Micro-sources of energy for wireless sensor applications

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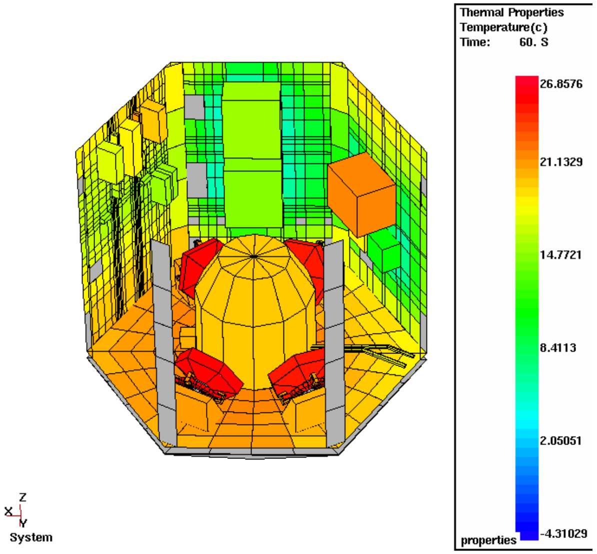
Outline

- Energy source available on-board a spacecraft
- Characterization of the commercial thermo-generator
- Characterization of the CEA batteries
- Conclusion and perspectives

Thermal environment on-board a spacecraft

❑ Thermal mapping for a LEO spacecraft

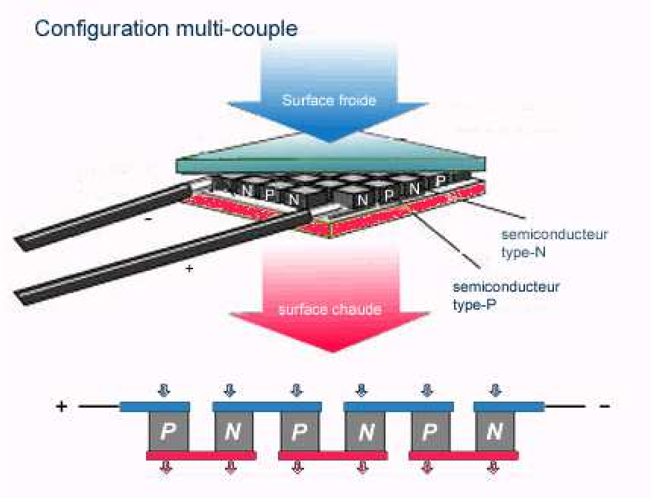
	Average orbital T° (°C)	Radiative sink T° (°C)	Delta T° (°C)
lowest T° structure or equipment	-4	19	**-23**
highest T° structure or equipment	35	19	16
Power distribution unit	27	19	8
On board computer	25	19	6
DCU	24	19	5
Transponders	20	19	1
payload video unit	35	19	16
Batteries	10	19	-9
RIU	32	19	13
Wheels	26	19	7
TWTs	14 to 22	19	-5 to 3
External radiator -x,+Y T°	18	-69	**87**
External radiator +Y T°	18	-50	68
External radiator +x,+Y T°	9	-69	78
External radiator -x,-Y T°	19	-33	52
External radiator -Y T°	-5	-88	83
External radiator -x,-Y T°	15	-59	74



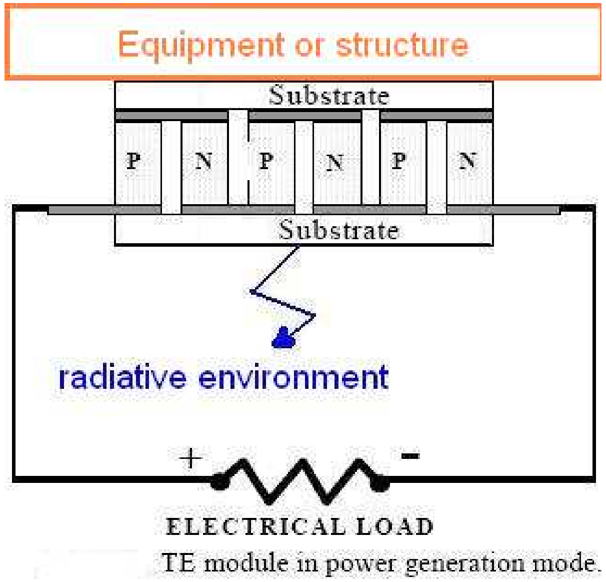
❑ Thermal gradient close to 23°C inside the spacecraft and 87°C outside the spacecraft

Supplier data

- Thermoelectric devices: direct energy conversion from thermal energy (T gradient) into electrical energy (Seebeck effect)



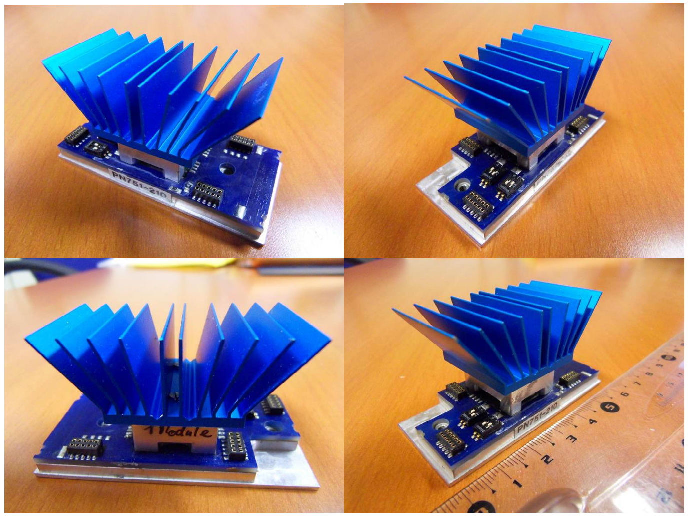
- The more realistic way to use the thermoelectric device

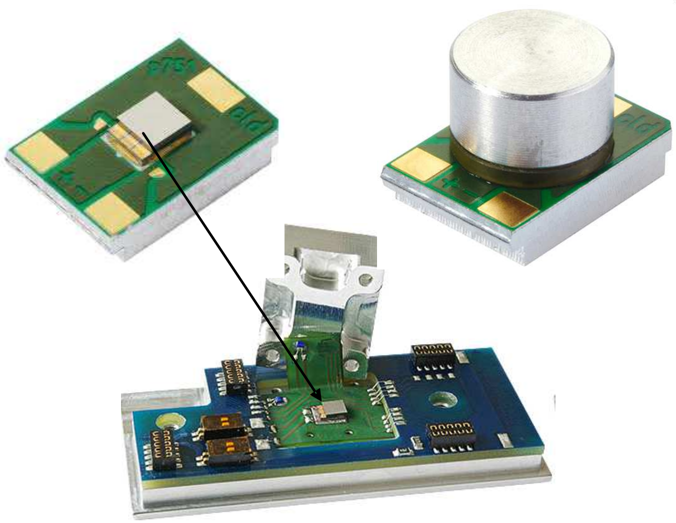


TE module in power generation mode.

Characterization of a commercial TEG

❑ The thermoelectric device : Micropelt





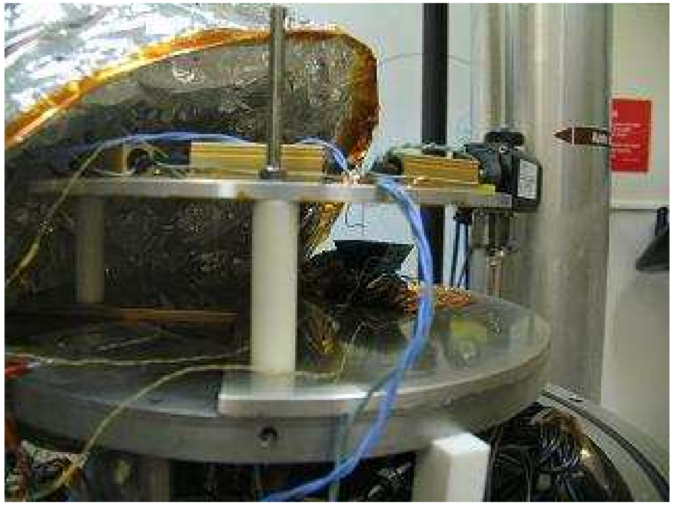
Dimensions	Base Total height incl. standard heat sink Weight	27 mm x 60 mm 33.5 mm 51g
Electrical characteristic of TGP 751 (neat)	Thermal resistance R Seebeck voltage Electrical resistance	18K / W 110mV / K (T_{amb} = 25°C) 240 to 350Ω (typical 300 Ω)
Operating temperature	For TGP751 (neat) For the module - Substrate side - Ambient side	[-40°C; + 140°C] Max. 105°C Max. 85°C

Supplier data

Characterization of a commercial TEG

ΔTap = Ts(ubstrate) – Ta(mbient)

- ❑ **Evaluation of the electrical performances under vacuum (10^{-4}mBars)**
  - ✓ Conventional measurements at Ta = 20°C and 50°C
    - In open circuit
    - On calibrated resistances:
    - ⇒ 100Ω, 250Ω, 450Ω, 750Ω and 900Ω
  - ✓ In dynamic conditions
    - Controlled-computer power alimentation



Characterization of a commercial TEG

ΔTap = Ts(ubstrate) – Ta(tmosphere)

❑ Experimental conditions and devices used in vacuum

- ✓ Ts managed
  - ✓ By a thermo-regulated plate: -15°C → 30°C
  - ✓ Several thermocouples on the heat sink of the TEG, on the plate, …
- ✓ Ta fixed
  - ✓ By a plate equipped with heating resistances above the TEG
  - ✓ Regulation ensured by a "floating" thermocouple
- ✓ Thermal isolation by MLI coverage improved at each new set up
- ✓ For various ΔT, measurements of :

Multimeter multichannels {

  - ✓ U = output voltage of the TEG
    - ✓ via **the plug-on module for the conventional measurements**
    - ✓ Via **the booster module for the test in "dynamic conditions"**
  - ✓ Rb(ottom) = resistance of the PT100 embedded on the basis of the TEG → T1
  - ✓ Rt(op) = resistance of the PT100 embedded on the TEG top → T2
  - ✓ Ts = temperature of the heating or cooling plate by a thermocouple put above
  - ✓ Ta = temperature of the atmosphere by a thermocouple
- ✓ Inversion of the heat flux is possible ➔ the polarity of the TEG reverses

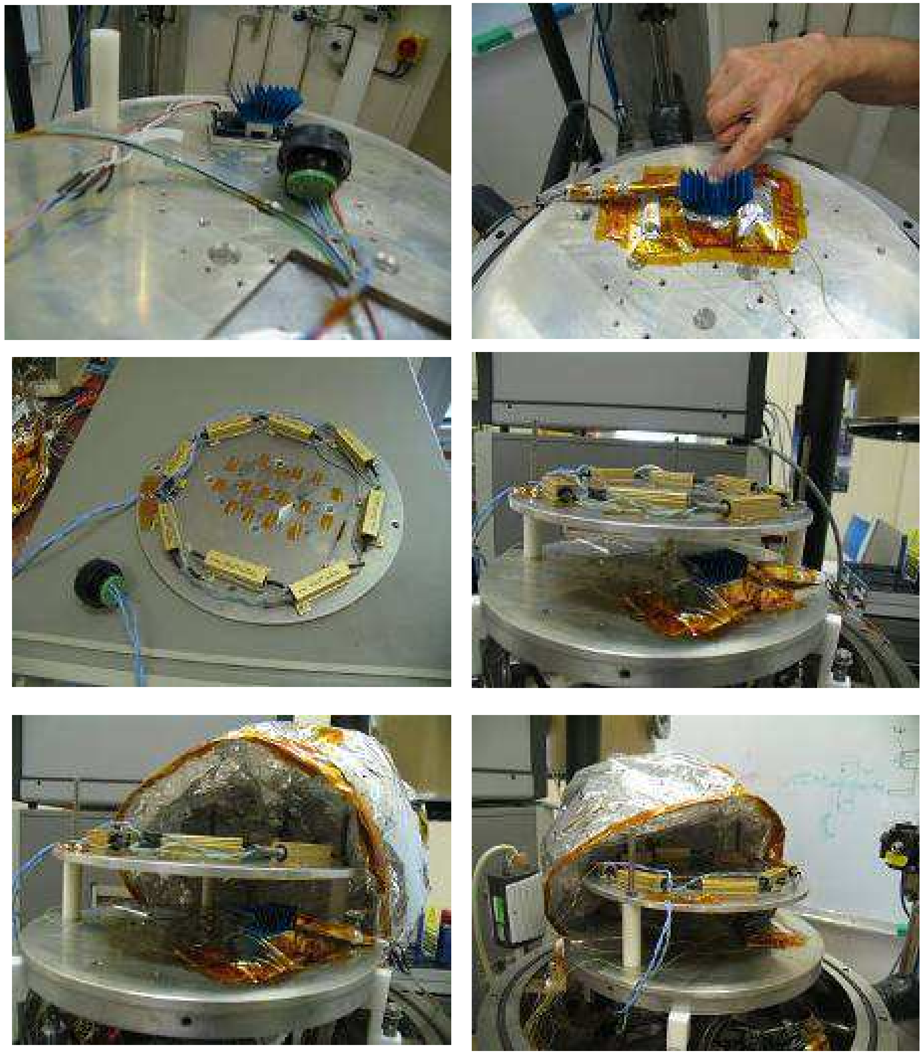
➔ necessity to switch manually the TEG output polarity when the sign of ΔTap changes ➔ not automatic !

Characterization of a commercial TEG

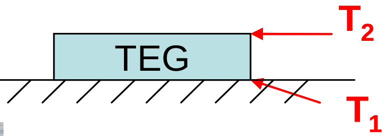
$\Delta T_e = T_1 - T_2$

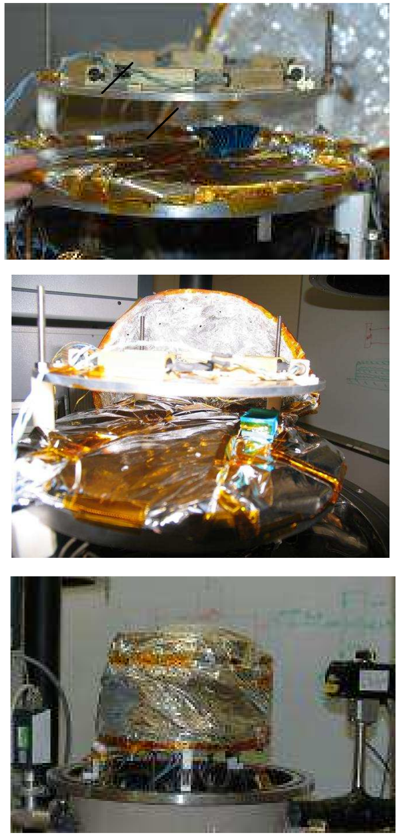
Tests under vacuum (CNES), $U = f(\Delta T_e)$

at 20°C



at 50°C



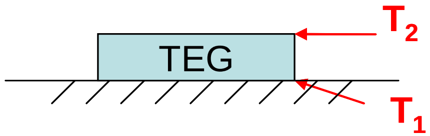


Characterization of a commercial TEG

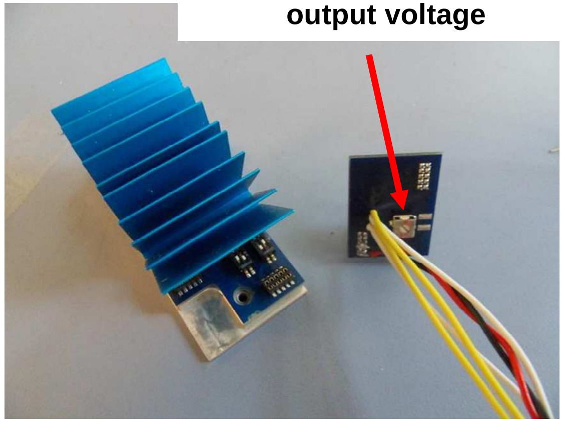
Tests under vacuum (CNES), dynamic conditions

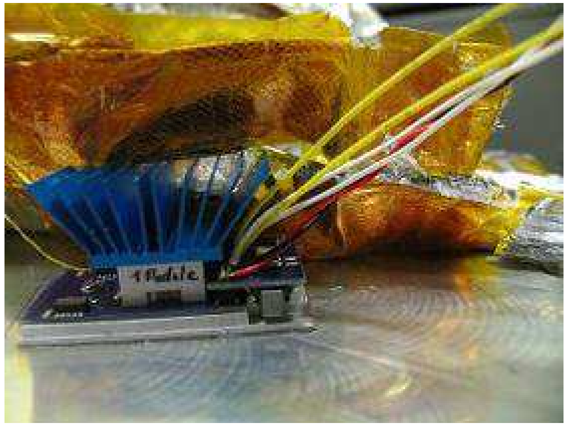
$\Delta T_e = T_1 - T_2$

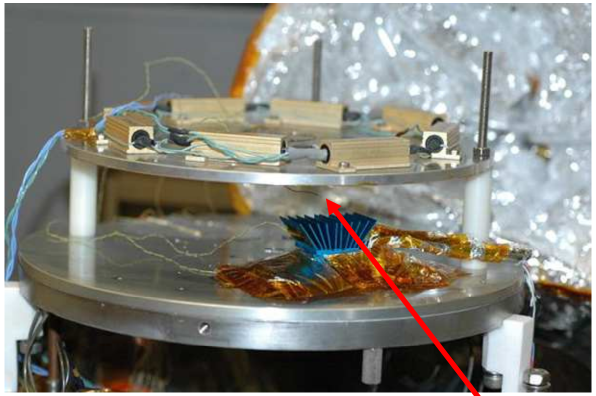
Ta = 50°C, Ts = -10°C, P ~10^{-4}mBars

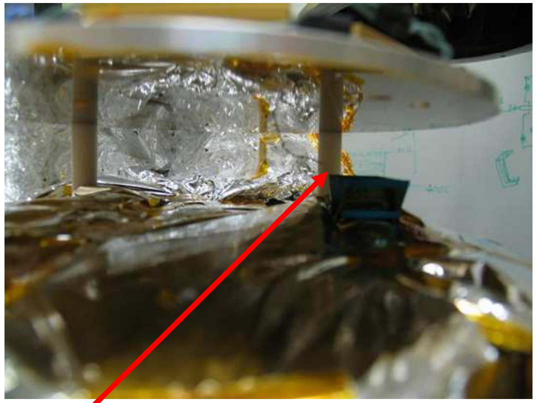


Potentiometer for adjusting the constant output voltage





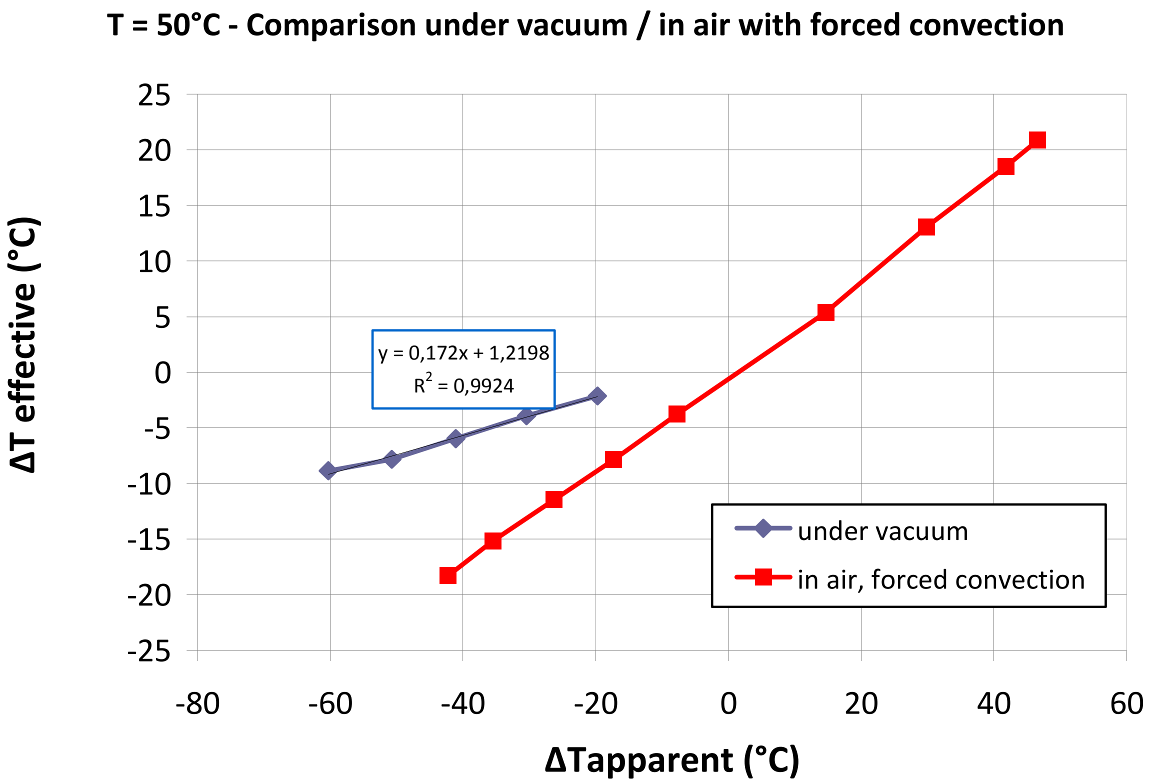




Position of the floating thermocouple

Characterization of a commercial TEG - results

Apparent and effective thermal gradient $\Delta Tap = Ts - Ta$ and $\Delta Te = T_1 - T_2$



➔ in vacuum, a very high apparent gradient is needed to reach equivalent ΔTe, compared to in air

For ΔTe = -8°C, Ts = 30°C in air and -10°C under vacuum at Ta = 50°C

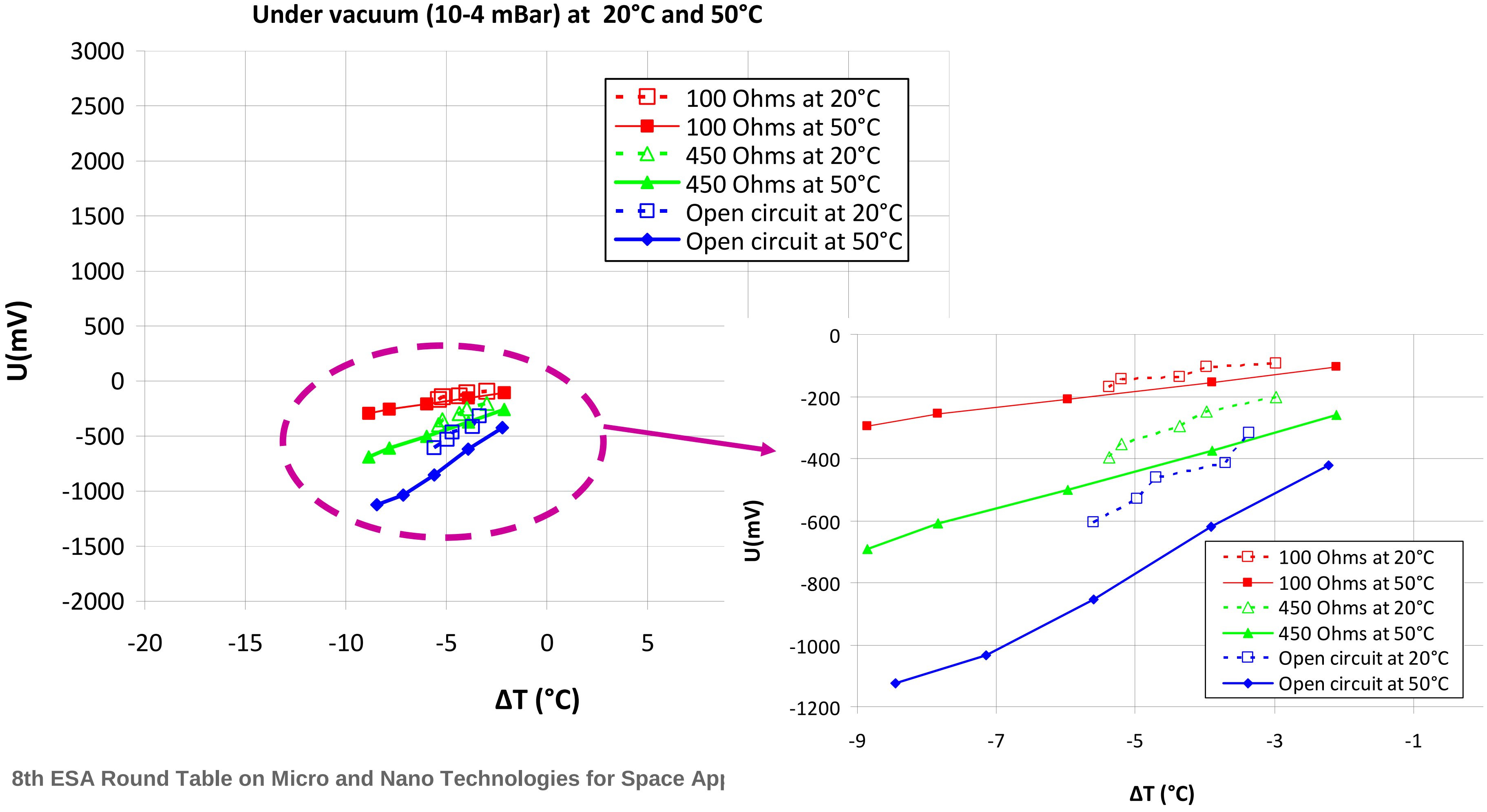
Characterization of a commercial TEG - results

Behaviour under vacuum (10^{-4}mBars) – static conditions ΔT = T1 – T2

➔Restricted domain of ΔT, so U compared to in the air

➔ similar performances at 20°C and 50°C

Under vacuum at 20°C and 50°C,
In open circuit and on load,



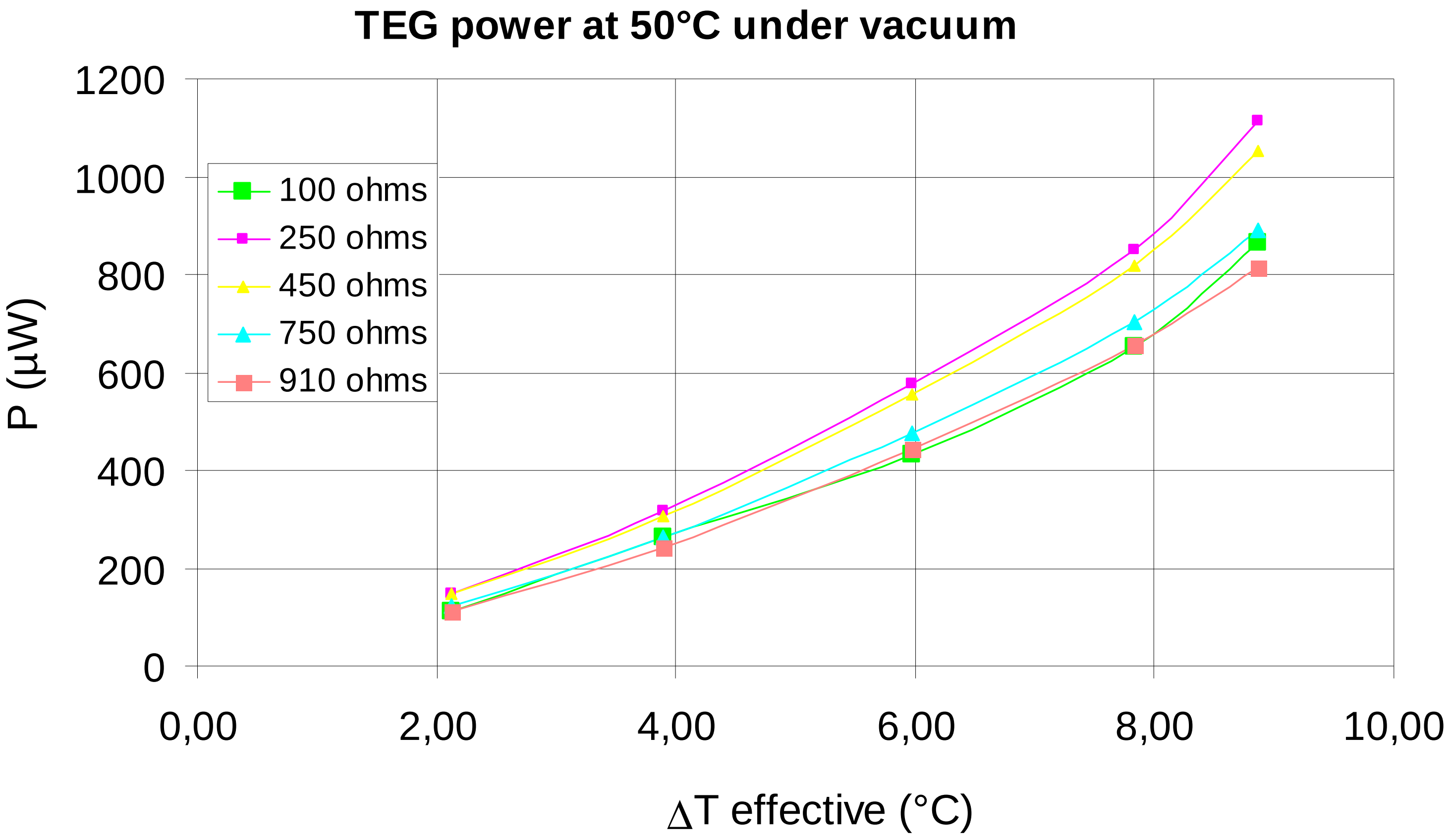
Characterization of a commercial TEG - results

Behaviour under vacuum (10^{-4}mBars) – static conditions

ΔT = T1 – T2

- ➔ **thermoelectric power of 100mV/K (supplier data: 110mV/K)**
- ➔ **Max output power developed at 50°C on R = 250 - 450Ω with ΔT = 9K➔ 1.1mW**

Compatible with supplier data



Characterization of a commercial TEG - results

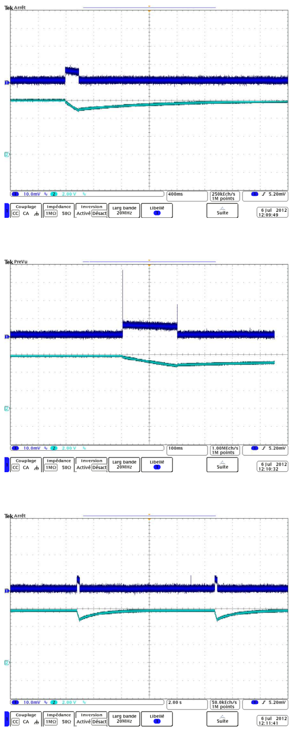
Behaviour under vacuum (10^{-4}mBars) in "dynamic conditions"

$\Delta T = T1 - T2$

➔ when $I_p < 5$mA, voltage drop but back to the base line of 6V

One current pulse per 10s
$\Delta t_{pulse} = 200$ms
Base line: 6V

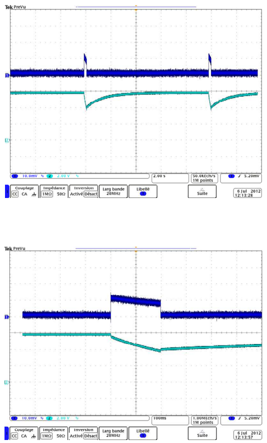
$I_p = 0.5$mA



$\Delta U = - 1$V

$\tau = 2$s

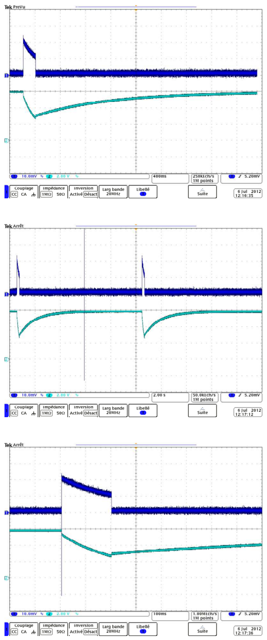
$I_p = 1$ mA



$\Delta U = - 2$V

$\tau = 4$s

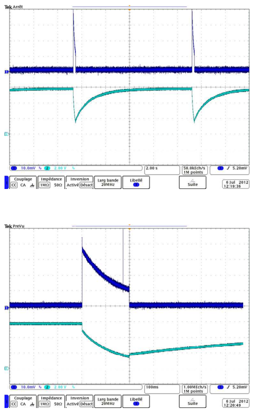
$I_p = 2$ mA



$\Delta U = - 3$V

$\tau = 3.2$s

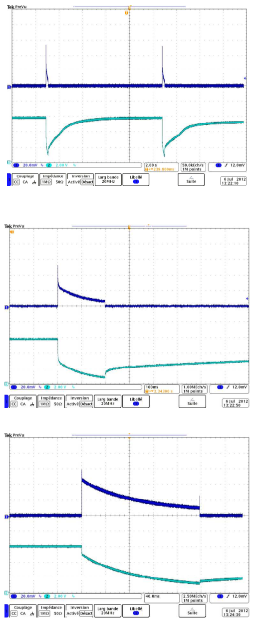
$I_p = 4$ mA



$\Delta U = - 4$V

$\tau = 5$s

$I_p = 5$ mA



$\Delta U = - 5$V

$\tau = 5$s

Ta = 52.5°C

Ts = -10.3°C

ΔTap = 62.8°C

$\Delta T = 9.8$°C

$U_0 = 4.1$V

Characterization of a commercial TEG - results

Behaviour under vacuum (10^{-4}mBars) in "dynamic conditions"

$\Delta T = T1 - T2$

➔ the TEG unit equipped with the booster module is capable to answer to pulses of ~ 10mW

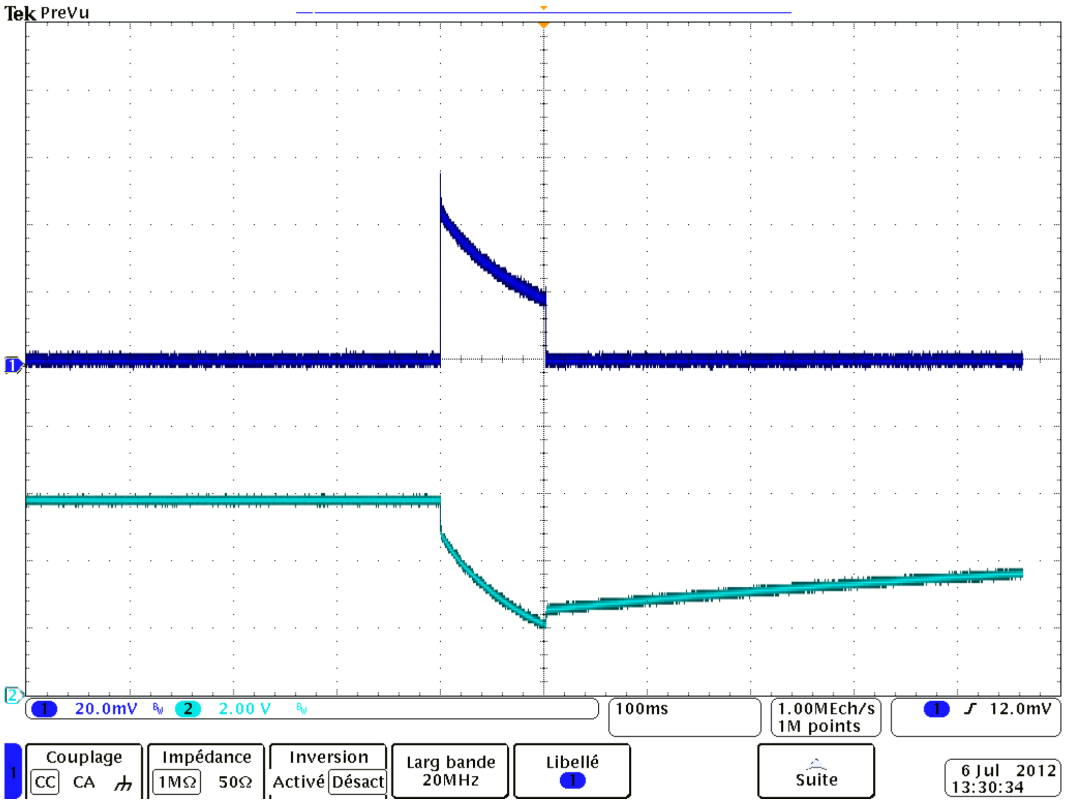
Ta = 52.5°C

Ts = -10.3°C

ΔTap = 62.8°C

$\Delta T = 9.8$°C

$U_0 = 4.1$V



One current pulse per 10s
I_{pulse} = 5mA
Δt = 100ms
Base line: 6V

$I_{average}$ ~ 3mA

$U_{average}$ ~3.2V

P ~10mW in pulse

Characterization of the CEA batteries

☐ Typical specifications of the CEA batteries

Technology	**NCA / Graphite** (CEA electrodes)
Nominal Capacity (mAh)	450
Nominal voltage (V)	3.6
Nominal Energy (Wh)	1.62
Cut-off Voltages (V)	3.0 - 4.0
Internal Resistance (mΩ)	175
Overall dimensions without pins (mm)	30 x 30 x 8.4
Volume (cm^3)	7.6
Mass (g)	15.5
Volumetric Energy Density (Wh/L)	213
Gravimetric Energy Density (Wh/kg)	105

✓ Stored in cold chamber (-6°C) since September 2010

✓ 4 batteries selected from their nominal capacity and their level of hermeticity (for sustaining the test in vacuum)

↳ PR028, 036, 038 and 044

CEA battery	PR028	PR036	PR038	PR044
Nominal capacity (mAh)*	471	475	495	400

* Before storage at 6°C

Characterization of the CEA batteries

Cycling tests under vacuum (2. 10^{-5}mBars) , Ta = 27°C (not regulated)

❑ The protocol of the cycling tests

- Cut off voltage : 3.0 and 4.0V
- Discharge and charge rates applied:
  - 3 cycles at C/10-D/10 ⇔ 60h
  - 4 cycles at C/5-D/5 ⇔ 40h
  - 4 cycles at C/2-D/2 ⇔ 16h
  - 5 cycles at C/2-D ⇔ 15h
  - 8 cycles at C/10-D/10 ⇔ 160h

9 days

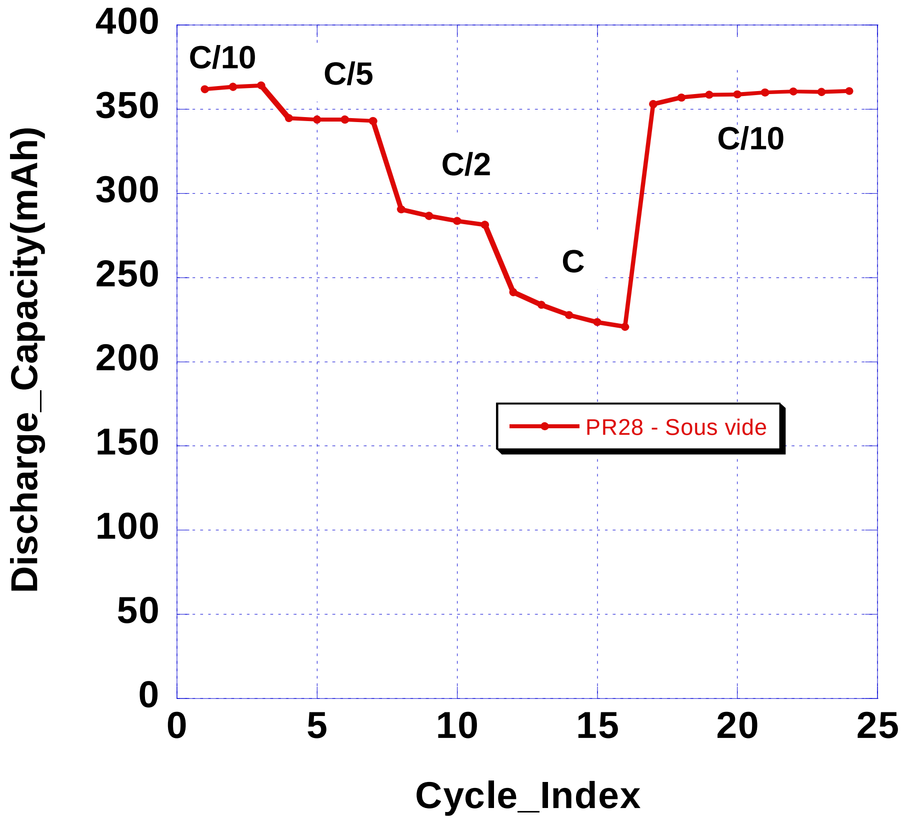
PR028 and 036

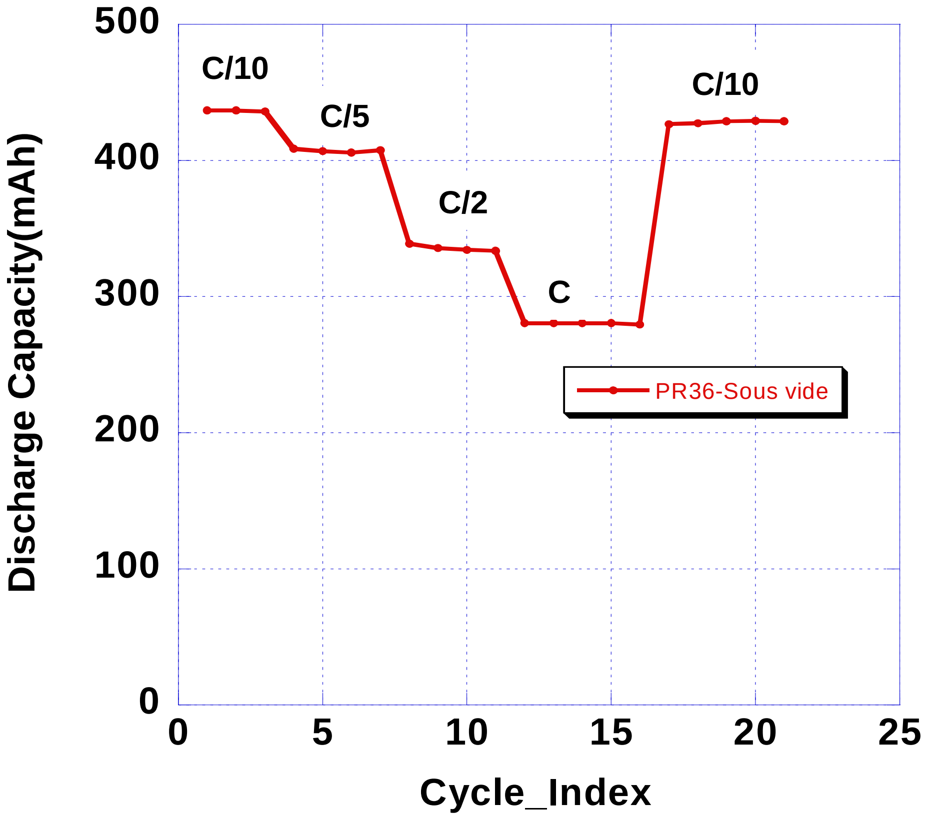
- Measurement of the internal resistance during the cycling tests

Protected in MLI coverage

Characterization of the CEA batteries - results

Cycling performances under vacuum

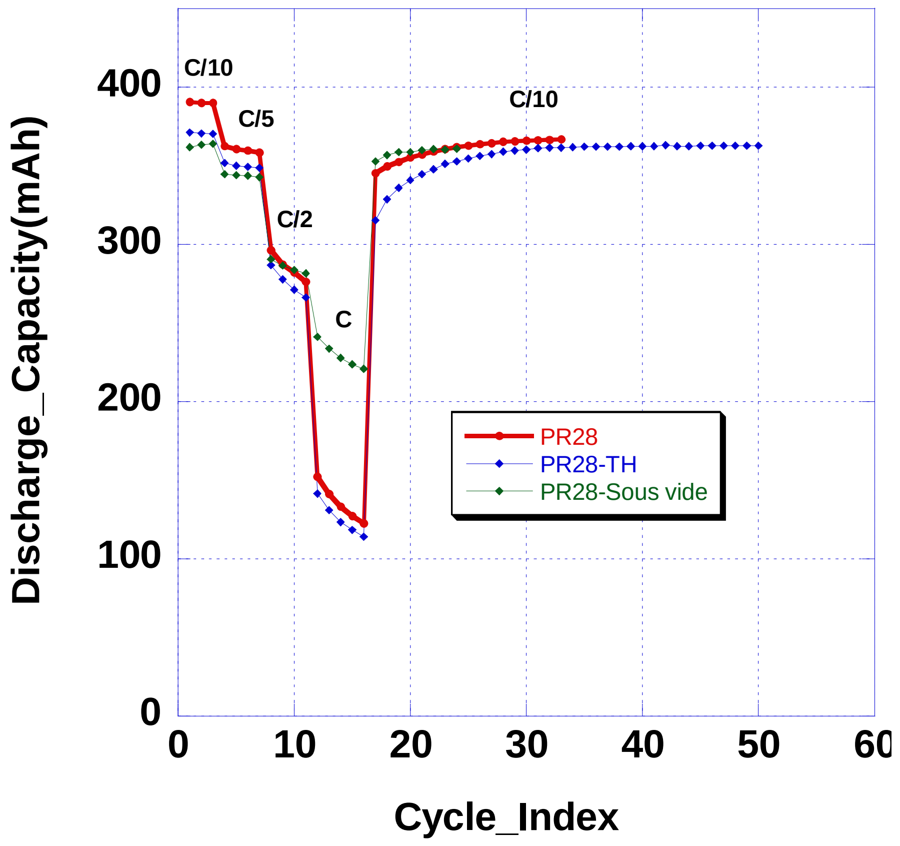


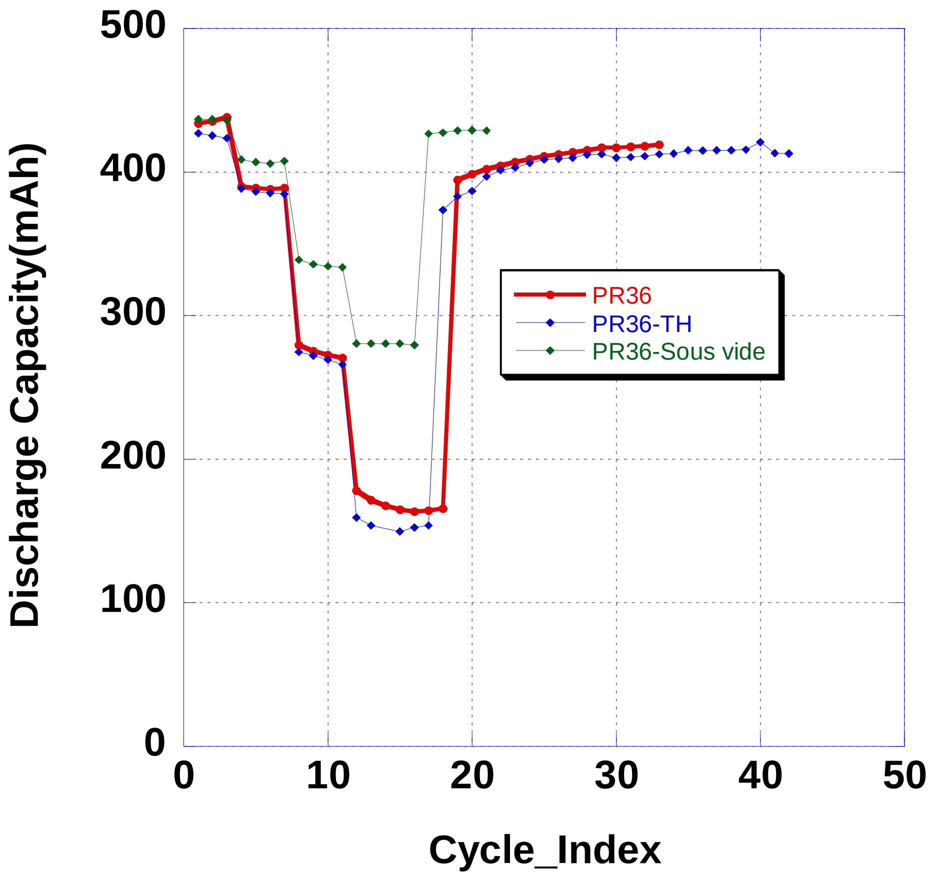


Relevant performances (in particular PR036)
→ similar capacity at low rates up to C/2 rate
→ higher capacity at higher rate

Characterization of the CEA batteries - results

Cycling performances in air before and after the thermal cycling and under vacuum





Promising performances under vacuum

→ effect of internal pressure ?

→ effect of $T_{ambient}$ = 27°C ?

PR028 and 036 resistant towards vacuum and thermal conditions

Conclusion and perspectives

- ❑ Held of the TEG and the batteries to vacuum and thermal conditions OK
  - ➢ electrical performances similar, even better than in air for the batteries
  - ➢ TEG : 100mV/K, max 10mW in pulse (under ΔT_{ap}= 60°C)
  - ➢ Batteries : 370 to 420mAh at C/10 – Up to ~300mAh at C

- ❑ To improve the local gradient of the TEG ➔ to improve the output power
  - ➢ To analyse a TEG unit without the heat sink → heat thermal model and association in series and/or in // of several TEG chips
  - ➢ To equip the thermal chamber (thermal screens) for a best management of the thermal environment

➔ ***test of evaluation in these new improved conditions***

- ❑ To propose another Li-ion technology with reduced working potential range
  - ➢ Based on another technology → 1.9V or 2.3V
  - ➢ Lower nominal capacity in rigid casing for vacuum (TVM, laser welded) → 20mAh? or less
  - ➢ Evaluation in cycling in space environment

➔ ***evaluation of the coupling small battery / TEG / Ultra Low Voltage Power Management***

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Thank you for your attention