A PHYSICS-BASED MODELING FRAMEWORK FOR PROGNOSTIC STUDIES

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Presented at
Indian Institute of Technology - Bombay
Powai, Mumbai
February 7th, 2014
Prognostics Center of Excellence

NASA Ames Research Center, CA

Mission: Advance state-of-the-art in prognostics technology development

• Investigate algorithms for estimation of remaining life
  – Investigate physics-of-failure
  – Model damage initiation and propagation
  – Investigate uncertainty management

• Validate research findings in hardware testbeds
  – Hardware-in-the-loop experiments
  – Accelerated aging testbeds
  – HIL demonstration platforms

• Disseminate research findings
  – Public data repository for run-to-failure data
  – Actively publish research results

• Engage research community

• Prognostics Center of Excellence, NASA Ames Research Center, CA [http://www.prognostics.nasa.gov]
Introduction to Prognostics

Outline
Today we will discuss…

• What is prognostics?
  – It’s relation to health management
  – Significance to the decision making process

• How is prognostics used?
  – Reliability
  – Scheduled maintenance – based on reliability
  – Kinds of prognostics – interpretation & applications
    • Type I, Type II, and Type III prognostics
    • Various application domains

• Condition based view of Prognostics

• Prognostic Framework
Also...

• What are the key ingredients for prognostics
  – Requirements specifications – Purpose
    • Cost-benefit-risk
  – Condition Monitoring Data – sensor measurements
    • Collect relevant data
  – Prognostic algorithm
    • Tons of them - examples
  – Fault growth model (physics based or model based)
  – Run-to-failure data

• Challenges in Validation & Verification
  – Performance evaluation
  – Uncertainty
    • representation, quantification, propagation, and management
Prognostics and Health Management

The Perspective
Health Management

Contingency Management View

- Condition Based Mission Planning
- System Reconfiguration
- Control Reconfiguration
- Contingency Data Analysis & Decision Making
- Prognostic Control
- Condition Monitoring Safety and Risk Analyses

On-Board Diagnostics & Prognostics

Integrated Data Bus

- Embedded Sensors

Data Comm
- Sensors
- Reporting
- Scheduled Inspections

Troubleshooting and Repair

Knowledgebase e.g. IETMs

Maintenance and Information systems

Command & Control

Maintenance and Information systems

Wholesale Logistics

Maintenance Data Analysis & Decision Making

- Predictive Maintenance
- Preventive Maintenance
- Condition Monitoring
- Reliability Analysis

Planning + Scheduling

Tech Support

Anticipatory Material

Training

- Feedback to Production Control

Preventive Maintenance

- On-Board Diagnostics & Prognostics
- Command & Control
- Data Comm
- Troubleshooting and Repair
- Knowledgebase e.g. IETMs
- Portable Maintenance Aids

Data Analysis & Decision Making

- Adapted from presentations and publications from Intelligent Control Systems Lab, Georgia Institute of Technology, Atlanta [http://icsl.gatech.edu/]
Prognostics

• Dictionary definition – “foretelling” or “prophecy”

• PHM definition –
  “Estimation of remaining life of a component or subsystem”

• Prognostics evaluates the current health of a component and, conditional on future load and environmental exposure, estimates at what time the component (or subsystem) will no longer operate within its stated specifications.

• These predictions are based on
  – Analysis of failure modes (FMECA, FMEA, etc.)
  – Detection of early signs of wear, aging, and fault conditions and an assessment of current damage state
  – Correlation of aging symptoms with a description of how the damage is expected to increase (“damage propagation model”)
  – Effects of operating conditions and loads on the system

• Prognostics Center of Excellence, NASA Ames Research Center, CA [http://www.prognostics.nasa.gov]
• Prognostics [http://en.wikipedia.org/wiki/Prognostics]
Goals for Prognostics

What does prognostics aim to achieve?

- Prognostics goals should be defined from users’ perspectives
- Different solutions and approaches apply for different users
## User Centric View on Prognostics Goals

<table>
<thead>
<tr>
<th>Category</th>
<th>End User</th>
<th>Goals</th>
<th>Metrics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operations</td>
<td>Program Manager</td>
<td>Assess the economic viability of prognosis technology for specific applications before it can be approved and funded</td>
<td>Cost-benefit type metrics that translate prognostics performance in terms of tangible and intangible cost savings</td>
</tr>
<tr>
<td></td>
<td>Plant Manager</td>
<td>Resource allocation and mission planning based on available prognostic information</td>
<td>Accuracy and precision based metrics that compute RUL estimates for specific UUTs. Such predictions are based on degradation or damage accumulation models</td>
</tr>
<tr>
<td></td>
<td>Operator</td>
<td>Take appropriate action and carry out re-planning in the event of contingency during mission</td>
<td>Accuracy and precision based metrics that compute RUL estimates for specific UUTs. These predictions are based on fault growth models for critical failures</td>
</tr>
<tr>
<td></td>
<td>Maintainer</td>
<td>Plan maintenance in advance to reduce UUT downtime and maximize availability</td>
<td>Accuracy and precision based metrics that compute RUL estimates based on damage accumulation models</td>
</tr>
<tr>
<td>Engineering</td>
<td>Designer</td>
<td>Implement the prognostic system within the constraints of user specifications. Improve performance by modifying design</td>
<td>Reliability based metrics to evaluate a design and identify performance bottlenecks. Computational performance metrics to meet resource constraints</td>
</tr>
<tr>
<td></td>
<td>Researcher</td>
<td>Develop and implement robust performance assessment algorithms with desired confidence levels</td>
<td>Accuracy and precision based metrics that employ uncertainty management and output probabilistic predictions in presence of uncertain conditions</td>
</tr>
<tr>
<td>Regulatory</td>
<td>Policy Makers</td>
<td>To assess potential hazards (safety, economic, and social) and establish policies to minimize their effects</td>
<td>Cost-benefit-risk measures, accuracy and precision based measures to establish guidelines &amp; timelines for phasing out of aging fleet and/or resource allocation for future projects</td>
</tr>
</tbody>
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Prognostics Categories

- **Type I: Reliability Data-based**
  - Use population based statistical model
  - These methods consider historical time to failure data which are used to model the failure distribution. They estimate the life of a typical component under nominal usage conditions
  - Example: Weibull Analysis

- **Type II: Stress-based**
  - Use population based fault growth model – learnt from accumulated knowledge
  - These methods also consider the environmental stresses (temperature, load, vibration, etc.) on the component. They estimate the life of an average component under specific usage conditions
  - Example: Proportional Hazards Model

- **Type III: Condition-based**
  - Individual component based data-driven model
  - These methods also consider the measured or inferred component degradation. They estimate the life of a specific component under specific usage and degradation conditions
  - Example: Cumulative Damage Model, Filtering and State Estimation

*For more details please refer to last year’s PHM09 tutorial on Prognostics by Dr. J. W. Hines: [http://www.phmsociety.org/events/conference/phm/09/tutorials]
Forecasting Applications

Predictions

- End-of-Life predictions
  - A prediction threshold exists
  - Use monotonic decay models

- Event predictions
  - History data
    - Statistics can be applied
    - Nominal data
    - Electronics, Aerospace
    - Medicine
    - Mechanical systems
  - No/Little history data
    - Model-based + Data-driven
    - Nominal & failure data
    - Aerospace, Nuclear

- Decay predictions
  - Trajectory Prediction

- Future behavior predictions
  - Non-monotonic models
  - No thresholds

- Discrete predictions
  - Economics, Supply Chain
  - Quantitative
    - Predict values

- Continuous predictions
  - Weather, Finance
  - Qualitative
    - Predict trends
      - Increase/decrease

References:
Predicting Remaining Useful Life

Understanding the Prognostic Process
Prognostics Framework

Decision Risk
How soon is too soon and how late is too late?

Model Uncertainty
Which model to trust? No Model is perfect!

Critical Fault Level
Chosen somewhat conservatively for most applications

Failure Threshold
Complete Failure

End of Life point
EoL adjusted accordingly

Time (t)
Fault Dimension (a)

EoL
RUL

Failure Threshold
RUL

Decision Risk
Model Uncertainty

Prognostics Framework

Ames Research Center

Complete Failure

RUL

EoL adjusted accordingly

End of Life point

Decision Risk
How soon is too soon and how late is too late?

Model Uncertainty
Which model to trust? No Model is perfect!
Prognostics Framework

We hardly have access to ground truth
Instead we have measurements, appropriate features of which may correlate to damage. Such data are usually noisy!
We use these data to learn the model, which may be noisy
Noise may have a significant effect on the learnt model…

Fault Dimension (\(a\))

Failure Threshold

Decision Risk
How soon is too soon and how late is too late?

Model Uncertainty
Which model to trust? No Model is perfect!

No Ground Truth
Ground truth measurements are hard to come by

Noisy Data
Measurement noise leads to more uncertainty!
Uncertainties in Prognostics

- Uncertainties arise from a variety of sources
  - Modeling uncertainties – Epistemic
    - Numerical errors
    - Unmodeled phenomenon
    - System model & Fault propagation model
  - Input data uncertainties – Aleatoric
    - Initial state (damage) estimate
    - Variability in the material
    - Manufacturing variability
  - Measurement uncertainties – Prejudicial
    - Sensor noise
    - Sensor coverage
    - Loss of information during preprocessing
    - Approximations and simplifications
  - Operating environment uncertainties – Combination
    - Unforeseen future loads
    - Unforeseen future environments
    - Variability in the usage history data
The diagram illustrates the Prognostics Framework, which includes:

1. **Fault Dimension (a)**: Represents the dimension of faults, starting from time $t_0$ to the end of life (EoL).

2. **Time (t)**: The timeline from $t_0$ to EoL.

3. **Failure Threshold ($a_{FT}$)**: The specified threshold for failure.

The framework is divided into two slices:

- **Horizontal Slice**: Tells us when the system can be expected to reach a specified failure threshold given "all" uncertainties considered.

- **Probability of Failure ($\pi$)**: Computes the total probability of failure for a given decision point.

- **RUL pdf**: Can be useful when planning a mission (usage) profile. Answers how long can the mission duration be?

- **Make decisions based on risks estimated from probability of failure (PoF)**:

Additional information includes:

- Probability distribution for EoL given a failure threshold ($p_{EoL}$).

- The probability distribution need not be Normal "always".

- We can propagate the learnt model along with a confidence bound until the Failure Threshold is reached.

- The Horizontal slice tells us when the system can be expected to reach a specified failure threshold given "all" uncertainties considered.

- The probability distribution can be too risky and may be too large...
Prognostics Framework

Risk is now a compound function of chosen failure threshold and the decision point.
Prognostics Framework

We can figure out if the system would withstand by the time mission is completed.
Prognostics Framework

Damage size pdf at a given time can be useful when planning a mission (usage) profile. Answers how risky it is to go on a mission of known duration?

\[
\pi_{t_3} = \int_0^{\infty} \left(1 - P_\alpha(a|t = t_0)\right)p_H(a)da
\]

\[
= 1 - \int_0^{\infty} P_\alpha(a|t = t_3)p_H(a)da
\]

Probability of damage given a hazard zone pdf - \(p_H(a)\)

We can figure out if the system would withstand by the time mission is completed.
Examples

Prognostics Applications
Application Examples

• Electro-Mechanical Actuators
• Electrochemical Storage
• Electronics
• Valves, Pumps
• Composite Materials
• Solid Rocket Motor Casing
• Rover
• UAV
• Distributed Health Management
Setting up the Problem

Prognostics Modeling
Data-Driven Prognostic Methods

Primarily use data obtained from the system for predicting failures

- **What kind of data?**
  - Something that indicates a fault and fault growth or is expected to influence fault growth
    - Sensor measurement to assess system state
    - Sensor measurements and communication logs to identify operational modes and operational environment
  - Process data to extract features that “clearly” indicate fault growth
    - Preferably monotonically changing since faults are expected to grow monotonically
  - Predictions can be made in many ways
    - Use raw measurement data to map onto RULs
    - Use processed data to trend in feature domain, health index domain, or fault dimension domain against a set threshold

- **How?**
  - Learn a mathematical model to fit changing observations
    - Regression or trending
    - Learnt model may not be transparent to our understanding but explains observed data
  - Use statistics if volumes of run-to-failure data is available
    - Map remaining useful life to various faulty states of the system
    - Reliability type RUL estimates
Example - Data-Driven Prognostics Model

- **Operational conditions**
  - Indicate level of stress on the system
- **Ground truth measurements**
  - Ground truth measurements are less frequent

Operational conditions seem to make an impact on how fast the damage grows!
Example - Data-Driven Prognostics Model

- **Sensor Measurements**
  - Features are extracted from sensor data
  - Depending on what is measured, features will have noise with respect to damage growth
  - All run-to-failure units follow their own track

Generally speaking, features indicate the level of damage at any given time.
Approach

• Learning/training
  – Learn a mapping (M1) between features and the damage state
  – Learn a mapping (M2) between operational conditions and damage growth rate

• Prediction
  – At any given time use M1 & latest measurements to estimate damage state
  – Assuming a future load profile (if unknown) estimate damage accumulation for all future instants using M2

Data-Driven Prognostic Methods

**Advantages**
- Relatively Simple to implement and faster
  - Variety of generic data-mining and machine learning techniques are available
- Helps gain understanding of physical behaviors from large amounts of data
  - These represent facts about what actually happened all of which may not be apparent from theory

**Disadvantages**
- Physical cause-effect relationships are not utilized
  - E.g. different fault growth regimes, effects of overloads or changing environmental conditions
- Difficult to balance between generalization and learning specific trends in data
  - Learning what happened to several units on average may not be good enough to predict for a specific unit under test
- Requires large amounts of data
  - We never know if we have enough data or even how much is enough

**Examples**
- Regression
- Neural Networks (NN)
  - RNN, ARNN, RNF
- Gaussian process regression (GPR)
- Bayesian updates
- Relevance vector machines (RVM)
Physics-Based Models for Prognostics

Use fault propagation models to estimate time of failure

• What kind of models?
  – A model that explains the failure mode of interest
  – A model that maps the effects of stressors onto accumulation of damage – Physics of failure driven
    • e.g. fatigue cycling increases the crack length, or continuous usage reduces the battery capacity over a long term can be modeled in a variety of ways
      • Finite Element Models
      • Empirical models
      • High fidelity simulation models, etc.
  – Modeled cause-effect phenomenon may be directly observable as a fault or not
    • Structural cracks are observable faults
    • Internal resistance changes in a battery causing capacity decay are not directly observable

• How?
  – Given the current state of the system simulate future states using the model
    • Recursive one step ahead prediction to obtain k-steps ahead prediction
  – Propagate fault until a predefined threshold is met to declare failure and compute RUL
Physics-Based Models for Prognostics

• Advantages
  – Prediction results are intuitive based on modeled case-effect relationships
    • Any deviations may indicate the need to add more fidelity for unmodeled effects or methods to handle noise
  – Once a model is established, only calibration may be needed for different cases
  – Clearly drives sensing requirements
    • Based on model inputs, it's easy to determine what needs to be monitored

• Disadvantages
  – Developing models is not trivial
    • Requires assumptions regarding complete knowledge of the physical processes
    • Parameter tuning may still require expert knowledge or learning from field data
  – High fidelity models may be computationally expensive to run, i.e. impractical for real-time applications

• Examples
  – Population growth models like Arrhenius, Paris, Eyring, etc.
  – Coffin-Manson Mechanical crack growth model

Hybrid Approaches

Use knowledge about the physical process and information from observed data together

• How?
  – Learn/fine-tune parameters in the model to fit data
  – Use model to make prediction and make adjustment based on observed data
  – Learn current damage state from data and propagate using model
  – Use knowledge about the physical behavior to guide learning process from the data
    • Improve initialization parameters for learning
    • Decide on the form for a regression model
  – Use understanding from data analysis to develop models
    • Discover the form of the fault growth model
  – Fuse estimates from two different approaches
  – or any other creative way you can think of…
Example 1 – Physics Model Tuned with Data

Predicting Battery Discharge – Short Term

- **Objective:** Predict when Li-ion battery voltage will dip below 2.7 volts
- **Hybrid approach using Particle Filter**
  - Model non-linear electro-chemical phenomena that explain the discharge process
  - Learn model parameters from training data
  - Let the PF framework fine tune the model during the tracking phase
  - Use the tuned model to predict EOD

\[
E = E^0 - \Delta E_{sd} - \Delta E_{rd} - \Delta E_{mt}
\]

- **mt:** mass transfer
- **sd:** self discharge
- **rd:** reactant depletion

| Data Source: NASA PCoE Data Repository [http://ti.arc.nasa.gov/tech/dash/pcoe/prognostic-data-repository/]
Example 2 – Develop Empirical Model from Data

Battery Schematic

Lumped Parameter Model

Example2 – Data-driven Regression

• Use a regression algorithm to make predictions
  – Gaussian Process Regression
Hybrid Approaches

• Advantages
  – Does not necessarily require high fidelity models or large volumes of data – works in a complementary fashion
  – Retains intuitiveness of a model but explains observed data
  – Helps in uncertainty management
  – Flexibility

• Disadvantages
  – Needs both data and the models
  – An incorrect model or noisy data may bias each other’s approach

  *Otherwise, it’s a compromise to get the best out of both so any disadvantage may be alleviated*

• Examples
  – Particle Filters, Kalman Filters, etc.
  – or any clever combination of different approaches…
Example 1

Electrolytic Capacitors
Research Approach

Electrolytic Capacitor

Nominal / Accelerated Aging Experiments

Physics based Degradation Models

Capacitance vs. Time for 2200uF @ 105C

\[ D_1 : C(t) = \left( \frac{2 \varepsilon_R \varepsilon_0 c_{bk}}{d_C} \right) \left( \frac{V_0 - V_e(t)}{i_{eo} t w_e} \right) \]

\[ D_4 : C_{k+1} = C_k - \left( \frac{2 \varepsilon_R \varepsilon_0 w_e A_s i_{eo} c_{bk}}{d_C^2} \right) \Delta t \]
Capacitor Degradation Model

Pristine Capacitor

Electrolyte volume $V_e$ maximum
Capacitance Value maximum

Ideal

Non-Ideal

$M_1$

Degradation

Thermal Stress

Electrical Stress

Avg. surface area decreases ($A_s$) + oxide layer breakdown

Electrolyte degradation + Decrease in ($A_s$) + crystallization + oxide layer breakdown

$M_2$

$M_3$
Capacitor Structure

• An aluminum electrolytic capacitor, consists of
  – Cathode aluminum foil,
  – Electrolytic paper, electrolyte
  – Aluminum oxide layer on the anode foil surface, which acts as the dielectric.
  – Equivalent series resistance (ESR) and capacitance (C) are electrical parameters that define capacitor health
Degradation Mechanisms

Degradation Causes\Mechanisms

- Aging in the dielectric material
- Prolonged Use
- Electrical Stress
- Over Voltage Stress
- Excess Ripple Current
- Charging/Discharging Cycles
- High Ambient Temperature
- Increase in internal Temperature
- Prolonged Use - Nominal Degradation

Electrolyte Evaporation

- Over Voltage Stress
- Excess Ripple Current
- Charging/Discharging Cycles
- High Ambient Temperature
- Increase in internal Temperature
- Prolonged Use - Nominal Degradation

Degradation in Anode foil

- Over Voltage Stress
- Excess Ripple Current
- Charging/Discharging Cycles
- High Ambient Temperature

Degradation of Oxide Film

Degradation in Cathode foil

Failure Modes

Decrease in capacitance
Increase in ESR

PhD Dissertation Defense -
Experimental Setups

• Conditions under investigation
  – Nominal Degradation
  – Electrical Over Stress
  – Thermal Over Stress

• Characterization of capacitors at regular intervals

• Impedance measurement instrument used to characterize the capacitors.

• ESR and Capacitance values are computed using a system identification tool.
Accelerated Aging Studies

• Under normal operating conditions
  – Device lasts for several years
  – Process of condition based monitoring becomes difficult

• Advantage of accelerated stressors
  – We can run the component to failure
  – Allows for the understanding of the effects of failure mechanisms,
  – Identification of leading indicators of failure
  – The development of physics-based degradation models and RUL prediction
Accelerated Electrical Aging

**Electrical Overstress**

\[ V_{\text{applied}} \geq V_{\text{rated}} \]

- **Charge/discharge power**
  - Heat Generation
    - \[ W_{\text{in}} = \frac{1}{2T} \int_0^T I(t)V(t)dt \]
    - Electrolyte evaporation
      - \[ V = V_0 - (w_e A_s j_{eo} t) \]
    - Capacitance decrease
      - \[ C = \frac{(2 \varepsilon R \varepsilon_0 A_s)}{d_C} \]
  - Oxide layer breakdown
    - \[ R_i, C_i \]

- **Localized Breakdowns**
  - Degradation in oxide layer

- **Exchange of ions**
  - Electrolyte degradation
    - \[ ESR = \rho_E d_C \frac{P_E}{(2A_s)} \]

- **Chemical reaction**
  - Gas generation - Faraday's first law
    - \[ n(t) = n_d [1 - \exp(-kt)] \]
  - Depolarizer absorb some amount
    - \[ n_g \geq n_d \]
  - Pressure increase
    - Capacitor popping

PhD Dissertation Defense - April 25, 2023
Capacitance Degradation Model

• Decrease in electrolyte volume:

\[ V_e(t) = V_{e0} - (w_e A_s j_{eo} t) \]  \hspace{1cm} (1)

where:
- \( V \): dispersed volume at time \( t \), \( V_e \): initial electrolyte volume
- \( A_s \): surface area of evaporation, \( j_{eo} \): evaporation rate
- \( t \): time in minutes, \( w_e \): volume of ethyl glycol molecule

• Capacitance (C): Physics-Based Model:

\[ C = \frac{2 \epsilon_R \epsilon_O A_s}{d_C} \]  \hspace{1cm} (2)

• Electrolyte evaporation dominant degradation phenomenon
  – First principles: Capacitance degradation as a function of electrolyte loss

\[ D_1 : C(t) = \left( \frac{2 \epsilon_R \epsilon_O}{d_C} \right) \left( \frac{V_{e0} - V_e(t)}{j_{eo} t w_e} \right) \]  \hspace{1cm} (3)

where:
- \( C \): capacitance of the capacitor,
- \( \epsilon_R \): relative dielectric constant,
- \( \epsilon_O \): permittivity of free space,
- \( d_C \): oxide thickness.
Capacitance Degradation Model

- Oxide breakdown observed - experimental data
- The breakdown factor is exp. function of electrolyte evaporation

\[ C_{bk}(t) = \exp f(V_{eo} - V_{e(t)}) \]

- Updated in capacitance degradation model:

\[
C = \frac{(2\epsilon R\epsilon_0 A_s c_{bk})}{d_C},
\]

\[
\mathcal{D}_{11}: C(t) = c_{bk}(t) \left( \frac{2\epsilon R\epsilon_0}{d_C} \right) \left( \frac{V_{e0} - V_e(t)}{j_{eo} t w_e} \right)
\]
Dynamic Model of Capacitance

From the structure of capacitor we have the electrolyte volume \(V_e\) expressed in the form of oxide surface area \(A_s\) as:

\[
V_e = A_s d_C, \quad \text{Equation (4)}
\]

\[
A_s = \frac{V_e}{d_C}.
\]

The first order discrete approximation for change in electrolyte volume can be expressed as:

\[
\frac{dV_e}{dt} = -(w_e A_s j_{eo}), \quad \text{Equation (5)}
\]

\[
V_{e(k+1)} = V_{e(k)} + \frac{dV_e}{dt} \Delta t,
\]

\[
V_{e(k+1)} = V_{e(k)} - (w_e A_s j_{eo}) \Delta t.
\]
Dynamic Model of Capacitance

\[
V_{e(k)} = \frac{C_k}{2\epsilon R \epsilon_0 c_{bk}} d_C^2, \\
V_{e(k)} = (C_k) \alpha
\]  \hspace{1cm} (6)

Similarly Capacitance can be expressed as:

\[
C_{k+1} \alpha = C_k \alpha + \frac{dV_e}{dt} \Delta t, \\
C_{k+1} \alpha = C_k \alpha - (w_e A_s j_{eo}) \Delta t, \text{ hence} \\
C_{k+1} = C_k - \left(\frac{w_e A_s j_{eo}}{\alpha}\right) \Delta t.
\]  \hspace{1cm} (7)

The complete discrete time dynamic model for capacitance degradation can be summarized as:

\[
D_4 : C_{k+1} = C_k - \left(\frac{2\epsilon R \epsilon_0 w_e A_s j_{eo} c_{bk}}{d_C^2}\right) \Delta t
\]
Dynamic Model of ESR

- Decrease in electrolyte volume:
  \[ V_e(t) = V_{e0} - (w_e A_s j_{eo} t) \]

- ESR
  - Based on mechanical structure and electrochemistry.
  - With changes in \( R_E \) (electrolyte resistance)

\[
ESR = \frac{1}{2} \left( \frac{\rho_E d_C P_E e_{bk(t)}}{A_s} \right)
\]

\[
\mathcal{D}_2: \ ESR(t) = \frac{1}{2} \left( \rho_E d_C P_E \right) \left( \frac{j_{eo} t w_e e_{bk(t)}}{V_e(t)} \right)
\]  \hspace{1cm} (8)

Dynamic ESR degradation Model:

\[
\mathcal{D}_5: \ \frac{1}{ESR_{k+1}} = \frac{1}{ESR_k} - \left( \frac{2 w_e A_s j_{eo}}{\rho_E P_E d_C^2 e_{bk(t)}} \right) \Delta t
\]

where:
- \( \rho_E \): electrolyte resistivity,
- \( P_E \): correlation factor related to electrolyte spacer porosity and average liquid pathway,
- \( e_{bk(t)} \): resistance dependence oxide breakdown factor
Electrical Overstress Experiment

- Electrolytic capacitors of 2200μF, 10V, 1A and at 85°C
- Stress voltages
  - 120%, 150% of rated voltage
- Under Electrical Overstress
  - Capacitance Health Threshold – 20%
  - ESR Health Threshold – 250 – 280%
- Charging / discharging cycle – 15V

For this experiment ESR ( > 55% ) and capacitance decrease ( > 22-24% )
Electrical Overstress Experiment

• EOS Experiments:
  • 3 Capacitors failed due to vent opening.
  • Pressure increase in other devices observed.

Increase in pressure
Opening of the pressure vent
Electrical Overstress Degradation Data

- Devices were characterized at regular intervals.
- Impedance data shows degradation in C and ESR with aging.
- C and ESR values were computed from the impedance data.

Nyquist Impedance Plots

ESR Increase

Capacitance Decrease
Thermal Overstress Experiment

- Exposure of the capacitors to temperatures $T_{\text{applied}} (105 \, \text{C}) \geq T_{\text{rated}} (85 \, \text{C})$ results in accelerated aging of the devices
- High temperature on the surface causes heat to flow radially towards the core of the capacitor
- Temperature increase leads to electrolyte evaporation
- Health Threshold Storage condition - capacitance decreases > 10%
- Oxide breakdown observed

PhD Dissertation Defense -

<table>
<thead>
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<th>Capacitor Value</th>
<th>Voltage</th>
<th>Temperature</th>
<th>Duration</th>
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<tbody>
<tr>
<td>2200uF, 10V</td>
<td>85°C</td>
<td>105°C</td>
<td>3400 hrs</td>
</tr>
<tr>
<td>10,000uF, 10V</td>
<td>85°C</td>
<td>105°C</td>
<td>3400 hrs</td>
</tr>
</tbody>
</table>

Capacitance decrease ( > 15 - 17%) Linear decrease till 2800 hrs
Nominal Operation Experiment

• Three sets of DC-DC converters with electrolytic capacitors under test
• Main components include MOSFET's, isolating transformers, PWM controller chip and an electrolytic capacitor
• Characterization of capacitors done at regular time intervals.
  – Voltage source shut down, capacitors discharged
  – Experiment was started with conditions intact again till the next measurement

For this experiment ESR increase ( > 103% ) and capacitance decrease ( > 8% )
RUL and Validation – EOS -Experiment – ESR Degradation Model

Tracking

ESR (Ω)

Aging Time ( Hours)

Measured data
Filter data

Output Error - Cap #2

ESR (Ω)

Aging Time ( Hours)

Alpha Lambda

\[ \alpha = 0.3, \beta = 0.5 \]

RUL (hours)

Aging Time (Hours)

Predictions at different aging time
Experiments

- 2200μF capacitors at 105°C
- Capacitance Degradation Model

<table>
<thead>
<tr>
<th>Aging Time</th>
<th>Evaporation Rate ($j_{eo}$)</th>
<th>Evap. Rate and Oxide Breakdown</th>
</tr>
</thead>
<tbody>
<tr>
<td>RA_a_1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2421.92</td>
<td>90.15</td>
<td>94.47</td>
</tr>
<tr>
<td>2500</td>
<td>85.71</td>
<td>97.86</td>
</tr>
<tr>
<td>2650</td>
<td>78.18</td>
<td>94.76</td>
</tr>
<tr>
<td>2800</td>
<td>65.00</td>
<td>95.15</td>
</tr>
<tr>
<td>3000</td>
<td>43.18</td>
<td>95.00</td>
</tr>
<tr>
<td>RA_b</td>
<td>92.32</td>
<td>93.52</td>
</tr>
</tbody>
</table>
RUL and Validation – TOS -Experiment - Capacitance

Tracking

Alpha Lambda

\[ \alpha = 0.3, \beta = 0.5 \]

Predictions at different aging time

\[ t_p = 607 \]

\[ t_p = 1495 \]

\[ t_p = 2131 \]

\[ t_p = 2800 \]
Example 2

Li-Ion Batteries
Background

• For Li-ion, a common chemistry
  – positive electrode consisting of lithium cobalt oxide \((\text{Li}_x\text{CoO}_2)\)
  – negative electrode of lithiated carbon \((\text{Li}_x\text{C})\).

• Electrolyte enables lithium ions \((\text{Li}^+)\) to diffuse between the positive and negative electrodes.

• Intercalation/charging and deintercalation/discharging process
Background - Discharging

- On connecting to load
  - current flow leads to oxidation reaction
    \[ \text{Li}_x \text{C} \xrightarrow{\text{discharge}} C + x\text{Li}^+ + xe^- \]
  - liberation of Li ions and electrons
  - positive electrode the reduction reaction takes place

\[ \text{Li}_{1-x} \text{CoO}_2 + x\text{Li}^+ + xe^- \xrightarrow{\text{discharge}} \text{LiCoO}_2 \]
• During charging
  • active material in the positive electrode (anode) is oxidized and Li ions are de-intercalated

\[ \text{LiCoO}_2 \xrightarrow{\text{charge}} \text{Li}_{1-x}\text{CoO}_2 + x\text{Li}^+ + xe^- \]

• results in the loss of Li ions and electrons, which can then move to the negative electrode (cathode).

\[ \text{C} + x\text{Li}^+ + xe^- \xrightarrow{\text{charge}} \text{Li}_x\text{C} \]
Aging Process

- **Solid-electrolyte interface (SEI) layer**
  - degradation in the negative electrode
  - increase in impedance

- **Lithium corrosion**
  - degradation with aging
  - decrease in capacity

- **Lithium plating**
  - irreversible loss due to plating formation

- **Contact Loss**
  - SEI layer disconnects from the negative electrode, impedance increase
Problem Formulation

• Prognostics goal
  – Compute EOL = time point at which component no longer meets specified performance criteria
  – Compute RUL = time remaining until EOL

• System model

\[
\begin{align*}
\dot{x}(t) &= f(t, x(t), \theta(t), u(t), v(t)) \\
y(t) &= h(t, x(t), \theta(t), u(t), n(t))
\end{align*}
\]

• Define threshold that determines if EOL has been reached

\[
T_{EOL}(x(t), \theta(t)) = \begin{cases} 
1, & \text{if EOL is reached} \\
0, & \text{otherwise.}
\end{cases}
\]

• EOL and RUL defined as

\[
EOL(t_P) \triangleq \arg \min_{t \geq t_P} T_{EOL}(x(t), \theta(t)) = 1 \quad RUL(t_P) \triangleq EOL(t_P) - t_P
\]

Compute \( p(EOL(t_P)|y_{0:t_P}) \) and/or \( p(RUL(t_P)|y_{0:t_P}) \)
Prognostics Architecture

1. System receives inputs, produces outputs

2. Estimate current state and parameter values

3. Predict EOL and RUL as probability distributions

Prognostics

\[ p(x(k), \theta(k) | y(k_0 : k_P)) \]

Prediction

\[ p(k_{E}(k_P) | y(k_0 : k_P)) \]
Battery Modeling

• Overall Battery Voltage
  – potential at positive current collector
  – potential Negative current collector
  – resistance losses

• Equilibrium potential
  – Nernst Equation

• Surface over-potential
  – Butler-Volmer

• Solid-phase resistance
  – treated as constant and lumped together
Battery Voltage

- The total battery voltage can be given as:

\[ V = V_{U,p} - V_{U,n} - V_0 - V_{\eta,p} - V_{\eta,n}. \]

- Change in voltage levels and transients

\[ V = V_{U,p} - V_{U,n} - V'_0 - V'_{\eta,p} - V'_{\eta,n} \]

where

\[ \dot{V}'_0 = \frac{(V_0 - V'_0)}{\tau_0} \]

\[ \dot{V}'_{\eta,p} = \frac{(V_{\eta,p} - V'_{\eta,p})}{\tau_{\eta,p}} \]

\[ \dot{V}'_{\eta,n} = \frac{(V_{\eta,n} - V'_{\eta,n})}{\tau_{\eta,n}} \]
Constant 2A discharge

- Model fits very well

- The accuracy towards the end of discharge is most sensitive to the
  - Redlich-Kister parameters
  - Diffusion constant
  - Volume of surface layer
Variable Loading

- Load changes every 2 mins
- Results in corresponding changes in voltage
- Predictions are fairly accurate
- Some errors still present possibly accounted by thermal effects
Battery Aging - Experiments

- EOD point moves earlier in time due to diminished capacity.
- Voltage drops down during discharge due to increased resistance.
- Steady-state voltage after discharge increases.

![Graph showing voltage over current for different cycles.](image-url)
Battery Aging Model

- Total available charge in the battery is represented through $q_{\text{max}}$
- Loss of active material
- Decrease in voltage due to Butler-Volmer term
- Increase in internal resistance captured through an increase in the Ro parameter
Battery Aging Model

- Dynamics near EOD are dominated mainly by the equilibrium potential contribution with some contribution from the Butler-Volmer dynamics
- Combined effects, with $q_{\text{max}}$ decreasing by 1% and $R_o$ increasing by 5% with each new discharge.
- Similar to observed in experimental data
Prognostics Performance

- UKF is used for state estimation
- Each sigma point is simulated forward using the model until EOD is reached
- We assume future loading points
- Model tracks very well under different conditions

Prognostics results for 2 A discharge
Prognostics Performance

- Each sigma point is simulated forward using the model until EOD is reached
- We assume future loading points are known
- Model tracks very well under different conditions

<table>
<thead>
<tr>
<th>$i_{app}$</th>
<th>PRMSE</th>
<th>RA</th>
<th>RMAD$_{RUL}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>0.19</td>
<td>92.77</td>
<td>1.07</td>
</tr>
<tr>
<td>1.5</td>
<td>0.17</td>
<td>96.02</td>
<td>0.88</td>
</tr>
<tr>
<td>2.0</td>
<td>0.17</td>
<td>99.38</td>
<td>0.75</td>
</tr>
<tr>
<td>2.5</td>
<td>0.26</td>
<td>97.75</td>
<td>0.82</td>
</tr>
<tr>
<td>3.0</td>
<td>0.41</td>
<td>96.08</td>
<td>0.92</td>
</tr>
</tbody>
</table>
Prognostics Performance

- EOD being defined in this case as 3.35 V.
- In the open loop, the model slightly overestimates EOD
- Model tracks very well under different conditions
- RA averages 88.41%
Conclusions

• Discussed the lumped parameter electrical equivalent models
  – Study the links between the equivalent models and different degradation conditions.

• Stressors leading to degradation in capacitors are electrical and thermal overstress conditions respectively

• Developed appropriate experimental setups,
  – conducted laboratory experiments
  – Simulating capacitors under different operating conditions.

• Development of generalized physics based degradation models for $C$ and $ESR$
  – Structural and manufacturing data
  – First principles of operation
  – Experimental Data
Discussion

- Electrochemistry based model discussed
- Prognostics results for EOD predictions are accurate
- The model can be applied to battery packs
- Two approaches
- Either each battery modeled individually
- Battery pack lumped to a single cell
Acknowledgements
Member of the Prognostics Center of Excellence (PCoE) at Ames Research Center

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http://prognostics.nasa.gov

THANK YOU !!!
Prognostic Performance Evaluation

Prognostics Metrics
Role of Prognostics Metrics

- Cost of lost or incomplete mission
- Cost of incurred damage
- Failure Criticality
- Time required for repair action
- Best achievable algorithm fidelity
- Desired minimum performance criteria
- Algorithm Complexity

**Requirement Variables**
- Time required to make a prediction
- Desired minimum performance criteria
- Algorithm Complexity

**Algorithm Fine-tuning**
- Fault Evolution Rate

**Performance Specifications**
- Performance Evaluation
- PROGNOSTICS METRICS

**PROGNOSTICS METRICS**
Prognostic Performance Metrics

- New metrics were proposed specific to prognostics for PHM
- These metrics were applied to
  - A combination of different algorithms and different datasets
- Metrics were evaluated and refined

- Prognostics horizon
- $\alpha$-$\lambda$ performance
- Relative accuracy
- Cumulative relative accuracy
- Convergence

Prognostic Performance Metrics

- Metrics Hierarchy

I. Prognostic Horizon
   - Does the algorithm predict within desired accuracy around EoL and sufficiently in advance?

II. \( \alpha - \lambda \) Performance
   - Further does the algorithm stay within desired performance levels relative to RUL at a given time?

III. Relative Accuracy
   - Quantify how well an algorithm does at a given time relative to RUL

IV. Convergence Rate
   - If the performance converges (i.e. satisfies above metrics) quantify how fast does it converge
Prognostic Horizon (PH)

- **Prognostic Horizon** is defined as the difference between the time index $i$ when the predictions first meet the specified performance criteria (based on data accumulated until time index $i$) and the time index for End-of-Life (EoL). The performance specification may be specified in terms of allowable error bound ($\alpha$) around true EoL.

\[ \text{PH} = t_{\text{EoL}} - t_{i_{\alpha\beta}} \]

- $i_{\alpha\beta}$ is the first time index when predictions satisfy $\beta$-criterion for a given $\alpha$
- $p$ is the set of all time indexes when predictions are made
- $l$ is the index for $l^{th}$ unit under test (UUT)
- $\beta$ is the minimum acceptable probability mass
- $\pi[r(k)]_{\alpha}^{\alpha^+}$ is the probability mass of the prediction between $\alpha$-bounds given by $\alpha^+ = r_s + \alpha \cdot t_{\text{EoL}}$ and $\alpha^- = r_s - \alpha \cdot t_{\text{EoL}}$
- $r(k)$ is the predicted RUL distribution at time $t_j$
- $t_{\text{EoL}}$ is the predicted End-of-Life

The range of PH is between $(t_{\text{EoL}} - t_p)$ and $\max[0, t_{\text{EoL}} - t_{\text{EoP}}]$
\[ \alpha - \lambda \text{ Accuracy} = \begin{cases} 1 & \text{if } \pi[r(i_\lambda)]^{+\alpha}_{-\alpha} \geq \beta \\ 0 & \text{otherwise} \end{cases} \]

- \( \alpha - \lambda \text{ Accuracy} \) determines whether at given point in time (specified by \( \lambda \)) prediction accuracy is within desired accuracy levels (specified by \( \alpha \)). Desired accuracy levels for any time \( t \) are expressed as a percentage of true RUL at time \( t \).

- \( \lambda \) is the time window modifier such that \( t_\lambda = t_P + \lambda(t_{EoL} - t_P) \)
- \( \beta \) is the minimum acceptable probability mass
- \( r(i_\lambda) \) is the predicted RUL at time \( t_\lambda \)
- \( \pi[r(i_\lambda)]^{+\alpha}_{-\alpha} \) is the probability mass of the prediction between \( \alpha \)-bounds given by \( \alpha^+ = r_s(i_\lambda) + \alpha \cdot r(i_\lambda) \) and \( \alpha^- = r_s(i_\lambda) - \alpha \cdot r(i_\lambda) \)
Comparing Various Algorithms

**Prediction Horizon (5% error)**

<table>
<thead>
<tr>
<th>PH (weeks)</th>
<th>RVM</th>
<th>GPR</th>
<th>ANN</th>
<th>PR</th>
</tr>
</thead>
<tbody>
<tr>
<td>PH</td>
<td>8.46</td>
<td>12.46</td>
<td>12.46</td>
<td>24.46</td>
</tr>
</tbody>
</table>

**Prediction Horizon (10% error)**

<table>
<thead>
<tr>
<th>PH (weeks)</th>
<th>RVM</th>
<th>GPR</th>
<th>ANN</th>
<th>PR</th>
</tr>
</thead>
<tbody>
<tr>
<td>PH</td>
<td>12.46</td>
<td>16.46</td>
<td>12.46</td>
<td>24.46</td>
</tr>
</tbody>
</table>

PR > GPR = ANN > RVM

PR > GPR > ANN = RVM