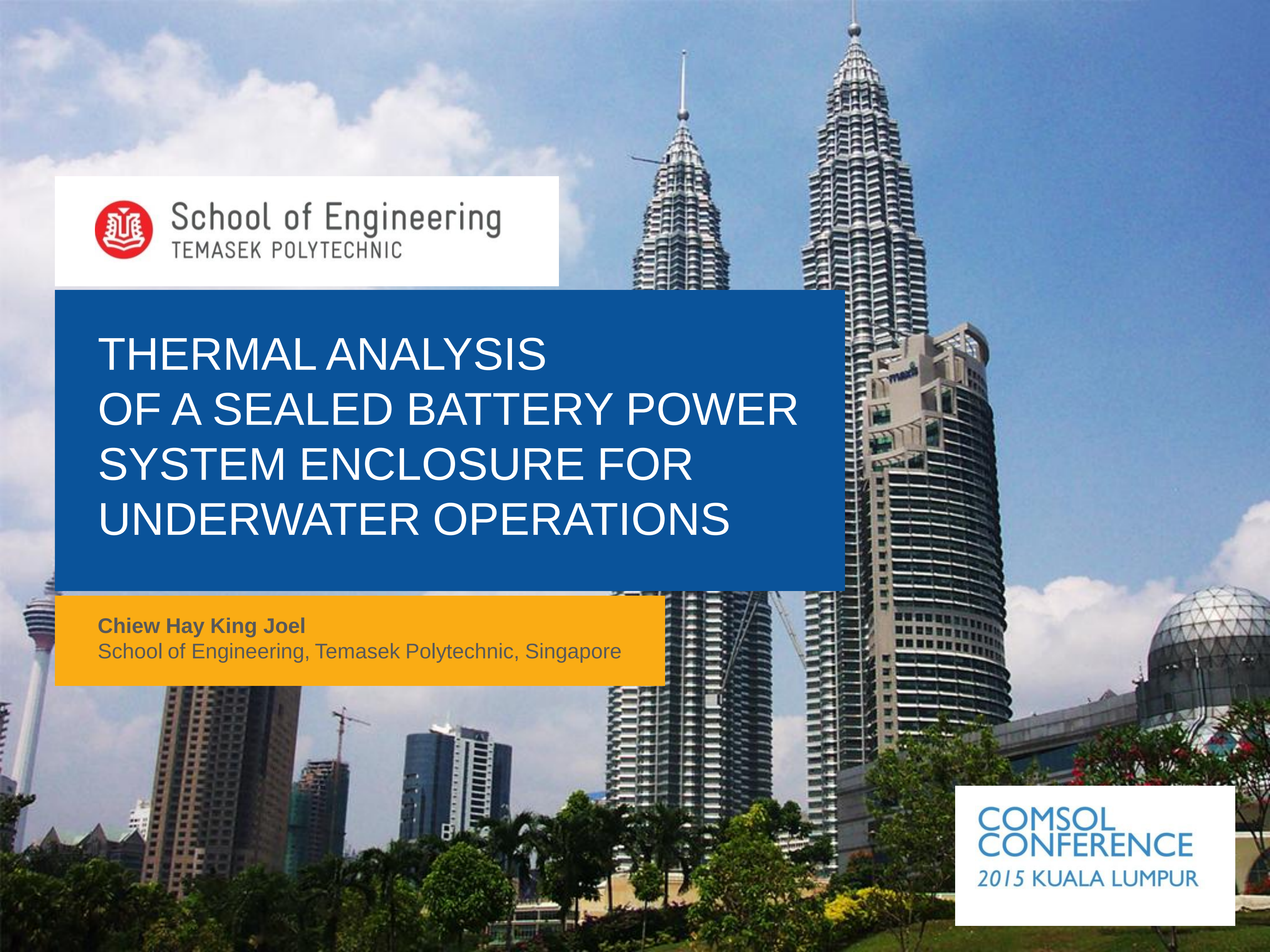

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THERMAL ANALYSIS OF A SEALED BATTERY POWER SYSTEM ENCLOSURE FOR UNDERWATER OPERATIONS

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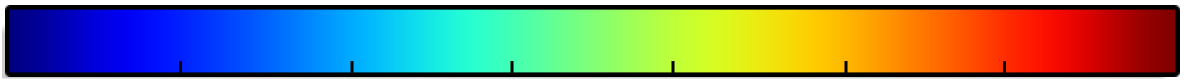
COMSOL CONFERENCE
2015 KUALA LUMPUR

BATTERY POWER SYSTEM

- To power unmanned underwater vehicle
- Completely sealed
- Rugged and safe during operations
- $LiFePO_4$ battery cells
- Maximum Operating temperature of 50°C

BATTERY THERMAL THEORY



HIGH TEMPERATURE

- Faster chemical reactions
- More power to be extracted
- Improves electron and ion mobility
- Reduces cell’s internal impedance
- Increasing cell’s capacity

HIGHER TEMPERATURE

- At upper end of scale
- Irreversible chemical reactions
- Loss of electrolytes
- Permanent damage
- Complete failure

THERMAL RISKS

BATTERY OPERATING AT HIGH TEMPERATURES

- Swelling of cell due to expanding chemicals
- Chemical reactions speed up
- Pressure build up in cell well due to gas production
- Cell may rupture and explode

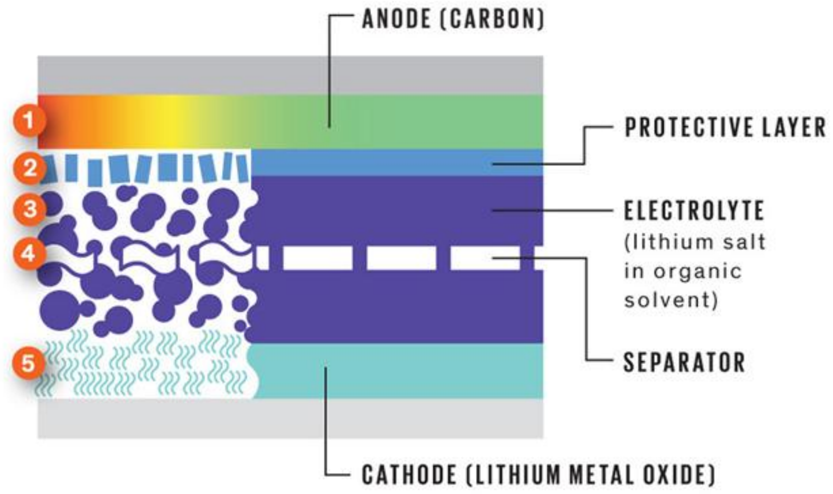
Burnt Batteries: http://www.komonews.com/news/boeing/Japan-787-probe-finds-thermal-runaway-in-battery-189836111.html

THERMAL RUNAWAY

- Destruction of battery by thermal energy
- Occurs when rate of heat generation has exceeded the battery’s limitation
- Continuous degenerative cycle

THERMAL RUNAWAY IN A LITHIUM-ION BATTERY

1. Heating starts.
2. Protective layer breaks down.
3. Electrolyte breaks down into flammable gases.
4. Separator melts, possibly causing a short circuit.
5. Cathode breaks down, generating oxygen.



Thermal Runaway : http://www.extremetech.com/extreme/208888-doping-lithium-ion-batteries-could-prevent-overheating-and-explosion

JOULE HEATING EFFECT

BATTERIES GIVE OFF HEAT VIA

- Thermochemical heating
- Joule heating

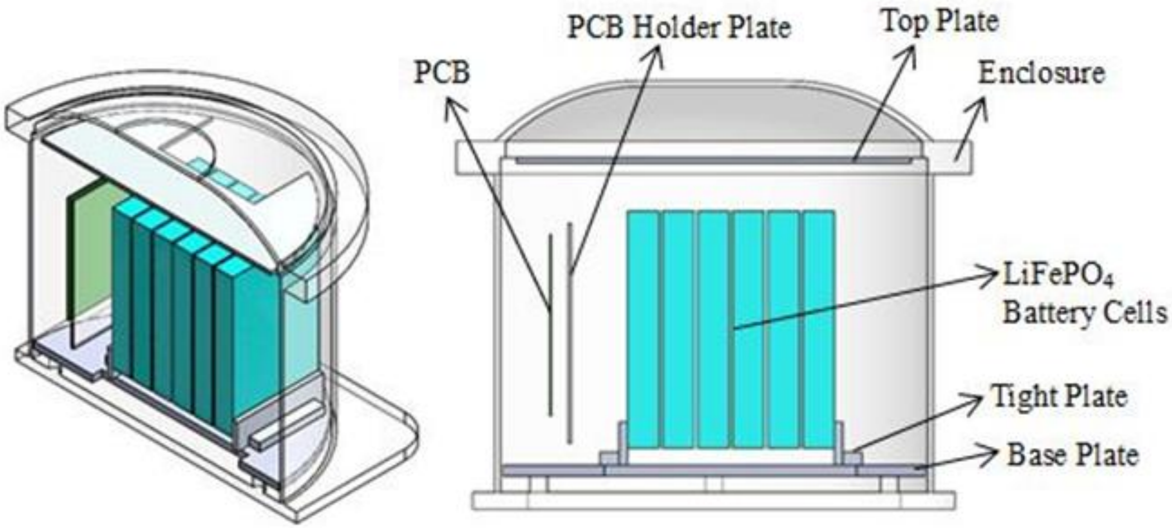
RESISTIVE LOSS OR OHMIC HEATING

OCCURS WHEN CURRENT FLOWS THROUGH A RESISTIVE ELEMENT

$$Q_{Joule} = I^2 Ri$$

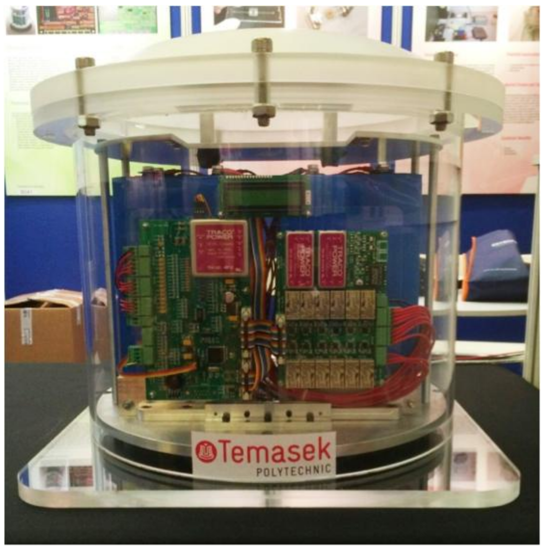
Where, *I* is the current (A) and *Ri* is the internal resistance of the battery (Ω).

CAD MODEL



- Designed in **SOLIDWORKS**
- Imported to **COMSOL Multiphysics**
- Symmetrical geometry – Symmetry function in COMSOL
- Reduces memory usage and computation time

PROTOTYPE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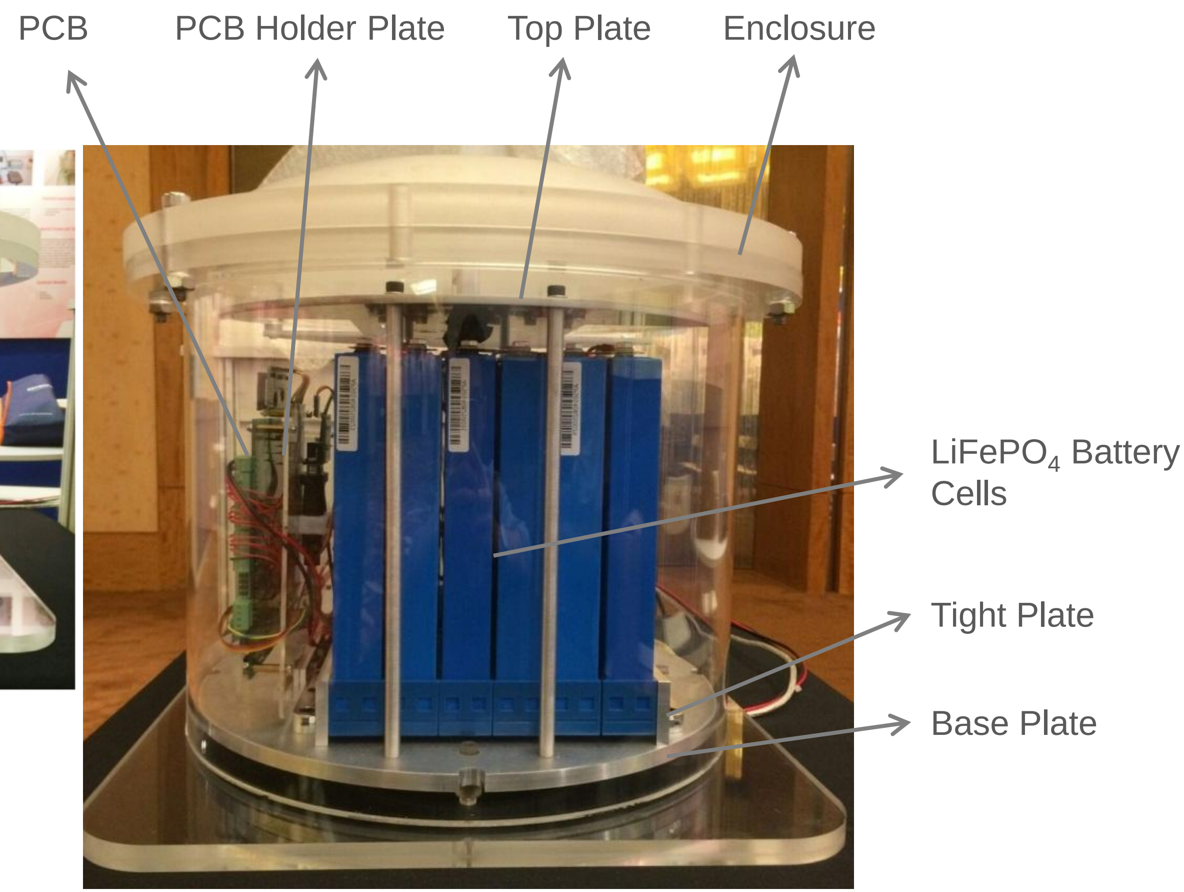
POLYTECHNIC


PCB
PCB Holder Plate
Top Plate
Enclosure
$LiFePO_4$ Battery Cells
Tight Plate
Base Plate

HEAT TRANSFER

TIME DEPENDENT HEAT TRANSFER EQUATION

$$\rho C_P \frac{\partial T}{\partial t} + \rho C_P \boldsymbol{u} \cdot \nabla T = \nabla \cdot (k \nabla T) + Q$$

Where, $\boldsymbol{\rho}$ is the density (kg/m^3), $\boldsymbol{C_P}$ is the heat capacity at constant pressure (J/kgK), T is the temperature (K), $\boldsymbol{u}$ is the velocity field (m/s), $\boldsymbol{k}$ is the thermal conductivity (W/mK) and $\boldsymbol{Q}$ is the heat source (W/m^3).

FLUID FLOW

NAVIER-STOKES EQUATION FOR A COMPRESSIBLE NEWTONIAN FLUID

$$\rho\left(\frac{\partial \boldsymbol{u}}{\partial t}+\boldsymbol{u}\cdot\nabla\boldsymbol{u}\right)=-\nabla p+\nabla\cdot\left(\mu(\nabla\boldsymbol{u}+(\nabla\boldsymbol{u})^T)-\frac{2}{3}\mu(\nabla\cdot\boldsymbol{u})\boldsymbol{I}\right)+\boldsymbol{F}$$

Where, $\boldsymbol{u}$ is the fluid velocity field (m/s), p is the fluid pressure (Pa), ρ is the fluid density (kg/m^3), μ is the fluid dynamic viscosity (Pa.s) and $\boldsymbol{F}$ is the volume force field (N/m^3).

Each term of the equation represents the inertia forces, pressure forces, viscous forces and the external forces applied to the fluid.

FLUID FLOW

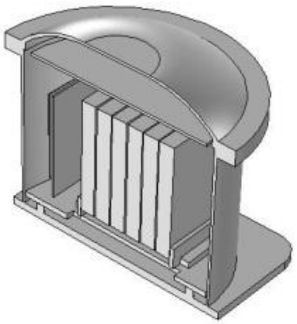
THE NAVIER-STOKES EQUATION REPRESENTS THE CONSERVATION OF MOMENTUM.
THE CONTINUITY EQUATION REPRESENTS THE CONSERVATION OF MASS.

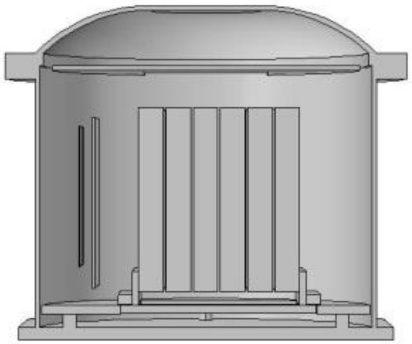
$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{u}) = 0$$

Where, $\boldsymbol{u}$ is the fluid velocity field (m/s) and ρ is the fluid density (kg/m^3).

THERMAL SIMULATION

CAD model in COMSOL





MATERIALS USED

Material	Phase	Thermal Conductivity, k [W/mK]	Heat Capacity, C_P [J/kgK]	Density, [kg/m^3]
Acrylic	Solid	0.18	1470	1190
Air	Liquid	Defined by piecewise functions, dependent on temperature		
Aluminum	Solid	238	900	2700
FR4 (Circuit Board)	Solid	0.3	1369	1900
$LiFePO_4$ (Battery)	Solid	1.58	1217	1950

THERMAL SIMULATION

BOUNDARY CONDITIONS

- Physics – Conjugate heat transfer
- Time dependent
- Simulation time of 10800 seconds, 60 seconds step size
- Initial temperature – 295 K
- Initial Pressure – 1 bar
- Heat source – 9.375 W
- Simulated effects of gravity – natural convection

THERMAL SIMULATION

ASSUMPTIONS

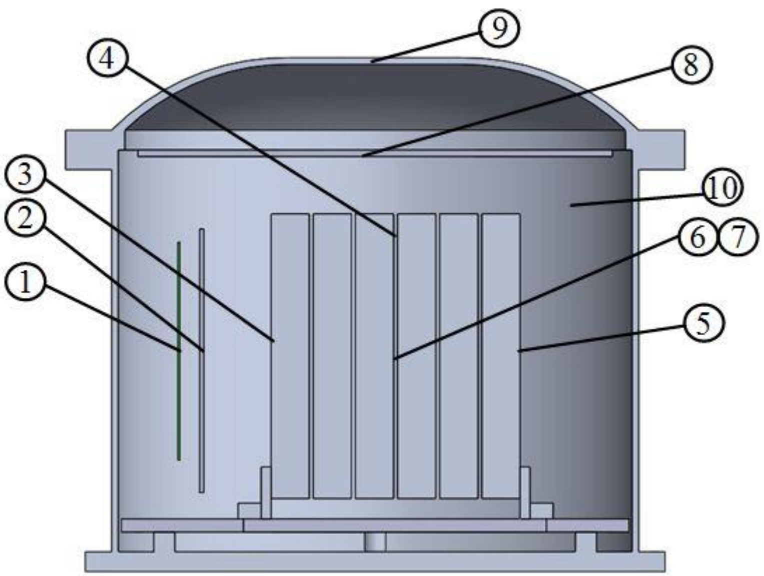
- Non-essential structural components removed
- Battery cell treated as a homogenous model
- Electrochemical heat generation not considered
- Heat generation from wiring and circuit board is ignored

EXPERIMENT

RESULTS USED TO VALIDATE ACCURACY OF SIMULATION

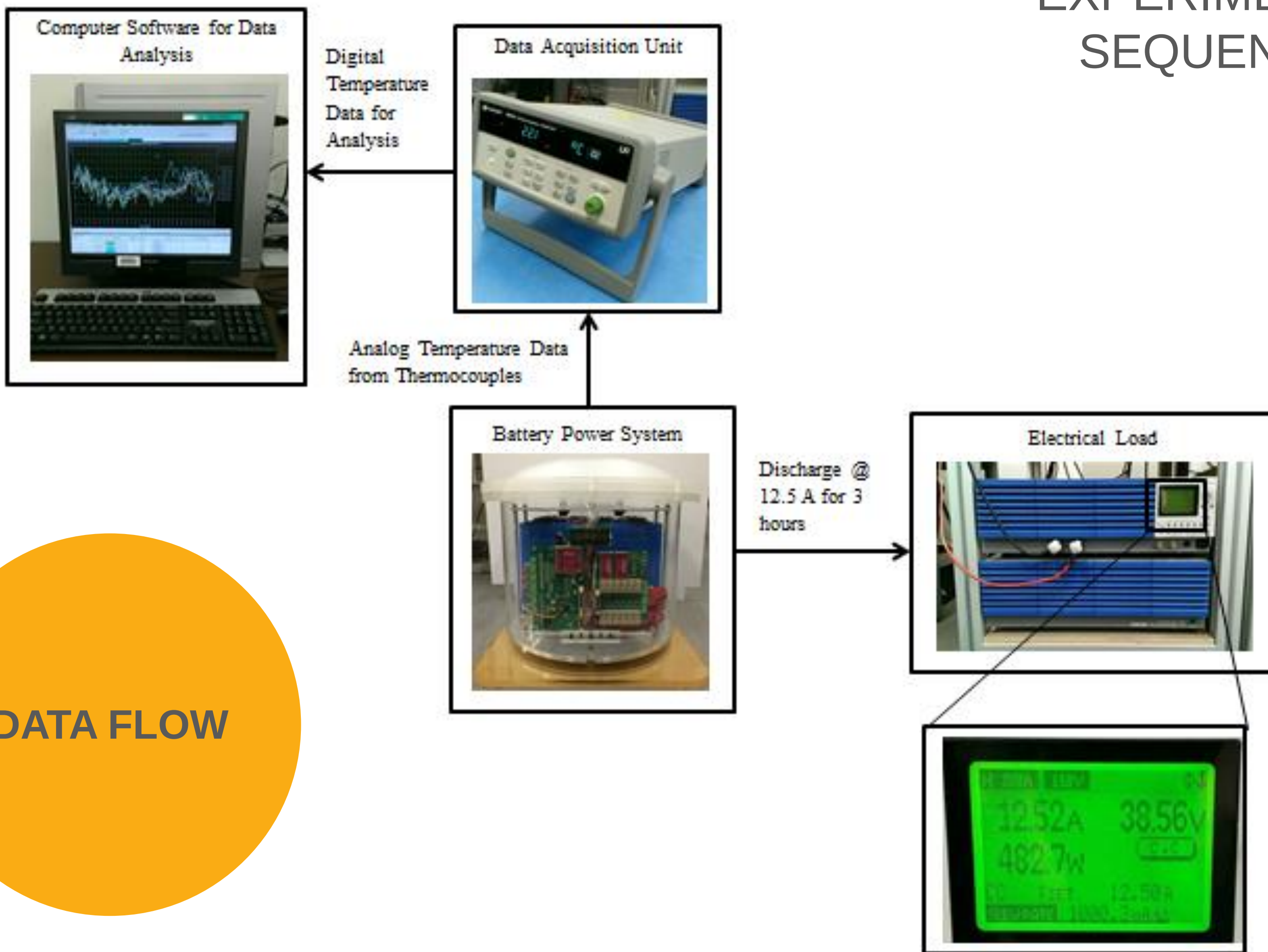
EXPERIMENT

LOCATION OF THERMOCOUPLES



Thermocouple Measuring Points	
N.O.	Location
1	PCB
2	PCB Holder Plate
3	Battery Cell 1
4	Top of Battery Stack
5	Battery Cell 6
6	Between the Battery Stacks
7	Between Battery Stack and Enclosure
8	Top Plate
9	Cover
10	Air Temperature Inside the Enclosure

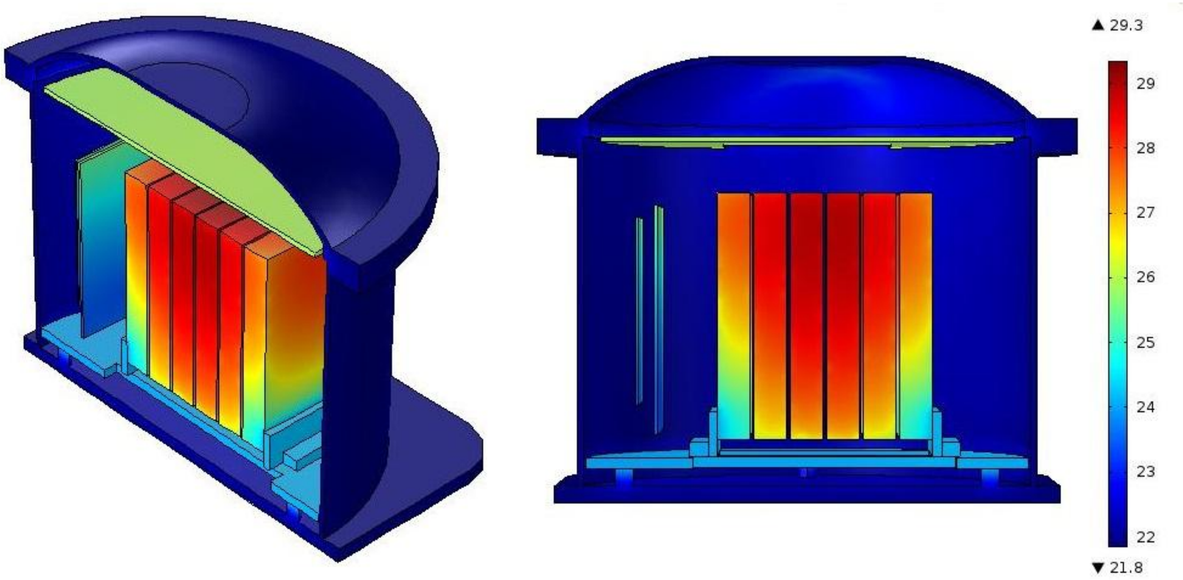
EXPERIMENT SEQUENCE



DATA FLOW

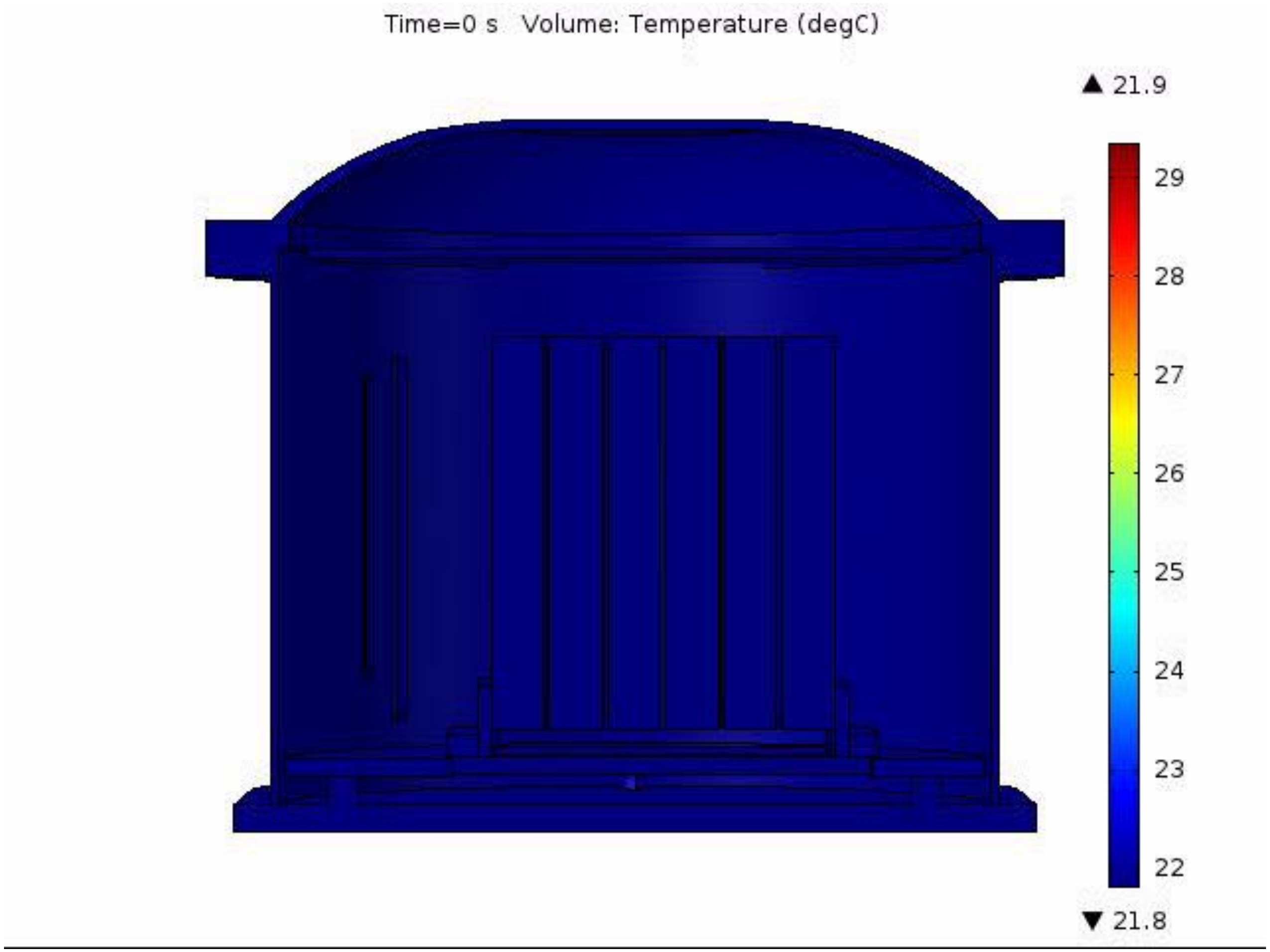
THERMAL SIMULATION RESULTS

TO DETERMINE THE MAXIMUM TEMPERATURE AND DEFINE ITS LOCATION



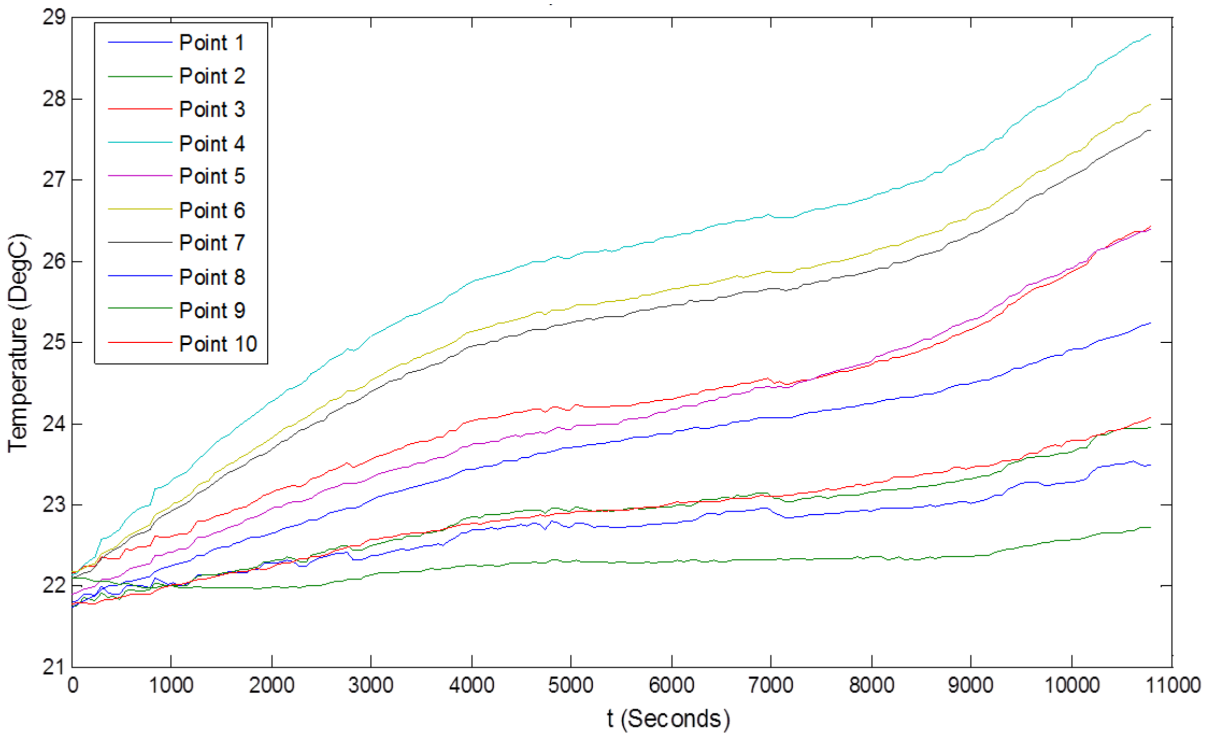
Maximum Temperature = 29.3°C

THERMAL SIMULATION RESULTS



EXPERIMENT RESULTS

TO VERIFY AND DETERMINE THE ACCURACY OF THE THERMAL SIMULATION



Maximum Temperature = 28.8°C

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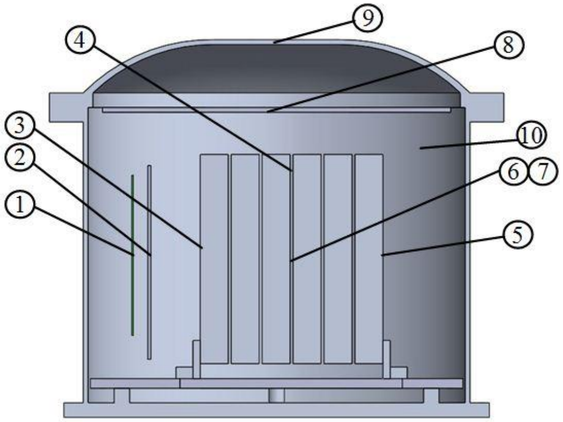
COMPARISON OF RESULTS

MAXIMUM DATA EXTRACTED FOR EACH DATA POINT

Data Points	Simulation (°C)	Experiment (°C)	Error (°C)	Error (%)
1	24.2	23.5	0.7	3.0
2	24.2	23.9	0.3	1.3
3	27.1	26.4	0.7	2.7
4	29.3	28.8	0.5	1.7
5	27.1	26.4	0.7	2.7
6	28.0	27.9	0.1	0.4
7	28.3	27.6	0.7	2.5
8	25.9	25.2	0.7	2.8
9	22.5	22.7	0.2	0.9
10	25.1	24.1	1.0	4.1

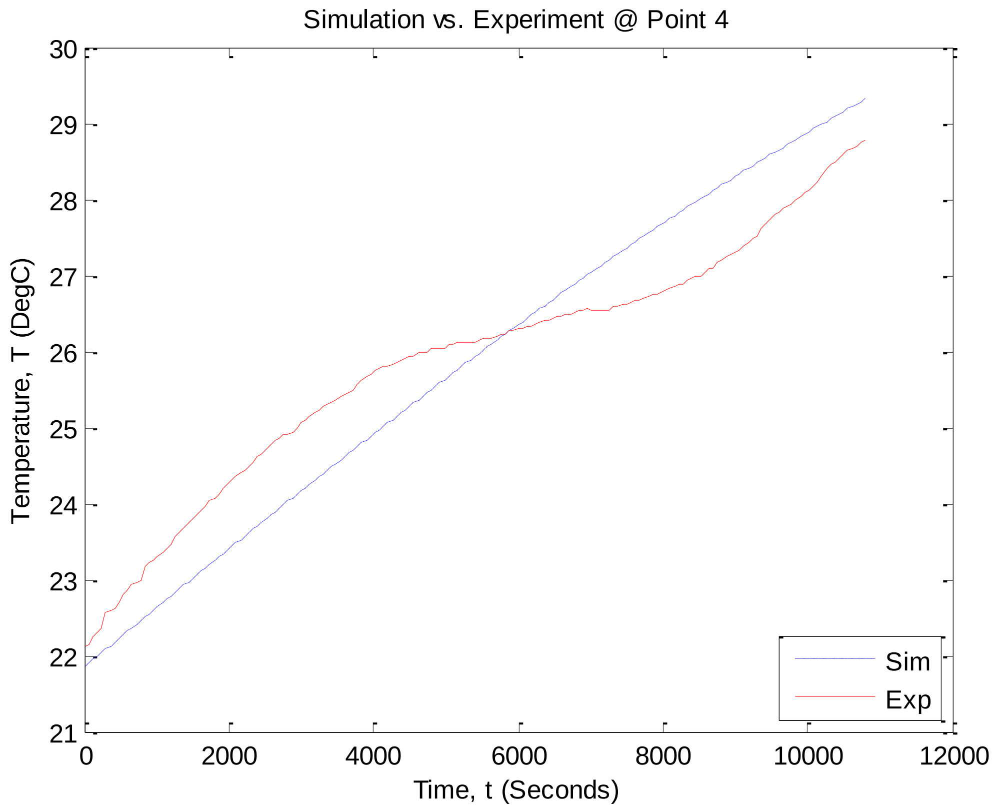
Mean Error (%)	**2.21**
Standard Error of the Mean (%)	**0.35**
Root Mean Squared Error (%)	**2.45**



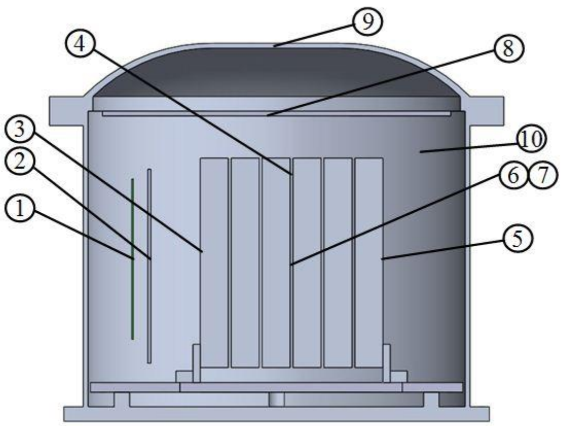
Marginal and acceptable error

COMPARISON OF *RESULTS*

MAXIMUM TEMPERATURE – POINT 4



Method	Temperature
Simulation (℃)	29.3
Experiment (℃)	28.8
Error (℃)	0.5



SUMMARY

- Maximum temperature during discharge cycle is lower than the safe working temperature of 50℃
- Battery power system capable of operating continuously for 3 hours without exceeding the temperature limit
- Validation of simulation results
- Capability of using the COMSOL simulation model for subsequent thermal simulations

FUTURE WORKS

- Implementation of thermal management via phase change material (PCM)
- Addition of temperature feedback control system

THANK YOU!

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