IDAJ
integrated digital advanced solution

IDAJ公司

V2020 GT-Autolion-1D 教程

IDAJ中国

GT小组

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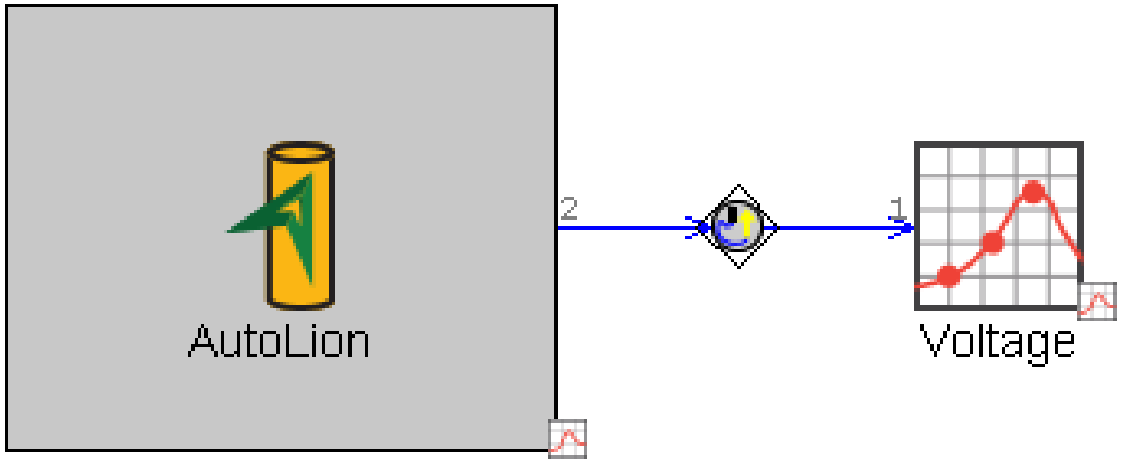
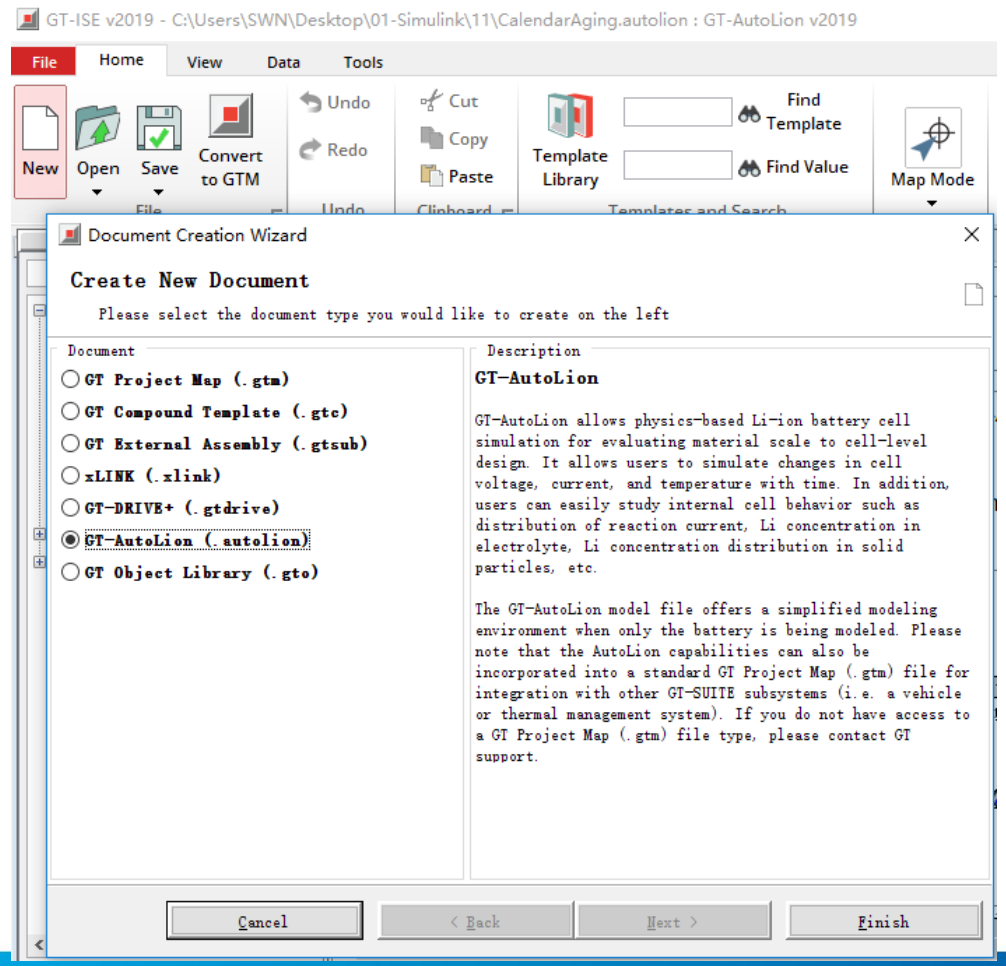
基础模型

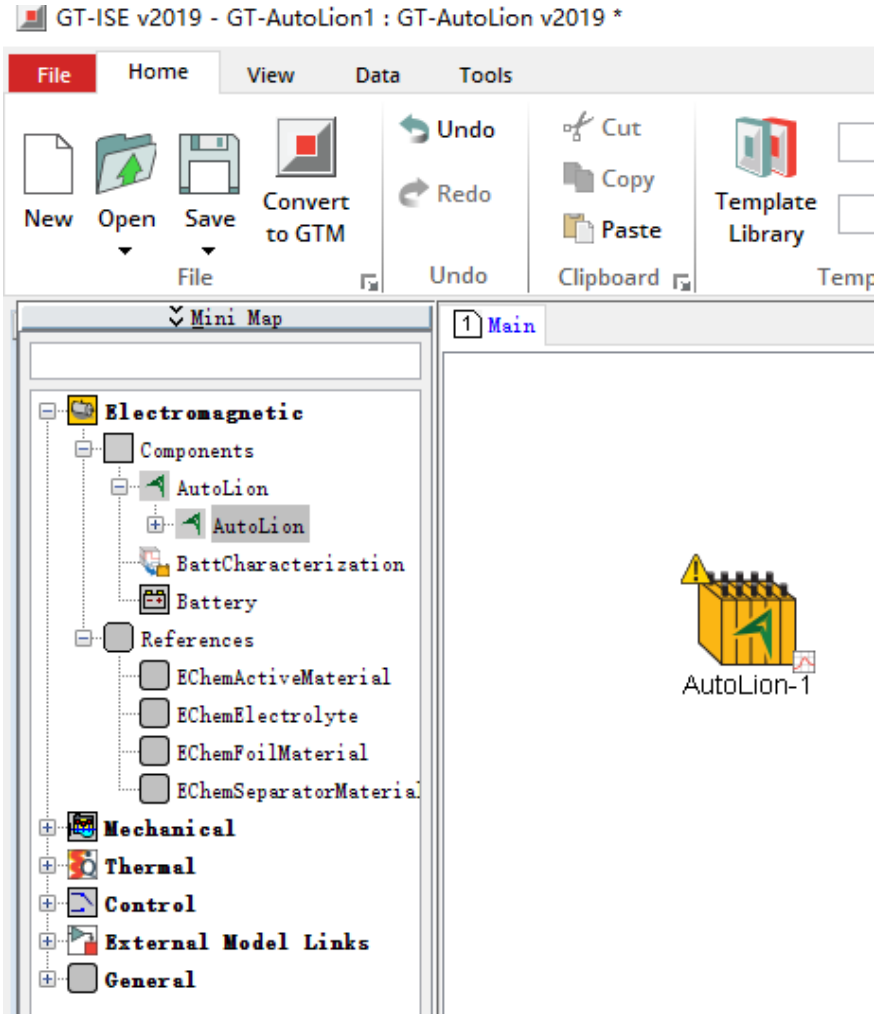
本模型为一个 18650型 NCM/C 电池进行 2.2A 的恒流放电，与外部环境进行对流换热，不考虑老化模型，监控端电压。



基础模型

- 新建 .autolion 程序，并将Autolion拖入map中

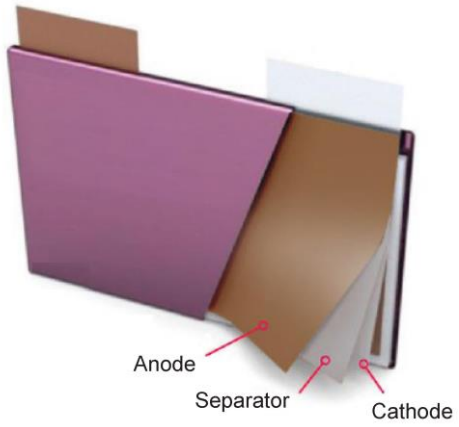




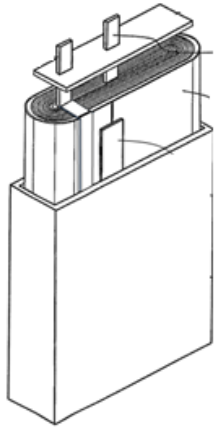
基础模型

- 电池类型

4 种电池类型



棱形: 叠片式电极(SED)



棱形: 卷绕式电极(RED)

圆柱形电池

纽扣电池

基础模型

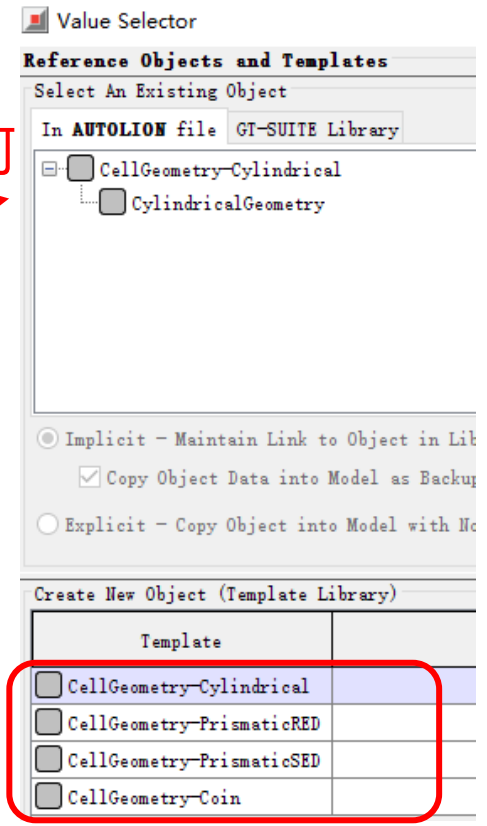
主窗口设置

Main | Model Setup | Cathode | Anode | Assembly | Thermal Behavior | Advanced | Plots

Attribute	Unit	Object Value
Cell Geometry		
Cell Geometry		CylindricalGeometry ...
Pack Model		
☐ Build Lumped Pack Model		
Analysis Mode		
Analysis Mode		Time Simulation
Time Simulation		
Load Type		Current
Current Request	A	2.2 ...
Initialization		
Initial State of Charge	fraction	1 ...
☐ Initialize as Aged Model		

新建电池几何

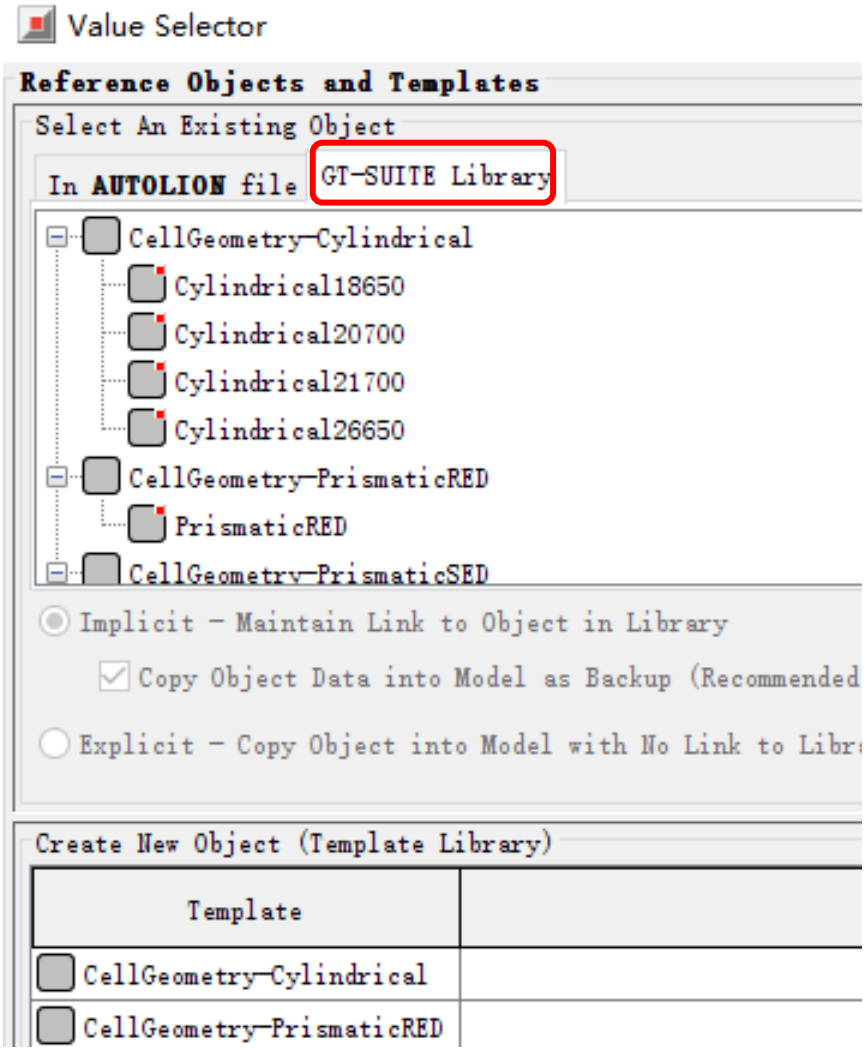
电池几何



四种电池

基础模型

- 主窗口设置
  - 可以选择数据库中的自带电池

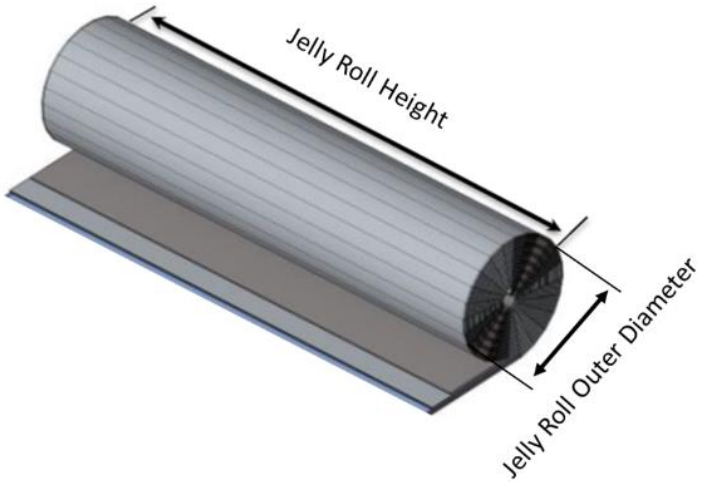


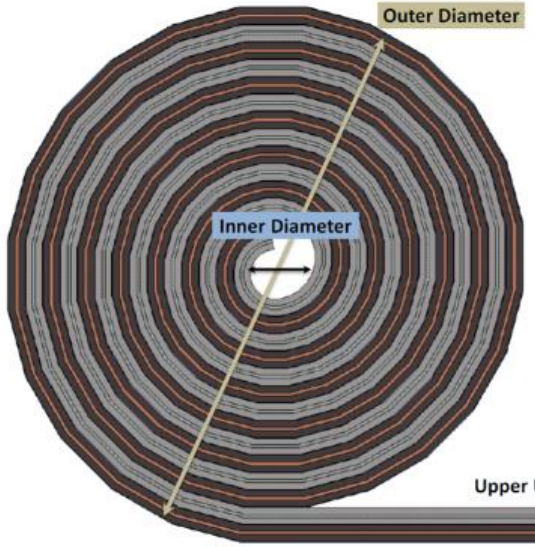
基础模型

- 圆柱形电池几何参数

Main

Attribute	Unit	Object Value
Cell Dimensions		
Outer Diameter	mm	18.6
Outer Height	mm	65.2
Wall Thickness	mm	0.3
Jelly Roll Dimensions		
Jelly Roll Inner Diameter	mm	4
Jelly Roll Outer Diameter	mm	17.2
Jelly Roll Details		
Cathode Uncoated Length	mm	15
Anode Uncoated Length	mm	52
Anode Extra Length	mm	40
Thicknesses		
Cathode	micron	77.5
Anode	micron	81
Separator	micron	20
Cathode Foil	micron	15
Anode Foil	micron	8

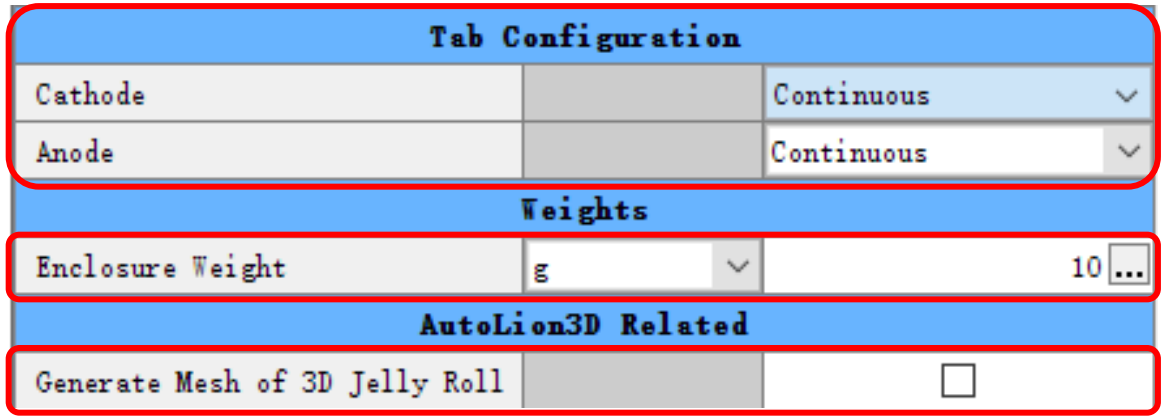




电极厚度：单层厚度

基础模型

- 圆柱形电池几何参数



极耳形式

外壳重量

Autolion3D网格设置

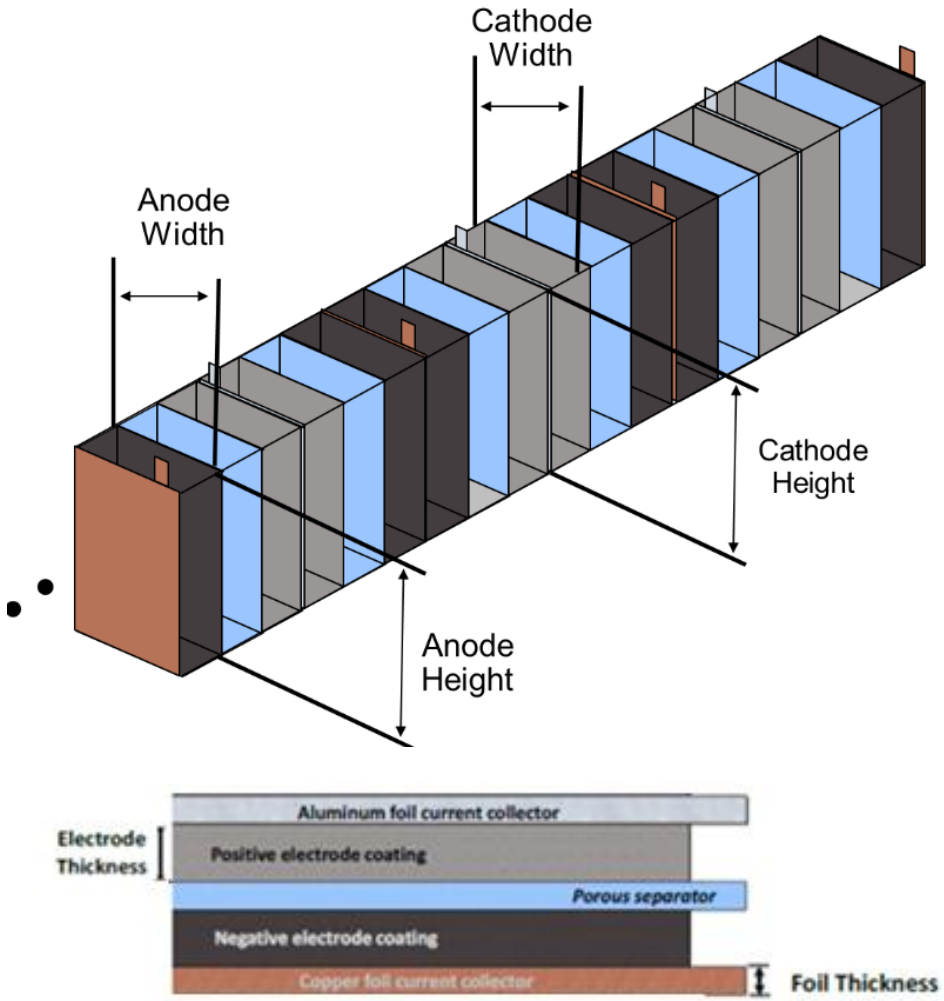
基础模型

- SED 电池几何参数

Main

	Attribute	Unit	Object Value
Cell Dimensions			
	Outer Width	mm	420
	Outer Height	mm	65.2
	Outer Thickness	mm	100
	Wall Thickness	mm	0.3
Jelly Roll Dimensions			
	Jelly Roll Width	mm	200
◉	Jelly Roll Thickness	mm	15.3
○	Number of Anode Foil Plates		1
Thicknesses			
	Cathode	micron	77.5
	Anode	micron	81
	Separator	micron	20
	Cathode Foil	micron	15
	Anode Foil	micron	8

Nanode = Ncathode + 1



基础模型

- SED 电池几何参数

Heights		
Cathode	mm	57.5
Anode	mm	58
Separator	mm	59.7
Cathode Foil	mm	57.5
Anode Foil	mm	58
Widths		
Cathode	m	
Anode	m	
End Plate Type		
End Plate Coating Type		Double-side Anode
Weights		
Enclosure Weight	g	123
Generate Mesh of 3D Jelly Roll		☐

End plate 涂敷形式？？？

Autolion3D网格设置

基础模型

- RED 电池几何参数

Main

Attribute	Unit	Object Value
Cell Dimensions		
Outer Width	mm	420
Outer Height	mm	65.2
Outer Thickness	mm	100
Wall Thickness	mm	0.3
Jelly Roll Dimensions		
Winding Axis Direction		Cell Height
Number of Jelly Rolls		1
Jelly Roll Width	mm	200
Jelly Roll Thickness	mm	15.3
Jelly Roll Details		
Cathode Uncoated Length	mm	15
Anode Uncoated Length	mm	52
Anode Extra Length	mm	40

定义卷绕方向

卷芯个数

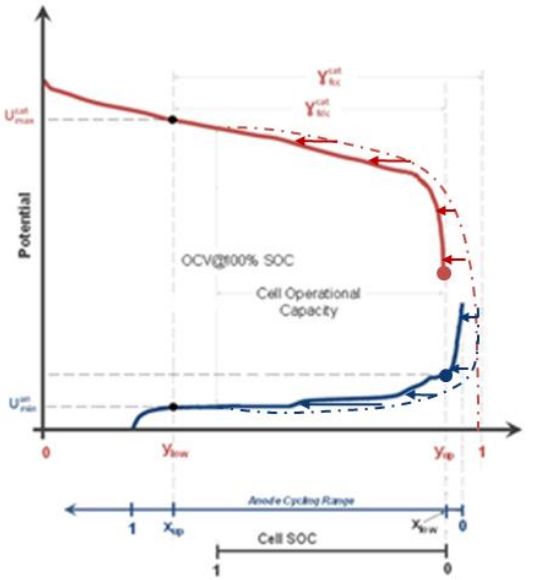
Thicknesses		
Cathode	micron	77.5
Anode	micron	81
Separator	micron	20
Cathode Foil	micron	15
Anode Foil	micron	8
Heights		
Cathode	mm	57.5
Anode	mm	58
Separator	mm	59.7
Cathode Foil	mm	57.5
Anode Foil	mm	58
Tab Configuration		
Cathode		Continuous
Anode		Continuous
Weights		
Enclosure Weight	g	123

基础模型

模型设置

Main | Model Setup | Cathode | Anode | Assembly | Thermal Behavior | A

Attribute	Unit	Object Value
Number of Control Volumes		
Cathode		6
Separator		4
Anode		6
Cathode Particle		12
Anode Particle		12
Cell Operating Conditions		
Lower Cutoff Voltage	V	2.48
Upper Cutoff Voltage	V	4.3
Open Circuit Voltage of Full Cell (100% SOC)	V	4.2
Solver Settings		
Time Step Size	s	10
Spatial Plot Storage Frequency		10
Maximum Iteration per TimeStep		100
Convergence Criteria		1e-6



- 厚度方向网格数
- 颗粒物径向网格数

- 电池截止电压
- OCV@100%SOC：影响实际可用容量，即 Operational capacity

- 时间步长，该步长决定autolion求解器
- 一维分布图输出时间间隔/s
- 每个时间步内最大迭代步
- 收敛标准

基础模型

- 阴极

阴极配方

阴极载量及尺寸

Main | Model Setup | Cathode | Anode | Assembly | Thermal Behavior | Advan

Attribute	Unit	Object Value
Formula		
Active Material #1		NCM622 ...
Active Material #1 Mass Fraction	fraction	0.94 ...
☐ Active Material #2		
Conductive Agent Density	g/cm^3	1.95 ...
Conductive Agent Mass Fraction	fraction	0.03 ...
Binder Density	g/cm^3	1.77 ...
Binder Mass Fraction	fraction	0.03 ...
Additive Density	g/cm^3	ign ...
Additive Mass Fraction	fraction	0 ...
Cathode Coating		
◉ Capacity Loading	mAh/cm^2	3.9 ...
○ Porosity		
Expansion Ratio		1 ...
Conductivity		
Conductivity	S/m	3.8 ...
Contact Resistance (@ Foil/Cathode Interface)	Ohm_m^2	0.0002 ...
Terminal to Foil Resistance	Ohm	ign ...

阴极活性材料及质量百分比

导电剂密度及质量百分比

粘合剂密度及质量百分比

阴极载量：按首充容量计算

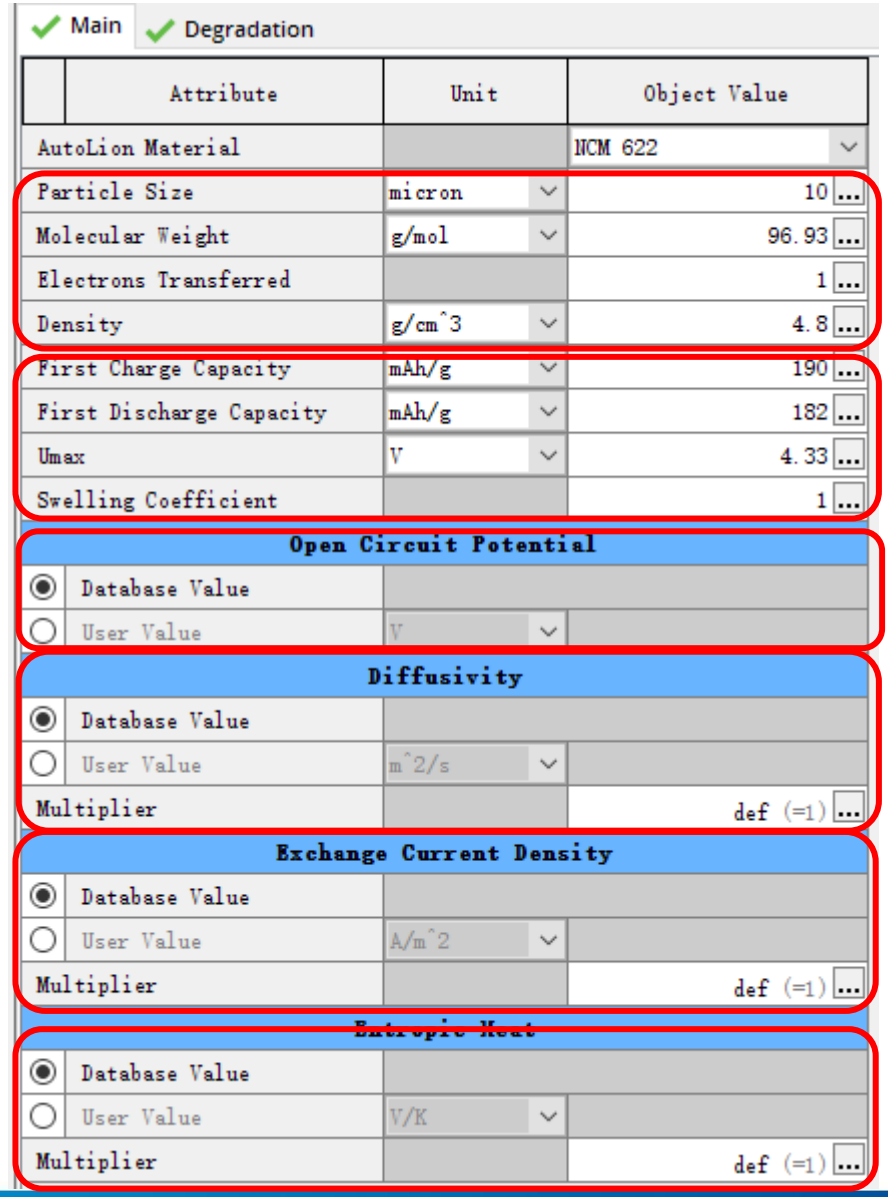
由于粘合剂或填充物弹性导致的阴极膨胀系数

阴极电导率及接触电阻

基础模型

- 阴极活性材料

活性材料膨胀系数



定义活性材料的颗粒物尺寸、摩尔质量、电荷数、密度

定义**半电池**首次充放电特性，其中质量指活性材料质量，Umax是半电池试验中最大开路电势，其会影响最大实际可用容量

活性材料开路电势，由数据库拟合

活性材料扩散系数，由数据库拟合

交换电流密度，由数据库拟合

熵热

基础模型

- 阴极活性材料

Main | Degradation

	Attribute	Unit	Object Value
	Film Growth		
	Initial Film Thickness	nm	2
	Film Conductivity	S/m	CathodeFilmConductivity
◉	No Film Growth		
○	Anode SEI Layer Growth		
○	Cathode CEI Layer Growth		
	Active Material Isolation		
☐	Active Material Isolation		
	Lithium Plating		
☐	Anode Lithium Plating		

阴极膜电导率

Main

Attribute	Unit	Object Value
Value at Reference Temperature		1.5384615384615387E-5
Reference Temperature	K	def (=298.15)
Activation Energy	J/mol	3.2e4

参考膜阻

膜阻活化能

阴极膜生长模型

$$\Phi = \Phi_{ref} \exp\left[\frac{E_{act,\Phi}}{R}\left(\frac{1}{T_{ref}} - \frac{1}{T}\right)\right]$$

阴极脱落模型

阳极析锂模型

基础模型

- 阳极

Main | Model Setup | Cathode | Anode | Assembly | Thermal Behavior | Advanced

	Attribute	Unit	Object Value
	Formula		
	Active Material #1		Graphite ...
	Active Material #1 Mass Fraction	fraction	0.94 ...
☐	Active Material #2		
	Conductive Agent Density	g/cm^3	1.95 ...
	Conductive Agent Mass Fraction	fraction	0.03 ...
	Binder Density	g/cm^3	1.77 ...
	Binder Mass Fraction	fraction	0.03 ...
	Additive Density	g/cm^3	ign ...
	Additive Mass Fraction	fraction	0 ...
	Anode Coating		
◉	N/P Ratio	fraction	1.15 ...
○	Capacity Loading	mAh/cm^2	
○	Porosity		
	Expansion Ratio		1 ...
	Conductivity		
	Conductivity	S/m	1e2 ...
	Contact Resistance (@ Foil/Anode Interface)	Ohm_m^2	0.0002 ...
	Terminal to Foil Resistance	Ohm	ign ...

N/P定义 $\left(\frac{N}{P}\right) = \left(\frac{m^{an} q_{th}^{an}}{m^{cat} q_{fcc}^{cat}}\right)$

基础模型

- 阳极活性材料

  与阴极意义相同

Main | Degradation

Attribute	Unit	Object Value
AutoLion Material		Graphite
Particle Size	micron	15
Molecular Weight	g/mol	72.06
Electrons Transferred		1
Density	g/cm^3	2.24
First Charge Capacity	mAh/g	371.933
First Discharge Capacity	mAh/g	350
Umax	V	2
Swelling Coefficient		1
Open Circuit Potential		
◉ Database Value		
○ User Value	V	
Diffusivity		
◉ Database Value		
○ User Value	m^2/s	
Multiplier		def (=1)
Exchange Current Density		
◉ Database Value		

Main

Attribute	Unit	Object Value
Value at Reference Temperature		1.5151515151515151E-5
Reference Temperature	K	def (=298.15)
Activation Energy	J/mol	3.2e4

Main | Degradation

Attribute	Unit	Object Value
Film Growth		
Initial Film Thickness	nm	5
Film Conductivity	S/m	AnodeFilmConductivity
◉ No Film Growth		
○ Anode SEI Layer Growth		
○ Cathode CEI Layer Growth		
Active Material Isolation		
☐ Active Material Isolation		
Lithium Plating		
☐ Anode Lithium Plating		

基础模型

- 装配体（Assembly）

Main | Model Setup | Cathode | Anode | Assembly

Attribute	Object Value
Foils and Separator	
Cathode Foil	Aluminum
Anode Foil	Copper
Separator	PolymericMembrane
Electrolyte	
Electrolyte	Electrolyte
Excess Ratio	1.3

Main

Attribute	Unit	Object Value
Density	g/cm^3	2.7
Electrical Conductivity	S/m	3.538E7
Thermal Conductivity	W/(m-K)	300
Specific Heat Capacity	J/kg-K	500

Main

Attribute	Unit	Object Value
Density	g/cm^3	8.96
Electrical Conductivity	S/m	5.8E7
Thermal Conductivity	W/(m-K)	300
Specific Heat Capacity	J/kg-K	500

Main

Attribute	Unit	Object Value
Density	g/cm^3	1.2
Porosity		0.4

电解液过量系数：

- 1.0：电极和隔板空隙充满电解液
- Def：电芯所有空隙充满电解液

基础模型

- 电解质

Main

Attribute	Unit	Object Value
AutoLion Electrolyte		LiPF6 in EC-EMC-DMC
Transference Number		0.38
Concentration	kmol/m^3	1.2
Density	g/cm^3	1.2
EC Volume Fraction		0.9
Ionic Conductivity		
Database Value		
User Value	S/m	
Multiplier		def (=1)
Diffusional Conductivity		
Database Value		
User Value	A/m	
Multiplier		def (=1)
Ionic Diffusivity		
Database Value		
User Value	m^2/s	
Multiplier		def (=1)

Electrolyte-phase charge conservation

$$0=\frac{\partial}{\partial x}\left(\kappa^{eff}\frac{\partial \phi_e}{\partial x}\right)+\frac{\partial}{\partial x}\left(\kappa_D^{eff}\frac{\partial \ln c_e}{\partial x}\right)+j^{Li}+a_{sl}C\frac{\partial(\phi_s-\phi_e)}{\partial t} \quad (6)$$

Electrolyte-phase Li^+ species conservation

$$\frac{\partial}{\partial t}[\varepsilon c_e]=\frac{\partial}{\partial x}\left(D_e^{eff}\frac{\partial c_e}{\partial x}\right)+\frac{1-t_+^o}{F}j^{Li}$$

电解质类型，密度和溶剂 $PF6^-$ 传递数

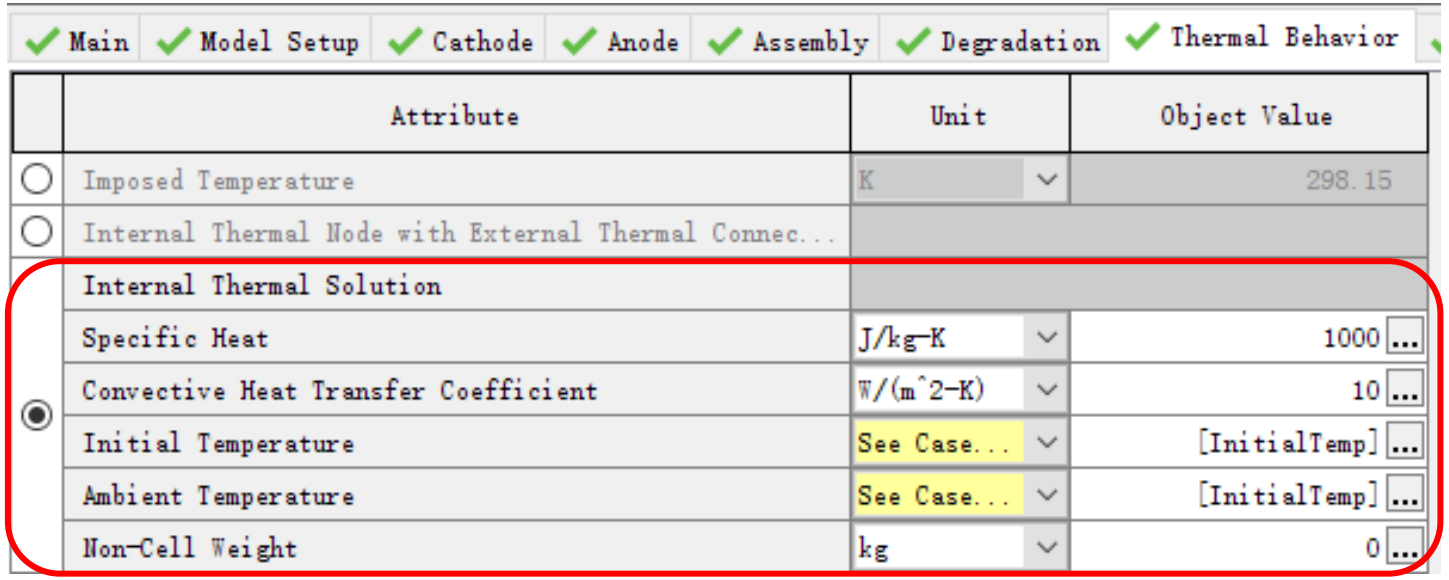
离子电导率

扩散电导率

离子扩散率

基础模型

传热



电池直接与外部大气换热

基础模型

高级

Attribute	Unit	Object Value
Bruggeman Exponents		
Cathode		1.5
Separator		1.5
Anode		1.5
Cathode Butler-Volmer Equations		
Anodic Charge Transfer Coefficient		0.5
Cathodic Charge Transfer Coefficient		0.5
Anode Butler-Volmer Equations		
Anodic Charge Transfer Coefficient		0.5
Cathodic Charge Transfer Coefficient		0.5
Double Layer Capacitance		
Cathode	F/m^2	ign
Anode	F/m^2	ign

多孔介质扩散系数Bruggeman修正

$$A_{eff} = A\varepsilon^{n},$$

阴阳极反应 BV 方程的转移系数

$$j_{rxn}^{Li} = a_s i_o \left\{ \exp\left[\frac{\alpha_a F}{RT} \left(\eta - \frac{R_f}{a_s} j_{rxn}^{Li} \right) \right] - \exp\left[-\frac{\alpha_c F}{RT} \left(\eta - \frac{R_f}{a_s} j_{rxn}^{Li} \right) \right] \right\}$$

双电层电容，ms级才会显著

$$i_{dl} = a_{dl} C \frac{\partial t(\phi_s - \phi_e)}{\partial t}$$

基础模型

- Plots 设置

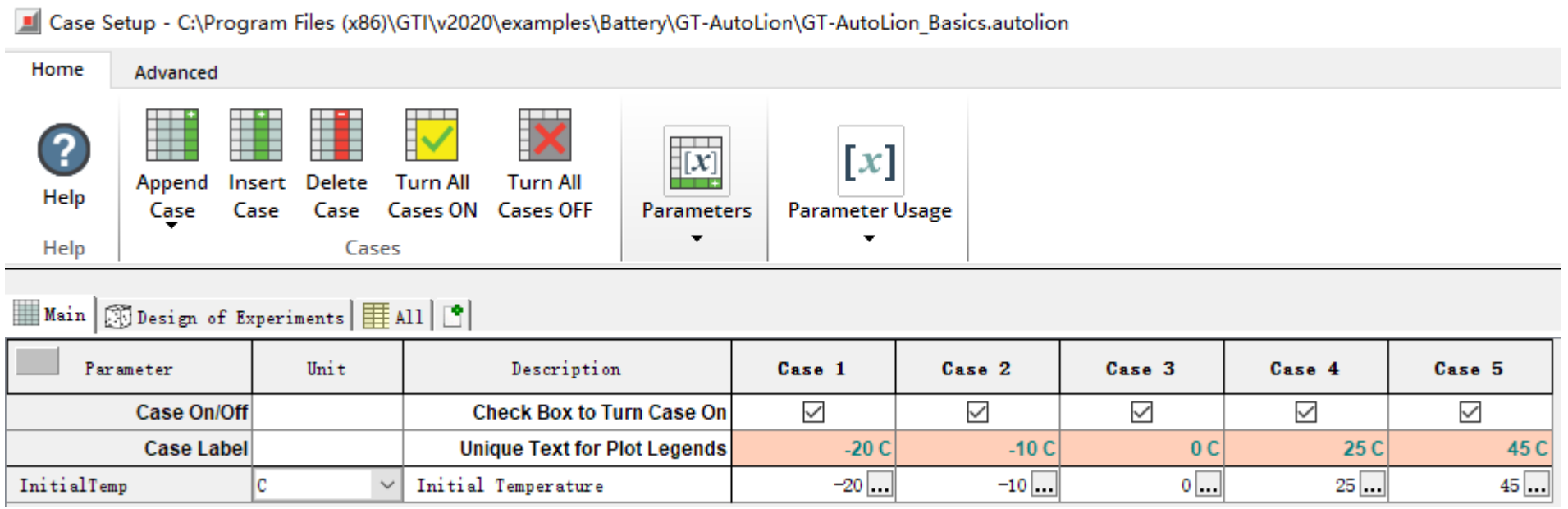
Main | Model Setup | Cathode | Anode | Assembly | Thermal Behavior | Advanced | Plots

Main | Aging | Details | Spatial Plots (Time) | Spatial Plots (Cycle) | Special Analyses | Anode | Cathode | Separator

Select / Unselect All Plots	☐	Max Plot Points	Plot Range	X-Axis	Sampling Type	Sampling Inte...
State of Charge	☑	def	def	def	def	def
Voltage	☑	def	def	def	def	def
Current	☑	def	def	def	def	def
Power	☑	def	def	def	def	def
Temperature	☑	def	def	def	def	def
Heat Generation Rate	☑	def	def	def	def	def
Open Circuit Voltage	☑	def	def	def	def	def
Internal Resistance	☐	def	def	def	def	def
Depleted/Added Capacity	☐	def	def		def	def
Electrolyte Concentrations	☐	def	def	def	def	def
Stoichiometry of Lithium Ions	☐	def	def	def	def	def
Voltage vs Capacity	☑	def	def		def	def
Temperature vs Capacity	☑	def	def		def	def

基础模型

- Case setup
  - 设置 5 个环境温度



Parameter	Unit	Description	Case 1	Case 2	Case 3	Case 4	Case 5
Case On/Off		Check Box to Turn Case On	☑	☑	☑	☑	☑
Case Label		Unique Text for Plot Legends	-20 C	-10 C	0 C	25 C	45 C
InitialTemp	C	Initial Temperature	-20 ...	-10 ...	0 ...	25 ...	45 ...

基础模型

- Run setup
  - 设置计算时长 4200s
  - 求解器选择隐式求解，最大时间步长10s，该步长建议与Autolion 一致

TimeControl | Initialization | ODEControl | SignalControl | ThermalControl

Attribute	Unit	Object Value
Maximum Simulation Duration (Time)	s	4200
Automatic Shut-Off When Steady-State		off
Improved Solution Sequence for Multi-Circuit Models		☐

TimeControl | Initialization | ODEControl | SignalControl | ThermalControl

Attribute	Unit	ODE Settings #1
Part Name List Object Identifying Circuits Belongi...		def
Integrator and Solution Control		DiffEqControl_Implicit
Time Step Output Frequency		def
Maximum Ratio of Time Steps in ODE Circuits		def (=20)
Maximum Ratio of Flow/ODE Time Step		def (=5)
Solve All Circuits Together (Single Solution Clust...		☑
Modal Analysis Property Object		ign

Main | SDC3

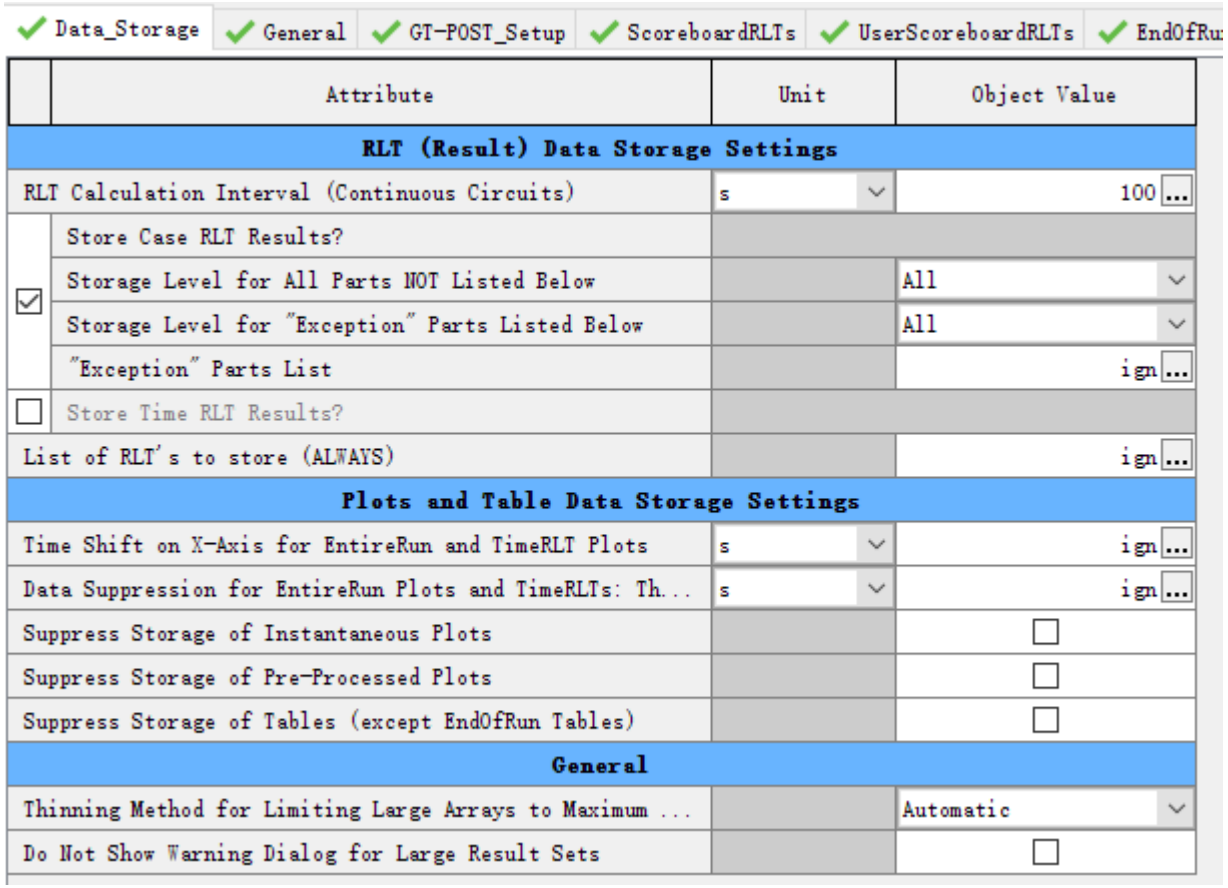
Attribute	Object Value
Integrator/Solver Type	Implicit-SDC3
Matrix Optimization Method	Cuthill-McKee
Matrix Storage Format	Skyline
Electrical Matrix Inversion Scheme	SVD

Main | SDC3

Attribute	Object Value
Maximum Integration Time Step	10
Initial Max. Integration Time Step	def
Time Step Relaxation Multiplier	5
Relative Tolerance	1E-5
Absolute Tolerance	1E-5
Convergence Control	
Jacobian Evaluation Convergence Criterion	0.001
Newton Raphson Convergence Criterion	0.1
Newton Raphson Iteration Limit	7

基础模型

- Output setup
  - RLT 数据存储间隔100s，

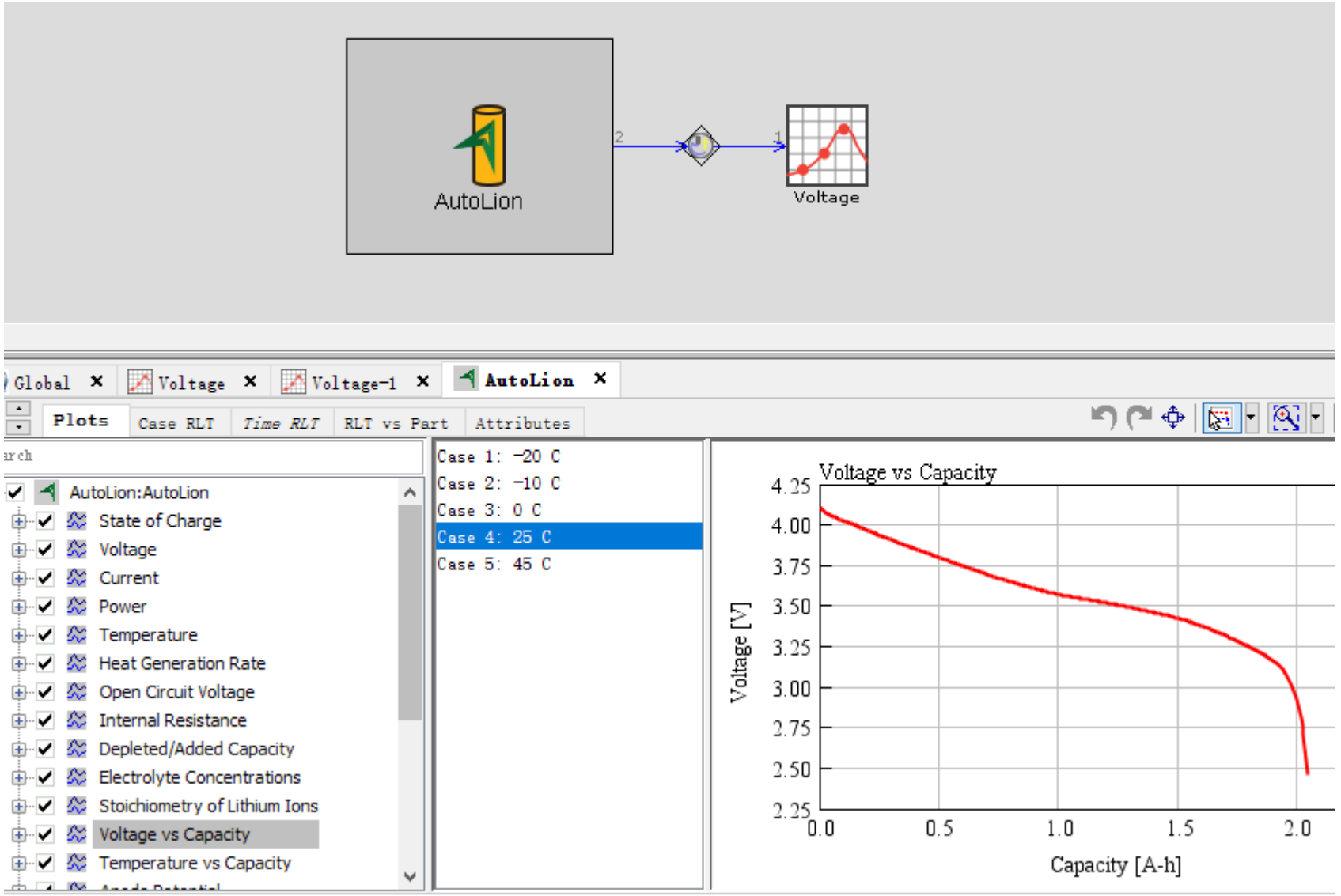


Data_Storage | General | GT-POST_Setup | ScoreboardRLTs | UserScoreboardRLTs | EndOfRu

	Attribute	Unit	Object Value
	RLT (Result) Data Storage Settings		
	RLT Calculation Interval (Continuous Circuits)	s	100 ...
☑	Store Case RLT Results?		
☑	Storage Level for All Parts NOT Listed Below		All
☑	Storage Level for "Exception" Parts Listed Below		All
☑	"Exception" Parts List		ign ...
☐	Store Time RLT Results?		
	List of RLT's to store (ALWAYS)		ign ...
	Plots and Table Data Storage Settings		
	Time Shift on X-Axis for EntireRun and TimeRLT Plots	s	ign ...
	Data Suppression for EntireRun Plots and TimeRLTs: Th...	s	ign ...
	Suppress Storage of Instantaneous Plots		☐
	Suppress Storage of Pre-Processed Plots		☐
	Suppress Storage of Tables (except EndOfRun Tables)		☐
	General		
	Thinning Method for Limiting Large Arrays to Maximum ...		Automatic
	Do Not Show Warning Dialog for Large Result Sets		☐

基础模型

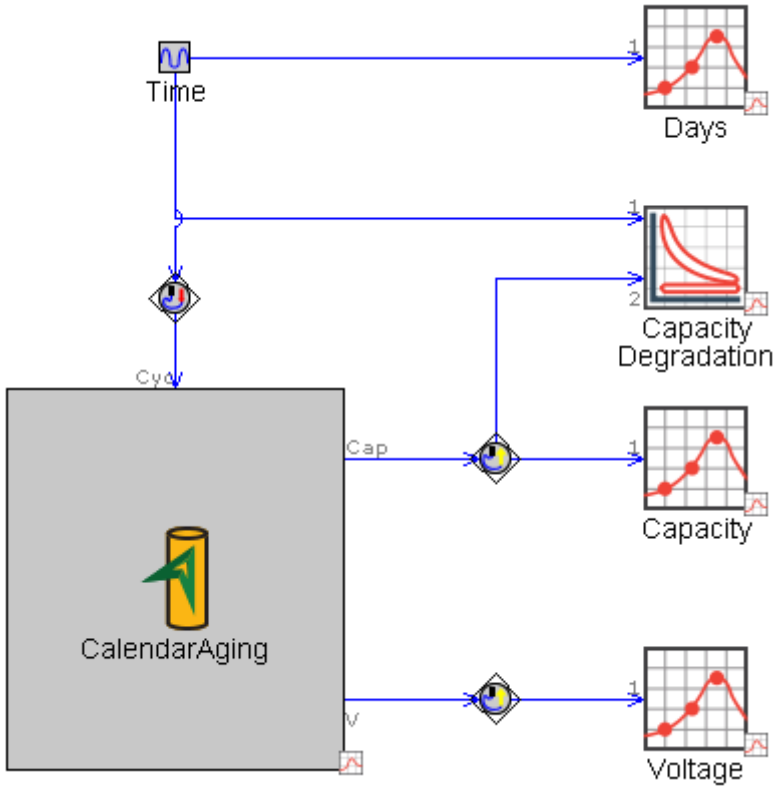
- 结果分析



目录

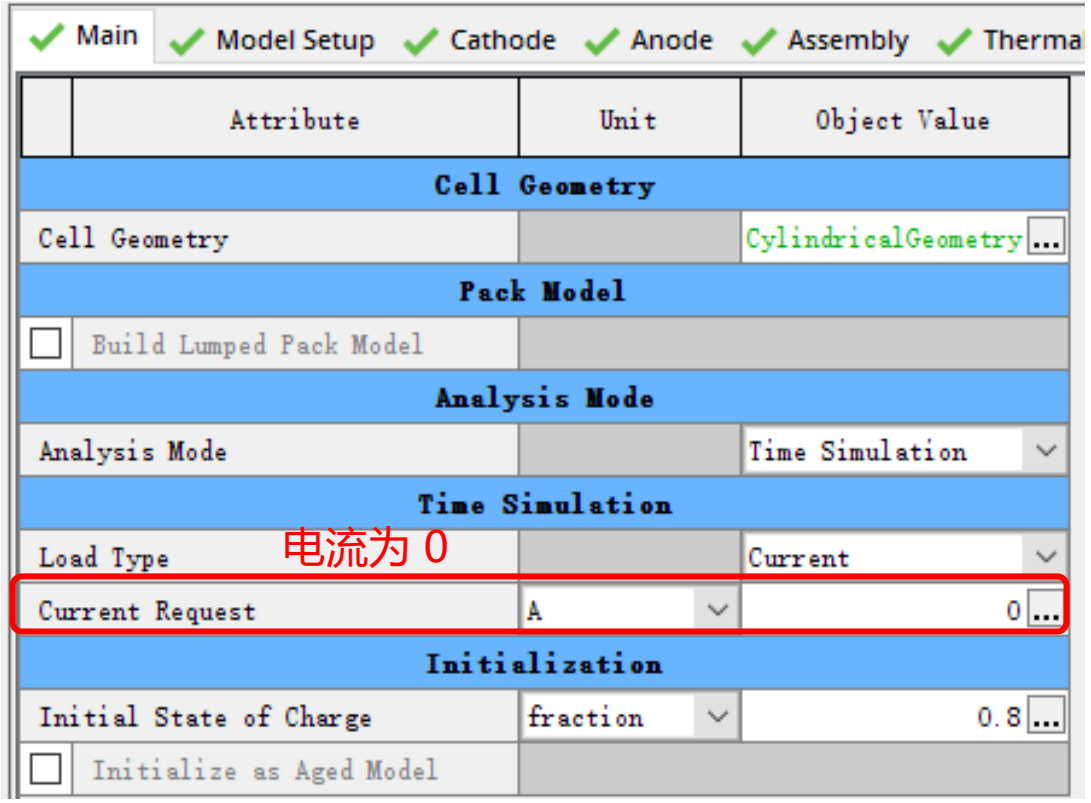
寿命计算——日历寿命

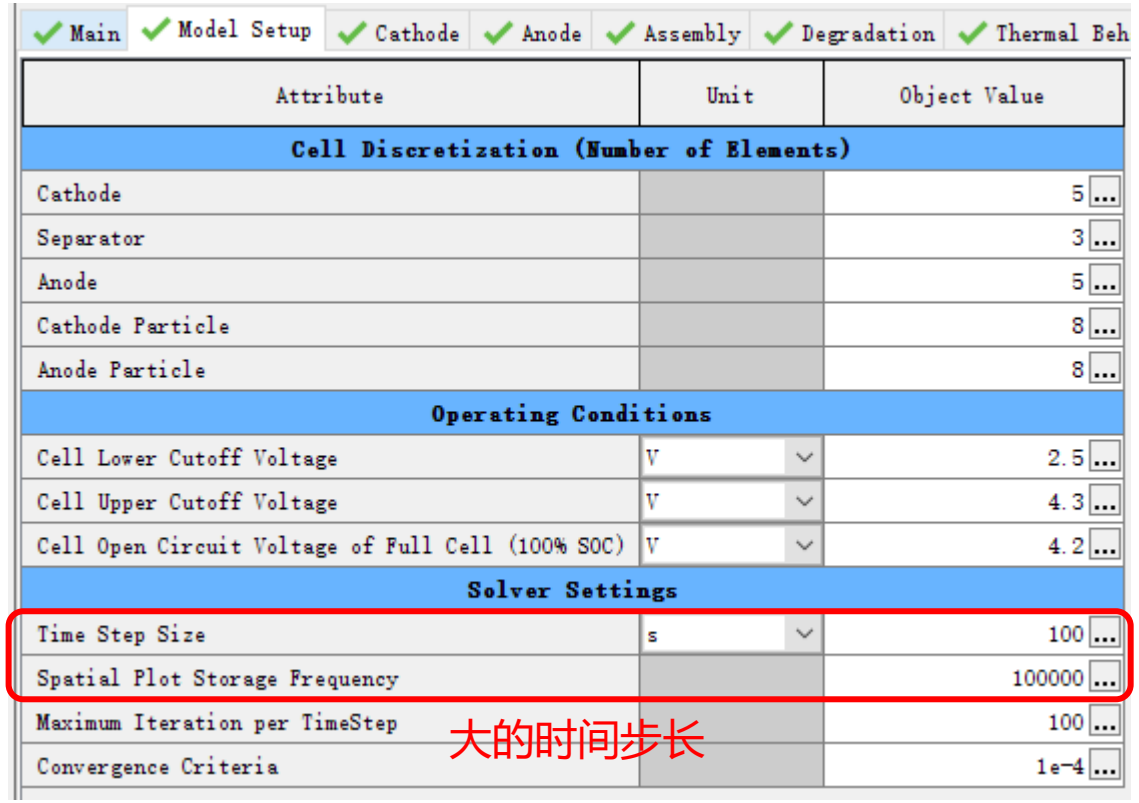
本模型为一个 18650型 NCM/C 电池静置100天，考虑 SEI 膜老化模型计算容量、电池电压的变化。



寿命计算——日历寿命

- 主窗口&模型设置

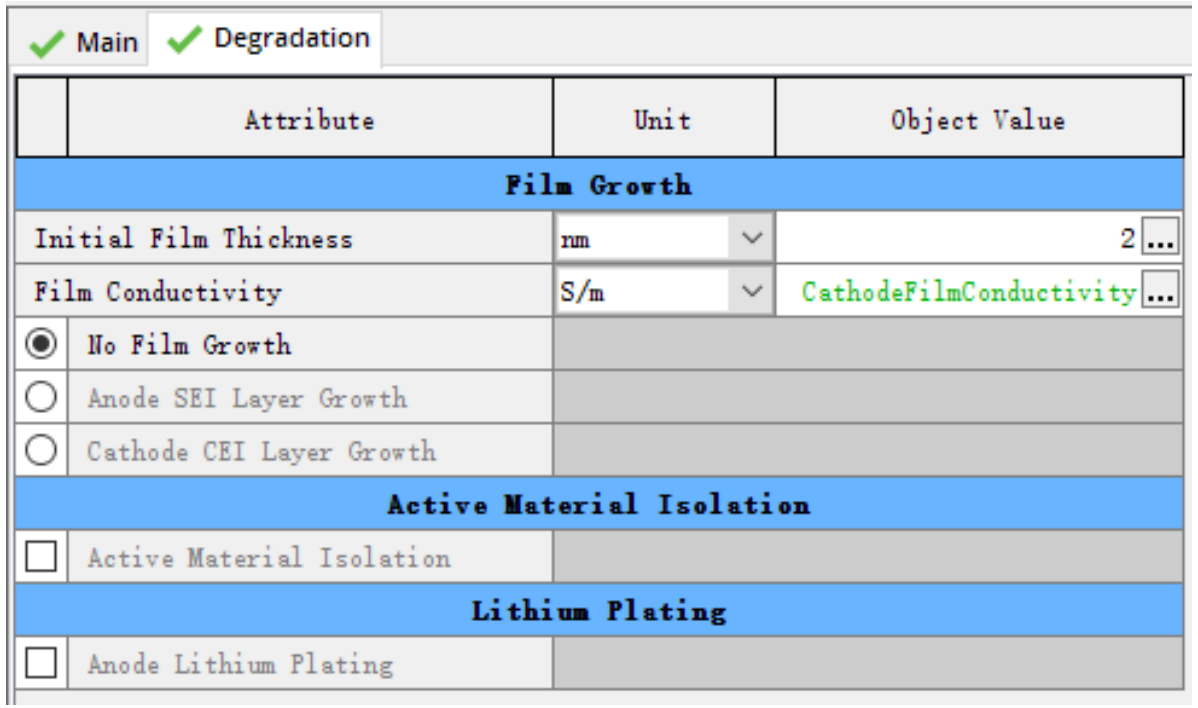




寿命计算——日历寿命

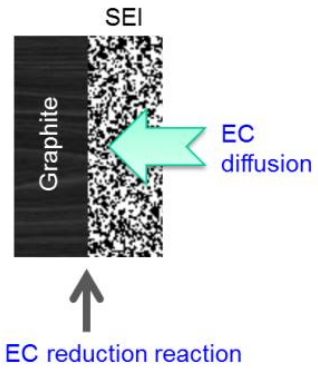
- 阴极活性材料老化模型设置

  本例不考虑阴极老化



寿命计算——日历寿命

- 阳极活性材料老化模型设置



Main | Degradation

	Attribute	Unit	Object Value
	Film Growth		
	Initial Film Thickness	nm	5
	Film Conductivity	S/m	AnodeFilmConductivity
○	No Film Growth		
	Anode SEI Layer Growth		
	EC Diffusivity	m^2/s	AnodeECDiff
	SEI Reaction Rate Coefficient		AnodeFilmGrowth
◉	SEI Equilibrium Potential	V	0.4
	SEI Charge Transfer Coefficient		0.5
	SEI Molecular Weight	g/mol	162
	SEI Density	g/cm^3	1.69
	SEI Porosity		0.05
○	Cathode CEI Layer Growth		
	Active Material Isolation		
☐	Active Material Isolation		
	Lithium Plating		
☐	Anode Lithium Plating		

Main

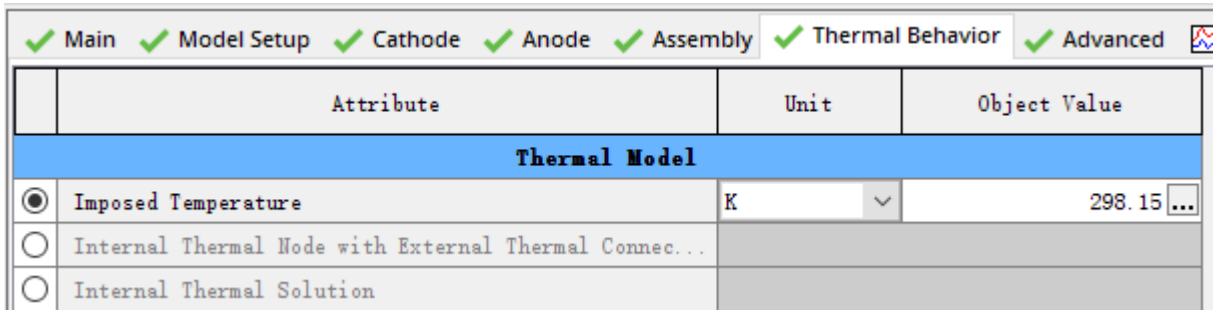
Attribute	Unit	Object Value
Value at Reference Temperature		1e-19
Reference Temperature	K	def (=298.15)
Activation Energy	J/mol	7e4

Main

Attribute	Unit	Object Value
Value at Reference Temperature		1.5e-16
Reference Temperature	K	def (=298.15)
Activation Energy	J/mol	6e4

寿命计算——日历寿命

- 传热、高级
  - 给定固体温度

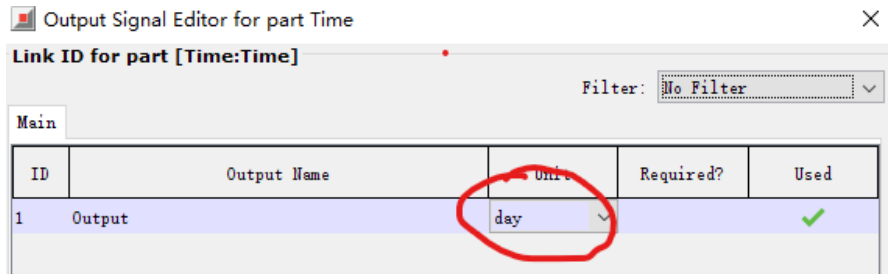


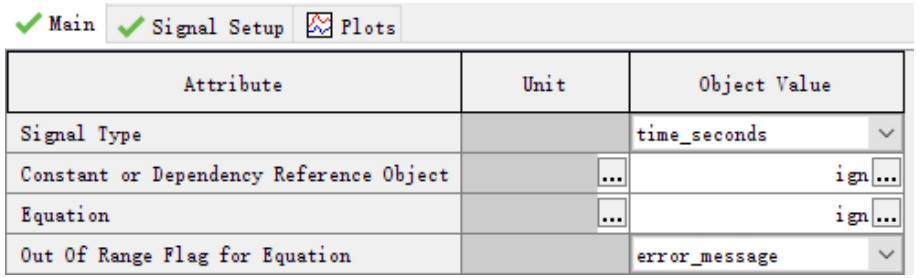
Attribute	Unit	Object Value
Bruggeman Exponents		
Cathode		1.5
Separator		1.5
Anode		1.5
Cathode Charge Transfer Coefficient		
Anodic		0.5
Cathodic		0.5
Anode Charge Transfer Coefficient		
Anodic		0.5
Cathodic		0.5
Double Layer Capacitance		
Cathode	F/m^2	ign
Anode	F/m^2	ign

寿命计算——日历寿命

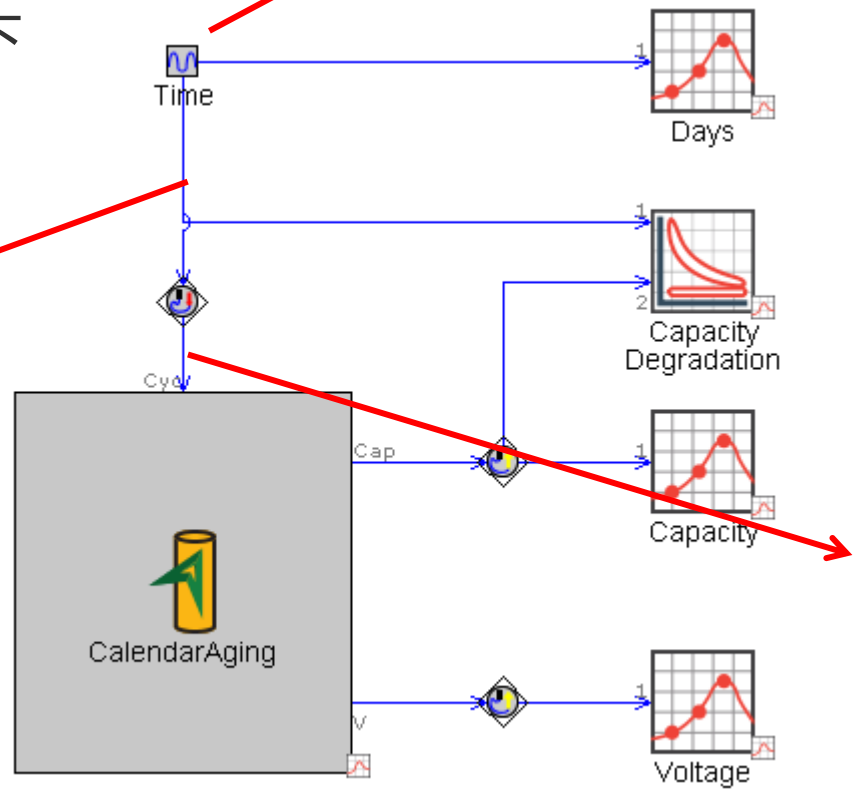
- 设置循环数
  - 将SignalGenerator, Gain，MathFunction模板拖入map中，并设置如下

单位：day

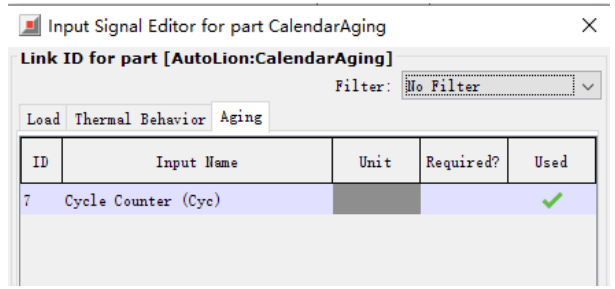




时间发生器



循环计数



寿命计算——日历寿命

- Run setup
  - 设置最大计算时长，单位day
  - 隐式求解器，最大时间步长100s

TimeControl | Initialization | ODEControl | SignalControl | ThermalControl

	Attribute	Unit	Object Value
◉	Maximum Simulation Duration (Time)	day	100
	Automatic Shut-Off When Steady-State		off
	Improved Solution Sequence for Multi-Circuit Models		☐

TimeControl | Initialization | ODEControl | SignalControl | ThermalControl

Attribute	Unit	ODE Settings #1
Part Name List Object Identifying Circuits Belongi...		def
Integrator and Solution Control		DiffEqControl_implicit
Time Step Output Frequency		def
Maximum Ratio of Time Steps in ODE Circuits		def (=20)
Maximum Ratio of Flow/ODE Time Step		def (=5)
Solve All Circuits Together (Single Solution Clust...		☑
Modal Analysis Property Object		ign

TimeStepControl | ConvergenceControl

Attribute	Object Value
Maximum Integration Time Step	100
Initial Max. Integration Time Step	def
Time Step Relaxation Multiplier	def
Maximum Ratio of Time Steps in ODE Circuits	def (=20)
Maximum Ratio of Flow/ODE Time Step	def (=5)

寿命计算——日历寿命

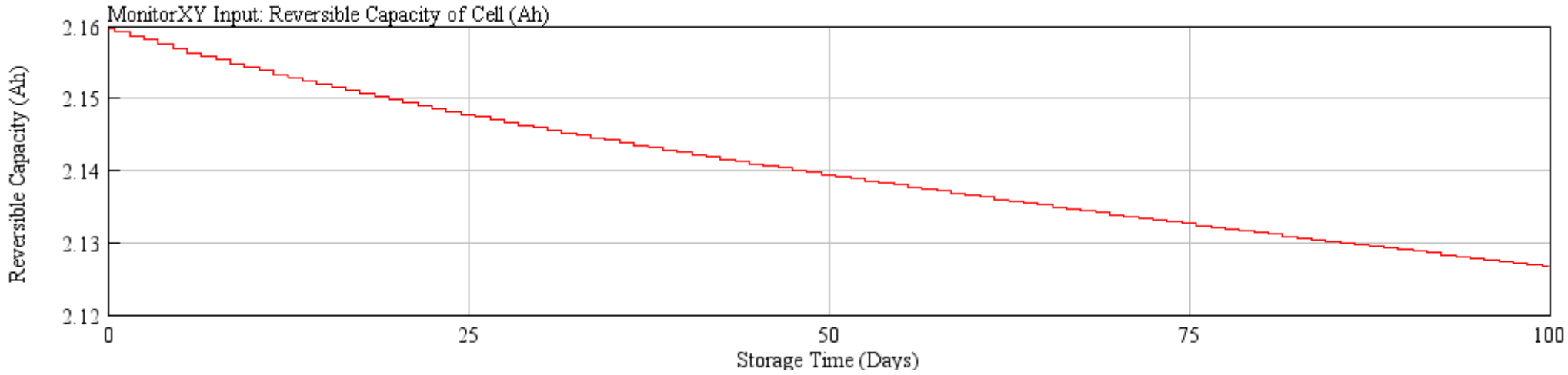
- Output setup
  - RLT 数据存储间隔200s

Data_Storage | General | GT-POST_Setup | ScoreboardRLTs | EndOfRunTables

	Attribute	Unit	Object Value
	RLT (Result) Data Storage Settings		
	RLT Calculation Interval (Continuous Circuits)	s	200
☑	Store Case RLT Results?		
	Storage Level for All Parts NOT Listed Below		All
	Storage Level for "Exception" Parts Listed Below		All
	"Exception" Parts List		ign
☐	Store Time RLT Results?		
	List of RLT's to store (ALWAYS)		ign
	Plots and Table Data Storage Settings		
	Time Shift on X-Axis for EntireRun and TimeRLT Plots	s	ign
	Data Suppression for EntireRun Plots and TimeRLTs: Th...	s	ign
	Suppress Storage of Instantaneous Plots		☐
	Suppress Storage of Pre-Processed Plots		☐
	Suppress Storage of Tables (except EndOfRun Tables)		☐
	General		
	Thinning Method for Limiting Large Arrays to Maximum ...		Automatic
	Do Not Show Warning Dialog for Large Result Sets		☐

寿命计算——日历寿命

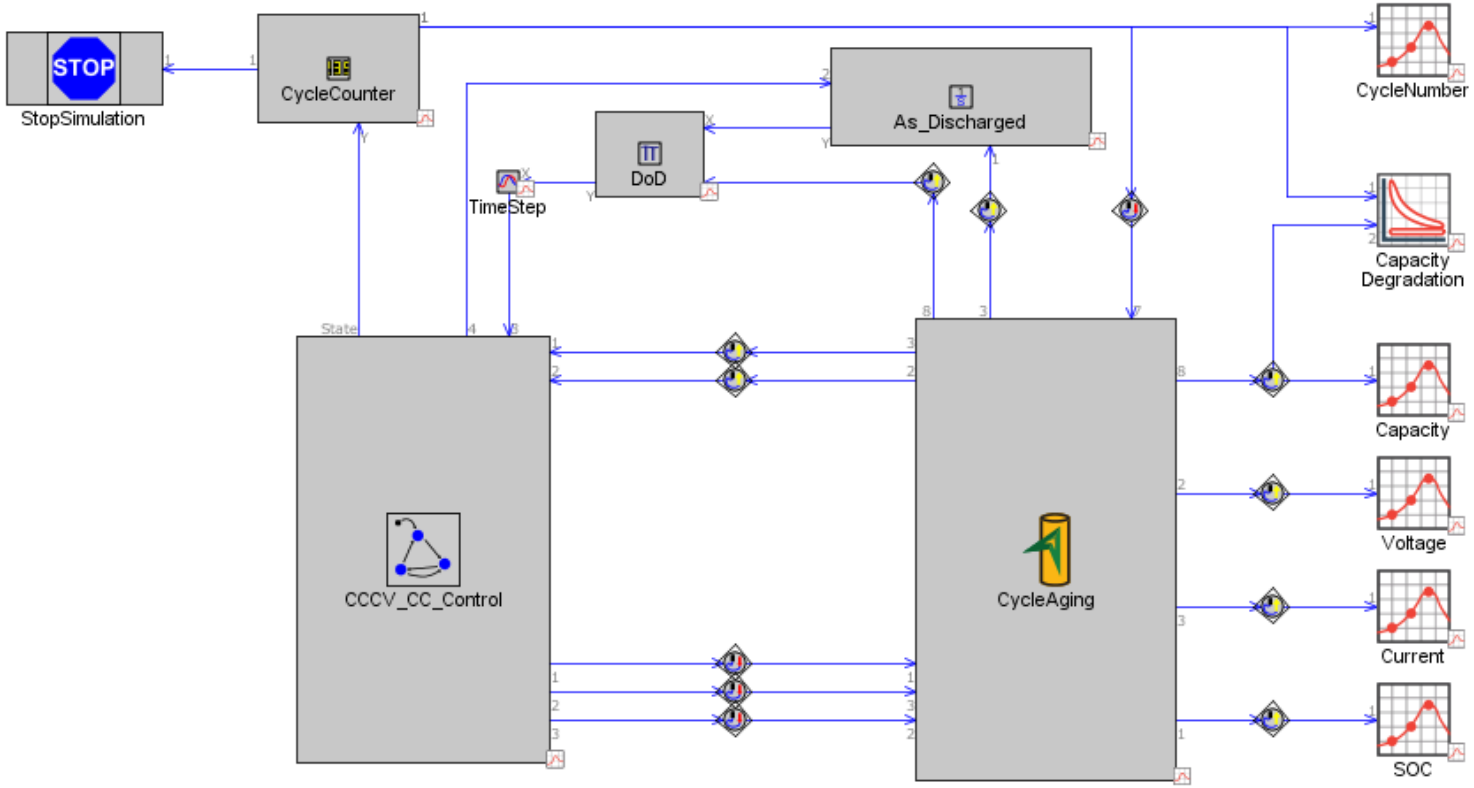
- 结果分析
  - 运行模型，查看结果



寿命计算——循环寿命

- 恒流放电：3.6A

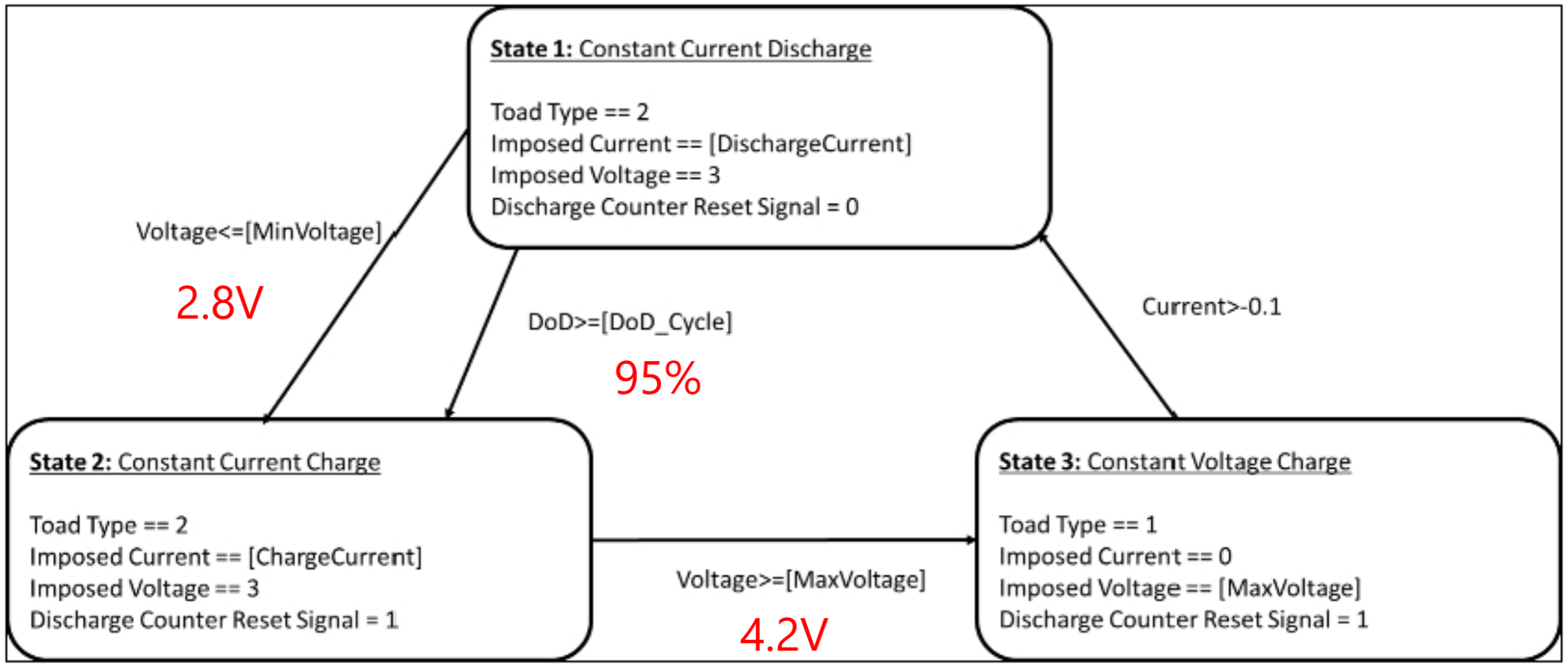
本模型为一个 18650 型 NCM/C 电池进行100次 CCCV_CC 循环，初始 SOC=1，考虑 SEI 膜老化模型和阳极活性材料隔离模型



寿命计算——循环寿命

- 控制逻辑

- 输入信号：电流、电压、DoD
- 输出信号：负荷形式、电流需求、电压需求、放电计数重置信号



寿命计算——循环寿命

- 新建一个auto.lion 模型，命名为 CycleAging，并定义电池

Main | Model Setup | Cathode | Anode | Assembly | Thermal Behavior

Attribute	Unit	Object Value
Cell Geometry		
Cell Geometry		CylindricalGeometry
Pack Model		
Build Lumped Pack Model		
Analysis Mode		
Analysis Mode		Time Simulation
Time Simulation		
Load Type		Mixed Requests (External Signal)
Voltage Request	V	3
Current Request	A	1
Power Request	W	350
Resistance	Ohm	10
Initialization		
Initial State of Charge	fraction	1
Initialize as Aged Model		

将通过外部控制信号控制负荷需求，本例中有电流和电压两种模式

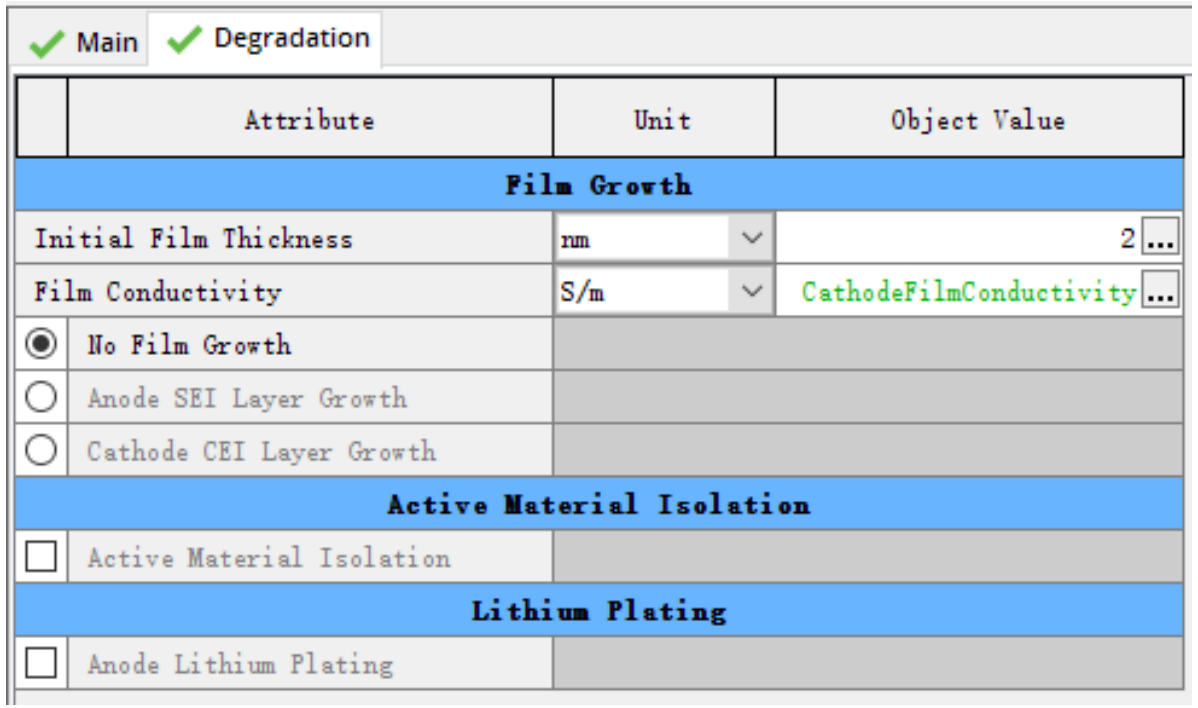
Main | Model Setup | Cathode | Anode | Assembly | Thermal Behavior

Attribute	Unit	Object Value
Number of Control Volumes		
Cathode		5
Separator		3
Anode		5
Cathode Particle		8
Anode Particle		8
Cell Operating Conditions		
Lower Cutoff Voltage	V	2.5
Upper Cutoff Voltage	V	4.3
Open Circuit Voltage of Full Cell (100% SOC)	V	4.2
Solver Settings		
Time Step Size	s	1
Spatial Plot Storage Frequency		100000
Maximum Iteration per TimeStep		100
Convergence Criteria		1e-4

寿命计算——循环寿命

- 阴极活性材料老化模型设置

  本例不考虑阴极老化



寿命计算——循环寿命

$$\Phi = \Phi_{ref} \exp\left[\frac{E_{act,\Phi}}{R}\left(\frac{1}{T_{ref}} - \frac{1}{T}\right)\right]$$

- 阳极活性材料老化模型设置

SEI 膜生成模型

活性材料脱落模型

Main | Degradation

	Attribute	Unit	Object Value
	Film Growth		
	Initial Film Thickness	nm	5
	Film Conductivity	S/m	AnodeFilmConductivity
○	No Film Growth		
◉	Anode SEI Layer Growth		
	EC Diffusivity	m^2/s	AnodeECDiff
	SEI Reaction Rate Coefficient		AnodeFilmGrowth
	SEI Equilibrium Potential	V	0.4
	SEI Charge Transfer Coefficient		0.5
	SEI Molecular Weight	g/mol	162
	SEI Density	g/cm^3	1.69
	SEI Porosity		0.05
○	Cathode CEI Layer Growth		
	Active Material Isolation		
☑	Active Material Isolation		
	Isolation Rate		AnodeAMI
	Lithium Plating		
☐	Anode Lithium Plating		

Main

Attribute	Unit	Object Value
Value at Reference Temperature		1e-19
Reference Temperature	K	def (=298.15)
Activation Energy	J/mol	7e4

Main

Attribute	Unit	Object Value
Value at Reference Temperature		1.5e-16
Reference Temperature	K	def (=298.15)
Activation Energy	J/mol	6e4

Main

Attribute	Unit	Object Value
Value at Reference Temperature		2e-14
Reference Temperature	K	def (=298.15)
Activation Energy	J/mol	0

寿命计算——循环寿命

- 传热、高级
  - 给定电池固体温度

Main | Model Setup | Cathode | Anode | Assembly | Degradation | Thermal Behavior

	Attribute	Unit	Object Value
◉	Imposed Temperature	K	298.15
○	Internal Thermal Node with External Thermal Connec...		
○	Internal Thermal Solution		

Main | Model Setup | Cathode | Anode | Assembly | Degradation

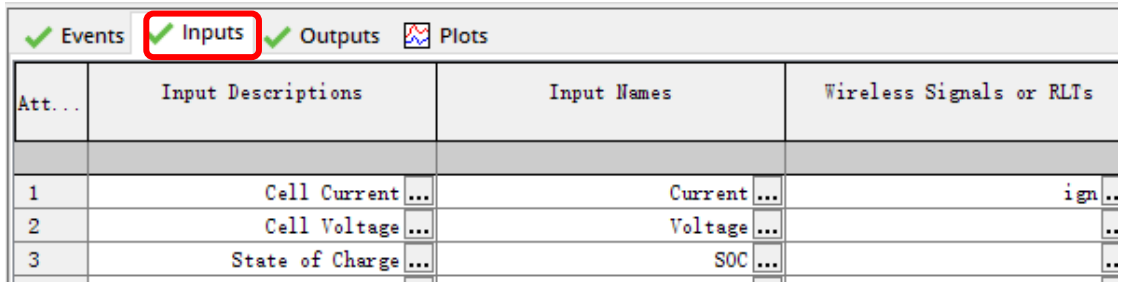
Attribute	Unit	Object Value
Bruggeman Exponents		
Cathode		1.5
Separator		1.5
Anode		1.5
Cathode Butler-Volmer Equations		
Anodic Charge Transfer Coefficient		0.5
Cathodic Charge Transfer Coefficient		0.5
Anode Butler-Volmer Equations		
Anodic Charge Transfer Coefficient		0.5
Cathodic Charge Transfer Coefficient		0.5
Double Layer Capacitance		
Cathode	F/m^2	ign
Anode	F/m^2	ign

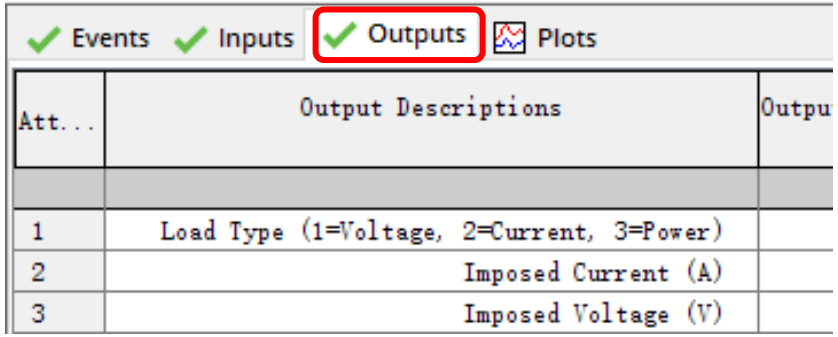
寿命计算——循环寿命

- CCCV_CC 控制器
  - 本节将通过EventManager来完成该CCCV_CC 的控制逻辑，其中下一个模式不仅与输入信号有关，而且还与当前状态有关，相对于If-then-else 更简明
  - 将 EventManager 模板拖入map中，并命名为 CCCV_Controls；分别定义输入量和输出量

状态转移表

当前状态 → 条件 ↓	状态 A	状态 B	状态 C
条件 X	…	…	…
条件 Y	…	状态 C	…
条件 Z	…	…	…





寿命计算——循环寿命

- CCCV_CC 控制器

  - 定义控制模块的模式(State)和转移条件，本例定义了 4 种模式，4 个转移条件

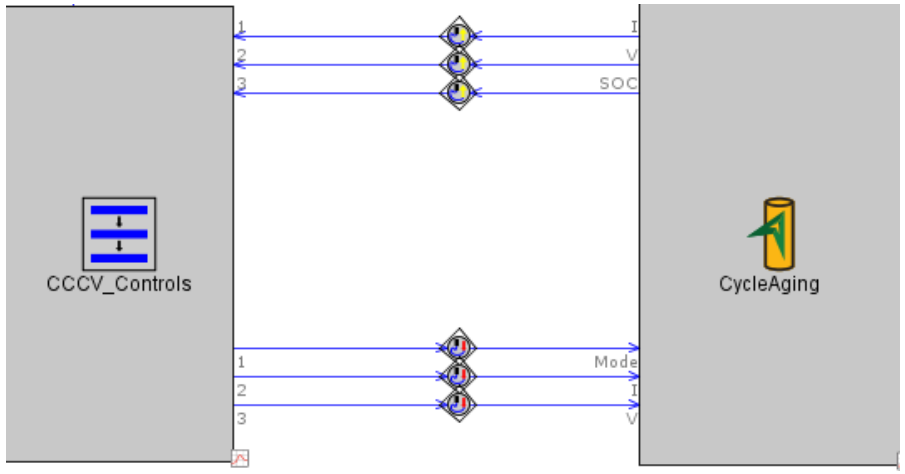
Events | Inputs | Outputs | Plots

Att...	Event Descriptions	Event Exit Criterion	Next Event No.	Load Type (1=Voltage, 2=Current, 3=Power)	Imposed Current (A)	Imposed Voltage (V)
1	Initialize	etime>1	2	2	0	3
2	CC Discharge	SOC<=[MinSOC]\\ Voltage<=[MinVoltage]	3	2	[DischargeCurrent]	3
3	CC Charge	Voltage>=[MaxVoltage]	4	2	[ChargeCurrent]	3
4	CV Charge	Current>-0.1	2	1	0	[MaxVoltage]

所用参数：
etime：固有参数，代表处于当前模式的时间
MinSOC: SOC下限（5%）
MinVoltage: 放电最小电压（2.8V）
MaxVoltage: 放电最大电压（ 4.2V）
DischargeCurrent: 放电电流(3.6A)
ChargeCurrent: 充电电流（-3.6A）

寿命计算——循环寿命

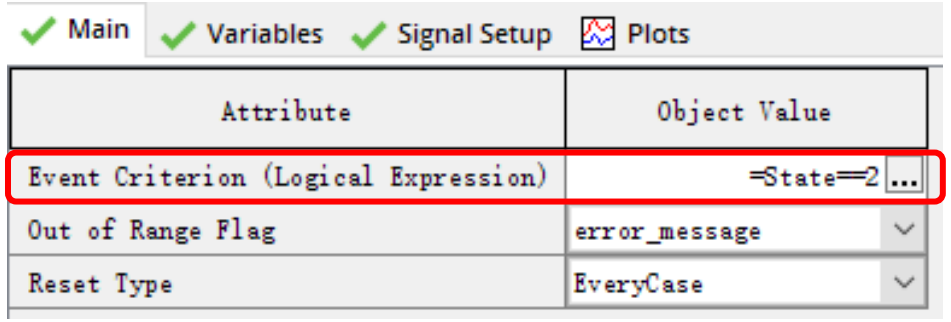
- 连接模型
  - 按下表连接模型

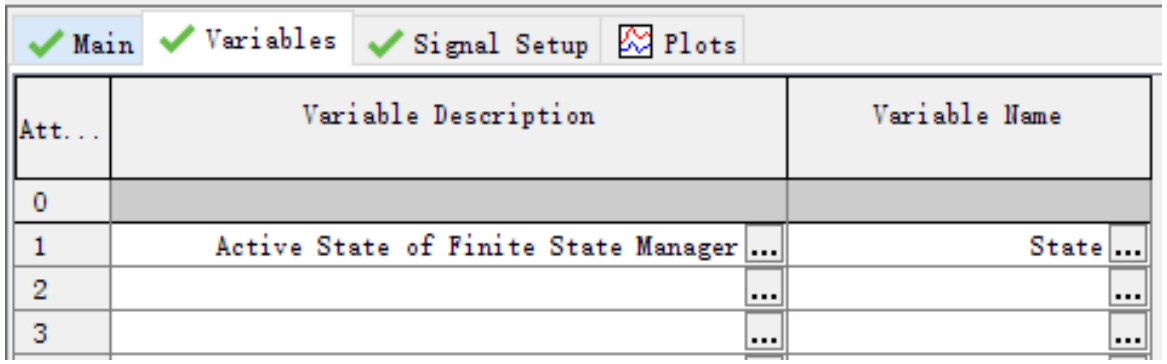


Start		End	
Part	signal	Part	signal
CycleAging	current	CCCV_Controls	Cell Current
CycleAging	voltage	CCCV_Controls	Cell voltage
CycleAging	SOC	CCCV_Controls	State of Charge
CCCV_Controls	Load type	CycleAging	Load type
CCCV_Controls	Imposed current	CycleAging	Current request
CCCV_Controls	Imposed voltage	CycleAging	Voltage request

寿命计算——循环寿命

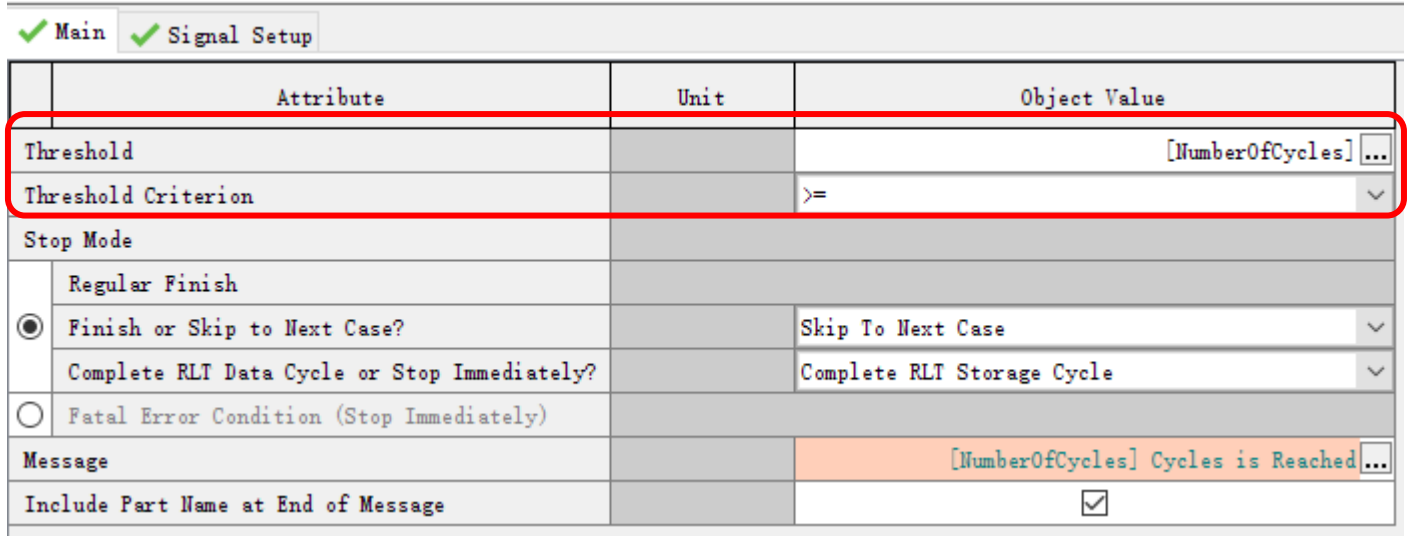
- 循环计数
  - 将模板 EventCounter 拖入map，命名为 CycleCounter





寿命计算——循环寿命

- 计算终止器
  - 将模板 StopSimulation 拖入map，设置如下

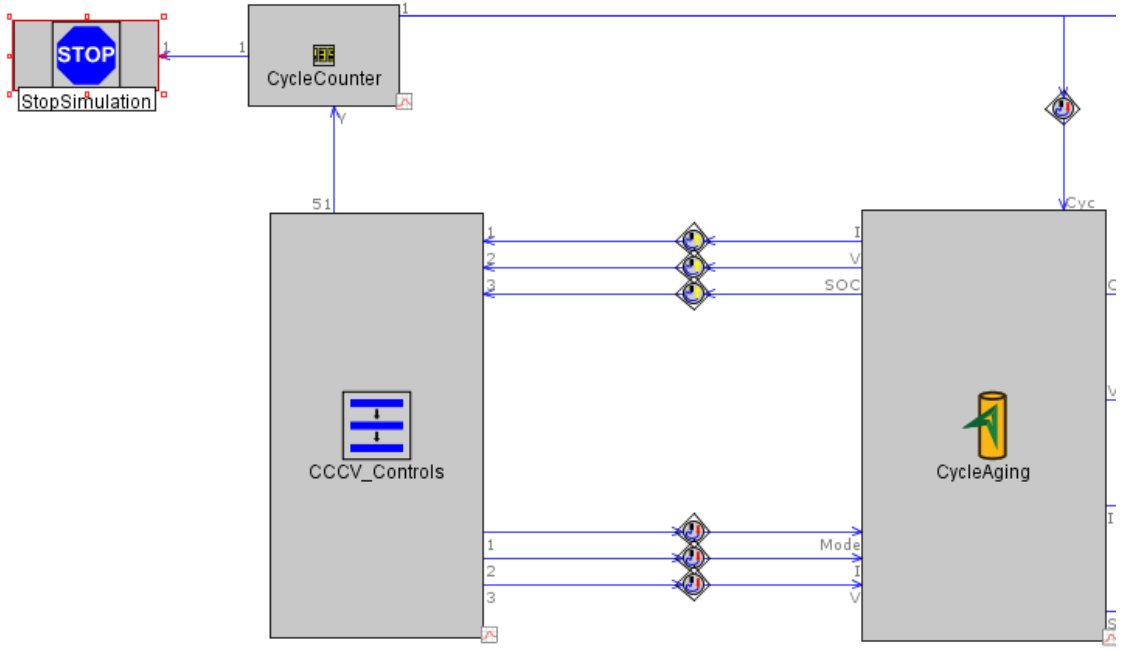


达到设定循环数，计算停止

寿命计算——循环寿命

- 连接模型

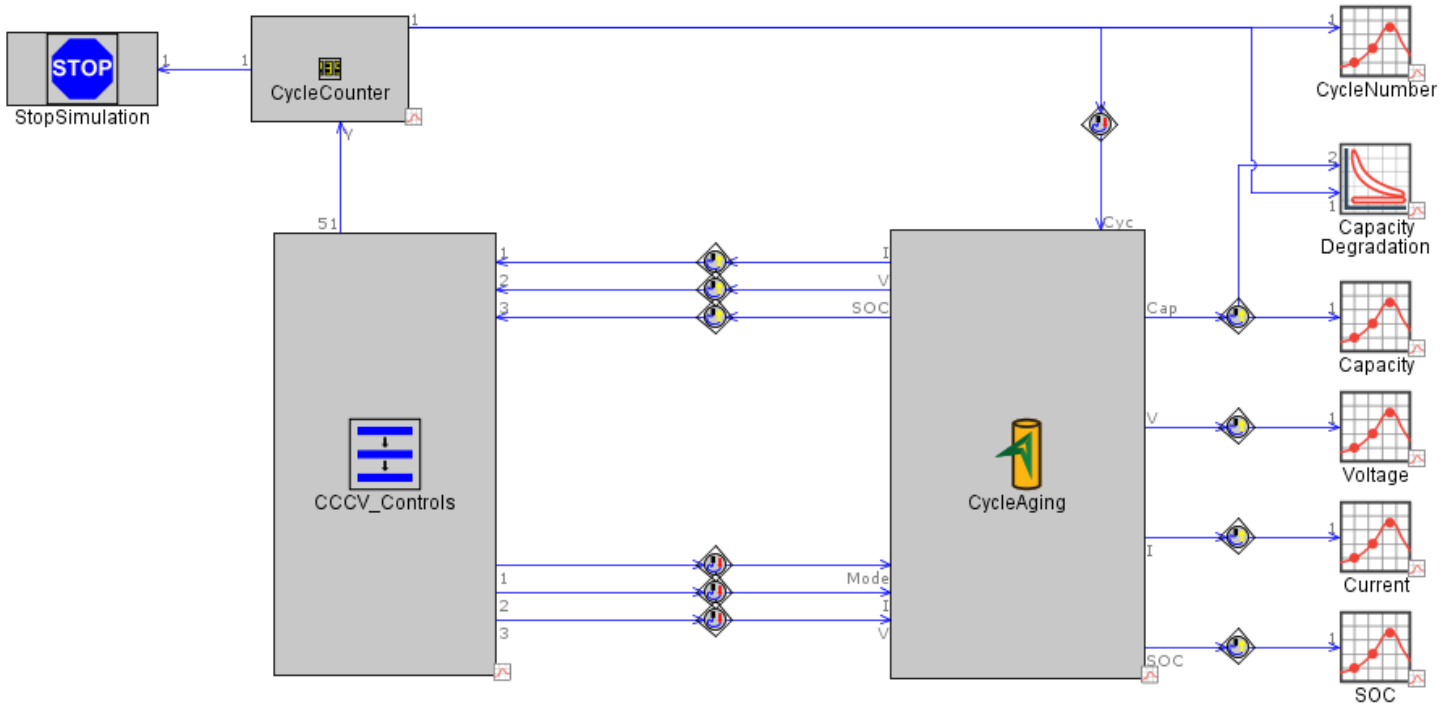
Start		End	
Part	signal	Part	signal
CCCV_Controls	state	CycleCounter	input
CycleCounter	output	CycleAging	Cycle counter
CycleCounter	output	StopSimulation	input



寿命计算——循环寿命

- 监控器设置

  - 将模板 MonitorSignal 拖入map，建立 5 个监控器，分别监控 CycleNumber，capacity，voltage，current，SOC
  - 将模板 MonitorXY 拖入map，建立容量退化的XY图，即capacity degradation
  - 最终结果如右图



寿命计算——循环寿命

- Run setup
  - 设置最大计算时长，足够长即可
  - 本例采用显式求解，设置最大时间步长为5s

TimeControl | Initialization | ODEControl | SignalControl | ThermalControl

	Attribute	Unit	Object Value
◉	Maximum Simulation Duration (Time)	h	=[NumberOfCycles]*4 f(x)
	Automatic Shut-Off When Steady-State		off
	Improved Solution Sequence for Multi-Circuit Models		☐

TimeControl | Initialization | ODEControl | SignalControl | ThermalControl

Attribute	Unit	ODE Settings #1
Part Name List Object Identifying Circuits Belongi...		def ...
Integrator and Solution Control		DiffEqControl_expltest ...
Time Step Output Frequency		def ...
Maximum Ratio of Time Steps in ODE Circuits		def (=20) ...
Maximum Ratio of Flow/ODE Time Step		def (=5) ...
Solve All Circuits Together (Single Solution Clust...		☑
Modal Analysis Property Object		ign ...

Main | RungeKutta

Attribute	Object Value
Integrator/Solver Type	Explicit-Runge-Kutta
Matrix Optimization Method	Cuthill-McKee
Matrix Storage Format	Skyline
Electrical Matrix Inversion Scheme	SVD

Main | RungeKutta

Attribute	Unit	Object Value
Maximum Integration Time Step		5 ...
Initial Max. Integration Time Step		def ...
Time Step Relaxation Multiplier		def (=5) ...
Mechanical Degrees of Freedom		
Integration Relative Accuracy		1E-4 ...
Translational Displacement Accuracy Norm	m	0.001 ...
Translational Velocity Accuracy Norm	m/s	0.01 ...
Rotational Displacement Accuracy Norm	deg	0.0572957795130823 ...
Rotation Velocity Accuracy Norm	RPM	0.095492965 ...

寿命计算——循环寿命

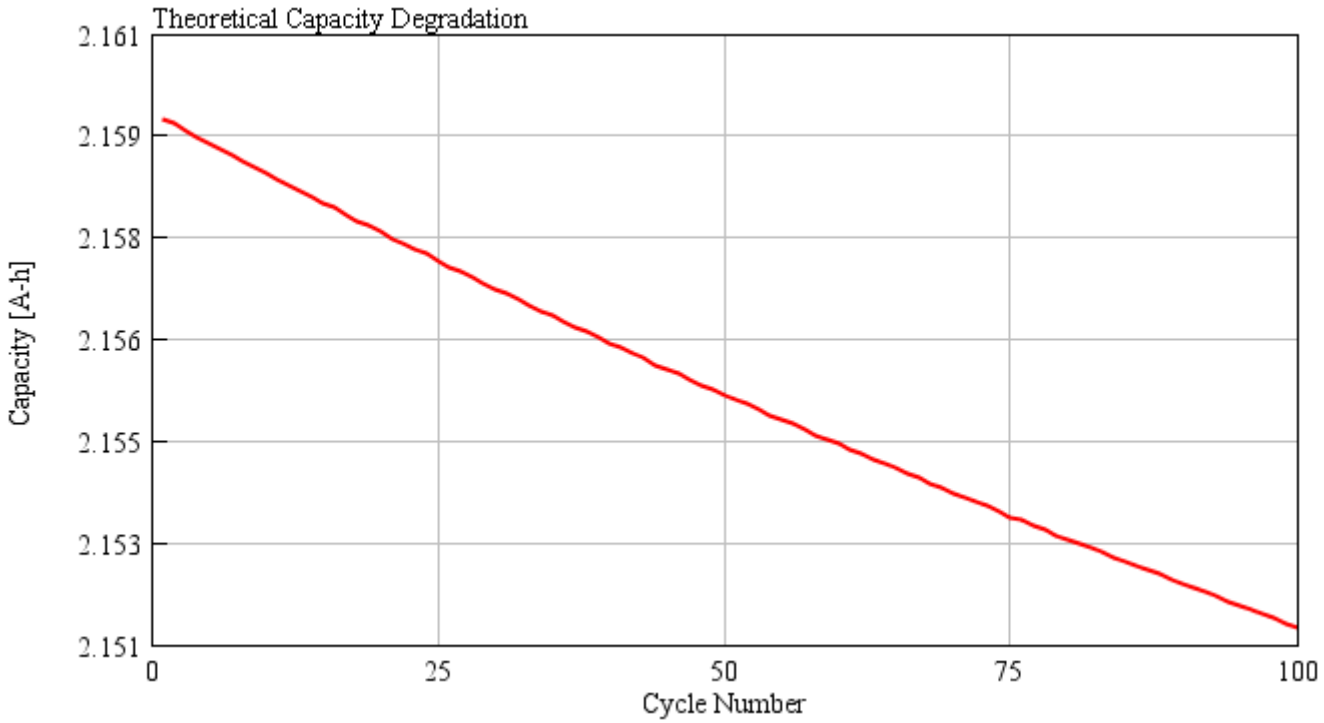
- Case setup

Main | Design of Experiments | All

Parameter	Unit	Description	Case 1
Case On/Off		Check Box to Turn Case On	☑
Case Label		Unique Text for Plot Legends	
DischargeCurrent	A	Discharge Current	3.6 ...
ChargeCurrent	A	Charge Current	-3.6 ...
MinVoltage	V	Minimum Voltage of Cell	2.8 ...
MaxVoltage	V	Max Voltage of Cell	4.2 ...
NumberOfCycles		Number of Cycles to Run	100
MinSOC		Minimum SOC	0.05 ...

寿命计算——循环寿命

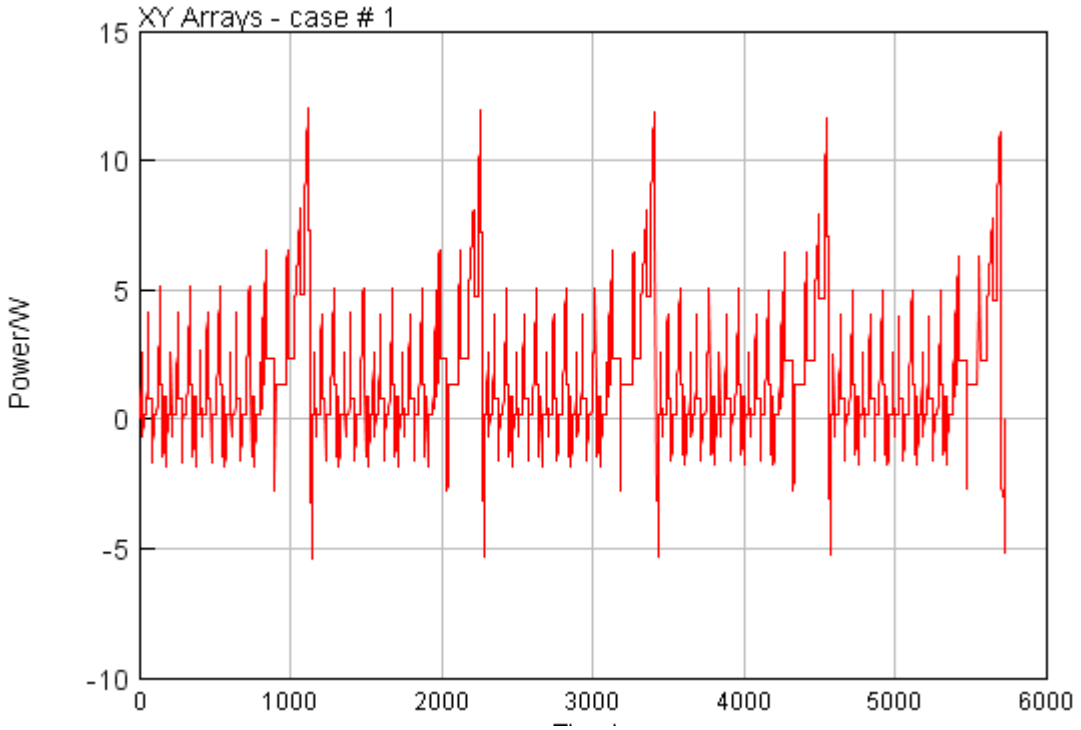
- 运行模型查看结果



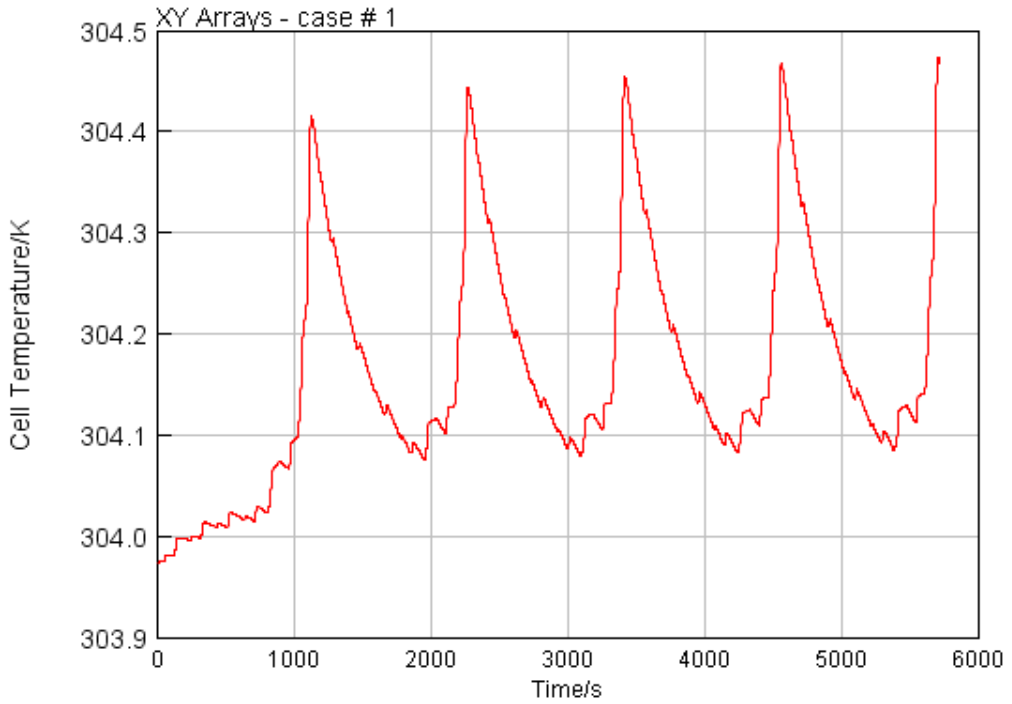
寿命计算——带循环工况的循环寿命

- 本例在前例的基础上进行修改，在循环中增加两个模式：5个NEDC循环+一个充电结束后休息1h

NEDC 功率需求

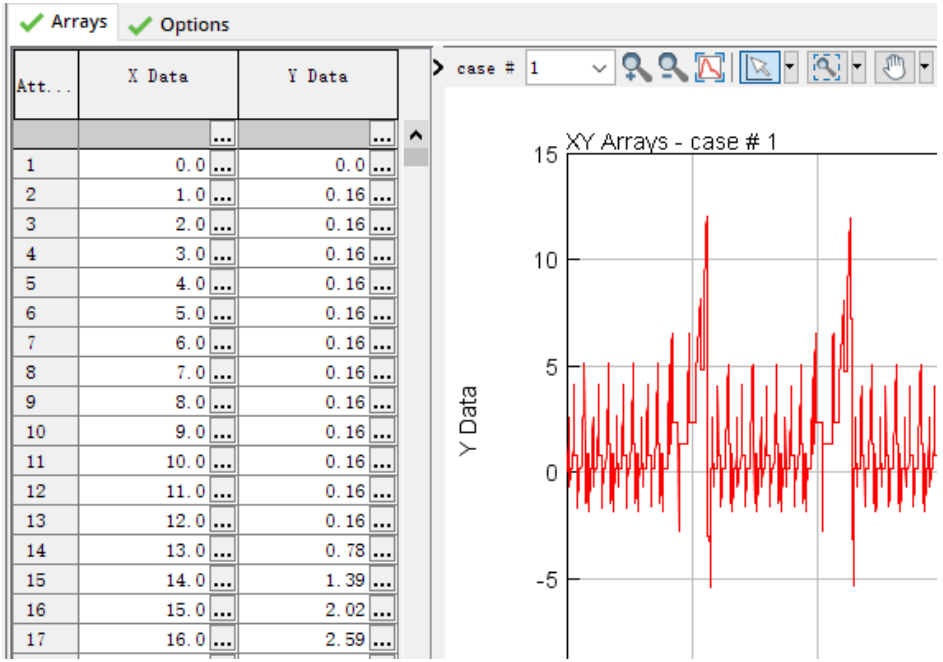


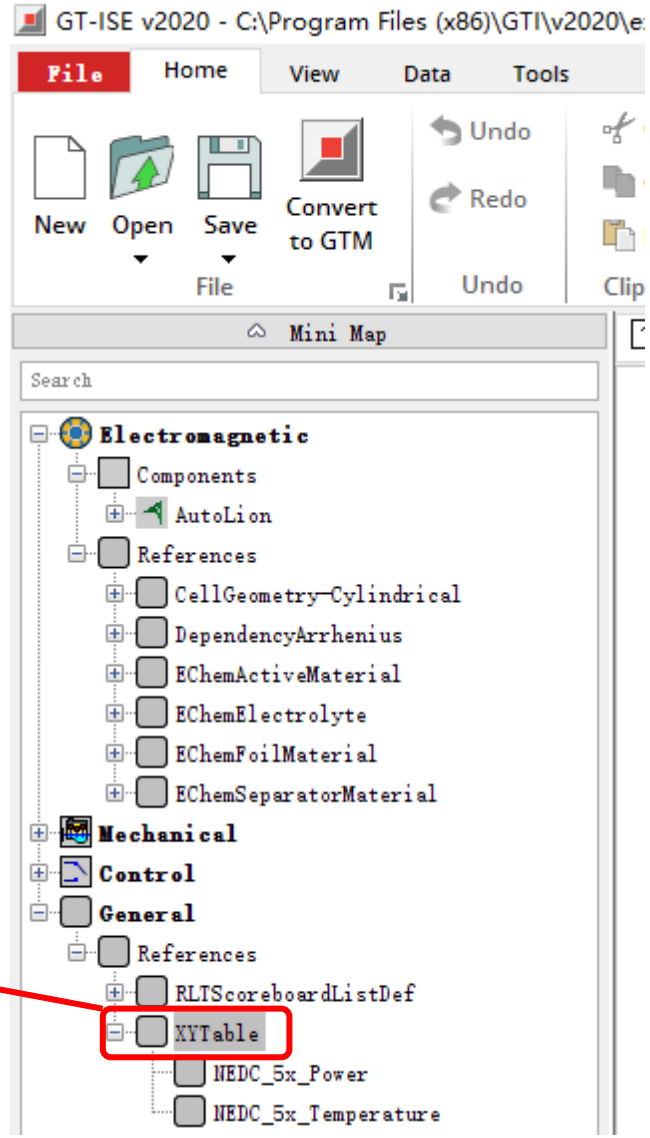
NEDC 过程中的电芯温度



寿命计算——带循环工况的循环寿命

- 首先建立两个 table，用于查表得到功率需求和电芯温度
  - 双击 XYTable，建立两个表，分别命名为 NEDC_5x_Power，NEDC_5x_Temperature





寿命计算——带循环工况的循环寿命

- 打开CCCV_Controls控制器，增加两个输出：功率和电芯温度。用于控制电芯的功率需求和温度

Events | Inputs | Outputs | Plots

Att...	Output Descriptions	Output Signal Map Labels
1	Load Type (1=Voltage, 2=Cu...	def
2	Imposed Current (A)	
3	Imposed Voltage (V)	
4	Imposed Power (W)	
5	Imposed Temperature (K)	

寿命计算——带循环工况的循环寿命

- 将放电模式修改为5个NEDC放电，并增加一个休息模式

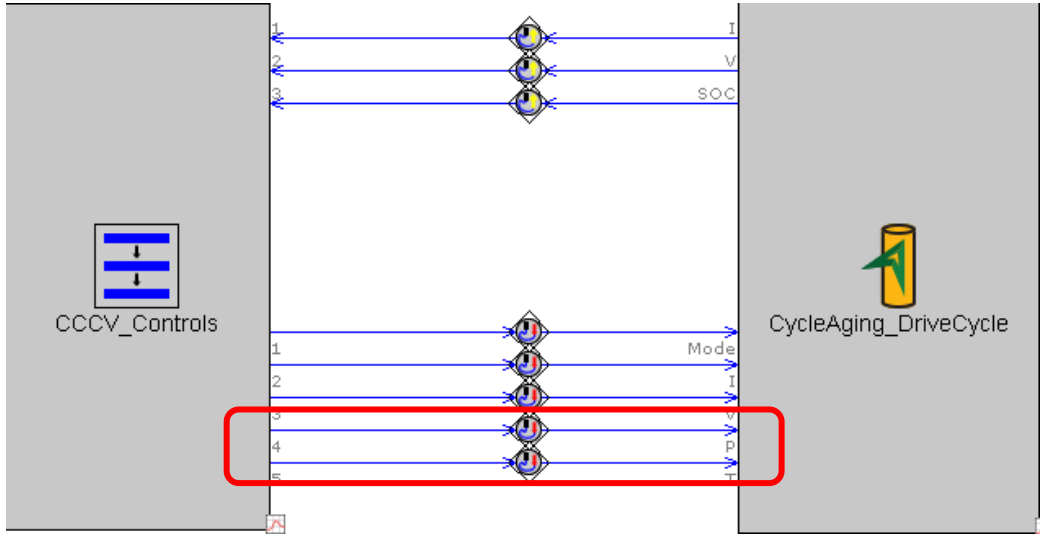
Events | Inputs | Outputs | Plots

Att...	Event Descriptions	Event Exit Criterion	Next Event No.	Load Type (1=Voltage, 2=Current, 3=Power)	Imposed Current (A)	Imposed Voltage (V)	Imposed Power (W)	Imposed Temp
1	Initialize	etime>1	2	2	0	3	0	
2	NEDC 5x Power Profile Discharge	etime>5725	3	3	0	3	=LookupXY(NEDC_5x_Power, etime)	=LookupXY(NEDC_5x_Te
3	CC Charge	Voltage>=[MaxVoltage]	4	2	[ChargeCurrent]	3	0	
4	CV Charge	Current>-0.1	5	1	0	[MaxVoltage]	0	
5	Rest for 1 Hour	etime>3600	2	2	0	3	0	
6								

功率查表函数：LookupXY(NEDC_5x_Power,etime)
温度查表函数：LookupXY(NEDC_5x_Temperature,etime)

寿命计算——带循环工况的循环寿命

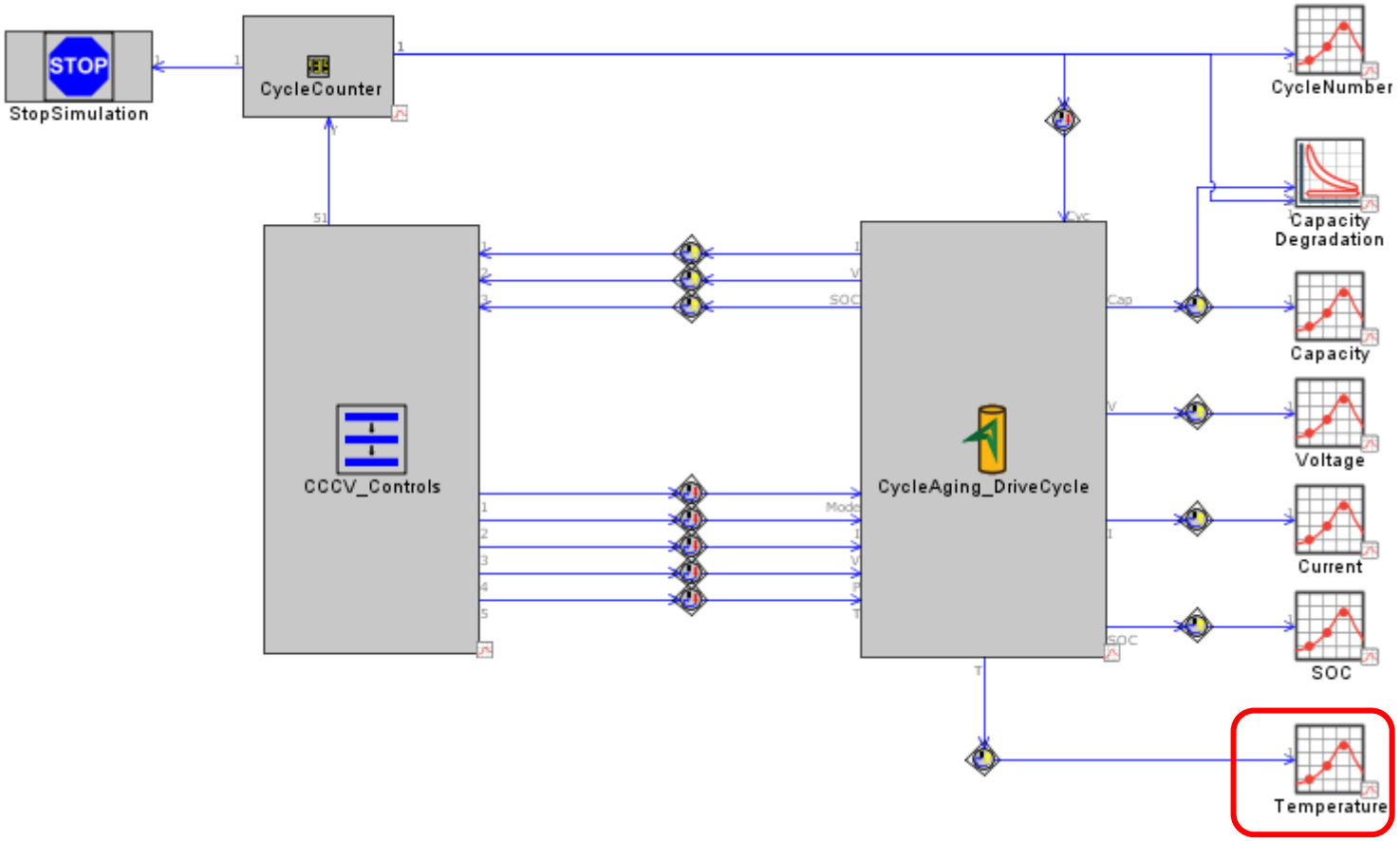
- 增加两个连接，将控制器输出的值赋予电芯功率需求和温度



Start		End	
Part	signal	Part	signal
CCCV_Controls	Imposed power	CycleAging	Power request
CCCV_Controls	Imposed temperature	CycleAging	Temperature

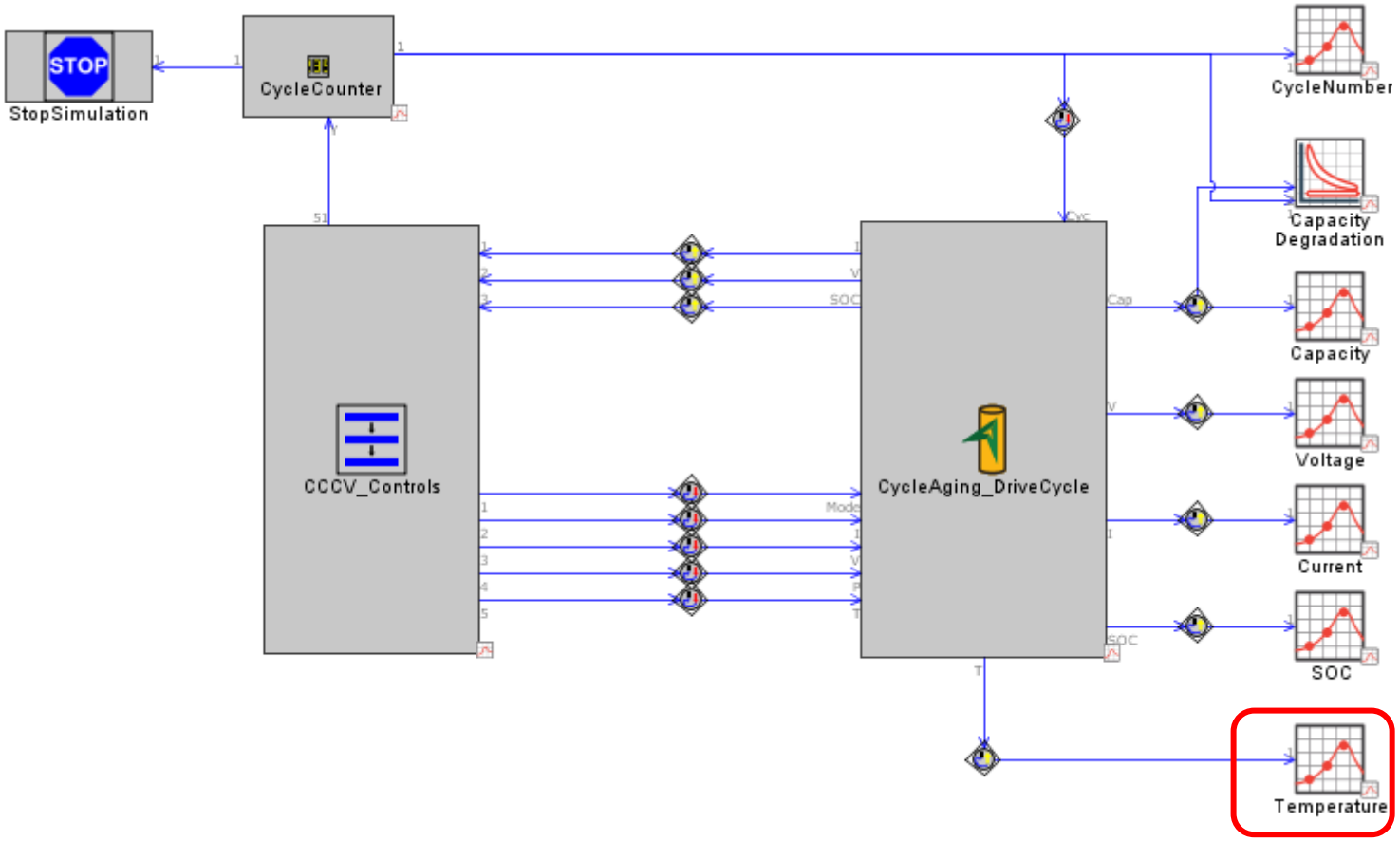
寿命计算——带循环工况的循环寿命

- 增加一个温度的监控，最终模型如下



寿命计算——带循环工况的循环寿命

- 增加一个温度的监控，最终模型如下



寿命计算——带循环工况的循环寿命

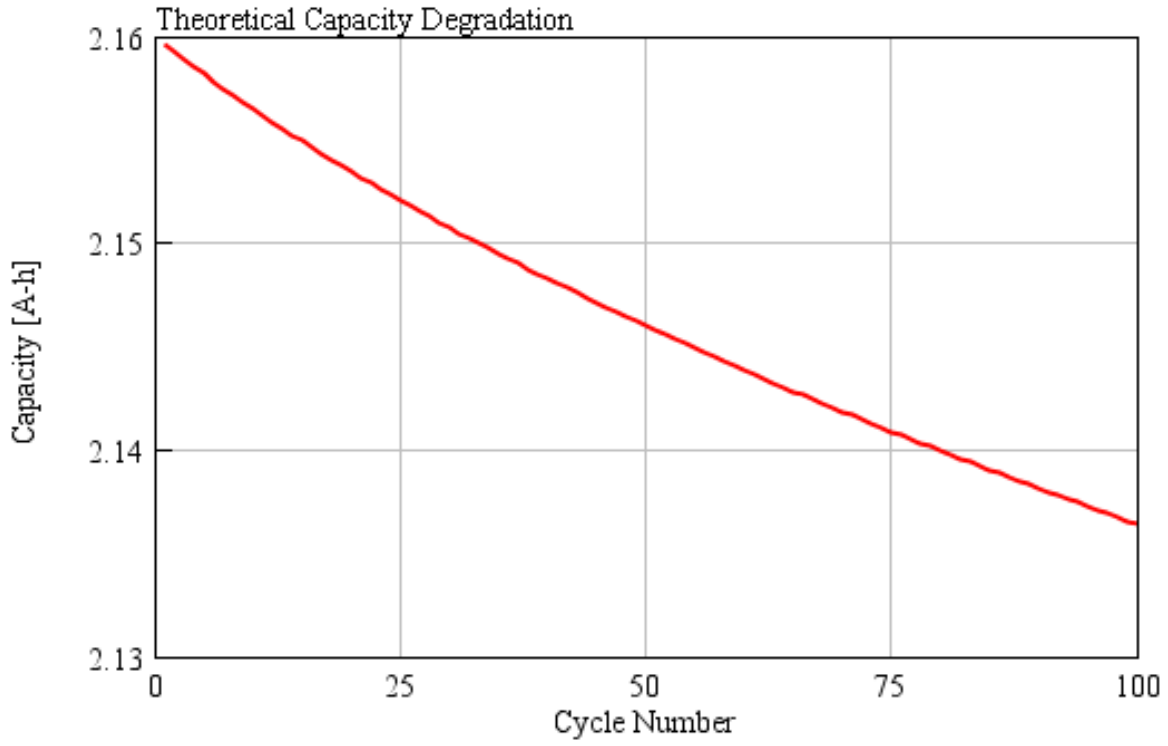
- Case setup

Main | Design of Experiments | All

Parameter	Unit	Description	Case 1
Case On/Off		Check Box to Turn Case On	☑
Case Label		Unique Text for Plot Legends	
ChargeCurrent	A	Charge Current	-3.6 ...
MaxVoltage	V	Max Voltage of Cell	4.2 ...
NumberOfCycles		Number of Cycles to Run	100

寿命计算——带循环工况的循环寿命

- 查看结果



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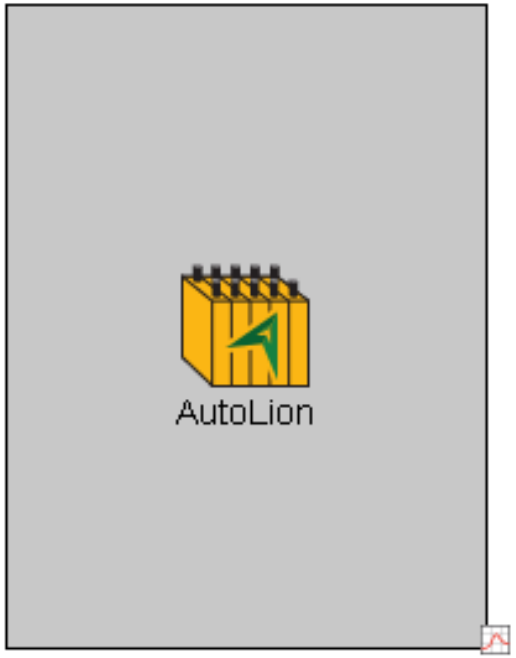
退化分析——容量退化

本例将利用寿命分析输出的 .state 文件，在指定的不同循环下（作为背景）进行恒流放电



退化分析——容量退化

- 电池设置

Main | Model Setup | Cathode | Anode | Assembly | Thermal Behavior | Advanced | Plots

	Attribute	Unit	Object Value
Cell Geometry			
	Cell Geometry		CylindricalGeometry
Pack Model			
	Build Lumped Pack Model		
☑	Number of Series Cells		96
	Number of Parallel Cells		3
Analysis Mode			
	Analysis Mode		Capacity Fade Analysis
	Life State Filename for Capacity or Power Fade Analysis		<CycleAging.state>
Capacity Fade Analysis			
	Discharge Current	A	2
	Frequency of Analysis (Cycles)		5
	Last Cycle of Analysis		26

选择分析模式，并指定.state文件

指定进行容量退化分析频率

Main | Model Setup | Cathode | Anode | Assembly | Thermal Behavior

Attribute	Unit	Object Value
Number of Control Volumes		
Cathode		5
Separator		3
Anode		5
Cathode Particle		10
Anode Particle		10
Cell Operating Conditions		
Lower Cutoff Voltage	V	2.5
Upper Cutoff Voltage	V	4.3
Open Circuit Voltage of Full Cell (100% SOC)	V	4.2
Solver Settings		
Time Step Size	s	1
Spatial Plot Storage Frequency		1000
Maximum Iteration per TimeStep		100
Convergence Criteria		1e-8

退化分析——容量退化

- 传热、高级

	Attribute	Unit	Object Value
○	Imposed Temperature	K	298.15
○	Internal Thermal Node with External Thermal Connec...		
	Internal Thermal Solution		
◉	Specific Heat	J/kg-K	1000
◉	Convective Heat Transfer Coefficient	W/(m^2-K)	10
◉	Initial Temperature	See Case...	[InitialTemp]
◉	Ambient Temperature	See Case...	[InitialTemp]
◉	Non-Cell Weight	kg	0

✓ Main ✓ Model Setup ✓ Cathode ✓ Anode ✓ Assembly ✓ Degradation

Attribute	Unit	Object Value
Bruggeman Exponents		
Cathode		1.5
Separator		1.5
Anode		1.5
Cathode Butler-Volmer Equations		
Anodic Charge Transfer Coefficient		0.5
Cathodic Charge Transfer Coefficient		0.5
Anode Butler-Volmer Equations		
Anodic Charge Transfer Coefficient		0.5
Cathodic Charge Transfer Coefficient		0.5
Double Layer Capacitance		
Cathode	F/m^2	ign
Anode	F/m^2	ign

退化分析——容量退化

- Run setup
  - 设置最大计算时长，足够长即可
  - 本例采用显式求解，设置最大时间步长为5s

TimeControl | Initialization | ODEControl | SignalControl | ThermalControl

Attribute	Unit	Object Value
Maximum Simulation Duration (Time)	s	4200
Automatic Shut-Off When Steady-State		off
Improved Solution Sequence for Multi-Circuit Models		☐

TimeControl | Initialization | ODEControl | SignalControl | ThermalControl

Attribute	Unit	ODE Settings #1
Part Name List Object Identifying Circuits Belongi...		def
Integrator and Solution Control		DiffEqControl_expltest
Time Step Output Frequency		def
Maximum Ratio of Time Steps in ODE Circuits		def (=20)
Maximum Ratio of Flow/ODE Time Step		def (=5)
Solve All Circuits Together (Single Solution Clust...		☑
Modal Analysis Property Object		ign

Main | RungeKutta

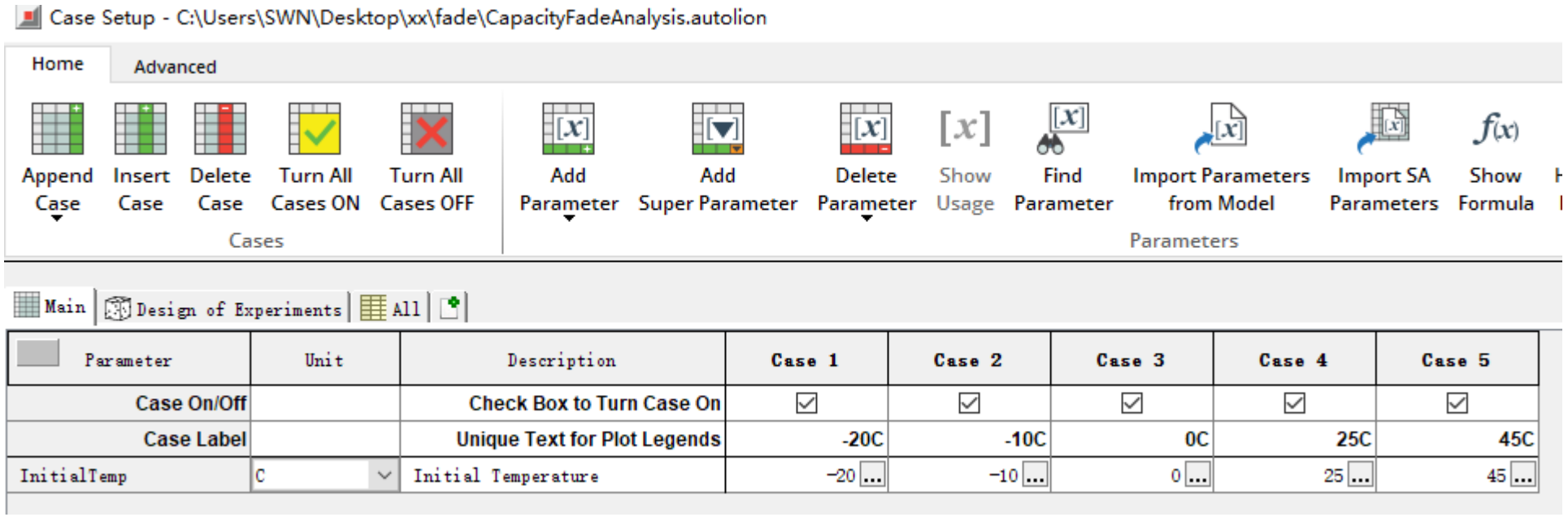
Attribute	Object Value
Integrator/Solver Type	Explicit-Runge-Kutta
Matrix Optimization Method	Cuthill-McKee
Matrix Storage Format	Skyline
Electrical Matrix Inversion Scheme	SVD

Main | RungeKutta

Attribute	Unit	Object Value
Maximum Integration Time Step		5
Initial Max. Integration Time Step		def
Time Step Relaxation Multiplier		def (=5)
Mechanical Degrees of Freedom		
Integration Relative Accuracy		1E-4
Translational Displacement Accuracy Norm	m	0.001
Translational Velocity Accuracy Norm	m/s	0.01
Rotational Displacement Accuracy Norm	deg	0.0572957795130823
Rotation Velocity Accuracy Norm	RPM	0.095492965

退化分析——容量退化

- Case setup

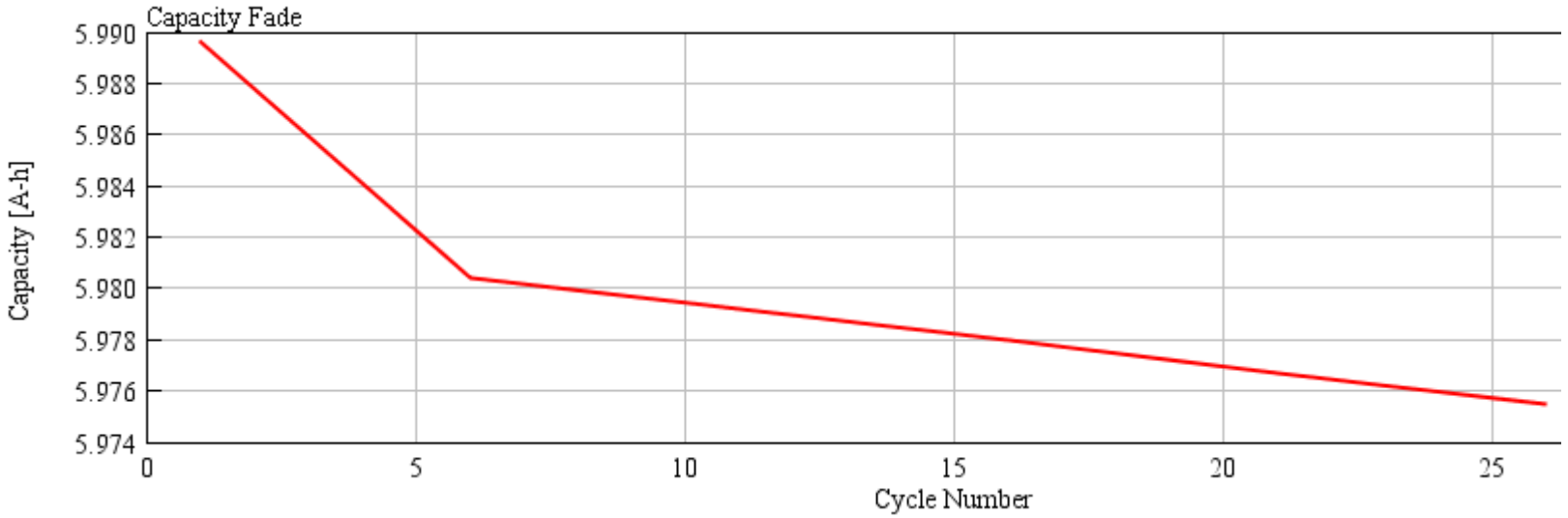


Parameter	Unit	Description	Case 1	Case 2	Case 3	Case 4	Case 5
Case On/Off		Check Box to Turn Case On	☑	☑	☑	☑	☑
Case Label		Unique Text for Plot Legends	-20C	-10C	0C	25C	45C
InitialTemp	C	Initial Temperature	-20	-10	0	25	45

退化分析——容量退化

- 运行模型查看结果

Capacity fade
(实际放电容量)



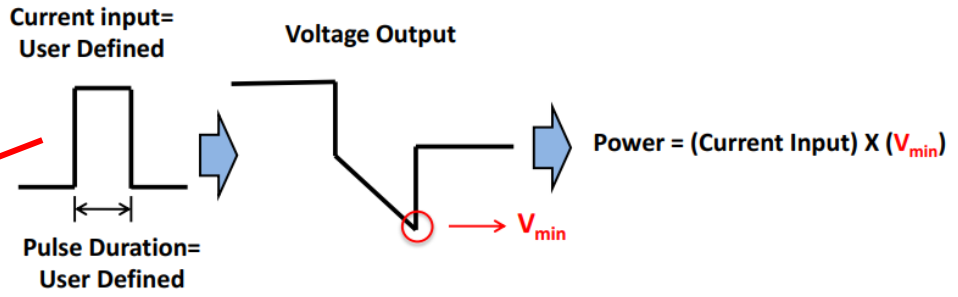
退化分析——功率退化

本例与容量退化相同，仅分析模式不同，

Main | Model Setup | Cathode | Anode | Assembly | Thermal Behavior | Advanced | Plots

	Attribute	Unit	Object Value
	Cell Geometry		
	Cell Geometry		CylindricalGeometry ...
	Pack Model		
	Build Lumped Pack Model		
☑	Number of Series Cells		96 ...
	Number of Parallel Cells		3 ...
	Analysis Mode		
	Analysis Mode		Power Fade Analysis
	Life State Filename for Capacity or Power Fade Analysis		<CycleAging.state> ...
	Power Fade Analysis		
	State of Charge	fraction	1 ...
	Discharge Current Pulse Amplitude	A	10 ...
	Discharge Current Pulse Duration	s	10 ...
	Frequency of Analysis (Cycles)		9 ...
	Last Cycle of Analysis		100 ...

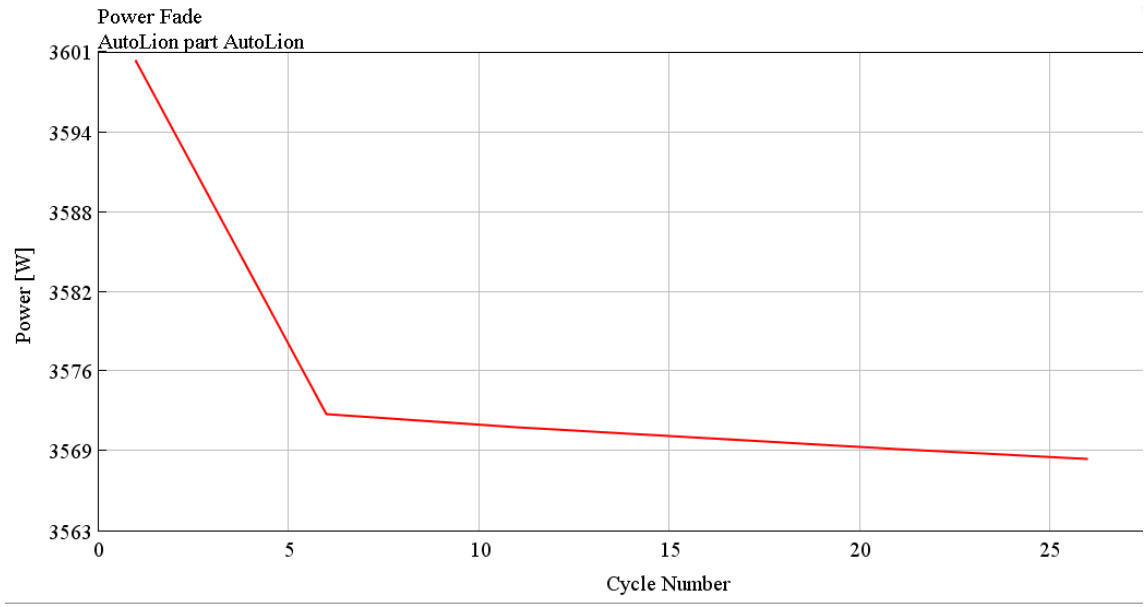
脉冲放电定义



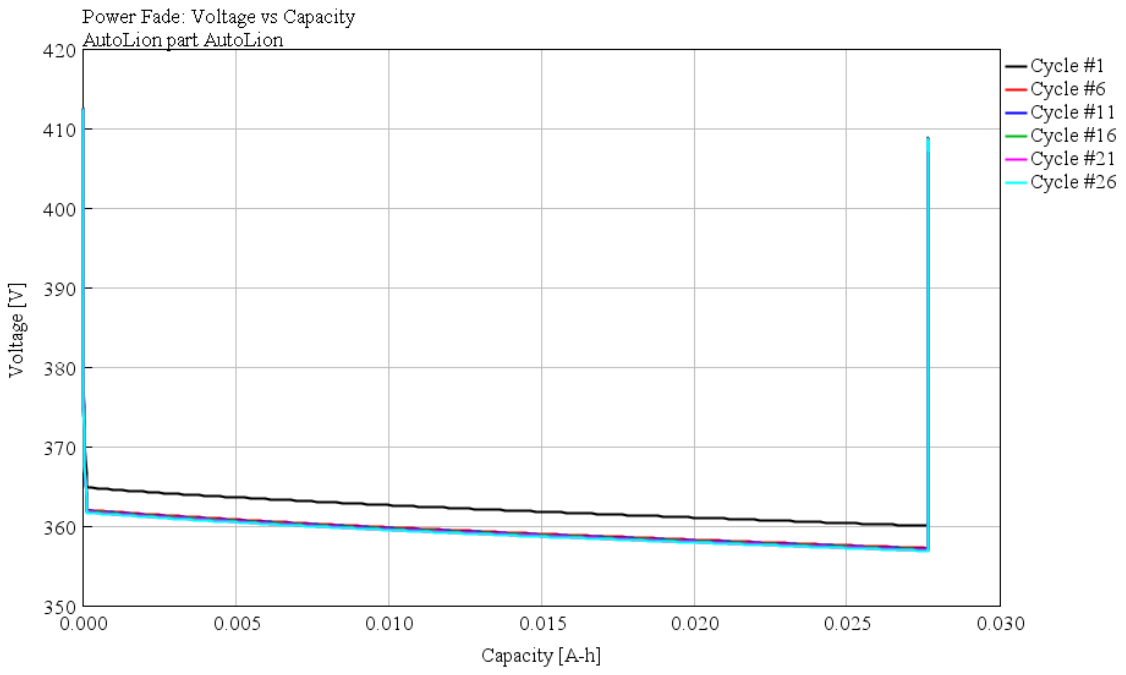
退化分析——功率退化

- 查看结果

Power fade



端电压



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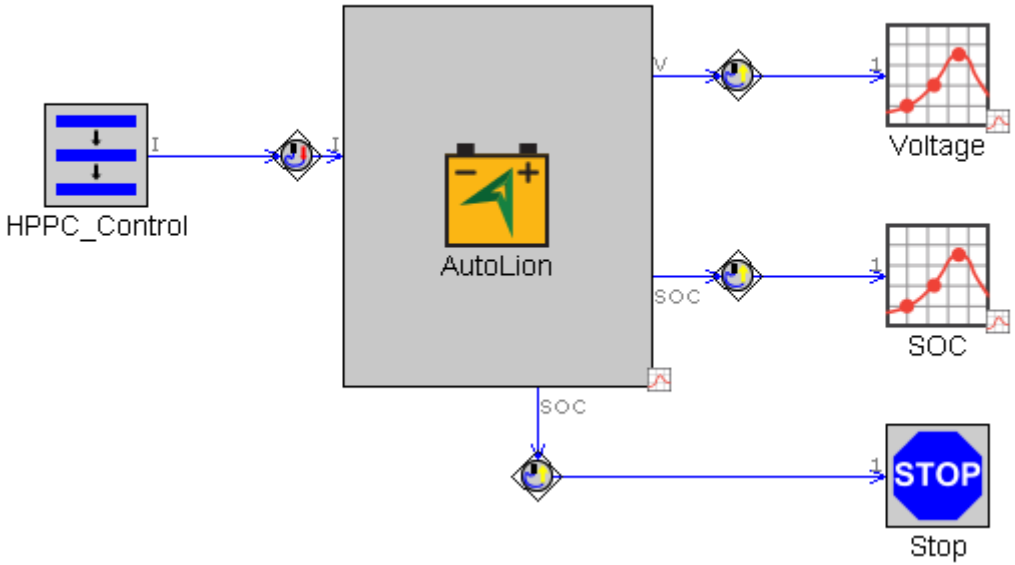
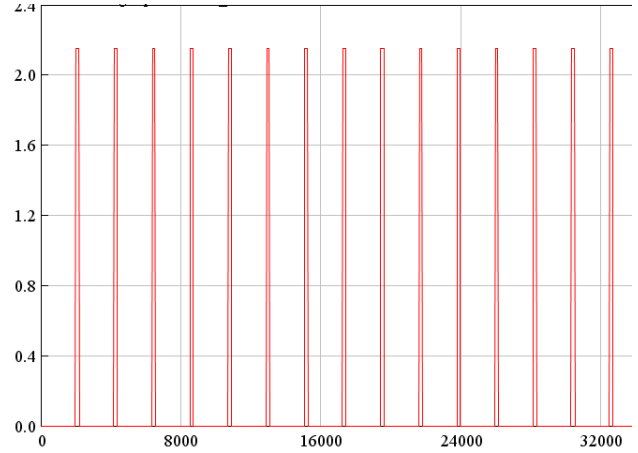
HPPC 分析

本例进行脉冲放电模拟，180s 以 1C 脉冲放电（Operational capacity 减小5%），2000s 休息。SOC 从 100% 开始以 5% 的间隔放电，直到小于 9.8% 时计算停止





HPPC 分析

- 新建模型，命名为 HPPC，并定义一个软包电池

Main | Model Setup | Cathode | Anode | Assembly | Thermal Behavior | Advanced | Plots

Attribute	Unit	Object Value
Cell Geometry		
Cell Geometry		SEDGeometry ...
Pack Model		
☐ Build Lumped Pack Model		
Analysis Mode		
Analysis Mode		Time Simulation
Time Simulation		
Load Type		Current
Current Request	See Case...	[Current] ...
Initialization		
Initial State of Charge	fraction	1 ...
☐ Initialize as Aged Model		

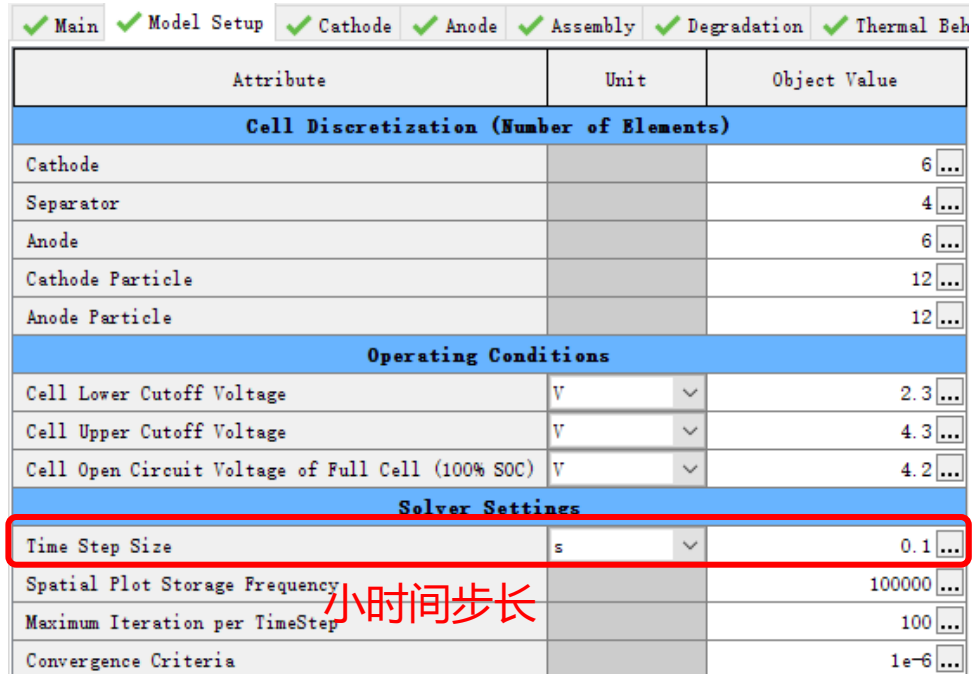
实际电流需求将由外部控制

Main

Attribute	Unit	Object Value
Cell Dimensions		
Outer Width	mm	140 ...
Outer Height	mm	190 ...
Outer Thickness	mm	8 ...
Wall Thickness	mm	0.3 ...
Jelly Roll Dimensions		
Jelly Roll Width	mm	136.3 ...
◉ Jelly Roll Thickness	mm	7.9 ...
○ Number of Anode Foil Plates		1
Thicknesses		
Cathode	micron	42.5 ...
Anode	micron	39.99999999999999 ...
Separator	micron	18 ...
Cathode Foil	micron	10 ...
Anode Foil	micron	8 ...
Heights		
Cathode	mm	182 ...
Anode	mm	182 ...
Separator	mm	185 ...
Cathode Foil	mm	185 ...
Anode Foil	mm	185 ...
Widths		
Cathode	mm	135 ...
Anode	mm	135 ...
End Plate Type		
End Plate Coating Type		Double-side Anode
Weights		
Enclosure Weight	g	5 ...
Generate Mesh of 3D Jelly Roll		☐

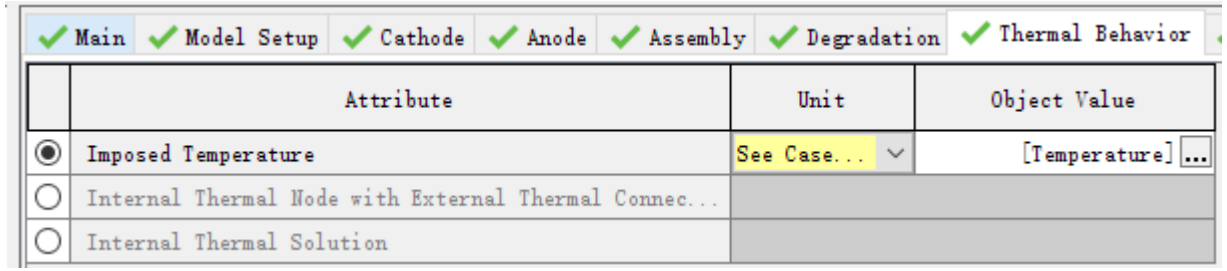
HPPC 分析

- 电芯计算时间步长设置



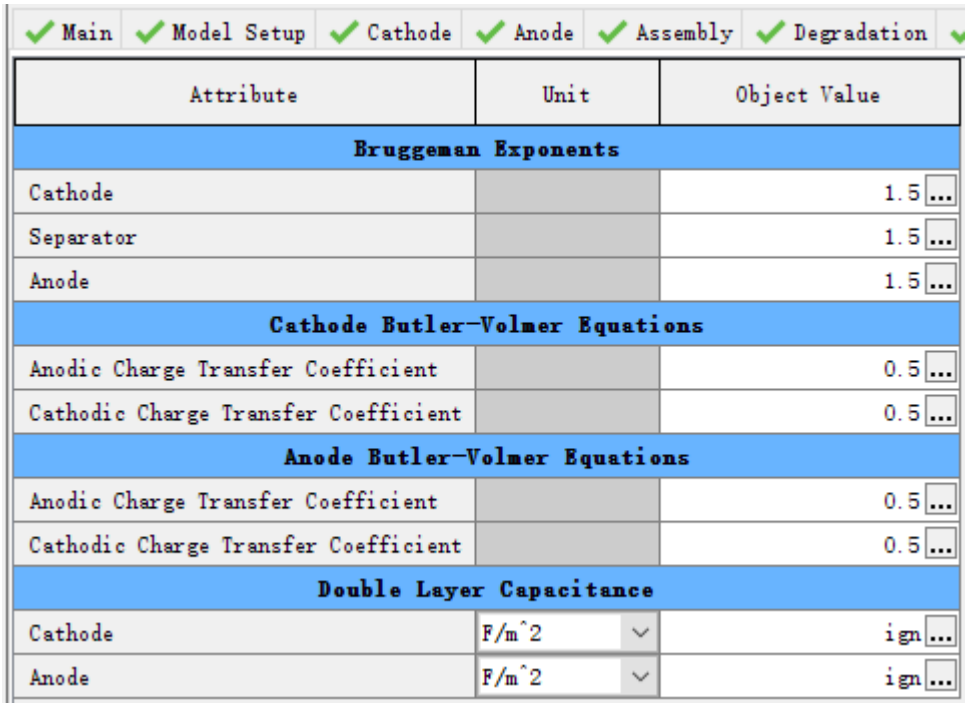
HPPC 分析

- 传热、高级



Main | Model Setup | Cathode | Anode | Assembly | Degradation | Thermal Behavior

	Attribute	Unit	Object Value
◉	Imposed Temperature	See Case...	[Temperature] ...
○	Internal Thermal Node with External Thermal Connec...		
○	Internal Thermal Solution		



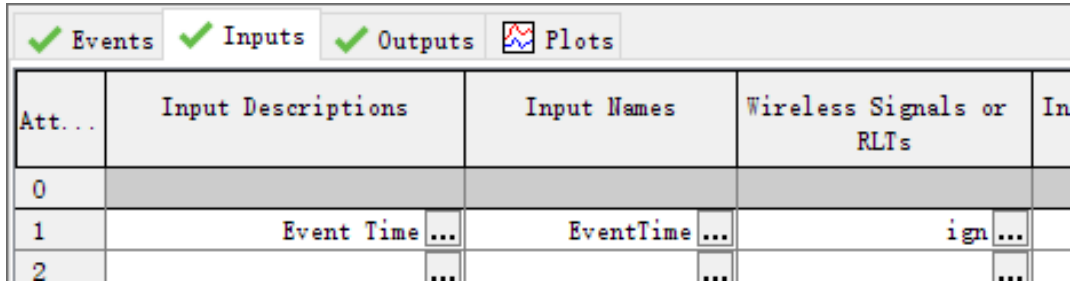
Main | Model Setup | Cathode | Anode | Assembly | Degradation

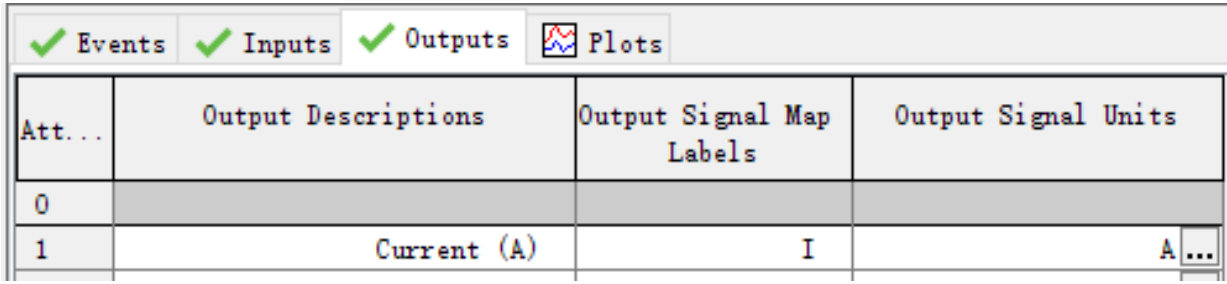
Attribute	Unit	Object Value
Bruggeman Exponents		
Cathode		1.5 ...
Separator		1.5 ...
Anode		1.5 ...
Cathode Butler-Volmer Equations		
Anodic Charge Transfer Coefficient		0.5 ...
Cathodic Charge Transfer Coefficient		0.5 ...
Anode Butler-Volmer Equations		
Anodic Charge Transfer Coefficient		0.5 ...
Cathodic Charge Transfer Coefficient		0.5 ...
Double Layer Capacitance		
Cathode	F/m^2	ign ...
Anode	F/m^2	ign ...

HPPC 分析

HPPC 控制器

- 通过事件管理器（event manager）来完成该 HPPC 的控制逻辑
- 将 eventmanager 模板拖入map中，并命名为 HPPC_control；定义输入量和输出量。本例中输入量没有意义，任意即可。





HPPC 分析

HPPC 控制器

- 本例定义了 2 种模式、模式退出条件、及该模式下对应的输出

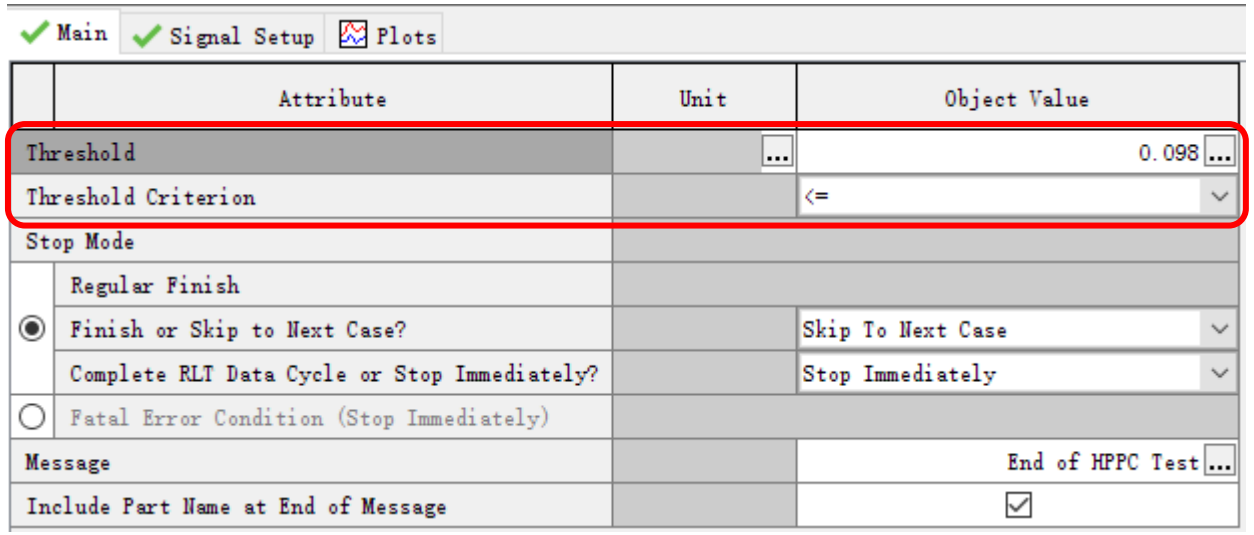
Events | Inputs | Outputs | Plots

Att...	Event Descriptions	Event Exit Criterion	Next Event No.	Output 1	Output 2
0					
1	Rest	etime>=[RestTime]	2	0	ign
2	Pulse	etime>=[PulseTime]	1	[Current]	
3					

HPPC 分析

计算终止器

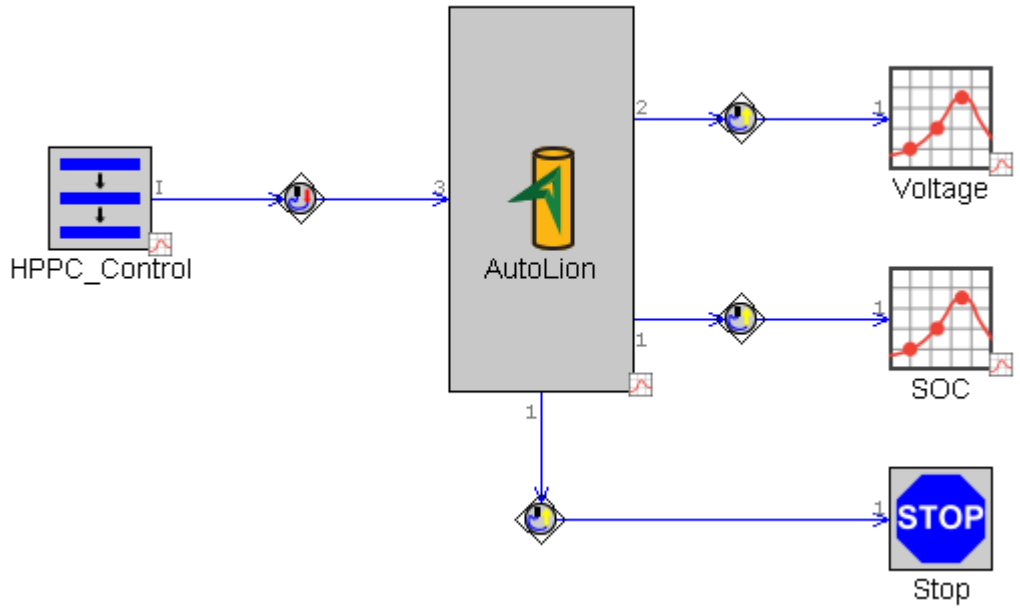
- 将模板 StopSimulation 拖入map，设置如下



达到指定 SOC，计算停止

HPPC 分析

- 连接模型



Start		End	
Part	signal	Part	signal
HPPC_Control	Current	AutoLion	Current request
AutoLion	State of charge	StopSimulation	input1

HPPC 分析

- Run setup
  - 设置最大计算时长，19个周期
  - 显式求解器，最大步长 0.1s，当前设置为变量[ts]，在casesetup中再设置具体值

TimeControl | Initialization | ODEControl | SignalControl | ThermalControl

Attribute	Unit	Object Value
Maximum Simulation Duration (Time)	s	=([PulseTime]+[RestTime])*19
Automatic Shut-Off When Steady-State		off
Improved Solution Sequence for Multi-Circuit Models		☐

TimeControl | Initialization | ODEControl | SignalControl | ThermalControl

Attribute	Unit	ODE Settings #1
Part Name List Object Identifying Circuits Belongi...		def
Integrator and Solution Control		DiffEqControl_ODE
Time Step Output Frequency		def
Maximum Ratio of Time Steps in ODE Circuits		def (=20)
Maximum Ratio of Flow/ODE Time Step		def (=5)
Solve All Circuits Together (Single Solution Clust...		☑
Modal Analysis Property Object		ign

Main | RungeKutta

Attribute	Unit	Object Value
Maximum Integration Time Step		[ts]
Initial Max. Integration Time Step		def
Time Step Relaxation Multiplier		def (=5)
Mechanical Degrees of Freedom		
Integration Relative Accuracy		1E-4
Translational Displacement Accuracy Norm	m	0.001
Translational Velocity Accuracy Norm	m/s	0.01
Rotational Displacement Accuracy Norm	deg	0.0572957795130823

HPPC 分析

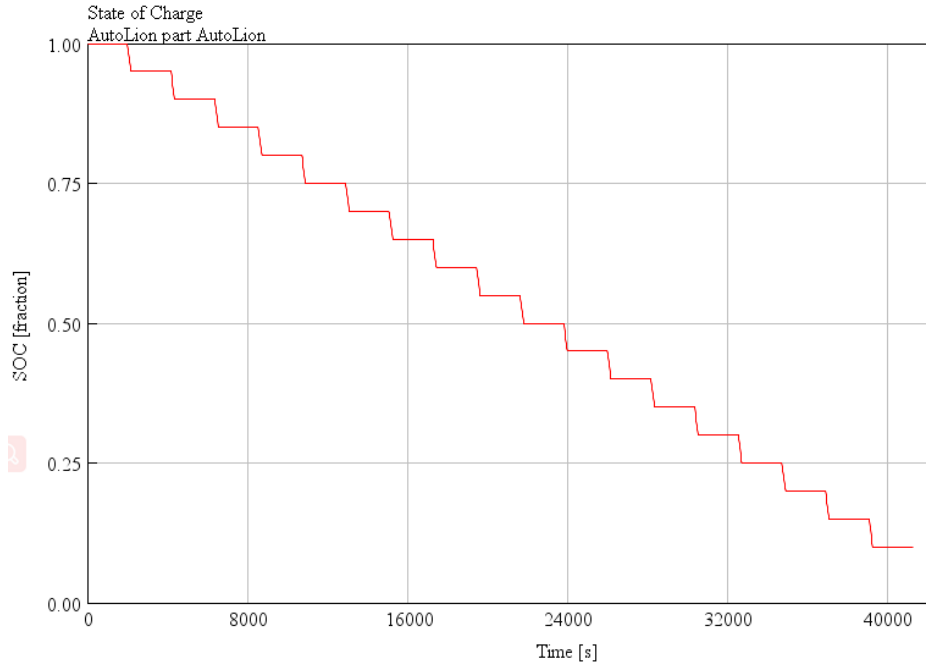
- Case setup
  - 四个不同电池温度

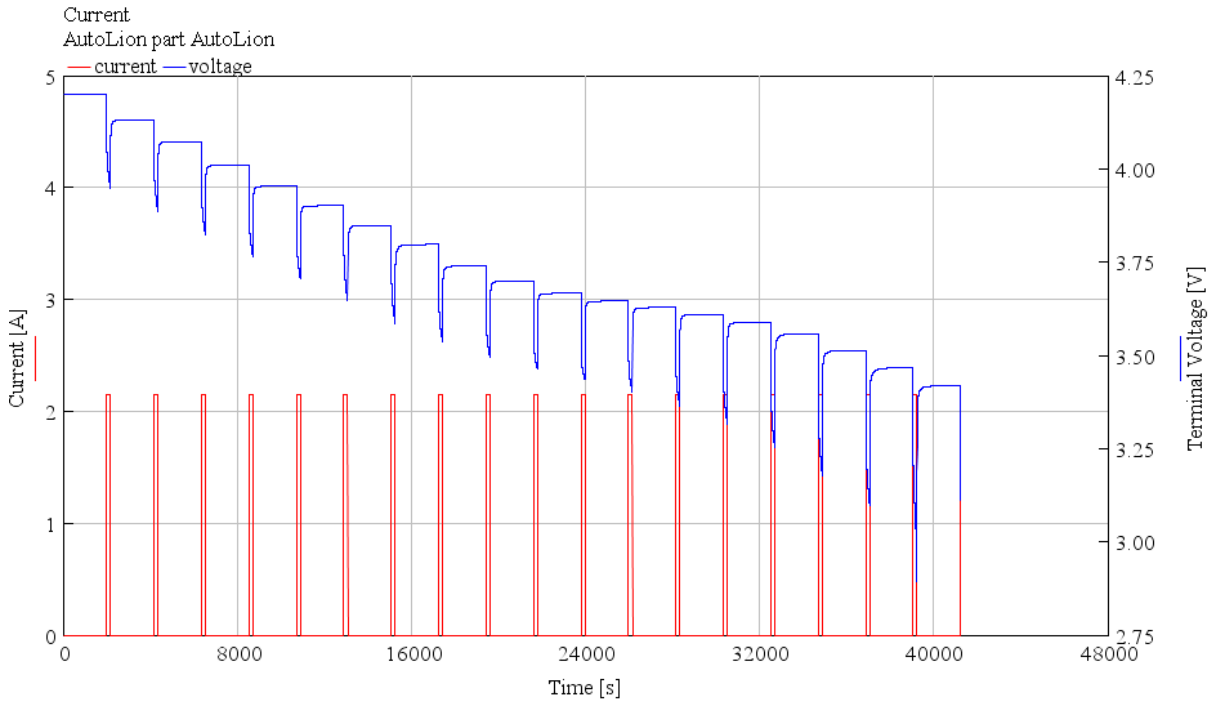
Main | Design of Experiments | Optimization_Results-OCV | Optimization_Dynamics | All

Parameter	Unit	Description	Case 1	Case 2	Case 3	Case 4
Case On/Off		Check Box to Turn Case On	☑	☑	☑	☑
Case Label		Unique Text for Plot Legends	10 C	20 C	30 C	40 C
ts	s	Time Step Size	0.1	0.1	0.1	0.1
Current	A	Current Rate for Pulses	17.8622	17.8622	17.8622	17.8622
RestTime	s	Rest Period	2000	2000	2000	2000
PulseTime	s	Pulse Period	180	180	180	180
Temperature	C	Imposed Temperature	10	20	30	40

HPPC 分析

- 结果分析





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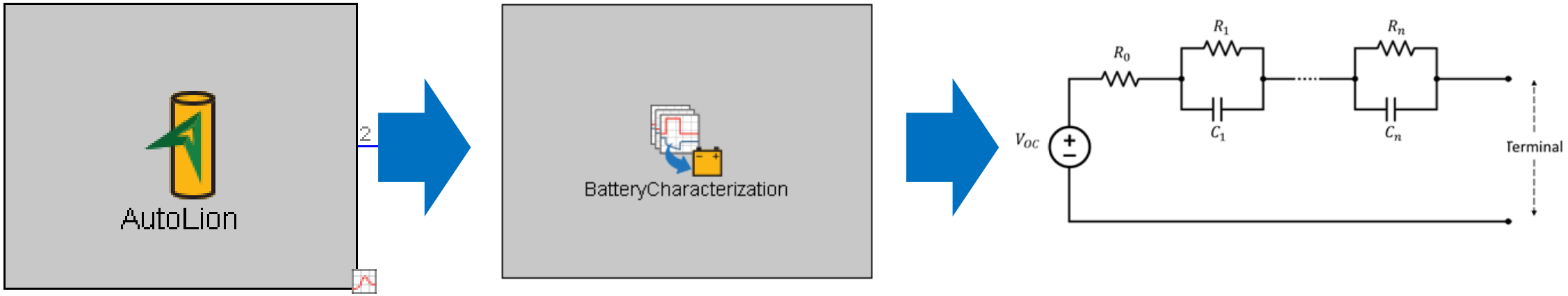
等效电路

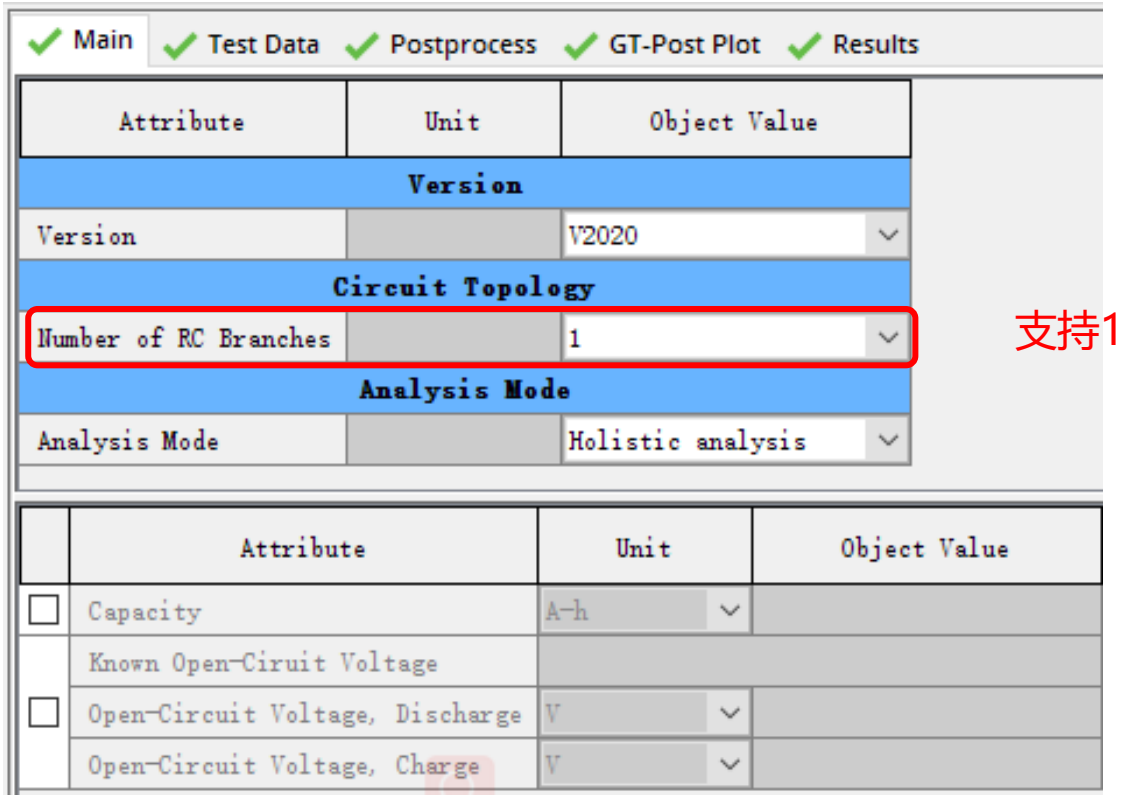
本例将根据 HPPC 的电流和电压结果计算等效电路，输出 OCV、欧姆内阻、非欧姆电阻以及电容与温度和 SOC 的关系。



等效电路

模型设置

- 新建一个 BattCharacterization part

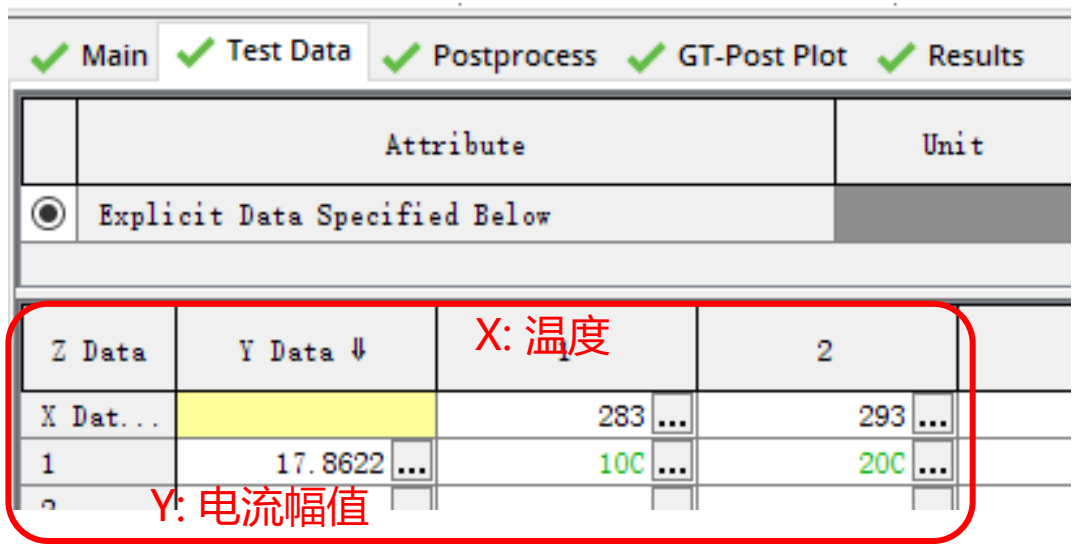


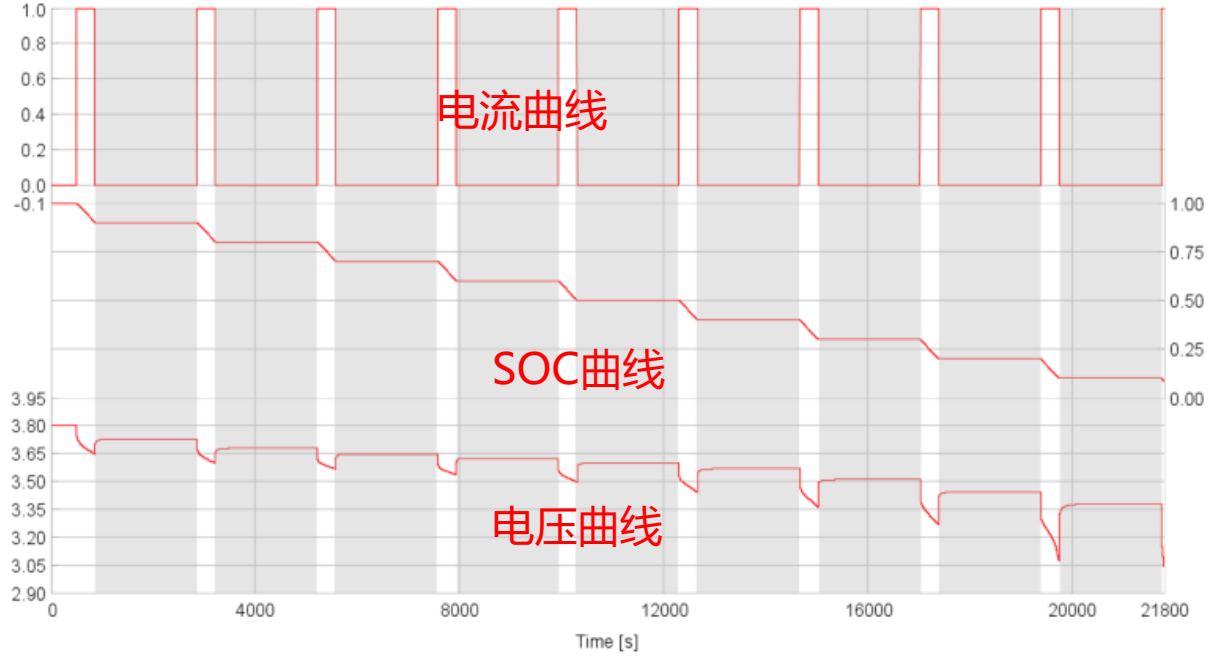
支持1-3个RC回路的拟合

等效电路

结果分析

- 新建一个 BattCharacterization part





将模型参数拟合为电流幅值、温度以及电流的map

等效电路

- 模型设置
  - 10C/20C

Data Options

Attribute	Unit	Object Value
SOC Input Method		Holistic Analysis: List Values in The Table Below
Advanced Input		

Att...	SOC
	fraction
1	0.95
2	0.9
3	0.85
4	0.8
5	0.75
6	0.7
7	0.65
8	0.6
9	0.55
10	0.5
11	0.45
12	0.4
13	0.35
14	0.3
15	0.25
16	0.2
17	0.15
18	0.1

SOC曲线

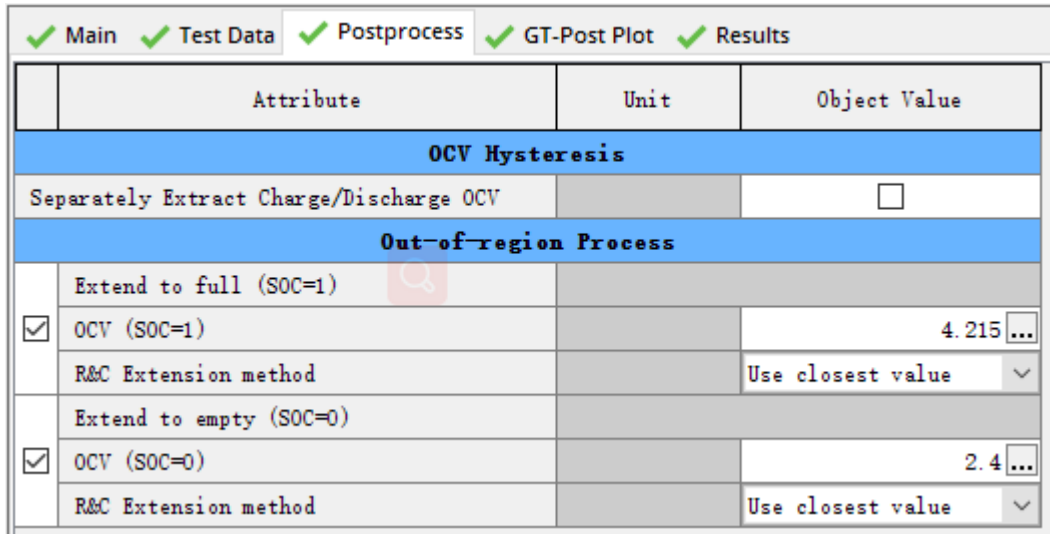
Att...	Time	Voltage	Current
	s	V	A
1	0.1	3.5310392	0
2	0.5	3.5310392	0
3	0.7	3.5310392	0
4	0.9	3.5310392	0
5	1.1	3.5310392	0
6	1.3	3.5310392	0
7	1.5	3.5310392	0
8	1.7	3.5310392	0
9	1.9	3.5310392	0
10	2.1	3.5310392	0
11	2.4	3.5310392	0
12	2.6	3.5310392	0
13	2.8	3.5310392	0
14	3	3.5310392	0
15	3.2	3.5310392	0
16	3.4	3.5310392	0
17	3.6	3.5310392	0
18	3.8	3.5310392	0
19	4	3.5310392	0
20	4.2	3.5310392	0
21	4.4	3.5310392	0
22	4.7	3.5310392	0
23	4.9	3.5310392	0

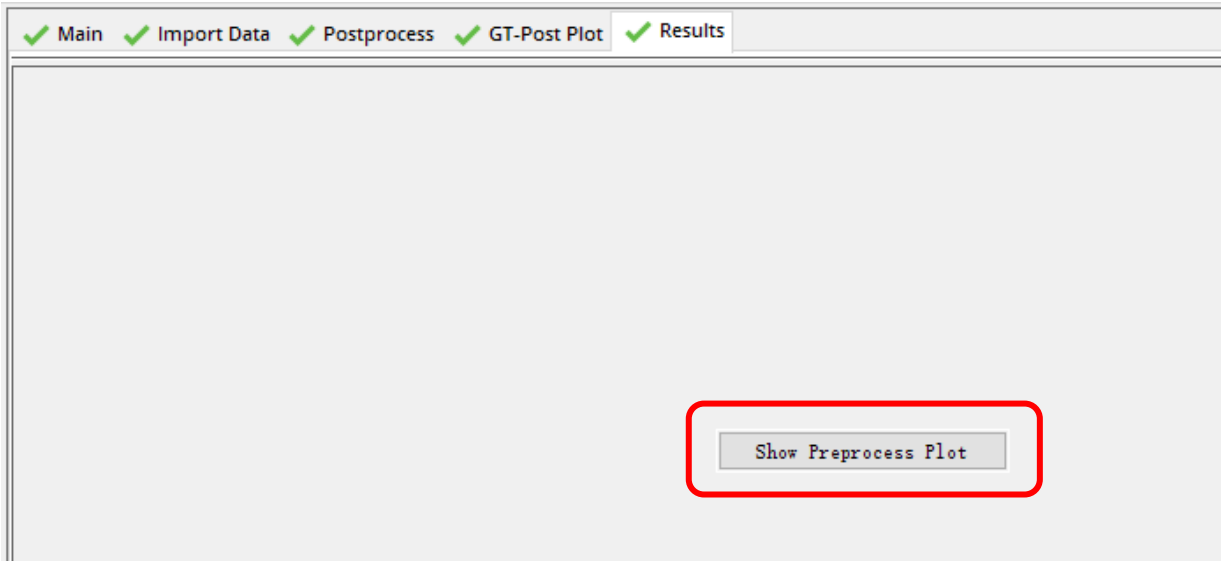
电压/电流曲线

等效电路

模型设置

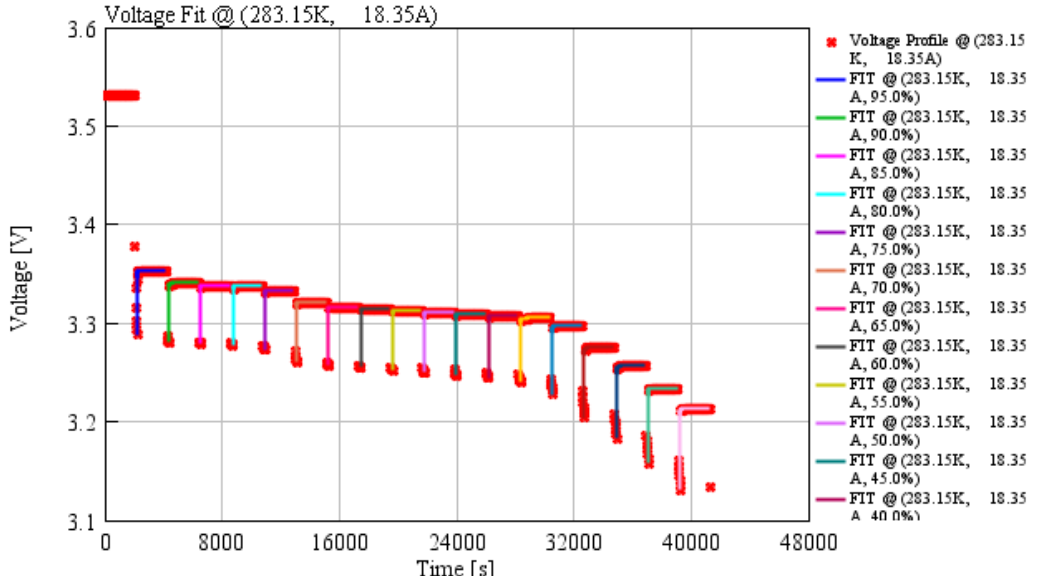
外推设置及查看结果

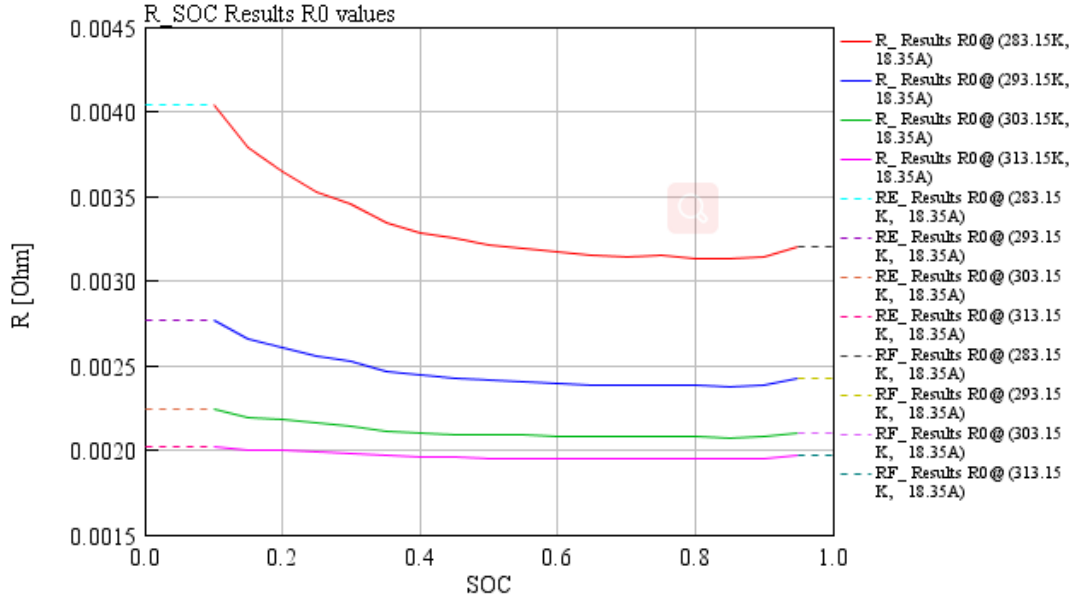




等效电路

- 查看结果
  - 查看 OCV、内阻和RC与温度和 SOC 的关系，该结果可输入电池等效电路模型用于系统仿真



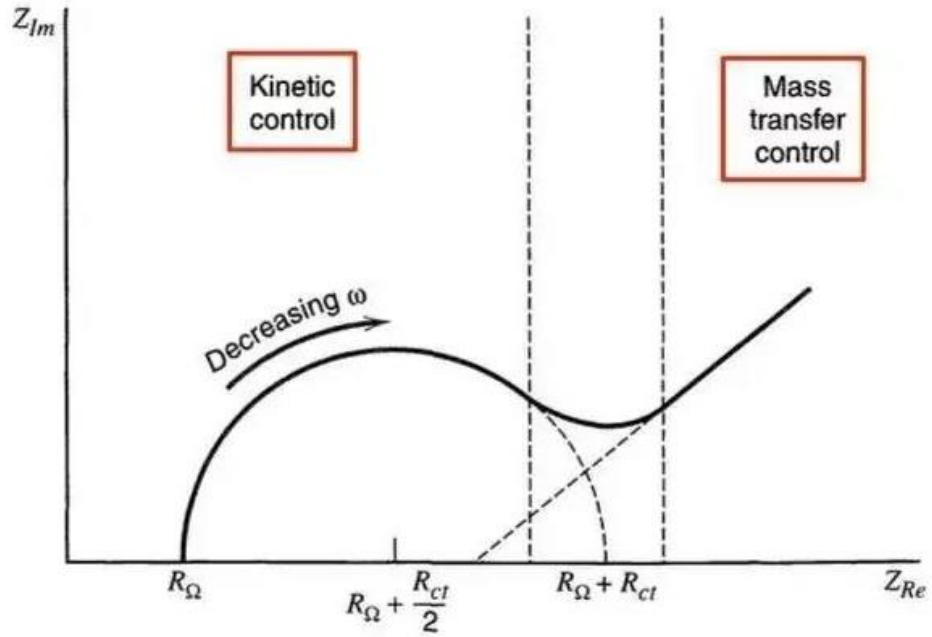


目录

阻抗谱分析

EIS 分析中输入一个幅值为 5mV 的正弦电压，通过电流幅值和相位计算阻抗。本例频谱范围在1e-5～1e5，每个数量级计算10个频率点，输出不同环境温度下的 Nyquist 图 和 Bode 图。

- 低频扩散过程主导
- 高频电荷转移和双电层主导
- 超高频欧姆电阻主导



阻抗谱分析

- 新建一个autolion，选择 EIS 模式，其他设置与基础模型一致

Main | Model Setup | Cathode | Anode | Assembly | Thermal Behavior | Advanced | Plots

Attribute	Unit	Object Value
Cell Geometry		
Cell Geometry		CylindricalGeometry
Pack Model		
Build Lumped Pack Model		
Analysis Mode		
Analysis Mode		Frequency Analysis (EIS)
Frequency Domain Analysis		
Low Frequency Limit	1/s	1e-5
High Frequency Limit	1/s	1e5
Number of Frequency Values per Decade		10
Initialization		
Initial State of Charge	fraction	1
Initialize as Aged Model		

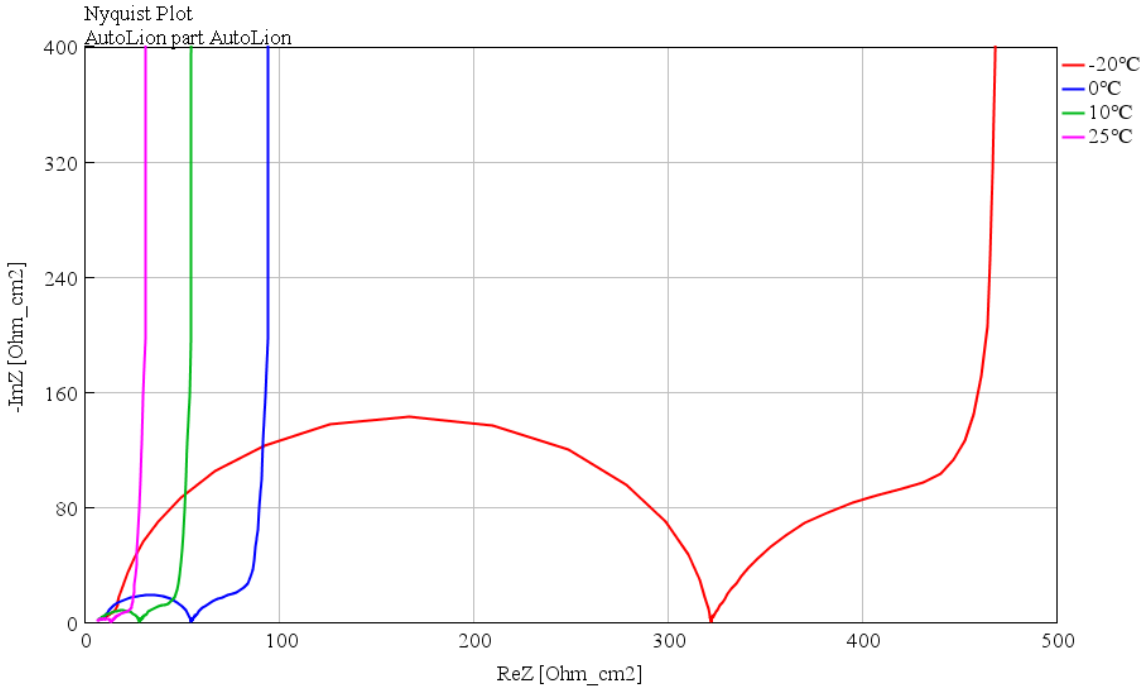
Main | Model Setup | Cathode | Anode | Assembly | Thermal Behavior

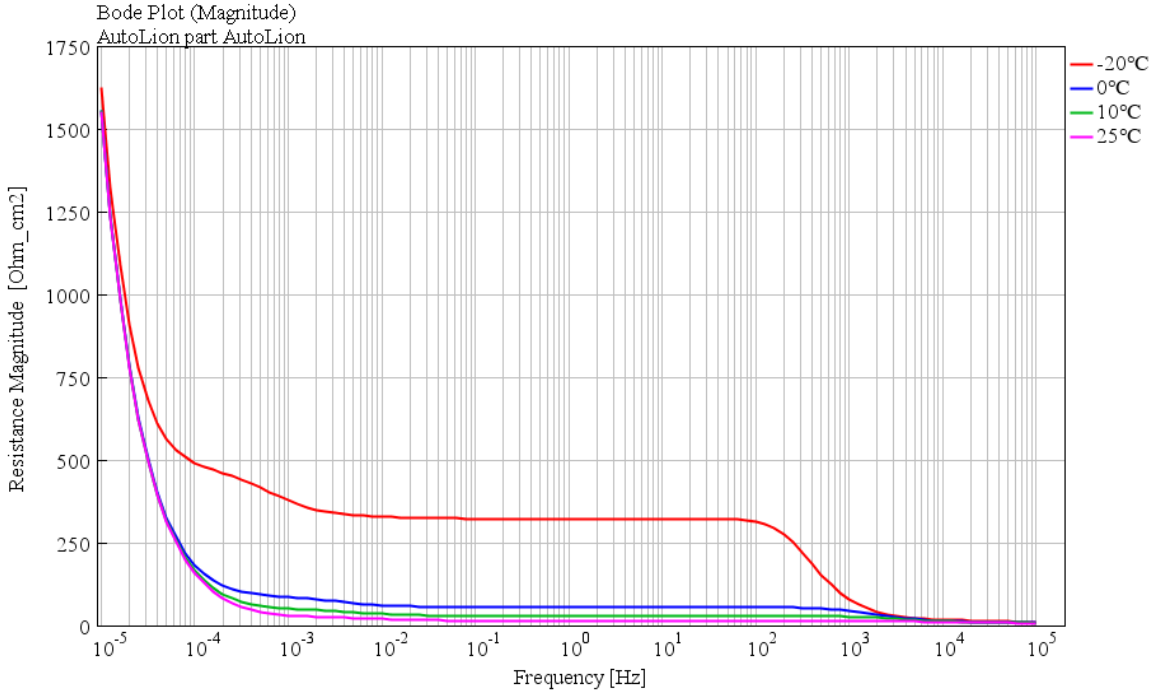
Attribute	Unit	Object Value
Number of Control Volumes		
Cathode		6
Separator		4
Anode		6
Cathode Particle		12
Anode Particle		12
Cell Operating Conditions		
Lower Cutoff Voltage	V	2.48
Upper Cutoff Voltage	V	4.3
Open Circuit Voltage of Full Cell (100% SOC)	V	4.2
Solver Settings		
Time Step Size	s	0.1
Spatial Plot Storage Frequency		10
Maximum Iteration per TimeStep		100
Convergence Criteria		1e-6

小时间步长

阻抗谱分析

- 结果分析
  - 温度越低阻抗越大





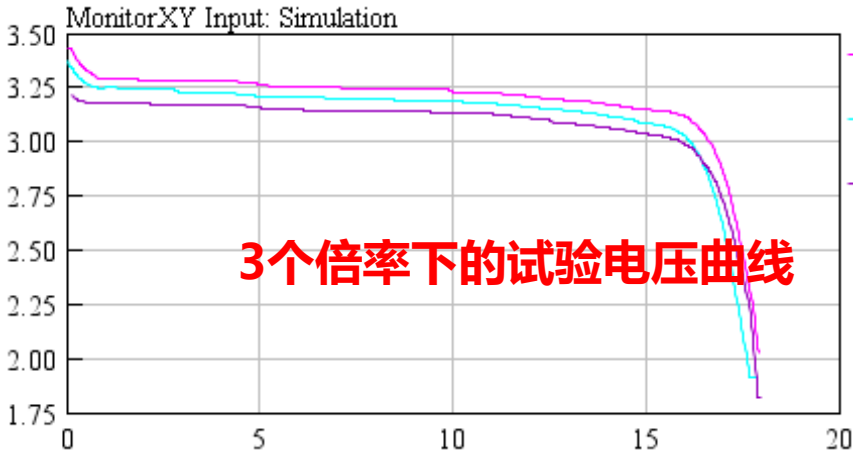
目录

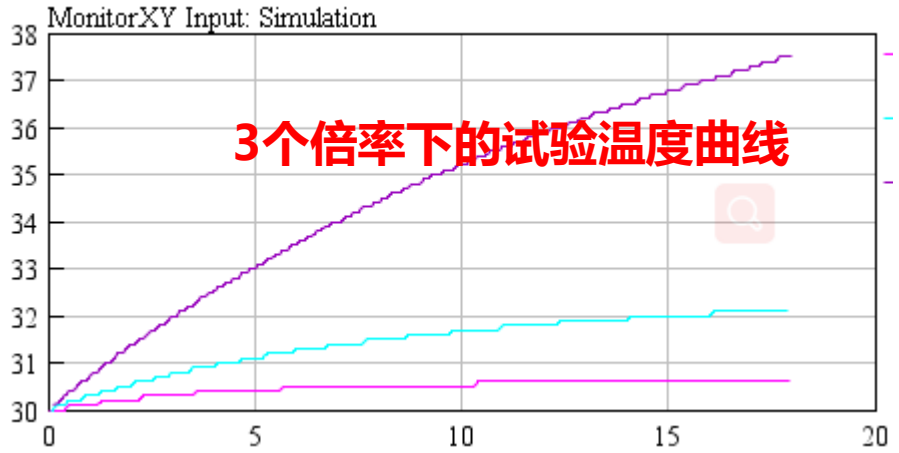
电压、温度自动标定

本例进行 3 个倍率（1C/2C/5C）下的电压、和温度曲线自动标定。

- 设计因子
  - 接触电阻：[ContactResistance]
  - 阳极固相扩散率：[DiffMult]
  - 对流换热系数：[HTC]
- 响应
  - 电压曲线
  - 温度曲线
- 约束条件
  - 实际容量/Ah：保持着该区间 [17.5,18]

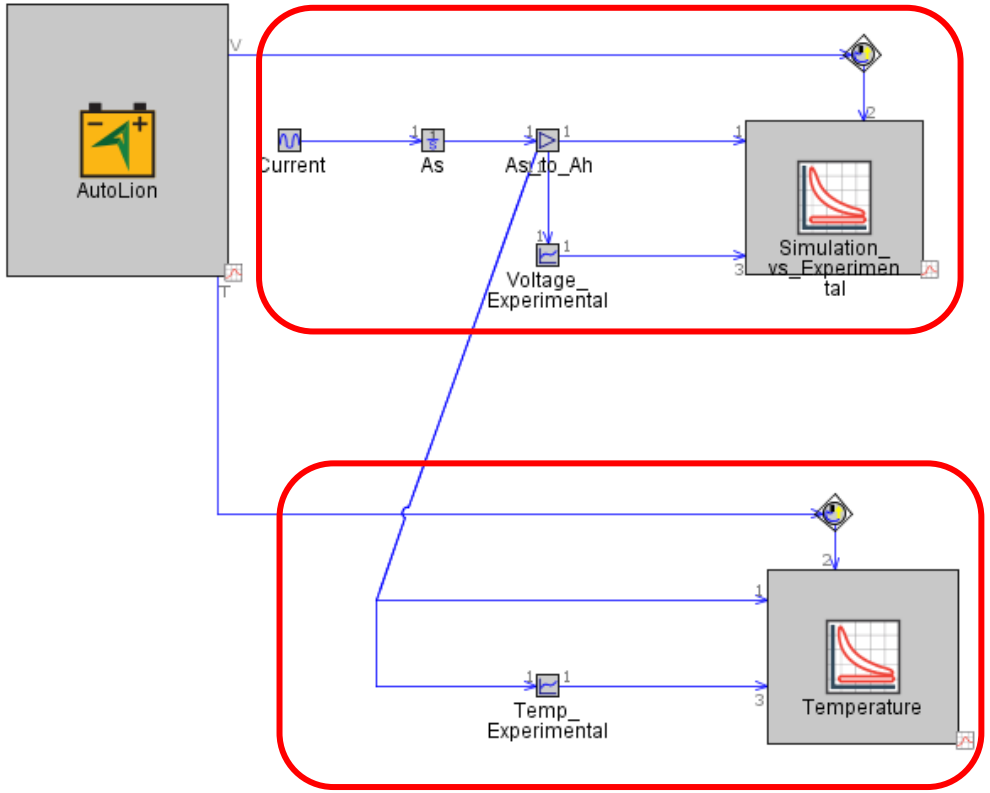
$$\begin{aligned} \min\ & f(\boldsymbol{X}) \quad \boldsymbol{X} \in \mathbf{R}^n \\ \text{s.t.}\ & g_u(\boldsymbol{X}) \leqslant 0 \quad (u = 1,2,\cdots,p) \\ & h_v(\boldsymbol{X}) = 0 \quad (v = 1,2,\cdots,m) \end{aligned}$$





电压、温度自动标定

- 打开文件 Step0_Pre-Calibration.autolion（GTI\v2020\examples\Battery\GT-AutoLion\Model_Calibration\4-Dynamics_Calibration）



电压试验数据与仿真对比

温度试验数据与仿真对比

电压、温度自动标定

- Casesetup

Main | Design of Experiments | Optimization_Results-OCV | Optimization_Dynamics | All

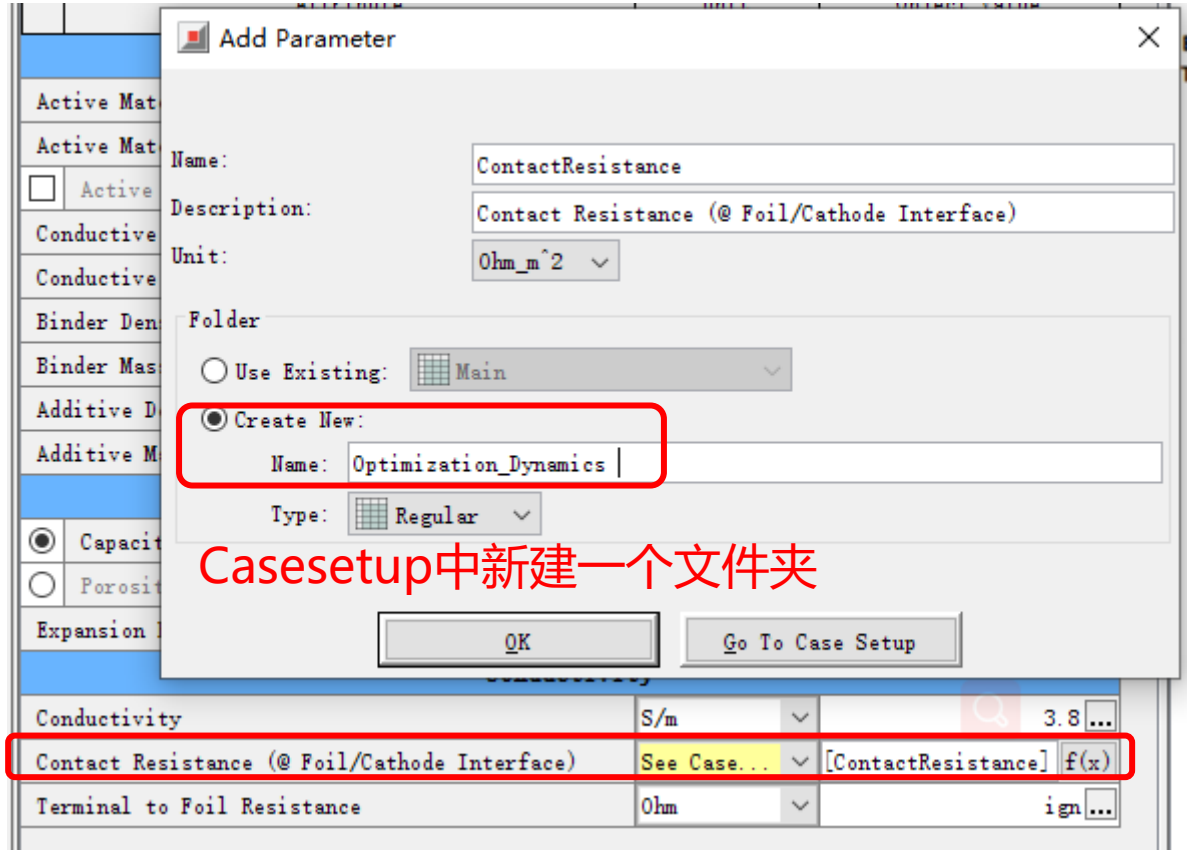
Parameter	Unit	Description	Case 1	Case 2	Case 3
Case On/Off		Check Box to Turn Case On	☑	☑	☑
Case Label		Unique Text for Plot Legends	1 C, HTC=40	2 C, HTC=40	5 C, HTC=40
C-Rate			1	2	5
Current	A	Current Request	18 ...	36 ...	90 ...
SimDur	s	Maximum Simulation Duration ...	3800 ...	1900 ...	760 ...
ts	s	Time Step Size	10 ...	10 ...	10 ...
VoltageProfile		Table or Function Object Name	V_Ah-1C ...	V_Ah-2C ...	V_Ah-5C ...
TemperatureProfile		Table or Function Object Name	Temp_Ah-1C ...	Temp_Ah-2C ...	Temp_Ah-5C ...
Voltage_Weighting		Sum Coefficients	12 ...	12 ...	12 ...
Temperature_Weighting		Sum Coefficients	1 ...	1 ...	1 ...

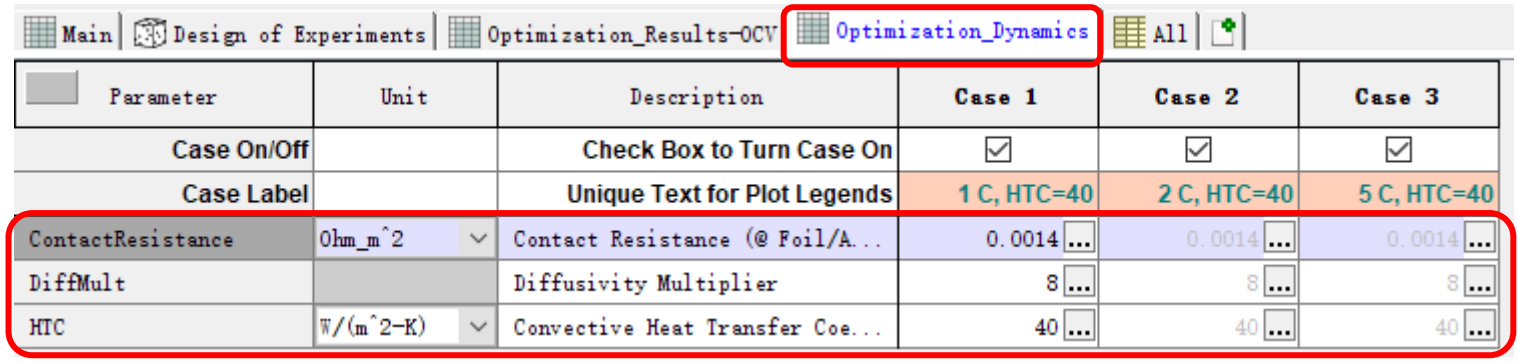
试验数据

电压、温度自动标定

■ 变参设置

- 将 3 个设计因子设置为变参
  - 阴阳极接触电阻：[ContactResistance]
  - 阳极固相扩散率：[DiffMult]
  - 对流换热系数：[HTC]
- 点击OK后，打开casesetup，将会看到所设置的这三个变参，按图输入典型值

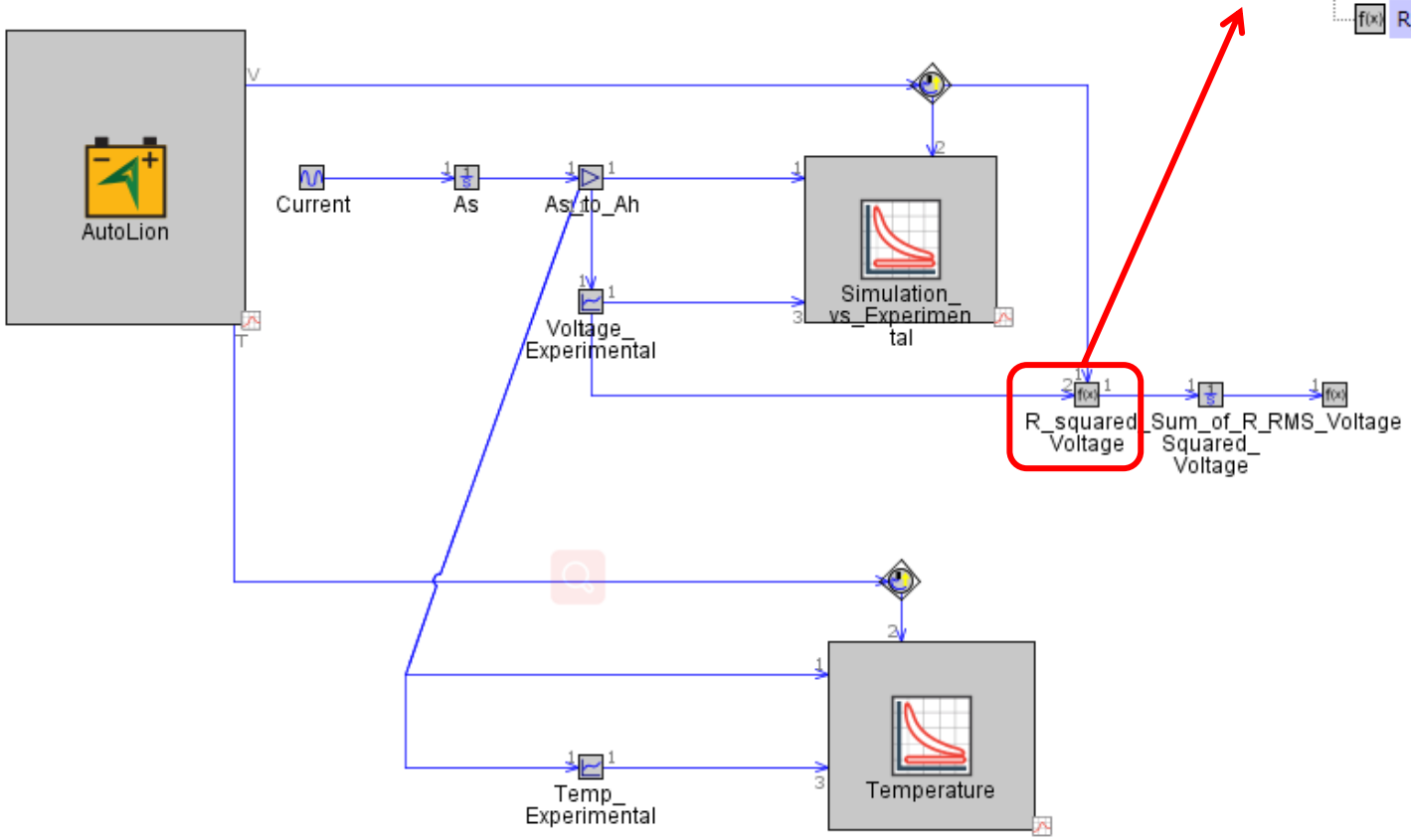




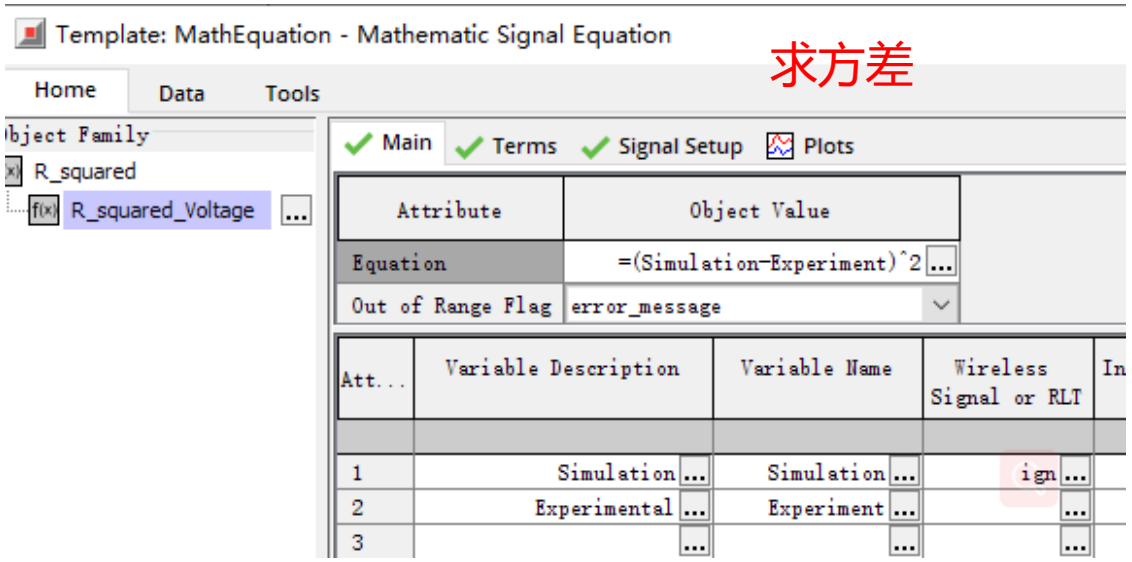
Parameter	Unit	Description	Case 1	Case 2	Case 3
Case On/Off		Check Box to Turn Case On	☑	☑	☑
Case Label		Unique Text for Plot Legends	1 C, HTC=40	2 C, HTC=40	5 C, HTC=40
ContactResistance	Ohm_m^2	Contact Resistance (@ Foil/A...	0.0014	0.0014	0.0014
DiffMult		Diffusivity Multiplier	8	8	8
HTC	W/(m^2-K)	Convective Heat Transfer Coe...	40	40	40

电压、温度自动标定

- 将电压瞬态响应转化为稳态响应



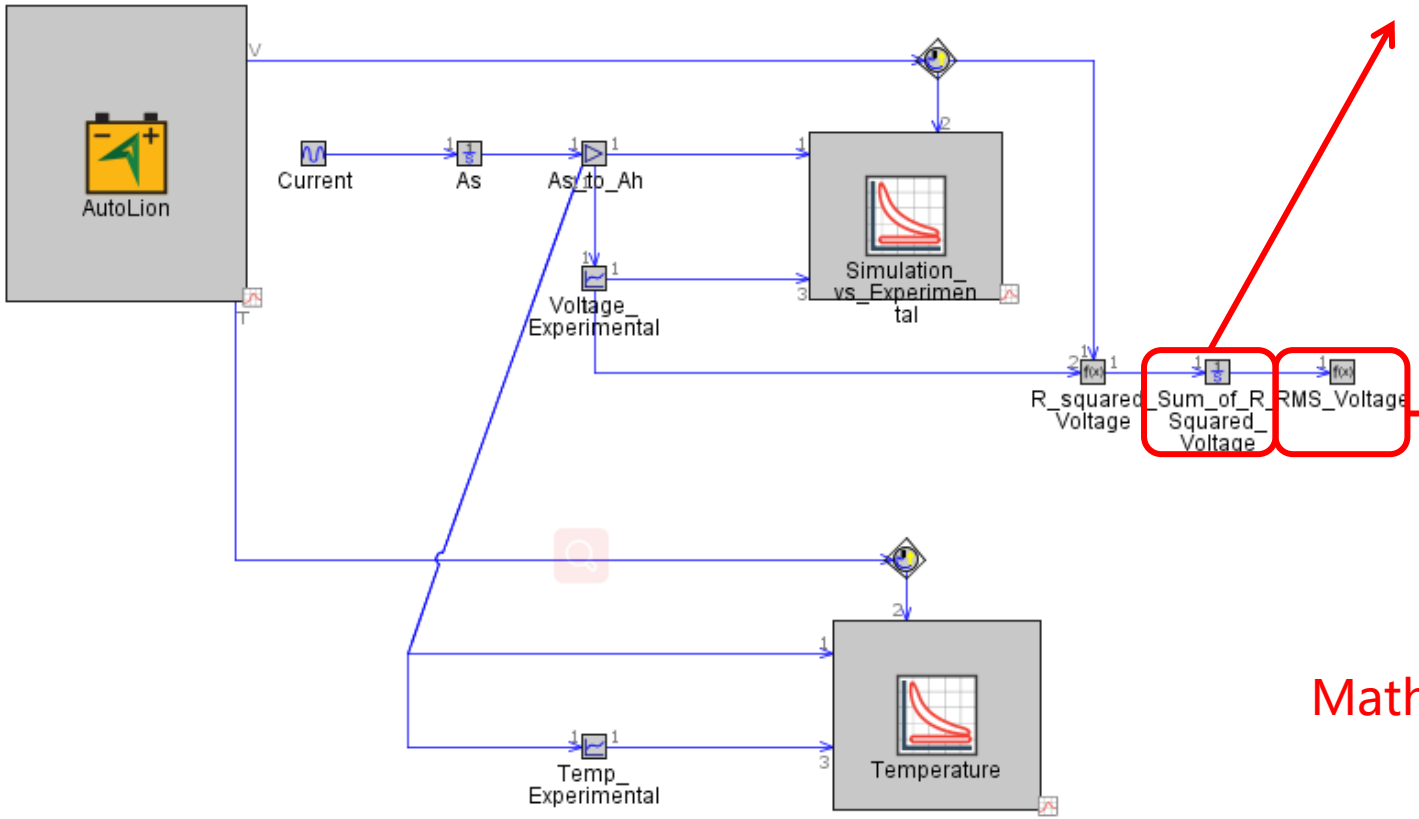
求方差



MathEquation 模板

电压、温度自动标定

- 将电压瞬态响应转化为稳态响应



Integrator 模板

对方差积分

Template: Integrator - Signal Integrator

Home | Data | Tools

ect Family
Sum_of_R_Squared
Sum_of_R_Squared_Voltage

Main | Limits | Signal Setup | Plots

Attribute	Unit	Object Value
Integrate With Respect to		time
Time Integration Unit		seconds
Integral Initial Condition	...	def (=0) ...
Reset Strategy		
Integral Reset Frequency		EveryCase
External Reset Mechanism		switch
Integrate in a Window		
Integration Window Type		seconds
Start of Integration Window		

MathEquation 模板

求根

Template: MathEquation - Mathematic Signal Equation

Home | Data | Tools

Object Family
RMS
RMS_Voltage ...

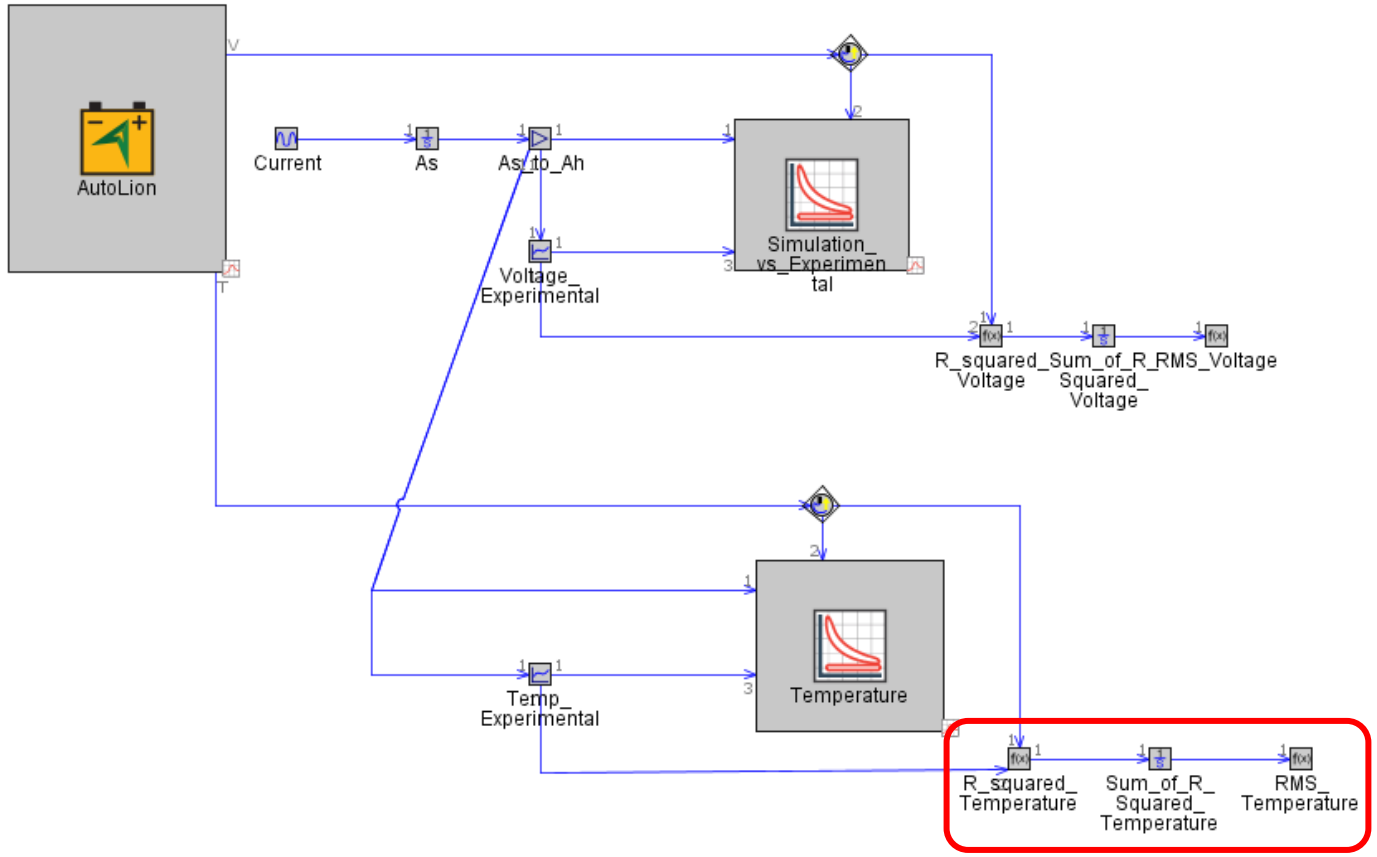
Main | Terms | Signal Setup | Plots

Attribute	Object Value
Equation	=sqrt(SumOfRSquared) ...
Out of Range Flag	error_message

Att...	Variable Description	Variable Name	Wireless Signal or RLT
1	Sum of R Squared ...	SumOfRSquared ...	ign ...
2	...	...	...

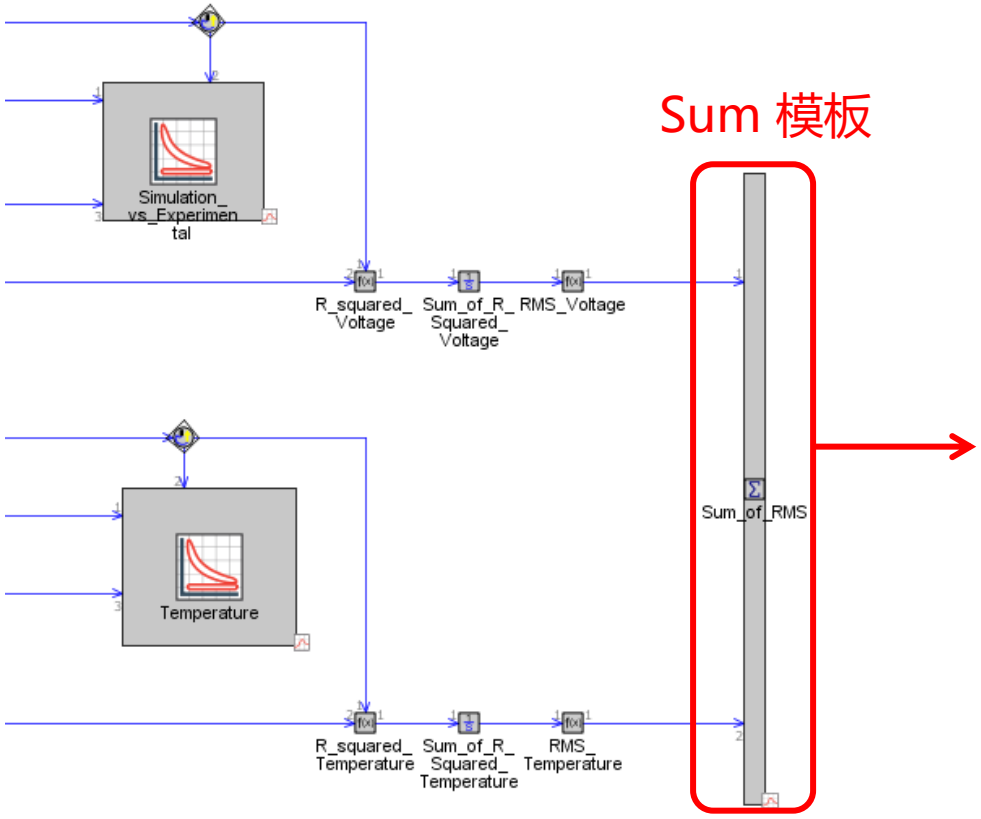
电压、温度自动标定

- 将温度瞬态响应转化为稳态响应，与上述电压曲线的转换相同

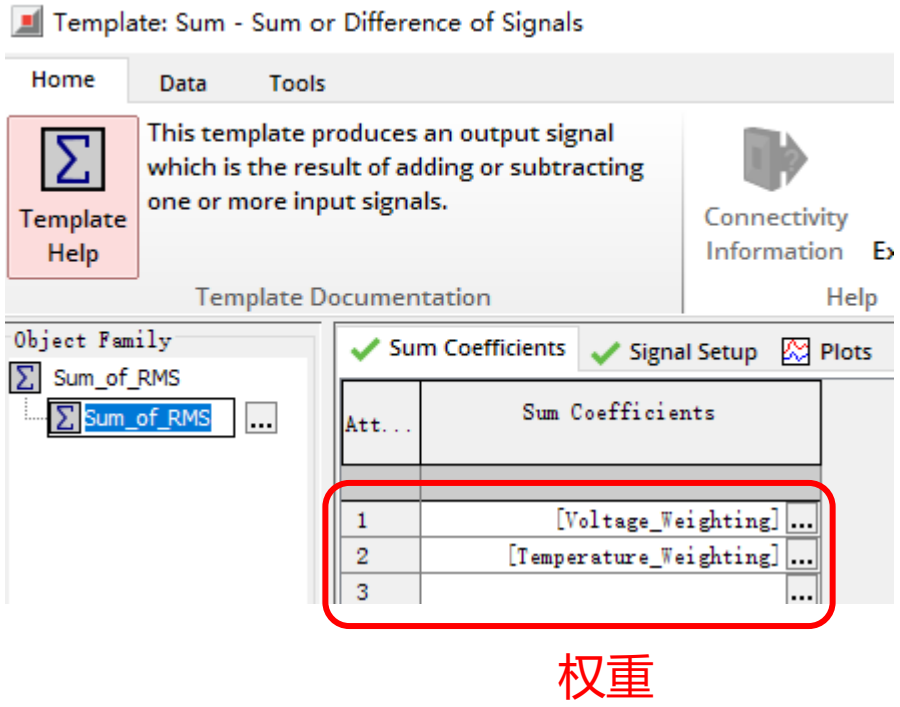


电压、温度自动标定

- 将电压和温度的稳态响应，通过权重转化为单目标优化问题。权重的设置根据两个响应的数量级确定，本例中设为12：1



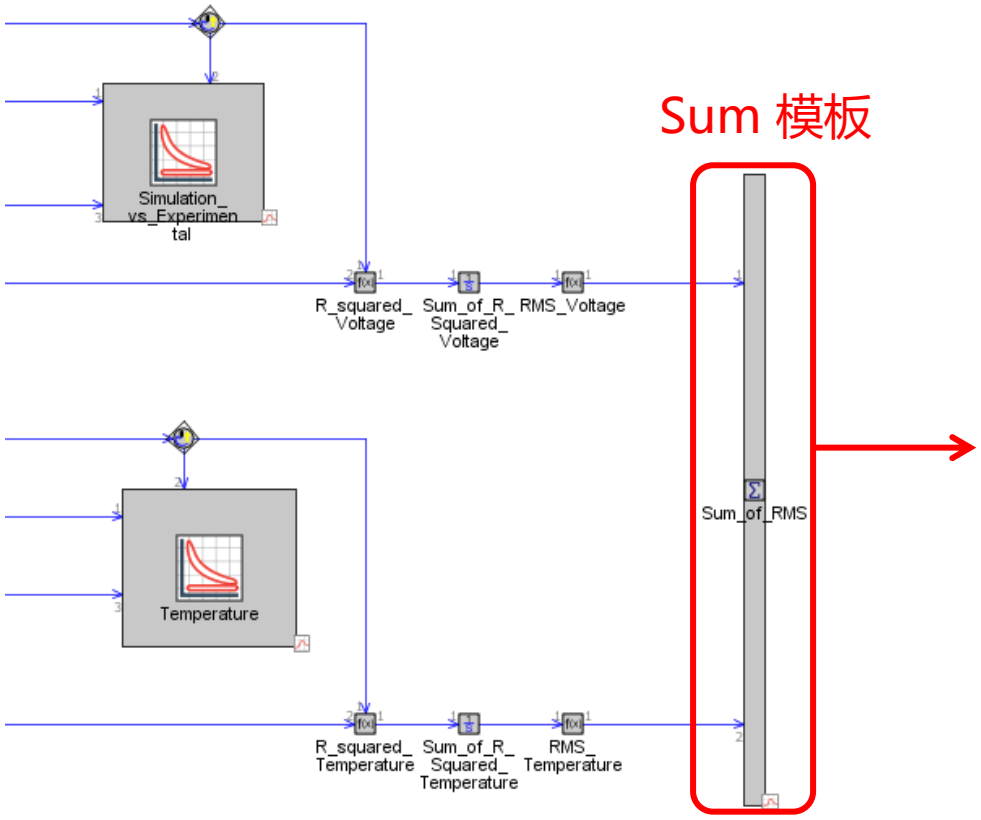
Sum 模板



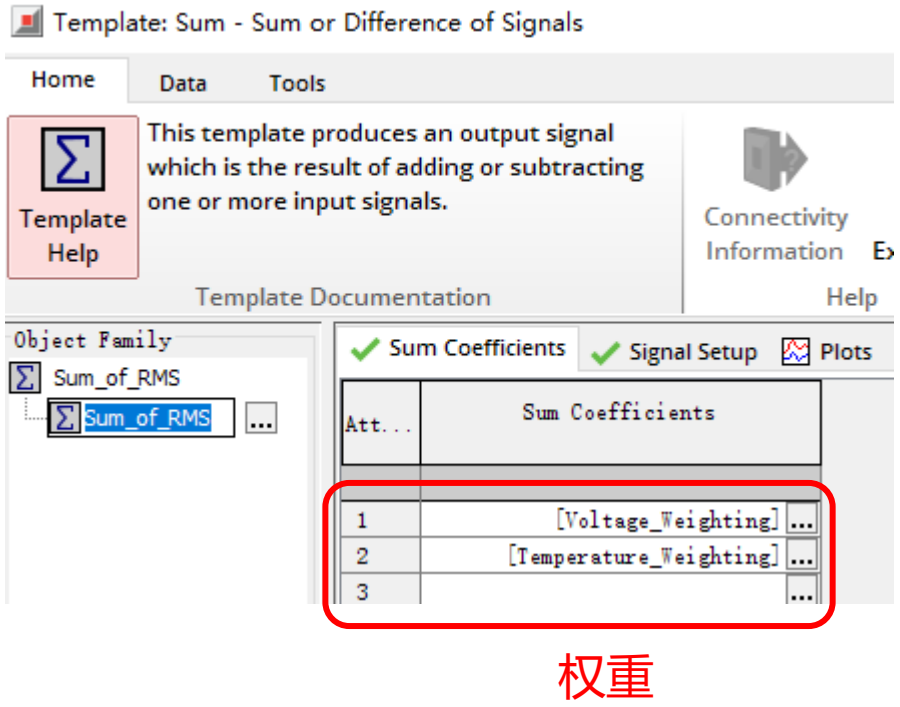
权重

电压、温度自动标定

- 优化器设置



Sum 模板

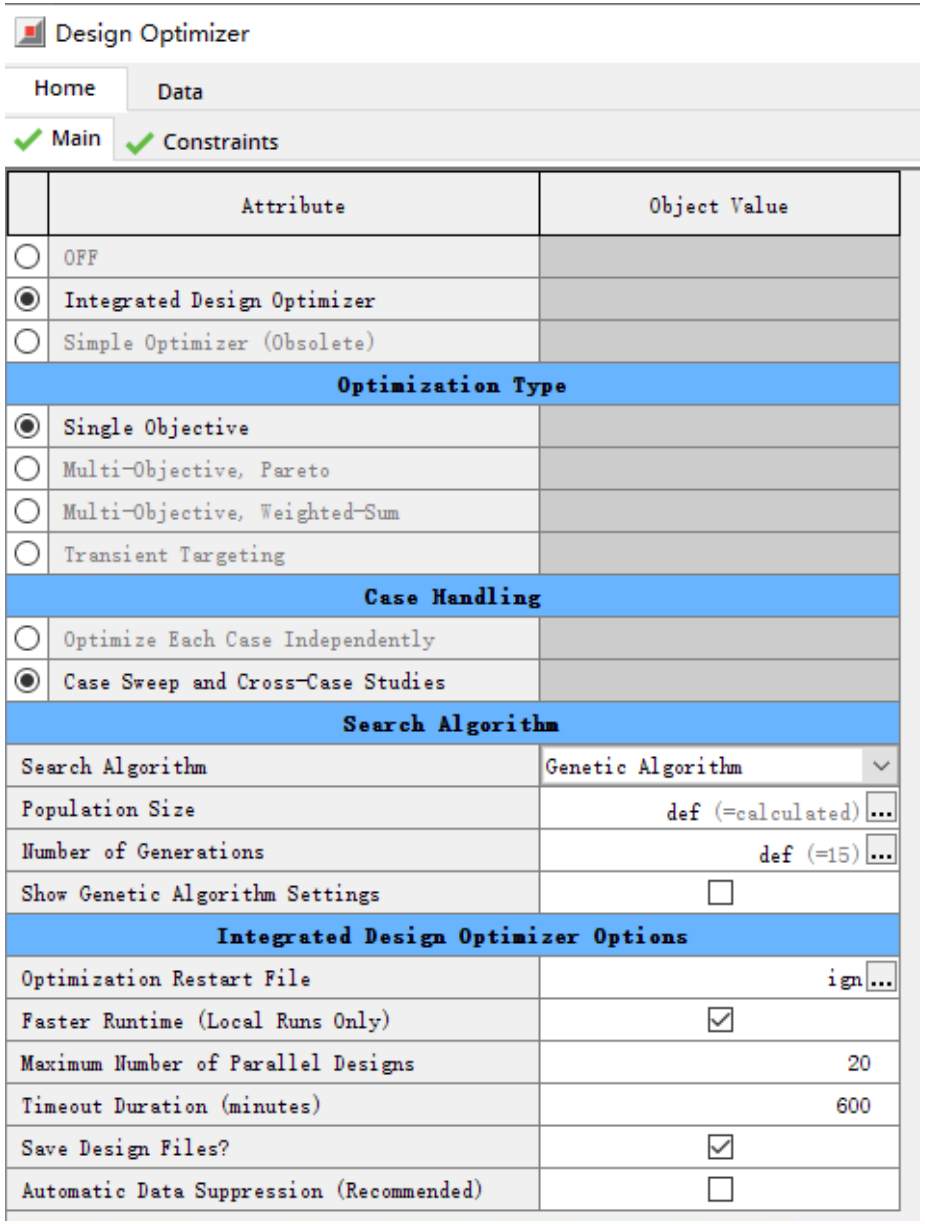


权重

电压、温度自动标定

- 优化器设置

  - 单目标优化，Single objective
  - 多case优化，case sweep and cross-case studies
  - 优化算法采用遗传算法，算法设置默认

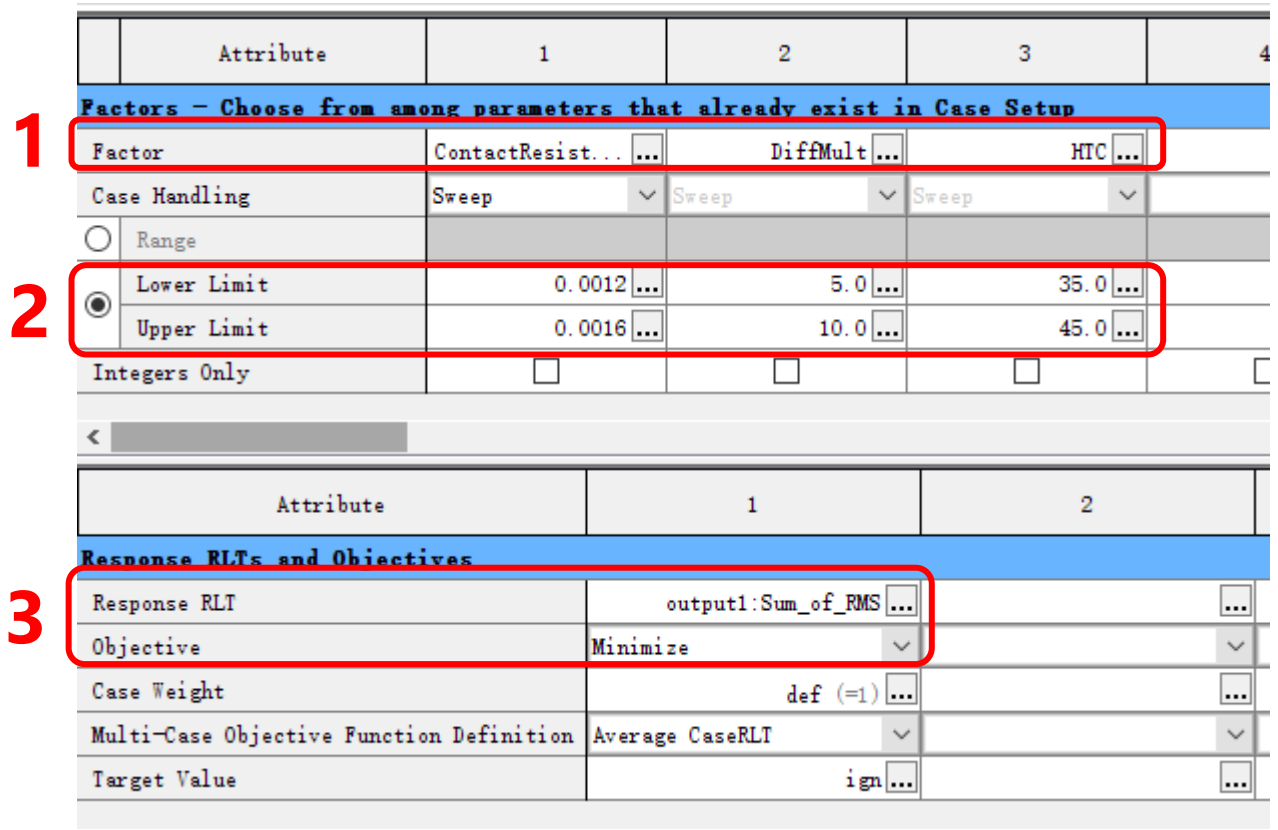


电压、温度自动标定

- 设计因子/响应设置

1. 选择所要优化的3个设计因子
2. 设置各因子搜索区间
3. 选择响应，并定义优化问题（最小化）

其他默认



电压、温度自动标定

- 约束条件设置

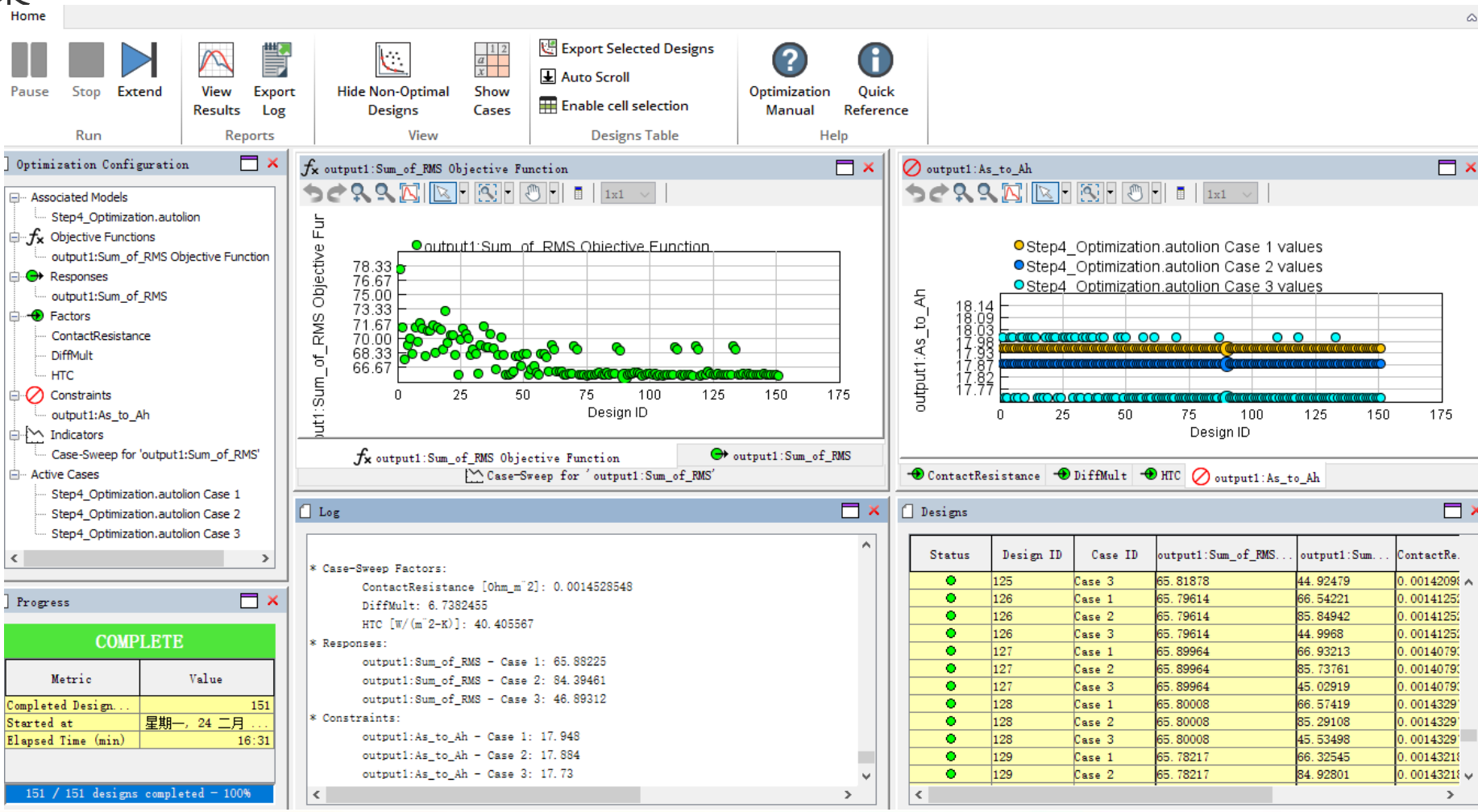
Main | Constraints

	Attribute	Constraint #1
Optional RLT Variable Constraints...		
	RLT Constraint Variables	output1:As_to_Ah ...
☑	Lower Limit	17.5 ...
	Upper Limit	18.0 ...

电压、温度自动标定

- 运行模型，查看优化结果

- ContactResistance [Ohm_m^2]: 0.00145
- DiffMult: 6.738
- HTC [W/(m^2-K)]: 40.4



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