Activation of Targets and Accelerator Components at PSI

- a Comparison of Simulation and Measurement

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Contents:
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- Nuclear reactions
- Codes used at PSI to calculate nuclide inventories, dose rates
- Applications:
  1) Nuclide inventory in samples around SINQ target 3
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  3) Dose rates at the PIREX beam line
  4) Nuclide inventory in samples from the μE4 beam line
- Comparison of the 2 calculational methods
- Summary
Birds view of the Paul Scherrer Institut (PSI)

Proton accelerator facilities + Experimental hall
PSI Proton Accelerator Facilities

Injector 1

Injector 2

Ring cyclotron 590 MeV

Target M

Target E

SINQ

Comet: 250 MeV

UCN

Gantry 1

Gantry 2

OPTIS

OPTIS 2

PROSCAN

Upgrade 2 mA to 3.0 mA in progress

WAKA

Experimentierhalle

Mod.pavillon
All beam line components are surrounded by iron shielding.
Components around beam line get activated ... need to be removed eventually

- for replacement \rightarrow \text{waste}
  \text{Nuclide inventory} needed before disposal as required by swiss authorities

- for repair/dismantling \rightarrow \text{planning of work procedures}
  \text{dose rate} estimation needed

in addition:
\text{for future (planned) installations/facilities:}
- estimation of the amount of total waste after operation
- dose rates needed for construction of shielding
1) Direct irradiation (590 MeV p): at loss points (target, collimators)

main process: spallation

2) Secondary particle fields:

after penetration of shielding: mainly neutrons,
thermalized in shielding material

→ equilibrated energy spectrum

important process: neutron capture at thermal energies,
e.g. $^{59}\text{Co}(n,\gamma)^{60}\text{Co}$, $^{107}\text{Ag}(n,\gamma)^{108m}\text{Ag}$

activation due to...
Calculation of the Activation
case 1: mainly due to primary irradiation

Monte Carlo particle transport program

Monte Carlo particle transport program **MCNPX**: n, p, γ, α, π, d, ³H, ...

**Input**: dedicated geometry, material compositions, cross sections: for n<20MeV ENDF-B-VI.6, otherwise models

**Output**: n-fluxes (E<20 MeV), residual nuclei production rates

via Perl script

decay codes: **Cinder’90** or **SP-Fispact** or **Orihet3**

**Input**: irradiation and cooling history cross sections: Cinder library, EAF 2003 decay properties of isotopes

**Output**: nuclide inventory, photon rate

via Perl script

used as γ-source in **MCNPX** → dose rate
case 2: mainly due to secondary particles

- book-keeping prg. to calculate nuclide inventory
- contains PSIMECX cross section library (developed at PSI)

**Input:**
- weight material
- choice of 11 material compositions
- surface dose + irradiation history
- location (58 zones)
- choice of the representative n-flux spectrum

**Output:**
- nuclide inventory, scaled to measured dose rate.
- Production rates by folding with cross sections (PSIMECX)
- Buildup/decay (Orihet)

PWWMBS
1. Activation in the close vicinity of the SINQ-Target 3

irradiation: 6.77 Ah for 2 years
geom. model in MCNPX:

3 samples:

Zr screw

AlMg3 hull

Zr tubes

shielding 316L
Nuclide inventory

- γ’s in Ge-detector
- chemical + quantitative Analysis + β measurement in Liquid Scintillator
- Accelerator mass spectrometry (AMS)

measurement done by radiochemist group at PSI in collaboration with AMS groups in Zürich + Munich

Results for steel shielding: exp. / calc. activity

simulation by MCNPX + Cinder‘90

2 different material compositions
Results for safety hull: exp. / calc. activity

remarks:
• overall good agreement with MCNPX+Cinder’90
• Na22: Data/SP-Fispact = 0.72
• Fe60: deviation of factor 8 seen in many other samples
• the right material composition (including impurities) is important!

simulation by MCNPX + Cinder‘90

2 different material compositions

Na22  Cl36  Ti44  Mn54  Co57  Co60  Zn65  Ag108m

not obtained in calculation

0.1  0.1  0.69  0.61  0.91  0.82  0.71  0.65  1.48  5.44  1.40  1.63  0.79  0.72
2. Planned: New Hot cell at PSI

What is the required wall thickness (shielding) ?

Most activated piece at PSI: **SINQ target** (Pb in Zr tubes)
→ calculation of the nuclide inventory with **MCNPX + Cinder’90**
→ calculation of the thickness of the shielding with **Microshield**

How good are the predictions?
5 SINQ targets were irradiated and dismantled

→ Compare calculated dose rates with measured data
Dose rates at SINQ Target 4

- **Irradiation**: 2 years with 10 Ah, **cooling**: 10 months
- Dose rates obtained at 3cm, 30cm, 100cm
- Dose rates calculated with **MCNPX + Cinder‘90**

**Dose rates in Sv/h at 100 cm distance**

- **Data**
- **Calculation**
Dose rates in Sv/h at 3 cm distance

discrepancy:
• factor 2 in the target region
• factor 10 for small distance at the shielding

reason: in calculation contribution also from target region

Geiger Müller tube: smaller solid angle
3. Dose rates at the Pirex beam line at PSI

purpose (1988 - 2004):
material irradiation and degradation for Gantry 1

2006:
dismantling of the beam line
→ calculation of dose rates with MCNPX
  + comparison with measured doses

1. Beam current monitor
2. Degrader (Cu + C)
3. Beam Dump (Cu)

Assumption (made in simulation):
Degrader 2 and Beam dump 3 are always in beam

Irradiation history (simplified):
16.6 y @ 8.3 μA
2.3 y cooling

model in MCNPX of vacuum chamber
Comparison with data:

- Overall agreement good
- Average ratio 1.13
- Two points with ratio $> 2$:
  - smaller dose as measured in beam dump:
  - → degrader was not always in

Results of dose rate comparison:

Calculated values by M. Wohlmuther in brackets
4. Activation of samples in the $\mu$E4 beam line

2004: Several samples were taken from
- bending magnet ASK61
- shutter behind ASK61
- shielding around shutter

→ components are not directly irradiated
→ calculation of the activity with PWWMBS
  use representative n-flux spectrum in vicinity of Target E

bending magnet ASK61 (stainless steel)
Results for beam entry at ASK61

Measured activities via
• γ detection
• Accelerator mass spectrometry for Al26, Cl36, Ni59
• Liquid Scintillation: Ni63

exp./calc. activity

calc. values from F. Atchison & M. Wohlmuther

calculation with PWWMBS + typical stainless steel composition
Radioactive waste filled into Containers

- Collimators
- Beam Diagnostic Monitors
- Magnets
- Shielding

Total activity per container: $10^{10} - 10^{12}$ Bq (4.5 t)

Material composition:

- Normal steel
- Stainless steel
- Concrete
- Cast iron
- Copper
- Aluminum
- Lead
- Insulation materials
- PVC
- Tungsten
- Other metals

CONTRIBUTION IN % OF TOTAL

for most of the components: nuclide inventory obtained with PWWMBS
Comparison of the calculational methods

• **PWWMBS**: activation due to secondary particles
  main purpose:
  nuclide activity calculation of radioactive waste
  + fast throughput, user friendly
  + minimizing of personal dose (no detailed measurements or samples)
  - no predictions possible (dose rate needed)
  - accuracy: factor 10 due to simplified assumptions, sufficient for authorities

• **MCNPX**: activation due to primary irradiated fields
  main purpose:
  ✓ nuclide inventory calculation
  ✓ dose rate calculation
  ✓ energy deposit (input for ANSYS → temperature distribution)
  + predictions possible
  - elaborate geometry input
  - large cpu time (~1day on 256 - 512 nodes), statistical limitations
  + accuracy: factor ~ 3 (except some outliers)

→ Comparison between simulation and measurement important
Summary:
Predictions/calculations of the nuclide inventory and dose rates important for:
- disposal
- personnel work at activated components

Solution at PSI:
direct irradiation:
MCNPX + Cinder’90 (or SP-Fispact, Orihet3)
secondary particle fields:
PWWMBS (nuclide inventory only)

Examples:
1) Nuclide inventory of shielding + safety hull of SINQ target 3: good agreement
2) Dose rates along the SINQ target 4 insertion: agreement within factor 2
3) Dose rates in vacuum chamber of PIREX: agreement within factor 2
4) Nuclide inventory of ASK61: exp/calc. < 10, except for Cl36
Division of the area in regions

1) direct irradiation
2) secondary particles:
   - n-flux spectra calculated for 72 and 590 MeV area,
     dependent on
     - shielding material
     - depth in shielding
3) thermal neutrons
Meson Production Area

Access to working platform after removing 3-4 m of concrete roof shielding

Use of remotely controlled shielded exchange flasks to remove defective components.

Repair work done in a hot cell.