FLUKA Simulations
of
ISAC Targets

2nd FLUKA Advanced Course & Workshop
Sep 20, 2012

Mina Nozar, TRIUMF
Outline

- Overview of ISAC Targets
  - Target location in the hall
  - Target components
  - Target life cycle

- FLUKA simulations
  - Time evolution of radio-nuclide inventory
  - Time evolution of dose rate
  - Shielding assessment for spent targets
- 500 MeV, 100 µA proton beam from the BL2A port of the H⁻ cyclotron

- Two Target Stations, one operating at a time

- One Hot Cell and one Conditioning Station in use at the moment
- New **Electron beam** via a Superconducting LINAC
  25 MeV, 4 mA
  50 MeV, 10 mA

- New **Proton beam** via the BL4N port of the existing Cyclotron
  500 MeV, 200 µA

- Addition of two new Target Stations, Hot cells, Target Conditioning Stations, Storage area
Location of things

- Hot cells and conditioning station
- Conventional Chemistry Lab
- Radio-chemistry Lab
- Crane Control Room
Target function

Different target materials to produce RIBs
Different assembly configurations
~10 targets irradiated per year

Mass separator, beam transport system, and RFQ

ISACI or ISACII experimental stations for nuclear structure and astrophysics
Target Components

- Target Oven
  - Target Material
  - Low Power
  - High Power

- Ion Source
  - Surface
  - FEBIAD
  - Resonant Laser
  - ECR

- Heat Shield
  - TM 1
  - TM 2-4
Target Components - Target Material

Different materials, depending on the radionuclide of interest
Heat dissipation through radiative cooling and conduction

Refractory target foils:
Nb, Ta

Compound targets:
TaC/Gr, TiC/Gr, SiC/Gr, ZrC/Gr, UO, Ucx/Gr, ...

Carbides bound onto a graphite foil to achieve higher thermal conductivity
Target Components: Target Oven

Low Power

- \( I_p \leq 40 \, \mu A \)
- Dissipates up to 5 kW of power deposited by beam

High Power

- \( 55 \, \mu A \leq I_p \leq 100 \, \mu A \)
- Dissipates up to 25 kW of power deposited by beam
Target Components - Heat Shield

Front View

- TM 4
- Plug connector mounting plate
- Gripper Arms
- Ion source
- VCR water connections

Back View

Beam's eye View
Target Life Cycle

Chemistry labs & Machine shop

- Raw material and Commercial Components
- Machine Shop
- Assembly
- Test & Inspection
- Target Exchange
- Conditioning
- RIB Production
- Storage & Disposal

Chemistry labs & Machine shop
Target Life Cycle

- Raw material and Commercial Components
- Assembly
- Test & Inspection
- Target Exchange
- Conditioning
- RIB Production
- Storage & Disposal

Test Stand
Target Life Cycle

Raw material and Commercial Components

Machine Shop

Assembly

Test & Inspection

Hot Cell

Target Exchange

Conditioning

RIB Production

Storage & Disposal
Target Life Cycle

- Raw material and Commercial Components
- Machine Shop
- Assembly
- Test & Inspection
- Conditioning Station
- Conditioning
- Target Exchange
- RIB Production
- Storage & Disposal
- Exchange
Target Life Cycle

Raw material and Commercial Components

Machine Shop

Assembly → Test & Inspection → Target Exchange → Conditioning → RIB Production → Storage & Disposal

Target Station

Photos of the Target Station:
1. Control room with multiple monitors and a man looking at a screen.
2. A large target setup in a laboratory with various instruments.
3. A person in protective gear working on an assembly.
4. Close-up of a component being worked on.
Target Life Cycle

Raw material and Commercial Components

Assembly

Test & Inspection

Target Exchange

Conditioning

RIB Production

Hot cell

Storage & Disposal

Machine Shop

Assembly → Test & Inspection → Target Exchange → Conditioning → RIB Production → Storage & Disposal
Target Life Cycle

1. Raw material and Commercial Components
2. Machine Shop
3. Assembly
4. Test & Inspection
5. Target Exchange
6. Conditioning
7. RIB Production
8. Storage & Disposal

Storage Vault
Target Life Cycle

Radiation field and activity measurements

Raw material and Commercial Components

Machine Shop

Assembly ➔ Test & Inspection ➔ Target Exchange ➔ Conditioning ➔ RIB Production ➔ Storage & Disposal

Portable HPGe detector

RAM R-200

Collimation & shielding
Target Life Cycle

- Raw material and Commercial Components
- Machine Shop
- Assembly
- Test & Inspection
- Target Exchange
- Conditioning
- RIB Production
- Storage & Disposal

Mini storage & Transport Flask
FLUKA SIMULATIONS
Standard (single step) FLUKA run

• Using standard FLUKA (single FLUKA simulation)
  • Production of radioactive isotopes in the target material
  • Time evolution of the radionuclide inventory and their activity
  • Time evolution of residual dose rate, 1 m from the target
  • Contribution of back-scattered neutrons to activation and dose rate

• Using Stefan Roesler's two-step method
  • First-step: Production of radio-nuclides at given cooling times for a given irradiation profile, in different regions
  • Second-step: Assessing shielding for dose rates calculated from transport of the $\beta^+$, $\beta^-$, $\gamma$ emitted from radio-nuclides of the first-step
FLUKA SIMULATIONS – Targets simulated

Studied six ISAC targets used between 2008 and 2010
Beam energy: 480 MeV
Beam profile: Gaussian with 7 mm FWHM

<table>
<thead>
<tr>
<th>Target</th>
<th>Target Oven</th>
<th>Ion Source</th>
<th>Heat Shield</th>
<th>Beam Intensity (µA)</th>
<th>Irradiation time (h)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LP</td>
<td>HP</td>
<td>SIS</td>
<td>TM1</td>
<td>TM4</td>
</tr>
<tr>
<td>Ta#27</td>
<td>x</td>
<td></td>
<td>x</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>SiCGr#24</td>
<td>x</td>
<td></td>
<td>x</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Ta#26</td>
<td>x</td>
<td></td>
<td>x</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>SiCGr#25</td>
<td>x</td>
<td></td>
<td>x</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Nb#4</td>
<td>x</td>
<td></td>
<td>x</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Nb#5</td>
<td>x</td>
<td></td>
<td>x</td>
<td>x</td>
<td></td>
</tr>
</tbody>
</table>
FLUKA SIMULATIONS – Material description

• **Target Material**
  
  • Single elements: Ta and Nb
    
    Volume = total length * disc area
    
    Effective Density = (total mass) / volume
  
  • Compounds: SiC bounded onto graphite (SiC/Gr)
    
    Find fractional masses:
    
    Mass(SiC): # SiC discs * t_SiC * ρ_SiC * disc area
    
    Mass(Gr): # gr discs * t_gr * ρ_gr * disc area
    
    Find compound effective density:
    
    Effective Density = (total mass) / volume

• **Target Oven + Heat Shield + Ion Source**
  
  Ta, Cu, AlN, Al alloy 6061-T6, and SST
FLUKA SIMULATIONS – Targets simulated

Six regions for activation study:
**Target material + Ta + Cu + 6061-T6 + AlN + SST**

<table>
<thead>
<tr>
<th>Target</th>
<th>Length (cm)</th>
<th>Mass (g)</th>
<th>Effective Density (g/cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ta#27</td>
<td>7.5</td>
<td>46.19</td>
<td>2.89</td>
</tr>
<tr>
<td>SiCGr#24</td>
<td>18.4</td>
<td>55.46</td>
<td>1.36</td>
</tr>
<tr>
<td>Ta#26</td>
<td>7.2</td>
<td>46.19</td>
<td>2.78</td>
</tr>
<tr>
<td>SiCGr#25</td>
<td>18.5</td>
<td>54.63</td>
<td>1.33</td>
</tr>
<tr>
<td>Nb#4</td>
<td>8.6</td>
<td>23.85</td>
<td>1.25</td>
</tr>
<tr>
<td>Nb#5</td>
<td>4.0</td>
<td>18.7</td>
<td>2.05</td>
</tr>
</tbody>
</table>
FLUKA SIMULATIONS – Targets simulated

Six regions for activation study:
Target material + Ta + Cu + 6061-T6 + AlN + SST

<table>
<thead>
<tr>
<th>Target Module</th>
<th>Quantity</th>
<th>Region</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Ta</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cu</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6061-T6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>AlN</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SST</td>
</tr>
<tr>
<td>TM1</td>
<td>Volume (cm³)</td>
<td>29.4</td>
</tr>
<tr>
<td></td>
<td>Density (g/cm³)</td>
<td>16.7</td>
</tr>
<tr>
<td></td>
<td>Mass (g)</td>
<td>489.2</td>
</tr>
<tr>
<td>TM4</td>
<td>Volume (cm³)</td>
<td>62.9</td>
</tr>
<tr>
<td></td>
<td>Density (g/cm³)</td>
<td>16.7</td>
</tr>
<tr>
<td></td>
<td>Mass (g)</td>
<td>1047.0</td>
</tr>
</tbody>
</table>
FLUKA SIMULATIONS – Geometry description

• **Target material**
  Solid cylinder inside the Target Oven with top cut off

• **Target Oven**
  Inf. Cylinders + planes + RPPs to mimic geometry in the drawings as closely as possible (fins' tot. Volume added to the T.O. tube)

• **Heat Shield + Ion Source**
  RCCs to describe cover, cover plate, and base for Heat Shield
  Copper tubes added into the above volume, using volumes from solid works
  All remaining components of H.S. And Ion Source, were added as simple geometrical shapes, using volume and material info. From solid works
FLUKA SIMULATIONS – Geometry

Ta#26
FLUKA Physics settings

Activated:

- Evaporation of heavy fragments
  PHYSICS SDUM=EVAPORAT WHAT(1)=3

- Coalescence mechanism
  PHYSICS SDUM=COALESCE WHAT(1)=1
FLUKA Transport settings (1)

Set:

- Production thresholds for $e^+, e^-, \gamma$ in all materials to 20 keV (KE)
  
  \begin{verbatim}
  EMFCUT SDUM=PROD-CUT WHAT(1)=2E-5 WHAT(2)=2E-5
  WHAT(4) and WHAT(5) to cover all materials
  \end{verbatim}

- Transport threshold for $e^+, e^-, \gamma$ in all regions to 20 keV (KE)
  
  \begin{verbatim}
  EMFCUT SDUM='empty' WHAT(1)=2E-5 WHAT(2)=2E-5
  WHAT(4) and WHAT(5) to cover all regions
  \end{verbatim}

- Proton transport cut-off for protons to 1 keV
  
  \begin{verbatim}
  PART-THR SDUM=Energy WHAT(1)=1E-6 WHAT(2)=PROTON
  \end{verbatim}
Radioactive decays

- Activate radioactive decays for build-up and cool-down times
- Set transport energy cut-off for $\beta^+, \beta^-, \gamma$ to 20 KeV
- Set transport energy cut-off mult. factor to 99999 (kill electromagnetic cascade in the prompt part)

RADDECAY SDUM=PROD-CUT WHAT(1)=Active WHAT(2)=On WHAT(3)=3 WHAT(4)=0 WHAT(5)=1099999
• Define irradiation profile

  Irradiation time: 578 hours ,  Beam Intensity: 70 µA
  IRRPROFI WHAT(1)=2080800  WHAT(2)=4.3694E14

• Set build-up times

  Build-up times (4): 1 h, 1 d, 3 d, 10 d after SOB
  DCYTIMES WHAT(1)=-2.0772E6  WHAT(2)=-1.9944E6
  WHAT(3)=-1.8216E6  WHAT(4)=-1.2168E6

• Set cool-down times

  Cool-down times (9): 0 s, 1 h, 1 d, 10 d, 40 d, 1 y, 2y, 3y, 5y after EOB
  DCYTIMES WHAT(1)=0  WHAT(2)=3600  WHAT(3)=86400
  WHAT(4)=864000  WHAT(5)=3.456E6  WHAT(6)=3.154E7
  WHAT(7)=6.307E7  WHAT(8)=9.461E7 WHAT(9)=1.577E8
FLUKA Scoring (1)

Looked at:

- Isotope production rate (nuclei/prim) in each of the 6 regions (6 RESNUCLE cards)
  Ex: Isotope production rate in the Tantalum target region
  
  RESNUCLE  3.  -21.  74.  49.  rTgtTa26  1.RNTgt

- Time evolution of activities (Bq) in each of the 6 regions (78 RESNUCLE plus 13 DCYSCORE cards)
  Ex: Activity in the Tantalum target region, 1 hour after EOB

  RESNUCLE  3.  -31.  74.  49.  rTgtTa26  1.SOB1hTgt
  DCYSCORE   1.  SOB1hTgt   RESNUCLE
FLUKA Scoring (2)

Looked at:

- Time evolution of residual dose rate (pSv/s) in a cylindrical detector (1m long x 10 cm thick) filled with air, placed 1 m away from the center of the beamline
  Ex: Residual dose rate, 1 hour after SOB

```
USRTRACK   -1.  DOSE-EQ   -47.  rDet   65973.46   100.DEDetSB1h
USRTRACK   0.010010   1E05
```

Used the default AMB74 fluence to dose equivalent conversion coefficients
FLUKA simulation results (1)

- Based on 100 M primaries (20 M prim/run * 5 runs)

- Post-processing:
  - Used flair to combine results of multiple runs
  - Used python, shell, and awk scripting to extract relevant information from “tab” and “sum” files for comparison purposes
FLUKA simulation results

Time evolution of residual dose rates in the detector

As a function of energy for Ta#26

Build-up times

Cool-down times

Detector placed 1 m away from the target (1m long x 10 cm thick)
FLUKA simulation results (3)
Time evolution of residual dose rates in the detector

Total dose rates for the 6 targets studied
### FLUKA simulation results (4)
Residual dose rates – comparison B/N FLUKA and measurement

<table>
<thead>
<tr>
<th>Target</th>
<th>Measurement time after EOB (years)</th>
<th>Dose Rate (mSv/h)</th>
<th>FLUKA/Measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Measurement +/- 10%</td>
<td>FLUKA +/- &lt; 0.5%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ta#27</td>
<td>2.65</td>
<td>2.71</td>
<td>2.96</td>
</tr>
<tr>
<td>SiCGr#24</td>
<td>1.20</td>
<td>1.99</td>
<td>1.55</td>
</tr>
<tr>
<td>Ta#26</td>
<td>3.14</td>
<td>3.34</td>
<td>3.51</td>
</tr>
<tr>
<td>Nb#4</td>
<td>2.13</td>
<td>3.89</td>
<td>3.31</td>
</tr>
</tbody>
</table>
### FLUKA simulation results (5)

**Total activities: Comparison between FLUKA & measurement**

<table>
<thead>
<tr>
<th>γ-emitting Isotopes</th>
<th>Total activity (Bq), 3 years after EOB</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ta#27</td>
</tr>
<tr>
<td>Isotope</td>
<td>FLUKA</td>
</tr>
<tr>
<td>Na-22</td>
<td>6.37e+7</td>
</tr>
<tr>
<td>Mn-54</td>
<td>4.09e+8</td>
</tr>
<tr>
<td>Co-56</td>
<td>7.28e+5</td>
</tr>
<tr>
<td>Co-57</td>
<td>8.94e+8</td>
</tr>
<tr>
<td>Co-58</td>
<td>1.34e+6</td>
</tr>
<tr>
<td>Co-60</td>
<td>8.93e+8</td>
</tr>
<tr>
<td>Zn-65</td>
<td>4.11e+7</td>
</tr>
<tr>
<td>Se-75</td>
<td>4.99e+5</td>
</tr>
<tr>
<td>Y-88</td>
<td>9.19e+5</td>
</tr>
<tr>
<td>Lu-172</td>
<td>1.63e+10</td>
</tr>
<tr>
<td>Lu-173</td>
<td>1.37</td>
</tr>
<tr>
<td>Hf-172</td>
<td>1.87</td>
</tr>
<tr>
<td>Hf-175</td>
<td>1.19</td>
</tr>
<tr>
<td>Ta-182</td>
<td>0.31</td>
</tr>
</tbody>
</table>
Residual dose rates calculated from activities and h*10

<table>
<thead>
<tr>
<th>Target</th>
<th>Dose Rats, 3 y after EOB (mSv/h)</th>
<th>FLUKA/Measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Measurement</td>
<td>FLUKA</td>
</tr>
<tr>
<td>Ta#27</td>
<td>2.56</td>
<td>5.50</td>
</tr>
<tr>
<td>SiCGr#24</td>
<td>2.43</td>
<td>1.46</td>
</tr>
<tr>
<td>Ta#26</td>
<td>3.63</td>
<td>10.2</td>
</tr>
<tr>
<td>Nb#4</td>
<td>1.47</td>
<td>4.01</td>
</tr>
</tbody>
</table>

Gamma factors from document 814.501 (Data for Operational Radiation Protection)
Added 50 cm steel outside the target assembly to assess contribution to activation from back-scattered neutrons
FLUKA simulation results (8)
Neutron and proton currents

Neutrons crossing the 'inner Air' and 'steel' boundary

Protons crossing the 'inner Air' and 'steel' boundary
**FLUKA simulation results (7)**

Contribution from back-scattered neutrons

<table>
<thead>
<tr>
<th>γ-emitting Isotopes</th>
<th>Total activity for Ta#26, 3 years after EOB</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>FLUKA</td>
</tr>
<tr>
<td></td>
<td>No shielding</td>
</tr>
<tr>
<td>Isotope</td>
<td></td>
</tr>
<tr>
<td>Na-22</td>
<td>2.60</td>
</tr>
<tr>
<td>Mn-54</td>
<td>0.86</td>
</tr>
<tr>
<td>Co-56</td>
<td>0.21</td>
</tr>
<tr>
<td>Co-57</td>
<td>0.74</td>
</tr>
<tr>
<td>Co-58</td>
<td>0.19</td>
</tr>
<tr>
<td>Co-60</td>
<td>5.28</td>
</tr>
<tr>
<td>Zn-65</td>
<td>0.67</td>
</tr>
<tr>
<td>Se-75</td>
<td>0.33</td>
</tr>
<tr>
<td>Y-88</td>
<td>0.29</td>
</tr>
<tr>
<td>Lu-172</td>
<td>0.02</td>
</tr>
<tr>
<td>Lu-173</td>
<td>1.37</td>
</tr>
<tr>
<td>Hf-172</td>
<td>1.87</td>
</tr>
<tr>
<td>Hf-175</td>
<td>1.19</td>
</tr>
<tr>
<td>Ta-182</td>
<td>0.31</td>
</tr>
</tbody>
</table>
First-step: Production of radio-nuclides at given cooling times for a given irradiation profile in different regions

- Geometry, material, physics, biasing, same as in the standard run
- Took out RADDECA, IRRPROFI, DCYTIMES under Transport

Additional files:

**Fortran file:** doserate11.2.f
Contains: usrin.f
usrout.f
usrrnc.f
source.f

**Data files:** Irrcyc.inp  irradiation cycle
grines.dat  γ emitters
plines.dat  β⁺ emitters
eiclines.dat  β⁻ emitters
ICRP38.BET  β energy spectra
Define irradiation cycle and cooling times in irrcyc.inp

4.369e14  Beam intensity (protons/sec for I = 70 µA)
h600.     Irradiation time (600 hours)
s0        Not used, don't change!

1
s1
FLUKA SIMULATIONS
Stefan Roesler's two-step method – First Step

Input settings (1)

- Under Scoring:
  - A single RESNUCLE card for a region in which nuclides are produced
  - A USERWEIG card to activate a call to usrrnc routine

RESNUCLE  3.  -21.  74.  49.  rTgtTa26  1.RNTgt
USERWEIG  1.0
**FLUKA SIMULATIONS**

Stefan Roesler's two-step method – First Step

**Input settings (2)**

- **Under General:**
  - Defined cooling times in units of days (1 week and 3 years)
    
    ```
    USRICALL  SDUM=TCOOLD  WHAT(1)=7  WHAT(2)=1095
    ```
  - Chose which emitters to save (gamma rays and positrons only)
    
    ```
    USRICALL  SDUM=DUMPING  WHAT(1)=4
    ```
  - Chose regions to save emitters from
    (Six regions: Ta:3, Cu:6, 6061: 7, AlN:8, SST:9, Tgt:11)

    ```
    USRICALL  SDUM=DUMPREG  WHAT(1)=3  WHAT(2)=3
    WHAT(3)=6  WHAT(4)=6
    WHAT(5)=7  WHAT(6)=7
    ```

    ```
    USRICALL  SDUM=DUMPREG  WHAT(1)=8  WHAT(2)=8
    WHAT(3)=9  WHAT(4)=9
    WHAT(5)=11  WHAT(6)=11
    ```
Input settings (3)

- **Under General:**
  - Chose biased isotope dumping
    
    Set number of entries in dump file used for adjusting biasing set to 200 (default)
    
    Set maximum fraction of abundance of an isotope within the 200 entries for applying biasing to 20%

    USRICALL  SDUM=BIASING WHAT(1)=200  WHAT(2)=0.2

  - Chose regions for biasing

    USRICALL  SDUM=BIASREG  WHAT(1)=3  WHAT(2)=3
    WHAT(3)=6  WHAT(4)=6
    WHAT(5)=7  WHAT(6)=7

    USRICALL  SDUM=BIASREG  WHAT(1)=8  WHAT(2)=8
    WHAT(3)=9  WHAT(4)=9
    WHAT(5)=11  WHAT(6)=11
FLUKA SIMULATIONS
Stefan Roesler's two-step method – First Step

Input settings (4)

• Under General
  - Chose ascii file format for the output (isotope dump) file
    USRICALL  SDUM=OUTPUT  WHAT(1)=1
  - Chose to actually write the dump file!
    USROCALL
Compilation and Running

- Compiled dorerate11.2.f and linked with fluka.o to make a new executable
- Used a modified rfluka script with the following piece added in to link additional files from running directory to the temporary fluka_##### directories

```bash
MYDATAFILES="irrcyc.inp"
for i in $MYDATAFILES ; do
  if [ -r ${CURDIR}/${i} ] ; then
    ${ECHOE} "\nFile ${CURDIR}/${i} exists and it is not a link!"
    ln -s -f ${CURDIR}/${i} ${i}
  else
    ln -s -f ${FTOP}/${i} ${i}
  fi
done
... 
for i in 
  $DATAFILES $MYDATAFILES $neuxsc.bin $XNLOANFIL xnloan.dat
```
**Output file**

Can not concatenate output files, one output file per run.
Need to run multiple runs.
Name: `<run>`-001_isodump.out

Format:

```plaintext
4 2
	tc 1  6.0480000E+05
	tc 2  9.4608000E+07
#1  1  73 178 2  3  -4.27468E-01  -9.50193E-02  -9.69216E+00  1.00000E+00
1.00000E+00
  9.29319E-08
#1  -1  73 178 2  11  -4.83913E-01  -2.88948E-01  -2.38690E+00  1.00000E+00
1.00000E+00
#1  1  73 176 1  11  1.06143E-01  -5.15467E-01  -1.76789E+00  1.00000E+00
2.79992E+08
#1  1  73 177 1  11  -4.31354E-02  3.19773E-01  -2.25109E+00  1.00000E+00
1.00000E+00
  6.36827E+13
#2  1  74 176 11  6.31583E-01  4.97915E-01  -7.46459E-01  1.00000E+00
2  0  0  0  0  0  0  0
1  73 176 1  4.0521E+09  74 176 1  0.29460E-05
```

Second Step: Assessment of shielding for dose rates calculated from transport of the $\beta^+$, $\beta^-$, $\gamma$ emitted from radio-nuclides of the first-step

- Need a different input file for each cooling time since the shielding geometry is different for each:

  - 1 week cooling time: Shielding to represent the Storage Vault (25 cm thick steel box)
  - 3 year cooling time: Shielding to represent the F308 transport flask (5 cm lead box encased in 0.8 cm steel)
General preparation

For each cooling time and shielding scenario:

- Set up 10 directories (A001 ... J001)
- Make symbolic links to the data files the isodump.out files generated from first step: <run>-<A-J>001_isodump.out to isodump.out in each dir
- Add the shielding structure to the geometry in the input file

Wrote a script to automate the process!
General preparation (2)

- Need weight information from standard output file of 1\textsuperscript{st} step, \texttt{(<run>-<A-J>001.out)} as input parameters for 2\textsuperscript{nd} step:

**Parameters for USRICALL:**

- all regions
  
  \begin{verbatim}
  9.304E-02 2.710E-02 0.000E+00 0.000E+00 0.000E+00 0.000E+00
  \end{verbatim}

- regions no. 3
  
  \begin{verbatim}
  4.118E-02 1.270E-02 0.000E+00 0.000E+00 0.000E+00 0.000E+00
  \end{verbatim}

- regions no. 6
  
  \begin{verbatim}
  8.405E-04 2.840E-04 0.000E+00 0.000E+00 0.000E+00 0.000E+00
  \end{verbatim}

- regions no. 7
  
  \begin{verbatim}
  1.040E-04 3.200E-05 0.000E+00 0.000E+00 0.000E+00 0.000E+00
  \end{verbatim}

- regions no. 8
  
  \begin{verbatim}
  1.650E-05 9.000E-06 0.000E+00 0.000E+00 0.000E+00 0.000E+00
  \end{verbatim}

- regions no. 9
  
  \begin{verbatim}
  1.079E-03 1.022E-03 0.000E+00 0.000E+00 0.000E+00 0.000E+00
  \end{verbatim}

- regions no. 11
  
  \begin{verbatim}
  4.981E-02 1.306E-02 0.000E+00 0.000E+00 0.000E+00 0.000E+00
  \end{verbatim}

**Weights for the two cooling times:**
Input settings (1)

- **Under General:**
  - Weight factors for the two cooling times
    \[ \text{USERICALL SDUM=WCOOL WHAT(1)=9.304E-02 WHAT(2)=2.710E-02} \]
  
  - Set format of the input isodump.out file to ascii
    \[ \text{USRICALL SDUM=OUTPUT WHAT(1)=1} \]

- Regions to consider for tracking of emitted radiation
  (Six regions: Ta:3, Cu:6, 6061: 7, AlN:8, SST:9, Tgt:11)
  \[ \text{USRICALL SDUM=SAMPREG WHAT(1)=3 WHAT(2)=3} \]
  \[ \text{WHAT(3)=6 WHAT(4)=6} \]
  \[ \text{WHAT(5)=7 WHAT(6)=7} \]

- Read in isodump.out as input source file
  \[ \text{USROCALL} \]
Input settings (2)

• Under Source:

- Set isotopes for which cooling time to consider for tracking and which radio-nuclides to consider
Ex: 1st cooling time and gamma ray and positron emitters only

SOURCE WHAT(1)=4 WHAT(2)=4
Input settings (3)

- **Under Scoring:**
  - Use **USRBIN** to look at spacial distribution of dose rate
    
    USRBIN 10. DosE-EQ   -94.  120 120. 55.DEDist
    USRBIN -120. -120. -55. 120. 55.&
  
  - Use **USRBIN** to look at the dose rate in the detector (reg binning)
    
    USRBIN 10. DosE-EQ   -94.  rDet  DEDistReg
    USRBIN  rDet  1. &
  
  - Use **USRTRACK** to look at the total dose rate in the detector
    
    USRTRACK         -1.   DOSE-EQ      -40.      rDet 659734.46      100.DEinDet
    USRTRACK     .010010      1E-5 &
Compilation and Running

- Compiled dorerate11.2.f and linked with fluka.o to make a new executable
- Used a modified rfluka script with the following piece added in to link additional files from running directory to the temporary fluka_##### directories

```bash
MYDATAFILES="glines.dat plines.dat eiclines38.dat ICRP38.BET irrcyc.inp isodump.out"
for i in $MYDATAFILES ; do
  if [ -r ${CURDIR}/$i ] ; then
    ${ECHOE} "\nFile ${CURDIR}/$i exists and it is not a link!"
    ln -s -f ${CURDIR}/$i $i
  else
    ln -s -f ${FTOP}/$i $i
  fi
done
...
for i in \
  $DATAFILES $MYDATAFILES $neuxsc.bin $XNLOANFIL xnloan.dat
```
Results based on:

- **First Step:**
  1M primaries, 10 independent runs, each producing an isodump file

- **Second step:**
  10 runs with 20M primaries
  Each run using isodump.out file of one of the 10 runs in the first step

For proton beam energy of 115.7 MeV, not 480 MeV (an unintended mistake from setting beam momentum of 480 MeV)
Residual rate distribution for Ta#26

1 week after EOB

25 cm steel

3 years after EOB

5 cm lead encased in 0.8 cm steel
<table>
<thead>
<tr>
<th>Target</th>
<th>Residual dose rate @ 1m (µSv/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Spent Target Storage Vault 1 week after EOB</td>
</tr>
<tr>
<td>Ta#27</td>
<td>2.79 +/- 8.3 %</td>
</tr>
<tr>
<td>SiCGr#24</td>
<td>0.78 +/- 13.3 %</td>
</tr>
<tr>
<td>Ta#26</td>
<td>4.08 +/- 14.3 %</td>
</tr>
<tr>
<td>SiCGr#25</td>
<td>1.51 +/- 9.6 %</td>
</tr>
<tr>
<td>Nb#4</td>
<td>4.95 +/- 5.4 %</td>
</tr>
<tr>
<td>Nb#5</td>
<td>7.1 +/- 11.0 %</td>
</tr>
</tbody>
</table>

* Results need to be repeated with the correct beam energy of 480 MeV
Questions & thoughts

- How does Stefan's two-step method compare with the standard run?
  - Check using no shielding (i.e. same geometry in the second step as in the first)

- FLUKA version where prompt material can be set to vacuum and decay to shielding material?
  - Can this serve our needs to assess shielding for spent target material at different cooling times using the standard FLUKA run? (geometry constrains)

- Can the two-step method become integrated into the current version of FLUKA?
FLUKA/FLAIR Community
Vasilis Vlachoudis
Stefan Roesler
Mario Santana
Francesco Ceruti
Alberto Fasso
Alfredo Ferrari
Thomas Otto
Joachim Vollaire
Sebastien Wurth
...

TRIUMF
Anne Trudel
Anders Mjos
John Wong
Kelvin Raywood
Roxana Ralea
Chad Fisher
Travis Cave
Daniel Rowbotham
Stuart Austen
...

Slides 5-20 inspired/contributed by Anders Mjos from the TRIUMF Target group to provide background
For Stefan Roesler’s two-step method, see: “Radioactive Isotopes – Production and Decay”, Stefan Roesler, 15 March 2007