Use of Instrumentation in a Radiological Environment

Christine Darve

August 18th, 2010

Headlines:

Instrumentation Identification
Radiological Environment
LHC measurements and Process
Instrumentation

- Think about instrumentation as a complete system – sensor, wiring feed through, DAQ rather than just the sensor itself.
  - Total system cost per measuring point can be ~ $500 - $1000 – trade off between cost, size, accuracy, easy of use, environment.

- Define requirements:
  - Resolution: what is the smallest detected change
  - Precision (reproducibility or stability): how close to the measurement value?
  - Accuracy: Closest between the results of a measurement and the true value.
  - Operating Range, excitation, Output signal, Size, Offset, Stability, interchangeability, Ease of Use, Cost
  - Effect on its environment
  - Environmental compatibility:
    - Robustness
    - Response time
    - Magnetic field effects
    - Radiation resistance
    - Electromagnetic noise effect

Courtesy of John Weisend
Instrumentation Rules of Thumb - Courtesy of John Weisend

- Don’t use more accuracy & precision than required
- Use commercially produced sensors whenever possible – there is a lot available
- When possible, mount sensors outside cryostat (e.g. pressure transducers, flow meters)
- For critical devices inside of cryostats, install redundant sensors whenever feasible
- Be sure to consider how to recalibrate sensors
- Once R&D is done, minimize number of sensors in series production of cryostats
Measurement of uncertainty, u

- The probable resolution, precision, or accuracy of a measurement can be evaluated using uncertainty analysis.
- Same unit than the quantity measured.

\[ u_c = \sqrt{u_1^2 + u_2^2 + u_3^2 + u_4^2 + \ldots + u_n^2} \]

- Source of measurement uncertainty
  1) Sensor excitation
  2) Sensor self-heating (in cryogenic environment)
  3) Thermo-electric voltage and zero drift
  4) Thermal noise
  5) Electromagnetic noise
  6) Sensor calibration
  7) Interpolation and fitting of the calibration data
Heat Sinking of Wires and Measurements Techniques

- Critical to the proper use of temperature sensors in vacuum spaces
  - You want to measure the temperature of the sensor not that due to heat leak down the wire
- Use 4-wire measurement
- Use low conductivity wires with small cross sections

<table>
<thead>
<tr>
<th>Material</th>
<th>$T_1$ [K]</th>
<th>$T_2$ [K]</th>
<th>$0.21 \text{ mm}^2$ (24 AWG)</th>
<th>$0.032 \text{ mm}^2$ (32 AWG)</th>
<th>$0.013 \text{ mm}^2$ (.56 AWG)</th>
<th>$0.005 \text{ mm}^2$ (40 AWG)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper</td>
<td>300</td>
<td>80</td>
<td>160</td>
<td>57</td>
<td>33</td>
<td>19</td>
</tr>
<tr>
<td></td>
<td>300</td>
<td>4</td>
<td>688</td>
<td>233</td>
<td>138</td>
<td>80</td>
</tr>
<tr>
<td>Phosphor-Bronze</td>
<td>300</td>
<td>80</td>
<td>32</td>
<td>11</td>
<td>6</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>300</td>
<td>4</td>
<td>38</td>
<td>13</td>
<td>7</td>
<td>4</td>
</tr>
<tr>
<td>Manganin</td>
<td>300</td>
<td>80</td>
<td>21</td>
<td>4</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>300</td>
<td>4</td>
<td>20</td>
<td>7</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>304 ss</td>
<td>300</td>
<td>80</td>
<td>17</td>
<td>6</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>300</td>
<td>4</td>
<td>14</td>
<td>5</td>
<td>3</td>
<td>2</td>
</tr>
</tbody>
</table>

*Note: Values are calculated assuming wires are in a vacuum environment, and the thermal conductivity of the adhesive is given by the fit to the thermal conductivity of GE 7011 varnish.*

Ref: “Cryogenic Instrumentation” – D.S. Holmes and S. Courts

*Handbook of Cryogenic Engineering*

Courtesy of John Weisend
Commercial Sources of Cryogenic Instrumentation

- Don’t reinvent the wheel – there is a lot already available. Catalogs can help you choose the correct sensor for your application.

- Two US Sources:
  - Lakeshore Cryogenics http://www.lakeshore.com/
  - Scientific Instruments http://www.scientificinstruments.com/

*Courtesy of John Weisend*
Strain Measurement

- Bond resistance strain gages, with relative resistance change according to the formula:

\[ \frac{\Delta R}{R} = F_s \left( \frac{\Delta L}{L} \right) \]
Level Measurement

- Superconducting level gauges for LHe service
- Differential pressure techniques
- Capacitive technique
- Self heating of sensors
- Floats (e.g. LN₂)

Courtesy of John Weisend
Flow Measurement

- Measure a mass flow or a volumetric flow

- Differential pressure
  (simple construction, no moving parts, external instrumentation and low maintenance) *e.g. Orifice, Venturi, V-Cone, Pitot tube*

  \[
  \rho \frac{v^2}{2} + p + \rho g z = \text{constant}
  \]

- Variable Area flow-meters
  (simplest and cheapest types of meter)

- Thermal Mass

  \[
  q = \Delta T \left[ k + 2(k C_v \rho \pi d \hat{v})^{1/2} \right]
  \]

- Others: Turbine, Vortex, Target
## Flow Measurement

<table>
<thead>
<tr>
<th>Method</th>
<th>Ultimate accuracy</th>
<th>Range-ability</th>
<th>Pressure loss and piping requirements</th>
<th>Recommended applications</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>orifice</td>
<td>1 - 2 %</td>
<td>medium</td>
<td>high / 10-30 D</td>
<td>clean gas</td>
<td>low</td>
</tr>
<tr>
<td>venturi</td>
<td>1 %</td>
<td>medium</td>
<td>low / 5-10 D</td>
<td>dirty gas</td>
<td>high</td>
</tr>
<tr>
<td>V-cone</td>
<td>0.5-1 %</td>
<td>medium</td>
<td>medium / 3-5 D</td>
<td>short pipes</td>
<td>medium</td>
</tr>
<tr>
<td>pitot tube</td>
<td>3%</td>
<td>medium</td>
<td>low / 20-30 D</td>
<td>velocity meas.</td>
<td>low</td>
</tr>
<tr>
<td>variable area</td>
<td>1-10 %</td>
<td>medium</td>
<td>medium / none</td>
<td>flow indicator</td>
<td>low</td>
</tr>
<tr>
<td>positive displacement</td>
<td>1 %</td>
<td>good</td>
<td>high / none</td>
<td>consumption measurement</td>
<td>high</td>
</tr>
<tr>
<td>thermal mass</td>
<td>1 %</td>
<td>good</td>
<td>low / none</td>
<td>mass flow measurement</td>
<td>high</td>
</tr>
<tr>
<td>turbine</td>
<td>0.3 %</td>
<td>good</td>
<td>high / 10-20 D</td>
<td>accuracy</td>
<td>high</td>
</tr>
<tr>
<td>vortex</td>
<td>0.75 %</td>
<td>good</td>
<td>low / 15-25 D</td>
<td>no maintenance</td>
<td>medium</td>
</tr>
<tr>
<td>target</td>
<td>0.5-2 %</td>
<td>low</td>
<td>high / 10-20 D</td>
<td>no maintenance</td>
<td>low</td>
</tr>
</tbody>
</table>
Temperature Sensors

- Metallic resistors
  - Platinum RTD
  - Rodium-iron RTD

- Semiconductor resistors
  - Carbon-glass RTDs
  - Carbon-Glass resistors
  - CernoxTM
  - Silicon Diodes
  - Germanium RTD
  - Ruthenium Oxide

- Semiconductor Diodes (fast response time, wide range)

- Capacitor

- Thermocouples
Temperature Measurement

### Temperature Range of Typical Lake Shore Sensors *

<table>
<thead>
<tr>
<th>Diodes</th>
<th>Model</th>
<th>Useful Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silicon Diodes</td>
<td>DT-670</td>
<td>1.4 - 500 K</td>
</tr>
<tr>
<td>GaAlAs Diode</td>
<td>TG-120</td>
<td>1.4 - 475 K</td>
</tr>
</tbody>
</table>

**Positive Temperature Coefficient (PTC) RTDs**

- 100 Ω Platinum RTD
  - PT-100, 250 Ω full scale
  - Useful Range: 30 - 675 K
- 100 Ω Platinum RTD
  - PT-100, 500 Ω full scale
  - Useful Range: 30 - 800 K
- Rhodium-Iron RTD
  - RF-800-4
  - Useful Range: 1.4 - 400 K

**Negative Temperature Coefficient (NTC) † RTDs**

- Germanium RTD
  - GR-200A-1000
  - Useful Range: 2 - 100 K
- Germanium RTD
  - GR-200A-250
  - Useful Range: 1.2 - 40 K
- Carbon-Glass™ RTD
  - CGR-1-500
  - Useful Range: 3 - 325 K
- Cernox™ RTD
  - CX-1050 AA or SD
  - Useful Range: 3.5 - 325 K
- Cernox™ RTD
  - CX-1030 AA or SD
  - Useful Range: 2 - 325 K
- High-Temperature Cernox™ RTD
  - CX-1030-SD-HT
  - Useful Range: 2 - 420 K
- Rox™ Ruthenium Oxide RTD
  - RX-102A
  - Useful Range: 2 - 40 K
- Rox™ Ruthenium Oxide RTD
  - RX-202A
  - Useful Range: 3 - 40 K

* Sensors sold separately.
† Single excitation current may limit the low temperature range of NTC resistors.

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Lakeshore Cryogenics
http://www.lakeshore.com/

Induced off-set (mK) for neutron and gamma rays

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Use of Instrumentation in a Radiolog.... Environment
Temperature Sensors + Radiation environment

→ By principle, use redundant system

**CERN Test benches:**

- Thermo cycle
- Irradiation test: fluence values close to $10^{15}$ neutrons/cm$^2$, corresponding to $2 \times 10^4$ Gy

<table>
<thead>
<tr>
<th>Thermometer (+number tested)</th>
<th>$R$ @ 1.8K</th>
<th>$dR/dT$ @ 1.8K</th>
<th>$\sigma_t$ @ 1.8K</th>
<th>beam heating $\text{mK/(n.cm}^2\text{s}^3)$</th>
<th>$\Delta T$ Irradiation for $4 \times 10^{14}$ n.cm$^2$</th>
<th>Expected $\Delta T$ in LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>AB (44)</td>
<td>6600 $\Omega$</td>
<td>-10600 $\Omega$.K$^{-1}$</td>
<td>8.10$^{-5}$</td>
<td>9 $10^{-6}$</td>
<td>+2 mK</td>
<td>&lt; 2 mK</td>
</tr>
<tr>
<td>TVO (44)</td>
<td>5700 $\Omega$</td>
<td>-3300 $\Omega$.K$^{-1}$</td>
<td>3.3 $10^{-5}$</td>
<td>3 $10^{-6}$</td>
<td>+0.3 mK</td>
<td>&lt; 0.5 mK</td>
</tr>
<tr>
<td>CX (66)</td>
<td>12600 $\Omega$</td>
<td>-12000 $\Omega$.K$^{-1}$</td>
<td>2.5 $10^{-5}$</td>
<td>10$^{-6}$</td>
<td>+1 mK</td>
<td>&lt; 2 mK</td>
</tr>
<tr>
<td>Ge (5)</td>
<td>9000 $\Omega$</td>
<td>-8000 $\Omega$.K$^{-1}$</td>
<td>1.2 $10^{-4}$</td>
<td>0</td>
<td>+300 mK</td>
<td>+300 mK</td>
</tr>
<tr>
<td>RhFe thin-film (46)</td>
<td>15 $\Omega$</td>
<td>+0.7 $\Omega$.K$^{-1}$</td>
<td>3.10$^{-5}$</td>
<td>0</td>
<td>+12 mK</td>
<td>+3 mK/year</td>
</tr>
<tr>
<td>RhFe wire (36)</td>
<td>5.4 $\Omega$</td>
<td>+0.6 $\Omega$.K$^{-1}$</td>
<td>2.6 $10^{-5}$</td>
<td>0</td>
<td>+15 mK</td>
<td>+1.5 mK/year</td>
</tr>
<tr>
<td>Pt (22)</td>
<td>1.7 $\Omega$</td>
<td>+3.5 $10^{4}$ $\Omega$.K$^{-1}$</td>
<td>-</td>
<td>-</td>
<td>+1.5 K</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 1: Results of irradiation at 1.8 K (average values)

Pressure Measurement

- Type: Absolute, differential, gauge
- Vacuum gage, e.g. cold cathode
- Problems with room temperature pressure measurement
  - Thermal acoustic Oscillations
  - Time response
- Some cold pressure transducers exist
- Capacitance pressure sensors
Pressure Measurement – Irradiation Test

Irradiated by neutrons (1-20 MeV, 10^{15} \text{n/cm}^2) ➞ 10 years of LHC operation at full intensity
Pressure Measurement – Irradiation Test

Example 1: HXTU - Process and Instrumentation Diagram

- The heaters provide the heat load
- The JT valve controlled the saturated He II flow
- The thermal equilibrium is dictated by the evolution of the dry-out point and the overflow in the accumulator.
# Instrumentation

<table>
<thead>
<tr>
<th>Instrumentation</th>
<th>Total</th>
<th>Range</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature (Cernox®, Pt100)</td>
<td>54</td>
<td>1.6 – 40 K, 50 K – 300 K</td>
<td>± 5 mK, ± 5 K</td>
</tr>
<tr>
<td>Pressure (Absolute, Differential)</td>
<td>5</td>
<td>0-1.3 bar, 0-0.13 bar, 0-7.5 mbar</td>
<td>0.2%, 0.03 mbar</td>
</tr>
<tr>
<td>Level (AMI)</td>
<td>5</td>
<td>0-6”, 0-12”, 0-28”</td>
<td>± 2% FS</td>
</tr>
<tr>
<td>Flowmeter (Turbine+RT)</td>
<td>2</td>
<td>0-20 g/s</td>
<td>± 2% FS</td>
</tr>
<tr>
<td>Heaters (Electrical resistances)</td>
<td>12</td>
<td>55, 90, 240 Watts</td>
<td></td>
</tr>
<tr>
<td>Control Valves</td>
<td>6</td>
<td>0-100 %</td>
<td></td>
</tr>
</tbody>
</table>

- Temperature sensors implemented in the pressurized He II bath

- Error of +/-5 mK on the temperature measurements.

- Stainless steel tubes to route the wires.

CD - July 20, 2001

He II HEAT EXCHANGER TEST UNIT FOR THE LHC INNER TRIPLET
Example 2: The Low-β Magnet Systems at the LHC

- Critical system for LHC performance
- Inner Triplet for final beam focusing/defocusing
- American contribution to the LHC machine

\[ Q = Q_{\text{Arc}} \times 10 \]
Underground views: 80-120 m below ground level
The low-β magnet system safety specification

Design and operation requirements:

- Critical system for LHC performance, but the system operation and maintenance should remain safe for personnel and for equipment, e.g. escape path, absorbed radiation dose, embrittlement, polymer prop. decay.

- Equipment, instrumentation and design shall comply with the CERN requirements, e.g. ES&H, LHC functional systems, Integration

- Risks identified: Mechanical, electrical, cryogenics, radiological

- Cryogenic risk → FMEA, Use the Maximum Credible Incident (MCI)

- Radiological → Use materials resistant to the radiation rate permitting an estimated machine lifetime, even in the hottest spots, exceeding 7 years of operation at the baseline luminosity of \(10^{34}\text{cm}^{-2}\text{s}^{-1}\).

- Personnel safety: Keep residual dose rates on the component outer surfaces of the cryostats below 0.1 mSv/hr.

- Apply the ALARA principle (As Low As Reasonably Achievable).
Radiological risk - Power density (mW/cm^3)

IR5 azimuthally averaged power distribution.

Particle tracks reaching the inner triplet and those generated there for a *pp-collision* in the IP1.
Power dissipation in the baseline IP5 inner triplet components. R1=35 mm, R2=81 mm in Q1 and Q3 and R2=67 mm in Q2a and Q2b.
Azimuthally averaged prompt dose equivalent (left) and residual dose rate on contact after 30-day irradiation and 1-day cooling (right) in mSv/hr in the TAS-Q1 region at the baseline luminosity

- The maximum of 12.5 mW/g (or 100 MGy/yr) at 15 cm (z=1960 cm) is determined by photons and electrons coming to the absorber

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Radiological risk

“Protecting LHC IP1/IP5 Components Against Radiation Resulting from Colliding Beam Interactions”, by N.V. Mokhov et. al

IR5 azimuthally averaged power distribution

Radial distribution of azimuthally averaged dose (Gy/yr)

→ Magnet quench limit = 1.6 mW/g

For comparison: Arc magnet ~ 1 Gy/yr

Use of Instrumentation in a Radiological

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Type of instrumentation

Low-β system

Interface with QRL

Use of Instrumentation in a Radiological Environment
Type of instrumentation

CV8xx: control valve

LT8xx: liquid helium level gauge (based on superconducting wire)

*HTS leads
*VCL leads
*Inner triplet feed through

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Use of Instrumentation in a Radiological Environment
Reliability – Performance measurement

Lambda transition, 
T=2.17 K, P=1.3 bar
Radiological risk

In order to compare energy deposition results with FLUKA 2006.3 and MARS 15

Energy deposition in GeV/primary, for proton-proton collision.


L = luminosity in collisions· 10^35 cm^-2s^-1

A = reaction cross section (including inelastic scattering and single diffraction events) in barn (80 mbarn)

<table>
<thead>
<tr>
<th>IR Elements</th>
<th>FLUKA</th>
<th>MARS</th>
</tr>
</thead>
<tbody>
<tr>
<td>TAS</td>
<td>1853.7</td>
<td>1827.3</td>
</tr>
<tr>
<td>Beam pipe</td>
<td>89.1</td>
<td>97.9</td>
</tr>
<tr>
<td>Q1 cable</td>
<td>158.0</td>
<td>159.1</td>
</tr>
<tr>
<td>Q1 yoke</td>
<td>96.3</td>
<td>78.5</td>
</tr>
<tr>
<td>Aluminium layer</td>
<td>2.3</td>
<td>2.4</td>
</tr>
<tr>
<td>Insulation</td>
<td>19.5</td>
<td>20.4</td>
</tr>
<tr>
<td>Stainless steel vessel</td>
<td>16.8</td>
<td>17.3</td>
</tr>
</tbody>
</table>


Power density[mW/cm^3 ] =1280*Energy [GeV/cm^3 /collision]

Comparison of total heat loads (W), upgrade luminosity L=1035cm^-2s^-1

IR Elements FLUKA MARS

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Radiological risk mitigation

• The inner-triplet final design included additional radiation shielding and copper absorber (TAS)

• The chosen instrumentation and equipment are radHard and halogen free (neutron irradiation experiment performed on temperature sensors: fluence values close to $10^{15}$ neutrons/cm$^2$, corresponding to $2.10^4$ Gy).

• PEEK versus Kel-F material used for the DFBX low temperature gas seal

• LHC tunnel accesses modes were defined, e.g. control and restricted modes
Radiological risk mitigation

- Specific hazard analysis is requested to intervene on the low-\(\beta\) systems
- Radiological survey systematically performed (< 1mSv/hr)
- Procedures written based on lessons learned
- Limit the personnel exposition time
- Process control w/ interlocks and alarm level for each operating mode

Averaged over surface residual dose rate (mSv/hr) on the Q1 side (z=2125 cm, bottom) of the TAS vs irradiation and cooling times. By courtesy of N. Mokhov
Risk mitigation: control operation upsets

- The so-called “Cryo-Start” and “Cryo-Maintain” threshold were tuned
- Temperature switch ultimately protect the operation of the HTS leads by using the power converter
- Temperature switch on the safety relief valve to monitor possible helium leak
- Interlocks on insulating vacuum pressure measurement
- DFBX Vapor Cooled Lead (VCL) voltage drop is 160 mV
- If pressure in the helium distribution line rise, then isolate DFBX (w/ low MAWP)
Risk mitigation: personnel training

• In addition to the use of software and hardware interlocks to limit risks, personnel’s training is of prime importance.

• New classes comply with the CERN safety policy. They train the personnel to behave safely in a cryogenic and radiation environment.

• Awareness and preventive actions are mandatory to complete each technical task. Dedicated hazard analyses are enforced to work in the low-β magnet system area.

“Compact” DFBX area
Opening to a new Engineering process approach:
A new engineering manual was issued at Fermilab: Engineering Process sequences

- This risk-based graded approach provides safe, cost-effective and reliable designs.
- The implementation flexible to loop within the given sequences.
- The implementation of this process will be adjusted to the Fermilab future projects
Cryogenic Instrumentation Identification

Adaptive Controller: Proportional Integral Derivative

Example: Response in process output for control system with original and re-tuned PI controller parameters

Diagram showing the control system with various components labeled:
- Setpoint
- Controller
- Process with varying dynamic properties
- Sensor and scaling
- Continuously calculation of controller parameters
- Continuously process model estimation
- Sensor and scaling
- Adjustment of controller parameters
- Gain scheduling variable

Graph showing the response over time with labels for y with re-tuned PI controller parameters and y with original PI controller parameters.
Availability: Data flow & LHC Logging Cryogenics Data

PLC, FEC: NTP synchronization

Courtesy of E. Blanco

LHC Logging

PLC TimeStamp

[~1500 ms worst case]

~ 10 s

(3) DB ARCH

CRYO SCADA

(2) DB DRIVER SCADA

(Impact Data Server Load)

~ 10 s

(1) DB FEC

(1) DB PLC

Controller

PROFIBUS DP

DI, DO

PROFIBUS PA

CV

Controller

~ 1500 ms

~ 500 ms

TT, PT, LT, DI, EH

TT, PT: ~1s

LT: 10s

EH: ~500 ms

Filter

AVG -> noise

MED -> spikes

500 ms

WFIP

SpecsDB

MTF

Card correction

DB layout

Noise correction

RadTol electronics

TT, PT, LT, DI, EHAI

IEPLC

TT, PT, LT, DI, EH

LTen, EHsp

1 s

1 s

Filter

A

VG

A

VG --> noise > noise

MED --> spikes > spikes

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Availability: Process Control Object

Courtesy of Mathieu Soubiran

SECTOR PCO

ARC PCO

He Guard Circuit
PV970

Cooling/Filling Circuit
CV920
QV920
QV923
QV927
EH821

1.9K Circuit
CV910/11
CV915/16

Beam Sreen Circuit
CV943
CV947
EH843
EH847

LSS PCO

Inner Triplet
He Guard Circuit
PV970

Cooling/Filling Circuit
CV920
QV920
QV923
QV927
EH821

Beam Sreen Circuit
CV910/11
CV915/16

Standalone Mag

Cooling/Filling Circuit
CV920
QV920
QV923
QV927
EH821

1.9K Circuit
CV947

Standalone Magnets PCOs
CV920
CV947
CV931
EH847
EH831
CV950

DFB

RF

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Use of Instrumentation in a Radiological Environment
Availability: Option modes / steppers

Option Mode 1

- Safety Position
- Cool Down + Filling

Option Mode 2
- T0
- T1

Option Mode 3
- Stand-by 75K
- T0

Option Mode 4
- Warm-up
- T0

System stopped

Cool Down

The Option Modes are defined at the Sector PCO level.

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Use of Instrumentation in a Radiological Environment

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