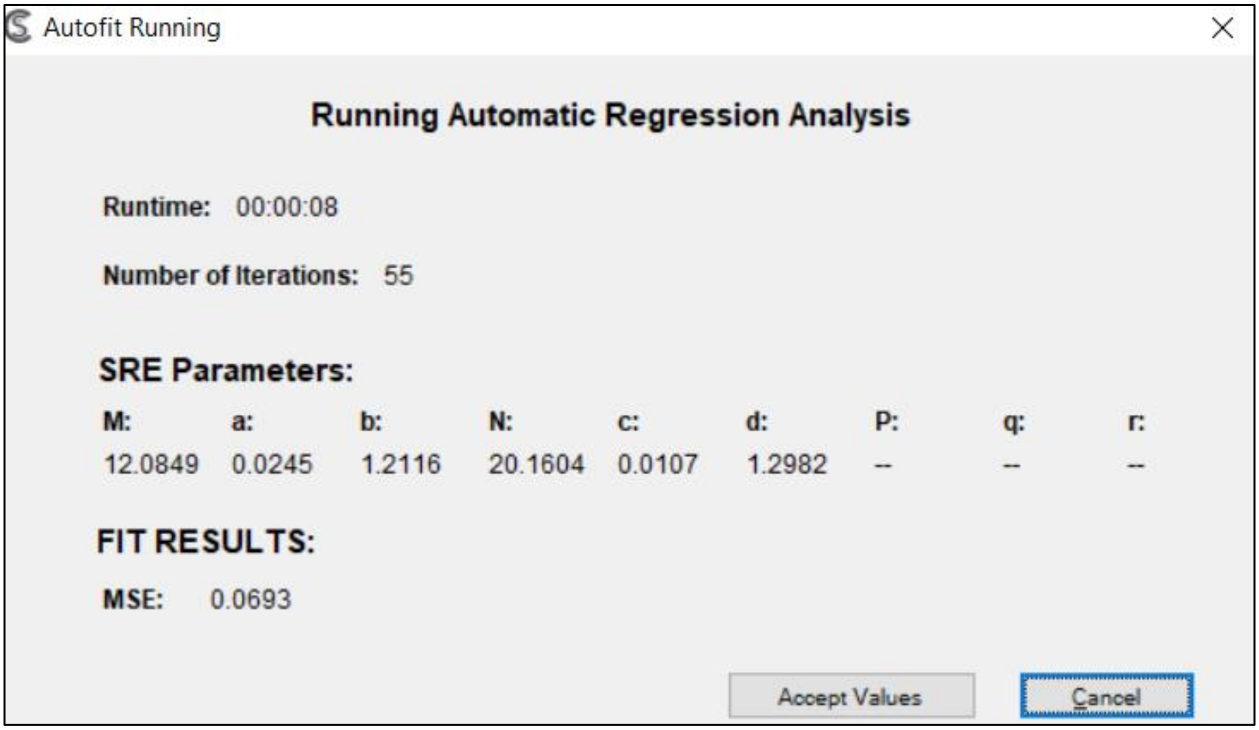



**Figure 65. Pop-up Window when running Autofit Function inside of CellSage New Chemistry Import Feature.**

# 5. Examples

## 5.1 Example 1: Reproducing Baseline Model Data

This example will cover how a user can run a basic CellSage™ simulation for the LFP-graphite (A123 26650) cell chemistry. It should be noted that the CellSage™ software architecture follows a linear programming flow where the user enters input conditions in sequential sections, and navigates through the tabs with the “Next” and “Previous” buttons in the lower right corner of the GUI. Each example shall start by opening the CellSage™ software application as shown in Step 1 of Section 2.3, or by opening the Windows Start Menu and searching for the CellSage™ GUI software program. When the program is opened successfully, the user will be on Tab 1 as shown in Figure 66.

Example 1 will be a simple simulation where we will reproduce the baseline aging data shown in the CellSage™ New Chemistry Import Feature. The temperature mode is set to 2.1: Single T Representative of Bulk Cell, and the options to include Detailed Cycling Conditions (DCC), Thermal Management (TM), and Daily Thermal Cycling (DTC) are not enabled. This example will simulate a 104-week set of baseline testing conditions at 25 °C and 45 °C respectively.

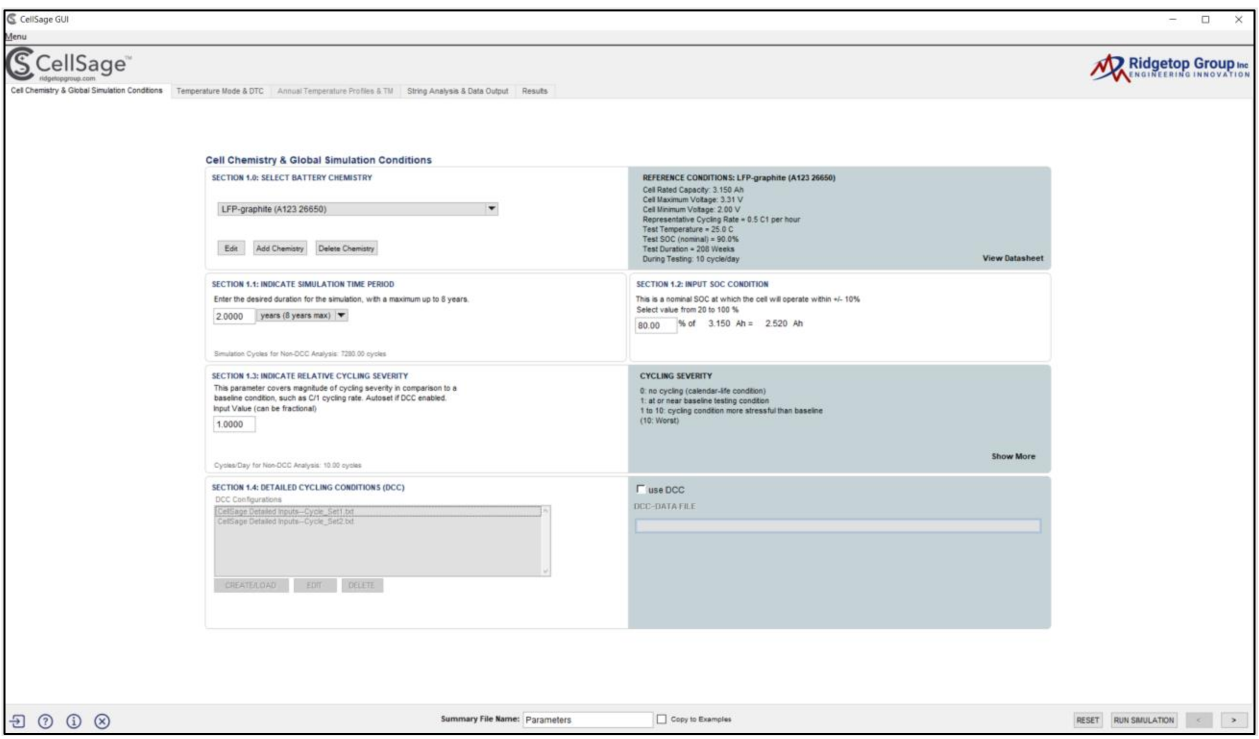



**Figure 66. Starting window of CellSage™ GUI.**

### 5.1.1 Importing Example 1 Parameters

We start off Example 1 by first using the Import Function to prepopulate each of the CellSage™ input conditions. This can be achieved by following the below list of instructions and referencing Figure 67 - Figure 68.

a) Click on the "Import" ( ) button in the lower left corner of the GUI.
b) Verify that the Windows File Explorer opens up in default "Examples" directory within the "CellSage™ Simulations" folder.
c) Select the "Ex-1_Parameters.txt" file and click the "Load" button.
d) Verify that the "Ex-1_Parameters.txt" file was loaded successfully as shown in Figure 68.

**IMPORTANT NOTE:** An error message will pop-up if the parameters.txt file was not imported successfully.

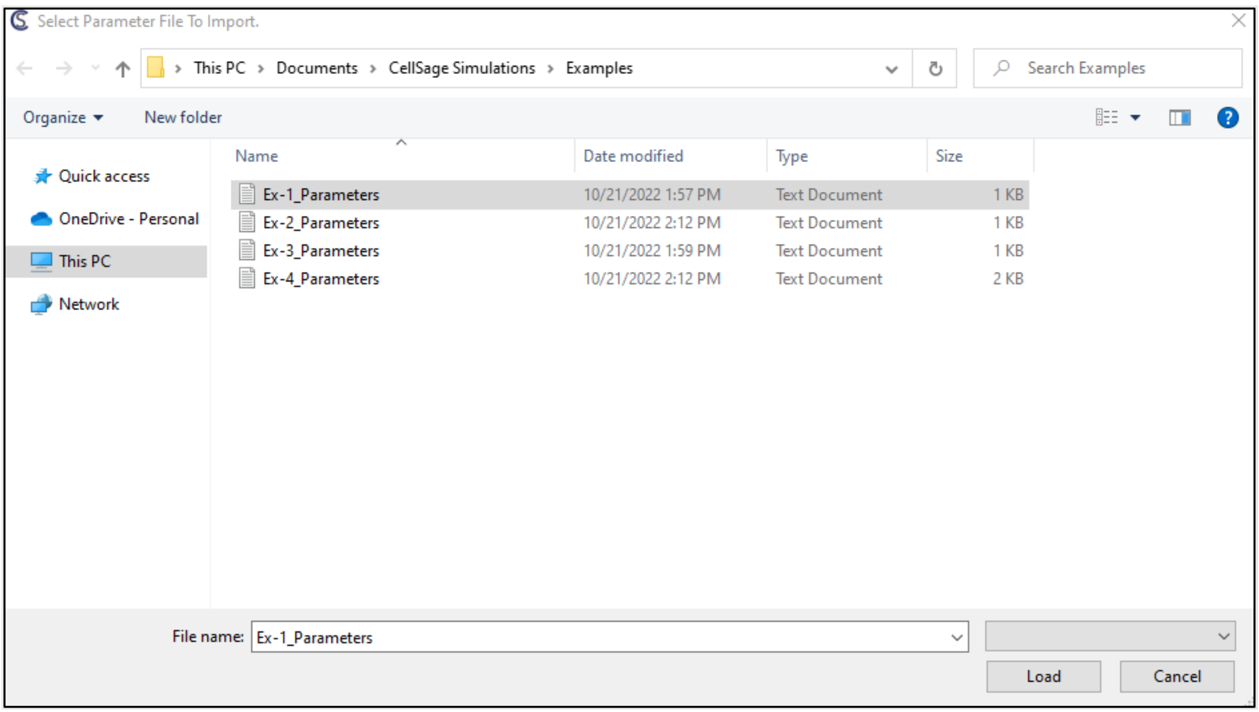



**Figure 67. Tab 1, Cell Chemistry and Simulation Conditions**

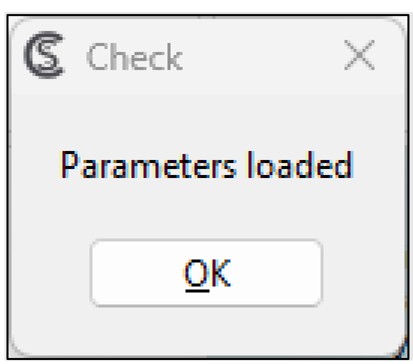



**Figure 68. Import success message after loading the "Ex-1_Parameters.txt" file.**

### 5.1.2 Example 1: Cell Chemistry & Global Simulation Conditions Tab

Now that the input parameters have been imported into the CellSage™ simulation, we will now step through each tab to verify that each condition has been entered. As shown in Figure 69, the following input parameters were loaded in the Cell Chemistry & Global Simulation Conditions tab:

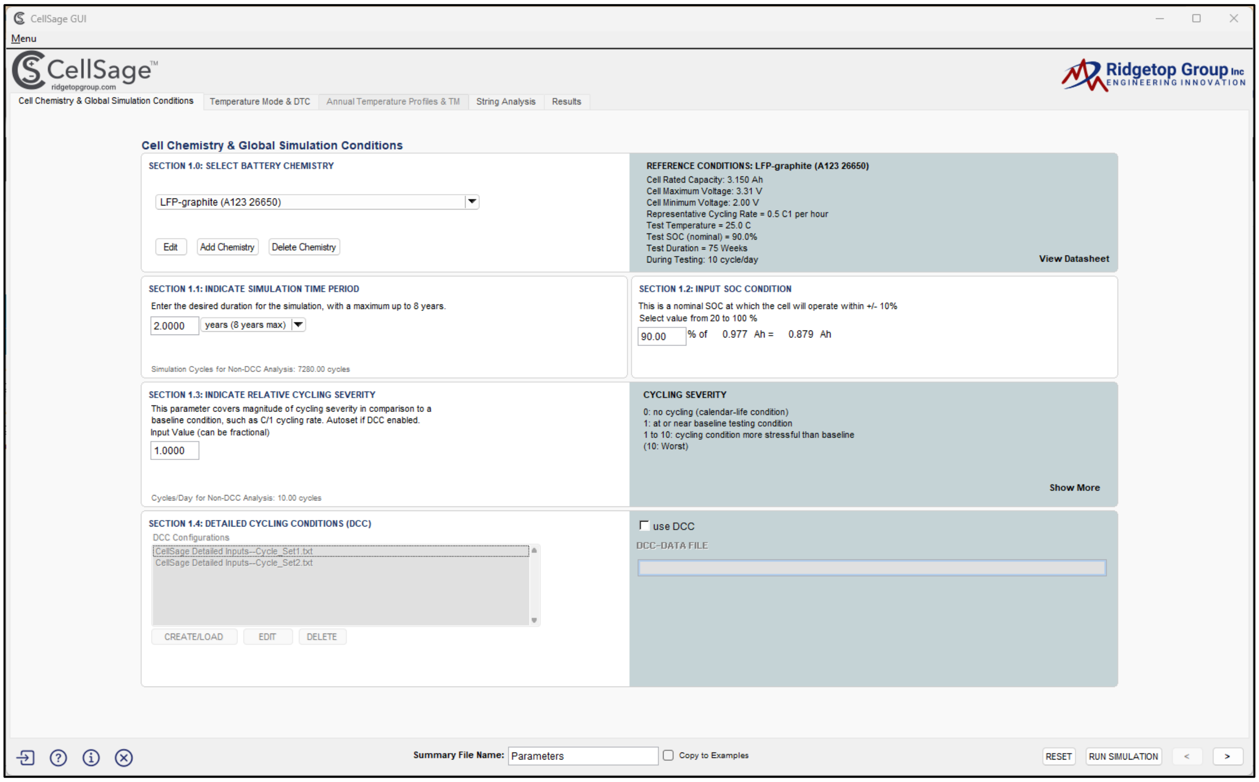



**Figure 69. Example 1, Cell Chemistry and Global Simulation Conditions tab.**

- **Section 1.0: Select Battery Chemistry** – This parameter was set to the LFP-graphite (A123 26650) chemistry model. The baseline reference conditions during the initial cycle life testing exercise are displayed in the text previewing box to the right.
- **Section 1.1: Indicate Simulation Time Period** – This parameter was set to 2 years or 104 weeks to approximately match 50% of the 208-week testing duration in the baseline reference conditions. This equates to 7280 total cycles based on 10 cycles per day for the LFP-graphite (A123 26650) chemistry model.
- **Section 1.2: Input SoC Condition** – This parameter was set to 90%, which equates to 0.879 Ah of the total 0.977 Ah battery. This condition represents the state of charge the simulation starts with when running. The manufacturers rated capacity for each cell can be found in stored data sheet.
- **Section 1.3: Indicate Relative Cycling Severity** – This parameter was set to 1.0 which is at or near the baseline testing conditions.
- **Section 1.4: Detailed Cycling Conditions** – The DCC feature was not enabled for this example, but this feature will be covered in Example 3 and 5.

**IMPORTANT NOTE:** Input parameters can be entered or changed as the user navigates through each tab, and as covered in Section 3.2 the program will generate a "parameters.txt" file that lists all input conditions that were used during a particular CellSage™ simulation run.

### 5.1.3 Example 1: Temperature Mode and Daily Thermal Cycling Conditions (DTC) Tab

Next, we navigate to Temperature Mode and DTC tab, and verify that the following input parameters were loaded into the simulation as shown in Figure 70:

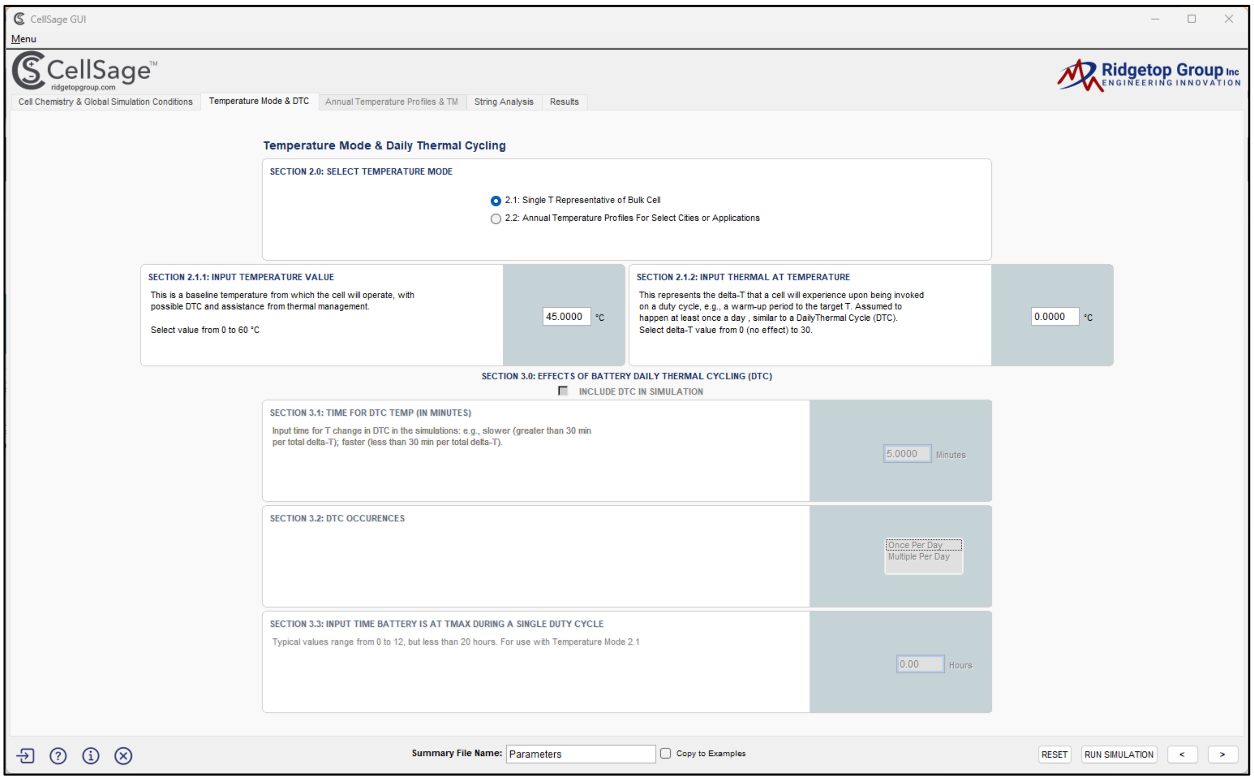



**Figure 70. Example 1, Temperature Mode & DTC tab.**

- **Section 2.0: Temperature Mode** – This parameter is set to 2.1: Single Representative of Bulk Cell.
- **Section 2.1.1: Input Temperature Value** – This parameter is set to 45 °C to represent the temperature of the Cycle-Life Two dataset that was uploaded in the CellSage™ New Chemistry Import Feature.
- **Section 2.1.2: Input Thermal Cycle at Temperature** – This parameter is set to 0 °C as we are not including the Effects of DTC which further indicates no warm-up period for the cells to reach operating temperature.

**IMPORTANT NOTE:** Section 3.0 is always disabled if 2.1.2 is set to 0 °C, as this option indicates that the cells are under a constant input temperature value specified in 2.1.1.

### 5.1.4 Example 1: Annual Temperature Profiles and Thermal Management Conditions Tab

Next, we navigate to the Annual Temperature Profiles and Thermal Management Conditions tab. As shown in Figure 71, these input conditions are disabled as they are meant to be used when the Temperature Mode is set to 2.2: Annual Temperature Profiles for Select Cities or Applications. These conditions will be covered in Examples 4-5, but for this example we will continue to Step 5.

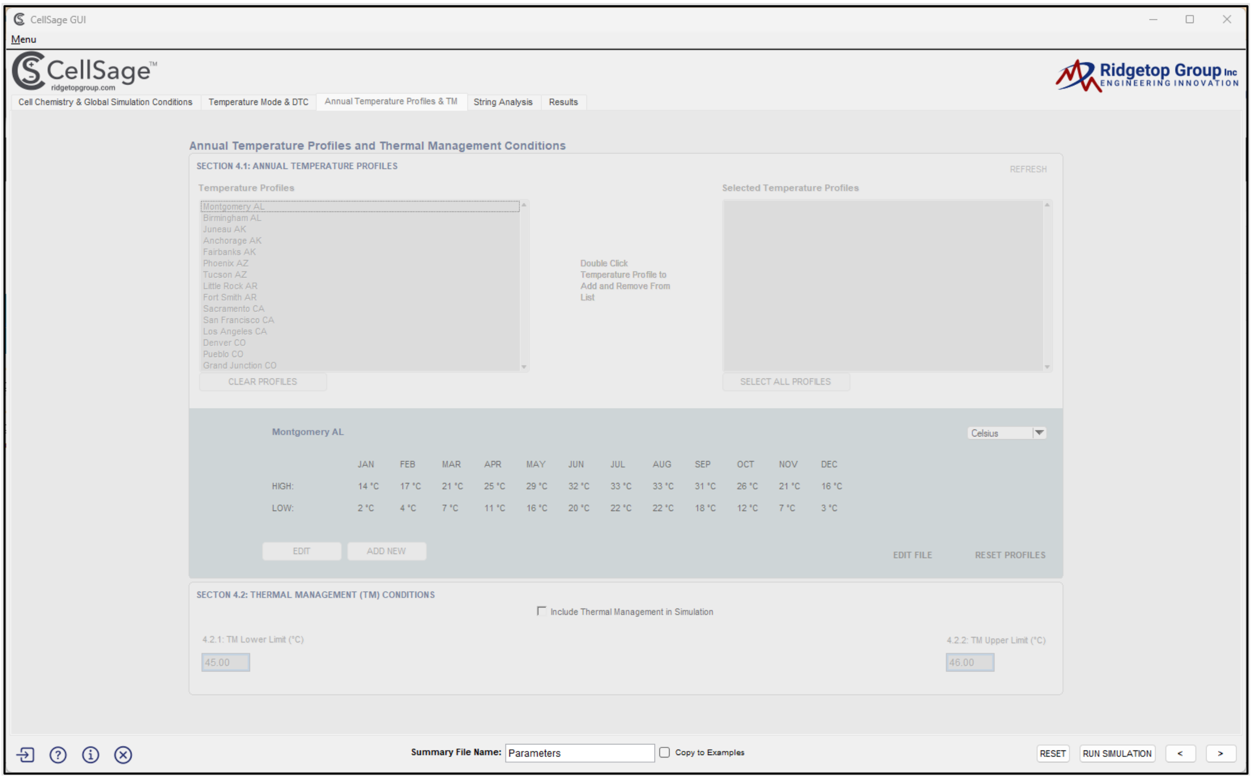



**Figure 71. Example 1, Annual Temperature Profiles & TM tab.**

### 5.1.5 Example 1: String Analysis Tab

The String Analysis tab is where specific input conditions related to a unique string configuration is entered. The String Analysis section is meant to evaluate capacity and power loss based on a hot spot in the middle cell of the string. These results are included in each simulation and help to simulate the impact of inconsistent thermal management.

For Example 1, we verify that the following conditions have been set as shown in Figure 72.

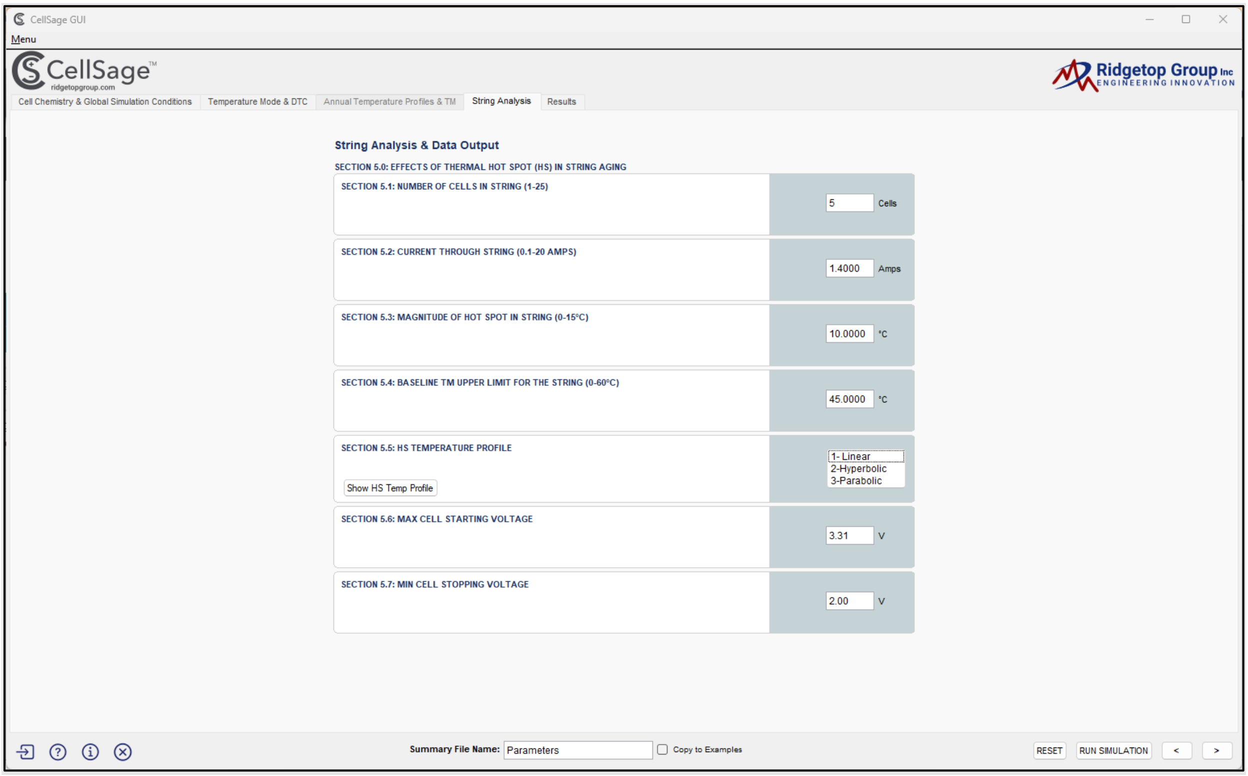



**Figure 72. Example 1, String Analysis tab.**

- **Section 5.1: Number of Cells in String** – This parameter is set to 5, which indicates the number of cells wired in series for this example (i.e. 5S1P). Note that if odd numbers are chosen for this input condition, then program will easily expose the full magnitude of the thermal hotspot in the middle cell. At this time, CellSage™ only supports cells in configured series. Parallel string analysis is a feature that Ridgetop expects to develop in future releases of the program.
- **Section 5.2: Current through String (Amps)** – This parameter is set to 1.4 Amps which represents the maximum discharge current through the 5-cell string.
- **Section 5.3: Magnitude of Hot Spot (HS) in String** – This parameter is set to 10 °C to represent the maximum temperature difference between the middle cell and the cells at the end of the string. This setting is used to reflect the natural mismatch or imbalanced temperature condition that arises during discharging when TM is not perfect over the entirety of the string.

- **Section 5.4: Baseline TM Upper Limit for the String** – This field reflects the upper limit for Thermal Management (TM) and must be set even if the TM capability is disabled. The chosen value is arbitrary and can vary from the assigned cell-level TM maximum temperature. String maximum temperatures will generally fall from 0 to 60 °C.
  If TM is enabled then this parameter should be set to the upper limit in the Thermal Management Conditions tab. If TM is not enabled then this temperature should be set to the same value as the Input Temperature Value in the Temperature Mode tab. The latter case will reflect the baseline temperature for which the cell will operate from 0 to 60 °C. For Example 1, this field is set to 45 °C.
- **Section 5.5: HS Temperature Profile** – This setting provides an optional means to characterize or describe how the cell thermal imbalance will manifest itself. In practice, the HS profile will be a consequence of string design in its enclosure, the nature of the duty cycle, and the effectiveness of thermal management. It is either linear or simple 1-to-1 correspondence, or a curved profile. The HS Temperature Profile in conjunction with the Magnitude of HS in String define how the simulation models the individual cells. The specific values are listed in the top or beginning of the String Analysis output data.
  For Example 1, this field is set to Option 1 – Linear and the HS Temperature Profile can be previewed by selecting the Show HS Temp Profile button. This will produce a preview as shown in Figure 73, where the center cell (#03) has the 10 °C hotspot specified in section 5.3:

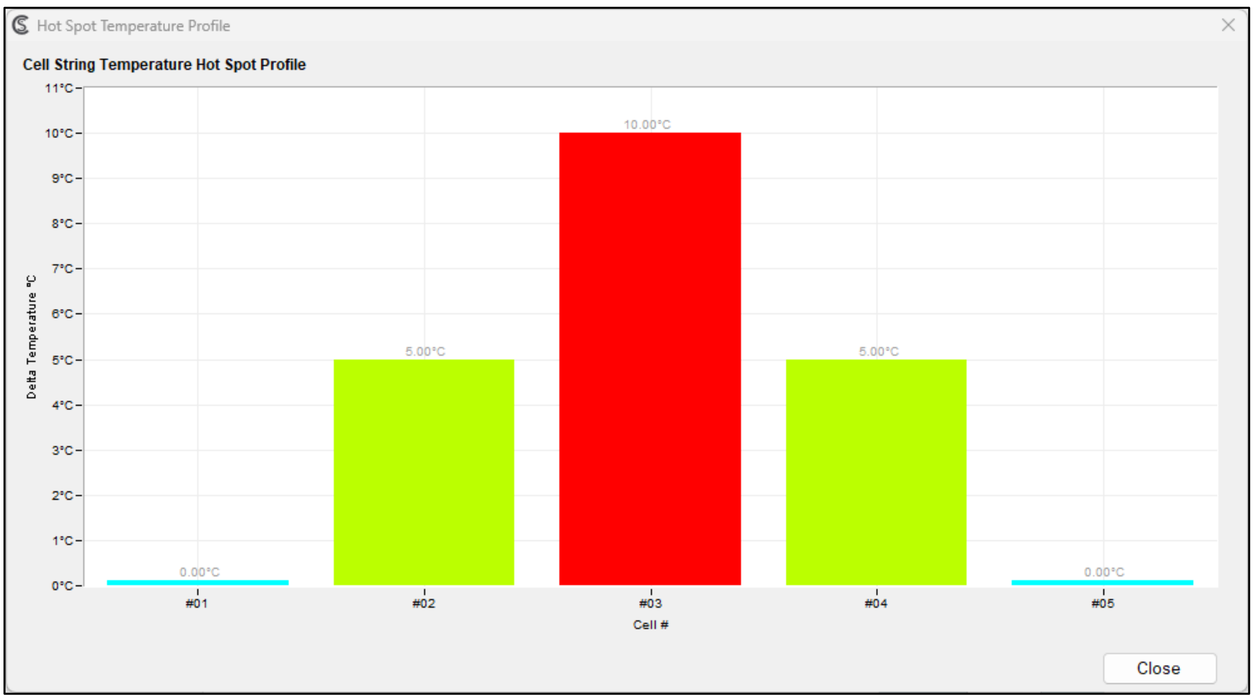



**Figure 73. Example 1, Hot Spot Temperature Profile on String Analysis tab.**

- **Section 5.6: Max. Cell Starting Voltage** – This value is populated with the maximum cell starting voltage for the selected cell chemistry. In some cases, this upper limit can be decreased to reflect a simulation with different aging effects. For Example 1, this field is set to 3.31 V.

- **Section 5.7: Min. Cell Stopping Voltage** – This value is populated with the minimum cell stopping voltage for the selected cell chemistry. The lower limit can be adjusted to reflect simulations with different aging effects. For Example 1, this field is set to 2 V.

At this point all simulation conditions have been entered, and we can now run the simulation by pressing the **RUN SIMULATION** button. The simulation is usually very fast even with multi-year and multi-city simulations. After a successful simulation run is executed a pop-up message box will appear as shown in Figure 74. The program will allow the fields to be modified for sequential simulation runs, and it will create a new data output folder for each sequential simulation.

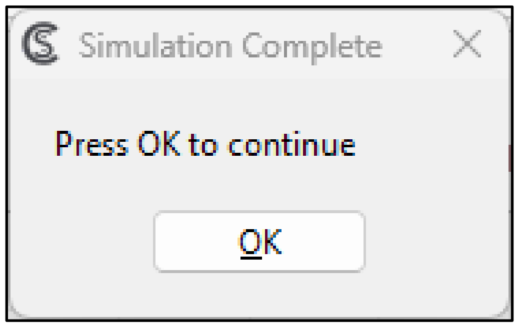



**Figure 74. Message box after running the Example 1 simulation.**

A new simulation can be done clicking the **RESET** button. This button resets the fields for the output filenames and displays a message box as shown in Figure 75.

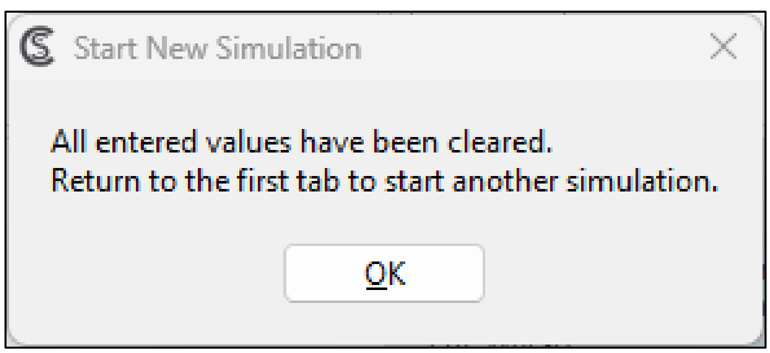



**Figure 75. Message box after clicking the RESET button.**

### 5.1.6 Example 1: Results Tab

Upon completing the CellSage™ Simulation run for Example 1, we can now navigate to the Results tab where we can select and preview our data output files as well as review some of the automated plots that were generated during the simulation. As covered in Section 3.2, the data output files are stored in a time stamped folder which include the "CS_Diagnostics.txt", "CS_Path-Dependence.txt", "CS_Path-Dependence-Dcc.txt", "CS_String-Analysis.txt", "Parameters.txt", and individual *.csv files that are stored in the data-plot subdirectory. Within the Results tab, the user can open a CellSage™ simulation run in the Windows File Explorer by clicking on the blue OPEN IN EXPLOER button, and/or the user can delete the simulation run by clicking on the red DELETE RUN button. This functionality is also extended to the list of data output files and data plot files in the subsequent scroll boxes.

Figure 76 provides a visual aid for the Results tab after running Example 1. It is important to note that the GUI does offer a text previewing window for a selected data output file. If desired by the user, the data output files can also be opened with any Windows application that can open plain ASCII text files such as Notepad, Notepad++, Excel, etc.

In addition to previewing the data output files, the GUI also allows the user to preview automated graphs and plots. As outlined in Section 3.1.5., specific data plot types depend on the type of simulation run.

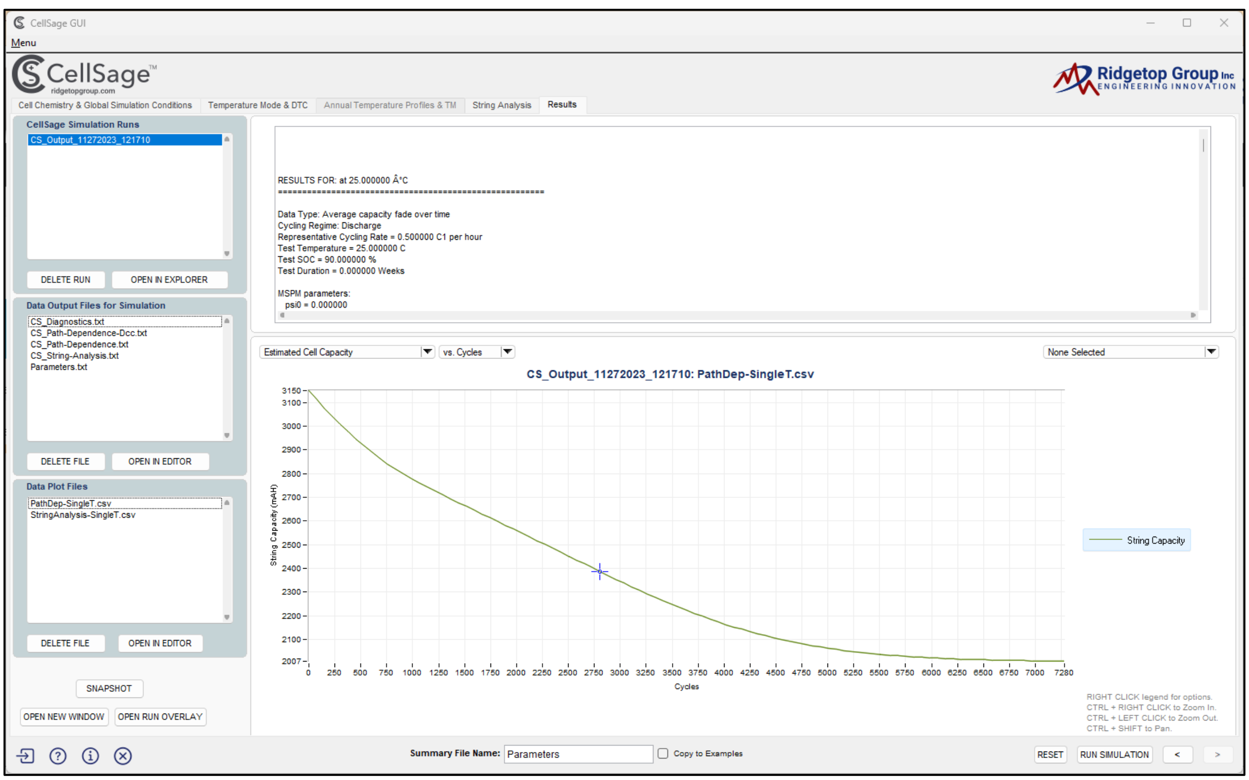



**Figure 76. Example 1, Results tab showing each of the data output files, a text previewing box, and drop-down window to select different plot types.**

### 5.1.7 Example 1: Discussion

During this example we have successfully walked through the process of importing the "Ex-1_parameters.txt" file, verified that each of those input conditions were entered into the CellSage™ GUI, and ran a complete CellSage™ simulation.

For this discussion we will focus on three particular data output plots to demonstrate how the baseline aging data can be accurately modeled at both 25 °C and 45 °C. As shown in Figure 77 and Figure 78, the estimated baseline capacity loss at 25 °C and week 74.7 is 16.6060%. The simulated capacity loss at 45 °C is shown in Figure 77 and is estimated to be approximately 34.9590% which is both quantitively and qualitatively accurate with the estimated capacity loss for the Cycle-Life Two data set shown in Figure 79.

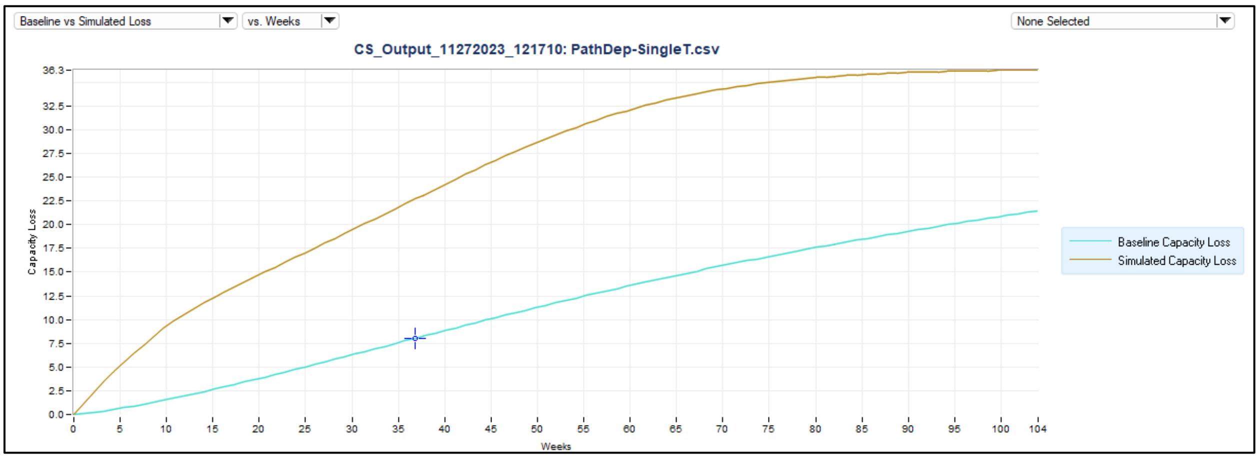



**Figure 77. Example 1, Baseline vs. Simulated Capacity Loss from Path Dependance data output file.**

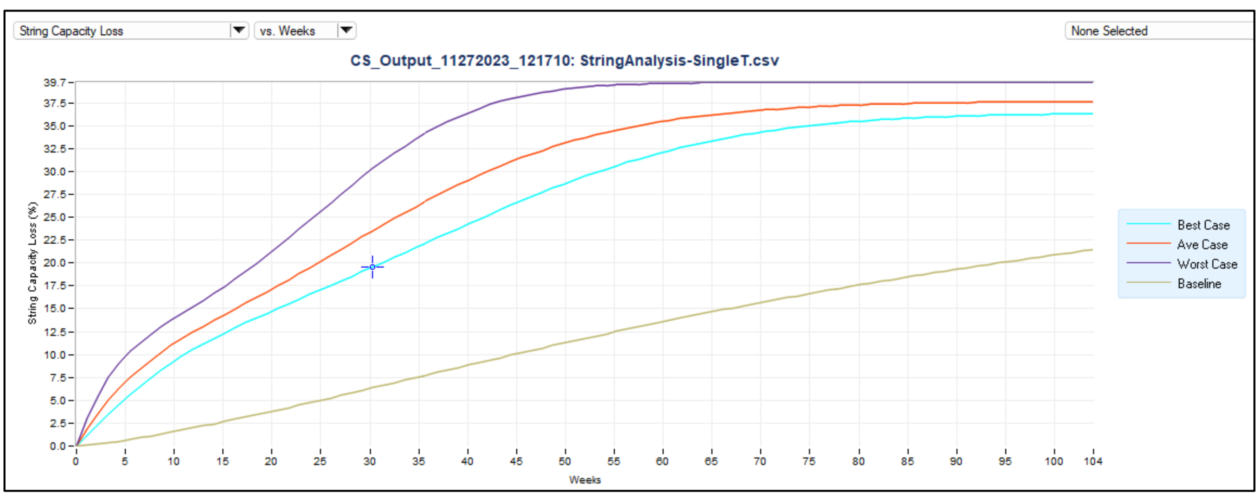



**Figure 78. Example 1, String Capacity Loss vs. weeks for Best Case, Average Case, Worst Case, and Baseline Conditions as determined from String Analysis data output file.**

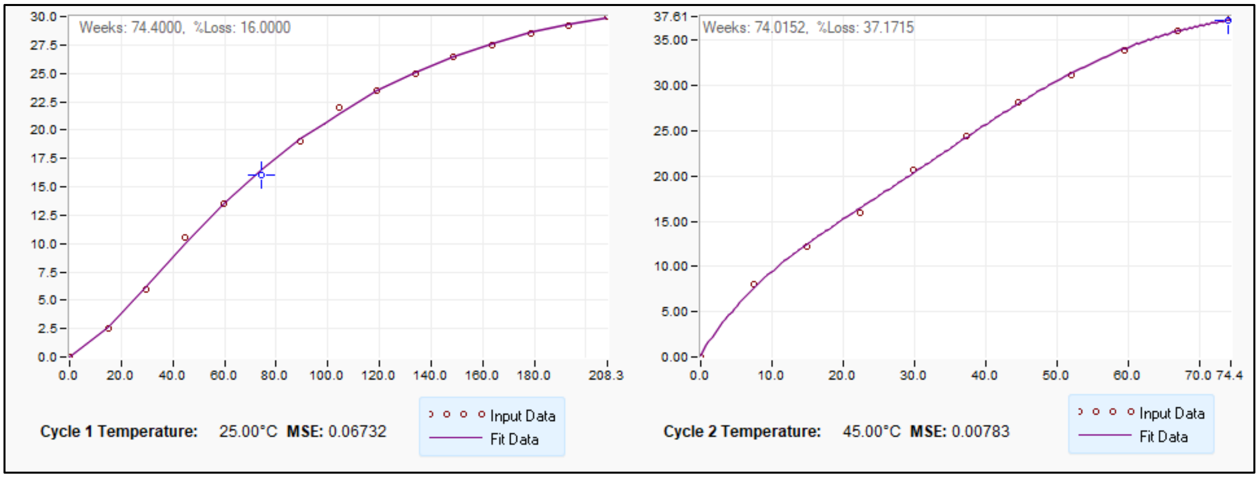



**Figure 79. Example 1, visual aid for reproduced baseline aging data (at 25 °C and 45 °C) as shown with the uploaded data in the New Chemistry Import Feature.**

## 5.2 Example 2: Running a Single T Simulation with no DCC, no DTC, and no TM

This example will cover how a user can run a basic CellSage™ simulation for the NMC/graphite (Panasonic UR18650) cell chemistry. It should be noted that the CellSage™ software architecture follows a linear programming flow where the user enters input conditions in sequential sections, and navigates through the tabs with the "Next" and "Previous" buttons in the lower right corner of the GUI. Each example shall start by opening the CellSage™ software application as shown in Step 1 of Section 2.3, or by opening the Windows Start Menu and searching for the CellSage™ software program. When the program is opened successfully, the user will be on the Cell Chemistry & Global Simulation Conditions Tab.

Example 2 will be a simple CellSage™ simulation where the temperature mode is set to 2.1: Single T Representative of Bulk Cell, and the options to include Detailed Cycling Conditions (DCC), Thermal Management (TM), and Daily Thermal Cycling (DTC) are not enabled. This example is representative of a two-year simulation where CellSage™ simulates the Panasonic UR 18650 chemistry at or near the baseline reference conditions during the initial cycle life testing exercise.

Similar to the previous example, we setup Example 2 by importing the "Ex-2_Parameters.txt" file to prepopulate each of our simulation conditions. We then begin to verify that each of our input conditions are loaded into the CellSage™ GUI.

### 5.2.1 Example 2: Cell Chemistry & Global Simulation Conditions Tab

Now that the input parameters have been imported into the CellSage™ simulation, we will now step through each tab to verify that each condition has been entered. As shown in Figure 80, the following input parameters were loaded in the Cell Chemistry & Global Simulation Conditions tab:

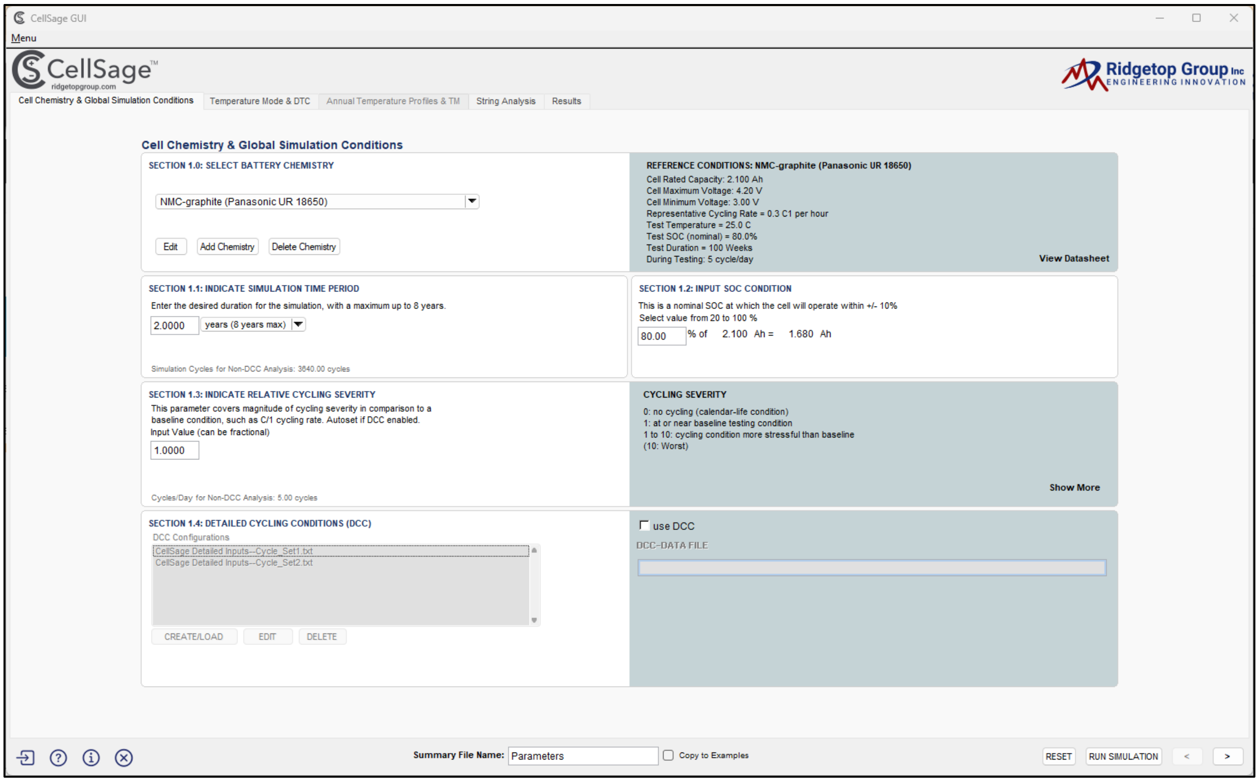



**Figure 80. Example 2, Cell Chemistry and Global Simulation Conditions tab.**

- **Section 1.0: Select Battery Chemistry** – This parameter was set to the NMC/graphite (Panasonic UR 18650) chemistry that is widely used in consumer electronics, and the baseline reference conditions during the initial cycle life testing exercise is displayed in the text previewing box to the right.
- **Section 1.1: Indicate Simulation Time Period** – This parameter was set to 2 years or 104 weeks to approximately match the 100-week testing duration in the baseline reference conditions. This equates to 3640.0 total cycles based on 5 cycles per day for the NMC/graphite (Panasonic UR 18650) chemistry.
- **Section 1.2: Input SoC Condition** – This parameter was set to 80%, which equates to 1.680 Ah of the total 2.1 Ah battery. This condition represents the state of charge the simulation starts with when running. The manufacturers rated capacity for each cell can be found in the Appendix.
- **Section 1.3: Indicate Relative Cycling Severity** – This parameter was set to 1.0 which is at or near the baseline testing conditions.
- **Section 1.4: Detailed Cycling Conditions** – The DCC feature was not enabled for this example, but this feature will be covered in Example 3 and 5.
- Note: Input parameters can be entered or changed as the user navigates through each tab, and as covered in Section 3.2 the program will generate a "parameters.txt" file that lists all input conditions that were used during a particular CellSage™ simulation run.

### 5.2.2 Example 2: Temperature Mode and Daily Thermal Cycling Conditions (DTC) Tab

Next, we navigate to Temperature Mode and DTC tab, and verify that the following input parameters were loaded into the simulation as shown in Figure 81:

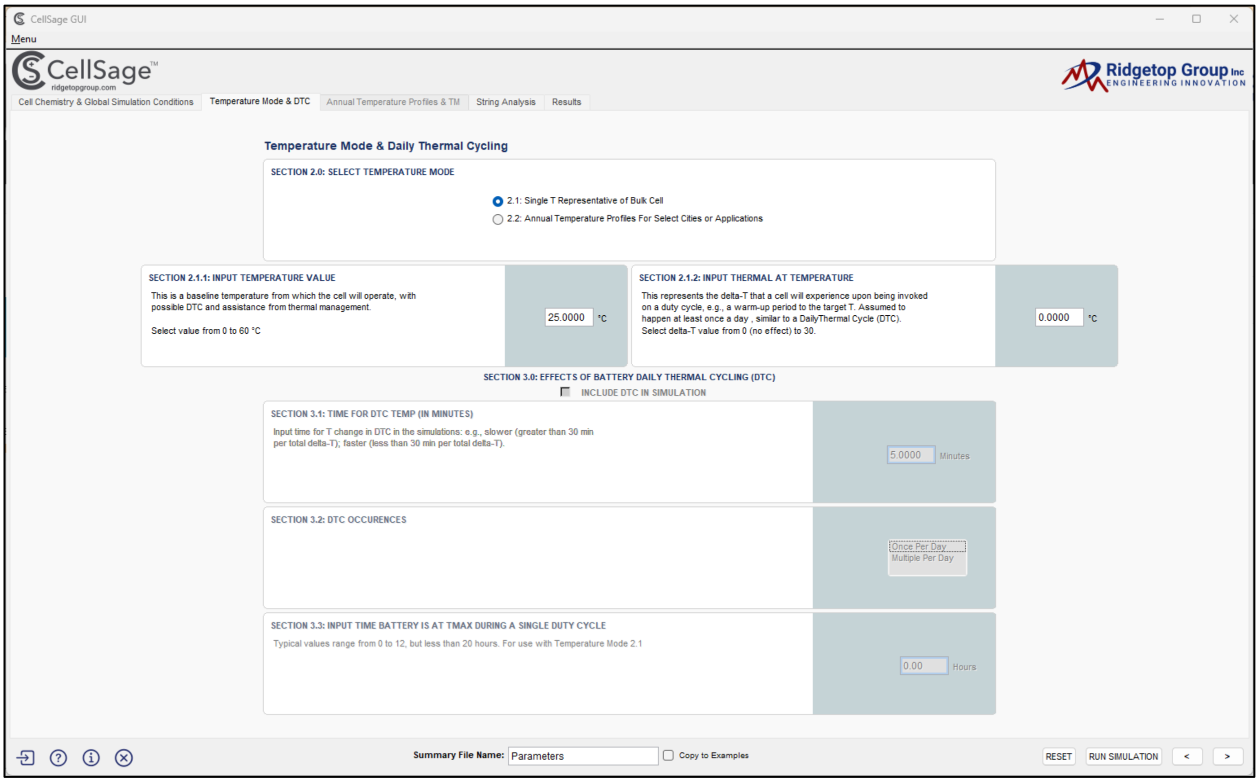



**Figure 81. Example 2, Temperature Mode & DTC tab.**

- **Section 2.0: Temperature Mode** – This parameter is set to 2.1: Single Representative of Bulk Cell.
- **2.1.1: Input Temperature Value** – This parameter is set to 25 °C to represent ambient room temperature in a laboratory operating environment.
- **2.1.2: Input Thermal Cycle at Temperature** – This parameter is set to 0 °C, as we are not including the Effects of DTC which further indicates no warm-up period for the cells to reach operating temperature.

**IMPORTANT NOTE:** Section 3.0 is always disabled if 2.1.2 is set to 0 °C, as this option indicates that the cells are under a constant input temperature value specified in 2.1.1.

### 5.2.3 Example 2: Annual Temperature Profiles and Thermal Management Conditions Tab

Next, we navigate to the Annual Temperature Profiles and Thermal Management Conditions tab. As shown in Figure 82 these input conditions are disabled as they are meant to be used when the Temperature Mode is set to 2.2: Annual Temperature Profiles for Select Cities or Applications. These conditions will be covered in Examples 4-5, but for this example we will continue to Step 5.

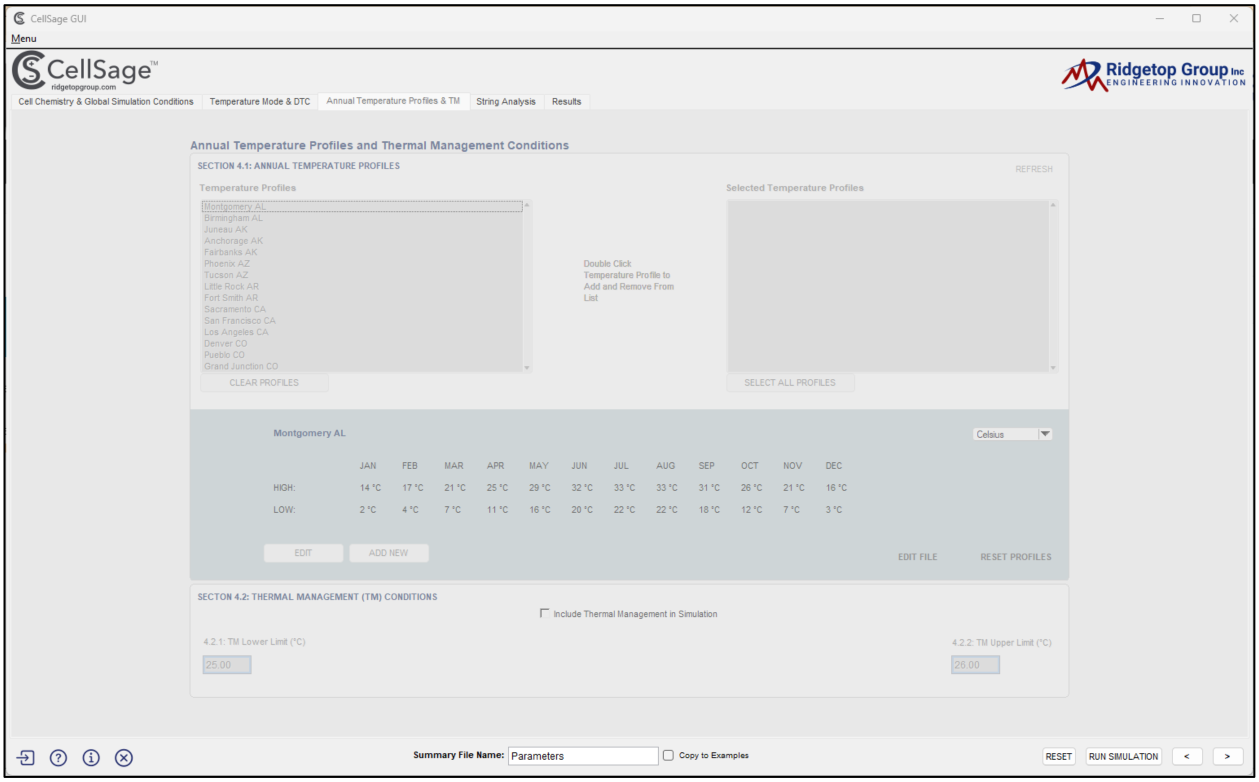



**Figure 82. Example 2, Annual Temperature Profiles & TM tab.**

### 5.2.4 Example 2: String Analysis Tab

For Example 2, we verify that the following conditions have been set as shown in Figure 83. We then click the Run Simulation button to execute the simulation, and proceed to the Results tab.

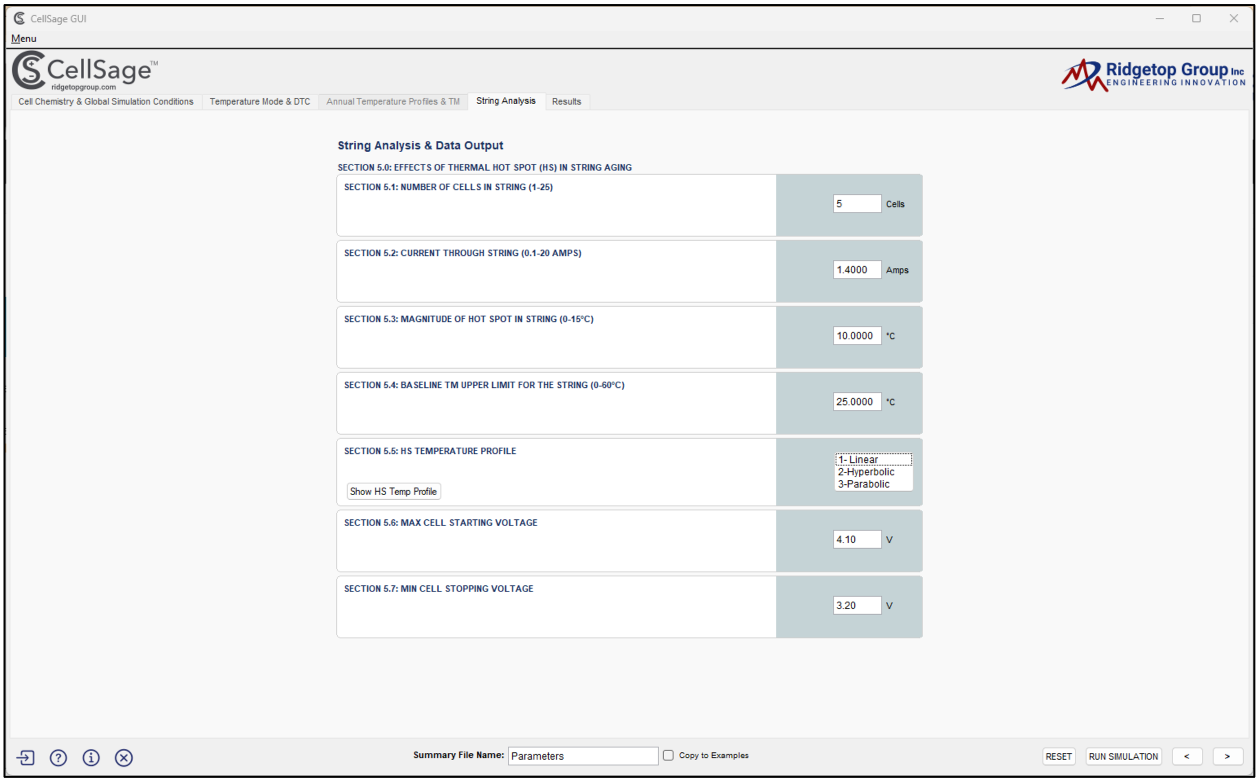



**Figure 83. Example 2, String Analysis tab.**

- **Section 5.1: Number of Cells in String** – This parameter is set to 5, which indicates the number of cells wired in series for this example (i.e. 5S1P). Note that if odd numbers are chosen for this input condition, then program will easily expose the full magnitude of the thermal hotspot in the middle cell. At this time, CellSage™ only supports cells in configured series. Parallel string analysis is a feature that Ridgetop expects to develop in future releases of the program.
- **Section 5.2: Current through String (Amps)** – This parameter is set to 1.4 Amps which represents the maximum discharge current through the 5-cell string.
- **Section 5.3: Magnitude of Hot Spot (HS) in String** – This parameter is set to 10 °C to represent the maximum temperature difference between the middle cell and the cells at the end of the string. This setting is used to reflect the natural mismatch or imbalanced temperature condition that arises during discharging when TM is not perfect over the entirety of the string.
- **Section 5.4: Baseline TM Upper Limit for the String** – This field reflects the upper limit for Thermal Management (TM) and must be set even if the TM capability is disabled. The chosen value is arbitrary and can vary from the assigned cell-level TM maximum temperature. String maximum temperatures will generally fall from 0 to 60 °C.

If TM is enabled then this parameter should be set to the upper limit in the Thermal Management Conditions tab. If TM is not enabled then this temperature should be set to the same value as the Input Temperature Value in the Temperature Mode tab. The latter case will reflect the baseline temperature for which the cell will operate from 0 to 60 °C. For Example 2, this field is set to 25 °C.

- **5.5: HS Temperature Profile** – This setting provides an optional means to characterize or describe how the cell thermal imbalance will manifest itself. In practice, the HS profile will be a consequence of string design in its enclosure, the nature of the duty cycle, and the effectiveness of thermal management. It is either linear or simple 1-to-1 correspondence, or a curved profile. The HS Temperature Profile in conjunction with the Magnitude of HS in String define how the simulation models the individual cells. The specific values are listed in the top or beginning of the String Analysis output data. For Example 2, this field is set to Option 1 – Linear.
- **5.6: Max. Cell Starting Voltage** – This value is populated with the maximum cell starting voltage for the selected cell chemistry. In some cases, this upper limit can be decreased to reflect a simulation with different aging effects. For Example 2, this field is set to 4.1 V.
- **5.7: Min. Cell Stopping Voltage** – This value is populated with the minimum cell stopping voltage for the selected cell chemistry. The lower limit can be adjusted to reflect simulations with different aging effects. For Example 2, this field is set to 3.2 V.

### 5.2.5 Example 2: Results Tab

Upon completing the CellSage™ Simulation run for Example 2, we can now navigate to the Results tab where we can select and preview our data output files. As outlined in Section 3.1.5., specific data plot types depend on the type of simulation run. For Example 2 we have the following list of automated plots that were based on the CS_Path-Dependence.txt and CS_String-Analysis.txt data output files:

**List of plots for PathDep-SingleT.csv (shown in Figure 85 - Figure 90):**

- Estimated Cell Capacity Loss vs. Weeks or Cycles
- State of Health vs. Weeks or Cycles
- Reference/Baseline (BL) vs. Weeks or Cycles
- At User Inputs (i*) vs. Weeks or Cycles
- Ratios (i*/BL) vs. Weeks or Cycles
- Temperature vs. Weeks or Cycles

**List of plots for StringAnalysis-SingleT.csv (shown in Figure 91 - Figure 96):**

- Cell Capacity vs. Weeks or Cycles
- State of Health vs. Weeks or Cycles
- String Capacity Loss vs. Weeks or Cycles
- Power vs. Weeks or Cycles
- Temperature vs. Weeks or Cycles

Some preliminary analysis on the Cell Capacity as it relates to the String Analysis inputs for this example will be covered in the Example 2 discussion.

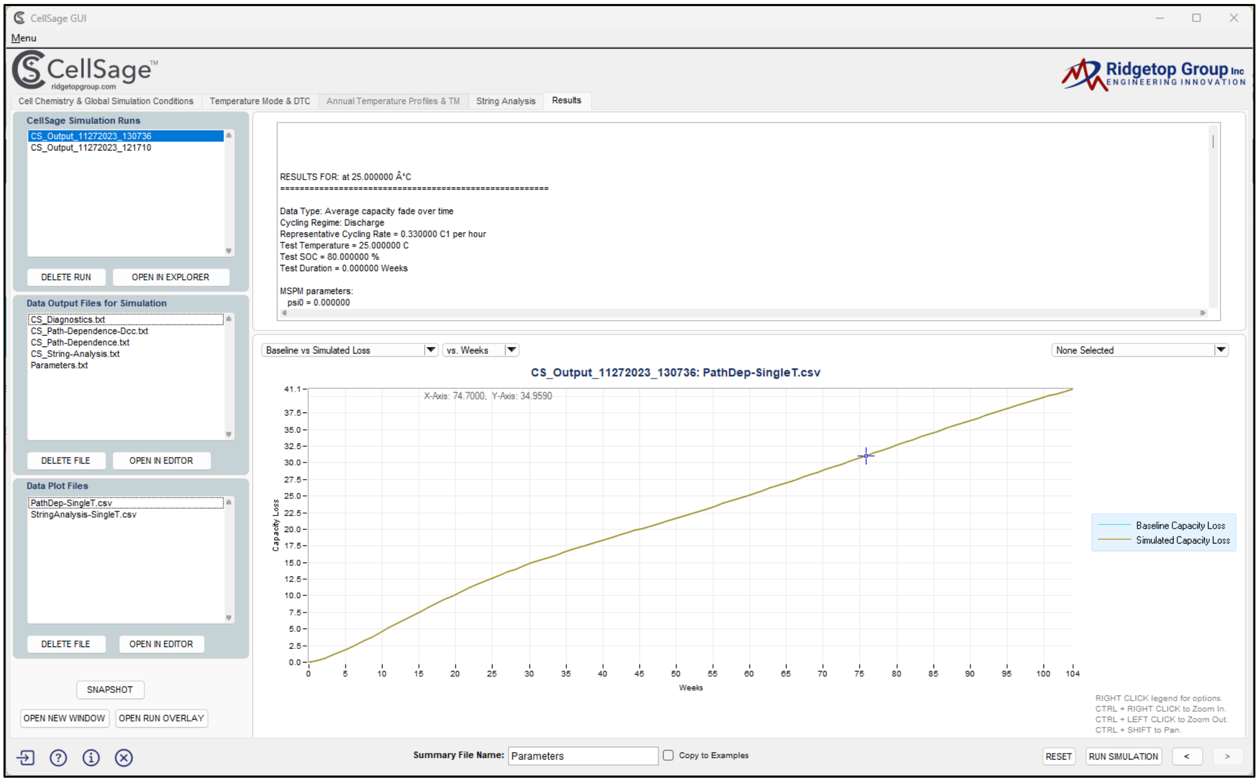



**Figure 84. Example 2, Results tab showing each of the data output files, a text previewing box, and drop-down window to select different plot types.**

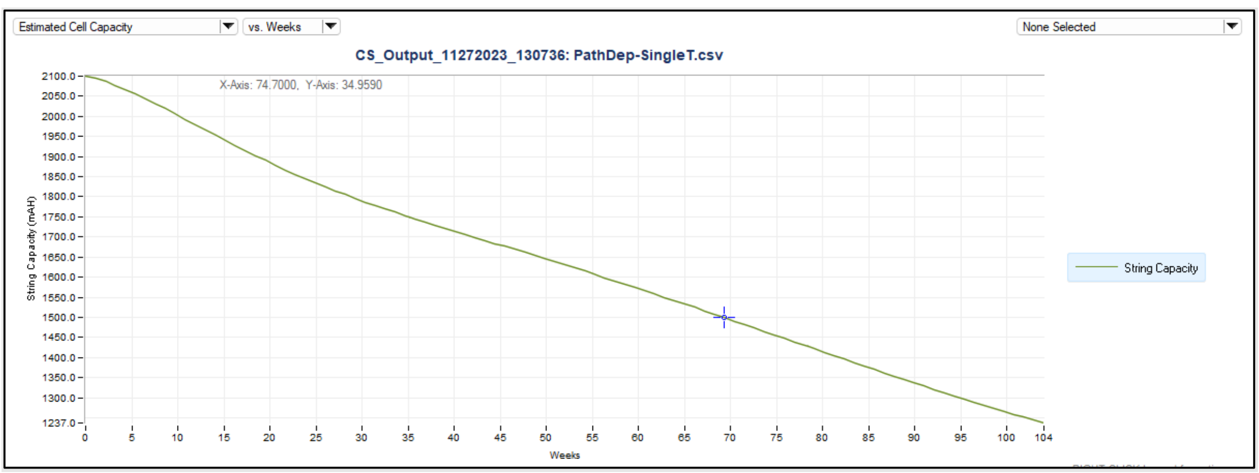



**Figure 85. Example 2, Estimated Cell Capacity vs. Weeks.**

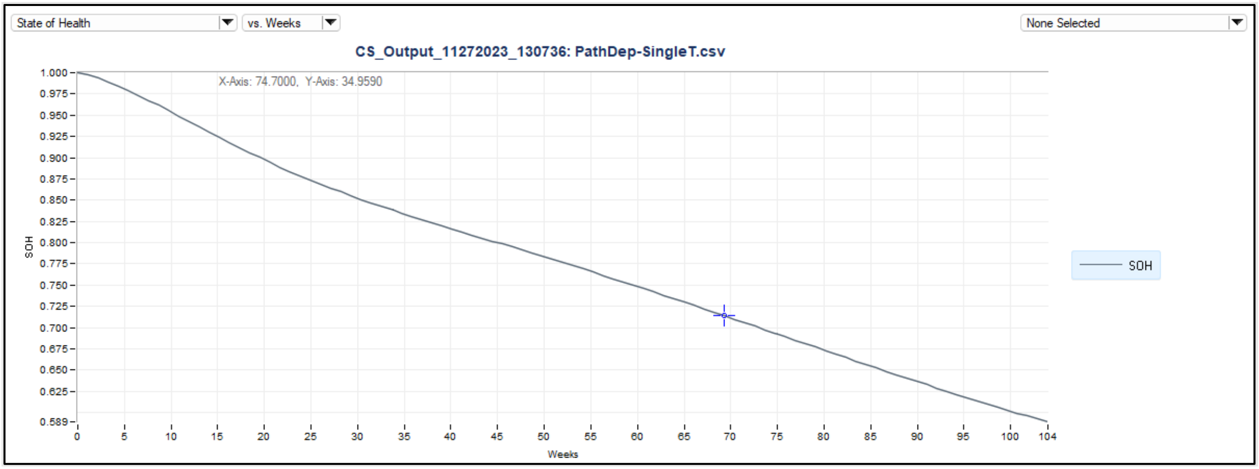



**Figure 86. Example 2, State of Health vs. Weeks.**

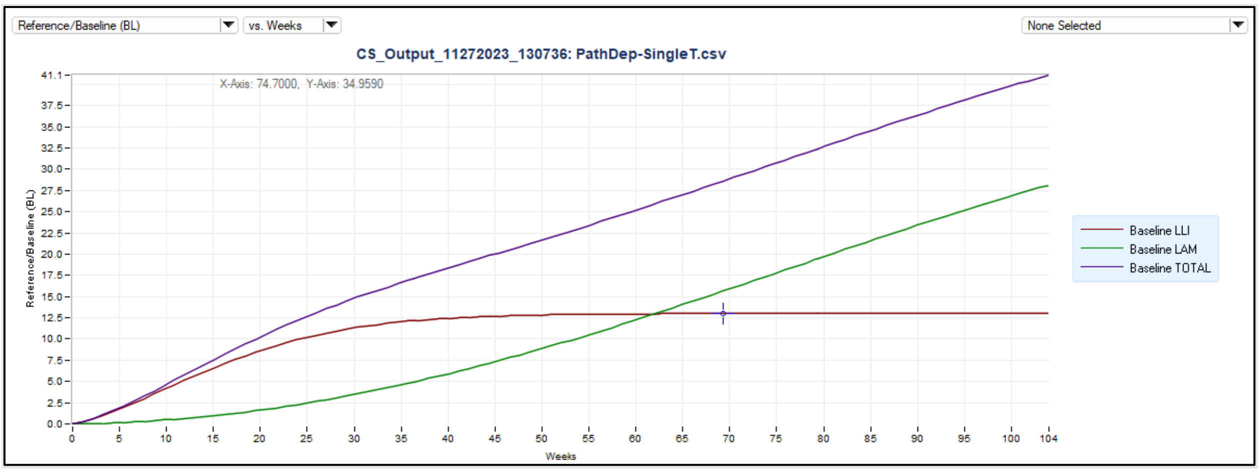



**Figure 87. Example 2, Reference/Baseline (BL) vs. Weeks.**

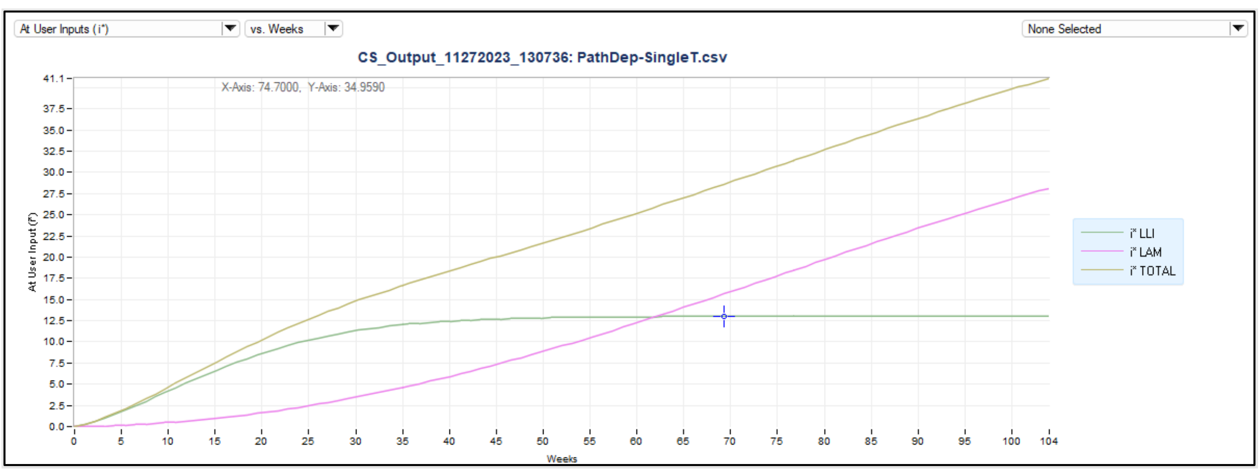



**Figure 88. Example 2, At User Inputs (i*) vs. Weeks.**

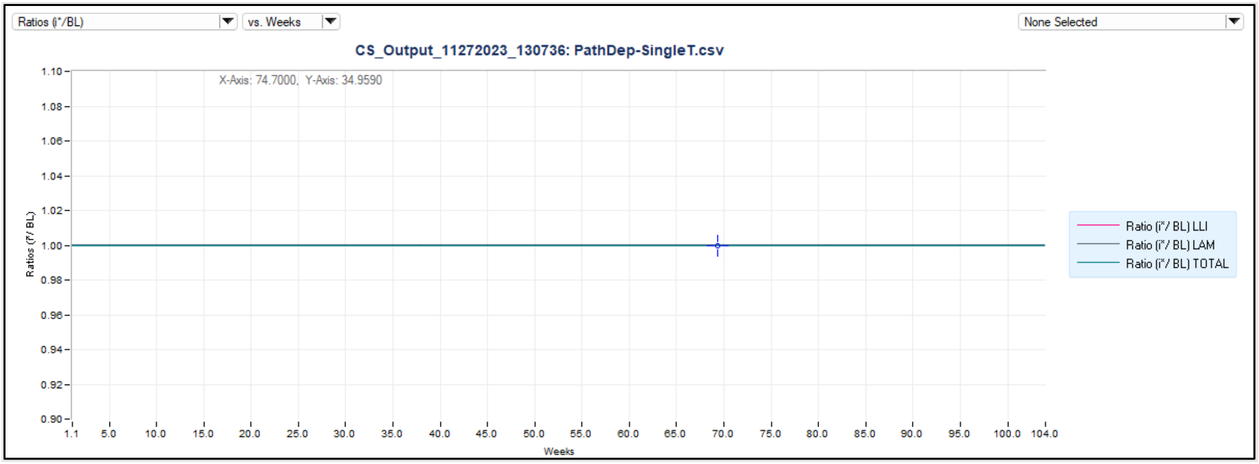



**Figure 89. Example 2, Ratios (i*/BL) vs. Weeks.**

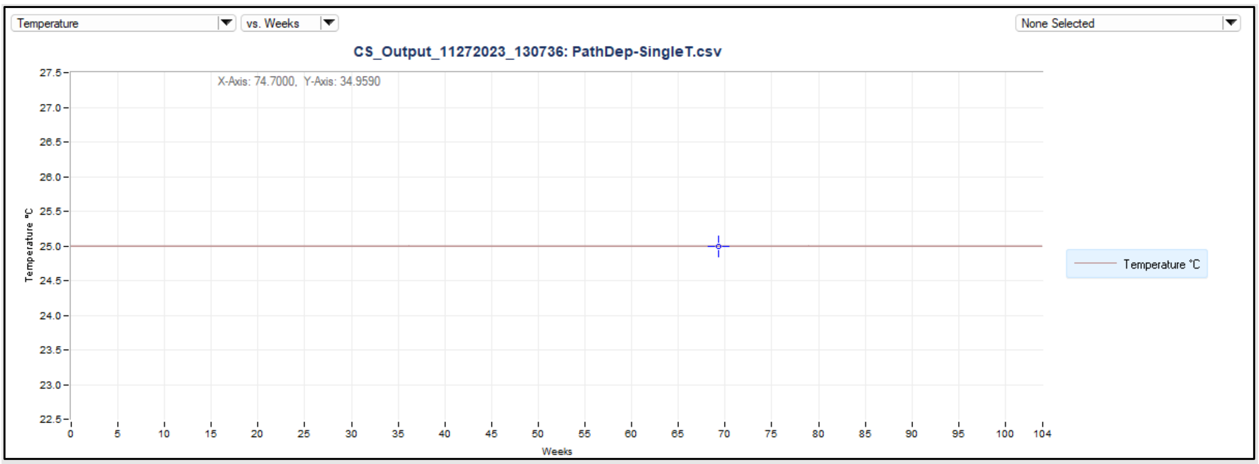



**Figure 90. Example 2, Temperature vs. Weeks.**

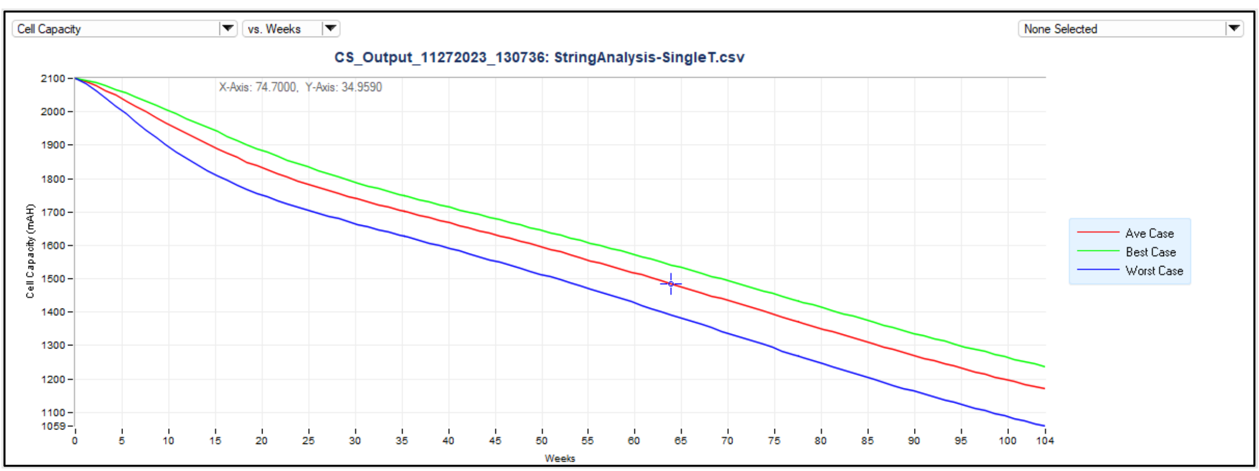



**Figure 91. Example 2, Cell Capacity vs. Weeks.**

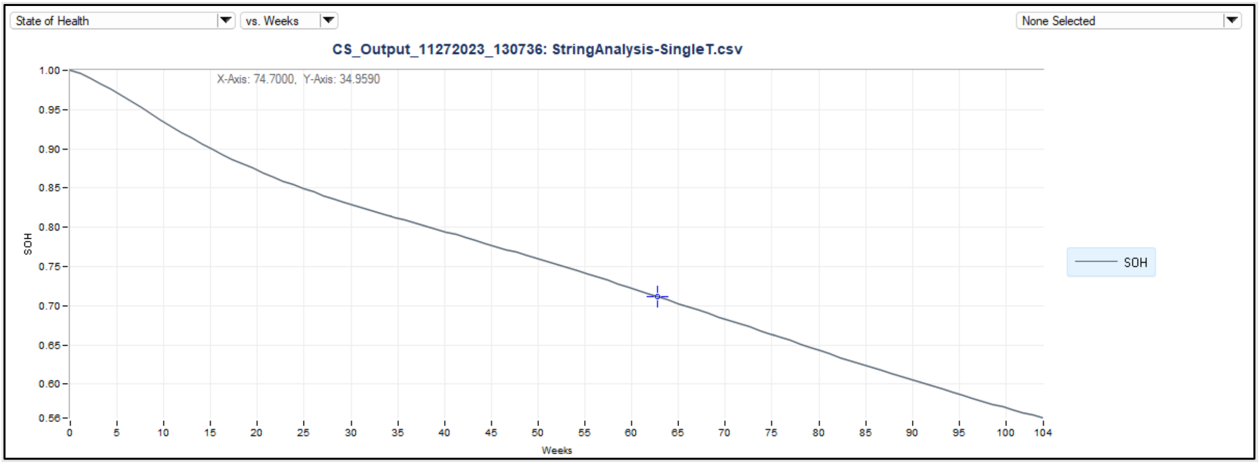



**Figure 92. Example 2, State of Health vs. Weeks.**

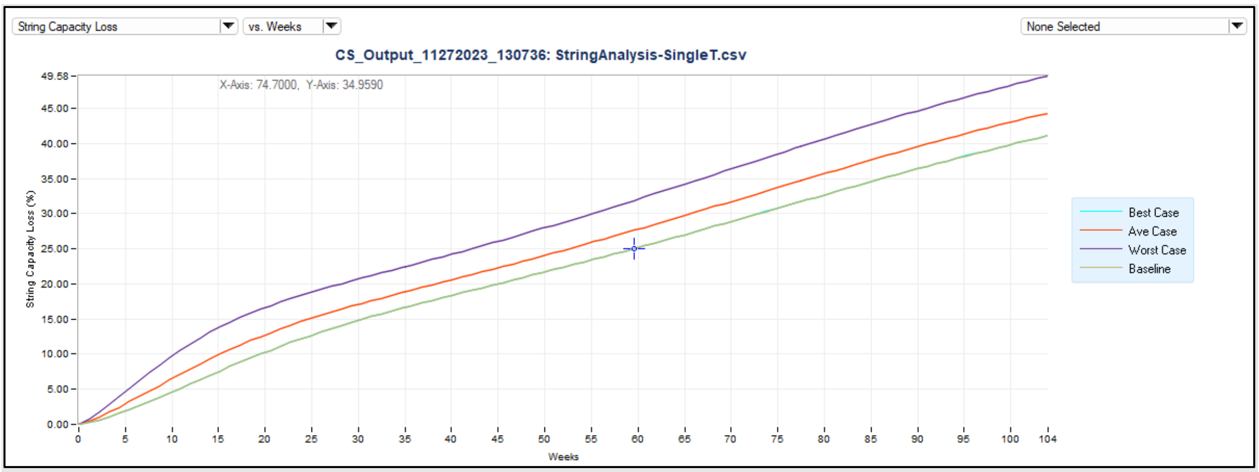



**Figure 93. String Capacity Loss (%) vs. Weeks.**

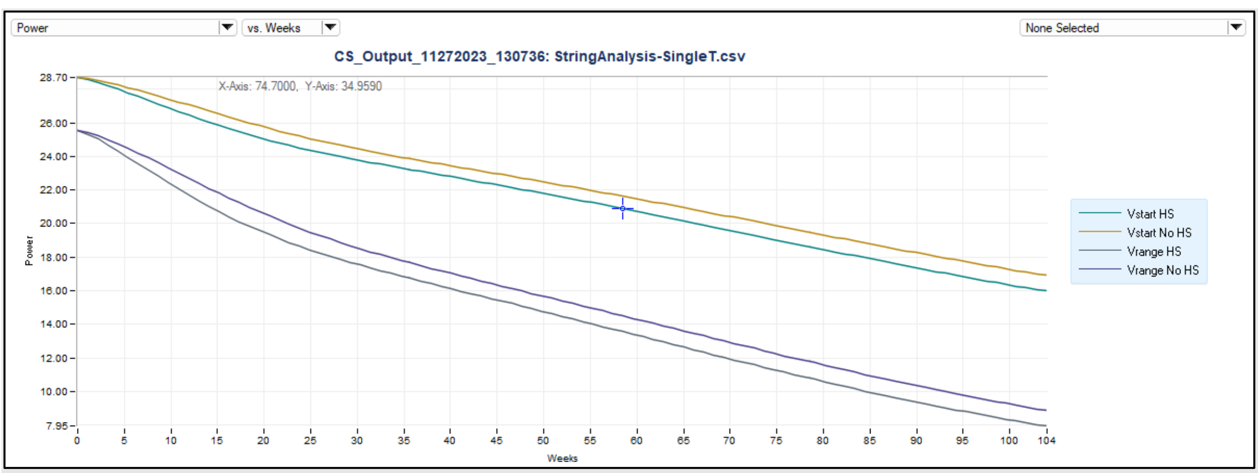



**Figure 94. Example 2, Power vs. Weeks.**

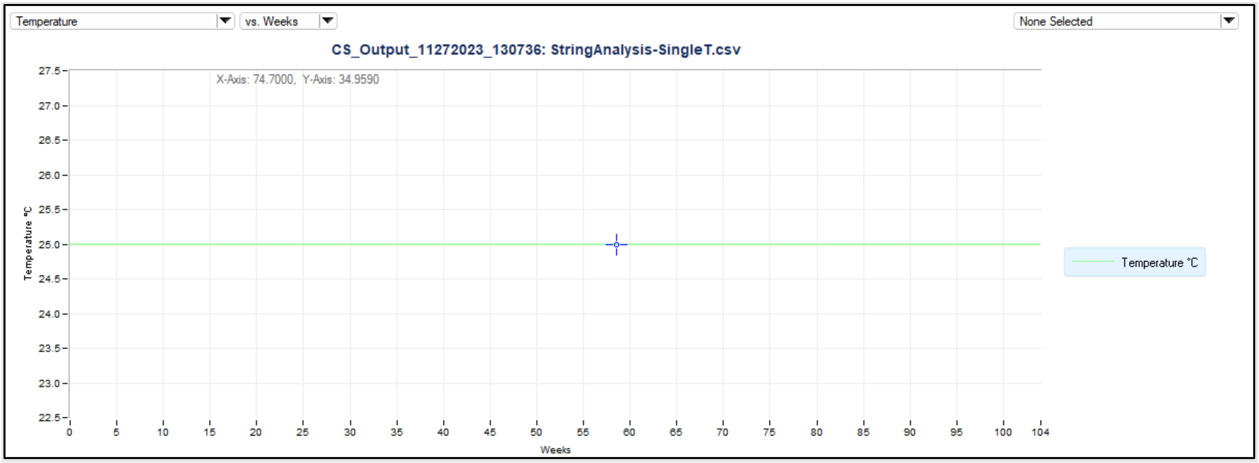



**Figure 95. Example 2, Temperature vs. Weeks.**

### 5.2.6 Example 2: Discussion

During this example we have successfully walked through the process of importing the "Ex-2_parameters.txt" file, verified that each of those input conditions were entered into the CellSage™ GUI, and ran a complete CellSage™ simulation. As shown in Figure 96, the estimated Cell Capacity vs. Cycles shows three different scenarios for loss of capacity in terms of the Best Case, Worst Case, and Average Case.

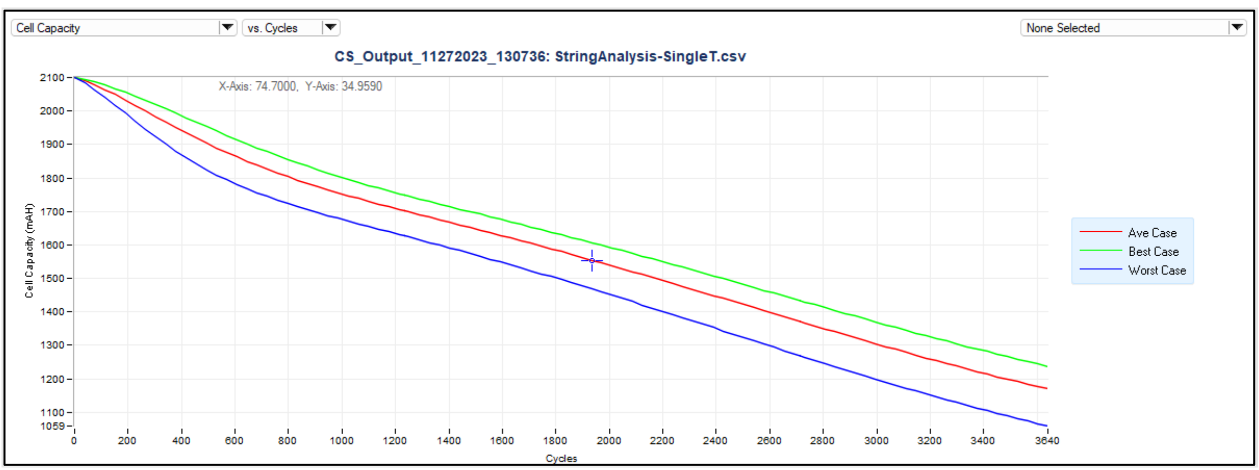



**Figure 96. Example 2, Cell Capacity vs. Cycles.**

Further analysis by opening the *.csv file in Excel has shown the following percentage changes by the end of the two year / 3640 cycle simulation:

- Best Case – 41.09% loss or 861.69 mAh from an original 2100 mAh
- Average Case – 44.32% loss or 930.38 mAh from an original 2100 mAh
- Worst Case – 49.58% loss or 1040.58 mAh from an original 2100 mAh

Figure 97 also shows these key outputs highlighted in the text previewing box when the "CS_String-Analysis.txt" data output file is selected. These CellSage™ simulation results have been proven to track very well with the actual cell capacity loss observed with the Panasonic UR18650 when tested by INL at the baseline reference conditions. These results from Example 2 will serve as a baseline for additional comparison and analysis with the data outputs from Example 3 that will be covered in the next section.

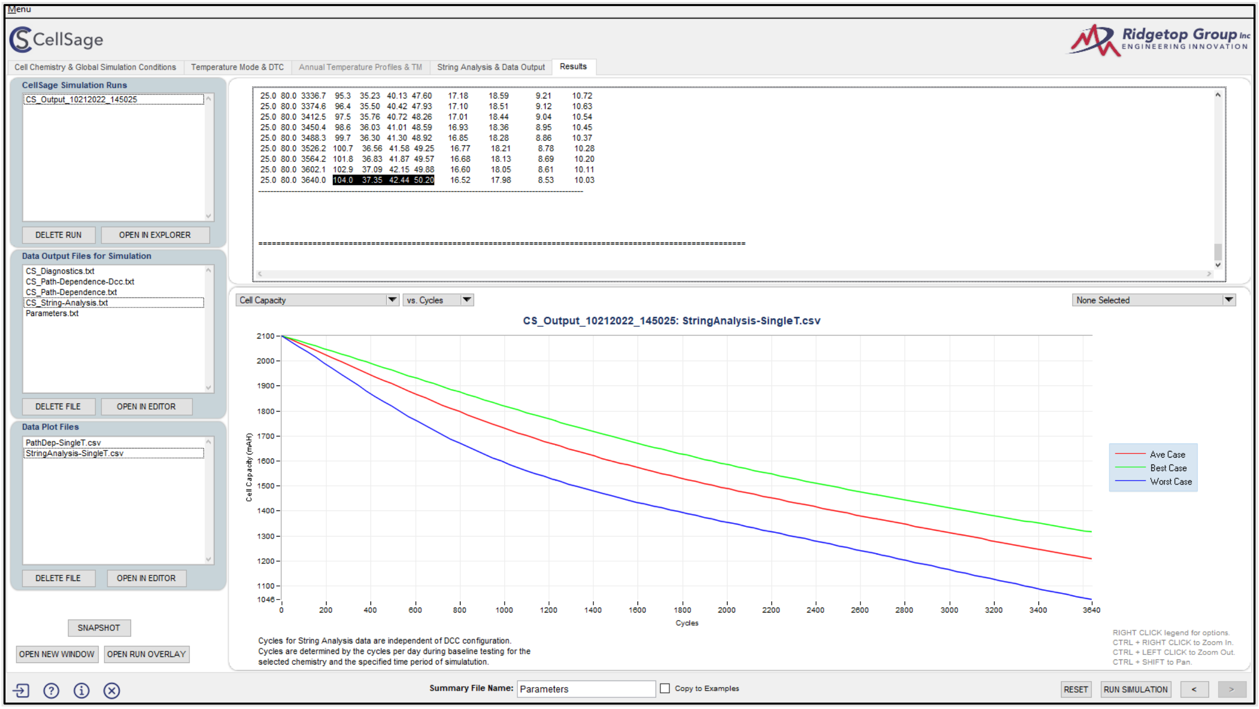



**Figure 97. Highlighted results from left to right include cycle count, weeks, and percentage of string capacity loss for Best Case, Average Case, and Worst Case scenarios.**

**IMPORTANT NOTE:** Referencing back to Section 3.1.1, the 3640 cycle count shown in the "CS_String-Analysis.txt" file (and Figure 96) was calculated using the 5 cycles per day reference condition during baseline testing.

## 5.3 Example 3: Running a Single T Simulation with DCC, with DTC, and no TM

This example will cover how a user can run a basic CellSage™ simulation for the NMC/graphite (Panasonic UR18650) cell chemistry. It should be noted that the CellSage™ GUI follows a linear programming flow where the user enters input conditions in sequential sections, and navigates through the tabs with the "Next" and "Previous" buttons in the lower right corner of the GUI. Each example shall start by opening the CellSage™ software application as shown in Step 1 of Section 2.3, or by opening the Windows Start Menu and searching for the CellSage™ software program. When the program is opened successfully, the user will be on the Cell Chemistry & Global Simulations Conditions tab.

For Example 3, we will run a CellSage™ Simulation that is similar to Example 2, except this time we will enable Detailed Cycling Conditions (DCC) and the effects of Daily Thermal Cycling (DTC). This example for the Panasonic UR 18650 chemistry allows the user to enter significantly more information as it relates to the duty cycle and exposes the full range of inputs for the Single T Temperature Mode.

### 5.3.1 Example 3: Cell Chemistry & Simulation Conditions Tab

Similar to the previous example, we setup Example 3 by importing the "Ex-3_Parameters.txt" file to prepopulate each of our simulation conditions. We then begin to verify that each of our input conditions are loaded into the GUI starting with the following list of parameters on the Cell Chemistry & Global Simulation Conditions tab as shown in Figure 98:

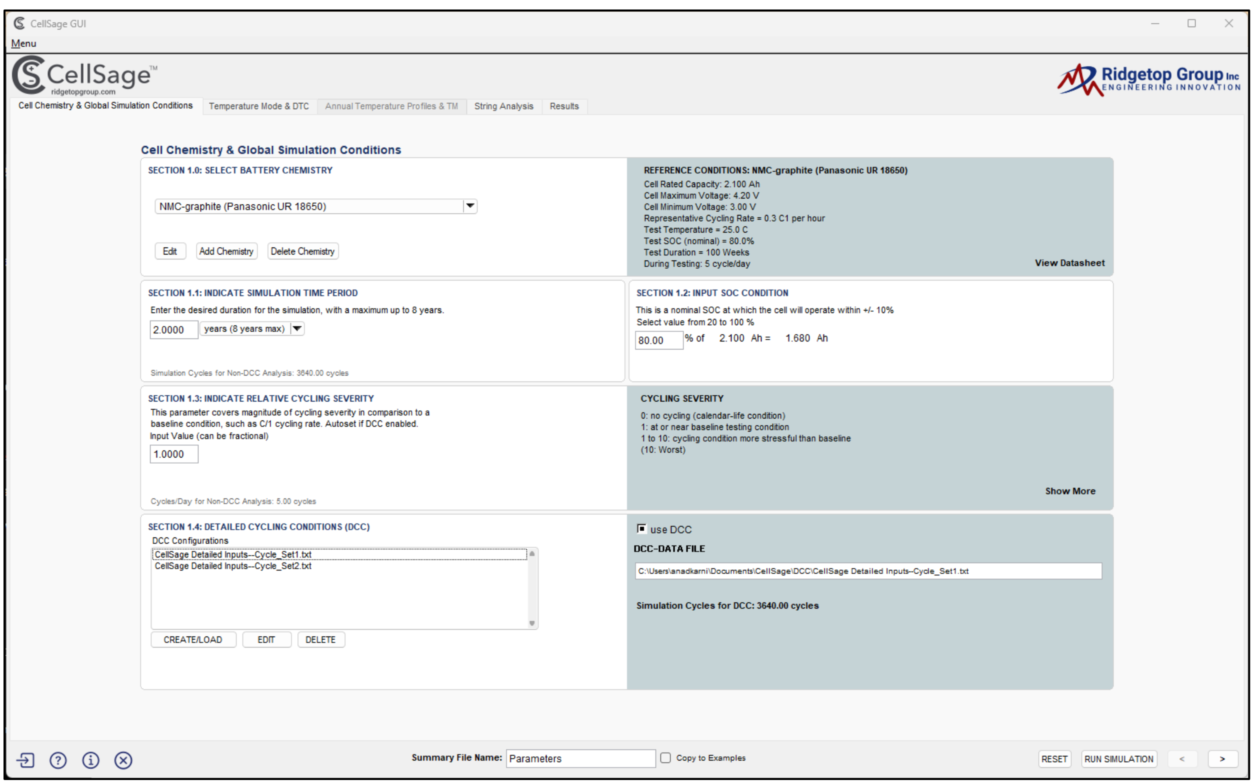



**Figure 98. Example 3, Cell Chemistry and Global Simulation Conditions tab.**

- **Section 1.0: Select Battery Chemistry** – This parameter was set to the NMC/graphite (Panasonic UR 18650) chemistry.
- **Section 1.1: Indicate Simulation Time Period** – This parameter was set to 2 years and equates to 3640.00 cycles for both the "CS_String_Analysis.txt" file, and the "CS_Path_Dependence-Dcc.txt" file.
- **Section 1.2: Input SoC Condition** – This parameter was set to 80%, which equates to 1.680 Ah of the total 2.1 Ah battery.
- **Section 1.3: Indicate Relative Cycling Severity** – This parameter was auto set to 1.00 to be at or near the baseline reference conditions which had 5 cycles per day.
- **Section 1.4: Detailed Cycling Conditions** – The DCC feature is now enabled in this example and the example selects the "CellSage™ Detailed Inputs—Cycles_Set1.txt" file as the DCC configuration input file. By selecting the EDIT button, we can see the specific inputs for this file as shown in Figure 99. The DCC input conditions that are specified in this example describe a battery use case / mission with the following key attributes:
    - Input Mode – Set to 1 to specify the charge and discharge rates as a C-Rate basis. Option 2 allows the user to specify the rates as a Current Basis.
    - Duty Cycle has 5 cycles per day with 5 charge steps per cycle, 5 charge rest steps per cycle, 3 discharge steps per cycle, and 3 discharge rest steps per cycle.
    - Discharge Mode is set to 1 for Constant Current.
    - Discharge Power Target is set to 40 Watts.
    - Cells in Series String is set to 5 cells (5S1P).
    - Days Per Week the system is on Cyc-Life is set to 7 days.
    - Days per Week the system is on Cal-Life is set to 0 days.
    - Cell Voltage at Cal-Life is set to 3.0 Volts.

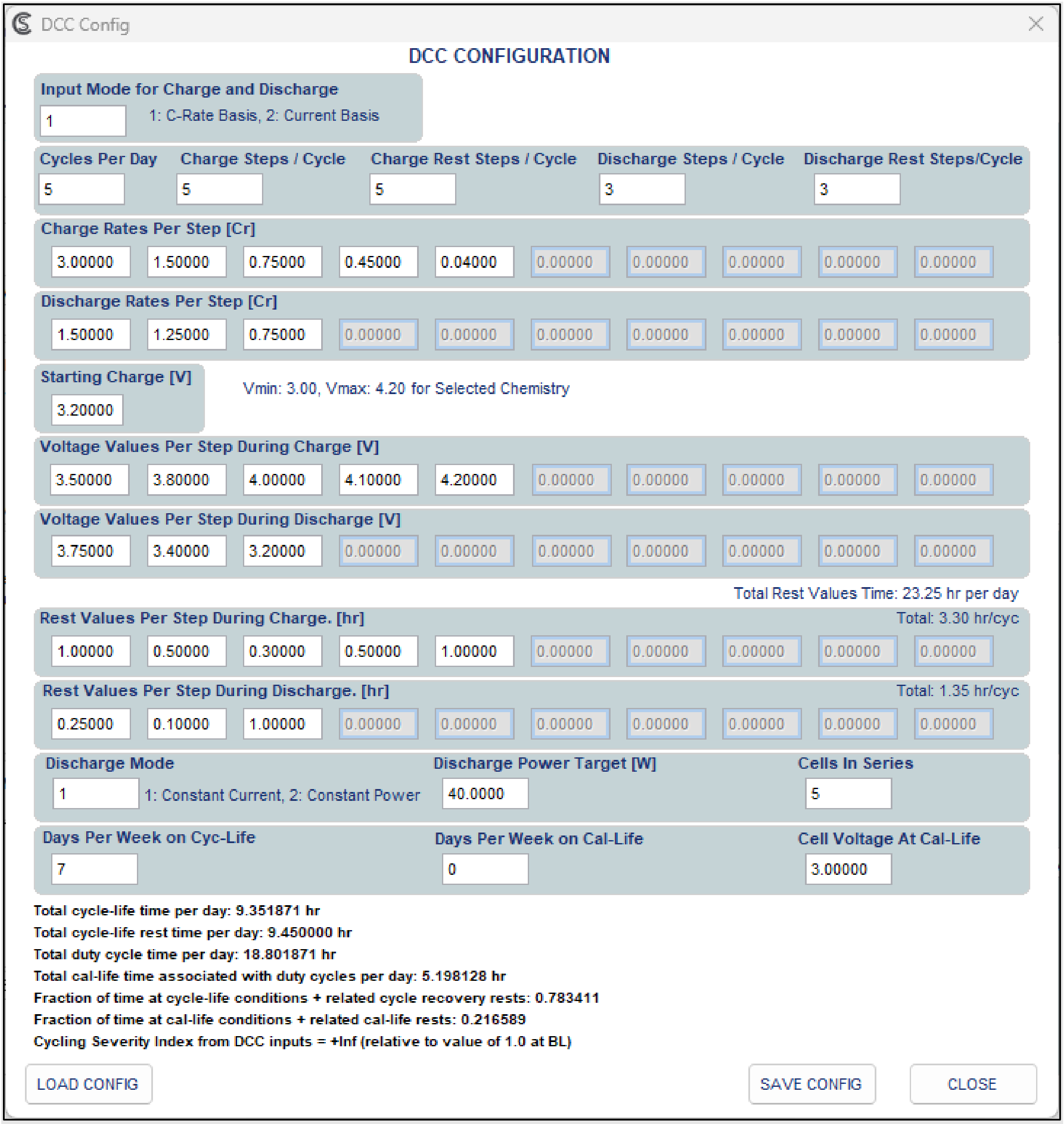



**Figure 99. View of DCC Configuration user form for Example 3.**

### 5.3.2 Example 3: Temperature Mode and Daily Thermal Cycling Conditions Tab

Moving on to Tab 2, we will now verify that the following simulation conditions have been pre-loaded as specified in our EX-2_Parameters.txt file and shown in Figure 100:

- **Section 2.0: Temperature Mode** – This parameter is set to 2.1: Single Representative of Bulk Cell.
- **Section 2.1.1: Input Temperature Value** – This parameter is set to 25 °C to represent ambient room temperature in a laboratory operating environment.
- **Section 2.1.2: Input Thermal Cycle at Temperature** – This parameter is set to 5 °C to reflect the delta-T the cell may experience when warming up to the operating temperature of 30 °C. Because this input condition is no longer zero, we can also specify DTC input parameters for Section 3.0.
- **Section 3.1: Time for DTC Temp (in Minutes):** This parameter is set to 20 minutes to represent the time it takes for the system to ramp up to operating temperature.
- **Section 3.2: DTC Occurrences:** This parameter is set to multiple DTC cycles per day as specified in the DCC Config file.
- **Section 3.3: Input Time battery is at Tmax during a single duty cycle:** This parameter is set to 2 hours to reflect the time the battery is at the max operating temperature.

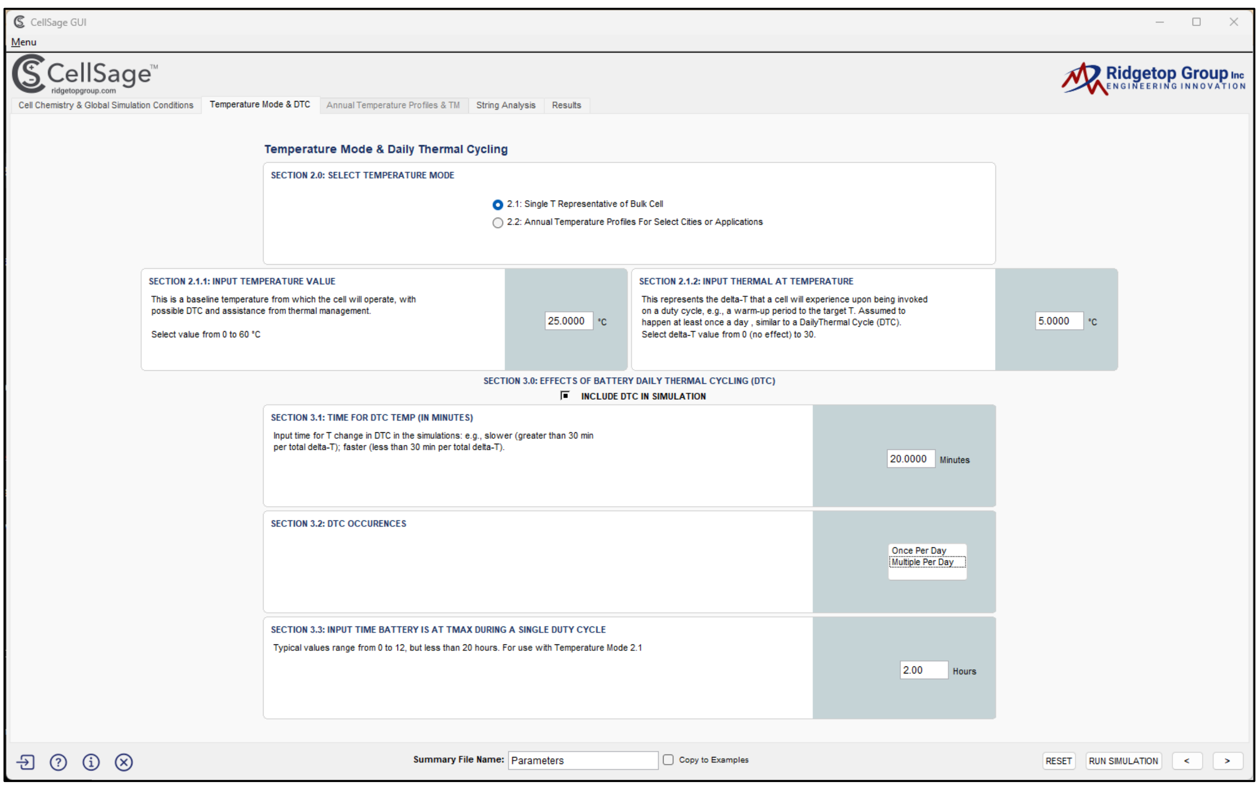



**Figure 100. Example 3, Temperature mode and Daily Thermal Cycling tab.**

### 5.3.3 Example 3: Annual Temperature Profiles and Thermal Management Conditions Tab

As previously demonstrated in Example 2 this tab is disabled as the simulation used a temperature mode that is set to 2.1: Single T Representative of Bulk Cell.

### 5.3.4 Example 3: String Analysis Tab

Next, we will move on to the String Analysis Tab where we will use the same input parameters and data output directory as Example 2. A visual of these inputs is shown in Figure 101. We will then click the Run Simulation button to execute the simulation, and proceed to the Results tab.

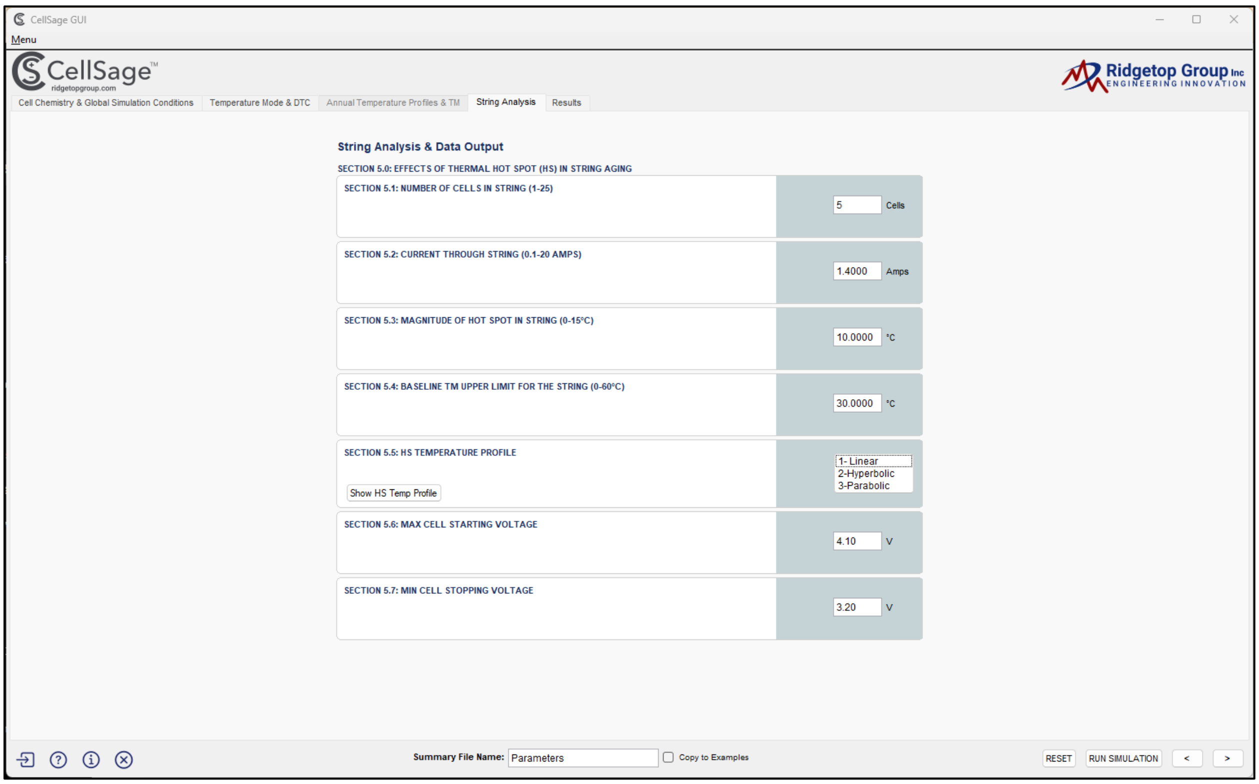



**Figure 101. Example 3, String Analysis tab.**

### 5.3.5 Example 3: Results Tab

After pressing the OK button and completing the Example 3 simulation, we can now move to the Results tab where we will see an additional simulation run added to the list of output folders as shown in Figure 102. We will also see that there is an additional data plot file that was generated from the CS_Path-Dependence-DCC.txt file. Previously in Example 2 we only generated data plots based on the CS_Path-Dependence.txt and CS_String-Analysis.txt data outputs files. For this example, we now have additional data plots as a result of enabling Detailed Cycling Conditions (DCC) for this simulation, and they are outlined and previewed in this section.

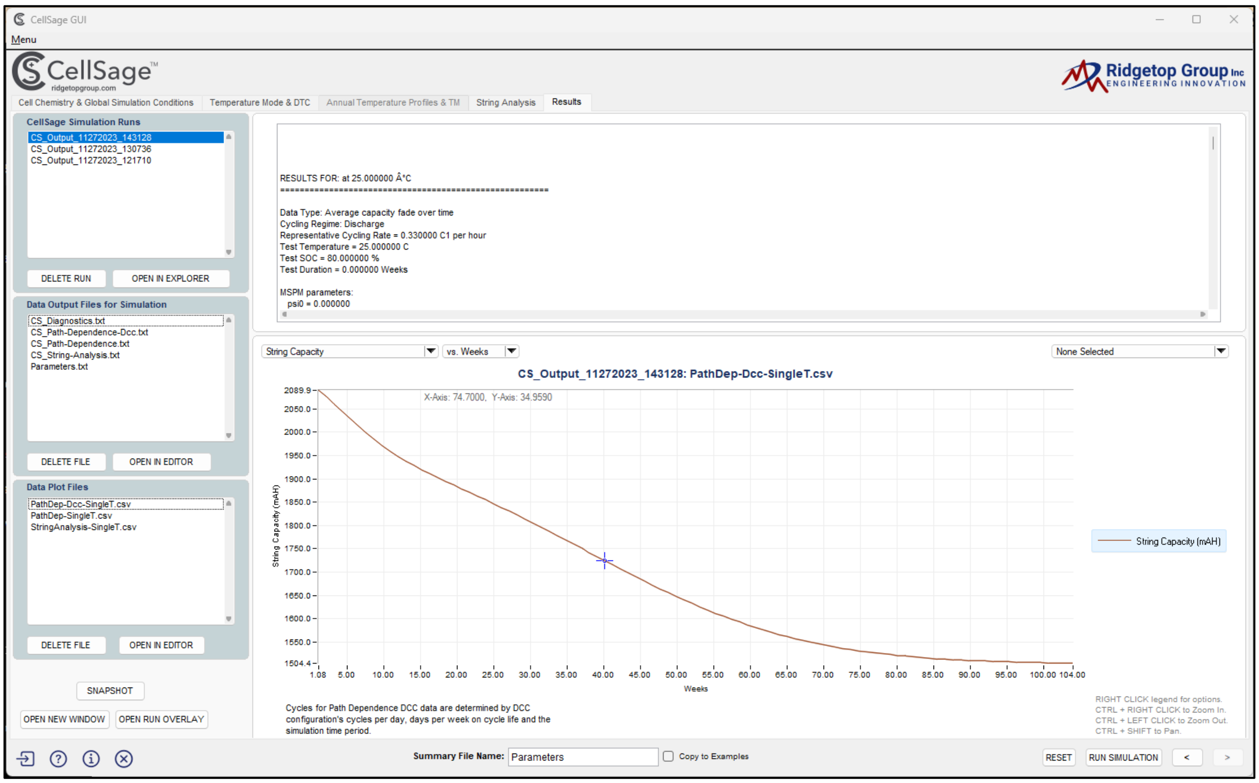



**Figure 102. Example 3, Results tab.**

**List of plots for PathDep-Dcc-SingleT.csv (Figure 103 - Figure 112):**

- String Capacity vs. Weeks or Cycles
- State of Health vs. Weeks or Cycles
- Fraction Capacity Loss vs. Weeks or Cycles
- Total AH through String vs. Weeks or Cycles
- Ohmic Resistance vs. Weeks or Cycles
- Net Ohmic Heat vs. Weeks or Cycles
- Fraction of Effective Discharge Power vs. Weeks or Cycles
- Temperature vs. Weeks or Cycles
- Fraction of Achievable Duty Cycle vs. Weeks or Cycles
- Baseline vs Simulated Loss vs. Weeks or Cycles

**List of plots for PathDep-SingleT.csv (shown in Figure 113 - Figure 118):**

- Estimated Cell Capacity Loss vs. Weeks or Cycles
- State of Health vs. Weeks or Cycles
- Reference/Baseline (BL) vs. Weeks or Cycles
- At User Inputs (i*) vs. Weeks or Cycles
- Ratios (i*/BL) vs. Weeks or Cycles
- Temperature vs. Weeks or Cycles

**List of plots for StringAnalysis-SingleT.csv (shown in Figure 119 - Figure 123):**

- Cell Capacity vs. Weeks or Cycles
- State of Health vs. Weeks or Cycles
- String Capacity Loss vs. Weeks or Cycles
- Power vs. Weeks or Cycles
- Temperature vs. Weeks or Cycles

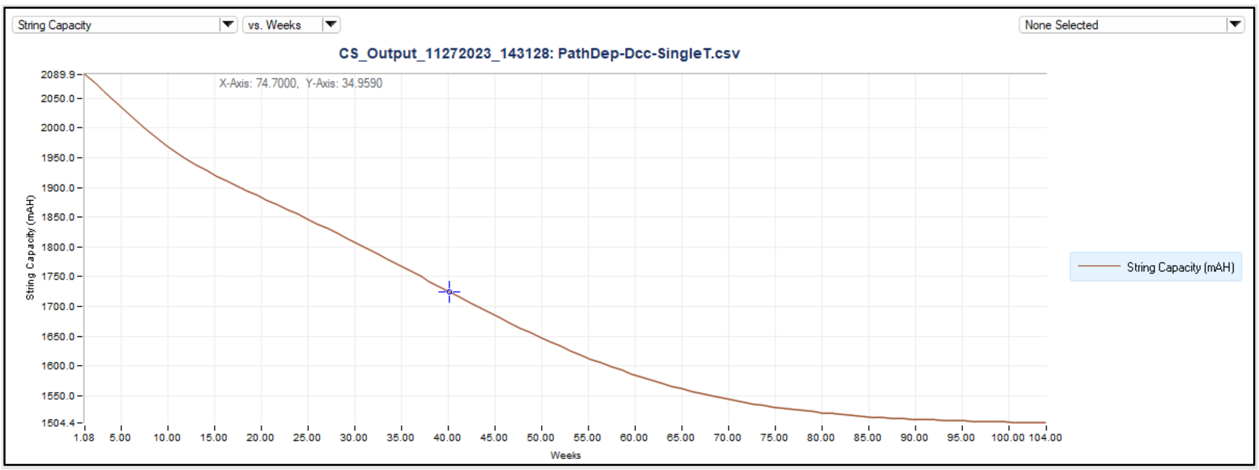



**Figure 103. Example 3, String Capacity vs. Weeks.**

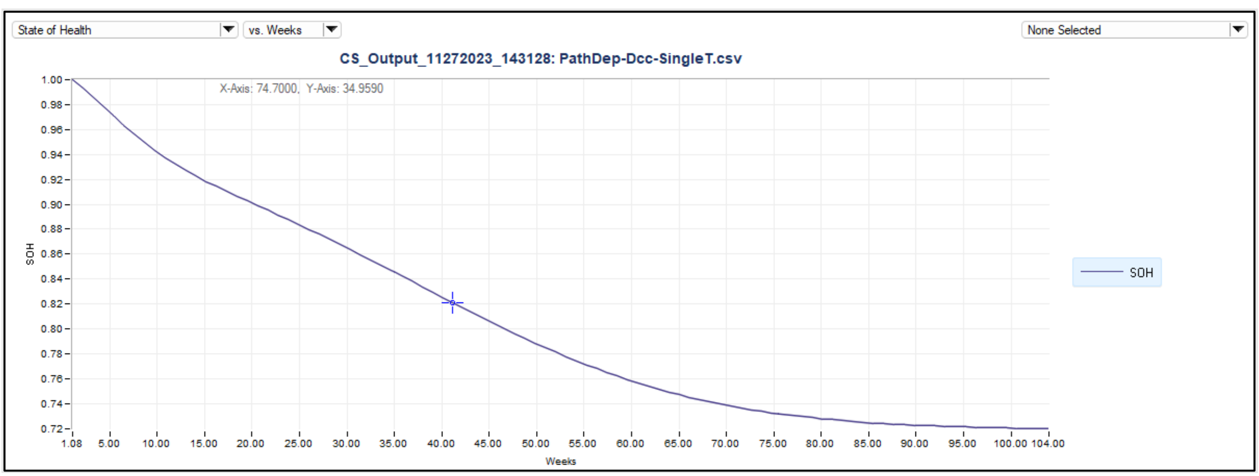



**Figure 104. Example 3, State of Health vs. Weeks.**

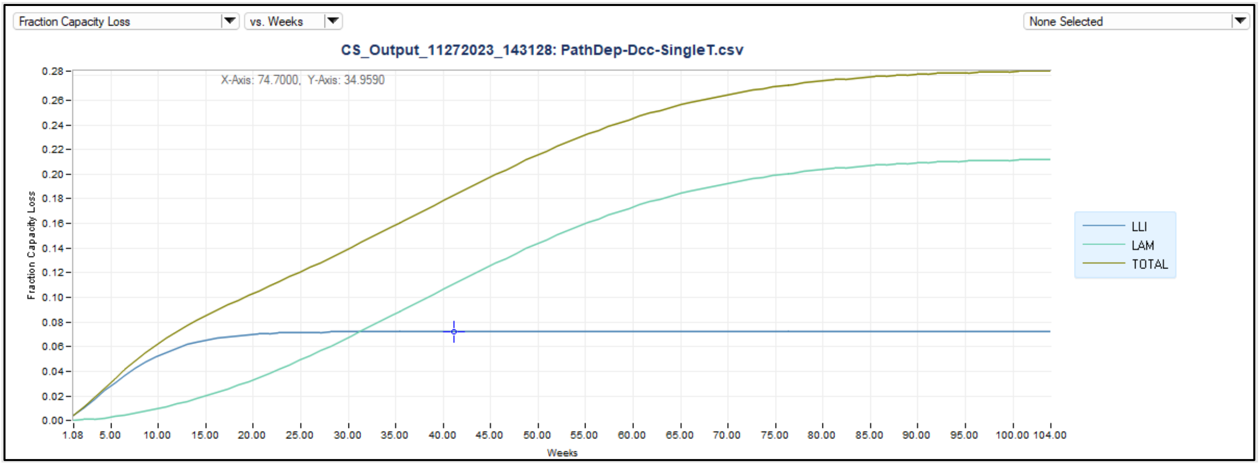



**Figure 105. Example 3, Fraction Capacity Loss vs. Weeks.**

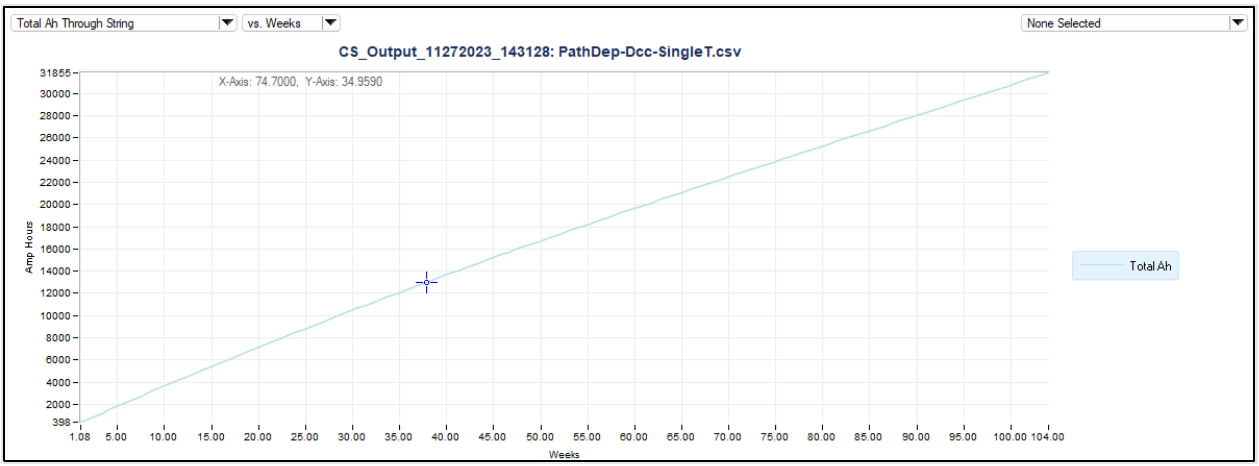



**Figure 106. Example 3, Total AH through String vs. Weeks.**

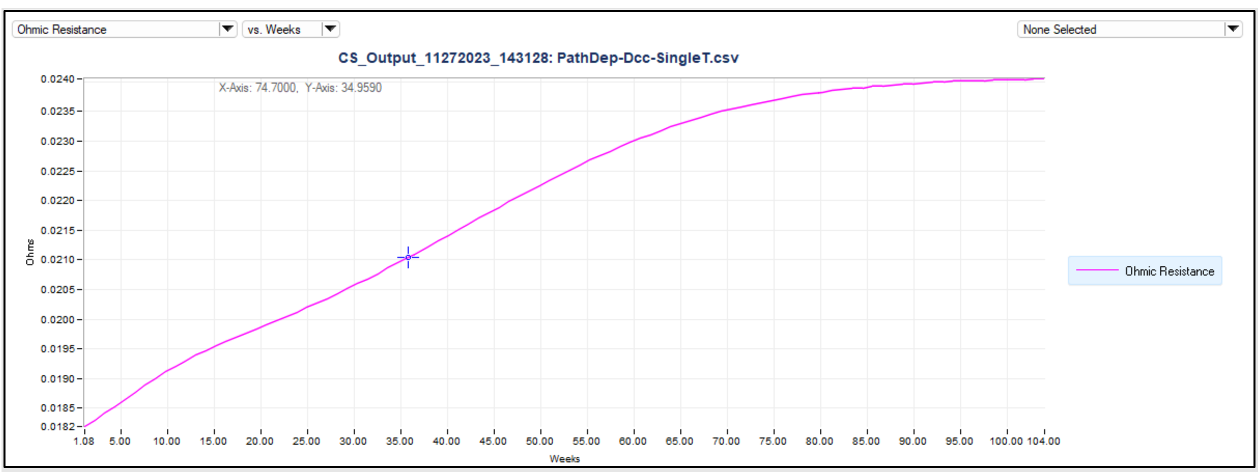



**Figure 107. Example 3, Ohmic Resistance vs. Weeks.**

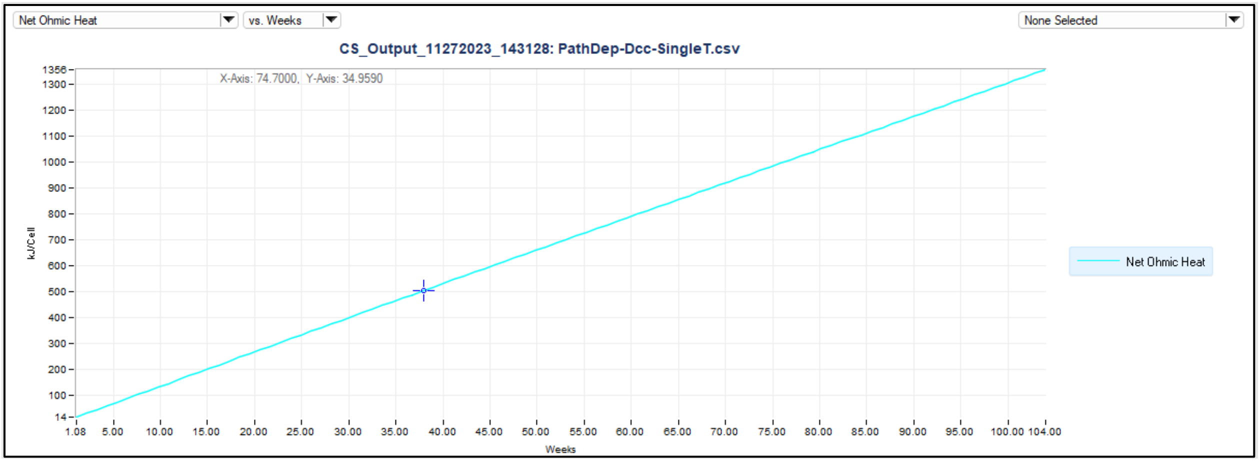



Figure 108. Example 3, Net Ohmic Heat vs. Weeks.

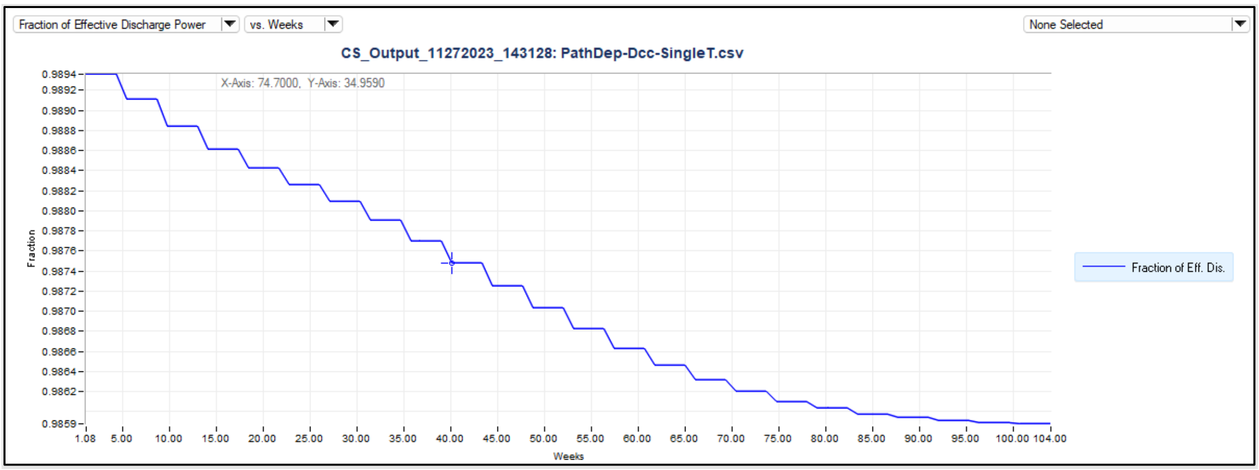



Figure 109. Example 3, Fraction of Effective Discharge Power vs Weeks.

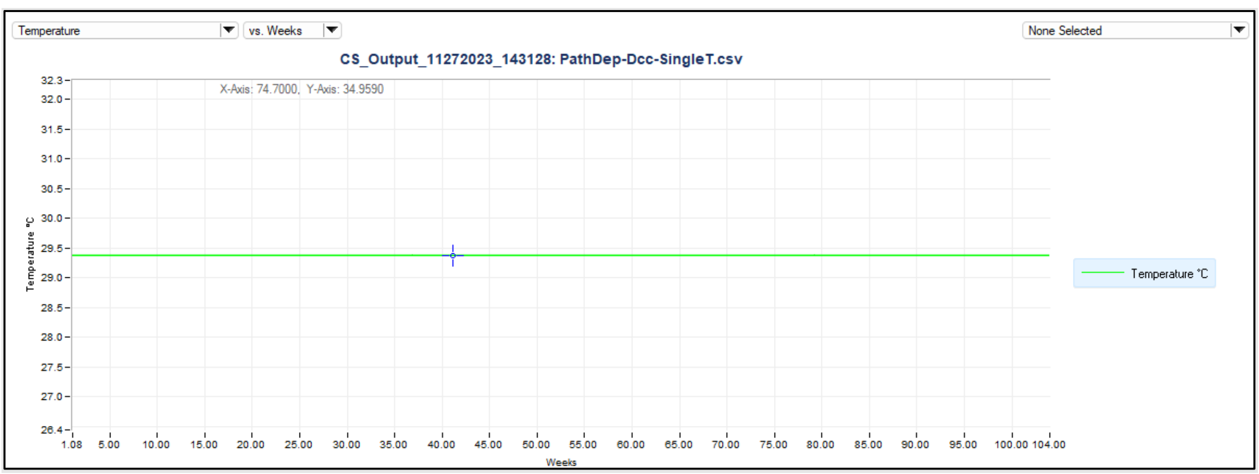



Figure 110. Example 3, Temperature vs. Weeks.

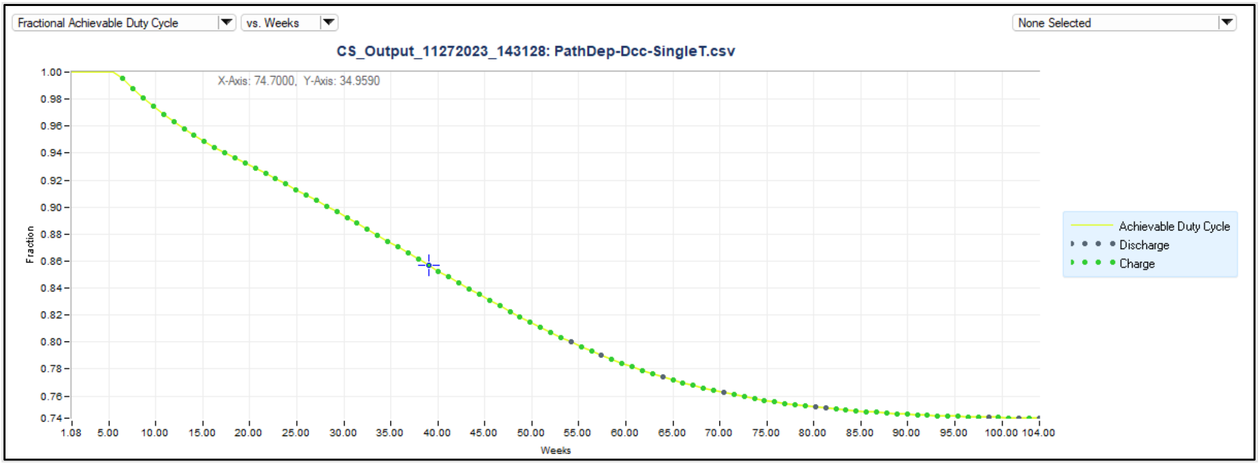



**Figure 111. Example 3, Fraction of Achievable Duty Cycle vs. Weeks.**

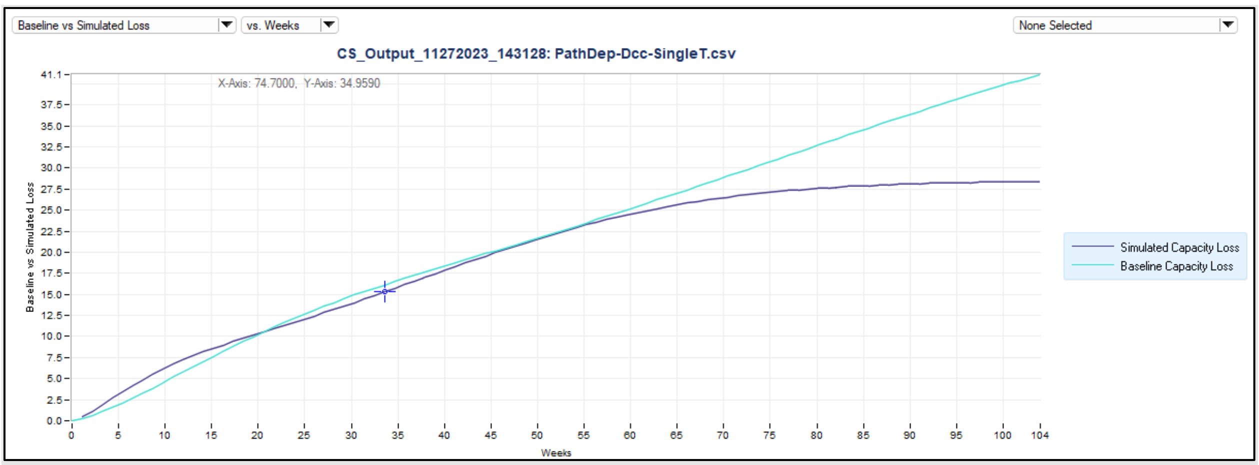



**Figure 112. Example 3, Baseline vs Simulated Loss vs. Weeks.**

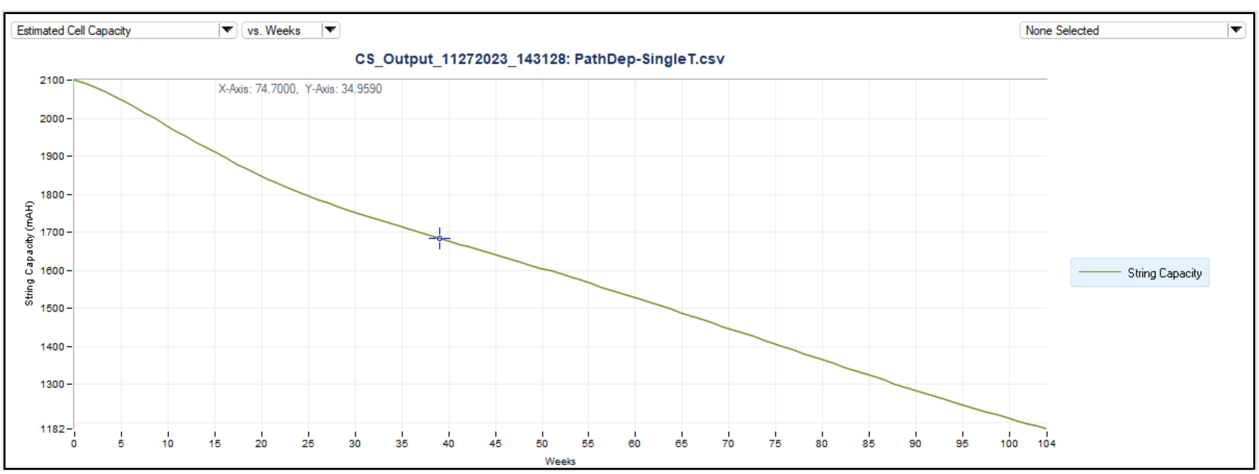



**Figure 113. Example 3, Estimated Cell Capacity vs. Weeks.**

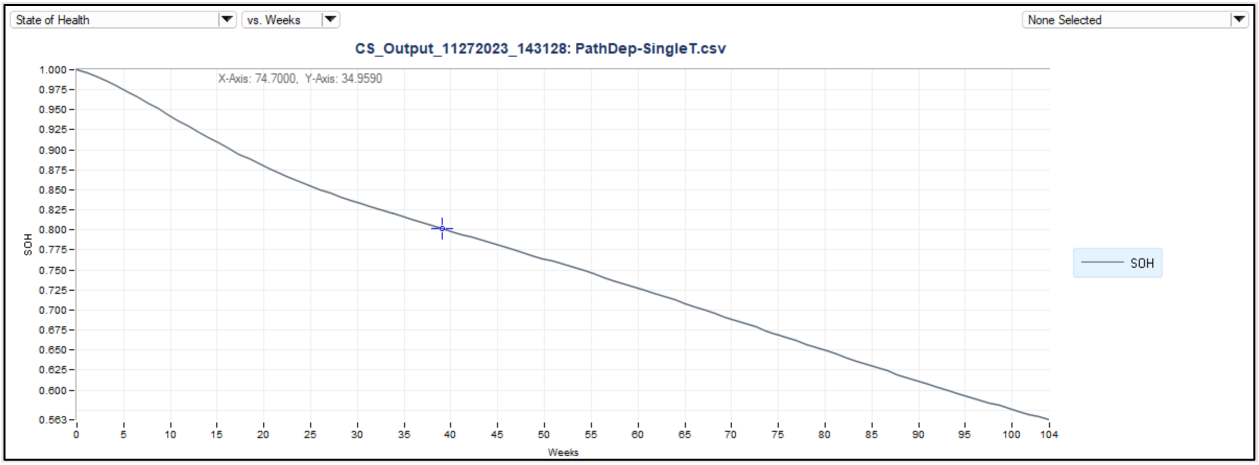



**Figure 114. Example 3, State of Health vs. Weeks.**

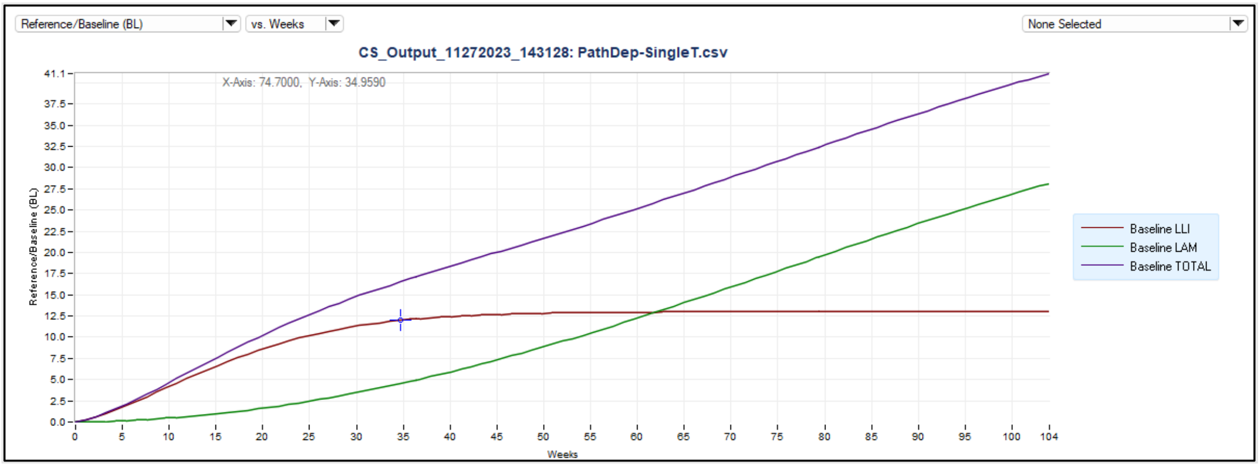



**Figure 115. Example 3, Reference/Baseline (BL) vs. Weeks.**

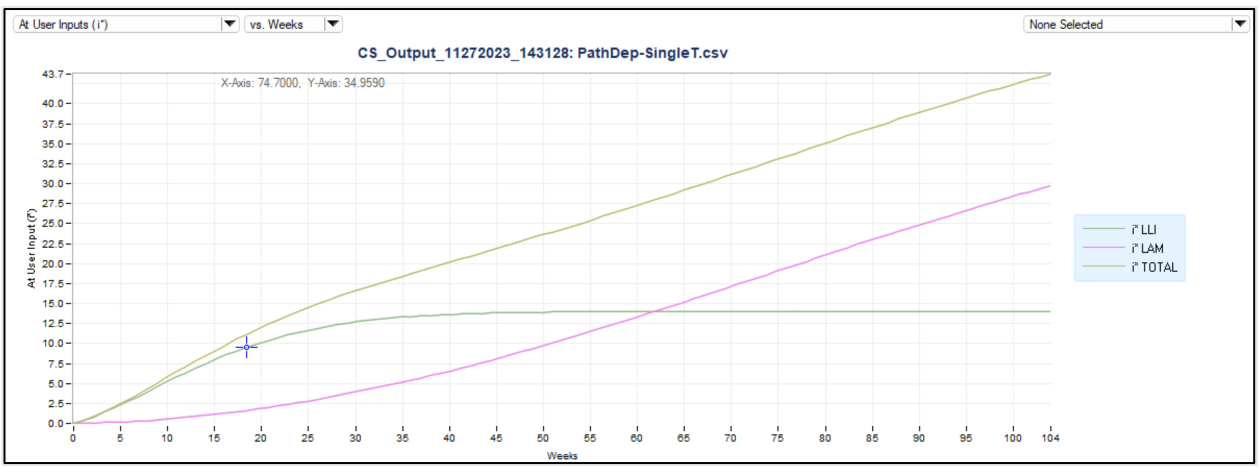



**Figure 116. Example 3, At User Inputs (i*) vs. Weeks.**

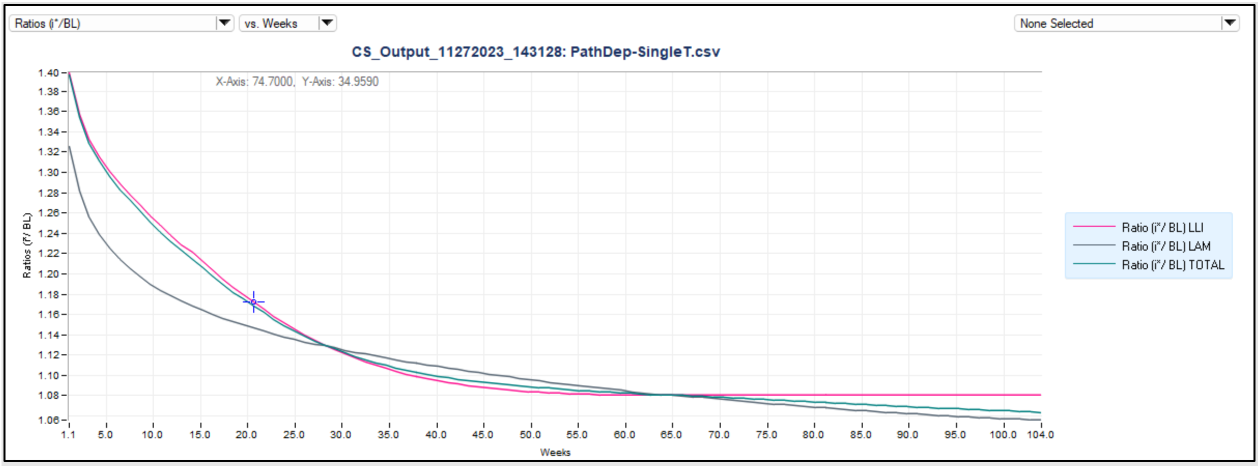



**Figure 117. Example 3, Ratios (i*/BL) vs. Weeks.**

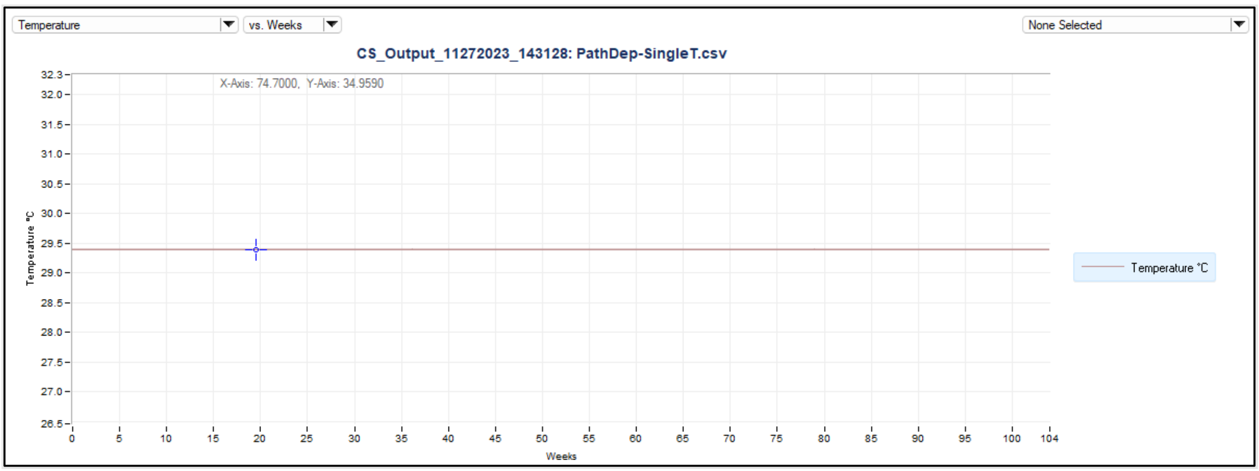



**Figure 118. Example 3, Temperature vs. Weeks.**

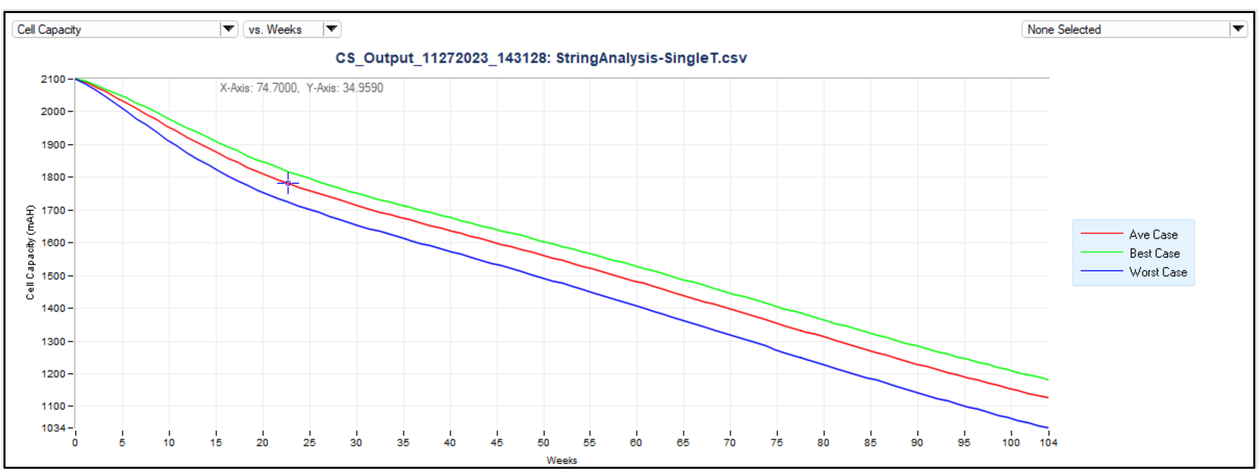



**Figure 119. Example 3, Cell Capacity vs. Weeks.**

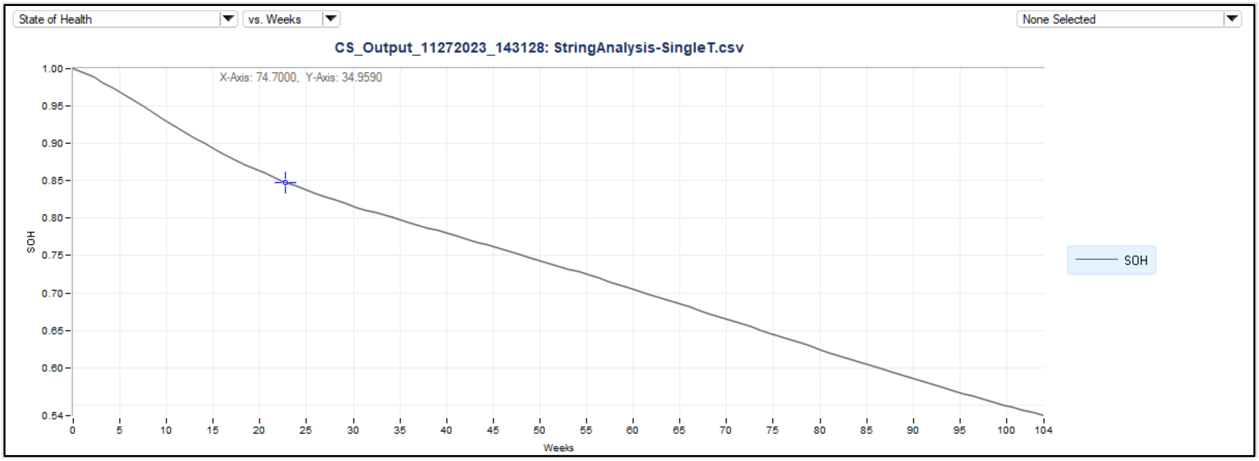



**Figure 120. Example 3, State of Health vs. Weeks.**

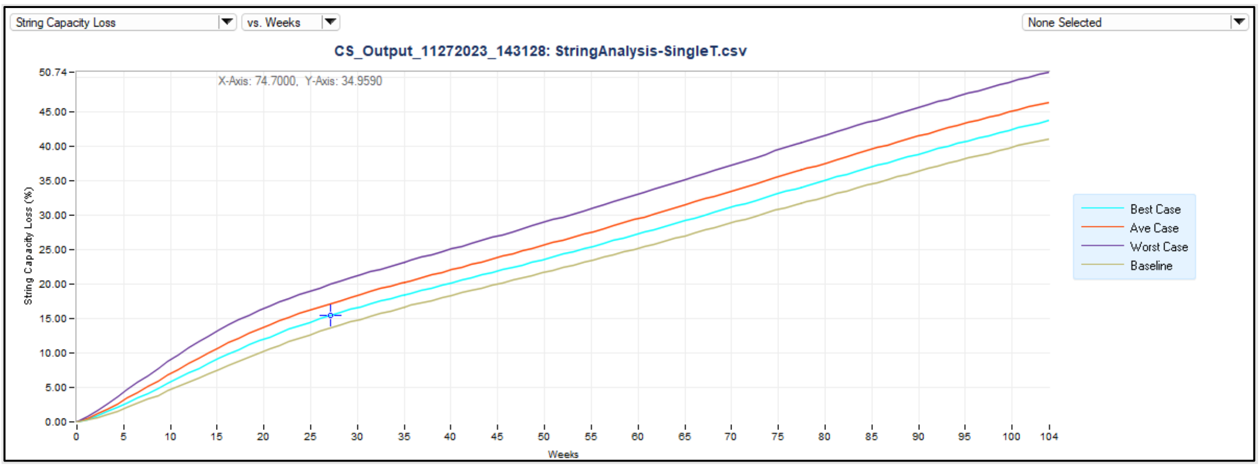



**Figure 121. Example 3, String Capacity Loss vs. Weeks.**

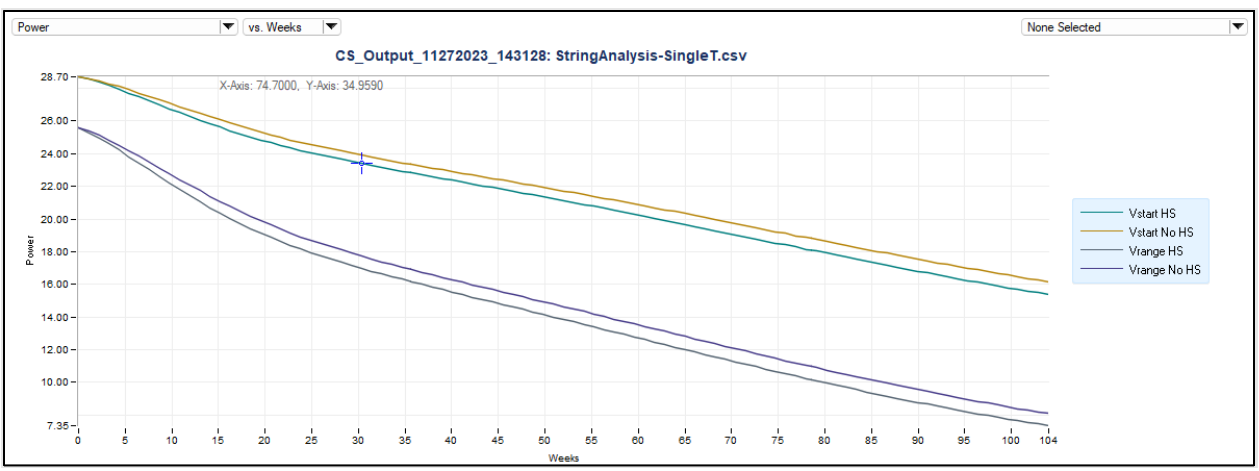



**Figure 122. Example 3, Power vs. Weeks.**

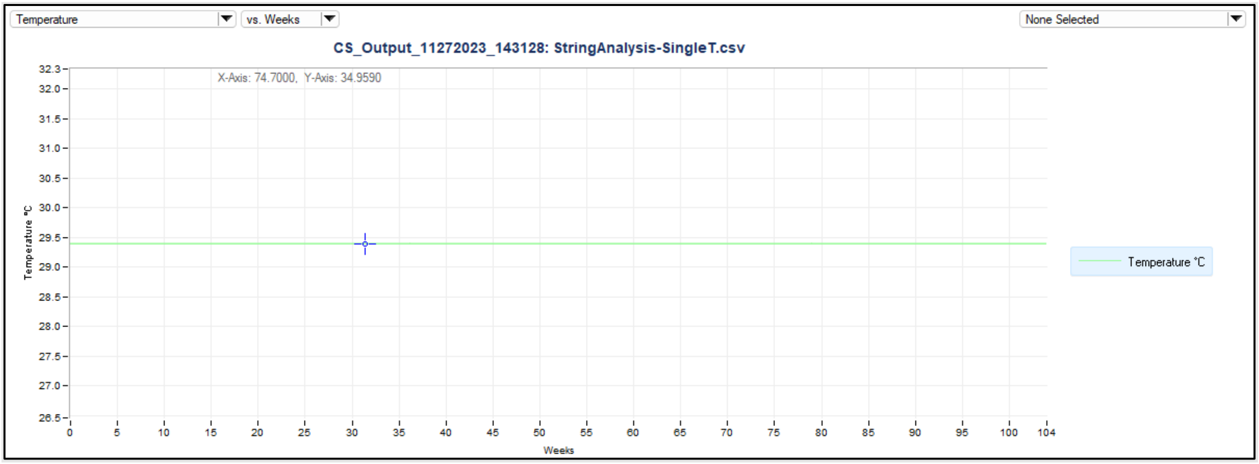



**Figure 123. Example 3, Temperature vs. Weeks.**

### 5.3.6 Example 3: Discussion

Congratulations on completing your third CellSage™ simulation example! As one may notice, this second simulation example provided access to many more input conditions that allowed us to specify a more detailed battery use case with our DCC configuration file. This example also allowed us to generate more data plots of interest to battery engineers and researchers. To continue our discussion from Example 2, we notice that the percentage of Cell Capacity Loss increased in Example 3 as detailed below:

- Best Case – 43.70% or 918.57 mAh, where as in Example 2 it was 41.09% loss or 861.69 mAh.
- Average Case – 46.42% or 974.82 mAh, where as in Example 2 it was 44.32% loss or 930.38 mAh.
- Worst Case – 50.74% or 1066.74 mAh, where as in Example 2 it was 49.58% loss or 1040.58 mAh.

The increased percentage of capacity loss can be attributed to many factors such as the DCC Configuration input parameters, the Input Thermal Cycle, as well as the DTC parameters. To visualize these changes on the same plot, the user can click the OPEN RUN OVERLAY button to select matching plot types from different simulations to easily compare the results. Two examples of this are shown in Figure 124 and Figure 125. Additional CellSage™ simulations can also be performed to compare slight changes in the available parameters, and hopefully help end users determine logical combinations that yield the best simulation results.

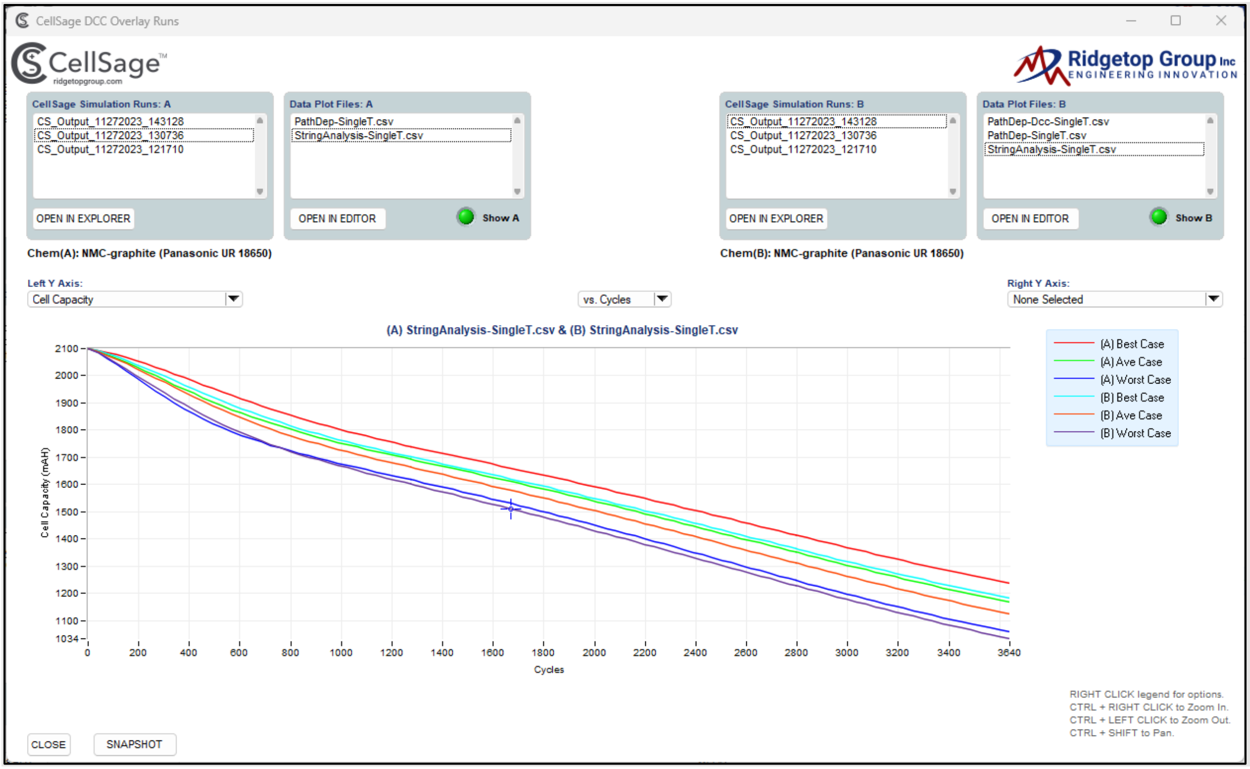



**Figure 124. Overlay view of Cell Capacity vs. Cycles from “StringAnalysis-SingleT.csv” for Example 2 and Example 3.**

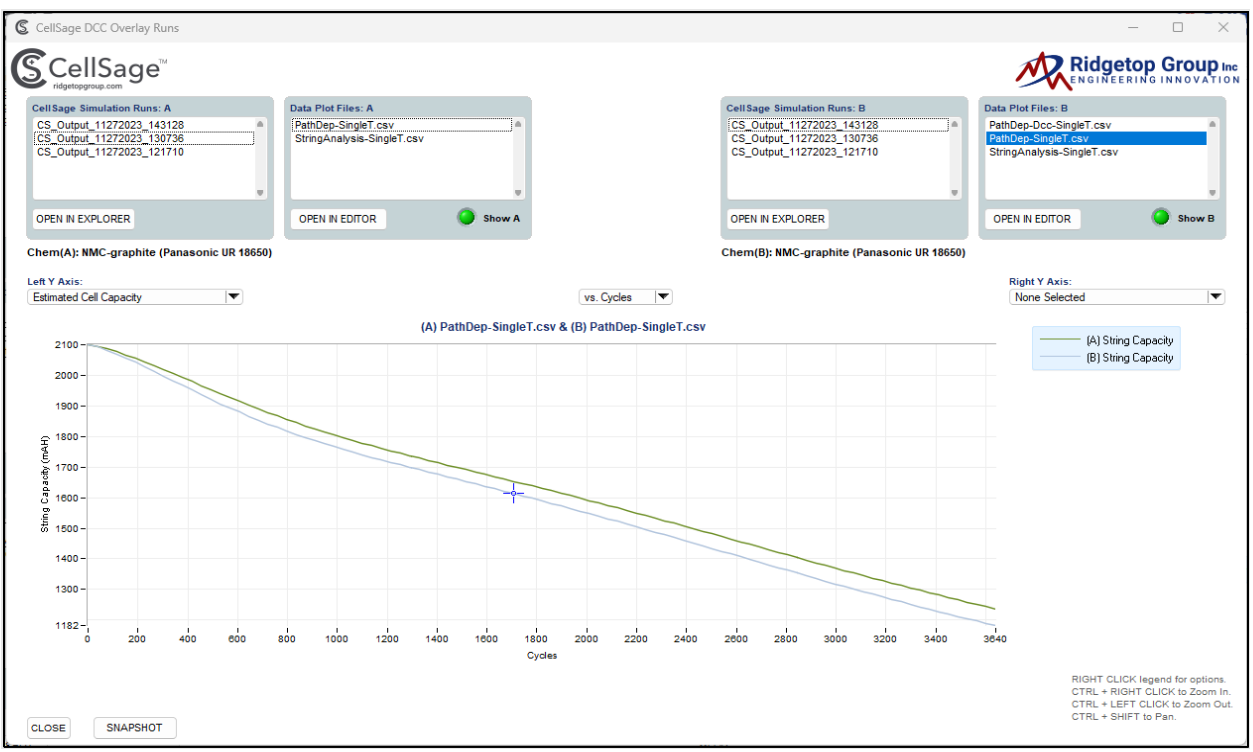



**Figure 125. Overlay view of Estimated Cell Capacity vs. Cycles from “PathDep-SingleT.csv” for Example 2 and Example 3.**

For additional comparison with Example 5, we shall study our String Capacity vs. Cycles data output which is shown in Figure 126. This plot shows the estimated loss of capacity for the entire string of 5 cells that we specified in the DCC config file. As referenced in Section 3.1.1, the DCC config file that impacts the "CS_Path-Dependence-Dcc.txt" data output file is independent of the "CS_String-Analysis.txt" data output file that utilizes the user defined string conditions from GUI Tab 4. With this information, in mind we can calculate the estimated Path Dependence string capacity loss to be 29.38%, or 593.04 mAh, during the 2 year / 104 weeks simulation period.

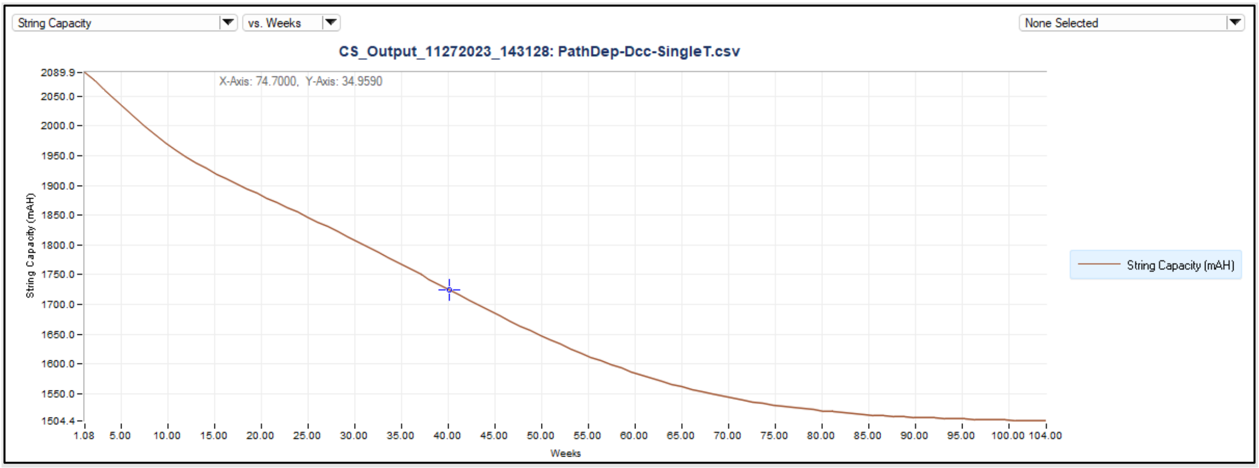



**Figure 126. Example 3, String Capacity vs. weeks for DCC.**

## 5.4 Example 4: Running a Multi-city Simulation with no DCC, no DTC, and no TM

This example will cover how a user can run a basic CellSage™ simulation for the NMC/graphite (Panasonic UR18650) cell chemistry. It should be noted that the CellSage™ GUI follows a linear programming flow where the user enters input conditions in sequential sections, and navigates through the tabs with the "Next" and "Previous" buttons in the lower right corner of the GUI. Each example shall start by opening the CellSage™ software application as shown in Step 1 of Section 2.3, or by opening the Windows Start Menu and searching for the CellSage™ software program. When the program is opened successfully, the user will be on the Cell Chemistry & Global Simulations Conditions tab.

For Example 4, we will run a CellSage™ Simulation that is similar to Example 2, except this time we use Temperature Mode 2.2: Annual Temperature Profiles for Select Cities or Applications. We will then use the import function to automatically select annual temperature profiles for Juneau AK, Tucson, AZ, and Idaho Falls ID. This example simulation will also use the common Panasonic UR 18650 chemistry that is found in consumer electronics, and the results provided in this example as well as Example 5 will be very useful for seeing how this chemistry performs with respect to different geographic regions.

### 5.4.1 Example 4: Cell Chemistry & Simulation Conditions Tab

To start off Example 4, we will use the import feature to load the "EX-3_Parameters.txt" file into our simulation as previously done in Examples 1-2. We will then begin to verify that each of our input conditions are preloaded into the GUI starting with the following list of parameters on the Cell Chemistry & Global Simulation Conditions tab that is shown in Figure 127:

- **Section 1.0: Select Battery Chemistry** – This parameter was set to the NMC/graphite (Panasonic UR 18650) chemistry.
- **Section 1.1: Indicate Simulation Time Period** – This parameter was set to 2 years (104 weeks), and equates to 3640.0 cycles based on 5 cycles per day for the NMC/graphite (Panasonic UR 18650) chemistry.
- **Section 1.2: Input SoC Condition** – This parameter was set to 80%, which equates to 1.680 Ah of the total 2.1 Ah battery.
- **Section 1.3: Indicate Relative Cycling Severity** – This parameter was set to 1.0 which is at or near the baseline testing conditions.
- **Section 1.4: Detailed Cycling Conditions** – The DCC feature is not enabled in this example.

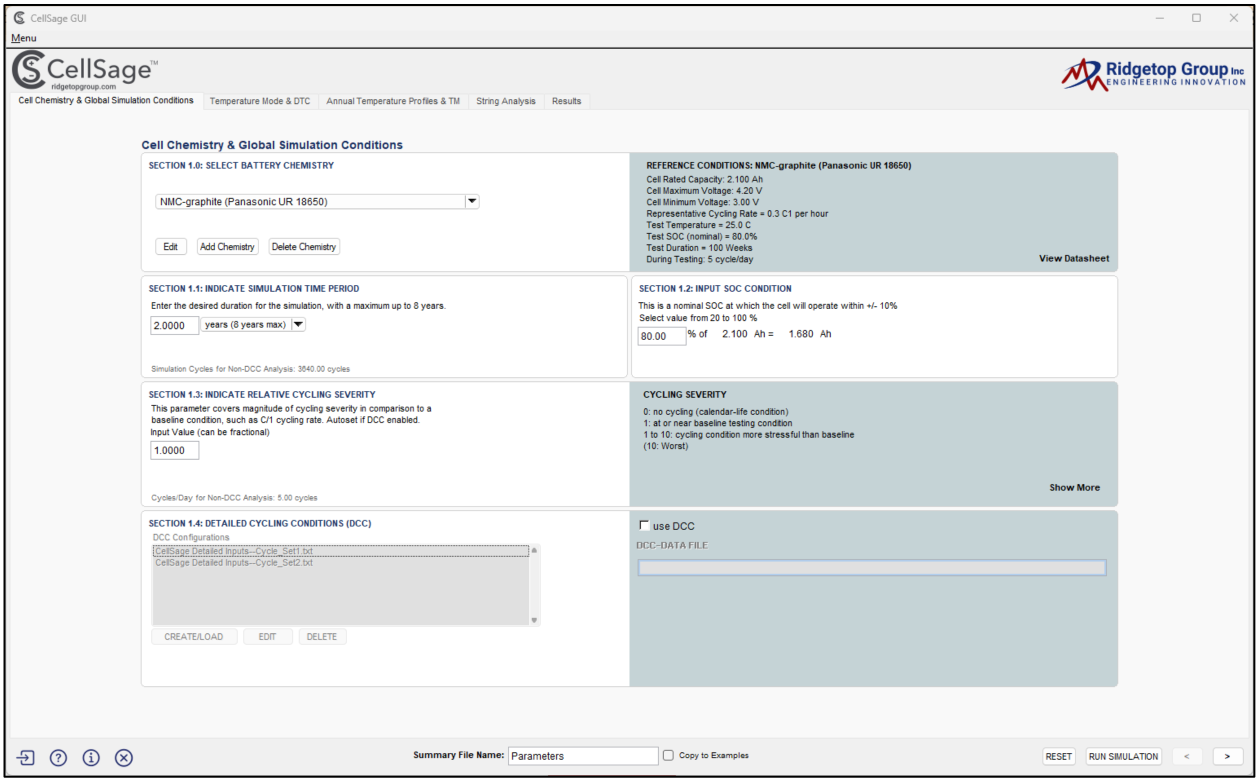



**Figure 127. Example 4, Cell Chemistry & Global Simulation Conditions tab.**

## 5.4.2 Example 4: Temperature Mode and Daily Thermal Cycling Conditions Tab

Next, we move on to the Temperature Mode and DTC tab for Example 4. Given that this example is a multi-city simulation with no DTC, we will verify that the Temperature Mode is set to 2.2: Annual Temperature Profiles for Select Cities or Applications and that the Section 3.0 checkbox is not checked as shown in Figure 128.

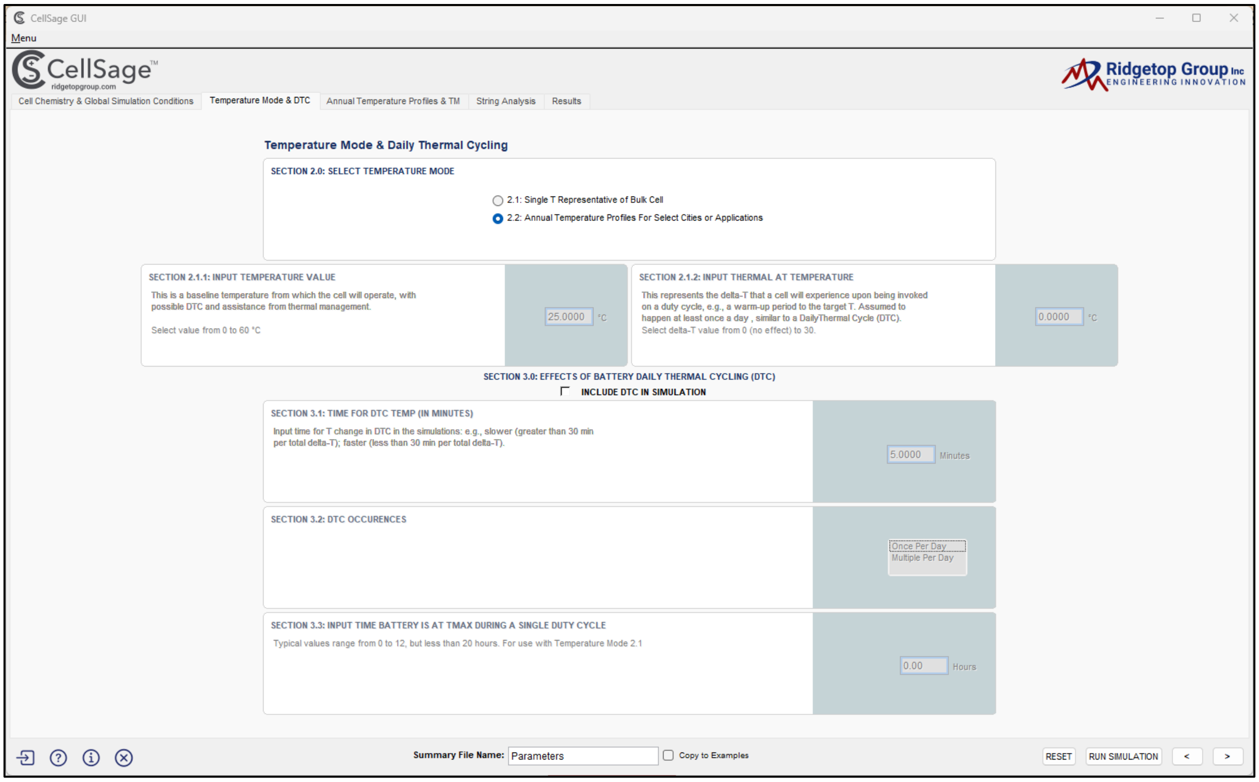



**Figure 128. Example 4, Temperature Mode & DTC tab.**

### 5.4.3 Example 4: Annual Temperature Profiles and Thermal Management Conditions Tab

Moving on to the third tab, we verify that the import function added the selected temperature profiles for Juneau AK, Tucson AZ, and Idaho Falls ID as shown in Figure 129. We also verify that the Thermal Management check box is disabled, as that feature will be covered in Example 5.

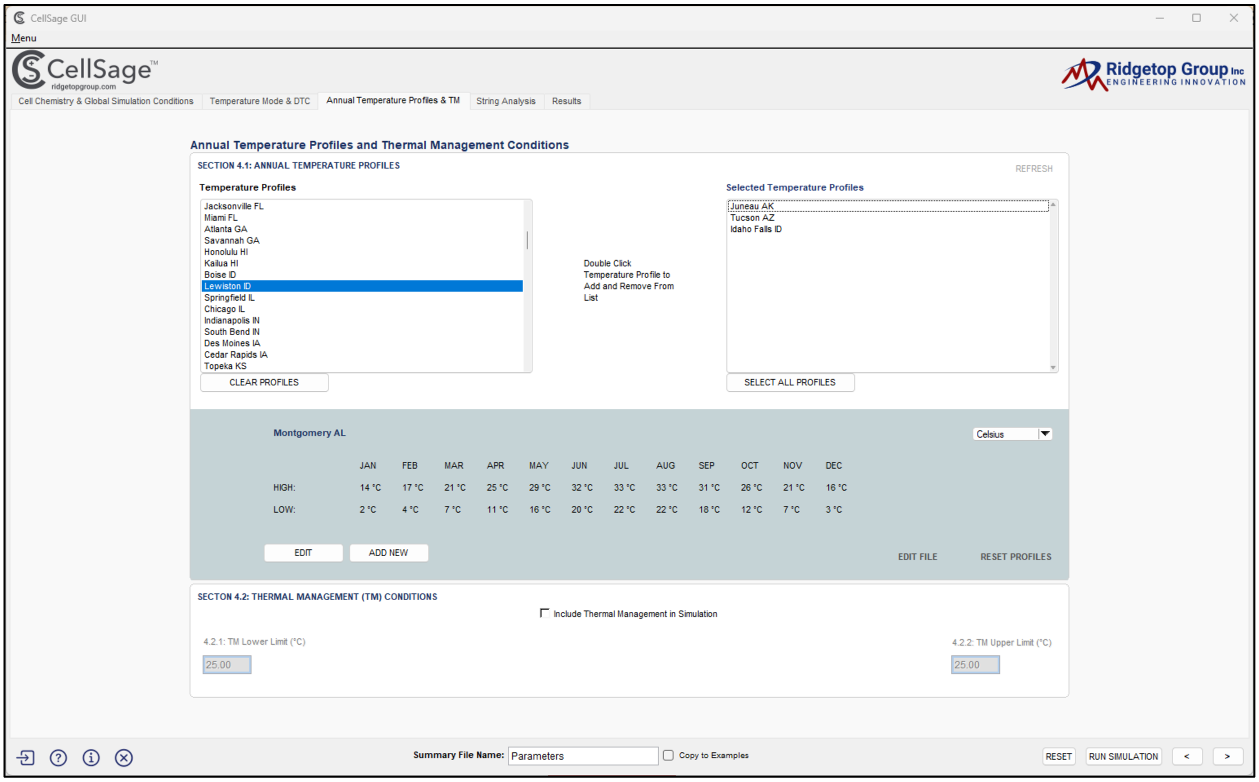



**Figure 129. Example 4, Annual Temperature Profiles and Thermal Management Conditions tab.**

### 5.4.4 Example 4: String Analysis Tab

Next, we will move on to the String Analysis tab where we will use the same input parameters and data output directory as Examples 1-3. A visual of these inputs is shown in Figure 130. We will then click the Run Simulation button to execute the simulation, and proceed to the Results tab.

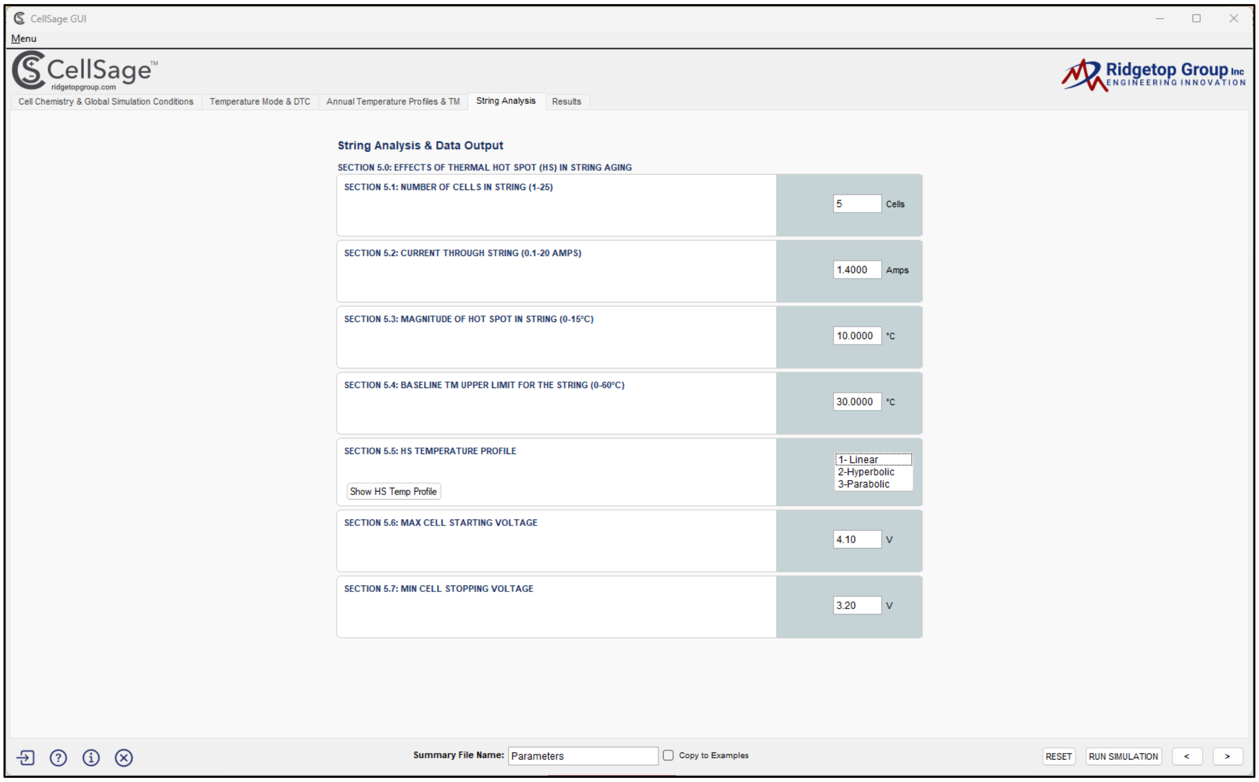



**Figure 130. Example 4, String Analysis tab.**

### 5.4.5 Example 4: Results Tab

In the Results tab we see our standard data output files, as well as three individual *.csv files for each of the selected cities as shown in Figure 13194. As previously noted, these *.csv files were generated from the different data output files, and are used to create the list of automatic outlined in Section 3.1.5. This section will not provide a visual for all generated data plots in this example, but we will cover the Estimated Cell Capacity vs. Weeks plots from the "PathDep-*Temperature-ID*.csv" file, as well as the Cell Capacity vs. Weeks plot from the "StringAnalysis-*Temperature-ID*.csv" file. The rationale for this, is because these plot types are the primary simulation results that are being analyzed in the discussion sections of each example. Both plot types for all three cities are shown in Figure 132 - Figure 137.

It should also be noted that the data outputs for the x-axis in the plots starts in January and proceeds through each sequential month for the two-year / 104-week simulation.

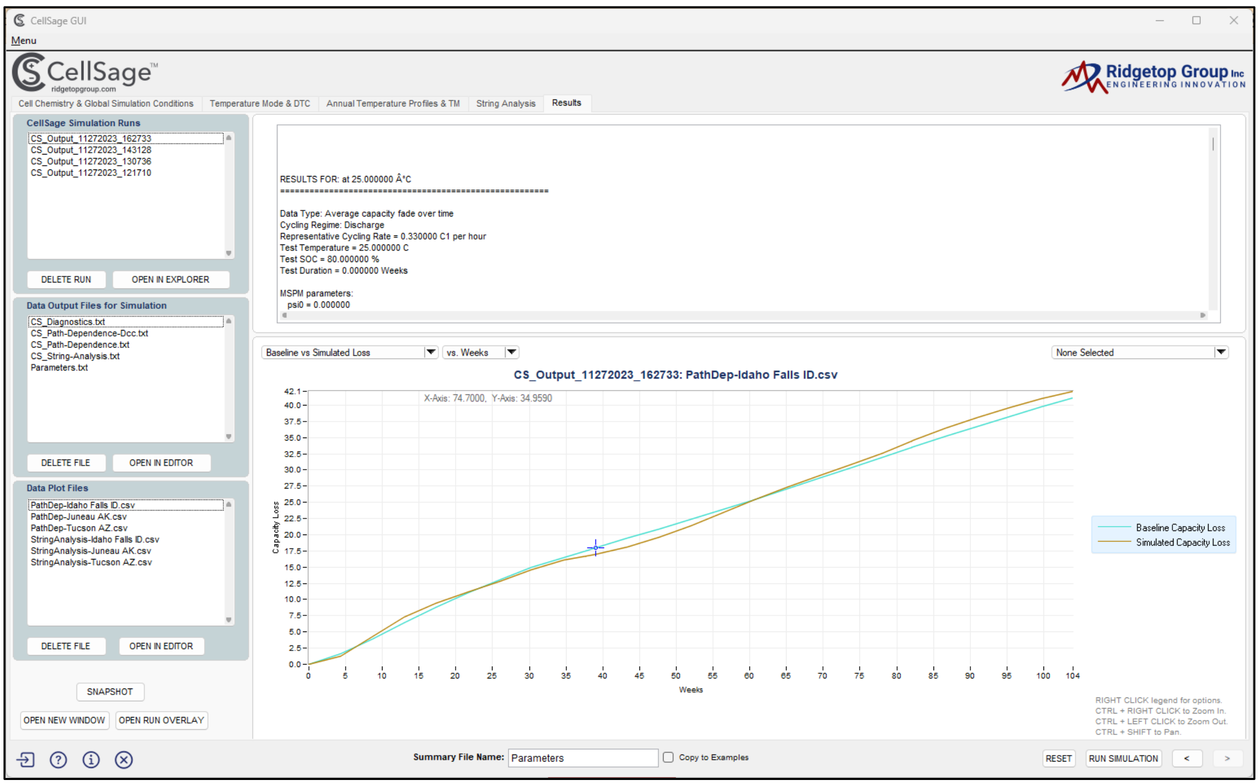



**Figure 131. Example 4, Results tab.**

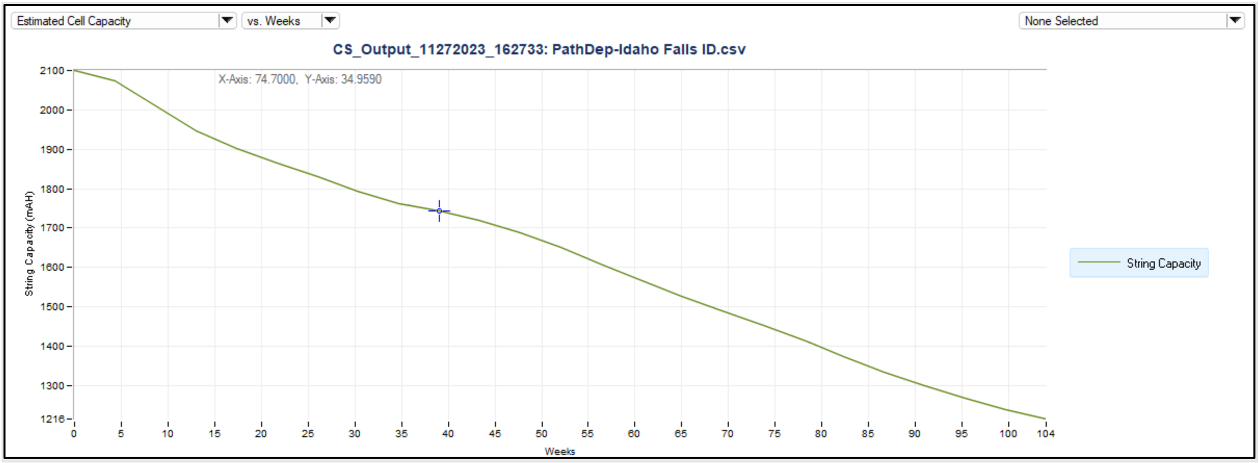



**Figure 132. Example 4, Estimated Cell Capacity vs. Weeks for Idaho Falls, ID (based on the "CS_Path-Dependence.txt" data output file).**

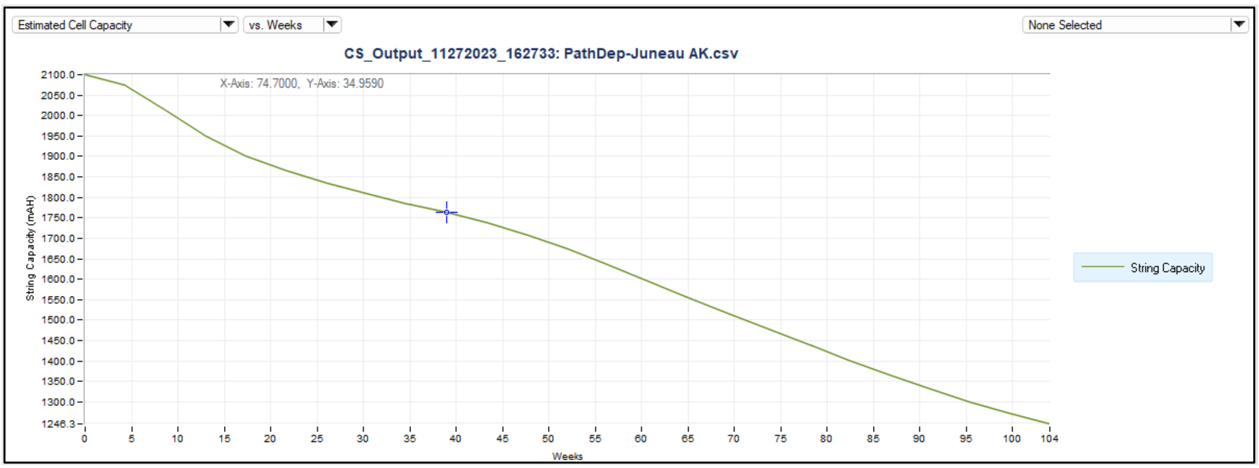



**Figure 133. Example 4, Estimated Cell Capacity vs. Weeks for Juneau, AK (based on the "CS_Path-Dependence.txt" data output file).**

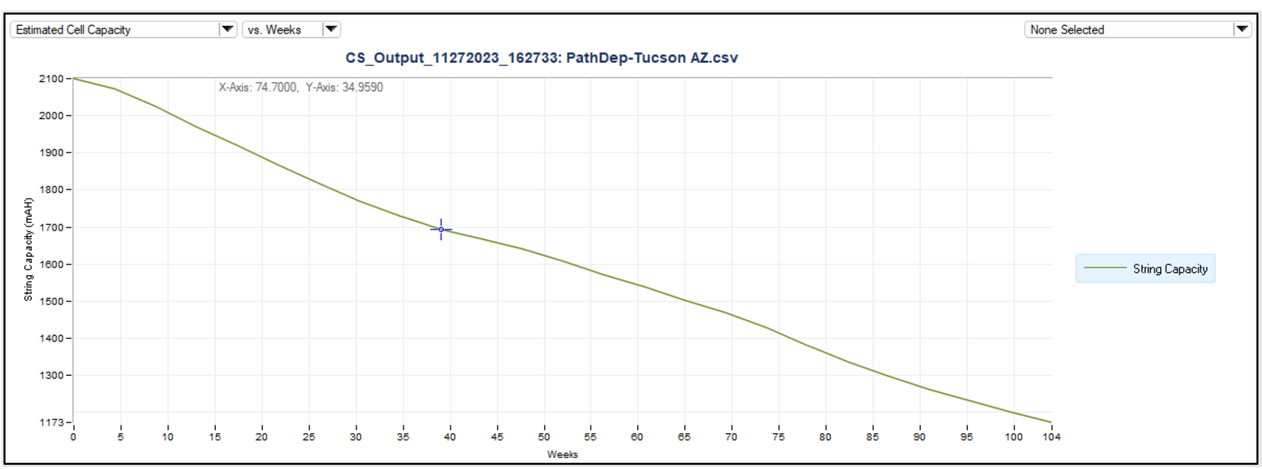



**Figure 134. Example 4, Estimated Cell Capacity vs. Weeks for Tucson, AZ (based on the "CS_Path-Dependence.txt" data output file).**

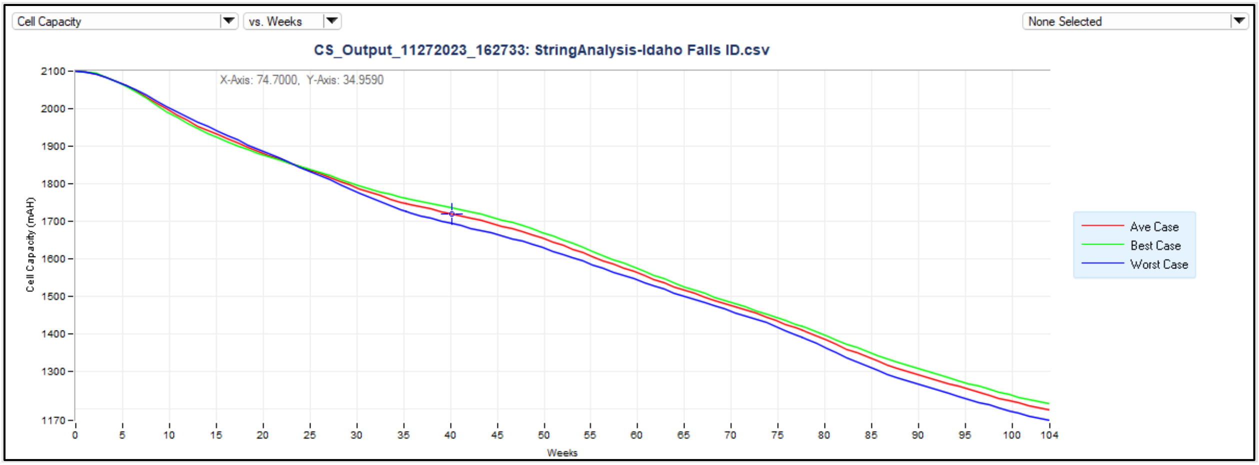



**Figure 135. Example 4, Cell Capacity vs. Weeks for Idaho Falls, ID (based on the "CS_String-Analysis.txt" data output file).**

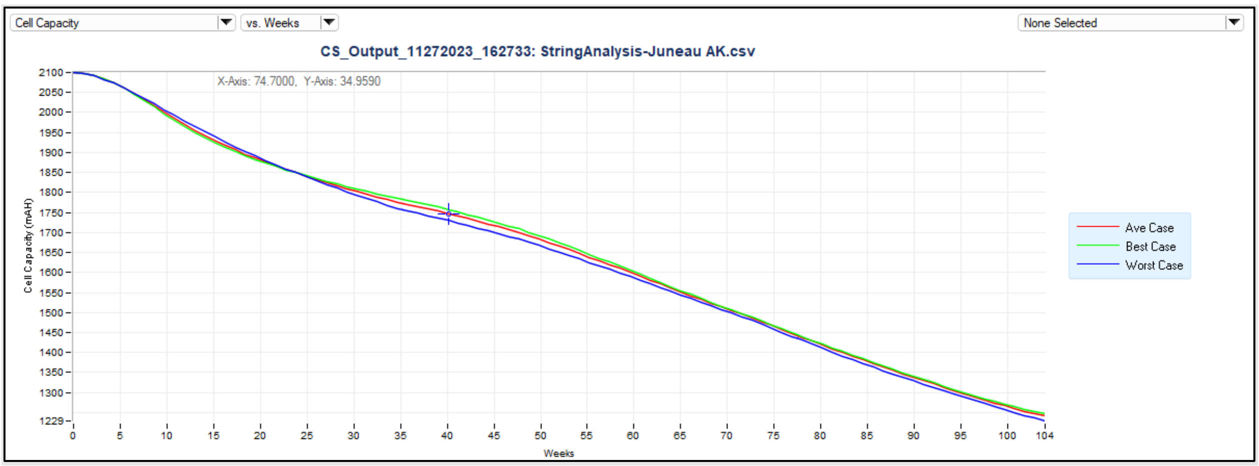



**Figure 136. Example 4, Cell Capacity vs. Weeks for Juneau, AK (based on the "CS_String-Analysis.txt" data output file).**

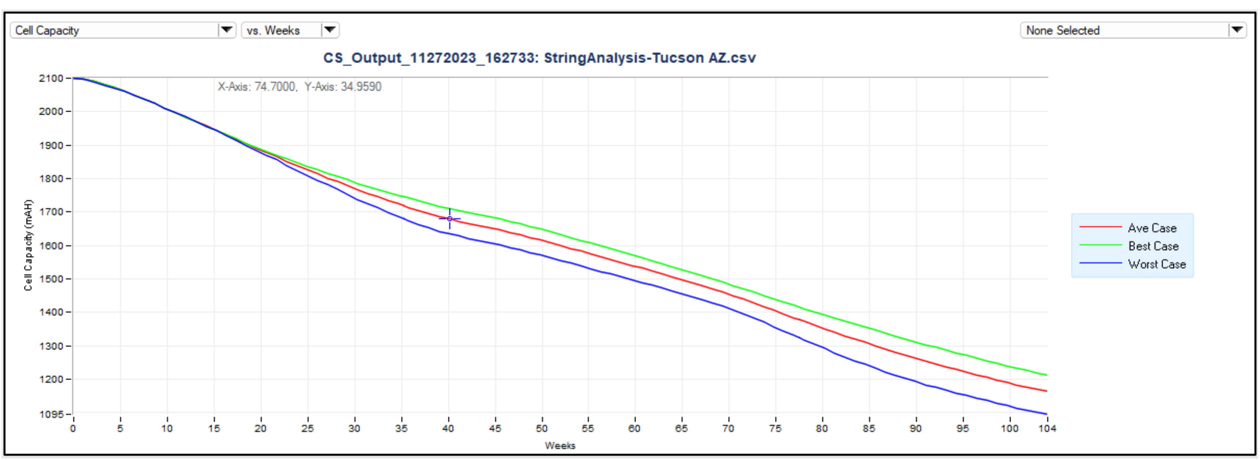



**Figure 137. Example 4, Cell Capacity vs. Weeks for Tucson, AZ (based on the "CS_String-Analysis.txt" data output file).**

### 5.4.6 Example 4: Discussion

During this example we have successfully walked through the process of running a CellSage™ simulation with annual temperature profiles from three different cities / geographic regions. As expected, the temperature profile for each city yielded different simulation results as shown in in Figure 132 - Figure 137. Further analysis by opening the .csv files in Excel has shown the following percentage changes by the end of the two-year / 104-week simulation for each city.

**Table 6. Example 4 Analysis for Cell Capacity Loss.**

| Temperature Profile | Cell Capacity Loss Results |
|---|---|
| Idaho Falls ID | • Best Case – 42.14% loss or 884.94 mAh from an original 2100 mAh<br>• Average Case – 42.94% loss or 902.94 mAh from an original 2100 mAh<br>• Worst Case – 44.29% loss or 929.79 mAh from an original 2100 mAh |
| Juneau AK | • Best Case – 40.65% loss or 854.65 mAh from an original 2100 mAh<br>• Average Case – 40.92% loss or 859.32 mAh from an original 2100 mAh<br>• Worst Case – 41.48% loss or 871.08 mAh from an original 2100 mAh |
| Tucson AZ | • Best Case – 42.27% loss or 887.67 mAh from an original 2100 mAh<br>• Average Case – 44.60% loss or 937.26 mAh from an original 2100 mAh<br>• Worst Case – 47.85% loss or 1004.85 mAh from an original 2100 mAh |

These CellSage™ simulation results from Example 4 will serve as a baseline for additional comparison and analysis with the data outputs from Example 5 that will be covered in the next section.

## 5.5 Example 5: Running a Multi-city Simulation with DCC, DTC, and TM

This example will cover how a user can run a basic CellSage™ simulation for the NMC/graphite (Panasonic UR18650) cell chemistry. It should be noted that the CellSage™ GUI follows a linear programming flow where the user enters input conditions in sequential sections, and navigates through the tabs with the "Next" and "Previous" buttons in the lower right corner of the GUI. Each example shall start by opening the CellSage™ software application as shown in Step 1 of Section 2.3, or by opening the Windows Start Menu and searching for the CellSage™ software program. When the program is opened successfully, the user will be on the Cell Chemistry & Global Simulations Conditions tab.

For Example 5, we will run a CellSage™ Simulation that is similar to Example 4, except this time we will enable Detailed Cycling Conditions (DCC), the effects of Daily Thermal Cycling (DTC), and Thermal Management (TM) Conditions in our simulation. This example is for the Panasonic UR 18650 chemistry, and as demonstrated in Example 3, these additional parameters will allow us to enter significantly more information as it relates to the battery duty cycle and application.

### 5.5.1 Example 5: Cell Chemistry & Simulation Conditions Tab

We setup Example 5 similar to our previous examples by importing the "EX-4_Parameters.txt" file to prepopulate each of our simulation conditions. We then begin to verify that each of our input conditions are loaded into the GUI starting with the following list of parameters on the Cell Chemistry & Global Simulation Conditions tab as shown in Figure 138:

- **Section 1.0: Select Battery Chemistry** – This parameter was set to the NMC/graphite (Panasonic UR 18650) chemistry.
- **Section 1.1: Indicate Simulation Time Period** – This parameter was set to 2 years (104 weeks) and equates to 3640 cycles for both the "CS_String_Analysis.txt" file, and the "CS_Path_Dependence-Dcc.txt" file.
- **Section 1.2: Input SoC Condition** – This parameter was set to 80%, which equates to 1.680 Ah of the total 2.1 Ah battery.
- **Section 1.3: Indicate Relative Cycling Severity** – This parameter was set to 1.0 which is at or near the baseline testing conditions.
- **Section 1.4: Detailed Cycling Conditions** – The DCC feature is now enabled in this example and the example selects the "CellSage™ Detailed Inputs—Cycles_Set1.txt" file as the DCC configuration input file. By selecting the EDIT button, we can see the specific inputs for this file as shown in Figure 139. The DCC input conditions that are specified in this example describe a battery use case / mission with the following key attributes:
    - Input Mode – Set to 1 to specify the charge and discharge rates as a C-Rate basis. Option 2 allows the user to specify the rates as a Current Basis.
    - Duty Cycle has 5 cycles per day with 5 charge steps per cycle, 5 charge rest steps per cycle, 3 discharge steps per cycle, and 3 discharge rest steps per cycle.
    - Discharge Mode is set to 1 for Constant Current.
    - Discharge Power Target is set to 40 Watts.
    - Cells in Series String is set to 5 cells (5S1P).

- Days Per Week the system is on Cyc-Life is set to 7 days.
- Days per Week the system in On Cal-Life is set to 0 days.
- Cell Voltage at Cal-Life is set to 3.6 Volts.

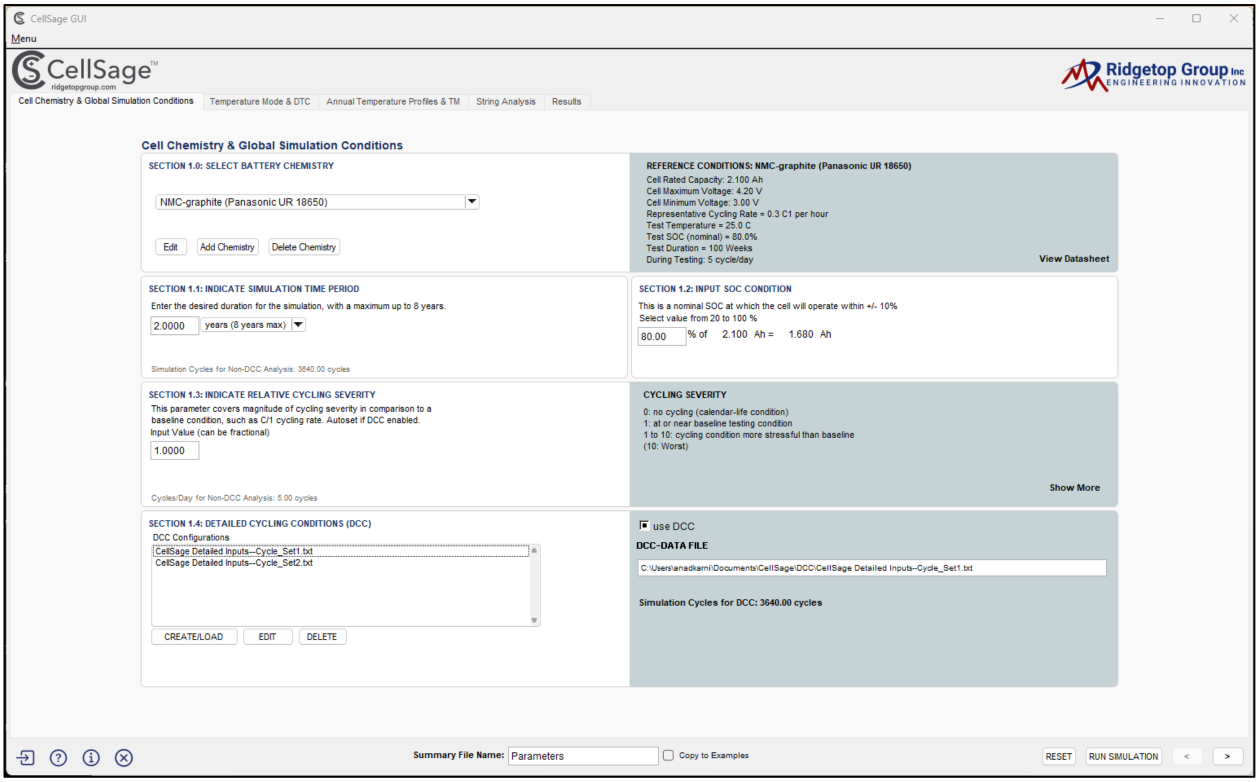



**Figure 138. Example 5, Cell Chemistry and Global Simulation Conditions tab.**

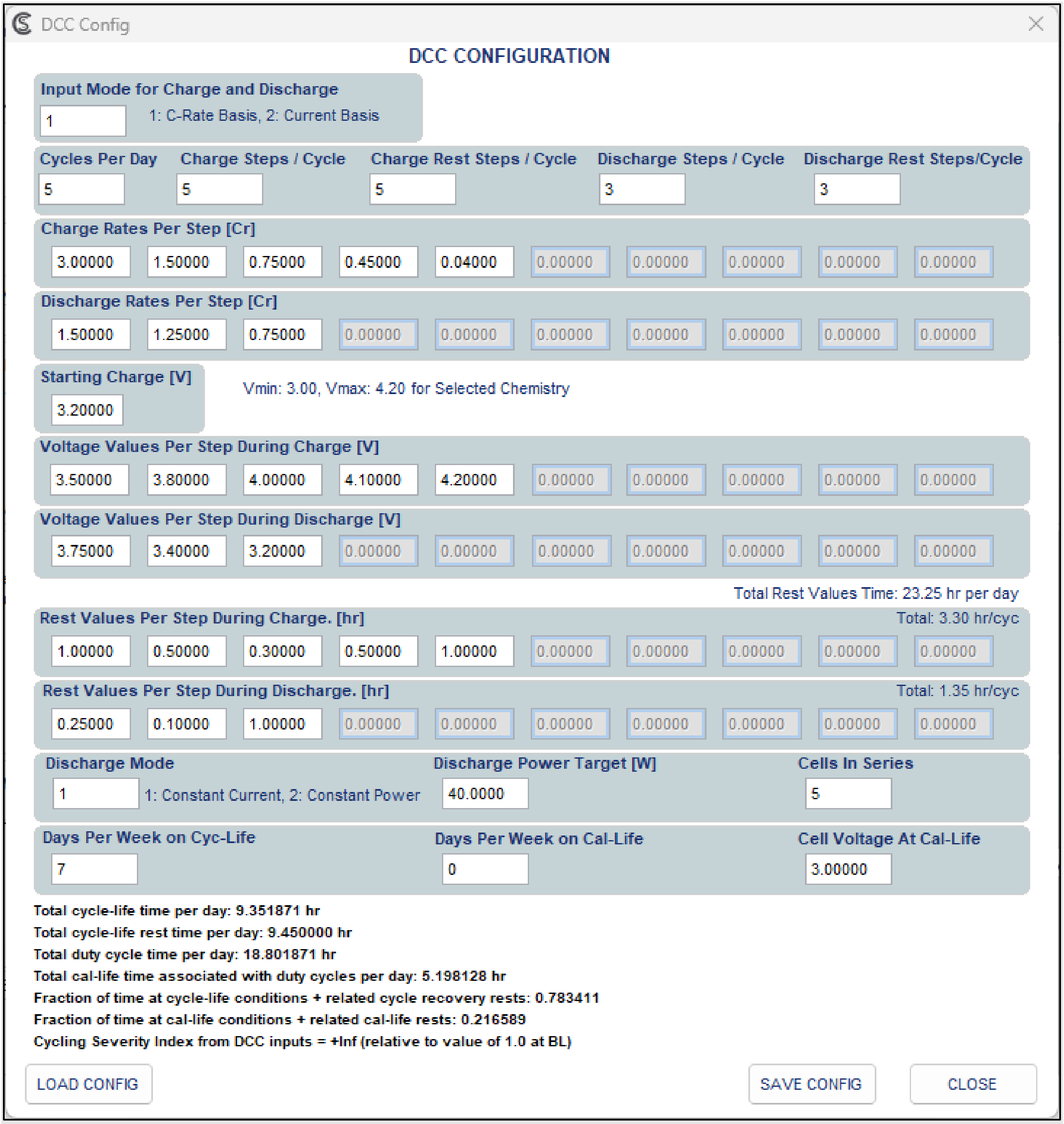



**Figure 139. View of DCC Configuration user form for Example 5.**

### 5.5.2 Example 5: Temperature Mode and Daily Thermal Cycling Conditions Tab

Next, we move on to the Temperature Mode and DTC tab to verify that we are continuing to use the 2.2 Temperature Mode, and have set the DTC parameters according to Figure 140. For this example, we have specified that the warm up time to be 20 minutes in 3.1 and that there are multiple DTC occurrences in 3.2 as specified in the DCC configuration file. The input for Section 3.3 (Input Time Battery is at TMAX…) is disabled in this example as that input is only available for Temperature Mode 2.1.

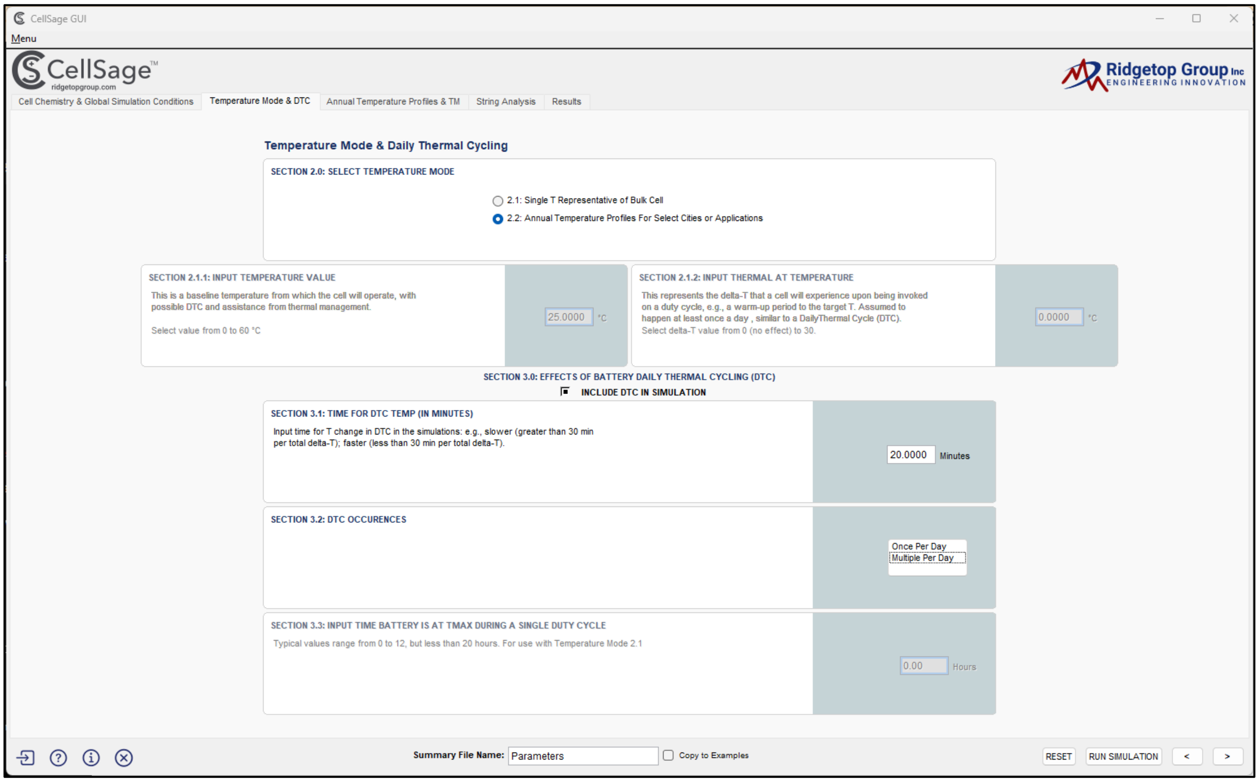



**Figure 140. Example 5, Temperature Mode and DTC tab.**

### 5.5.3 Example 5: Annual Temperature Profiles and Thermal Management Conditions Tab

As done in Example 4, we now verify that our 3 temperature profiles have been selected for Juneau AK, Idaho Falls ID, and Tucson AZ. We also verify that Thermal Management has been enabled and that our lower limit is set to 0 °C and the upper limit is set at 30 °C as done in Figure 141. These upper and lower limits are realistic temperature constraints that will assume an active thermal management system is in place or a part of the battery management system.

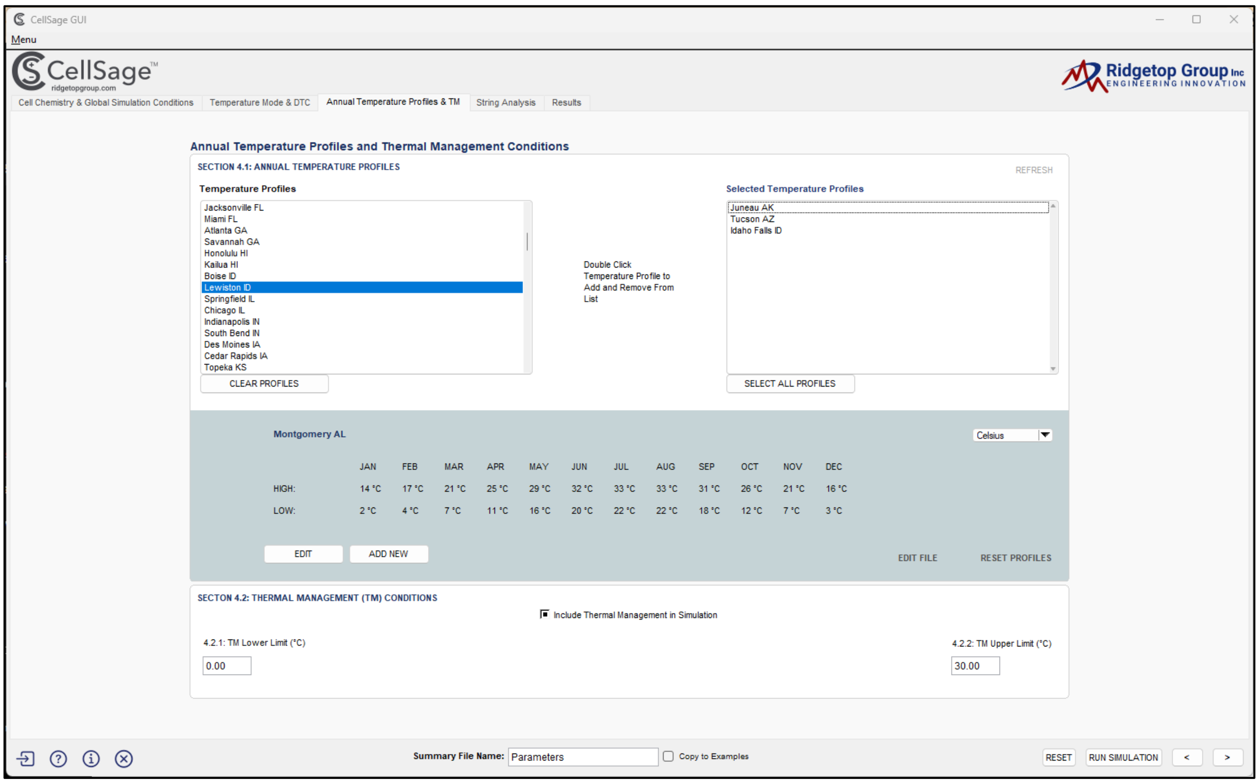



**Figure 141. Example 5, Annual Temperature Profiles & TM tab.**

### 5.5.4 Example 5: String Analysis Tab

Next, we will move on to the String Analysis tab where we will use the same input parameters and default data output directory as done with Examples 1-4. A visual of these inputs is shown in Figure 142. We will then click the Run Simulation button to execute the simulation, and proceed to the Results tab.

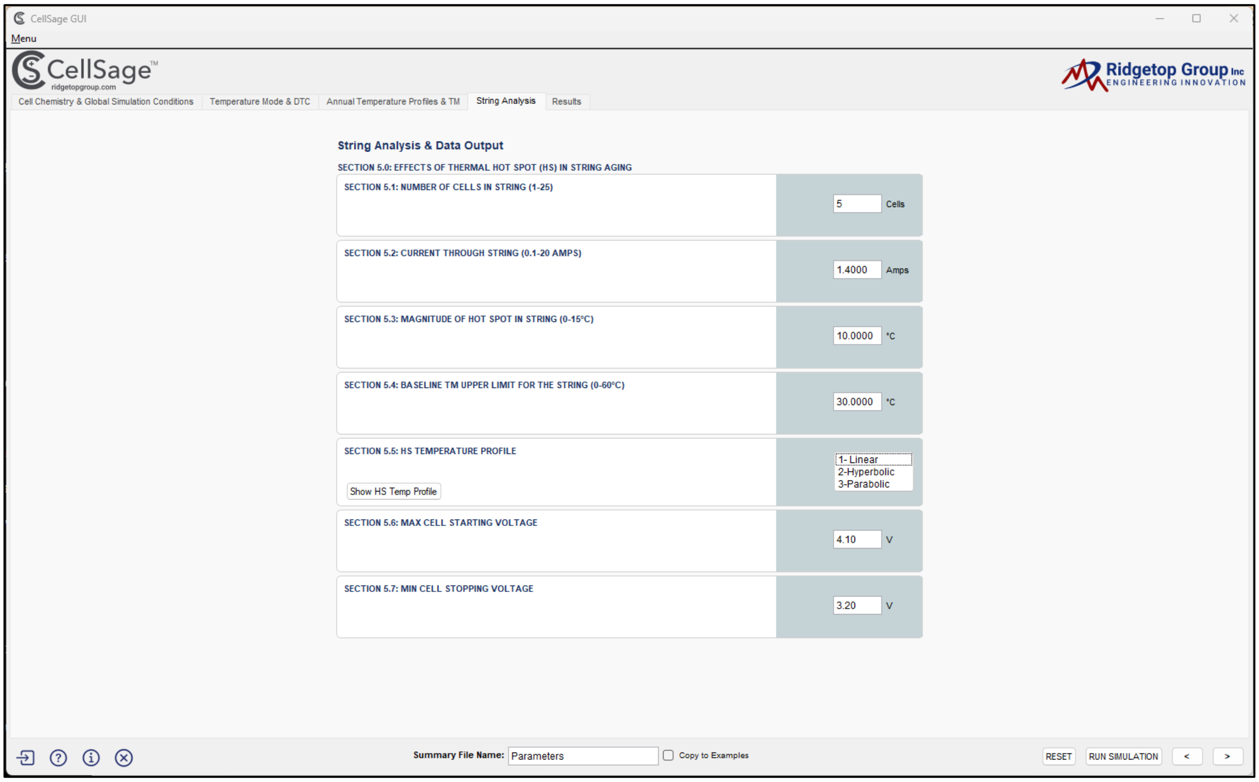



**Figure 142. Example 5, String Analysis tab.**

### 5.5.5 Example 5: Results Tab

In the Results tab for Example 5 we see our standard data output files, as well as the three different *.csv files for each of the selected cities. As shown in Figure 143, the program has yielded a total of 9 different *.csv files, where each of the selected cities has three data plot files based on the “CS_Path-Dependence-Dcc.txt”, the “CS_Path-Dependence.txt”, and the “CS_String_Analysis.txt” data output files. Referring back to Section 3.1.5, these plots can be previewed by selecting the data plot type and the corresponding drop down for the data type of interest.

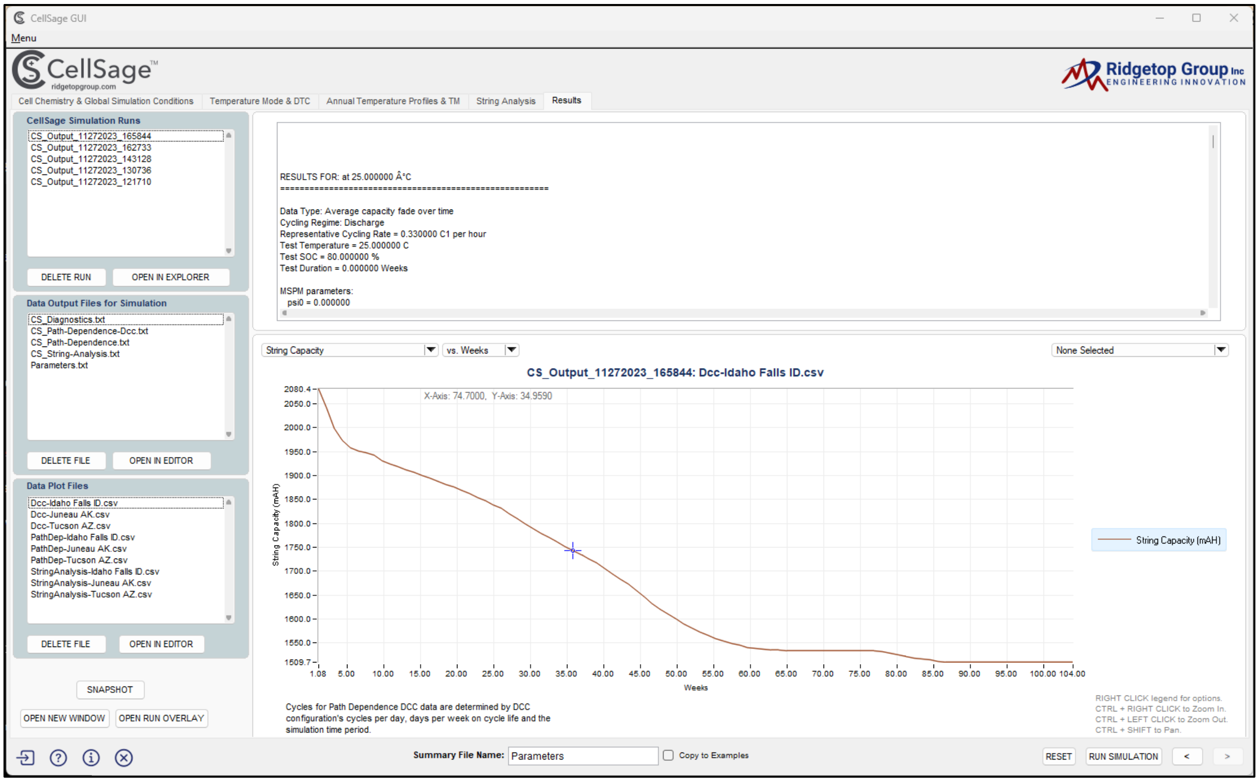


Figure 143. Example 5, Results tab.

### 5.5.6 Example 5: Discussion

We will now compare our Example 4 and Example 5 simulation results using the OPEN RUN OVERLAY button located on the Results tab. This software feature will open up a new window that will allow us to select different CellSage™ simulation results and compare them on the same plot. The first comparison will be for Cell Capacity vs. Weeks for Example 4 vs. Example 5. We will also compare our simulation results as it relates to String Capacity vs. Weeks for Example 3 and Example 5 as they both use the same DCC config file.

For the first set of comparison exercises for Cell Capacity vs. Weeks, Figure 144 – Figure 146 show the Example 4 simulation results vs. the Example 5 simulation results for each of the three temperature profiles. For the second set of comparison exercises for String Capacity vs. Weeks, Figure 147 - Figure 149 show the Example 3 simulations results vs. the Example 5 simulation results that used the same DCC config file.

After studying these plots and results one may notice the following list of observations:

- The results from Example 5 generally indicate more Cell Capacity loss when compared to Example 4 for each city. This is consistent with the comparison against Example 2 vs. Example 3, as we used the same DCC configuration file.
- It was also noted that the estimated String Capacity loss was less in Example 5 when compared against Example 3, despite using the same DCC config file. Although the annual temperature profiles vary a lot more than the Single T Temperature mode in Example 3,

these results are as expected as Example 5 did incorporate a thermal management system that effectively reduced the path dependent aging results.

- It appears the largest loss of cell capacity was observed in Example 4 for the worst-case scenario in Tucson, AZ. This should make logical sense as that example did not have the Thermal Management option enabled, and annual temperature profiles in Tucson, AZ are typically hotter than Idaho Falls, ID and Juneau, AK.

At this stage, we have now completed 4 different CellSage™ simulation examples, and Ridgetop Group encourages any user feedback or comments that could help make this User Guide and documentation more useful or easier to understand.

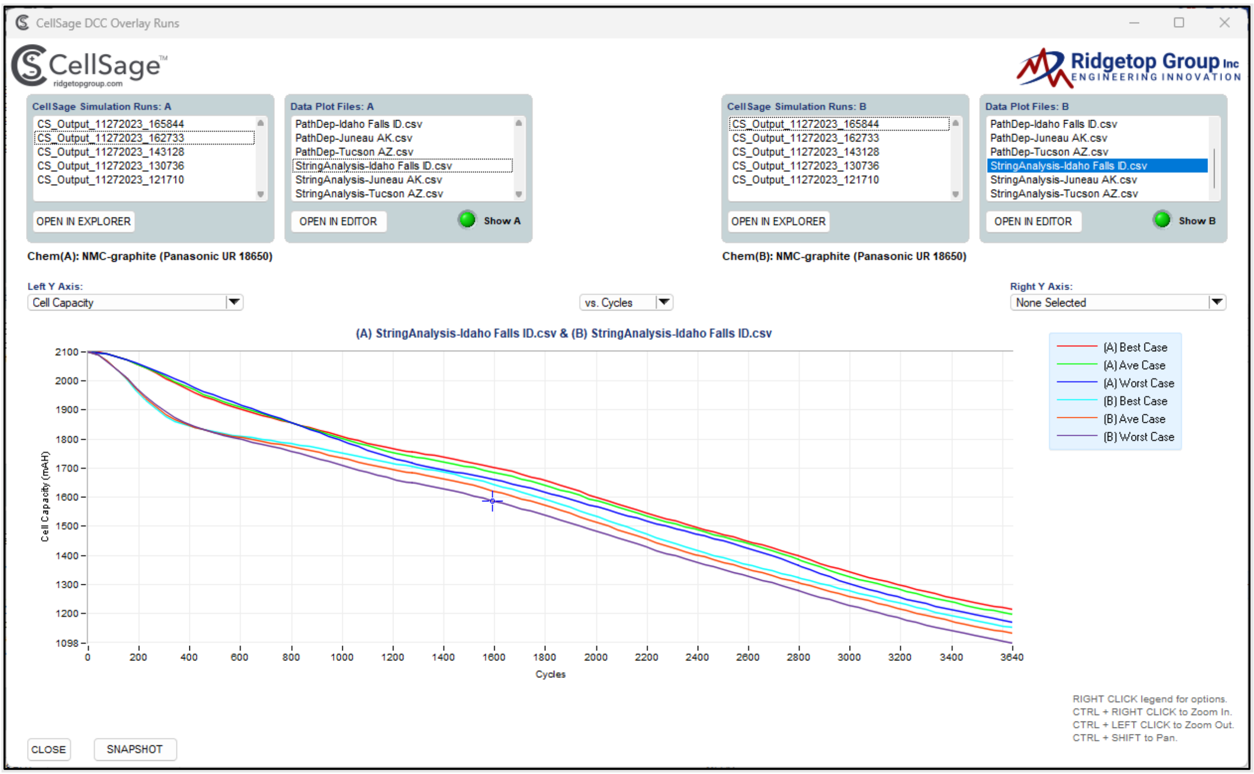



**Figure 144. Example 4 (A) vs. Example 5 (B) Cell Capacity Comparison for Idaho Falls ID.**

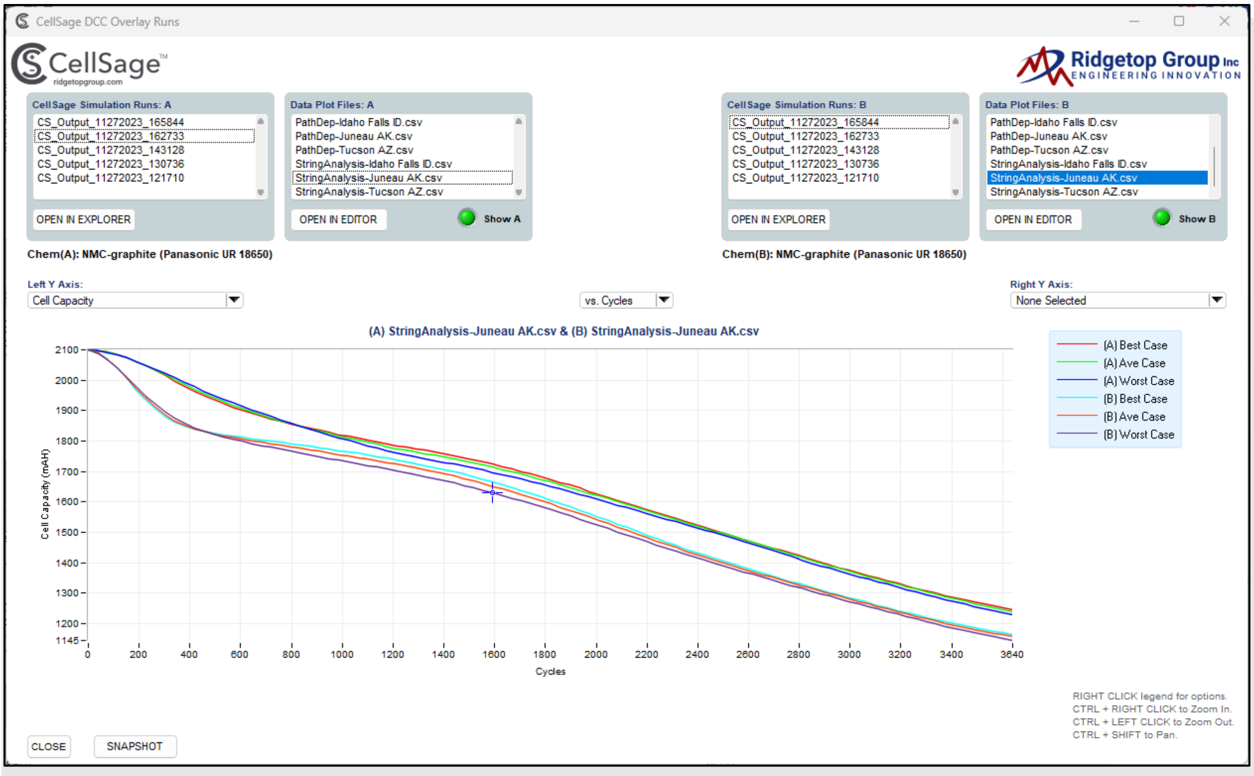



**Figure 145. Example 4 (A) vs. Example 5 (B) Cell Capacity Comparison for Juneau AK.**

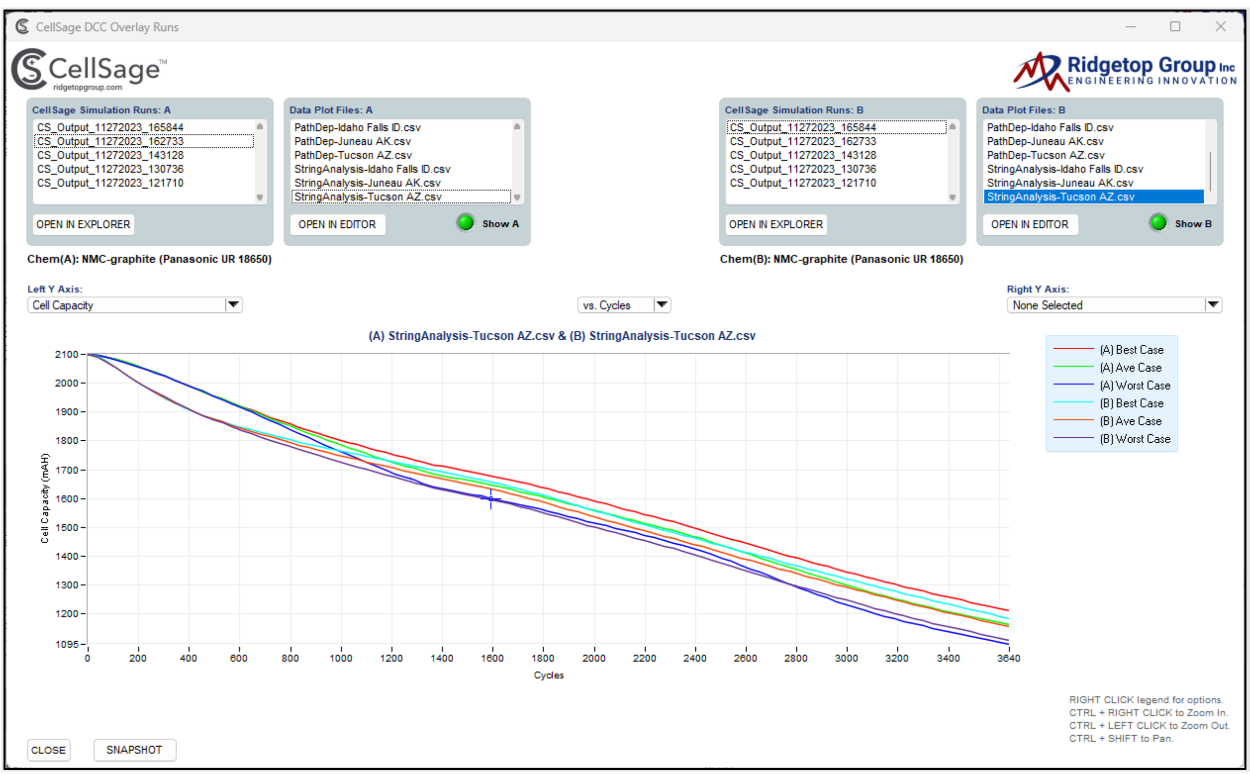



**Figure 146. Example 4 (A) vs. Example 5 (B) Cell Capacity Comparison for Tucson, AZ.**

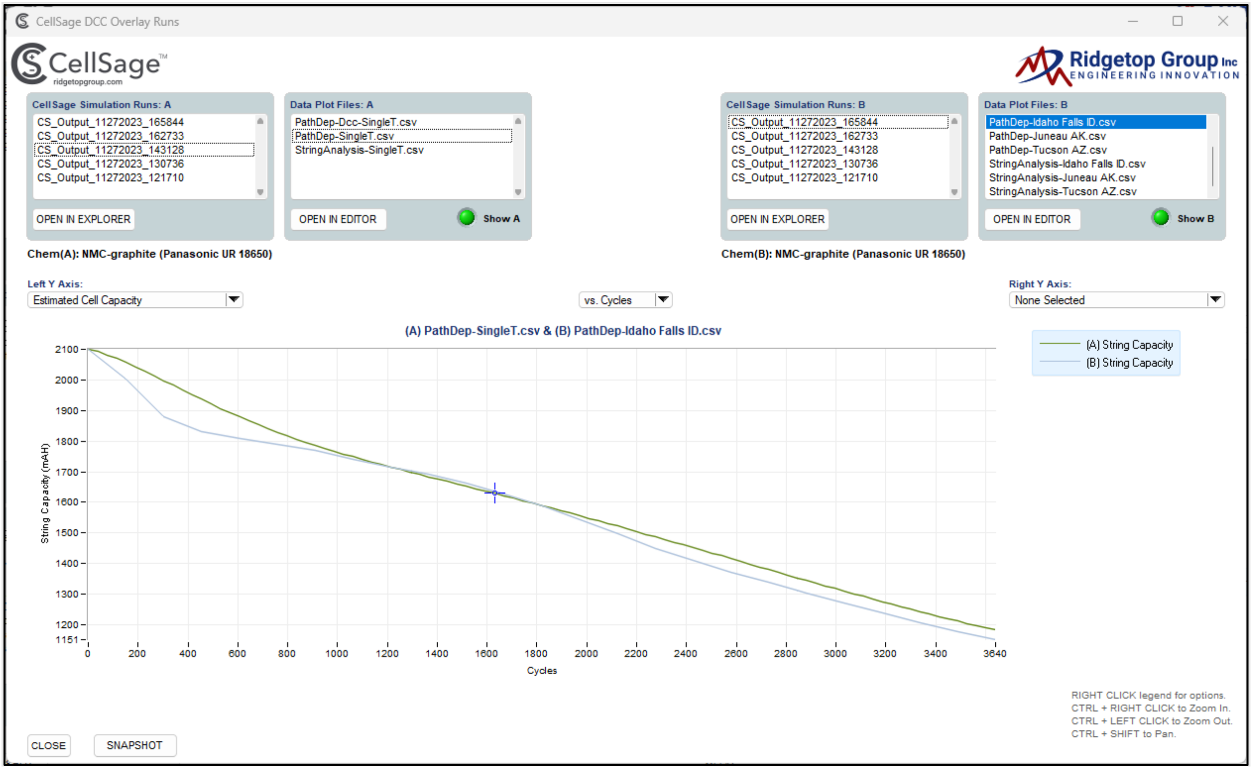



**Figure 147. Example 3 (A) vs. Example 5 (B) Cell Capacity Comparison for Idaho Falls, ID.**

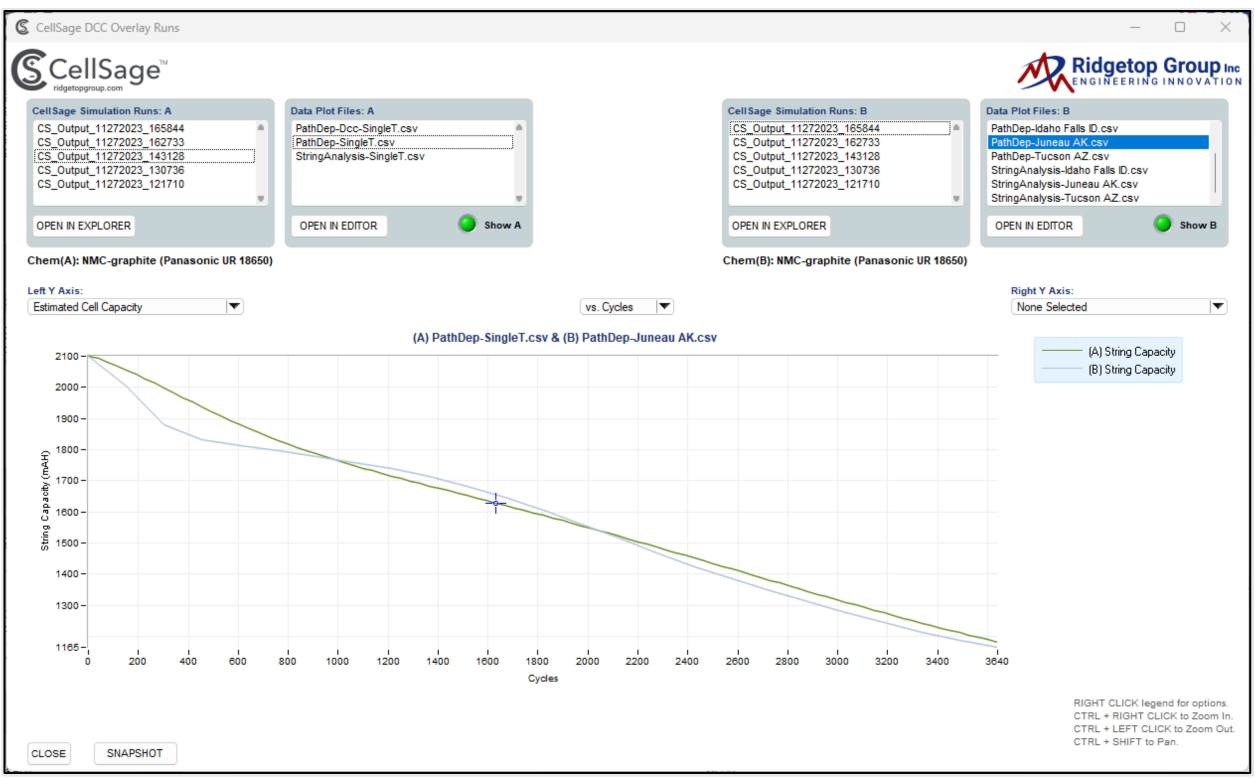



**Figure 148. Example 3 (A) vs. Example 5 (B) Cell Capacity Comparison for Juneau, AK.**

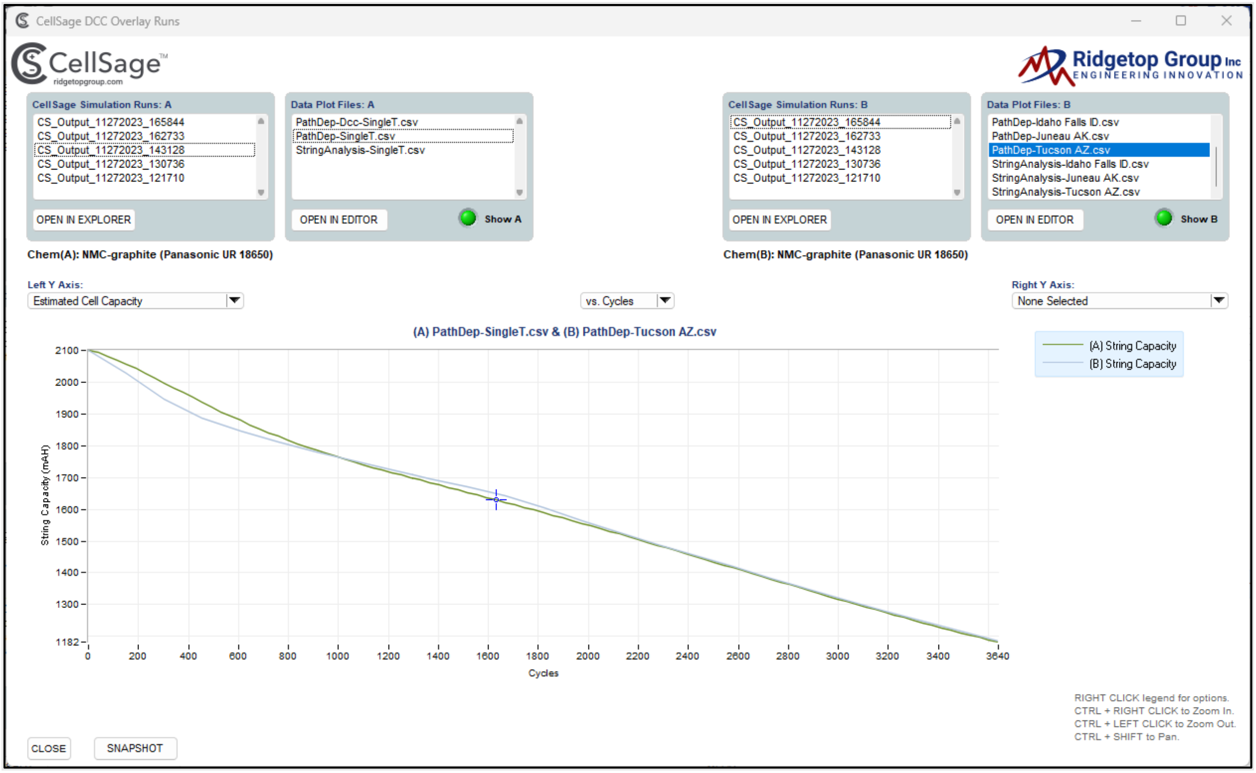



**Figure 149. Example 3 (A) vs. Example 5 (B) Cell Capacity Comparison for Tucson, AZ.**

# 6. Appendix

## 6.1 Licensed Patents and Licensed Copyrights

**PATENTS:**

All U.S. patent(s) and patent applications, including divisionals, reissues, reexaminations, continuations, but not continuations-in-part applications, that issue from or claim priority to:

1. U.S. Patent Serial No. 8,521,497 issued August 27, 2013, entitled "Systems, methods and computer-readable media for modeling cell performance fade of rechargeable electrochemical devices", having BEA Attorney Docket No. BA-435.
2. U.S. Patent Serial No. 8,346,495 issued January 1, 2013, entitled "Systems, methods and computer-readable media to model kinetic performance of rechargeable electrochemical devices", having BEA Attorney Docket No. BA-436.
3. U.S. Patent Serial No. 8,476,984 issued June 18, 2013, entitled "Systems, methods and computer readable media for estimating capacity loss in rechargeable electrochemical cells", having BEA Attorney Docket No. BA-437.
4. U.S. Patent Serial No. 9,625,532 issued April 18, 2017, entitled "Method, system, and computer-readable medium for determining performance characteristics of an object undergoing one or more arbitrary aging conditions", having BEA Attorney Docket No. BA-676.
5. U.S. Patent Serial No. 11,815,557 issued November 14, 2023, entitled “Systems and methods for managing energy storage operations”, having BEA Attorney Docket No. BA-1100.
6. U.S. Patent Application No. 17/015,369 filed September 9, 2020, entitled “Systems and methods for managing energy storage operations”, having BEA Attorney Docket No. BA-1100.
7. U.S. Patent Application No. 18/001,304 filed December 9, 2022, entitled “Determining effects from transient active agents and transient events upon static or semi-static populations, having BEA Attorney Docket No. BA-1178.

**COPYRIGHTS:**

1. Copyright in Software entitled "CellSage™-Kinetics" copyright reassertion granted by DOE to BEA October 26,2015, BEA Attorney Docket Number CW-I0-10.
2. Copyright in Software entitled "CellSage™-Capacity'' copyright reassertion granted by DOE to BEA October 26,2015, BEA Attorney Docket Number CW-I0-10.

## 6.2 List of Select City's with Annual Temperature Profiles

The CellSage™ GUI has temperature profiles for 130 cities in select states throughout the U.S.A. The CellSage™ system architecture has been modified so that additional temperature profiles for other cities, geographic regions, and/or controlled environments such as laboratories can be added the list in a .csv file. The full list of default cities with pre-loaded monthly temperature profiles is listed below:

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| AL | Montgomery | ..1 | ME | Augusta | ..44 | OR | Portland | ..87 |
| | Birmingham | ..2 | | Portland | ..45 | | Medford | ..88 |
| AK | Juneau | ..3 | MD | Annapolis | ..46 | | Pendleton | ..89 |
| | Anchorage | ..4 | | Baltimore | ..47 | PA | Harrisburg | ..90 |
| | Fairbanks | ..5 | | Salisbury | ..48 | | Philadelphia | ..91 |
| AZ | Phoenix | ..6 | MA | Boston | ..49 | | Pittsburgh | ..92 |
| | Tucson | ..7 | | Worcester | ..50 | RI | Providence | ..93 |
| AR | Little Rock | ..8 | MI | Lansing | ..51 | | Newport | ..94 |
| | Fort Smith | ..9 | | Detroit | ..52 | SC | Columbia | ..95 |
| CA | Sacramento | ..10 | MN | Minneapolis | ..53 | | Charleston | ..96 |
| | San Francisco | ..11 | | Duluth | ..54 | SD | Pierre | ..97 |
| | Los Angeles | ..12 | MS | Jackson | ..55 | | Rapid City | ..98 |
| CO | Denver | ..13 | | Tupelo | ..56 | | Sioux Falls | ..99 |
| | Pueblo | ..14 | MO | St. Louis | ..57 | TN | Nashville | ..100 |
| | Grand Junction | ..15 | | Kansas City | ..58 | | Memphis | ..101 |
| | Durango | ..16 | MT | Helena | ..59 | | Chattanooga | ..102 |
| CT | Hartford | ..17 | | Billings | ..60 | TX | Austin | ..103 |
| | Bridgeport | ..18 | | Great Falls | ..61 | | Houston | ..104 |
| DE | Dover | ..19 | NE | Lincoln | ..62 | | Dallas | ..105 |
| | Wilmington | ..20 | | Omaha | ..63 | | Amarillo | ..106 |
| FL | Tallahassee | ..21 | | Alliance | ..64 | | San Antonio | ..107 |
| | Jacksonville | ..22 | NV | Carson City | ..65 | | Brownsville | ..108 |
| | Miami | ..23 | | Las Vegas | ..66 | UT | Salt Lake City | ..109 |
| GA | Atlanta | ..24 | NH | Concord | ..67 | | Cedar City | ..110 |
| | Savannah | ..25 | | Plymouth | ..68 | | Moab | ..111 |
| HI | Honolulu | ..26 | NJ | Newark | ..69 | VT | Montpelier | ..112 |
| | Kailua | ..27 | | Atlantic City | ..70 | | Burlington | ..113 |
| ID | Boise | ..28 | NM | Santa Fe | ..71 | VA | Richmond | ..114 |
| | Idaho Falls | ..29 | | Albuquerque | ..72 | | Virginia Beach | ..115 |
| | Lewiston | ..30 | | Las Cruces | ..73 | | Roanoke | ..116 |
| IL | Springfield | ..31 | NY | Albany | ..74 | WA | Olympia | ..117 |
| | Chicago | ..32 | | New York City | ..75 | | Seattle | ..118 |
| IN | Indianapolis | ..33 | | Rochester | ..76 | | Spokane | ..119 |
| | South Bend | ..34 | NC | Raleigh | ..77 | | Bellingham | ..120 |
| IA | Des Moines | ..35 | | Charlotte | ..78 | WV | Charleston | ..121 |
| | Cedar Rapids | ..36 | ND | Bismarck | ..79 | | Parkersburg | ..122 |
| KS | Topeka | ..37 | | Fargo | ..80 | WI | Madison | ..123 |
| | Wichita | ..38 | | Minot | ..81 | | Milwaukee | ..124 |
| KY | Frankfort | ..39 | OH | Columbus | ..82 | | Green Bay | ..125 |
| | Louisville | ..40 | | Cleveland | ..83 | WY | Cheyenne | ..126 |
| LA | Baton Rouge | ..41 | OK | Oklahoma City | ..84 | | Gillette | ..127 |
| | New Orleans | ..42 | | Tulsa | ..85 | | Casper | ..128 |
| | Shreveport | ..43 | | Guymon | ..86 | | Cody | ..129 |
| | | | | | | Washington DC | | ..130 |

## 6.3 Cell Datasheets

1. **NCA/graphite (DOE Gen2 18650)**
   - Contact INL or Ridgetop Group for information regarding this cell type.

2. **NMC/graphite (Sanyo Y 18650)**
   - [https://voltaplex.com/media/whitepapers/specification-sheet/Sanyo_Y_Specification_Sheet.pdf](https://voltaplex.com/media/whitepapers/specification-sheet/Sanyo_Y_Specification_Sheet.pdf)

**Panasonic**
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Lithium Ion
**UR18650Y**

**Features & Benefits**

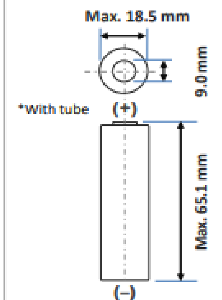
- General purpose model
- Stable power with a flat discharge voltage
- High safety performance
- Ideal for portable communications, portable computing, and robotics.

**Specifications**

| | |
|---|---|
| Rated capacity[1] | Min. 1850mAh |
| Capacity[2] | Min. 1900mAh<br>Typ. 2000mAh |
| Nominal voltage | 3.7V |
| Charging | CC-CV, Std. 1330mA, 4.20V, 3.0 hrs |
| Weight (max.) | 44.3 g |
| Temperature | Charge: 0 to +45°C<br>Discharge: -20 to +60°C<br>Storage: -20 to +50°C |
| Energy density[3] | Volumetric: 411 Wh/l<br>Gravimetric: 158 Wh/kg |

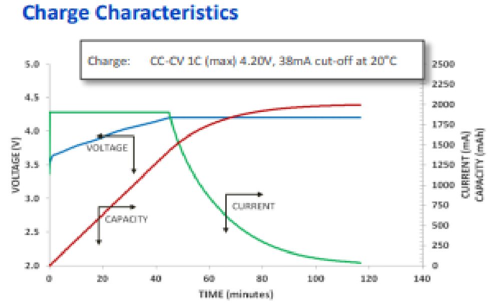
[1] At 20°C [2] At 25°C [3] Energy density based on bare cell dimensions

**Dimensions**

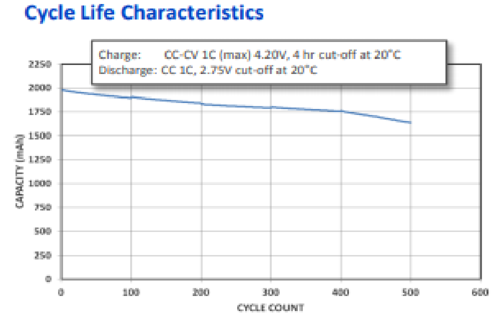



For Reference Only

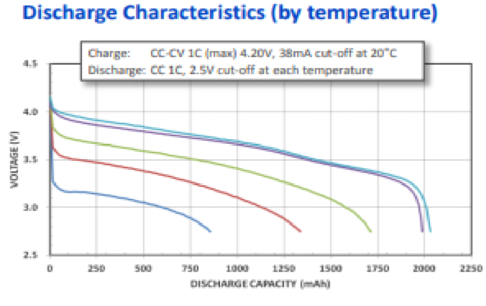
**Charge Characteristics**



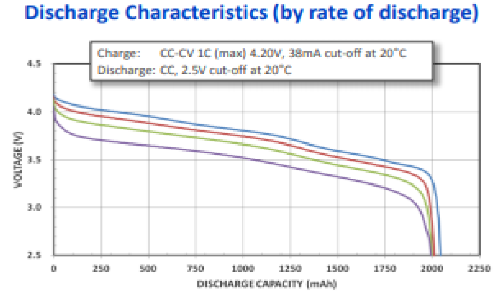

**Cycle Life Characteristics**




**Discharge Characteristics (by temperature)**




**Discharge Characteristics (by rate of discharge)**

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For more information on how Panasonic can assist you with your battery power solution needs, visit us at www.panasonic.com/industrial/batteries-oem or e-mail secsales@us.panasonic.com.

**3. LFP/graphite (A123 Nanophosphate 20 Ah)**

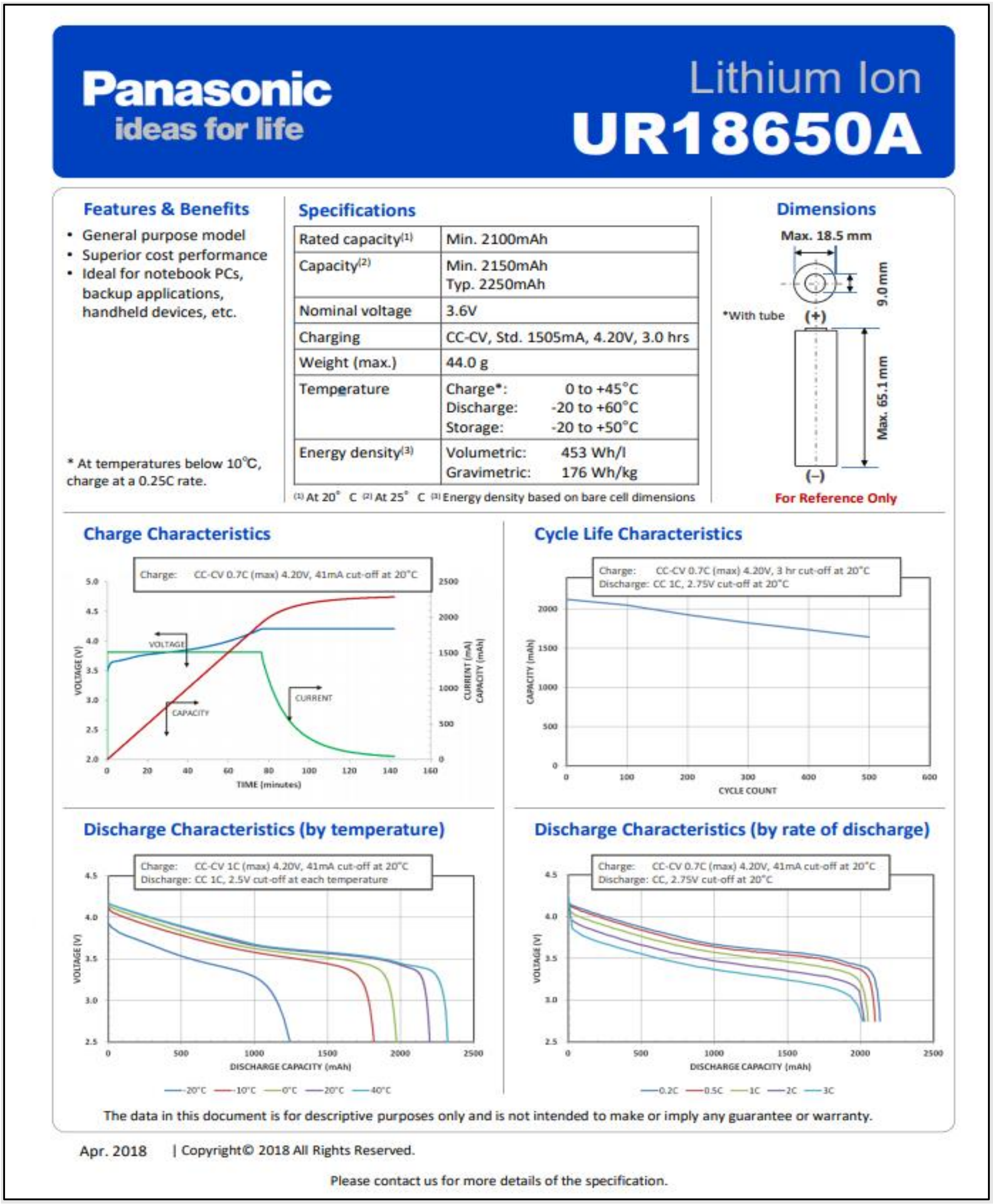
- https://formula-hybrid.org/wp-content/uploads/A123_AMP20_battery_Design_guide.pdf
- https://www.buya123products.com/uploads/vipcase/468623916e3ecc5b8a5f3d20825eb98d.pdf

**4. LFP/graphite (A123 26650-type)**

- https://www.batteryspace.com/prod-specs/6610.pdf

**5. NMC/graphite (Panasonic UR18650)**

- https://industrial.panasonic.com/cdbs/www-data/pdf2/ACA4000/ACA4000CE285.pdf



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Lithium Ion
UR18650A

**Features & Benefits**

- General purpose model
- Superior cost performance
- Ideal for notebook PCs, backup applications, handheld devices, etc.

* At temperatures below 10°C, charge at a 0.25C rate.

**Specifications**

| | |
|---|---|
| Rated capacity(1) | Min. 2100mAh |
| Capacity(2) | Min. 2150mAh<br>Typ. 2250mAh |
| Nominal voltage | 3.6V |
| Charging | CC-CV, Std. 1505mA, 4.20V, 3.0 hrs |
| Weight (max.) | 44.0 g |
| Temperature | Charge*: 0 to +45°C<br>Discharge: -20 to +60°C<br>Storage: -20 to +50°C |
| Energy density(3) | Volumetric: 453 Wh/l<br>Gravimetric: 176 Wh/kg |

(1) At 20° C (2) At 25° C (3) Energy density based on bare cell dimensions

**Dimensions**



For Reference Only

**Charge Characteristics**



**Cycle Life Characteristics**



**Discharge Characteristics (by temperature)**



**Discharge Characteristics (by rate of discharge)**



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Please contact us for more details of the specification.

## 6.4 Table of Figures



 

# CellSage™ Battery Modeling, Simulation & Analysis (MS&A) Software User Guide