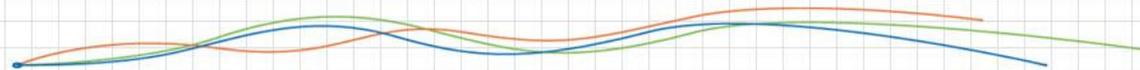




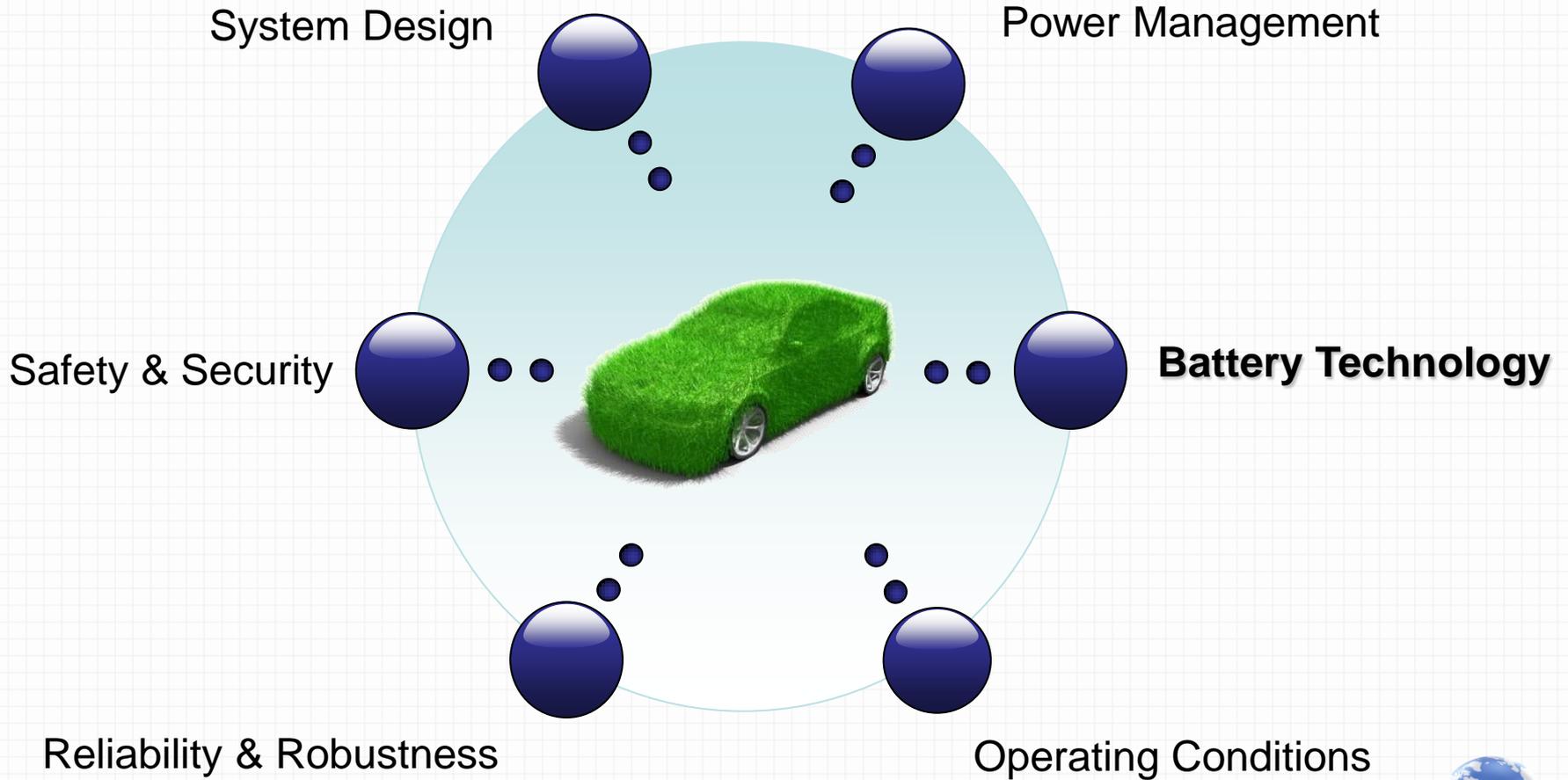
Battery Testing Solutions

April 28, 2010



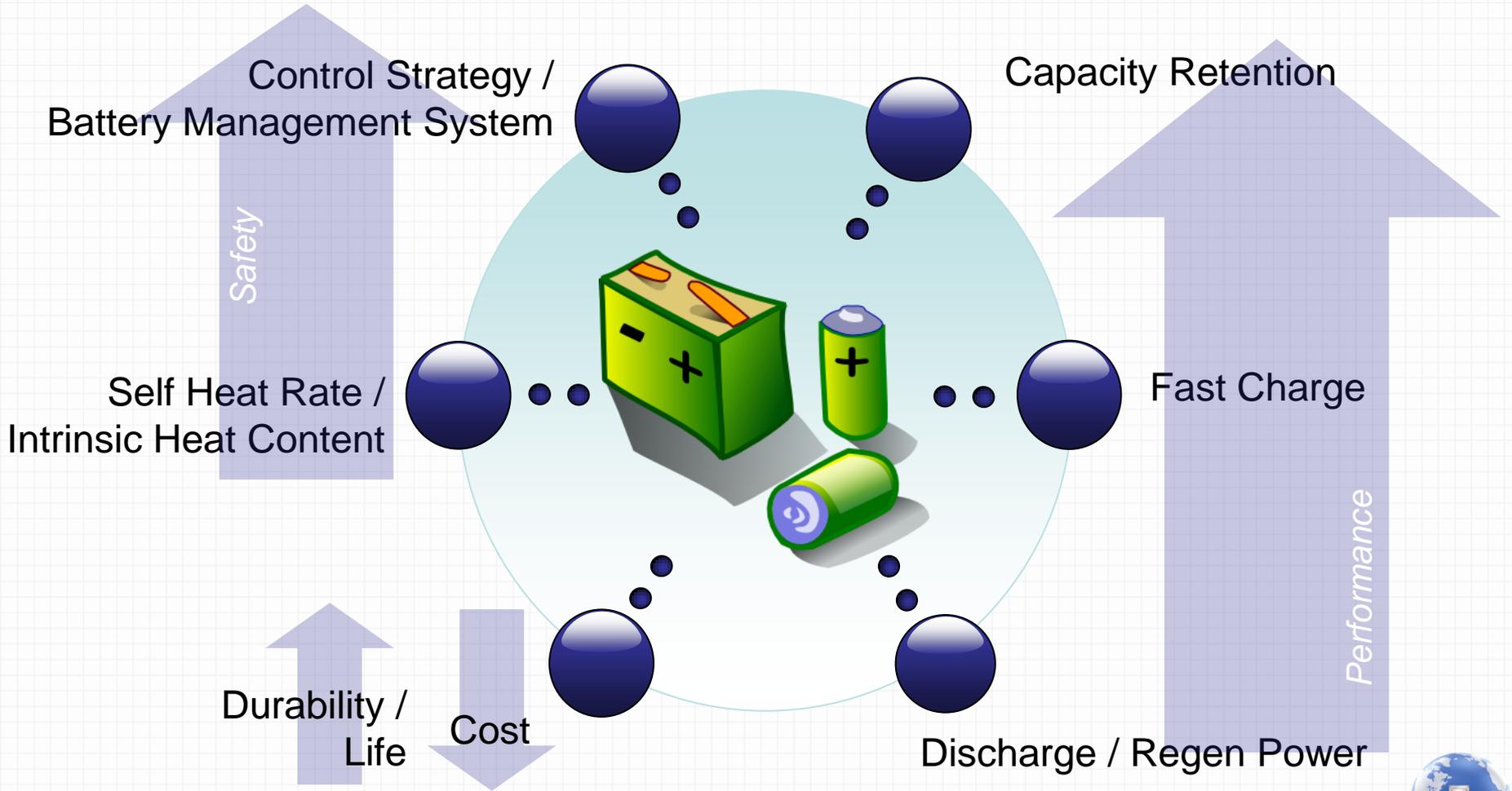
Challenges

Vehicle Electrification



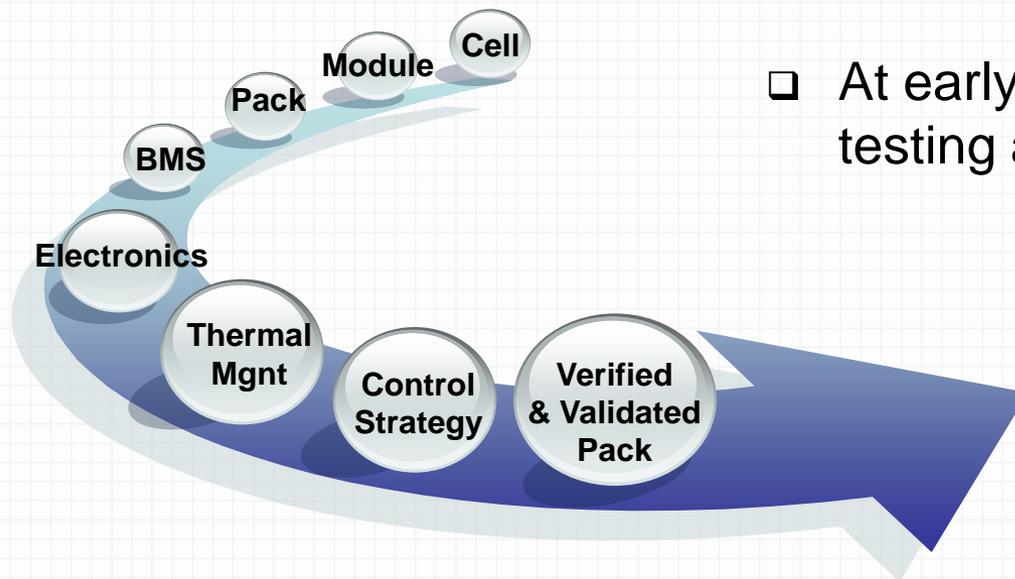
Challenges

Battery Technology



Challenges

- ❑ Incorporate design aspects of all system components with the KEY GOAL of reducing price and improving performance
 - ❑ Provide uncompromised high standard of durability

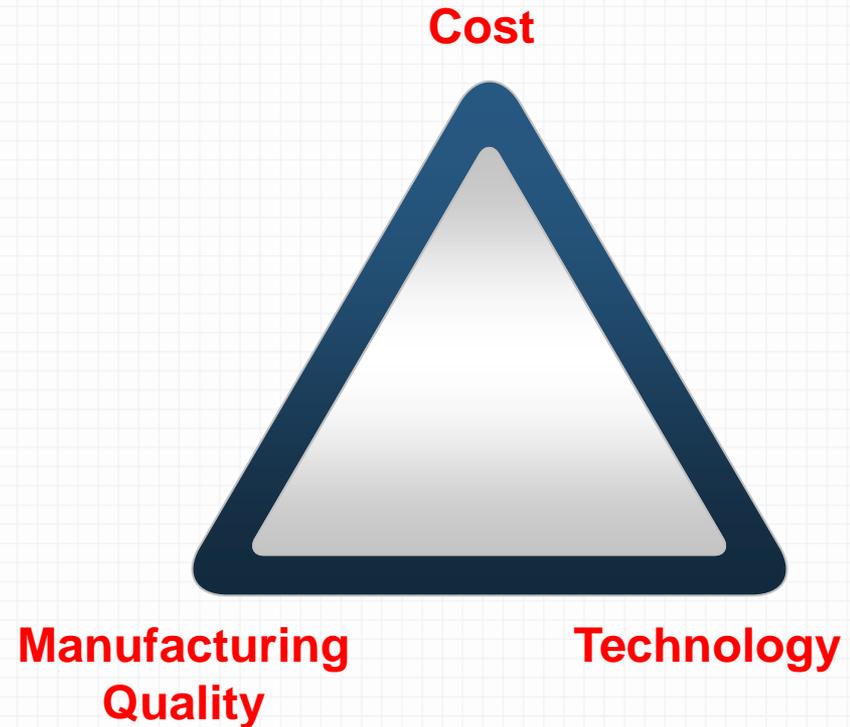


Advanced Battery Pack Scope of Components

- ❑ At early stage of product development testing and validation become critical
- ❑ Advanced, flexible test and simulation solutions are required

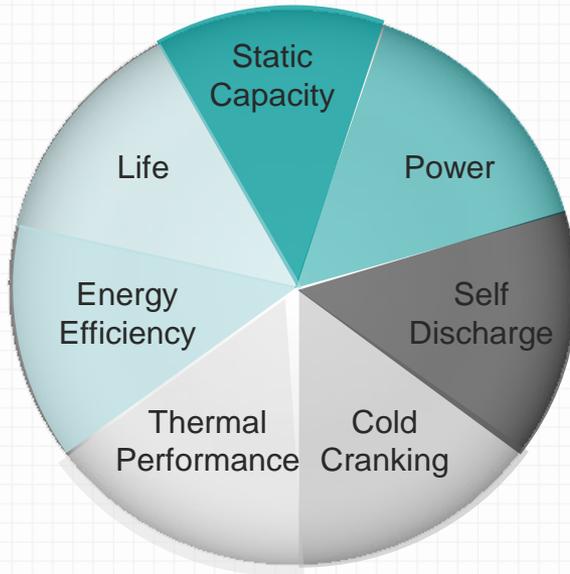
Battery Challenges

- ❑ Parallel and integrated development at component and system levels
- ❑ Validation of supplier products (e.g. contactor, fuse, control unit)
- ❑ Validation of system integration
- ❑ Validation of compliance to industrial standards
- ❑ Assure of functional and non-functional testing
- ❑ Assure of load patterns for durability patterns

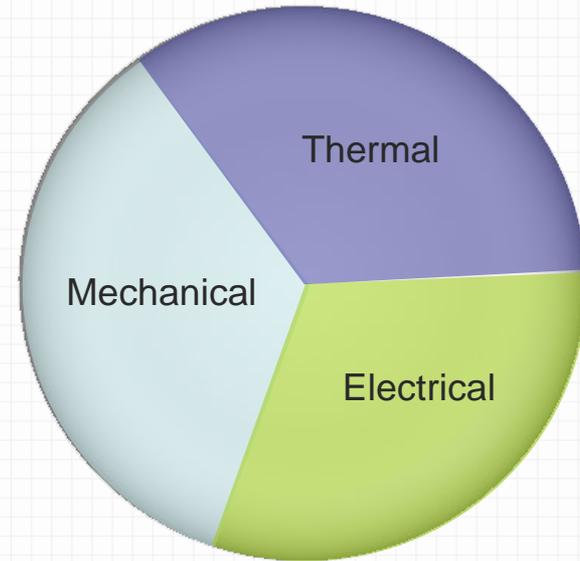


Battery Testing Tasks

Performance & Safety Tests in Battery Development



Performance Tests



Safety Tests

Source:

www.uscar.org, U.S. Department of Energy, Vehicle Technologies Program, Battery Test Manual for Plug-In Hybrid Electric Vehicles, 3/2008

www.uscar.org, United States Advanced Battery Consortium, Electrochemical Storage System Abuse Test Procedure Manual, 1999

Battery Performance Goals

Cycle life: >1,000 (charge depleting)
>300,000 (charge sustaining)

Overall life: 10 years

Operating temp: -40°C to +50°C

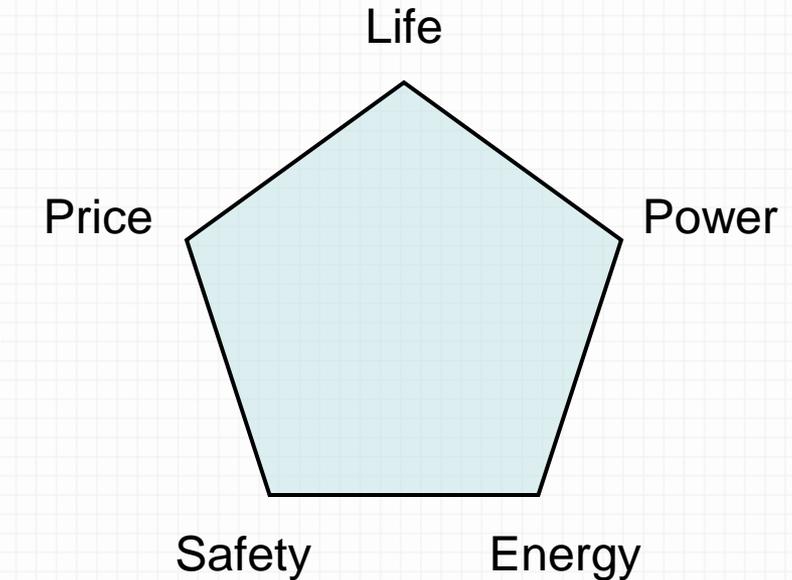
< \$150/kWh (25k units @ 40kWh)

Abuse conditions per USABC Abuse Test Manual

Charging time: 3 to 6 hours (normal recharge)
20-70% SOC in <20 minutes @
270W/kg (high rate)

Specific Energy: >150 Wh/kg¹)

Specific Power: >300 Wh/kg²)



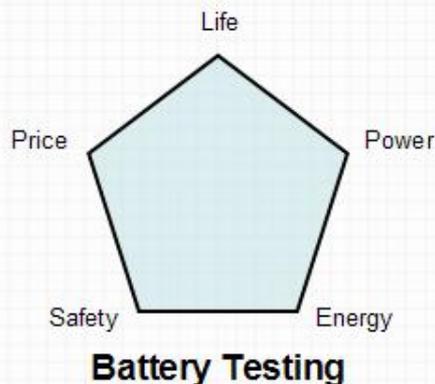
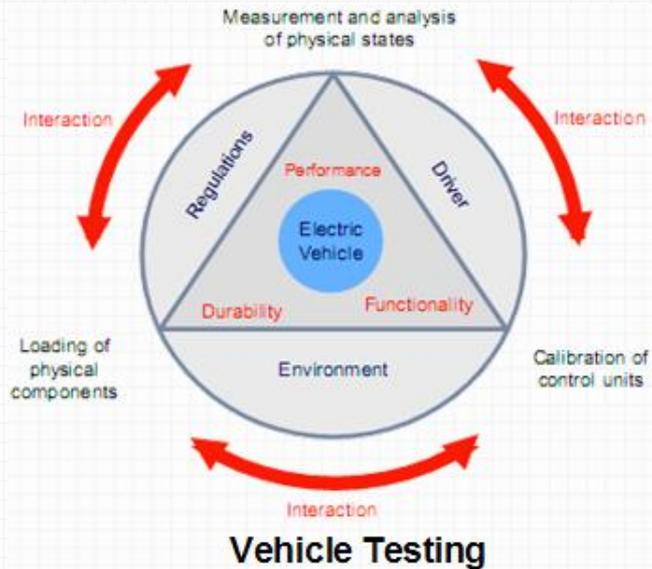
- 1) Discharge @ c/3 rate
- 2) Discharge @ 80%DOD, 30sec
- 3) Cycled @ 80%DOD
- 4) Charge sustaining HEV cycle life @ 50Wh profile

Source: www.uscar.org, United States Advanced Battery Consortium Goals for Advanced Batteries for EVs.pdf



Battery Performance Certainty

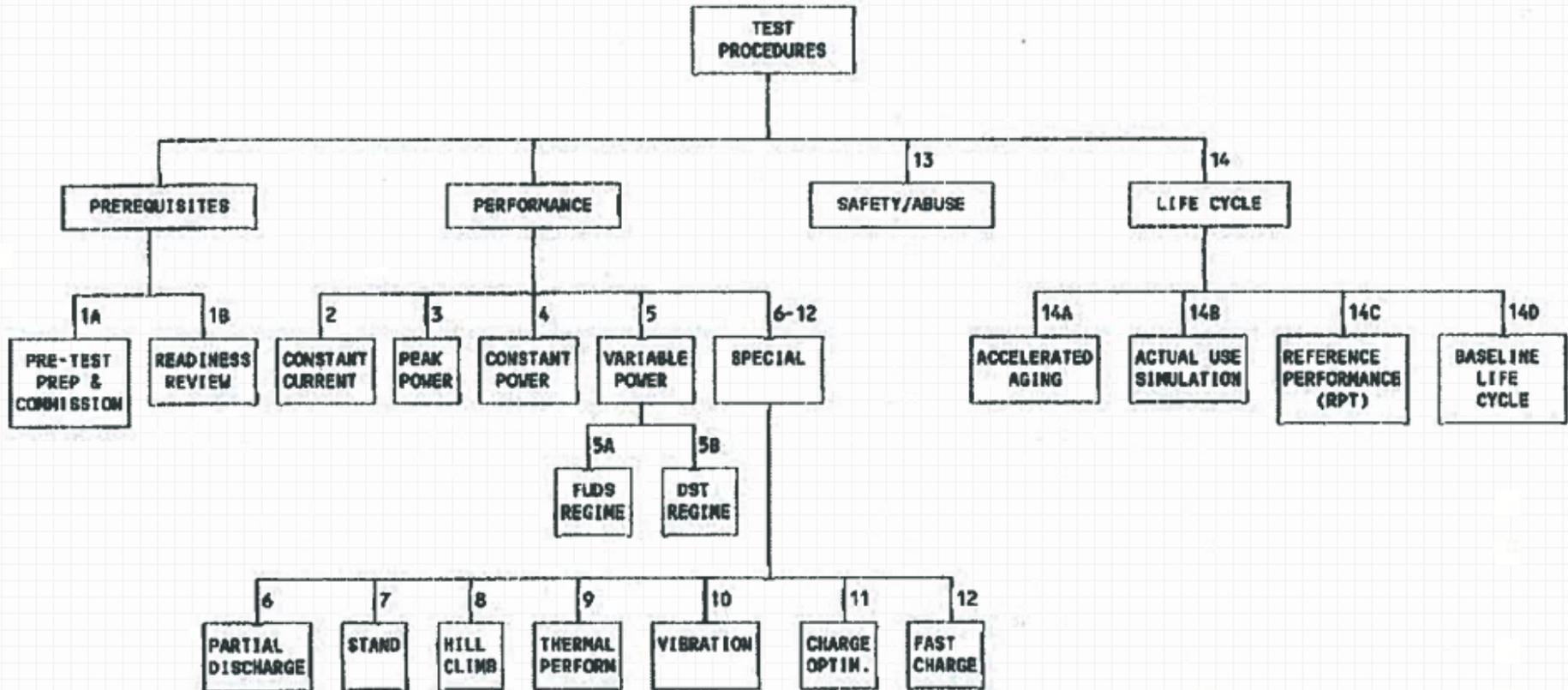
Real World Duty Cycle – More than Charge/Discharge the Battery



- ❑ Interaction of vehicle, driver, road, traffic has electrical, thermal & mechanical impact on all powertrain components including the battery
- ❑ Battery goals need to be achieved under these circumstances
- ❑ Going to high-energy cell designs will mean getting more abuse-sensitive active materials
- ❑ Not enough car related data is considered in standard testing (e.g. type of car, configuration of powertrain, duty cycle, etc.)
- ❑ Requires test solution system capable of advanced simulation and testing techniques
- ❑ A&D works hand-in-hand with universities & partners to address performance certainty

Battery Test Procedures

Organization Chart of Standard Verification Tests



Standard Verification Tests

Performance

- Constant Current
- Peak Power
- Constant Power
- Variable Power
- Special
 - ✓ Partial Discharge
 - ✓ Stand
 - ✓ Hill Climb
 - ✓ Thermal Performance
 - ✓ Vibration
 - ✓ Charge Optimization
 - ✓ Fast Charge

Safety

- Mechanical
 - ✓ Crush
 - ✓ Shock
 - ✓ Vibration
 - ✓ Drop
 - ✓ Immersion
- Electrical
 - ✓ Overcharge/voltage
 - ✓ Short circuit
 - ✓ Over discharge

Life Cycle

- Accelerated Aging
- Actual Use Simulation
- Reference Performance
- Baseline Life Cycle

Thermal Abuse

- Rapid Charge/Discharge
- Shock Cycling
- Thermal Stability
- Elevated Temp. Storage
- Simulated Fuel Fire

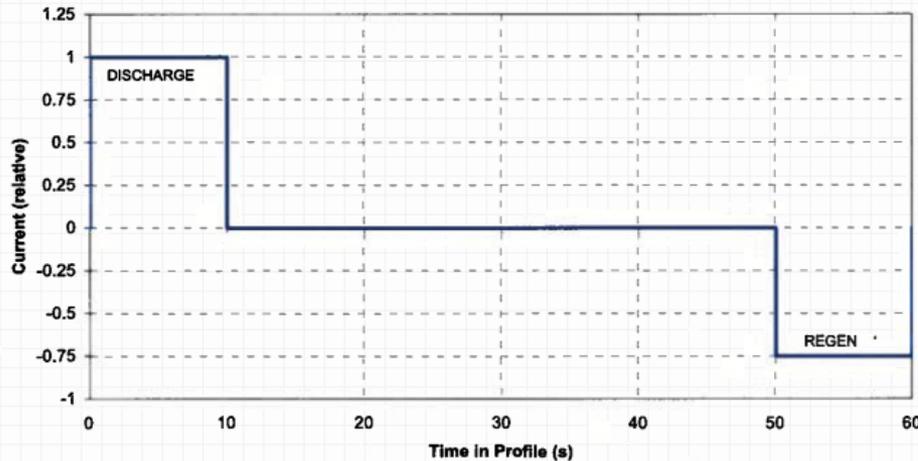
Environmental

- Humidity
- Altitude
- Salt Bath



Industry Standard Tests

Hybrid Pulse Power Characterization (HPPC)



Why HPPC: Determine dynamic power capability over usable voltage range

Objective: Determine 10sec discharge pulse & 10sec regen pulse power capabilities at 10% DOD

Result: Voltages recorded used to establish the cell's OCV behavior. Power and energy capabilities.

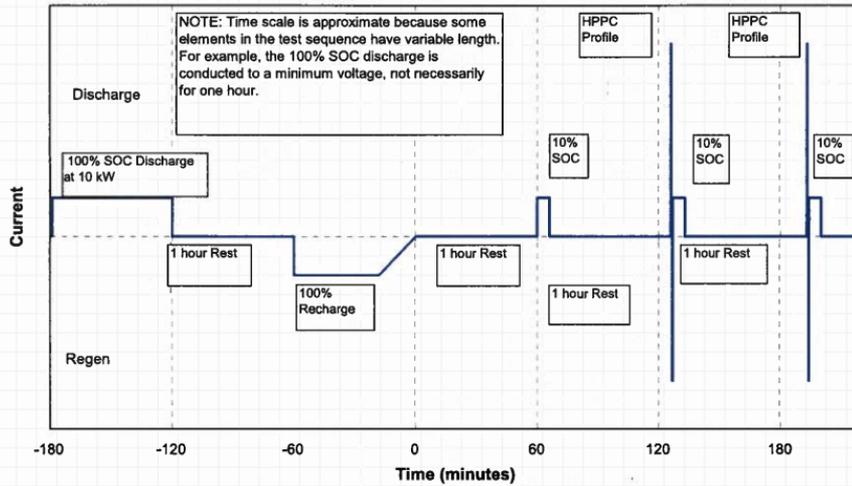
Procedure:

- ❑ Single repetitions of profile separated by 10% DOD constant discharge segments, each followed by 1hr rest period
 - ✓ Rest period allows cell to return to electrochemical & thermal equilibrium condition before applying next profile
- ❑ Test begins with fully charge unit after a 1hr rest
- ❑ Test ends after completing the final profile at 90% DOD, discharge of battery to 100% DOD, and final 1hr rest.



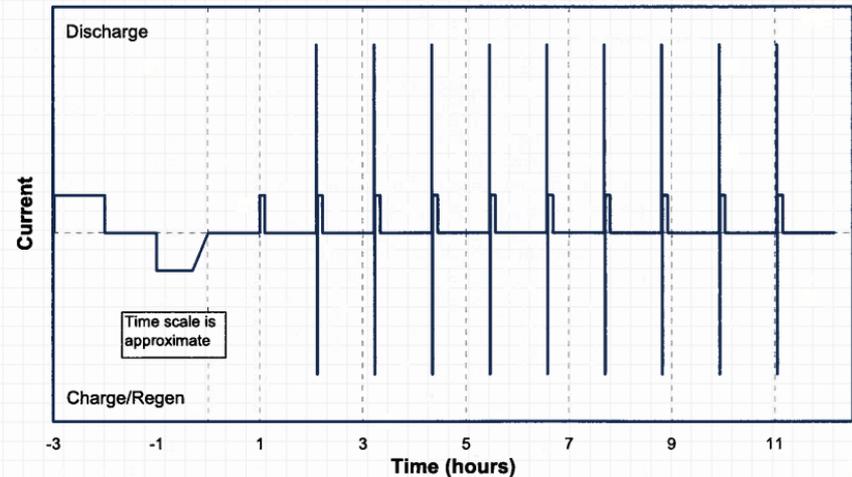
Industry Standard Tests

Hybrid Pulse Power Characterization (HPPC)



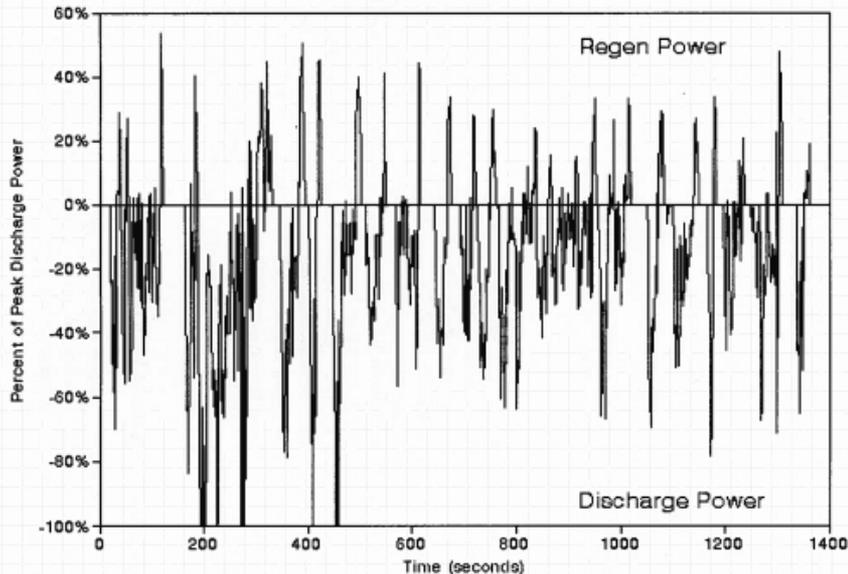
Start of HPPC Test Sequence

Complete HPPC Test Sequence



Industry Standard Tests

Federal Urban Driving Schedule (FUDS) – Variable Power Discharge



Why FUDS: Variable power discharge regime represents best simulation available of actual EV power requirements

Objective: Produce effects of EV driving behavior (including re-gen) on performance & life of battery

Result: Establish limits on regen power, current or voltage

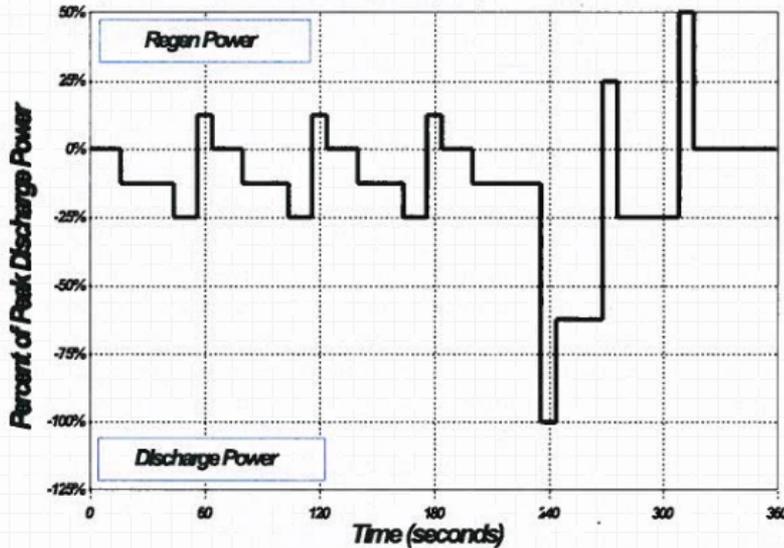
Procedure:

- Battery charged to full and temperature stabilized
- Discharge battery by applying FUDS profile
- Apply profiles continuously end-to-end with no rest period until end of discharge point (normally rated capacity or discharge voltage limit) is reached



Industry Standard Tests

Dynamic Stress Test (DST) – Variable Power Testing



Why DST: Can be implemented at most test labs

Objective: Effectively simulate dynamic discharging

Result: Establish capacity of the unit & value of maximum power step

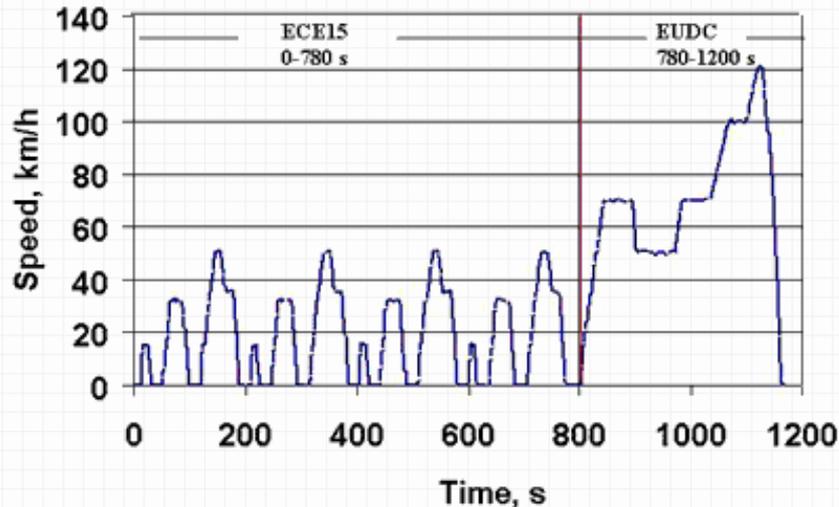
Procedure:

- ❑ Battery charged to full and temperature stabilized
- ❑ Battery discharged by applying DST profile
- ❑ Profiles repeated end-to-end with no rest period
- ❑ Regime continued until end-of-discharge point or inability to follow test profile within a battery limit occurs



Industry Standard Tests

Economic Commission for Europe (ECE) & Extra Urban Driving Cycle (EUDC)



Why ECE: Simulates driving conditions for Europe

Objective: Produce effects of EV driving behavior (including re-gen) on performance & life of battery

Procedure:

- ❑ Battery charged to full and temperature stabilized
- ❑ Discharge battery by applying ECE-15 profile
- ❑ Apply profiles continuously end-to-end with no rest period until end of discharge point (normally rated capacity or discharge voltage limit) is reached



Battery Testing Requirements

□ Safety

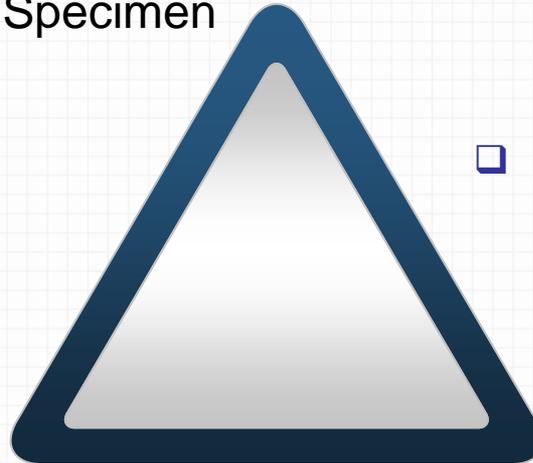
- ✓ People
- ✓ Equipment
- ✓ Specimen

□ Cost

- ✓ Initial
 - #channels * cost/channel + infrastructure
- ✓ Cost of ownership of equipment
 - Flexibility, upgrades
- ✓ Operational costs
- ✓ Efficiency
 - Transition time, down time, upgrade

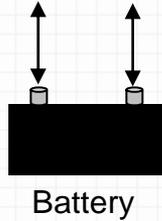
□ Data

- ✓ Consistency
 - Test procedures
 - Conditions
 - Bespoke data
- ✓ Accuracy
- ✓ Flexibility
 - Not compromise test



Generations of solutions - Pack

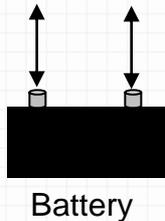
1st Generation



Programmer
 Battery Expert
 Operator
 Safety



2nd Generation



Test
 Safety



Programmer
 Battery Test Expert
 Operator



Lab Manager

Lab
 Safety



Lab Customer
 Battery Expert

Thermal Control
 Instrumentation
 (V-LCN, ROSS, Labview...)



Generations of Solutions - Pack



Programmer
Battery Expert



- **Safety (Expert Operator)**
 - + Flexible
 - high training cost
 - slow reaction
 - depends on people
- **Data**
 - Consistency –depends on operator
 - Slow rate
 - Tests different between equipment
 - Integrated between equipment (BMS/BCU, cycler, chiller, vibration table...)
Tests procedure, conditions, bespoke data
 - ? Accuracy – depends on setup
 - ? Flexibility - Compromise test/data based on limitations of equipment
- **Cost (#channels * cost/channel + infrastructure) / (# of Quality Tests)**
 - + Lower initial equipment cost / system
 - + Low infrastructure costs (lab data management,
 - Low efficiency requires more systems
 - Staff - Employee training & experience of broad experts, retention
 - Set-up (standard tests, integration, learnings, training)
 - Cost of ownership of equipment Flexibility, upgrades
 - Operational costs (usually not 24/7 lights out)
 - Efficiency Transition time, down time, upgrade
 - Infrastructure (floor space etc) from efficiency

1st Generati

2nd Genera



Therma
Instrum

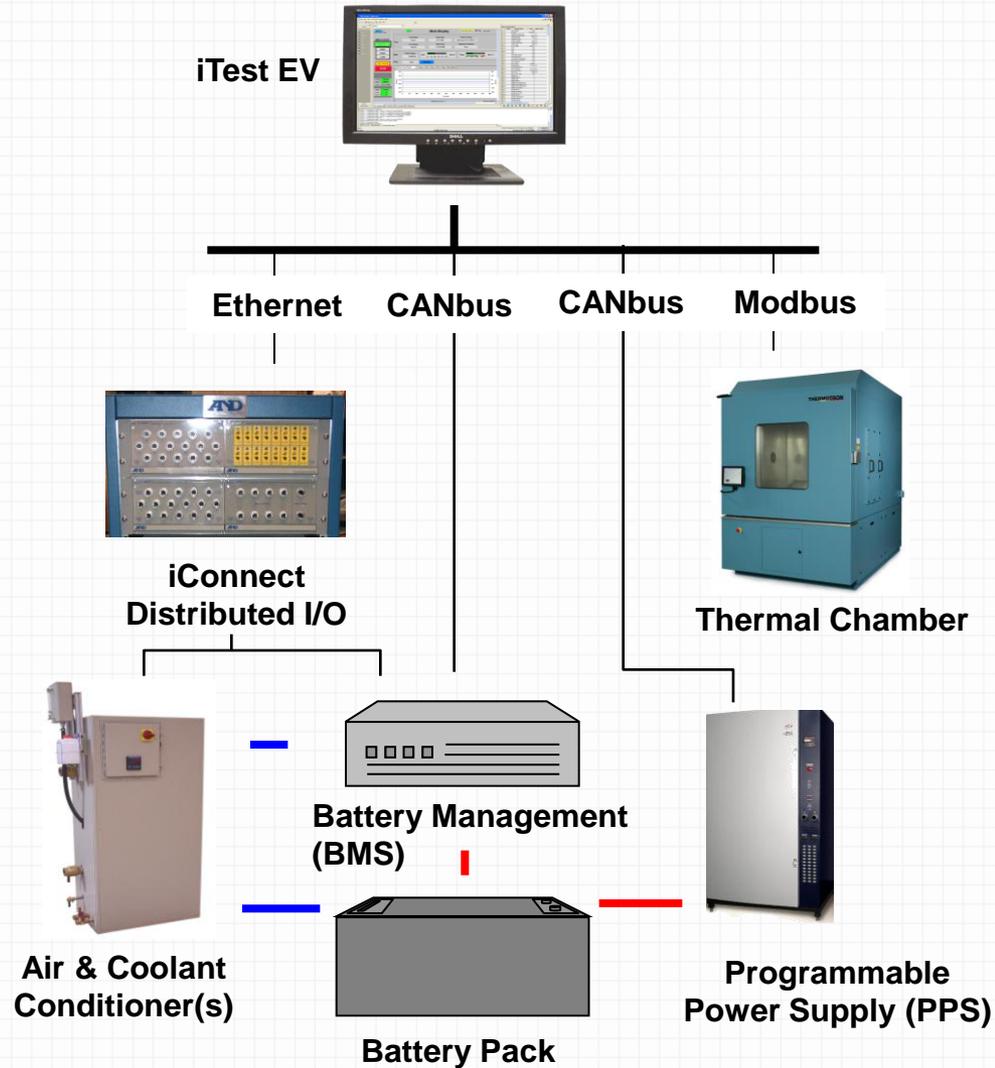
(V-LCN, ROSS, Labview...)



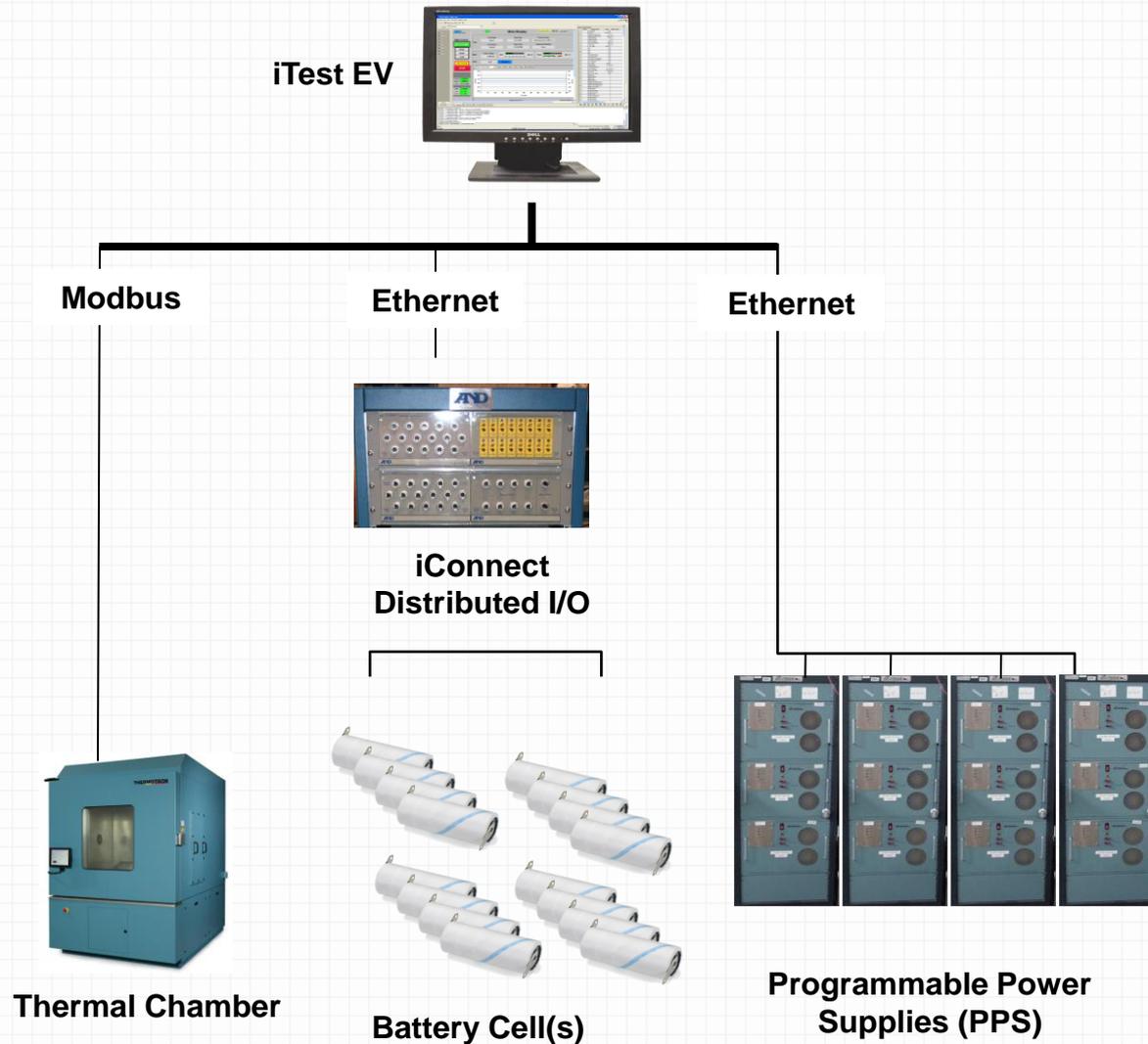
Lab Customer
Battery Expert



Battery Testing – Pack and Module

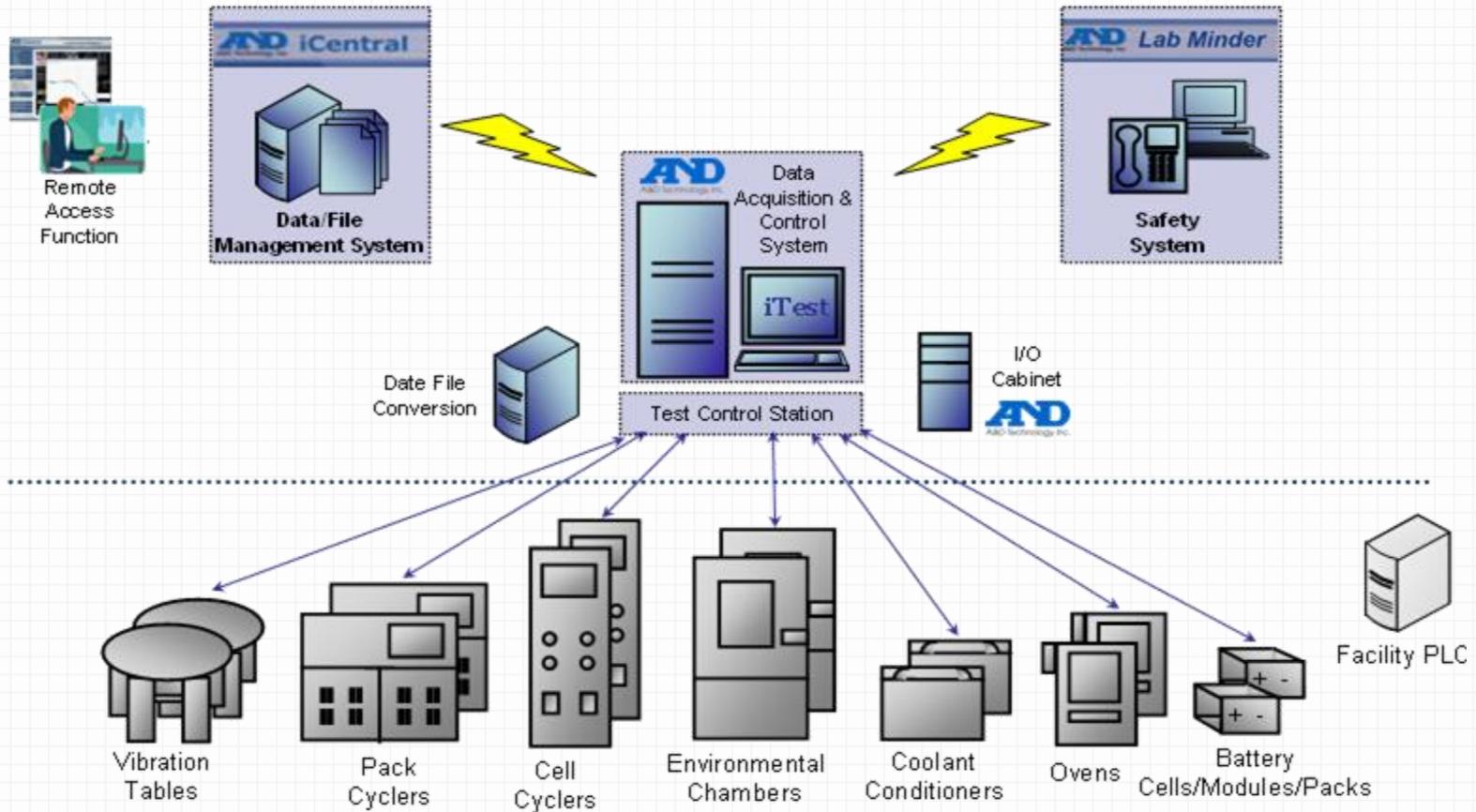


Battery Testing – Cell



A&D Battery Solution – Example System

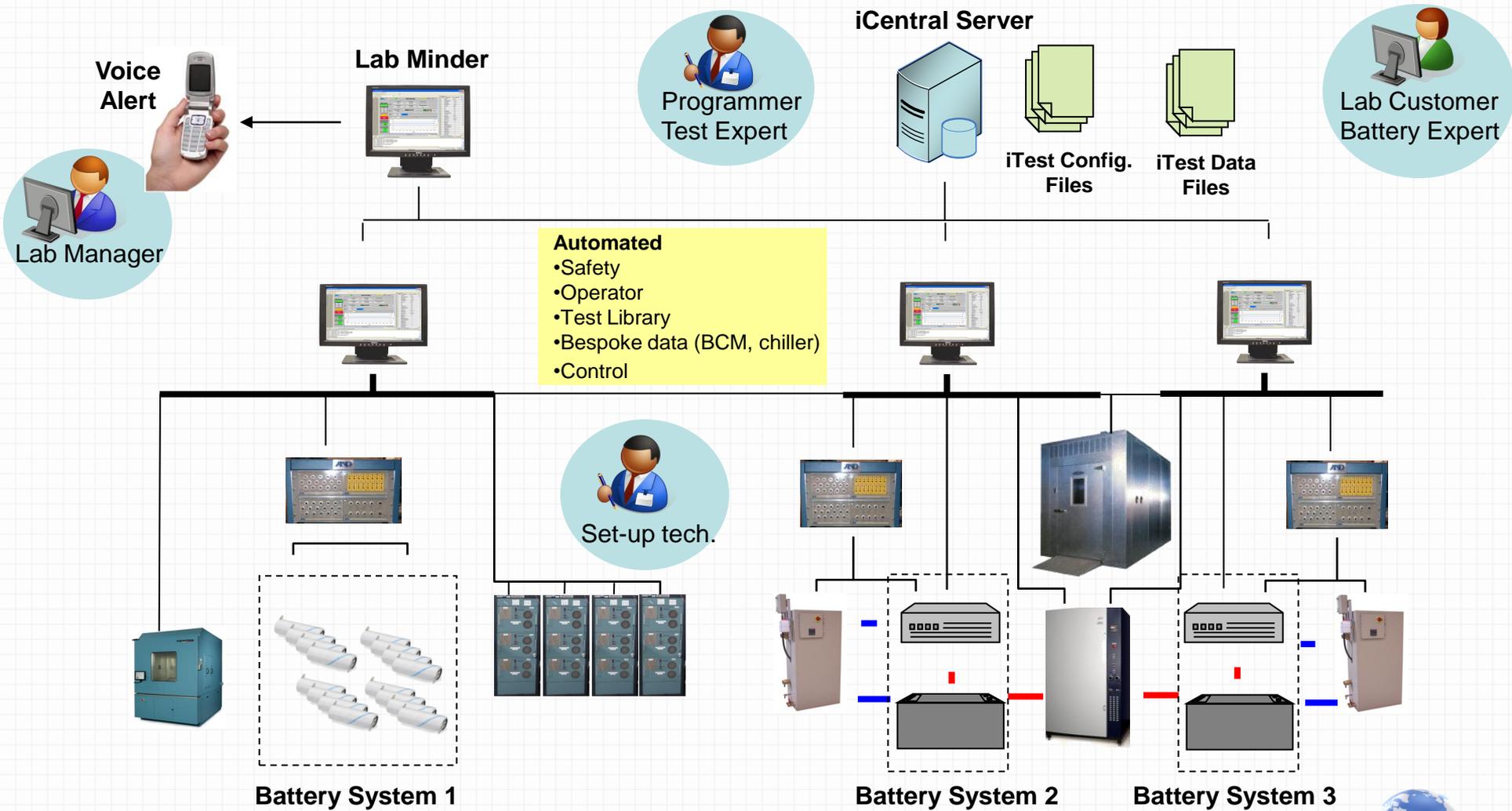
Complete Integrated Test Automation System



Equipment (multiple suppliers, operating systems, interfaces)



Current "State of the Art" Lab



Old/New Comparison

Semi-Automated

- **Safety** (Expert Operator)
 - + Flexible
 - High training cost
 - Slow reaction
 - Depends on people
- **Data**
 - Consistency –depends on operator
 - Slow rate
 - Tests different between equipment
 - Integrated between equipment (ECU, cycler, chiller, vibration table...)
 - Tests procedure, conditions, bespoke data
 - ? Accuracy – depends on setup
 - ? Flexibility - Compromise test/data based on system limitations
- **Cost** (#channels * cost/channel + infrastructure) / (# of Quality Tests)
 - + Lower initial equipment cost / system
 - + Low infrastructure costs (lab data management, monitoring, safety)
 - Low efficiency requires more systems
 - Staff - training & experience of broad experts, retention
 - Set-up (standard tests, integration, learnings, training)
 - Cost of ownership of equipment Flexibility, upgrades
 - Operational costs (usually not 24/7 lights out)
 - Efficiency Transition time, down time, upgrade

Automated

- **Safety** (Automated)
 - + Flexible
 - + Very fast reaction
 - + Incident prevention
 - + Automated fault detection at both channel and lab level
- **Data**
 - + Consistency (automated test)
 - + Fast 10Hz, 100Hz to 20kHz available
 - + Tests same between equipment
 - ++ Integrated between equipment (ECU, cycler, chiller, vibration table...)
 - Tests procedure, conditions, bespoke data
 - + Accuracy
 - + Flexibility – Test system open
- **Cost** (#channels * cost/channel + infrastructure) / (# of Quality Tests)
 - Higher initial equipment cost / system
 - Higher infrastructure costs (lab data management, monitoring, safety)
 - ++ High efficiency requires fewer systems
 - ++ Staff – divided tasks require narrower knowledge, fewer experts
 - ++ Set-up (standard tests, integration, learnings, training)
 - ++ Cost of ownership of equipment Flexibility, upgrades
 - ++ Operational costs (24/7 lights out)
 - ++ Efficiency Transition time, down time, upgrade



User Experiences



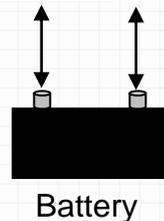
Set-up tech.

□ Mechanical

- ✓ Move battery into chamber
- ✓ Connect PPS to battery
- ✓ Connect instrumentation

□ Test

- ✓ Enter battery parameters
- ✓ Select Test
- ✓ Push Go



Battery Pack

Battery Control: Turn ON | Turn OFF | **Batt OFF** | Pack Info | **CAN OK**

Manufacturer Specs	
Max Pack V	360.00 V
Min Pack V	225.00 V
Max Cell V	4.00 V
Min Cell V	2.50 V
Max Current	300.0 A
Min Current	-300.0 A
Capacity	100.00 Ah
Max Temp	55.0 °C
Efficiency	0.98
Pause Time	20 s

CAN Data		Measured Data and Calculations	
Fan Speed	0.0	Max Cell V	0.00 V
Batt Voltage	0.0 V	Min Cell V	0.00 V
Batt. Current	0.0 A	Max Cell Temp	0.0 °C
SOC	0%	Min Cell Temp	0.0 °C
Cycler Voltage	0.00 V	Charge (Estimate)	0.980 Ah
Cycler Current	0.00 A	Charge In	1.000 Ah
Batt TC Temp	25.0 °C	Charge Out	0.000 Ah
Batt SOC (calc)	49.0%	Energy (Estimate)	100000.000 Wh
Capacity	2.00 Ah	Energy In	100000.000 Wh
Efficiency	0.98	Energy Out	0.000 Wh

SOC Settings: SOC Delta 49.0% | **Use Calc SOC** | Use CAN SOC

Max Charge Time: 3600 s
Max Discharge Time: 3600 s

Start

```

graph TD
  Start([Start]) --> A[Activate Chamber Watchdog Limit]
  A --> B[Turn Chamber On]
  B --> C[Set Chiller Temp to 30 °C]
  C --> D[Set Chamber to 30 °C and 50% RH]
  D --> E[Soak for 1 Hour]
  E --> F[Run Capacity Test]
  F --> G[Test Complete]
  G --> H[Turn Chamber Off]
  H --> End([End])
  
```

numSeq1Status	Running
numBatt1Status	Stable
Batt TC Temp	26.0 °C
Block Timer	00:00:48.3

BATTERY INFORMATION

Max. Pack Voltage	360.00	Min. Pack Voltage	225.00
Max. Cell Voltage	4.00	Min. Cell Voltage	2.50
Positive Current Limit	300.00	Negative Current Limit	-300.00
Capacity	100.00	Manuf. Pause Time	20
Storage SOC	50.00	Coul. Efficiency	0.98
Size Factor	1.00		



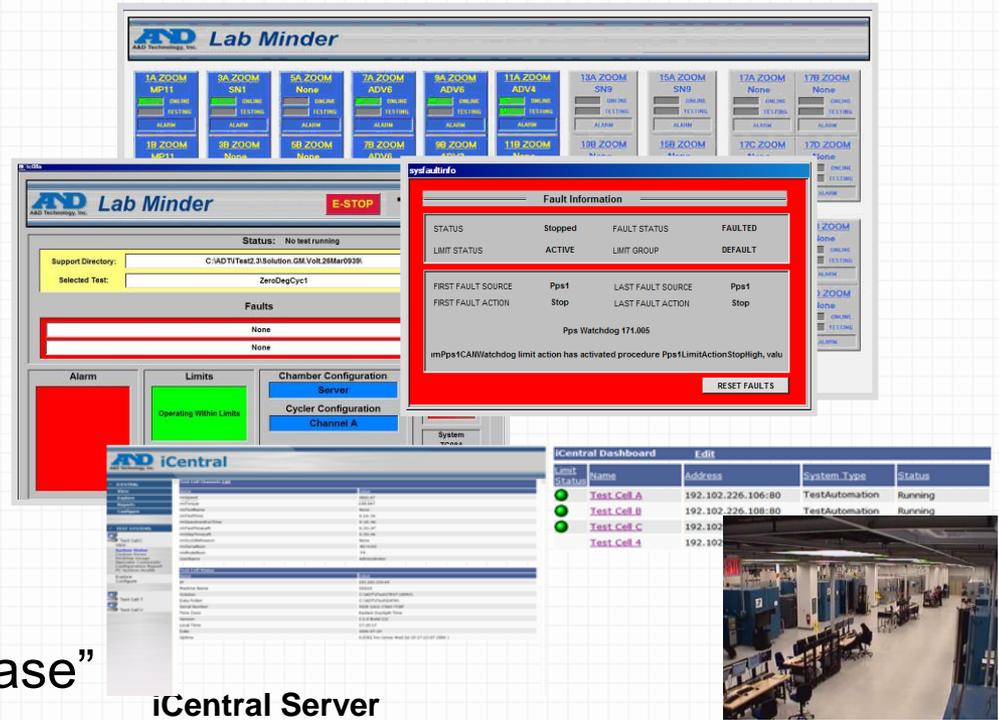


□ Safety and Status

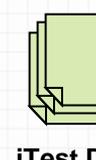
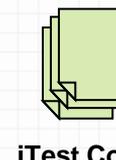
- ✓ Redundant fail-safe lab
- ✓ Prevention over reaction
- ✓ Complete lab status
 - Local & remote
 - Automated notification
 - Cameras

□ Data

- ✓ Continuous logging “just in case”
- ✓ Automated
 - Upload and availability
- ✓ Secure



iCentral Server



iTest Config. Files

iTest Data Files



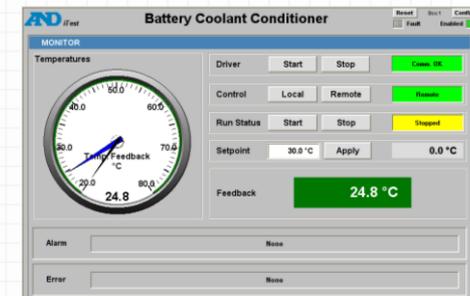
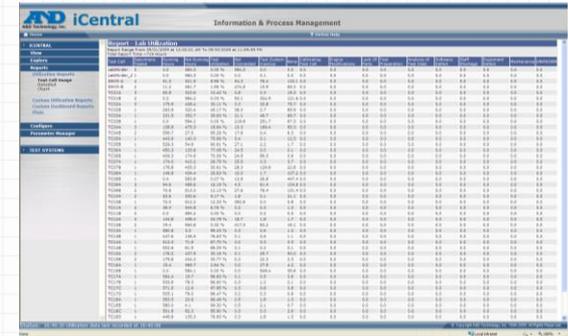
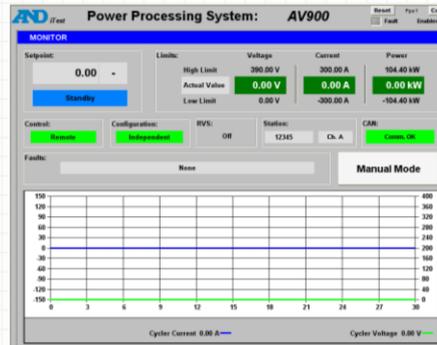
Lab Customer Battery Expert





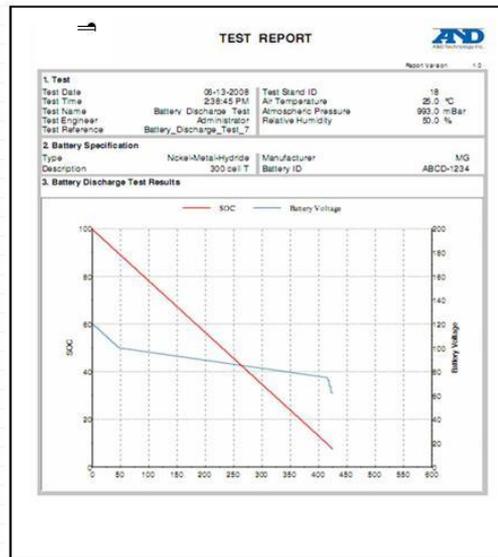
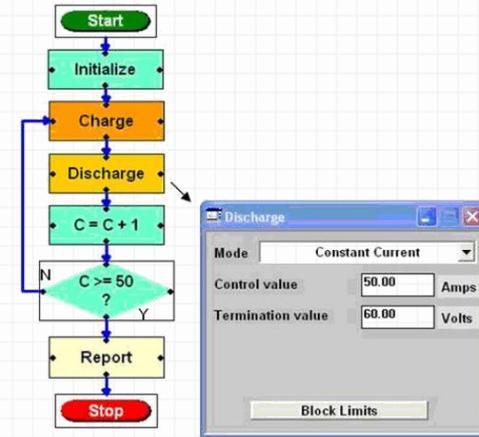
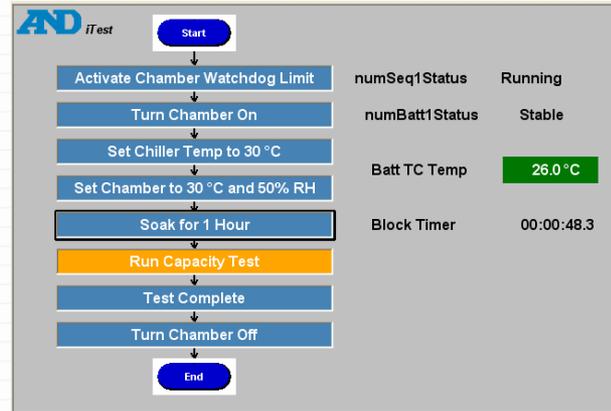
- Efficiency
 - ✓ Consistent across different equipment
 - ✓ Utilization tracking
 - ✓ 24/7 operation

- Trouble shooting
 - ✓ Equipment
 - ✓ Communications
 - ✓ Instrumentation
 - ✓ Battery





- ❑ Test Creation and Editing
 - ✓ Available standard tests
 - Open and customizable
 - ✓ Block Programming
 - ✓ Parameterized
 - ✓ Pack, Module & Cell
 - ✓ Equipment Independent
 - ✓ Test specific screens
 - ✓ Off line testing
 - ✓ Powerful
 - Equations
 - Strings
 - Models
 - Complex logic
 - Infinite Steps
 - ✓ Available training
 - ✓ Standard Reports



Learning iTest Console

Viewing a Report

The iTestReport.exe tool in iTest console allows you to run, view and/or print a report created in Test Manager.

NOTE: If the reporting tool doesn't already exist in the console toolbar you'll need to add it manually.

1. Click on the **Reports** icon from your toolbar
2. Click **File/Open**. The popup will default to the **Reports** folder of the current (or last used) iTest solution
3. Select the report you wish to open and click **Open**. If you choose to use an input file when configuring your parameters you will have to choose a data file to use

AND Learning Center
Proprietary and Confidential, A&D Technology, Inc. Course: iTest Software Training Slide 73





□ Data

- ✓ Equipment Independent
- ✓ Available
 - Searchable
 - Remote availability
- ✓ Standard Reports

□ Tests

- ✓ Consistent
- ✓ Flexible
- ✓ User Friendly

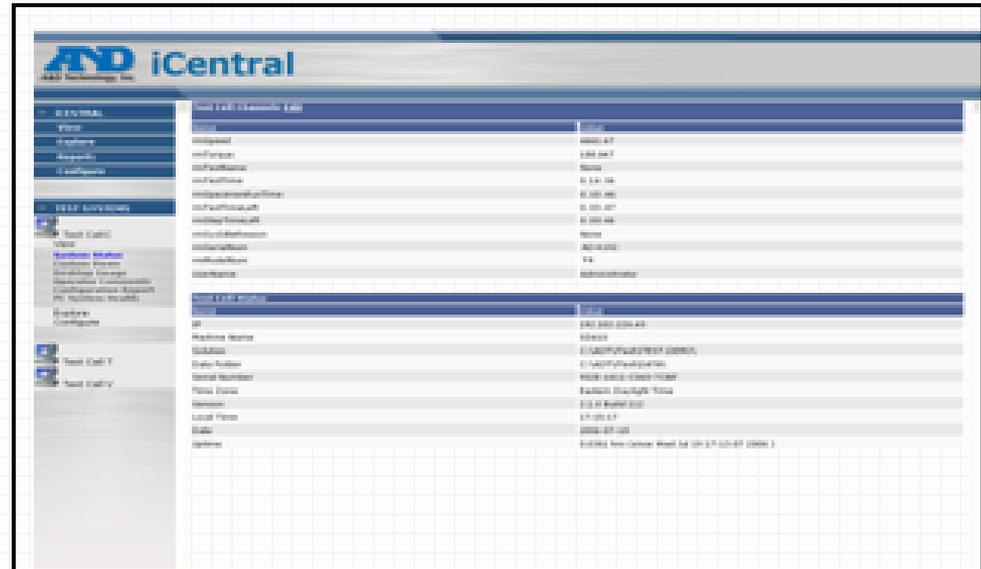
iCentral Server



iTest Config.
Files



iTest Data
Files



Conclusions

The fully automated third-generation system is not merely a possibility, but is currently deployed at the GM Global Battery Lab in Warren. According to the lab manager, “this kind of automation and lab management system is a requirement for our new lab. Despite our years of experience dating back to the EV-1 program this lab would have cost more and certainly not been completed 6 months ahead of schedule.”

This system is becoming the industry standard for advanced battery testing:

↓ ↓ ↓ ↓ Down time = ↑ ↑ ↑ ↑ Lab Utilization

↓ ↓ ↓ ↓ Resources = ↓ ↓ ↓ ↓ Cost (people, equipment, specimens, etc.)

↓ ↓ ↓ ↓ Human dependency (writing/recreating tests, data crunching, archiving)
= ↑ ↑ ↑ ↑ Test accuracy

↑ ↑ ↑ ↑ Runtime efficiency = ↓ ↓ ↓ ↓ Time on test
(24/7 operation with preventive safety systems allows for condensed test time, especially crucial for life cycling)



A&D Battery Testing Solution

Excerpt of Possible Test Runs

- ❑ Cycle life test
- ❑ Capacity test
- ❑ Internal ohmic resistance test
- ❑ Overcharge, discharge test
- ❑ Self discharge test
- ❑ Performance test
- ❑ Dynamic stress test
- ❑ Federal urban driving cycle
- ❑ Constant current profiles
- ❑ Constant voltage profiles
- ❑ Pulse profiles
- ❑ Ramp profiles, etc.

The screenshot displays the A&D Battery Testing software interface. At the top, there are control buttons for Start, Stop, and Pause, along with a status indicator 'Circuits Running 0 of 16'. Below this is a table listing various test circuits (C01_01 to C01_10) with columns for Status, Mode, Current, Voltage, Power, AmpHours, WattHours, TestStep, TestTime, Circuit, Tests, and Battery ID.

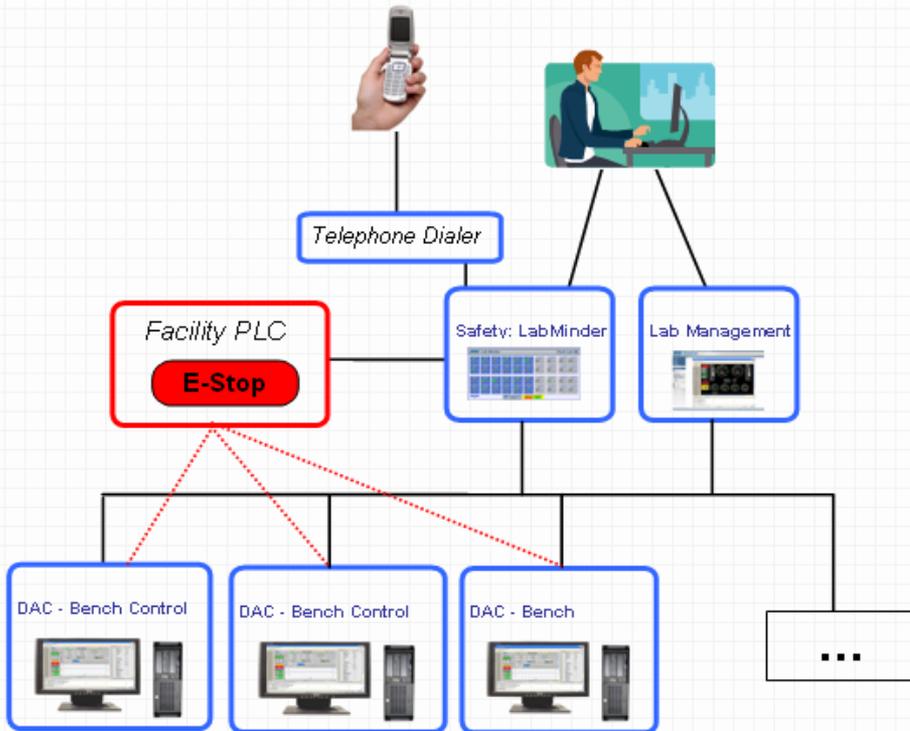
A 'ScheduleViewer2D - [HPPC.sc2]' window is open, showing a detailed test schedule with columns for Mode, Step Time (hms), Current (Amps), Voltage (Volts), Power (Watts), ResetARWh, Batt Lims, Data Log, Log Text, and Jump To. The schedule includes steps for Rest, Discharge, Charge, and Rest.

A 'Circuit Monitor Channel Selections' dialog box is open, prompting the user to check channels to show on the Circuit Monitor. The checked channels include Status, Mode, Current, Voltage, Power, AmpHours, and WattHours.

A 'c01_01.dsp' window shows a real-time test plot for Battery ID 'Cell_Lix_001'. The plot displays Voltage (3.65 V) and Current (0.00 A) over time. The test name is 'HPPC', and the test status is 'Running'. Other parameters shown include Battery Status (Rest), Battery Temp (25.0 °C), Battery SOC (98.0 %), and Battery DOD (2.0 %).



GM Battery Systems Lab



iCentral Data Management

Limit Status	Name	Address	System Type	Status
●	Test Cell A	192.102.226.106:80	TestAutomation	Running
●	Test Cell B	192.102.226.108:80	TestAutomation	Running
●	Test Cell C	192.102.226.109:80	TestAutomation	Running
	Test Cell 4	192.102.226.126:80	TestAutomation	Not Connected

- ❑ Test cell monitoring
- ❑ Web access to data and test results – central location for archive/retrieval
- ❑ Parameter manager to download test configurations
- ❑ Query/filtering – search by meta data

GM Battery Systems Lab

A&D Integrated Test Automation & Control System

- ❑ Assures safe operation of the battery lab equipment & test specimens
- ❑ Increase productivity of the system by increasing the Mean Time Between Failures & decreasing the Mean Time to Repair
- ❑ Introduces common systems & user interfaces to the lab
- ❑ Reduces construction costs without increasing maintenance costs
- ❑ Leverages engineering resources
- ❑ Facilitates lessons learned from program to program



A&D System Differentiators

- ❑ Safety System = 27/4 Testing
- ❑ Data Repository & Filter Analysis
- ❑ Global Collaboration (across programs & locations)
- ❑ Remote Web Access & Functionality



GM Battery Systems Lab

Lab Minder Safety System

- ❑ Emergency shutdown of the entire facility
- ❑ Critical error notification
- ❑ Remote control to react to the error reported

Phone Alert



Lab Minder

Lab Minder

1A ZOOM MP11 ONLINE TESTING ALARM	3A ZOOM SN1 ONLINE TESTING ALARM	5A ZOOM None ONLINE TESTING ALARM	7A ZOOM ADV6 ONLINE TESTING ALARM	9A ZOOM ADV6 ONLINE TESTING ALARM	11A ZOOM ADV4 ONLINE TESTING ALARM	13A ZOOM SN9 ONLINE TESTING ALARM	15A ZOOM SN9 ONLINE TESTING ALARM	17A ZOOM None ONLINE TESTING ALARM	17B ZOOM None ONLINE TESTING ALARM
1B ZOOM MP11 ONLINE TESTING ALARM	3B ZOOM None ONLINE TESTING ALARM	5B ZOOM None ONLINE TESTING ALARM	7B ZOOM ADV6 ONLINE TESTING ALARM	9B ZOOM ADV2 ONLINE TESTING ALARM	11B ZOOM None ONLINE TESTING ALARM	13B ZOOM None ONLINE TESTING ALARM	15B ZOOM None ONLINE TESTING ALARM	17C ZOOM None ONLINE TESTING ALARM	17D ZOOM None ONLINE TESTING ALARM
2A ZOOM None ONLINE TESTING ALARM	4A ZOOM MP11 ONLINE TESTING ALARM	6A ZOOM sample 2 ONLINE TESTING ALARM	8A ZOOM ADV6 ONLINE TESTING ALARM	10A ZOOM ADV1 ONLINE TESTING ALARM	12A ZOOM CPK15 ONLINE TESTING ALARM	14A ZOOM None ONLINE TESTING ALARM	16A ZOOM ADV6 ONLINE TESTING ALARM	18A ZOOM None ONLINE TESTING ALARM	18B ZOOM None ONLINE TESTING ALARM
2B ZOOM None ONLINE TESTING ALARM	4B ZOOM MP11 ONLINE TESTING ALARM	6B ZOOM None ONLINE TESTING ALARM	8B ZOOM None ONLINE TESTING ALARM	10B ZOOM ADV6 ONLINE TESTING ALARM	12B ZOOM SN6 ONLINE TESTING ALARM	14B ZOOM None ONLINE TESTING ALARM	16B ZOOM None ONLINE TESTING ALARM	18C ZOOM None ONLINE TESTING ALARM	18D ZOOM None ONLINE TESTING ALARM

GLOBAL E-STOP CONTROL
E-STOP RESET

Lab Minder E-STOP TC08A

Status: No test running

Support Directory: C:\ADT\Test2.3\Solution\GM Volt.26Mar\9939

Selected Test: ZeroDegCyc1

Faults: None

Alarm: [Red Panel]

Limits: Operating Within Limits
Non - Critical Ignore Time (sec): 900

Chamber Configuration: Server
Cycler Configuration: Channel A
Communication Watchdog: TC08A WD 17.0 sec, USWTLBD0412695

Controls: Fault Reset, System TC08A ONLINE/OFFLINE



A&D Battery Solution



A&D test solutions for cell, module, pack testing with

- maximum **usability**
- optimized **flexibility**
- best possible **safety** standard

Thus defining a new standard for battery test facilities



References:

- ❑ *General Motors Global Battery Systems Lab*
- ❑ *Magna E-Car Advanced Battery Test Lab*
- ❑ *University of Michigan Advanced Battery Coalition for Drivetrains (ABCD) Lab*
- ❑ *Leading Lithium-ion Battery Manufacturers (to be announced)*
- ❑ *USABC Supplier of Choice Endorsement*
- ❑ *Hitachi HEV BMS HILS*

GM Battery Systems Lab

