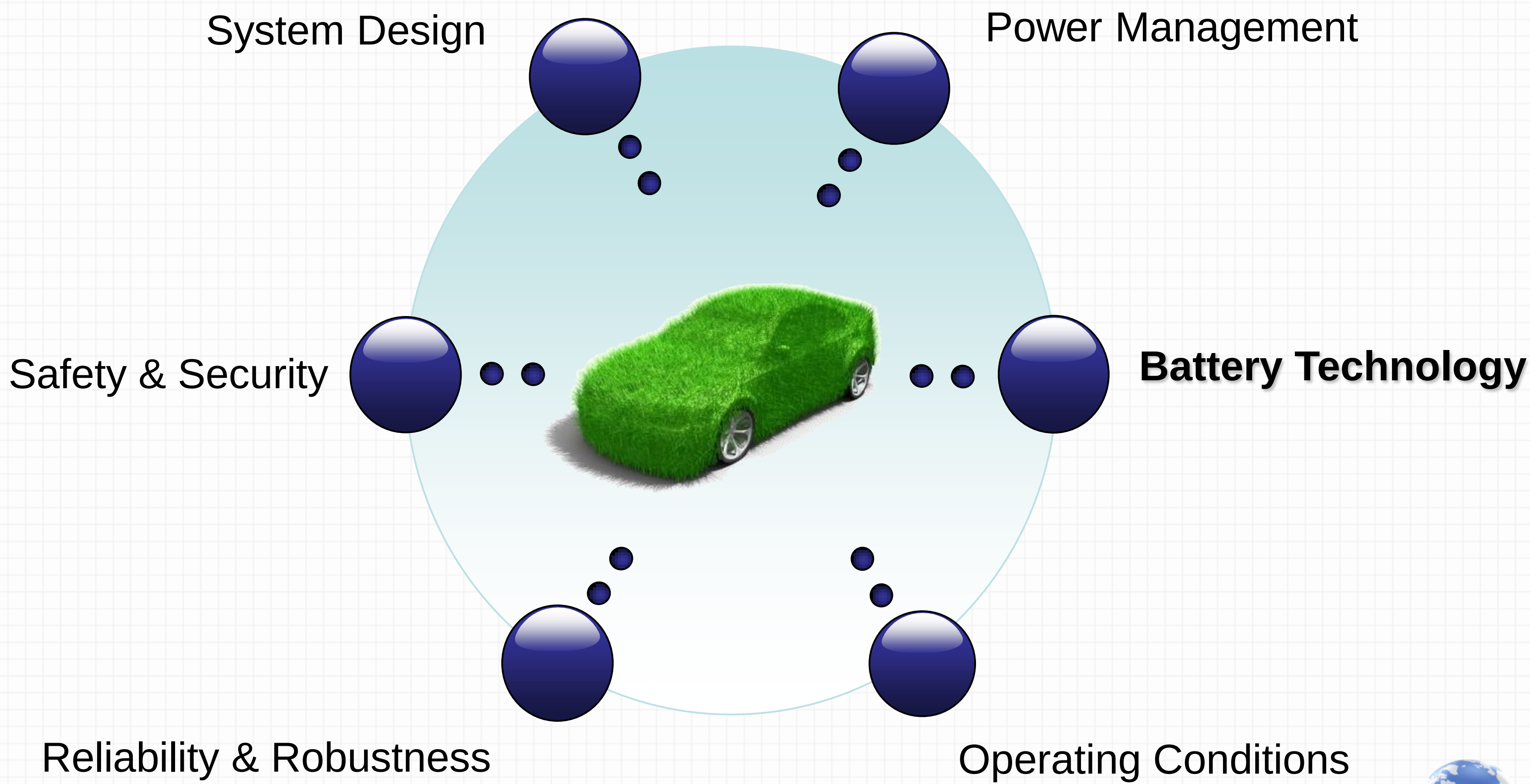
A&D Technology, Inc.

Battery Testing Solutions

April 28, 2010

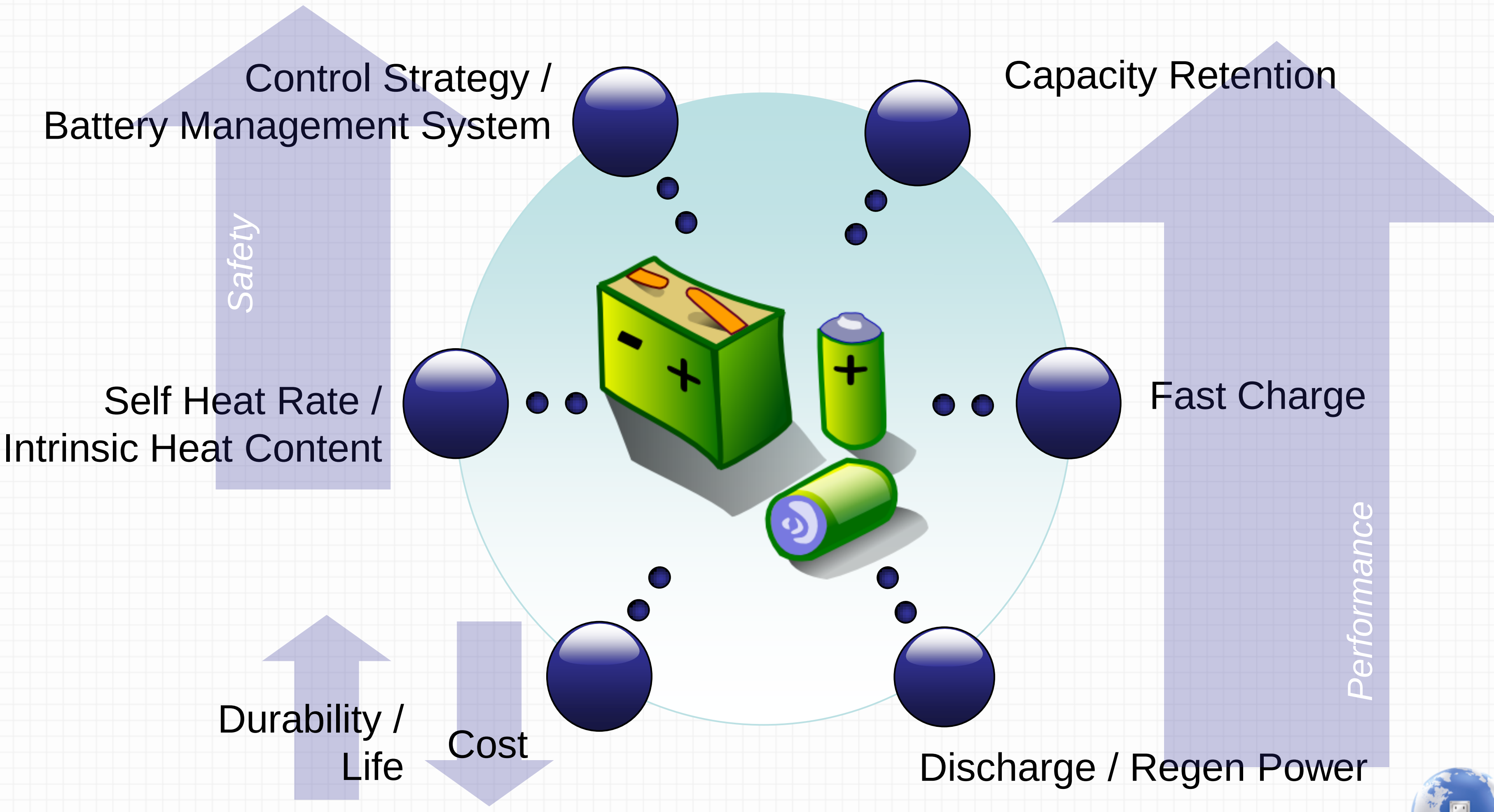
Challenges

Vehicle Electrification



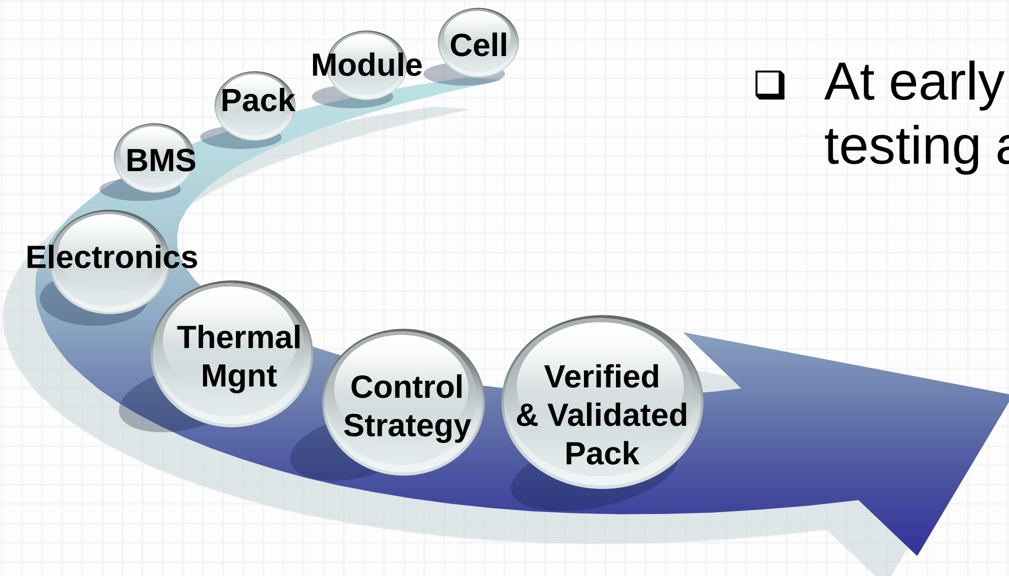
Challenges

Battery Technology



Challenges

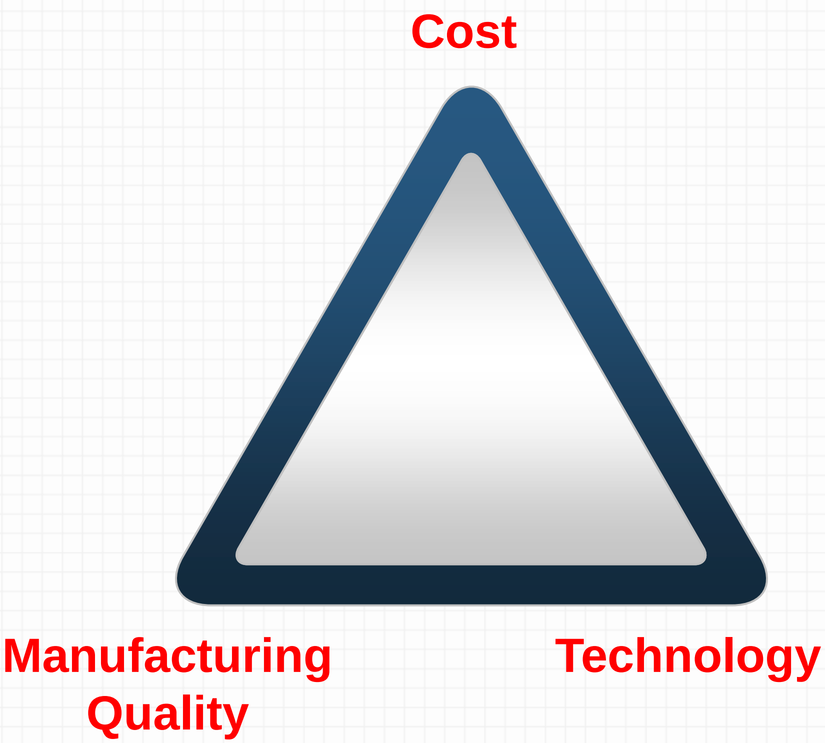
- ❑ Incorporate design aspects of all system components with the KEY GOAL of reducing price and improving performance
- ❑ Provide uncompromised high standard of durability
- ❑ At early stage of product development testing and validation become critical
- ❑ Advanced, flexible test and simulation solutions are required



Advanced Battery Pack Scope of Components

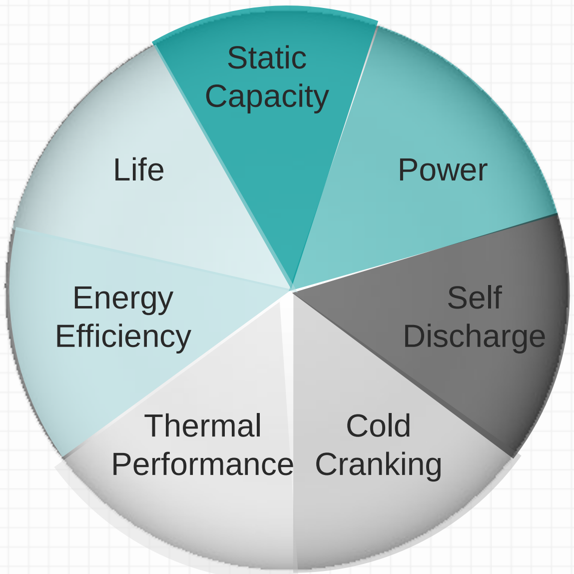
Battery Challenges

- ❑ 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

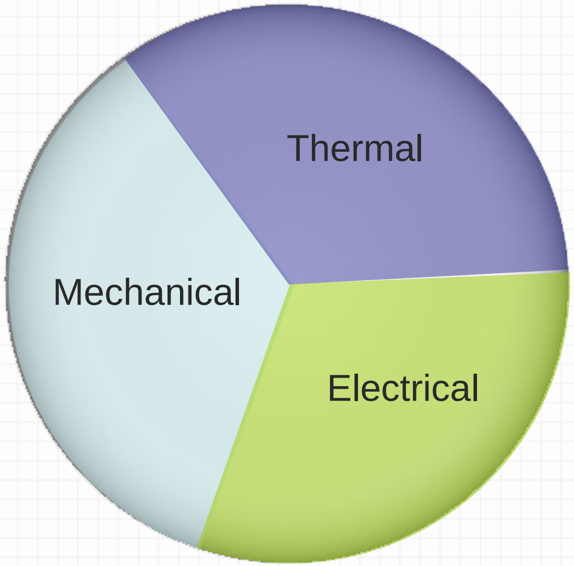


Battery Testing Tasks

Performance & Safety Tests in Battery Development



Performance Tests



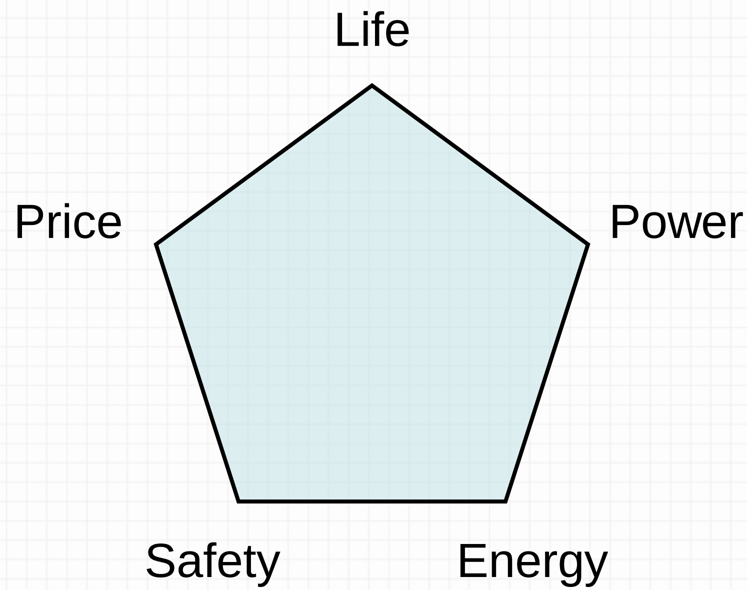
Safety Tests

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: >1,0003) (charge depleting)
>300,000 (charge sustaining)

Overall life: 10 years

Operating temp: -40ºC to +50ºC

< $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)

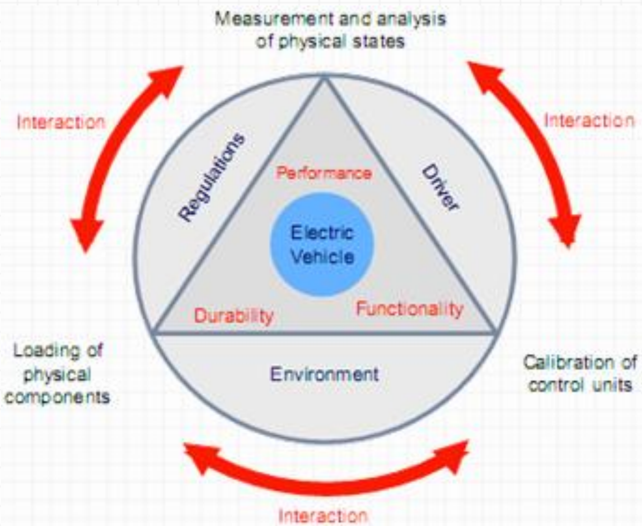
Specific Power: >300 Wh/kg2)

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

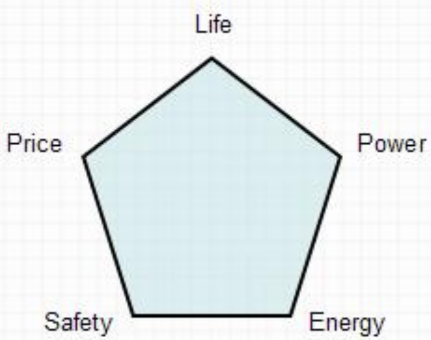
Source: www.uscar.org, United States Advanced Battery Consortium Goals for Advanced Batteries for EVs.pdf

Battery Performance Certainty

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



Vehicle Testing

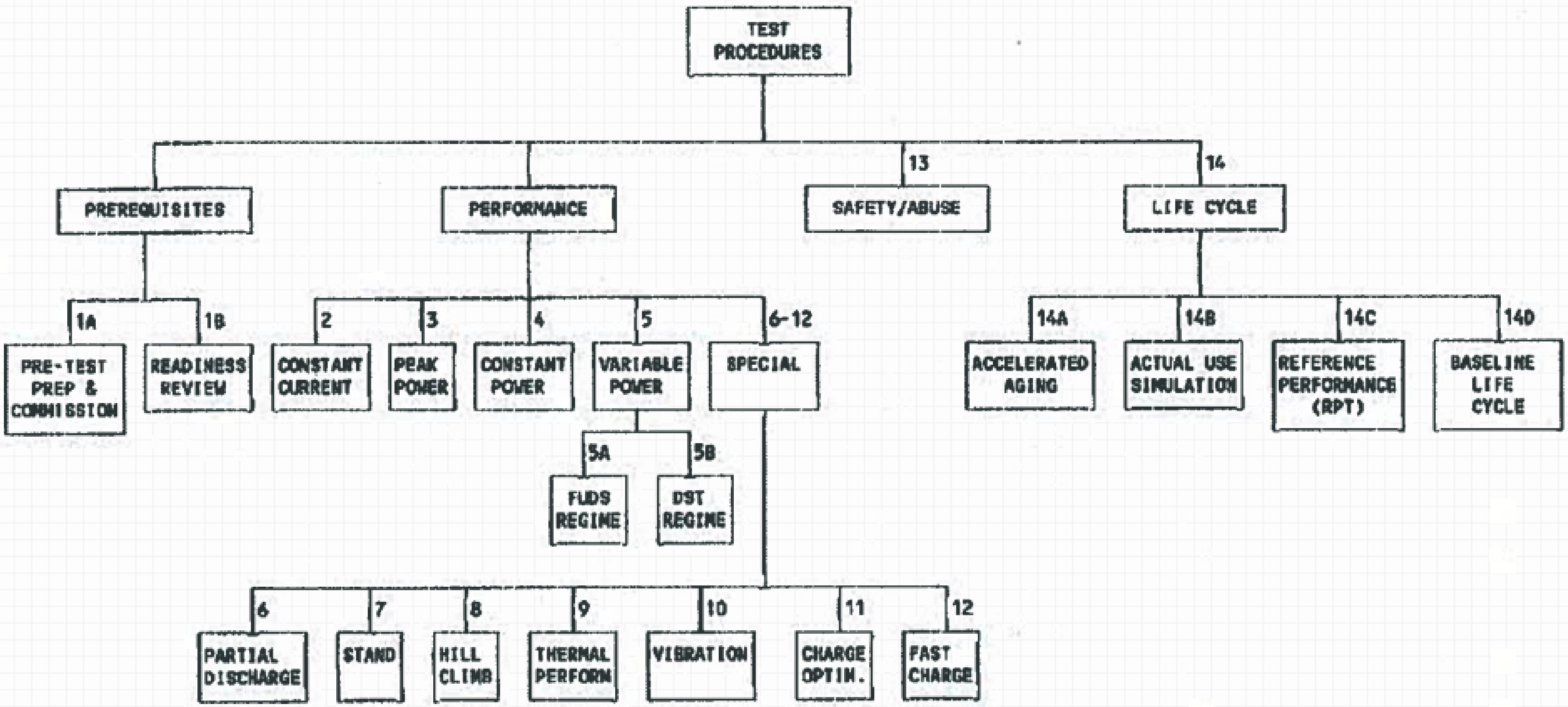


Battery Testing

- Interaction of vehicle, driver, road, traffic has electrical, thermal & mechanical impact on all powertrain components including the battery
- Battery goals need to 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

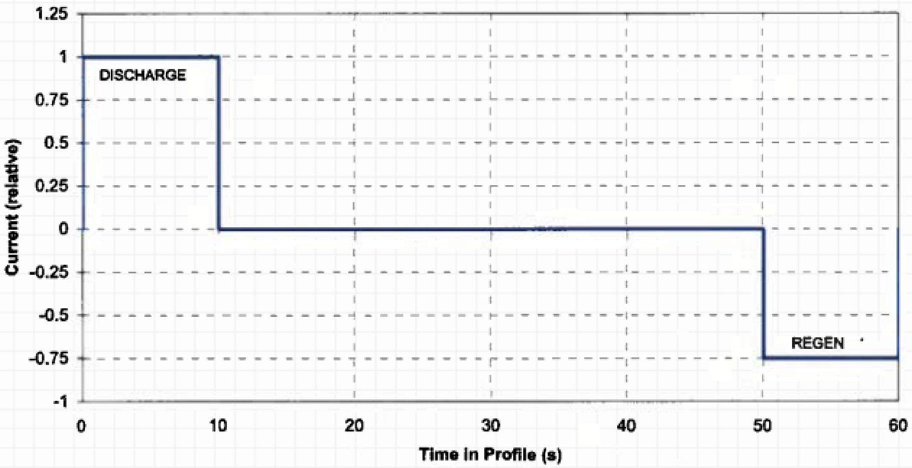
- ❑ Rapid Charge/Discharge
- ❑ Shock Cycling
- ❑ Thermal Stability
- ❑ Elevated Temp. Storage
- ❑ Simulated Fuel Fire

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

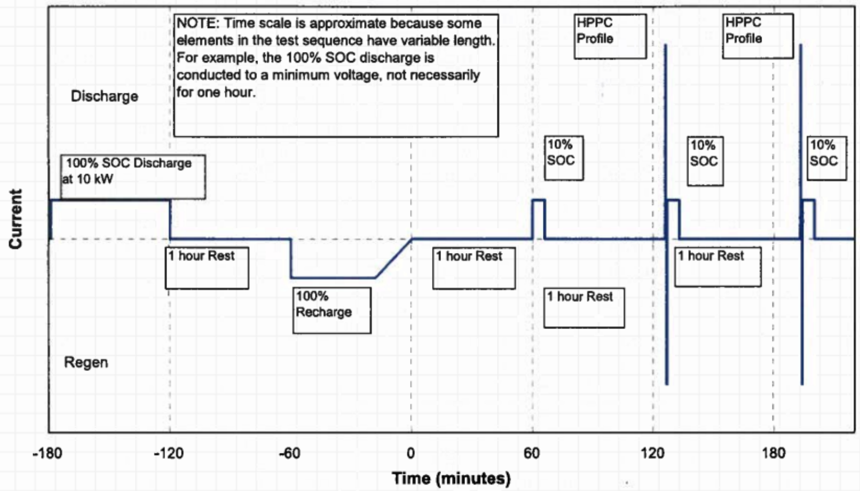
Result: Voltages recorded used to establish the cell's OCV behavior. Power and energy capabilities.

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.

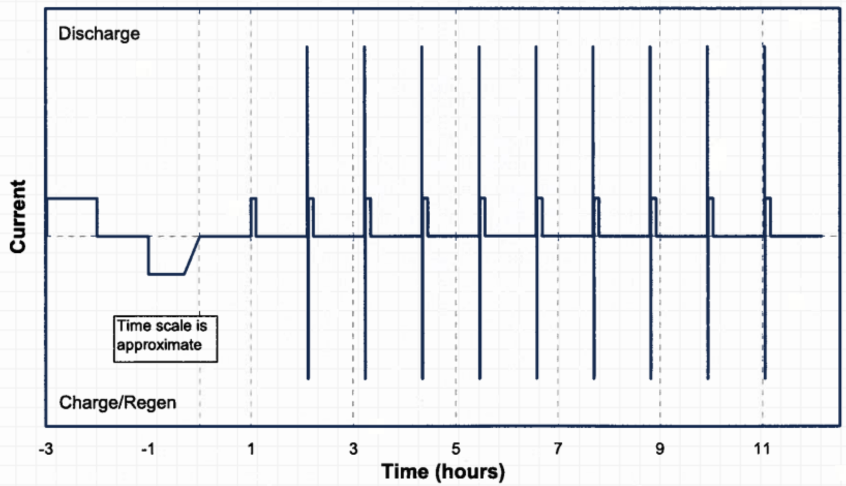
Industry Standard Tests

Hybrid Pulse Power Characterization (HPPC)



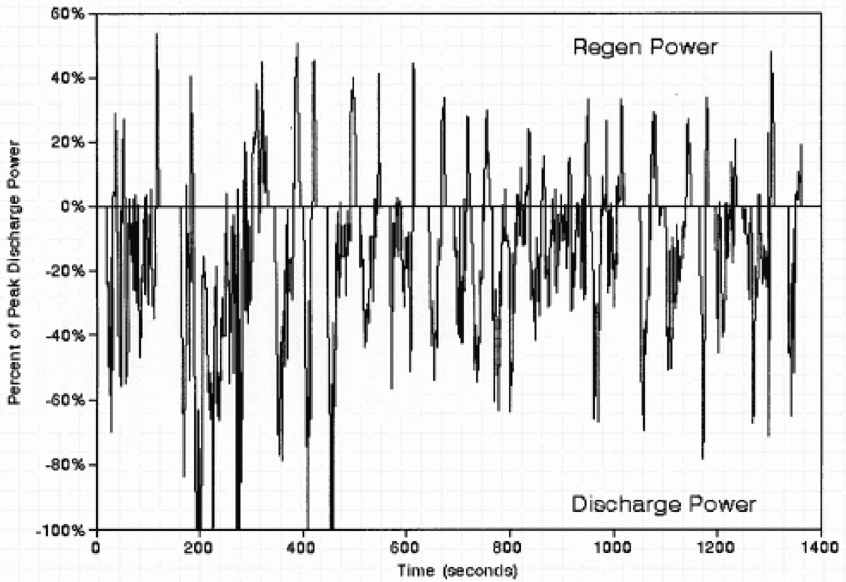
Start of HPPC Test Sequence

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

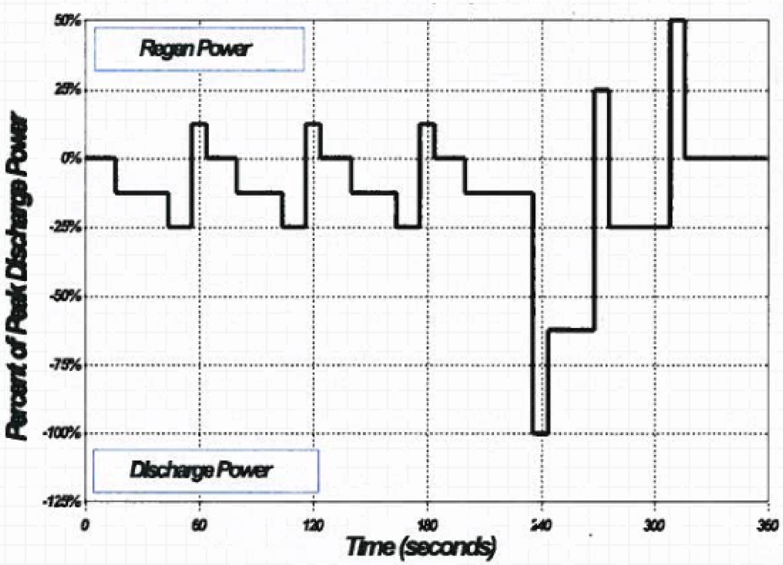
Result: Establish limits on regen power, current or voltage

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

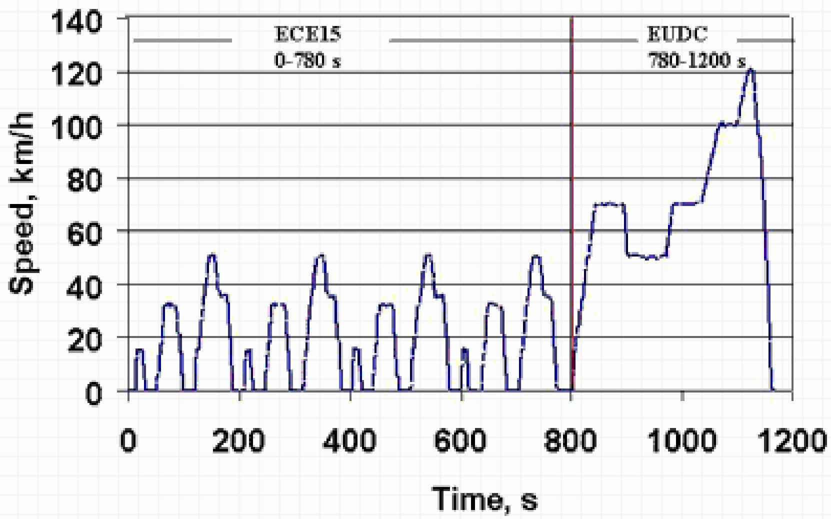
Result: Establish capacity of the unit & value of maximum power step

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

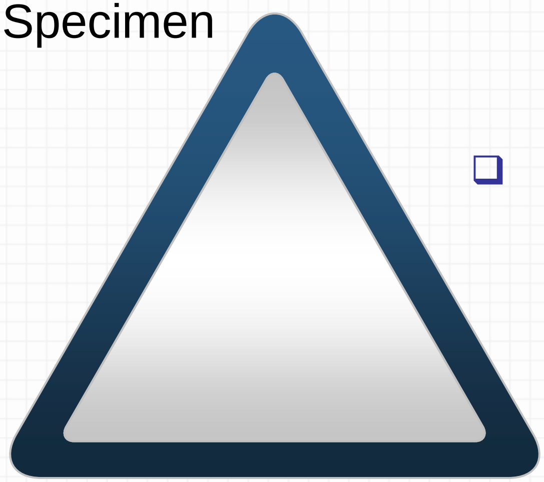
Objective: Produce effects of EV driving behavior (including re-gen) on performance & life of battery

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

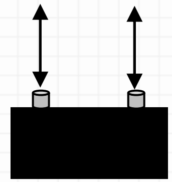
- Safety
  - ✓ People
  - ✓ Equipment
  - ✓ Specimen



- 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



Battery

Programmer
Battery Expert
Operator
Safety

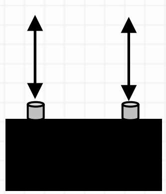
1st Generation

2nd Generation

Lab Safety

Lab Manager

Lab Customer
Battery Expert



Battery

Test Safety

Programmer
Battery Test Expert
Operator

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

Generations of Solutions - Pack

Programmer
Battery Expert

1st Generati

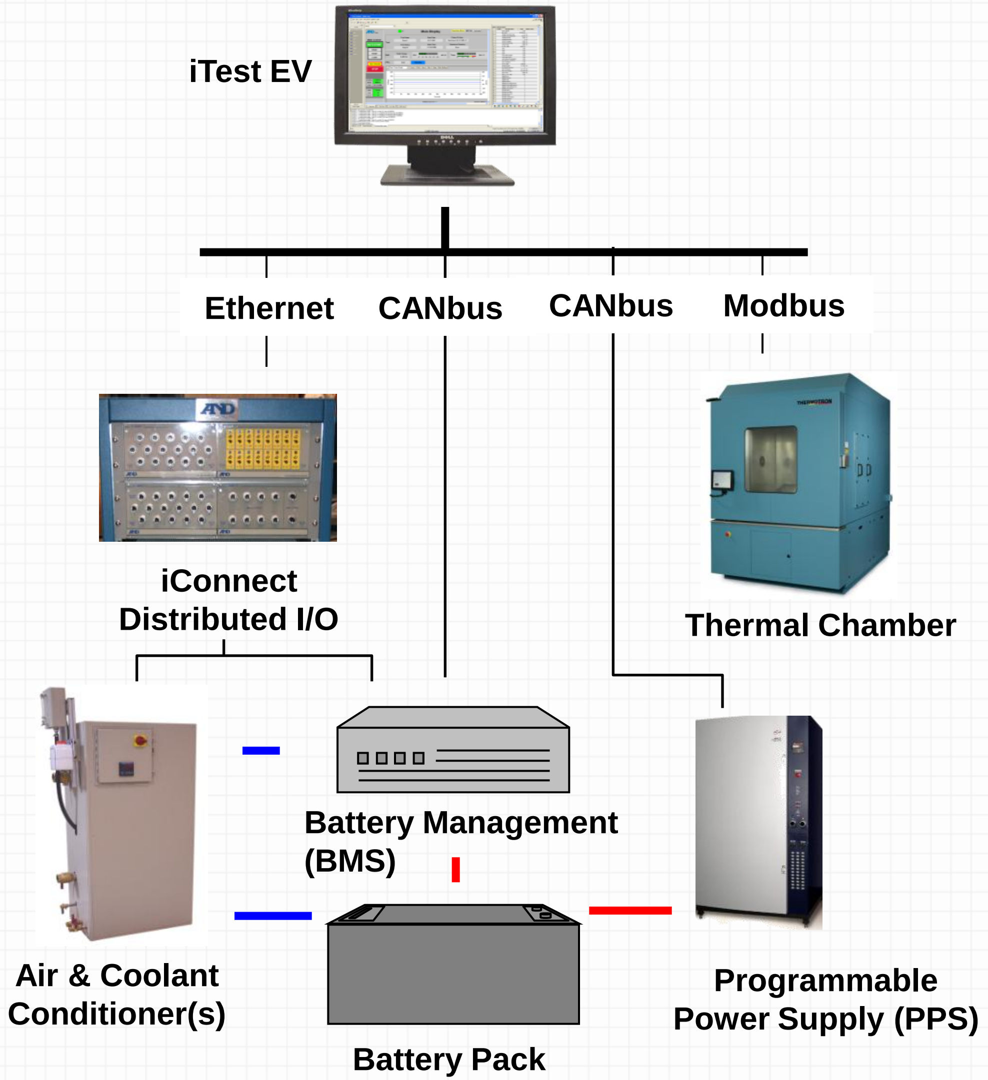
2nd Genera

- **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

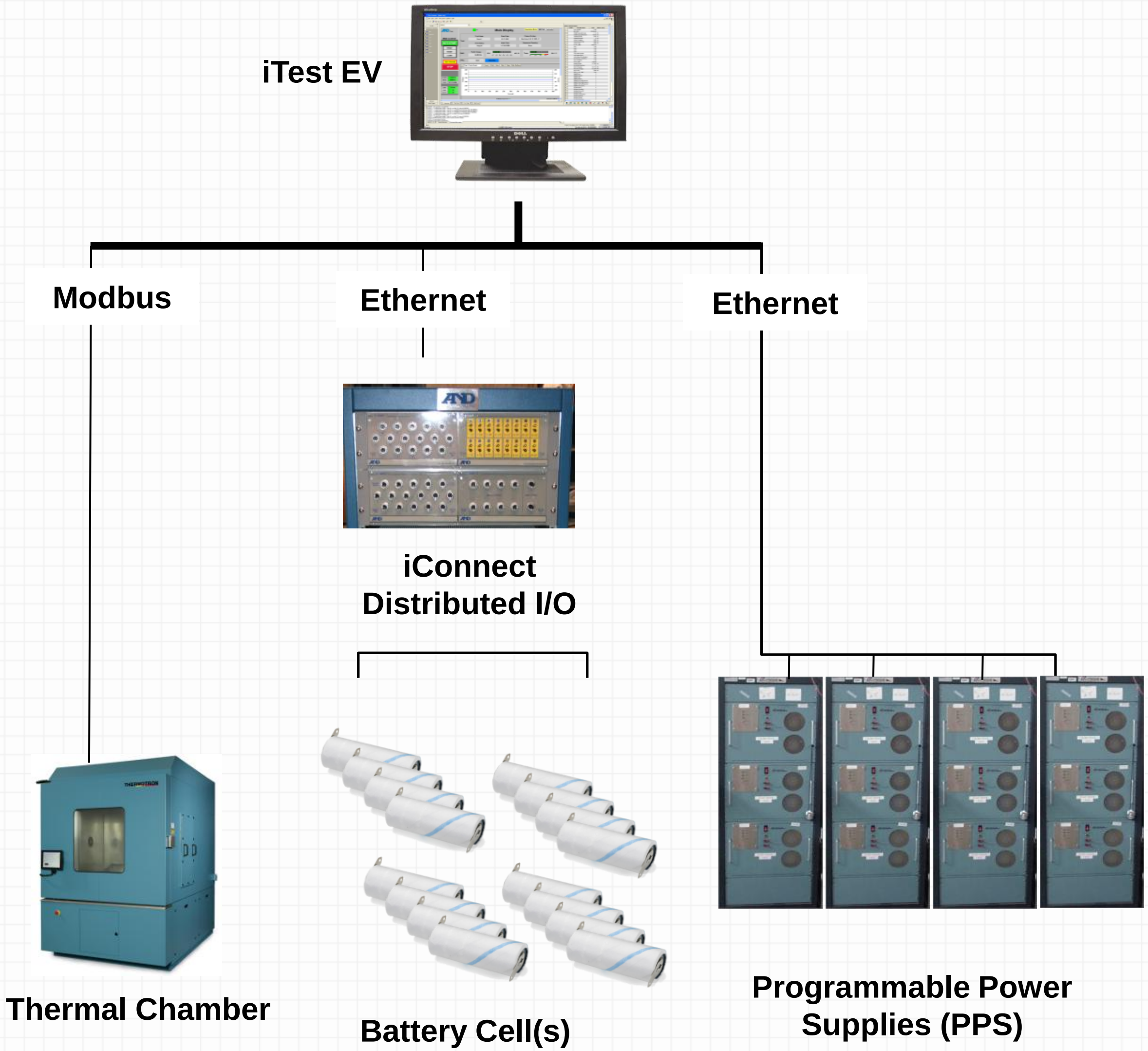
Lab Customer
Battery Expert

Therma
Instrum
(V-LCN, RO…, …)

Battery Testing – Pack and Module

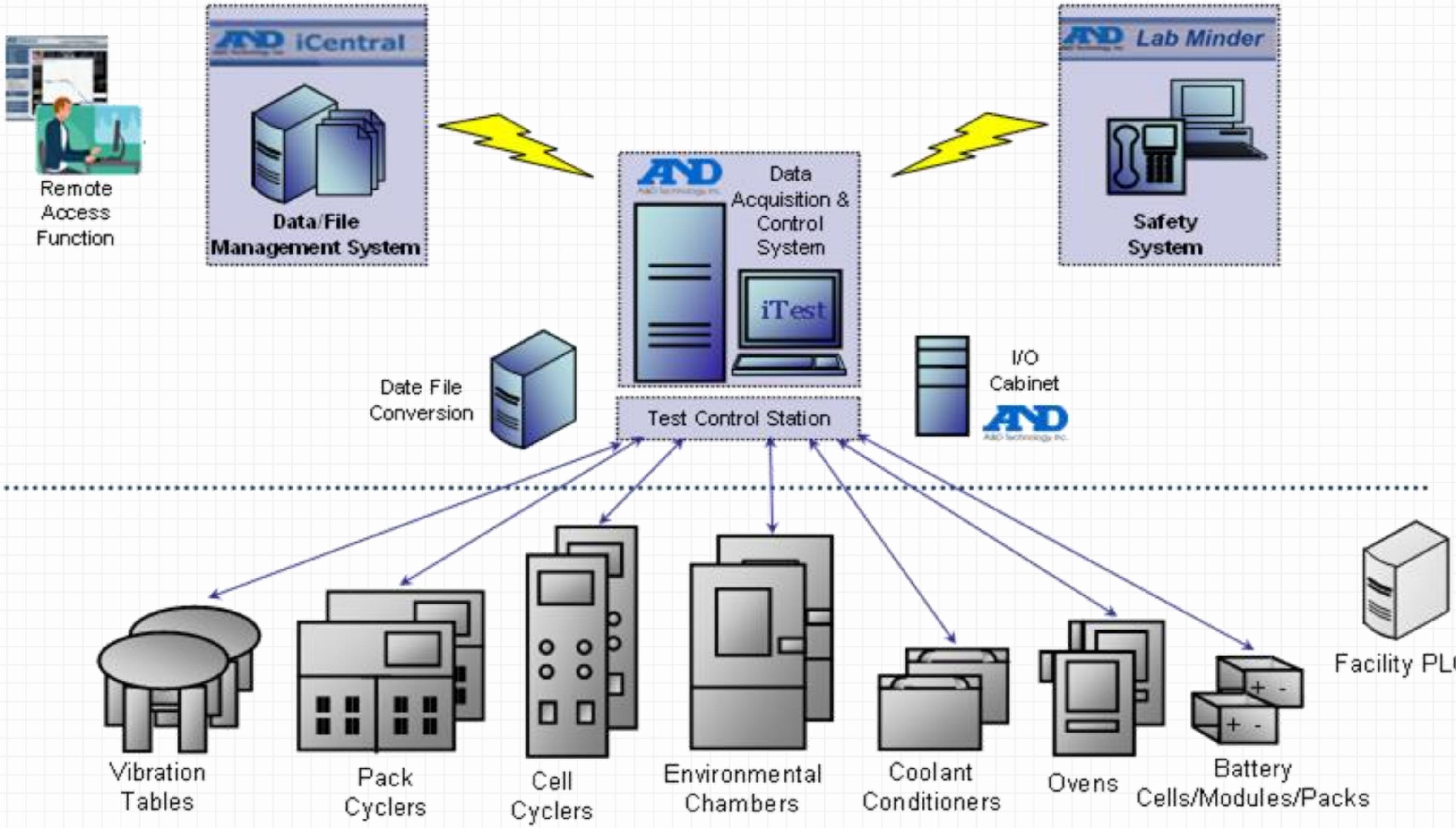


Battery Testing – Cell



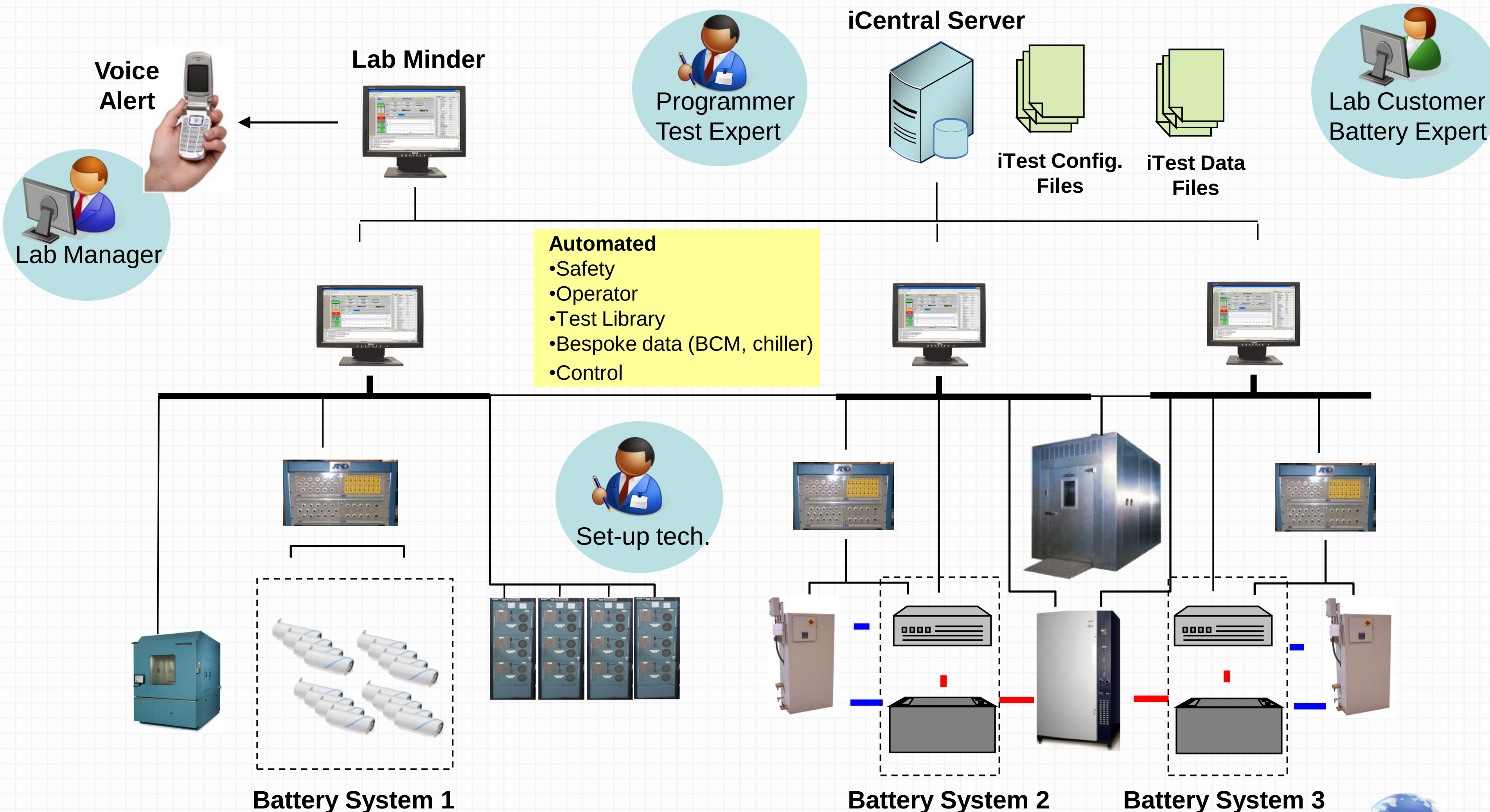
A&D Battery Solution – Example System

Complete Integrated Test Automation System



Equipment (multiple suppliers, operating systems, interfaces)

Current “State of the Art” Lab



Old/New Comparison

Semi-Automated

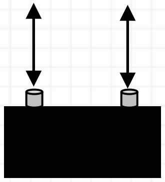
- **Safety** (Expert Operator)
  - + Flexible
  - -- High training cost
  - -- Slow reaction
  - -- Depends on people
- **Data**
  - -- Consistency –depends on operator
  - -- Slow rate
  - -- Tests different between equipment
  - -- Integrated between equipment (ECU, cycler, chiller, vibration table…)
    - 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,
  - -- 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

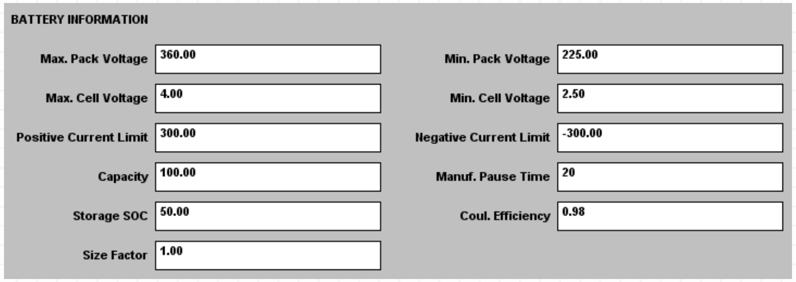
User Experiences

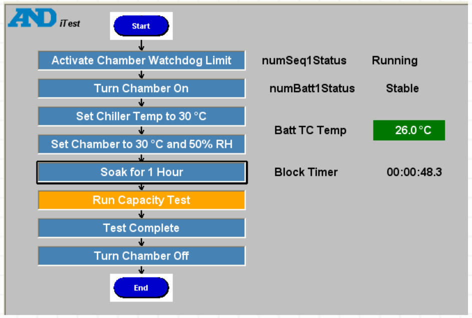
Set-up tech.



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

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

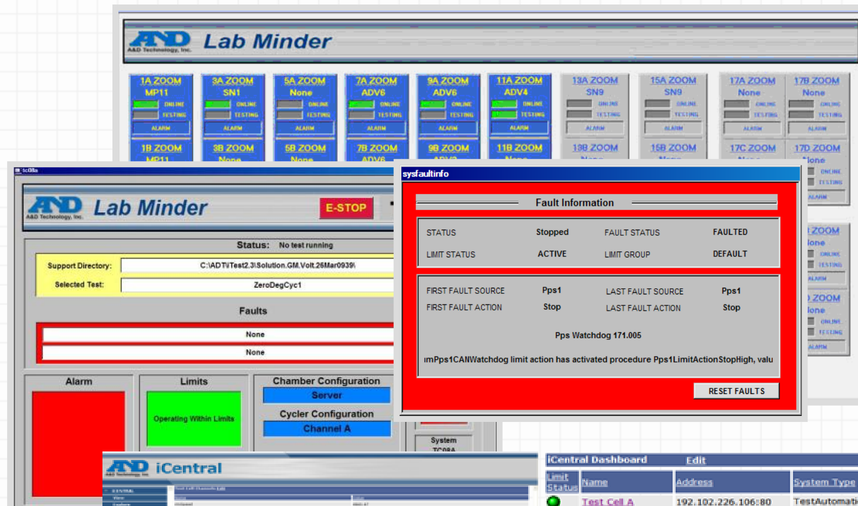


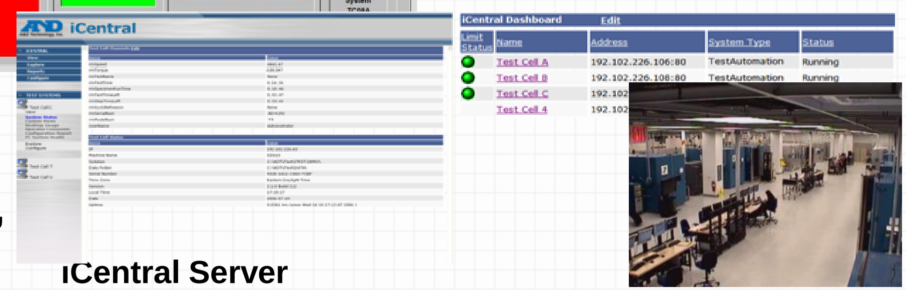


User Experience

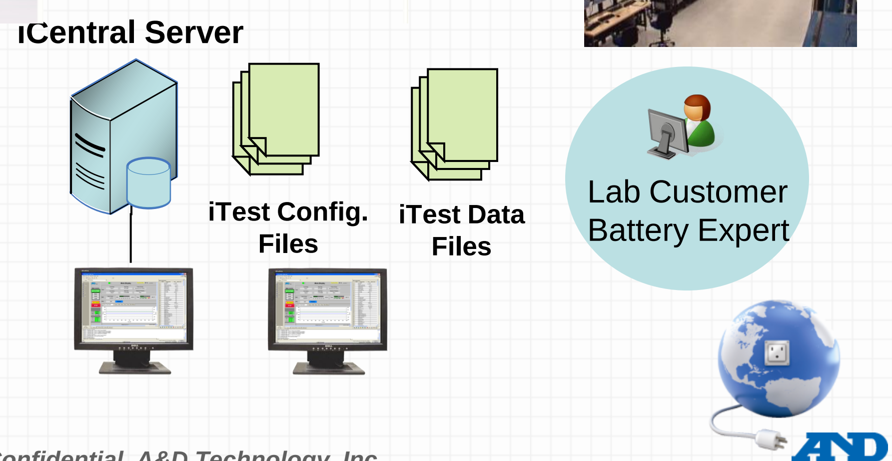
Lab Manager

- ❑ Safety and Status
  - ✓ Redundant fail-safe lab
  - ✓ Prevention over reaction
  - ✓ Complete lab status
    - • Local & remote
    - • Automated notification
    - • Cameras





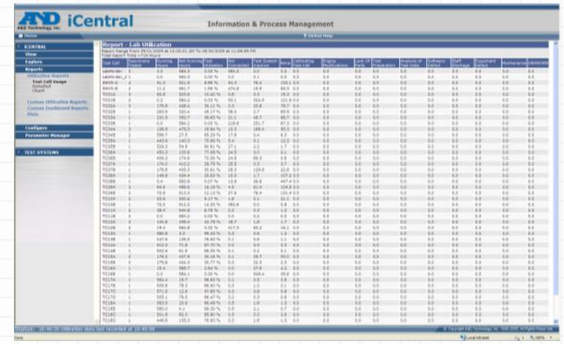
- ❑ Data
  - ✓ Continuous logging “just in case”
  - ✓ Automated
    - • Upload and availability
  - ✓ Secure

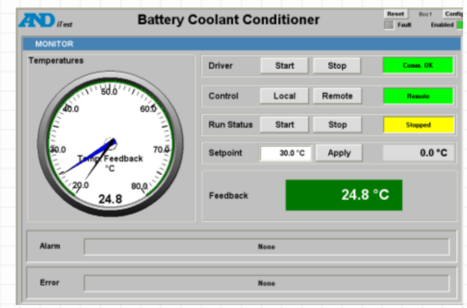


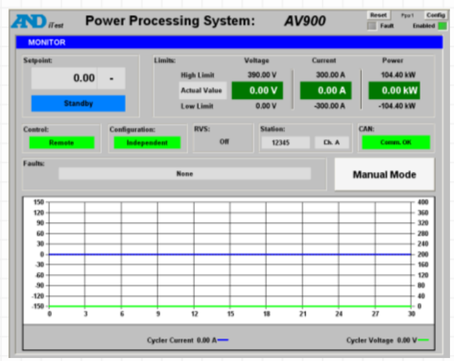
User Experience

Lab Manager

- ❑ Efficiency
  - ✓ Consistent across different equipment
  - ✓ Utilization tracking
  - ✓ 24/7 operation
- ❑ Trouble shooting
  - ✓ Equipment
  - ✓ Communications
  - ✓ Instrumentation
  - ✓ Battery



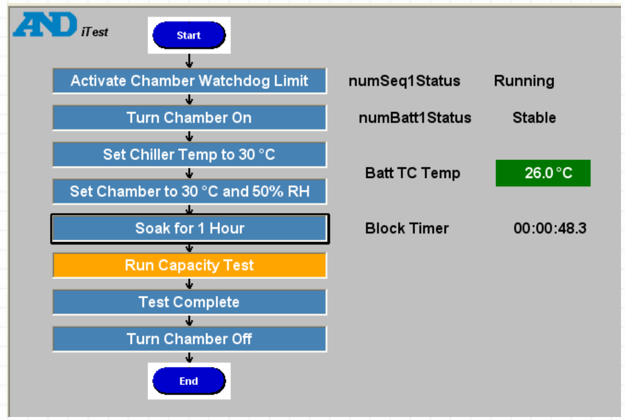


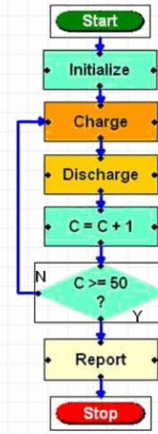


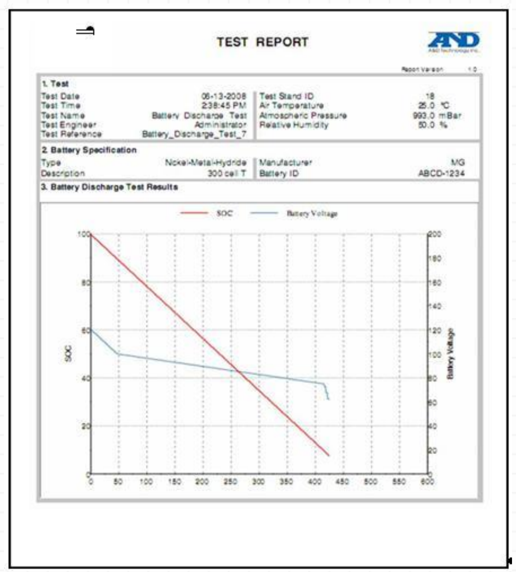
User Experience

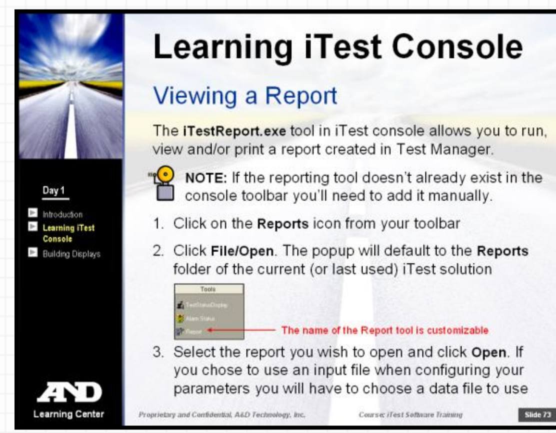
Programmer/Test Expert

- 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



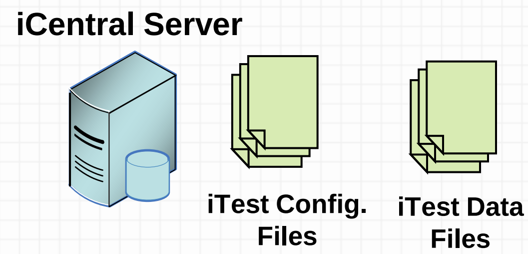




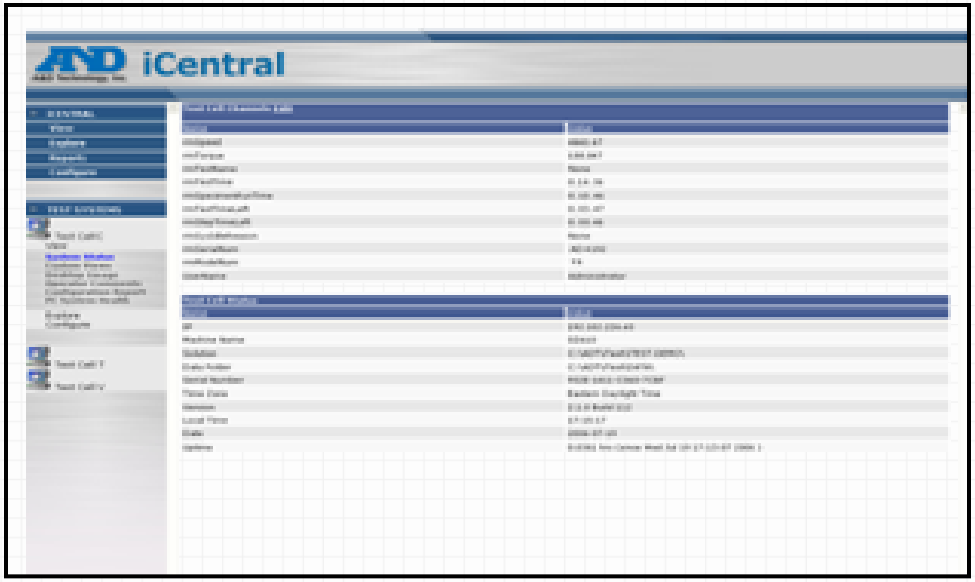


User Experience

Lab Customer/Battery Expert



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



- Tests
  - ✓ Consistent
  - ✓ Flexible
  - ✓ User Friendly

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.)

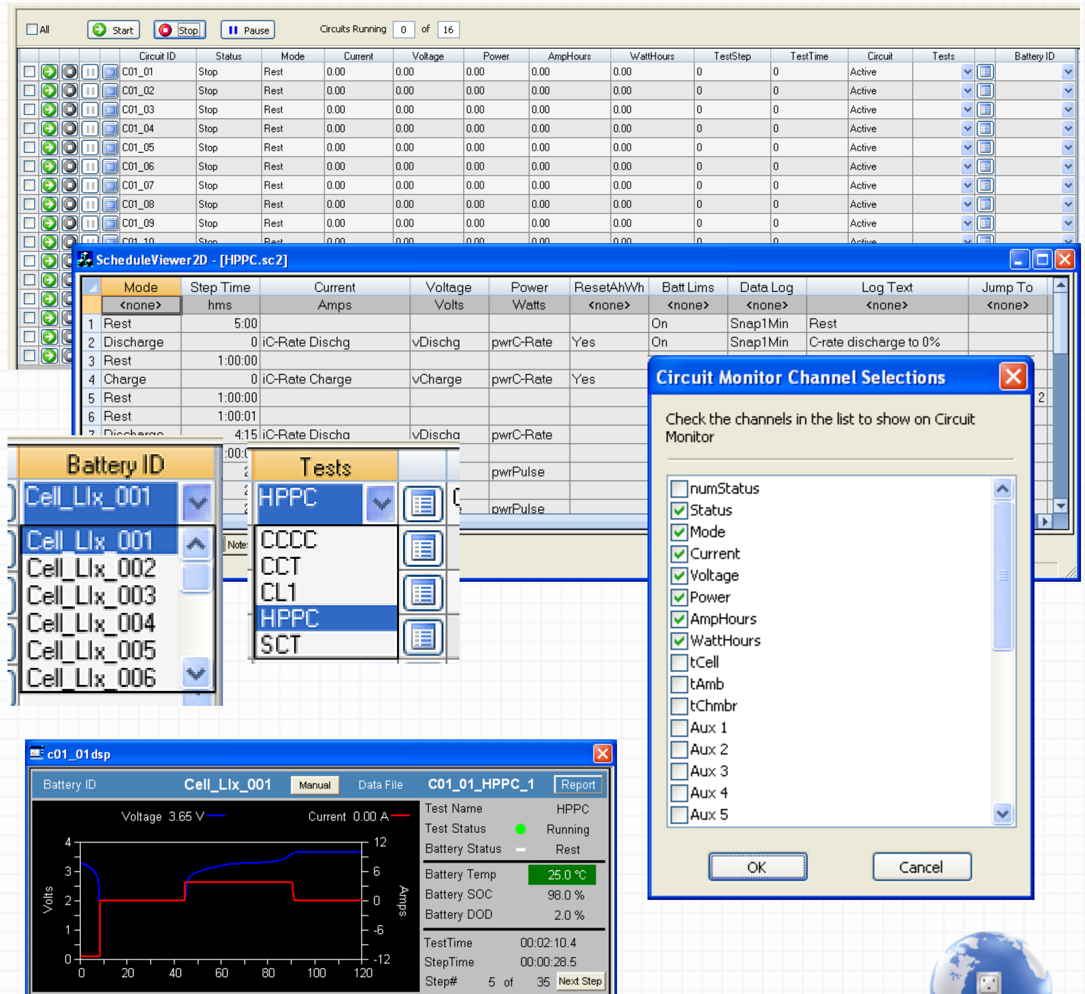
↓ ↓↓ ↓ Human dependency (writing/recreating tests, data crunching, archiving)
= ↑ ↑↑ ↑ Test accuracy

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

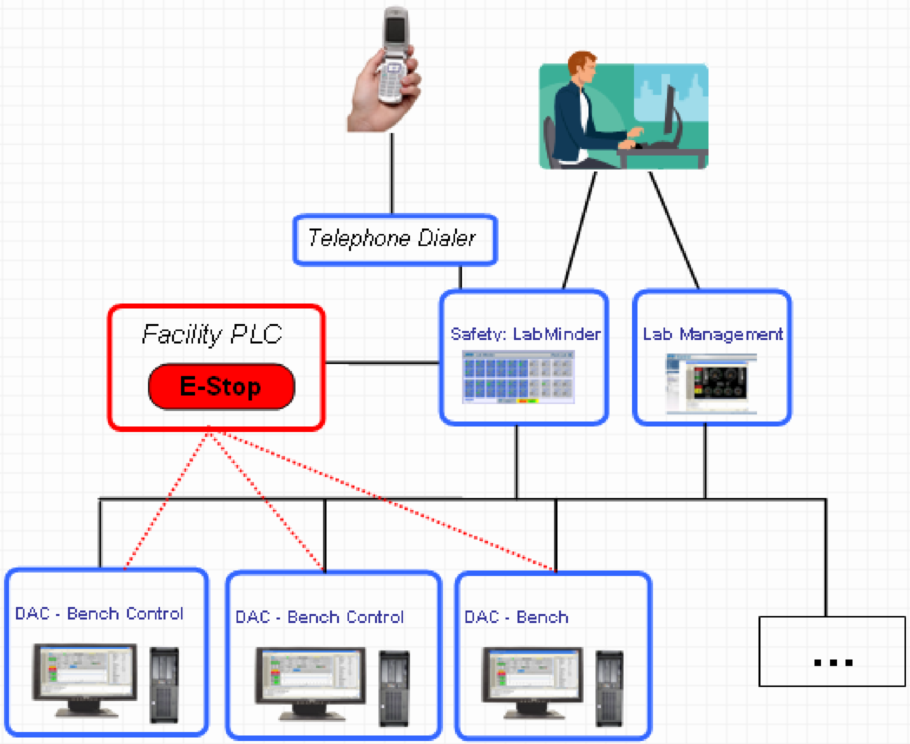
A&D Battery Testing Solution

Excerpt of Possible Test Runs

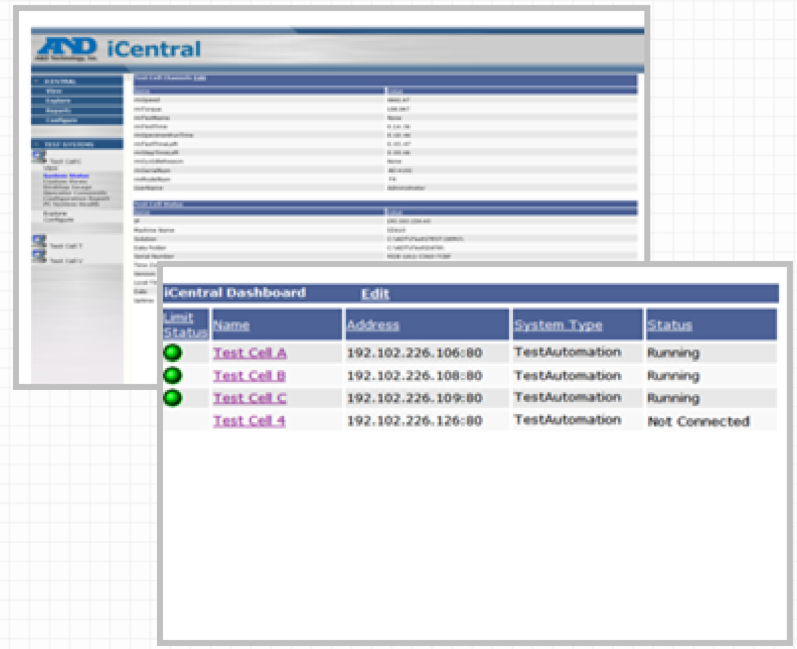
- Cycle life test
- Capacity test
- Internal ohmic resistance test
- Overcharge, discharge test
- Self discharge test
- Performance test
- Dynamic stress test
- Federal urban driving cycle
- Constant current profiles
- Constant voltage profiles
- Pulse profiles
- Ramp profiles, etc.



GM Battery Systems Lab



iCentral Data Management



- ❑ 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

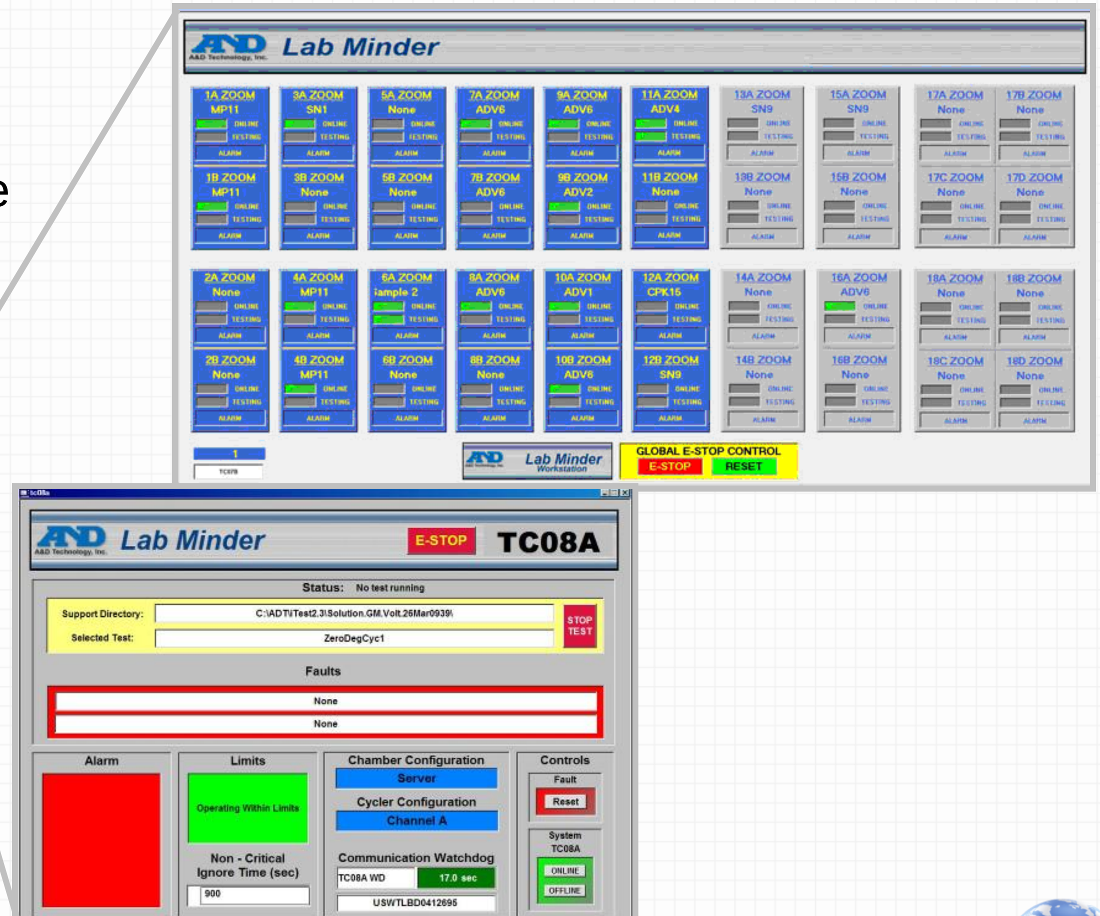
GM Battery Systems Lab

Lab Minder Safety System

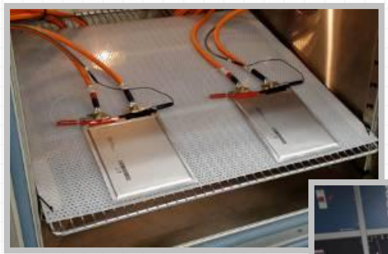
- Emergency shutdown of the entire facility
- Critical error notification
- Remote control to react to the error reported

Phone Alert

Lab Minder



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