2004 DOE Hydrogen, Fuel Cells & Infrastructure Technologies

Modeling and Control of a Solid Oxide Fuel Cell Auxiliary Power Unit

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PNNL

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This presentation does not contain any proprietary or confidential information

Objectives

SOFC-based APU development with a) control algorithms to optimize fuel efficiency and operating life, and b) models for stack response and structural failure under dynamic loading

- Controls
  - Develop dynamic system models.
  - Determine typical APU usage patterns.
  - Collect electrical usage data from a working truck.
  - Design control algorithms to optimize fuel efficiency and operating life.
- Shock & Vibration
  - Identify failure modes under characteristic dynamic loading.
  - Determine guidelines for durable SOFC/APU systems.
  - Measure truck excitations and experimentally validate the models.
  - Define requirements for APU isolation.

Budget

Fiscal Year	Activity	Funding
2003	Controls	$300k
	Shock & Vibration	$200k
2004	Controls	$300k
	Shock & Vibration	$200k

Technical Barriers and Targets

- DOE Technical Barriers for Transportation Systems and Fuel Cell Components
  - C. Thermal Management
  - D. Fuel Cell Power System Benchmarking
  - P. Durability
- DOE Technical Targets for Auxiliary Power Units
  - (2010) Efficiency: 35%
  - (2010) Cycle Capability: 500
  - (2015) Durability: 15,000 hours
  - (2010) Start-up Time: 15-30 minutes

Approach
Controls Analysis

- Develop advanced algorithms to control an SOFC based APU system for long haul trucks. The controller seeks to optimize fuel efficiency and system operating life.
  - Create a dynamic system model of APU operation.
  - Use experimental validation to improve models.
  - Integrate APU, power electronics and control models into a single operating model.

Approach
Shock & Vibration Analysis

- Evaluate mechanical dynamics of APU
  - Simple, fast lumped parameter representation
- Evaluate dynamic response of SOFC stack
  - Assume stack is component most prone to damage
  - Detailed multi-cell stack finite element model
- Evaluate stresses in the stack against failure criteria to determine permissible accelerations
  - Permissible acceleration envelope is defined by criteria
- Measure excitation levels from truck frame
- Define APU isolation requirements based on expected excitations for Class VIII trucks

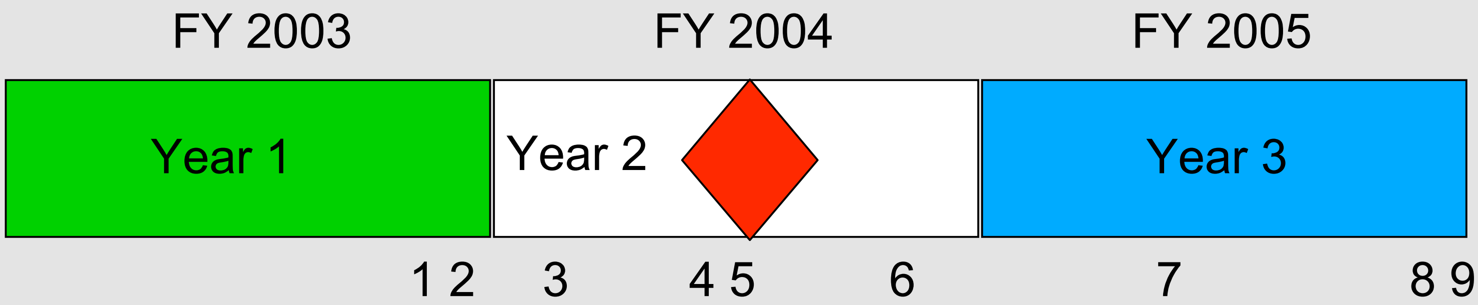
Approach
Shock & Vibration Analysis

- Thermal gradient stresses in stack are calculated for expected temperature distribution
- Dynamic stresses are calculated for unit excitation
- For elastic response, superposition is used to evaluate failure criteria:
  - Tensile stress-based: $\sigma_1^{fail} = \sigma_1^{thermal} + \beta\sigma_1^{dynamic}$
  - Fracture-based: $K_{1c} = K_1^{thermal} + \beta K_1^{dynamic}$
  - Displacement-based: $\delta_i^{fail} = \delta_i^{thermal} + \beta\delta_i^{dynamic}$
  - β is then the limiting excitation level
- Criteria applied to PEN and rigid seal materials
- Developing interfacial seal fracture criterion

Project Safety

- Majority of project is modeling work performed on computers.
- In the model validation experiments performed, all relevant PNNL and DOE laboratory safety procedures were implemented and observed.
- The project has had zero recordable safety incidents.

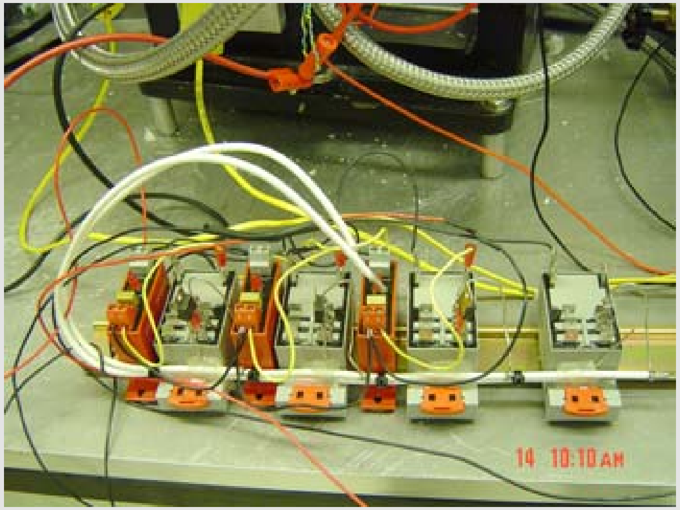
Project Timeline



- Major Milestones
  - Year 1
    1. Implement Initial System Controller – COMPLETE
    2. Initial Vibration Model Creation - COMPLETE
  - Year 2
    3. Collect initial data for truck vibration and electrical usage - COMPLETE
    4. Create Models to Analyze Shock - COMPLETE
    5. Experimental Validation of Dynamic V-I Relationship – COMPLETE
    6. Complete Inclusion of Cyclic Loading in Interfacial Failure Models
  - Year 3
    7. Shock, Vibration and Electrical Data Collection From Class VIII Truck APU
    8. Dynamic Bench Testing of APU/Stack for Durability and Isolation
    9. Extension of Controls to Full Truck Electrification

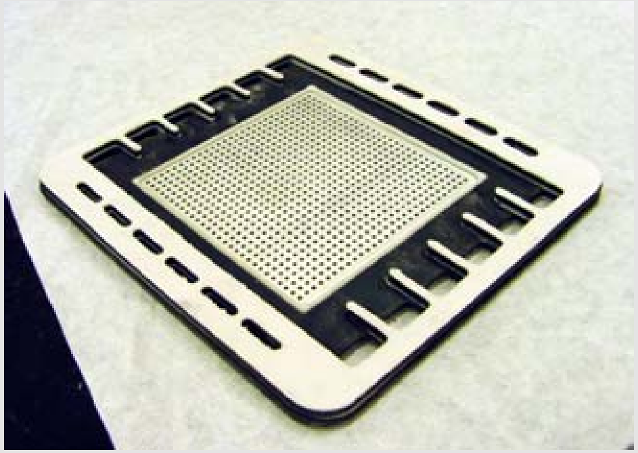
Stack Dynamic V-I Validation Experimental Setup

Fuel Cell Test Bed with Furnace, Fuel Source and Test Circuit

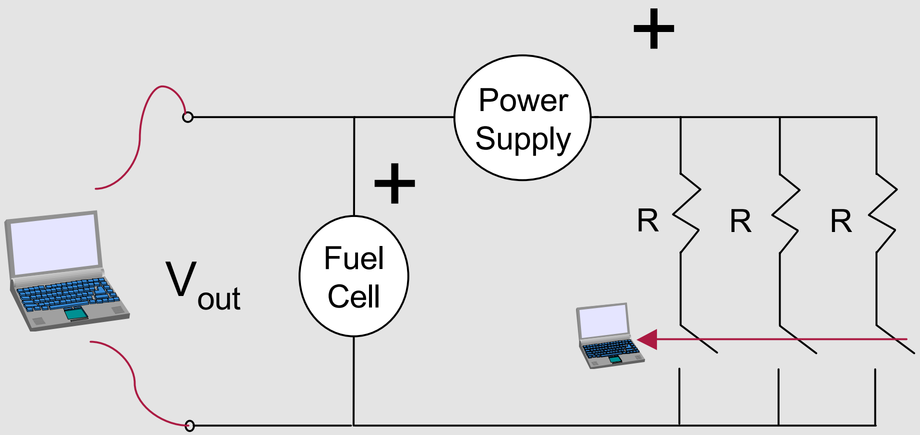


Close-up of test circuit

Cell with hearth plate



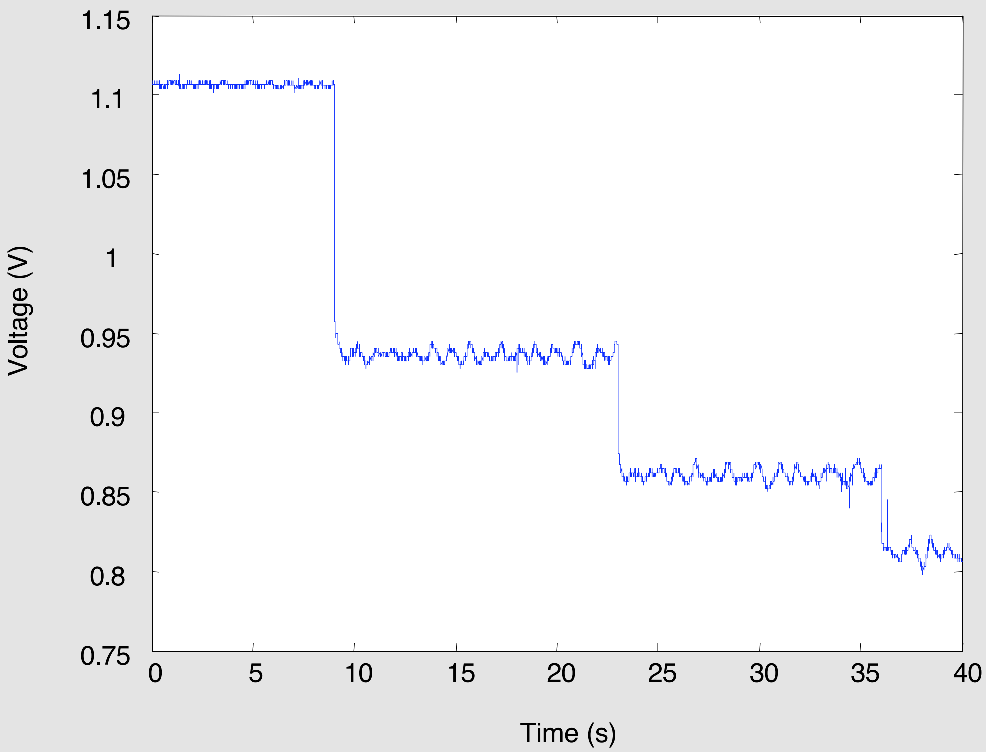
Cell before assembly



Experimental Circuit Schematic

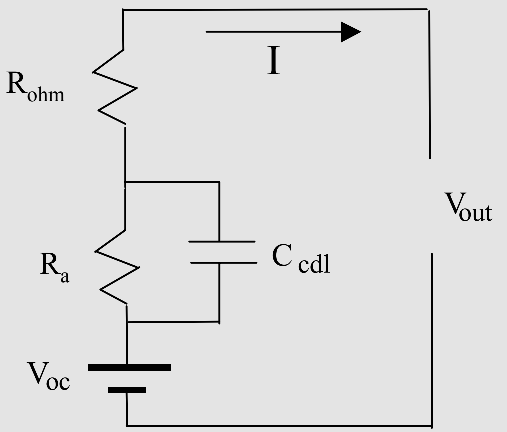
Raw Experimental Data

- Graph shows SOFC voltage versus time. The three load transitions are easily seen.



Dynamic V-I Relationship

Theoretical Model

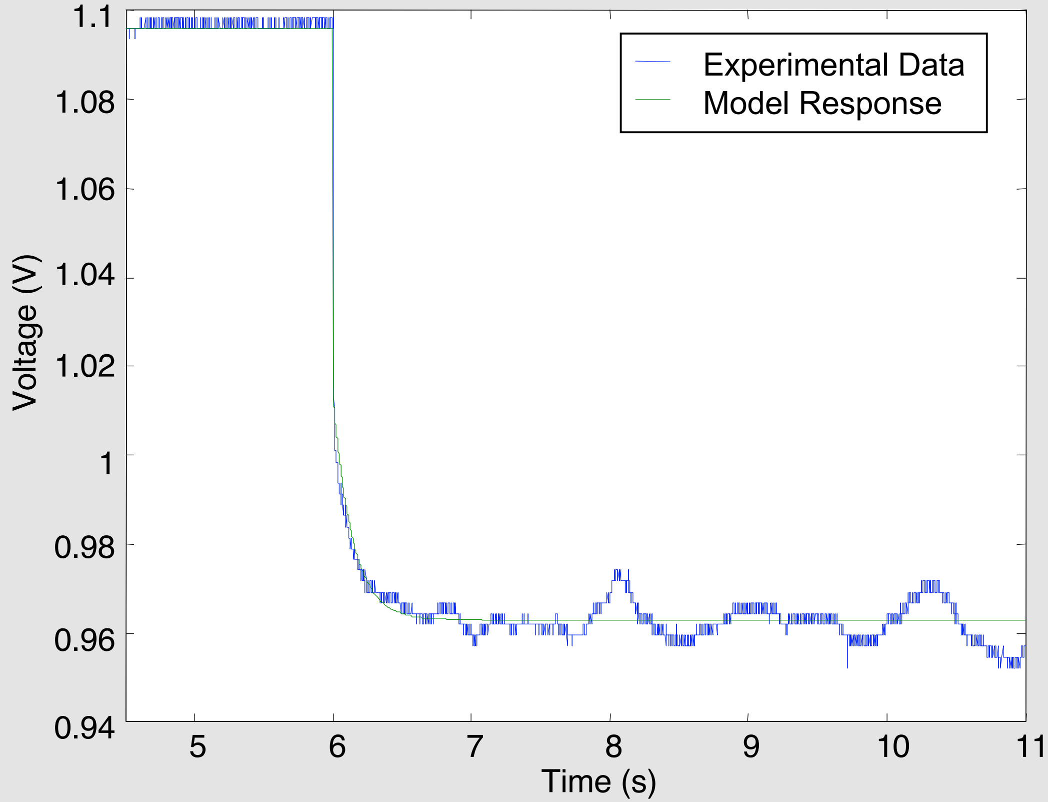


Transfer Function

$$\frac{V_{oc} - V_{out}(s)}{I(s)} = \frac{R_a R_{ohm} C_{cdl} \cdot s + R_a + R_{ohm}}{R_a C_{cdl} \cdot s + 1}$$

Voc = open circuit voltage
Rohm = ohmic resistance through cell
Ra = activation loss, caused by slowness of reaction
Ccdl = charge double layer effect capacitance
I = electrical current
s = Laplace variable

Rohm = 0.0167Ω Ra = 0.0101Ω Ccdl = 13.8F



Actual Truck APU Load Data

- Through collaboration with PACCAR we received the following data on typical APU usage in a real truck

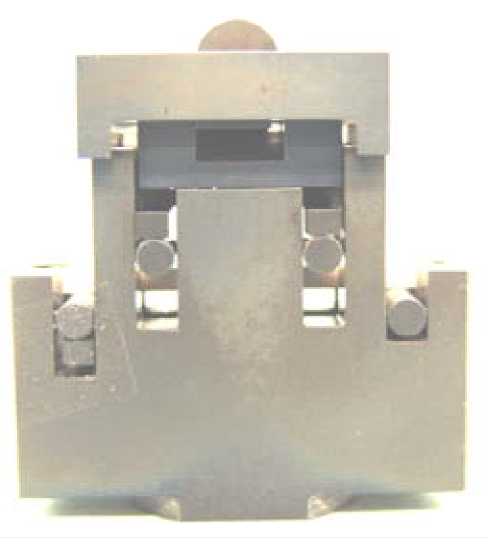
Source	Peak Load (watts)	Typical Load (watts)	Duty Cycle	Average Load (watts)
Audio System	350	50	25%	13
Television/VCR	75	75	15%	11
Satellite or Other Communication System	160	50	10%	5
Laptop Computer	65	65	25%	16
Microwave Oven	1400	1400	3%	42
Air Conditioning	4400	1700	70%	1190
Refrigerator	85	85	50%	43
Coffee Maker	250	250	2%	5
Lighting	100	60	50%	30
Miscellaneous	100	50	25%	13
Inverter Losses @ 15% of Load	300	290		20
TOTAL	**7285**	**4075**		**1387**

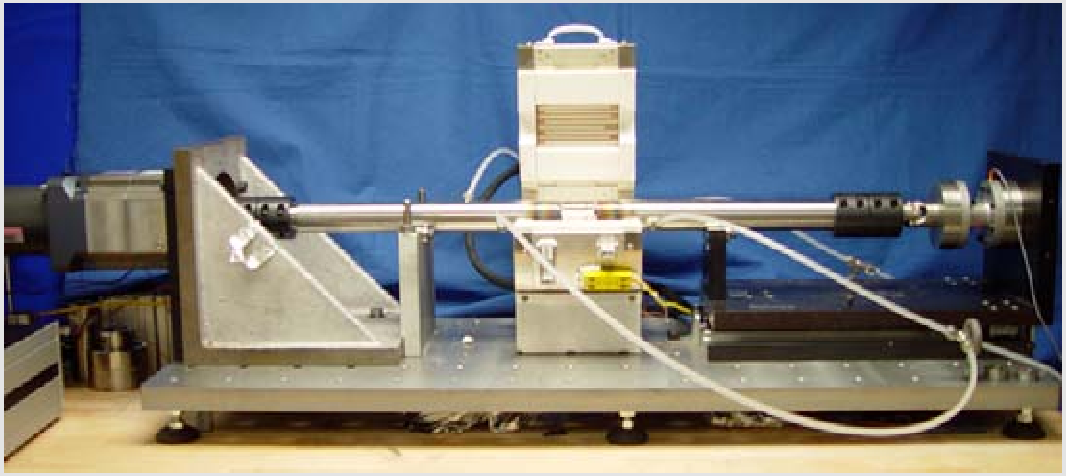
- We can use this data to show that an SOFC APU should be capable of providing 4075W steady state.
- The 3210W difference between typical and peak load can be made up with a battery or ultra-capacitor

Shock & Vibration Modeling Progress

Materials Testing

- Working with PNNL's SECA CTP team to determine elevated temperature strength and failure properties of seal materials for use in failure criteria
- Materials
  - G18 Glass
- Test methods
  - 4-point bend
  - Tension
  - Torsion

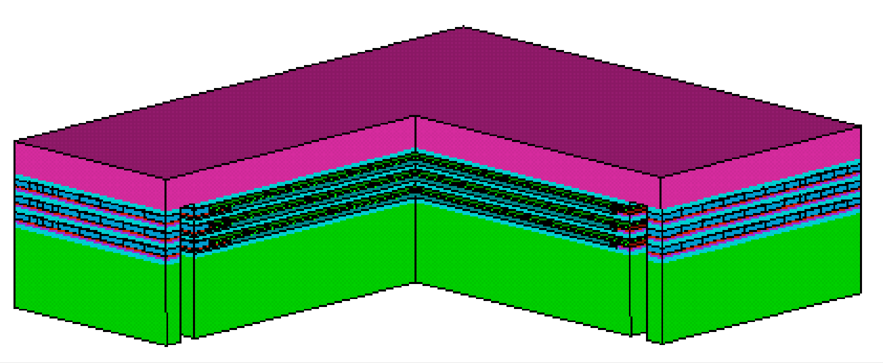




Shock & Vibration Modeling Progress

- Improved dynamic analysis capabilities
  - Modal (pre-stressed)
  - Harmonic
  - Spectrum response
  - Random vibration
  - Shock transient*
  - Multiple excitations/directions
- Added failure criteria
  - Component tensile stress
  - Anode fracture
  - Interfacial fracture in progress

3-cell planar stack

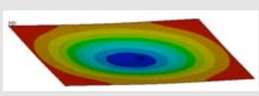
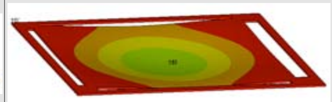
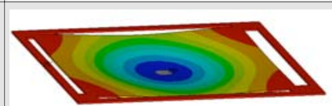
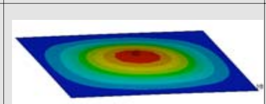
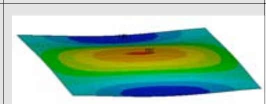
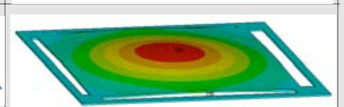
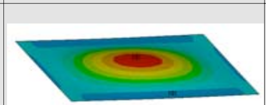
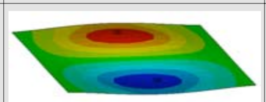
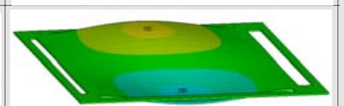
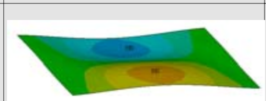
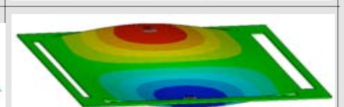
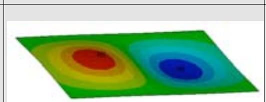
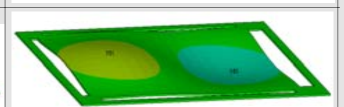


- Improved material properties and strengths obtained from SECA CTP
- Existing experimental data obtained for truck APU* and frame vibration amplitudes

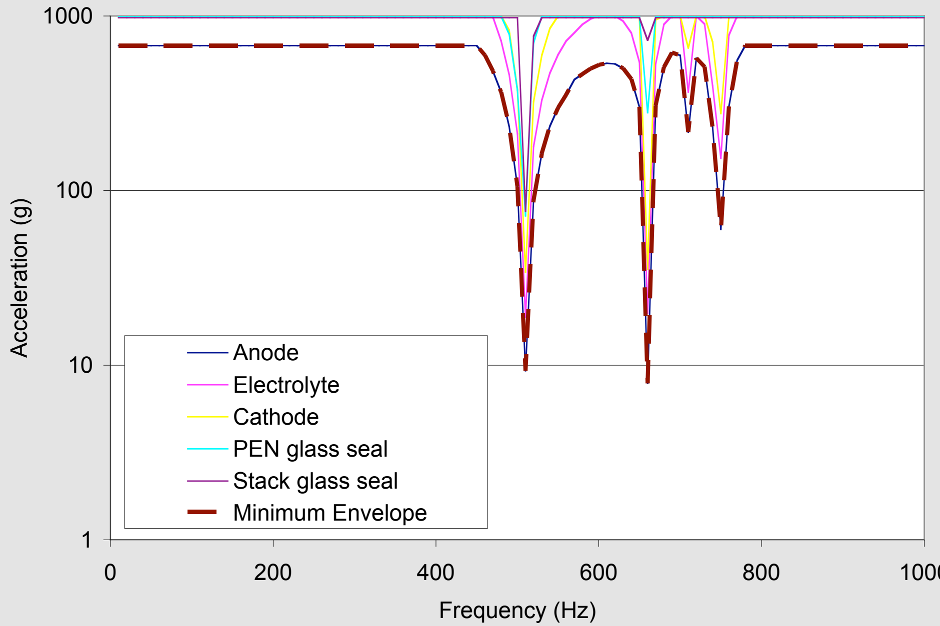
*milestone

Shock & Vibration Modeling Progress

Modal Response of 3-cell stack

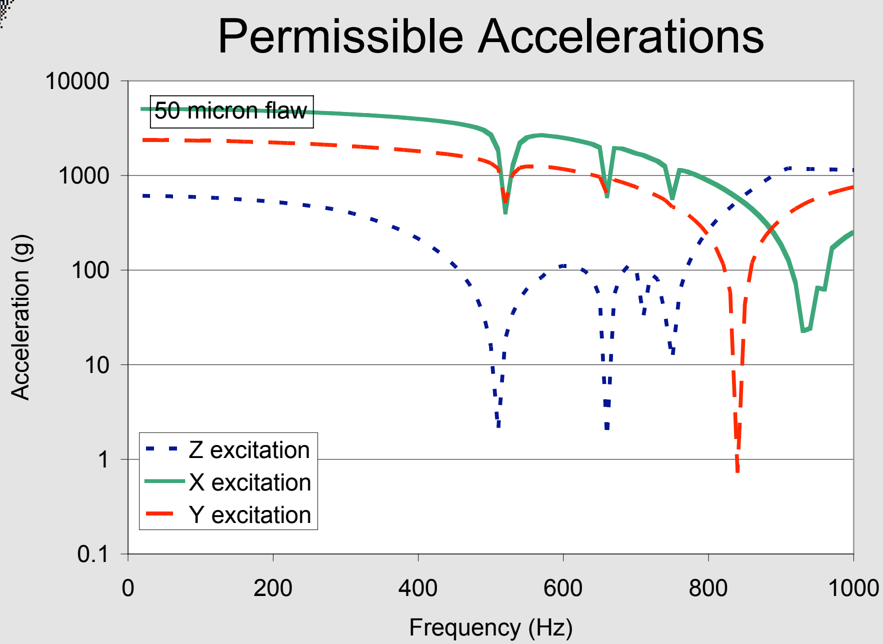
Freq	PEN UZ	Interconnect UZ
522		
567		
661		
709		
749		
843		
847		
936		

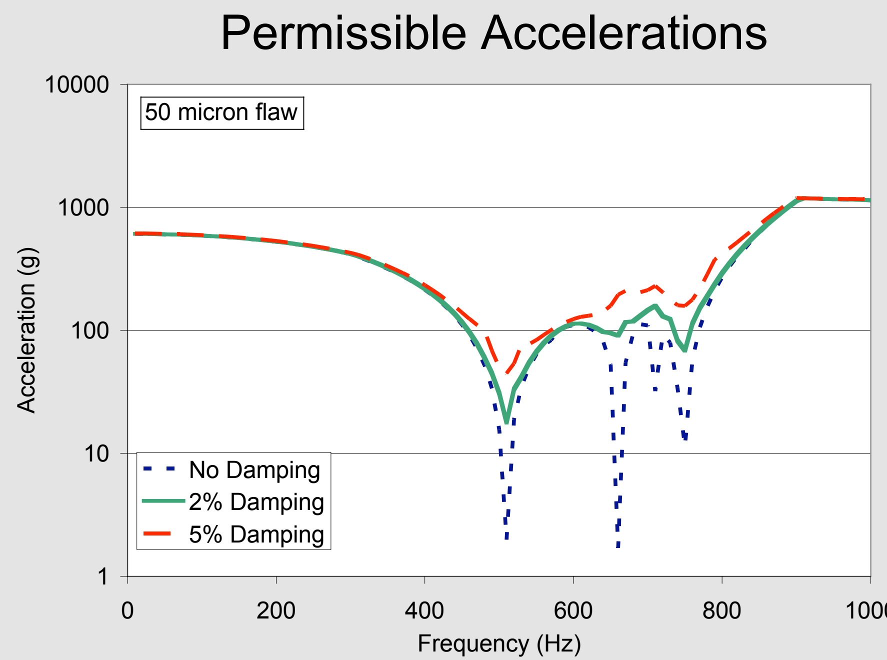
Permissible Acceleration Envelope



- Acceleration envelope
  - Defined by union of failure criteria
  - Response is limiting at coupled resonant frequencies of the PEN and interconnect (10-1000 Hz)

Shock & Vibration Modeling Progress





- Excitation direction
  - Validates amplitude criteria needed for 3 axes
  - Different modes excited, so cell orientation important
- Damping
  - Significant influence on response so must include conservative estimates for SOFC materials

Interactions and Collaborations

- PACCAR: Rich Bergstrand, provided experimental APU electrical usage and vibration data.
- Delphi: Steve Shaffer, providing assistance in model validation experiments including shaker table tests.
- Univ of Illinois, Chicago: Sudip Mazumder, collaboration in the modeling and design of power conversion electronics.
- Georgia Tech: Jianmin Qu, provided cell fracture models.
- SECA-CTP: Use of material data and constitutive models developed under Core Technology Program.

Responses to Previous Year Reviewers' Comments

- Develop strong integration with SECA
  - Working with PNNL and ORNL materials developers to get necessary mechanical data on seals and anodes.
  - Utilizing constitutive and fracture models developed under SECA Core Technology Program. In-progress leak model also of interest.
  - Performed dynamic V-I tests on a SECA funded cell.
- Demonstrate interest of industry
  - Using PACCAR provided data for power usage and component vibration.
  - Delphi to provide shaker table facilities for model validation tests.
- Perform experimental validation
  - Tested transient response of SOFC to validate dynamic voltage-current transfer function.

Conclusions

- The predominant V-I transfer function has one real pole and one zero, yielding a response without overshoot or oscillation.
- The dynamic response is being added to PNNL's SOFC system model.
- Working with University of Illinois, Chicago to design power conditioning electronics based on the dynamic V-I model developed here.
- Vibration models predict permissible acceleration envelope from multiple elastic failure criteria for PEN and seals.
- Acceleration limits needed for different orientations due to planar stack sensitivity to loading direction.
- Will continue to work with PACCAR to collect more detailed truck APU data for electrical usage (load vs. time) and expected vibrations (amplitude and frequency content).

Future Work

- Remainder of FY 2004
  - Define optimization equation for system fuel efficiency.
  - Incorporate power electronics model from Univ of Illinois.
  - Add failure criteria to shock analysis procedures.
  - Integrate interface fracture criteria with FEA model.
  - Define APU isolation requirements.
- FY 2005
  - Collection of APU electrical usage data from working truck.
  - Extension of system model and controls to full truck electrification.
  - Data collection for Class VIII truck shock & vibration.
  - Vibration testing of instrumented stack.