A long lifetime power source
- the radioisotopic battery

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Motivation

- >3 billion litres/day water leaks
- Buried pipe monitoring
- Sensor needs long term power
  - High replacement cost
  - Water pipes in ground for more than 100 years
  - Realistically power source needs to last 20+ years
- Harsh environment
- Maintain integrity of pipe
Power requirement

- Low measurement duty cycle
  - Spot measurements
  - once per day, once per hour
- Sensor nodes require
  - mW whilst transmitting
  - Very low average power 10’s μW
- Ideally: High energy density, low power density
Power source options

- Regenerative
  - Kinetic (vibration, fluid flow)
    - Piezoelectric
    - Electromagnetic
    - Electrostatic
  - Thermal
  - Electrochemical
- Non-regenerative
  - Micro-engines
    - Micro-IC
    - Micro-Fuel Cell
    - Micro-Turbine
  - Radioisotopic
    - Thermal
    - Non-thermal
Power source options - limitations

- Li-ion – can’t be sealed, max 20year lifetime
- Solar power – obviously not an option
- Thermoelectric – very small temperature differences
- Water turbine/flow harvester – integrity of pipe
- Fuel cells – limited lifetime/thermal losses
- Induction from surface – location dependent
- Vibration – location dependent, sporadic
- Radioisotopes?
Radioisotopes

- Same number of protons in their atomic nuclei but **differing numbers of neutrons.**
- Release energy when decay into a more stable form - $\beta$, $\gamma$ radiation
- Decay at different rates
  - half life : Minutes – 1000’s years
  - Opportunity for long term power
- e.g. Uranium-235, radium-226, Carbon-14, Tritium, Americerium-241, Nickel-63, Plutonium-238
Radioisotopic power sources

Advantages relative to conventional batteries

- Very high energy density
- Very long life (potentially) – isotope dependent
- Continuous operation devices
- No (or very few) moving parts
- Very little sensitivity to environmental changes
- High reliability
- Scalable to microns (generally)

Seem ideal !
Uses of Radioisotopes

Smoke detectors – Am241

Self powered emergency signs

Pacemakers 70’s

Batteries - University of Missouri 2009

RTG from Apollo 14 mission to the moon (NASA, 1971)

Pellet of Pu-238 (US Department of Energy)

Jae Wan Kwon, University of Missouri, 2009

NASA – since 1961

University of Missouri 2009

Pacemaker powered by Pu-238 decay (1974)
Non-thermal radiisotopic energy conversion

- **Direct Charge**
  - High Voltage (100kV+)
  - Low Current (< 100nA)

- **Direct conversion**
  - Low voltage (5V), higher current (0.1mA)
  - Semiconductor suffers radiation damage
Indirect conversion (ICRB)

Decay particle → Light → Electricity

How do we produce a phosphor coated radioisotope?
Gaseous Tritium Light Sources (GTLS)

- **Commercially available fishing lures!**
- A transparent glass tube having a thin layer of a scintillating agent coated to its inside walls (normally a phosphor)
- Pressurized Tritium (3H) is injected into the tube which is then sealed at both ends

\[
\text{Tritium } ^3\text{H } \rightarrow ^3\text{He} + \beta^- + \text{anti-neutrino}
\]

- Beta radiation from Tritium can travel 6mm in air, 6μm in water, and will not penetrate the dead layer of skin on humans
GTLS device regulation

- Environmental Protection, England and Wales: The Environmental Permitting (England and Wales) Regulations 2010

- 1000GBq limit for a device made of these sources

- Single ones 20GBq

- If contaminate ground water health consequences of ingesting tritium in the form of tritiated water

- Disposal route depends on amount
Prototype GTLS battery

a) 3D printed casing
b) reflective coating (Au or BaSO$_4$)
c) PV cells and GTLS Capacitor
Testing battery performance

Test circuit for ICRB battery testing
Charge 1\(\mu\)F Al Electrolytic capacitor

\[
p = \frac{1}{2} C (\Delta v)^2 \frac{\Delta t}{\Delta t}
\]
Battery configuration test

- Different GTLS/PV cell configurations investigated
- Harvested power compared

Charging curve
### Battery power testing results

#### Comparison of battery configurations

<table>
<thead>
<tr>
<th>PV cell type</th>
<th>PV cell dimensions (mm)</th>
<th>Reflective coating</th>
<th>GTLSs (mm)</th>
<th>Peak power (nW)</th>
<th>Power (nW/GBq)</th>
<th>Power (nW/cm³)</th>
<th>Power (nW/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>m-Si</td>
<td>2.599 X 3.00 X 2.6</td>
<td>none</td>
<td>12.25 X 3.0</td>
<td>10.2</td>
<td>0.05</td>
<td>0.68</td>
<td>0.58</td>
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<tr>
<td>p-Si</td>
<td>2.498 X 1.99 X 2.6</td>
<td>none</td>
<td>14.15 X 3.0</td>
<td>7.7</td>
<td>0.10</td>
<td>0.92</td>
<td>0.63</td>
</tr>
<tr>
<td>a-Si</td>
<td>6.545 X 4.5 X 1.2</td>
<td>gold</td>
<td>10.25 X 3.0 + 2 15 X 3.0</td>
<td>575.1</td>
<td>3.18</td>
<td>123.28</td>
<td>39.08</td>
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<tr>
<td>a-Si</td>
<td>2.919 X 2.48</td>
<td>none</td>
<td>30.25 X 3.0 + 1 22.5 X 3.0</td>
<td><em>1606.2</em></td>
<td>3.06</td>
<td>126.90</td>
<td>35.24</td>
</tr>
<tr>
<td>a-Si</td>
<td>2.349 X 1.38 X 1.2</td>
<td>none</td>
<td>12.15 X 3.0</td>
<td>241</td>
<td>3.79</td>
<td>78.31</td>
<td>25.02</td>
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<tr>
<td>a-Si</td>
<td>2.349 X 1.38 X 1.2</td>
<td>gold</td>
<td>12.15 X 3.0</td>
<td>250.1</td>
<td>3.93</td>
<td>75.15</td>
<td>25.96</td>
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<tr>
<td>a-Si</td>
<td>2.349 X 1.38 X 1.2</td>
<td>barium sulfate</td>
<td>12.15 X 3.0</td>
<td>283.6</td>
<td>4.46</td>
<td>72.22</td>
<td>29.44</td>
</tr>
<tr>
<td>a-Si</td>
<td>2.723 X 1.50 X 1.2</td>
<td>gold</td>
<td>24.15 X 3.0</td>
<td>696.9</td>
<td><em>5.48</em></td>
<td>114.12</td>
<td>32.13</td>
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<tr>
<td>a-Si</td>
<td>2.103 X 1.55 X 1.2</td>
<td>none</td>
<td>34.15 X 3.0</td>
<td>786.2</td>
<td>4.36</td>
<td>88.54</td>
<td>24.60</td>
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</tbody>
</table>

**Very low light levels for PV cell operation, low efficiency**

- **525 GBq**
- **127 GBq** – a scaled version would produce 2800nW @525GBq (1000GBq limit)
Other research on ICRB’s

<table>
<thead>
<tr>
<th>Battery type</th>
<th>PV cell</th>
<th>Radioisotope</th>
<th>Activity (GBq)</th>
<th>Voltage (V)</th>
<th>Power</th>
<th>Efficiency</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>AeroGel</td>
<td>a-Si</td>
<td>Tritium</td>
<td>214,600</td>
<td>-</td>
<td>2mW</td>
<td>1.00%</td>
<td>theory</td>
</tr>
<tr>
<td>AeroGel</td>
<td>AlGaAs</td>
<td>Tritium</td>
<td>118,400</td>
<td>-</td>
<td>2mW</td>
<td>1.80%</td>
<td>theory</td>
</tr>
<tr>
<td>Thin film</td>
<td>m-Si</td>
<td>Nickel 63</td>
<td>-</td>
<td>-</td>
<td>0.92nW</td>
<td>1.53%</td>
<td>theory</td>
</tr>
<tr>
<td>Polymer</td>
<td>Si</td>
<td>Promethium 147</td>
<td>166.5</td>
<td>-</td>
<td>20μW</td>
<td></td>
<td>practical</td>
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<tr>
<td>GTLS</td>
<td>a-Si</td>
<td>Tritium</td>
<td>24.2</td>
<td>0.24V</td>
<td>2.57nW</td>
<td>0.17%</td>
<td>practical</td>
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<tr>
<td>GTLS</td>
<td>AlGaAs</td>
<td>Tritium</td>
<td>8.2</td>
<td>&gt;0.78V</td>
<td>74nW</td>
<td>0.98%</td>
<td>practical</td>
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<tr>
<td>Thin film</td>
<td>AlGaAs/GaAs</td>
<td>Plutonium 238</td>
<td>11.1</td>
<td>0.75V</td>
<td>10μW</td>
<td>0.11%</td>
<td>practical</td>
</tr>
<tr>
<td>GTLS</td>
<td>AlGaAs</td>
<td>Tritium</td>
<td>48.84</td>
<td>1.2V</td>
<td>234nW</td>
<td>0.53%</td>
<td>practical</td>
</tr>
</tbody>
</table>


Buried trials

- Fourteen 14.5x2.5mm GTLS’s
- Two 34.9x13.8mm a-Si PV cells
- 294nW @1.8V at start of testing
- Radioisotopic battery potted in polyurethane in IP55 waterproof casing
- Attached to a buried water pipe
- Cables brought out to monitor battery
Battery performance over time whilst buried on a water pipe
Temperature alters PV cell output
Calculated battery power over time

- Tritium half life 12.3 years
- Need higher starting power for longer life at spec power
- Alternative radioisotope would give more stable power
Conclusions

- Designed and manufactured Indirect conversion Radioisotopic battery (ICRB) using Gaseous Tritium light sources (GTLS) and a-Si PV cells
- Limit on activity 1000GBq
- Highest power produced 1600nW (@525GBq)
- Best efficiency 5.48nW/GBq
- Survived burial
- 1 μW of power after 10 years requires 3.3μW at beginning of life
- Longer lifetime requires longer half life
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Questions ?