HSE

Occupational Health & Safety and Environmental Protection unit

Qualification of the Quality Control Process for Radiological Characterization of Radioactive Waste Packages: SHERPA and ELICA

Review of my internship at CERN

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Hugo SIRI

Studies

Master Degree in Nuclear Engineering (graduating in September 2023)

Bachelor’s Degree in Radiation Protection and Nuclear Safety

HND in Instrumentation and Measurements

Career History

4 years of diverse professional experience:

3 years at CEA. Cadarache center Dismantling field

1 year at Orano. Triscatin center Radiation protection field

Outside work

Love practicing sports.
Important to maintain the work life balance.

Goals

Widen my experience both professionally and personally

Outline

- Radioactive Waste Management at CERN
- ELICA/SHERPA RW packages and quality control
- Statistical studies
- Conclusions

CERN RW disposal pathways

- ✓ Close collaboration with host states Switzerland and France in matters of Radiation Protection and Radiation Safety
- ✓ Since 2010, tripartite agreement between CERN and Host States, represented by Swiss Federal Office of Public Health (OFSP) and the French Nuclear Safety Authority (ASN) -> link
- ✓ "Fair Share" principle revised in March 2022, with three indicators: the **volume eliminated. radiotoxicity and costs**

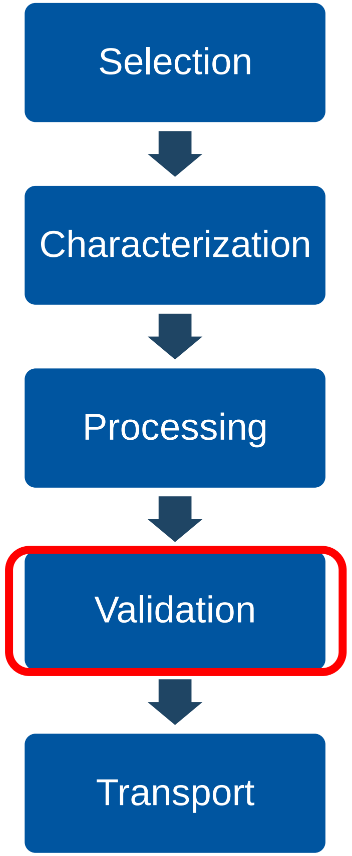
CERN's Radioactive Waste Classification	
Clearance candidates – CL Very Very Low-Level waste (VVLLW) (*Candidats à la Liberation inconditionnelle*)	Release from regulatory control in **Switzerland** (Clearance <> "free-release")
Very Low-Level Waste - VLL (TFA) (*Très Faibles Activités*)	Surface disposal in **France.** As defined by the acceptance criteria of the ANDRA CIRES repository
Low & Intermediate Level waste (Short Lived) - LL/IL (FMA-VC) (*Faibles et Moyennes Activités à Vies Courtes*)	Surface disposal in **France** (Short half-life $T_{1/2}$ < 30y) As defined by acceptance criteria in ANDRA CSA repository
Intermediate & Low-Level Waste - FA-MA (*Faibles Activités et Moyennes Activités*)	Disposal in **Switzerland**[(1)] When FMA-VC acceptance criteria (half-life. activity level) are not met

(1) In Switzerland. the PSI interim storage receives all FA-MA waste from research. industry and medical facilities. before its final disposal in a future deep geological repository

Slide from N. Menaa

Radioactive Waste processing

- Between **400** and **1000 m^3/y** of radioactive waste **produced** at CERN by the operation, dismantling and upgrade of experimental facilities.
- Specific processing, storage, and disposal strategies for **different waste classes** (e.g. TFA) and **families** (e.g. metallic waste. cables. etc.).
- Two TFA elimination pathways established
  - SHERPA (metallic)
  - ELICA (cables)
- The validation phase required a robust radiological characterization using gamma spectrometry

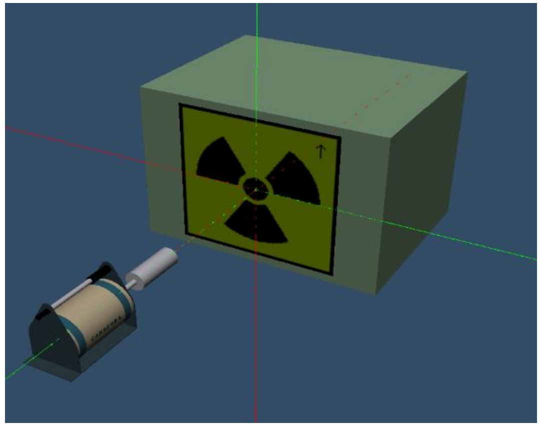


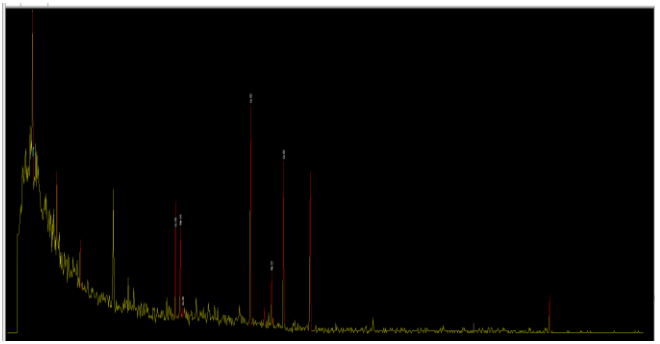
Wastes storage and processing

- Radioactive wastes are stored, sorted and processed at the RWTCS (B375)
- SHERPA and ELICA TFA wastes:
  - Metallic and cables
  - Packaged in 3 containers:
    - **1.35 m^3**
    - 2.77 m^3
    - 1.38 m^3 (2.77 m^3 half height)

RW validation

- Radiological analysis
- Using High Energy resolution Gamma spectrometry (HPGe)
- Analysis of the measurements
- Establishment of the ETM (Easy-To-Measure) nuclide inventory
- Reporting
- Activities of each nuclide are associated with an uncertainty with a confidence interval of 95% (2σ)





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********************* Radioprotection Group ***************************
*****   I N T E R F E R E N C E   C O R R E C T E D   R E P O R T   *****
*****                                                               *****
*************************************************************************
```

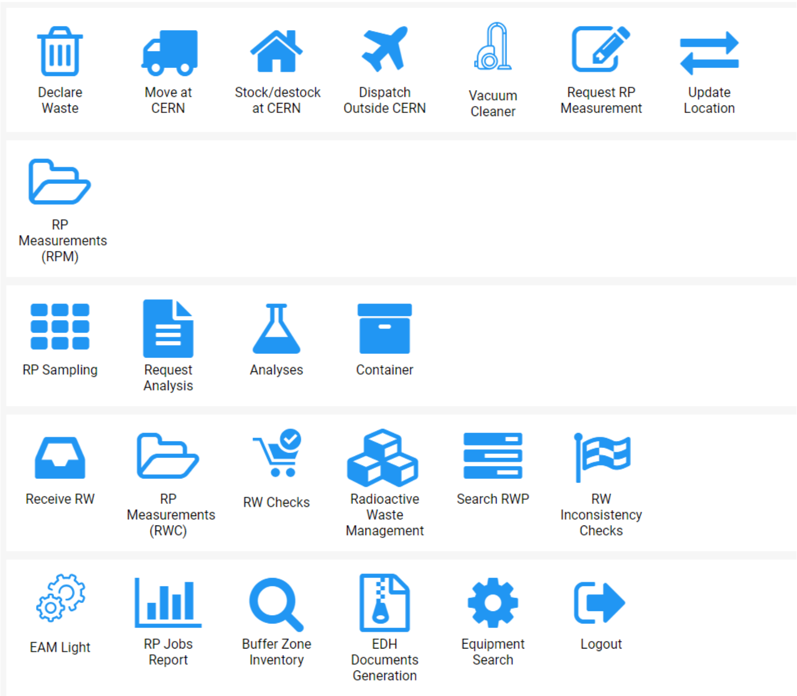
Nuclide	Halflife	Conf.	Weighted Mean Activity (Bq /gram)		MDA
Na-22	2.603E+00 Y	1.000	1.121E-01 ±	7.5%	7.92E-03
Mn-54	3.121E+02 D	1.000	4.001E-02 ±	14.9%	1.65E-02
Co-57	2.717E+02 D	0.998	2.605E-02 ±	73.0%	5.56E-02
Co-60	5.271E+00 Y	1.000	1.022E+00 ±	3.3%	5.60E-03
Eu-152	1.354E+01 Y	0.834	9.249E-02 ±	12.1%	1.55E-02

? = nuclide is part of an undetermined solution
X = nuclide rejected by the interference analysis
@ = nuclide contains energy lines not used in Weighted Mean Activity

Errors quoted at 2.000 sigma

Traceability - TREC

- Developed and maintained by CERN
- Used to request and implement RP measurements
- Declaration of radioactive waste
- Request for a radiological analysis: Gamma Spectrometry, Alpha Beta Counting, and others
  - Results and traceability in EDMS
- Sampling module to link samples to their origins
- And much more…



Agence Nationale pour la gestion des Déchets RAdioactifs

- ANDRA:
  - Public establishment
  - Independent of waste producers
  - Placed under the supervision of the French Ministries of Research, Industry and Environment
- IRAS (Radiological Index of Acceptance in Storage)
  - Calculated for each package
  - Must be < 10 for each package
  - Must be < 1 for the batch

Annexe 1 : Liste des radionucléides

Radionucléide	Période (ans)	Classe TFA	Seuil de déclaration (Bq/g)	Limite de déclaration forfaitaire (Bq/g)
H3	1,23E+01	3	1	10
Be10	1,60E+06	3	0,01	1
C14	5,73E+03	3	0,1	1
Na22	2,60E+00	1	0,1	
Al26	7,20E+05	1	0,1	
Si32	1,72E+02	3	10	
Cl36	3,02E+05	3	0,01	0,1
Ar39	2,69E+02	3	10	
Ar42	3,30E+01	3	10	
K40	1,28E+09	2	1	
Ca41	1,03E+05	3	0,01	0,1
Ti44	4,72E+01	1	0,1	
V49	9,03E-01	3	10	
Mn53	3,70E+06	3	10	
Mn54	8,56E-01	1	0,1	
Fe55	2,70E+00	3	10	
Fe60	7,51E+06	3	10	
Co57	7,43E-01	2	1	
Co60	5,27E+00	1	0,1	
Ni59	7,49E+04	3	10	100
Ni63	1,00E+02	3	10	
Zn65	6,69E-01	1	0,1	
Ge68	7,42E-01	1	0,1	

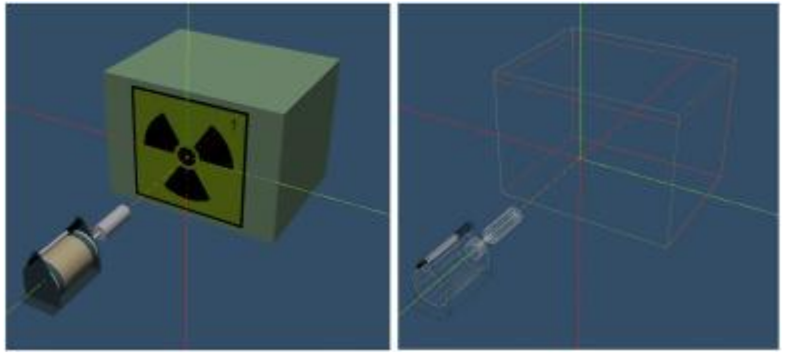
ANDRA

SPÉCIFICATION
Critères radiologiques d'acceptation des déchets TFA

$$\mathrm{IRAS} = \sum_i \frac{\mathrm{Am}_i}{10^{\mathrm{Classe}\ i}}$$

Quality Control

- Performing four measurements by gamma spectrometry on a SHERPA/ELICA package with a volume of 1.35 m^3 (instead of the usual two)
- Performed for every 20 waste packages (5% of packages in volume in each elimination pathway)
- Objective → Qualify the accuracy of the activity and IRAS values estimations
- 51 packages submitted to QC since 2019 (10 ELICA. 41 SHERPA)



Data analysis Tools

- Identify QC RW packages in TREC.
- Retrieve Gamma Spectrometry analysis reports.
- Used R which is widely used in data science by statisticians and data miners for data analysis and the development of statistical software
- Develop an R program to:
  - Establish a DataFrame of the results
  - Perform statistical analyses: average calculations. quantiles. hypothesis tests (Shapiro and Wilcoxon)…

```r
#Create some blank matrices first:
aDetect_4m <- matrix(NaN, nrow=lBig, ncol=nFiles_4m)
MDAsub_4m <- matrix(0, nrow=lBig, ncol=nFiles_4m)
aMeasured_4m <- matrix(NaN, nrow=lBig, ncol=nFiles_4m)

#Compare the measured activity of detected nuclides with the respective MDA.
#If the measured activity with 2 sigma uncertainties is higher than the MDA,
#the the final activity is the measured value + 2 sigma.
#Otherwise the final activity is the MDA
#For the packages 1.38m3 that were measured four times

for(f in seq(1, nFiles_4m)){
  for(i in seq(1,lBig)){
    if(is.na(A_4m[i,f])==FALSE){
      ifelse(A_4m[i,f] >= MDA_4m[i,f],
             aDetect_4m[i,f] <- as.numeric(A_4m[i,f])*(1+err_4m[i,f]*20),
             aDetect_4m[i,f] <- MDA_4m[i,f]
      )
      ifelse(A_4m[i,f] >= MDA_4m[i,f],
             aMeasured_4m[i,f] <- as.numeric(A_4m[i,f]),
             aMeasured_4m[i,f] <- MDA_4m[i,f]
      )
      if(A_4m[i,f]<MDA_4m[i,f] & is.na(MDA_4m[i,f])==FALSE){
        MDAsub_4m[i,f] <- 1 #Label MDA substitutions with '1', and '0' otherwise.
      }
    }
  }
}

#Create a matrix containing the file names for each unique CR code.
#Each column of the matrix is a CR code.
#The number of rows depends on the number of files with the same CR code.
Ref.Sample.unique_4m <- unique(Ref.Sample_4m)
RS.order_4m <- Ref.Sample.unique_4m[order(Ref.Sample.unique_4m)]
n.RS_4m <- length(RS.order_4m)
lRSf_4m <- matrix(0, nrow <- 1, ncol=n.RS_4m)
lRSf_4m_2 <- matrix(2, nrow <- 1, ncol=n.RS_4m)
for(k in seq(1, n.RS_4m)){
  lRSf_4m[k] <- length(files4m[Ref.Sample_4m==RS.order_4m[k]])
```

	Nuclide	HCPWCMS130-GK000399	HCPWCMS130-GK000563	HCPWCMS130-GK000870	HCPWCMS130-GK000906	HCPWCMS130-GK000908
9	Na-22	0.0195	0.0125	NaN	0.10834625	NaN
13	Al-26	NaN	NaN	NaN	NaN	NaN
29	K-42	NaN	NaN	NaN	NaN	NaN
37	Sc-44	NaN	NaN	NaN	NaN	NaN
39	Sc-46	NaN	NaN	NaN	NaN	NaN
43	Ti-44	NaN	NaN	NaN	0.0346352	0.05235
55	Mn-54	NaN	NaN	NaN	0.07141405	NaN
63	Co-57	NaN	NaN	NaN	NaN	NaN
64	Co-58	NaN	NaN	NaN	NaN	NaN
66	Co-60	1.5011	0.02394755	0.03442425	1.445515	6.87086
84	Zn-65	NaN	NaN	NaN	NaN	NaN
244	Ag-108m	NaN	NaN	NaN	NaN	NaN
297	Sb-124	NaN	NaN	NaN	NaN	NaN
366	Ba-137m	NaN	NaN	NaN	NaN	NaN
374	Ba-133	NaN	NaN	NaN	NaN	NaN
449	Eu-152	NaN	NaN	NaN	NaN	NaN
677	Bi-207	NaN	NaN	NaN	NaN	NaN
815	Sc<Ti-44	NaN	NaN	NaN	0.0346352	0.05235
816	Au<Hg194	NaN	NaN	NaN	NaN	NaN
817	Lu<Hf172	NaN	NaN	NaN	NaN	NaN
820	file 1	FA3---HCPWCMS130-GK000399-F1.txt	FA3---HCPWCMS130-GK000563-F1.txt	FA3---HCPWCMS130-GK000870-F1.txt	FA3---HCPWCMS130-GK000906-F1.TXT	FA3---HCPWCMS130-GK000908-F1.TXT
821	file 2	FA2---HCPWCMS130-GK000399-F3.txt	FA2---HCPWCMS130-GK000563-F3.txt	FA2---HCPWCMS130-GK000870-F3.txt	FA2---HCPWCMS130-GK000906-F3.TXT	FA2---HCPWCMS130-GK000908-F3.TXT

Uncertainties - Simplified

$$A = \frac{N_s}{\varepsilon(E).\Delta t} \times \frac{1}{I_\gamma}$$

A is the activity of a certain radioactive nuclide in the decay series;

N_s is the net peak area count subtract background of the sample;

$\varepsilon(E)$ is the absolute efficiency curve of the geometric model as a function of the gamma line energy;

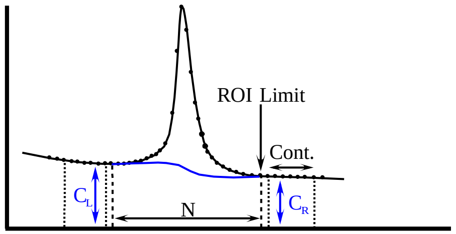
I_γ is the emission probability of a specific energy photo peak;

Δt is time for collecting the spectrum of the sample.

Neglecting correlations. Reported Activity Uncertainty is as follows:

$$\left(\frac{\partial A}{A}\right)^2 = \left(\frac{\partial N_s}{N_s}\right)^2 + \left(\frac{\partial \varepsilon(E)}{\varepsilon(E)}\right)^2 + \left(\frac{\partial I_\gamma}{I_\gamma}\right)^2$$

$$\left(\frac{\partial \varepsilon(E)}{\varepsilon(E)}\right)^2 = \left(\frac{\partial \varepsilon_{numeric}(E)}{\varepsilon_{numeric}(E)}\right)^2 + \left(\frac{\partial \varepsilon_{geometry}(E)}{\varepsilon_{geometry}(E)}\right)^2$$



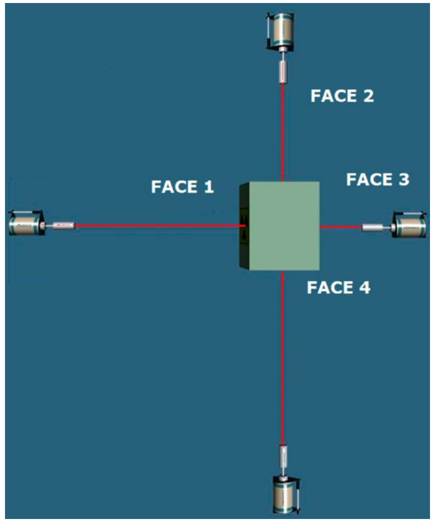
N_s due to the peak fit

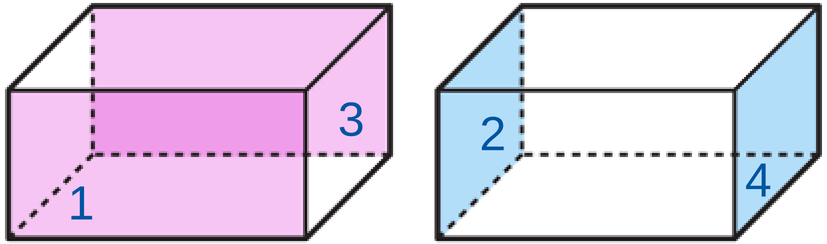
I_γ is found in the literature (nuclear database)

$\varepsilon(E)$ due to the numerical approximation (vertex. deterministic interpolation) and the qualification of MC code (comparison calculation / experiment) => do not take into account geometric modeling

Multiple counting

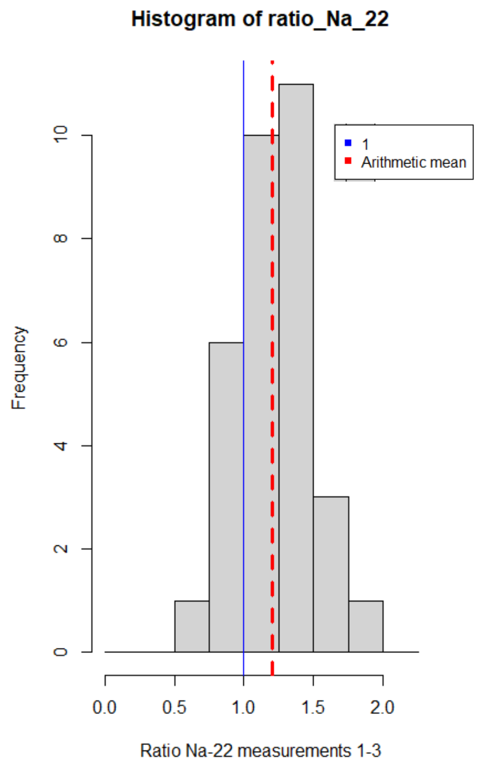
- We use a reference ISOCS efficiency calibration curve generated with the ISOCS/LabSOCS→ Uniform activity distribution
- Multiple counting to account for non-uniform activity distribution
- Activity heterogeneity is an important uncertainty component is due to the geometry of the waste

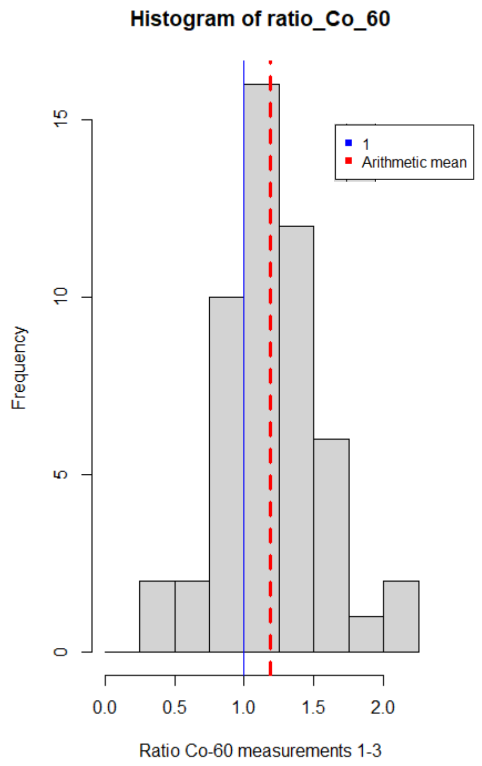




Measurements F1-F3

$$R = \frac{Mean(A_1(+2\sigma).A_3(+2\sigma))}{Mean(A_1, A_2, A_3, A_4)}$$

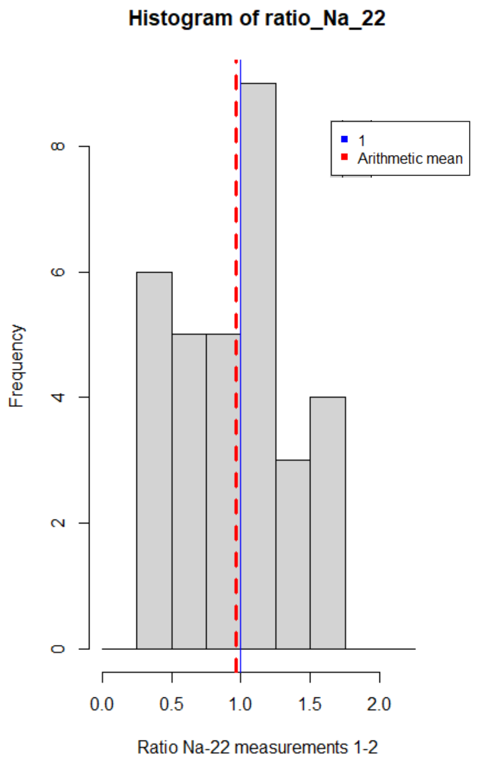


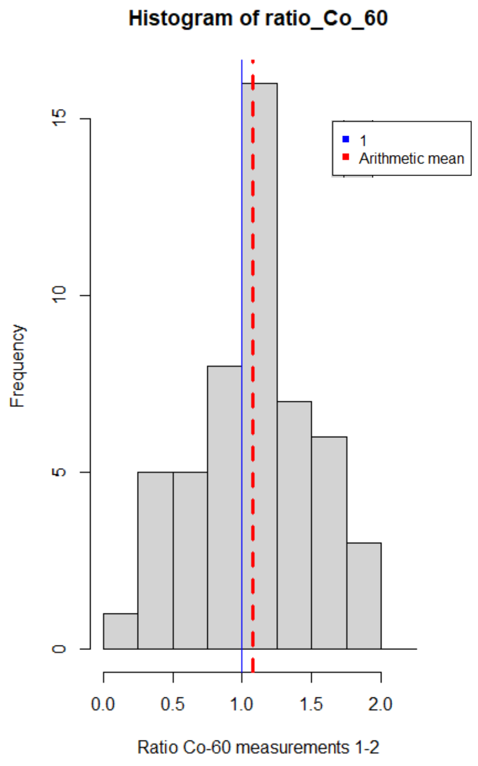


	Na-22	Co-60
Geometric mean	1.10	1.14
Median	1.20	1.19
1st quantile	1.01	0.98
5th percentile	0.84	0.63

Measurements F1-F2

$$R = \frac{Mean(A_1(+2\sigma).A_2(+2\sigma))}{Mean(A_1, A_2, A_3, A_4)}$$

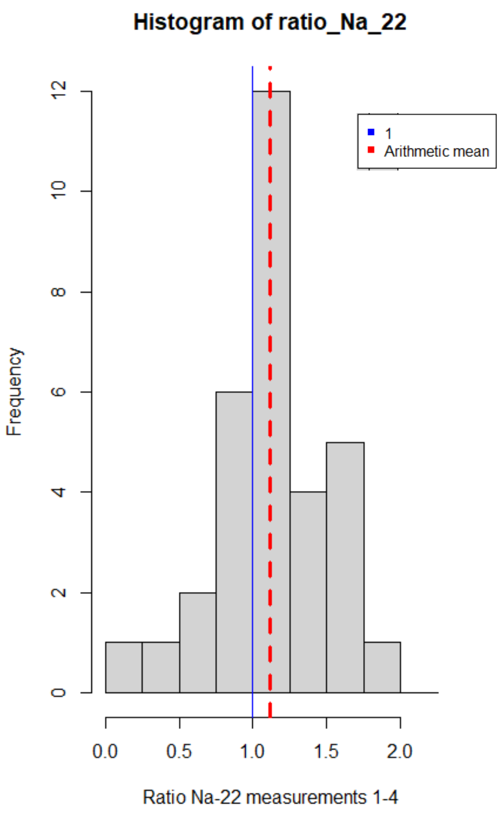


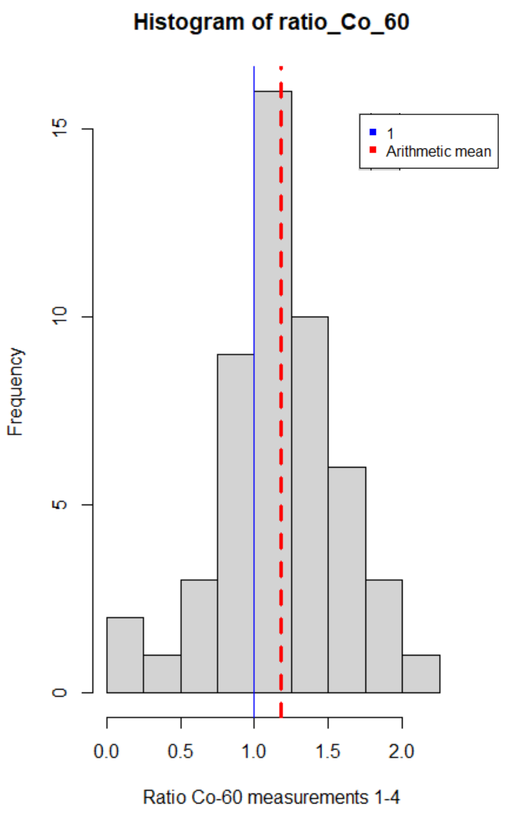


	Na-22	Co-60
Geometric mean	0.92	0.97
Median	0.99	1.08
1st quantile	0.63	0.83
5th percentile	0.37	0.38

Measurements F1-F4

$$R = \frac{Mean(A_1(+2\sigma).A_4(+2\sigma))}{Mean(A_1, A_2, A_3, A_4)}$$

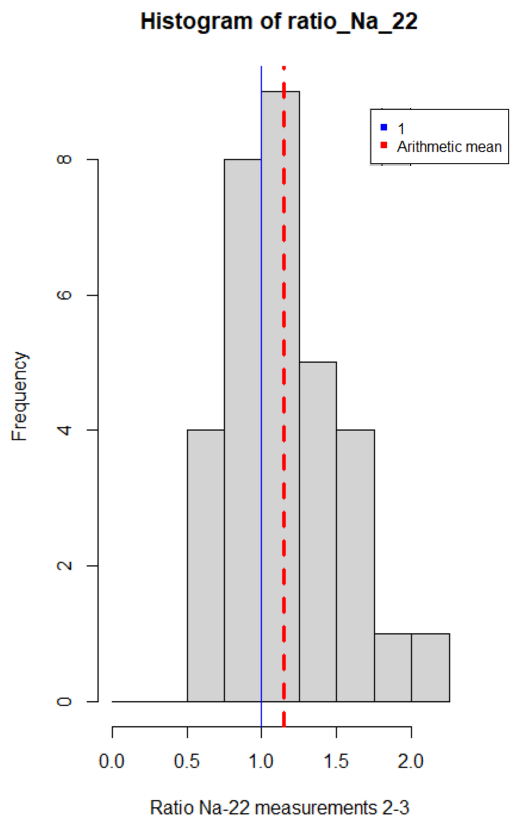


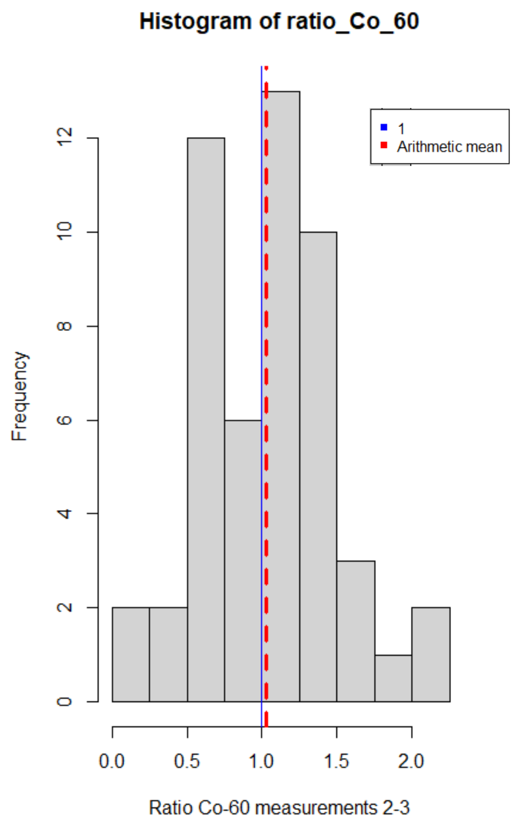


	Na-22	Co-60
Geometric mean	1.02	1.05
Median	1.11	1.18
1st quantile	0.91	0.96
5th percentile	0.52	0.49

Measurements F2-F3

$$R = \frac{Mean(A_2(+2\sigma).A_3(+2\sigma))}{Mean(A_1, A_2, A_3, A_4)}$$

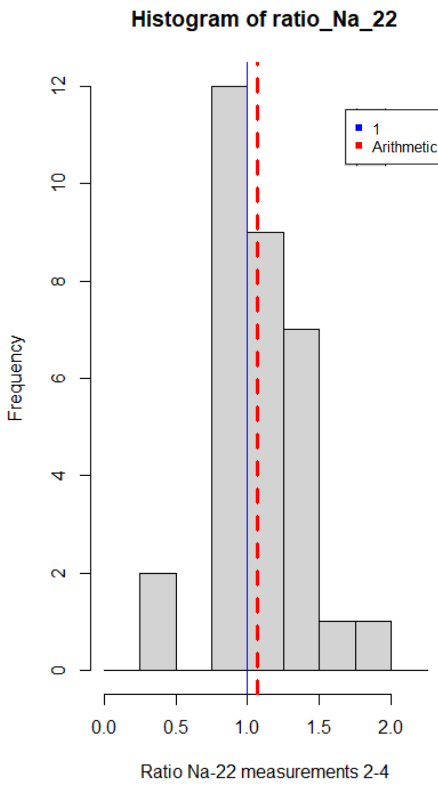


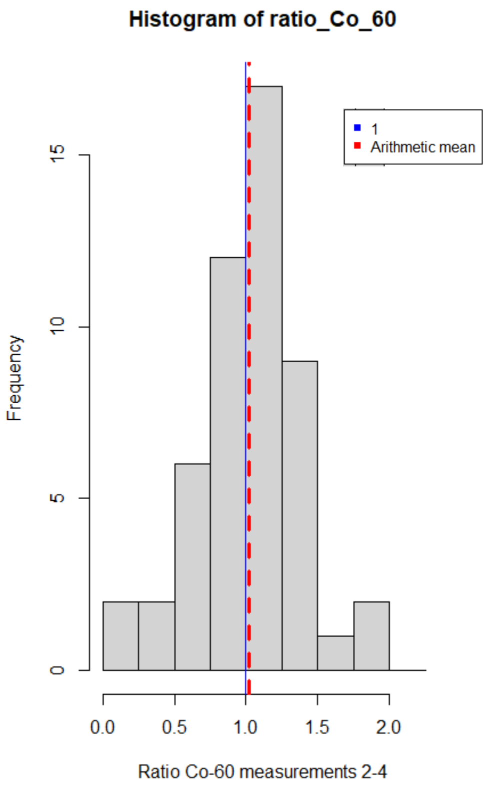


	Na-22	Co-60
Geometric mean	1.05	0.92
Median	1.12	1.04
1st quantile	0.90	0.72
5th percentile	0.61	0.26

Measurements F2-F4

$$R = \frac{Mean(A_2(+2\sigma).A_4(+2\sigma))}{Mean(A_1, A_2, A_3, A_4)}$$

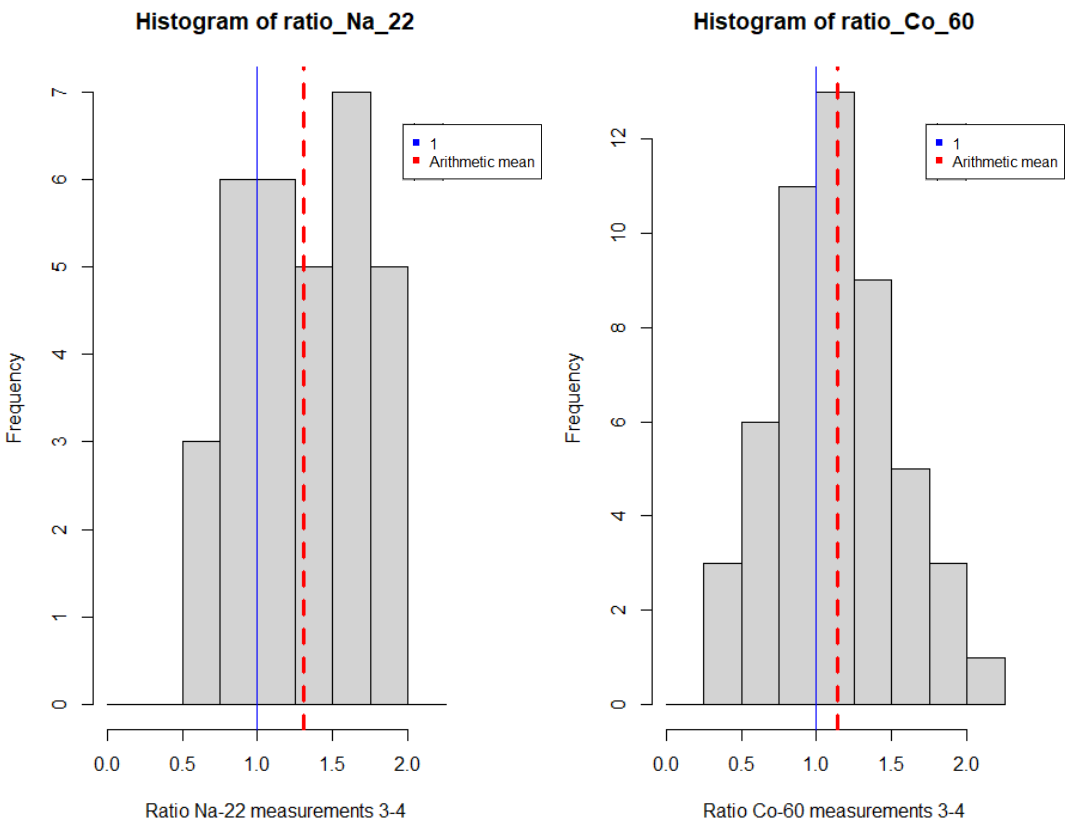




	Na-22	Co-60
Geometric mean	1.01	0.94
Median	1.07	1.06
1st quantile	0.86	0.83
5th percentile	0.64	0.45

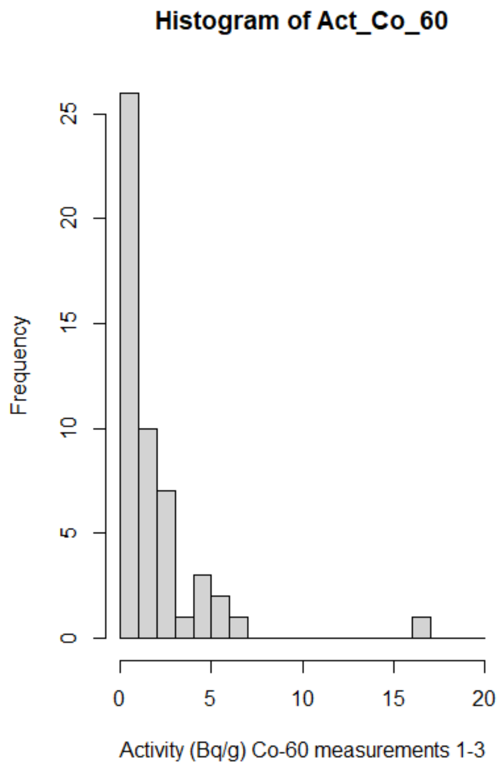
Measurements F3-F4

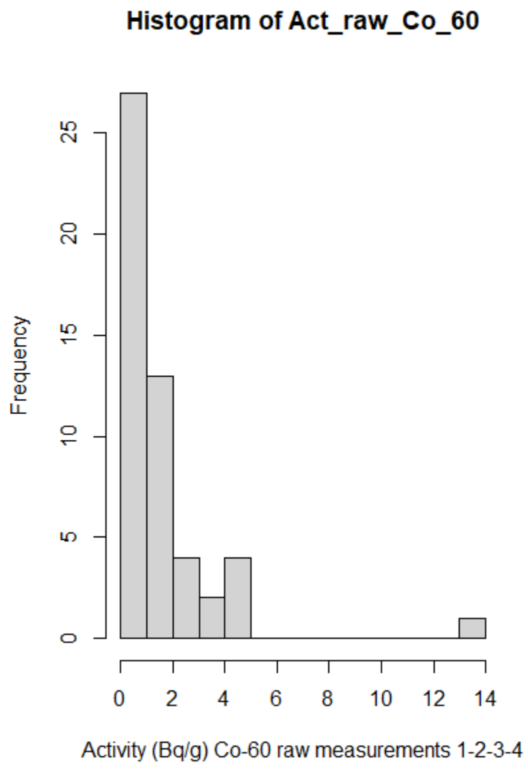
$$R = \frac{Mean(A_3(+2\sigma).A_4(+2\sigma))}{Mean(A_1, A_2, A_3, A_4)}$$

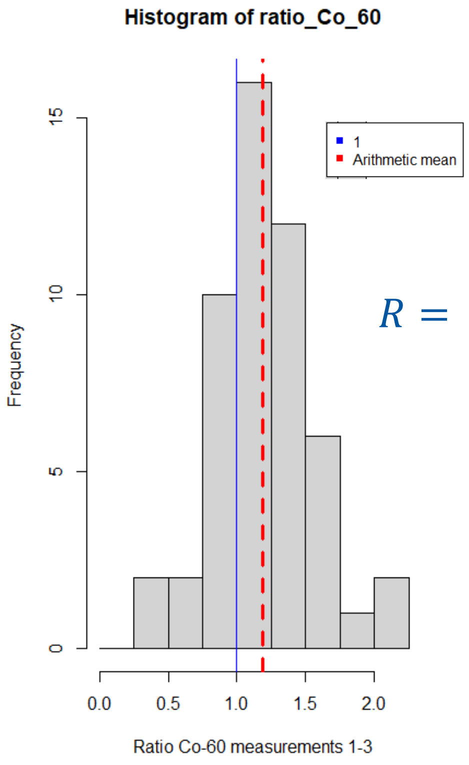


	Na-22	Co-60
Geometric mean	1.15	1.06
Median	1.31	1.14
1st quantile	0.98	0.87
5th percentile	0.71	0.52

Distribution of Co-60 activities

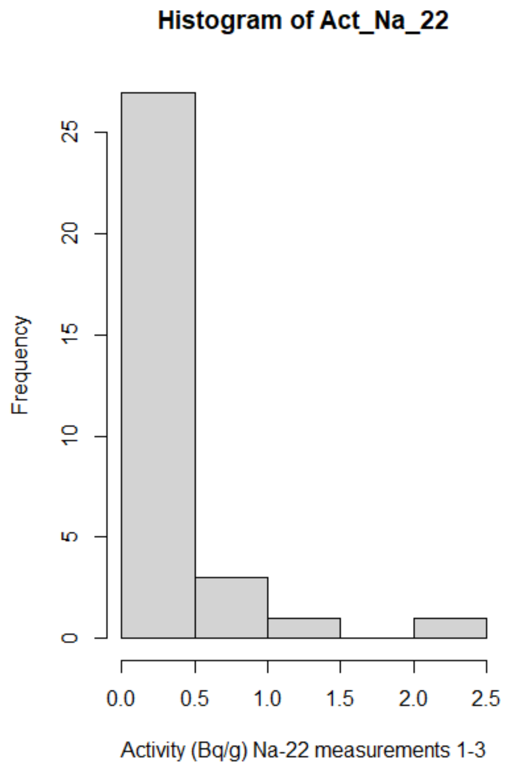


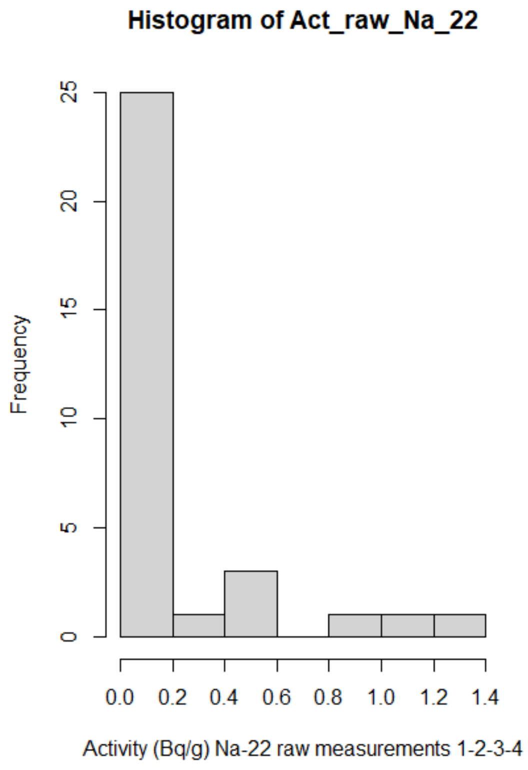


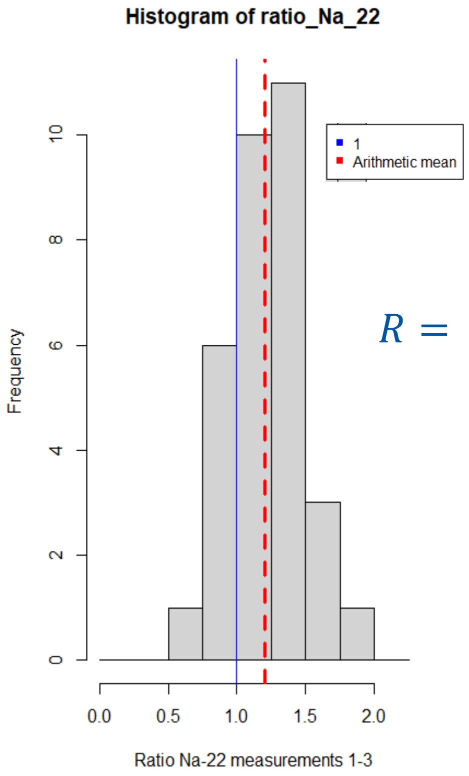


$$R = \frac{Mean(A_1(+2\sigma).A_3(+2\sigma))}{Mean(A_1.A_2.A_3.A_4)}$$

Distribution of Na-22 activities







$$R = \frac{Mean(A_1(+2\sigma).A_3(+2\sigma))}{Mean(A_1.A_2.A_3.A_4)}$$

Statistical hypothesis test activities (1)

- Normality test
  - Shapiro test

  H0 : Null hypothesis→ the function follows a normal distribution

  If p-value ≥ 0.05 then we cannot reject the null hypothesis H0

  If p-value < 0.05 then we reject H0

  Here. all the p-values are below 0.05 so we reject the H0 hypotheses. No function follows a normal distribution.

Measurements	p-value	
	Na-22	Co-60
(F1,F2)	$8.08*10^{-9}$	$3.29*10^{-8}$
(F1,F3)	$1.57*10^{-8}$	$2.33*10^{-10}$
(F1,F4)	$2.37*10^{-8}$	$8.31*10^{-8}$
(F2,F3)	$2.34*10^{-9}$	$1.10*10^{-11}$
(F2,F4)	$1.40*10^{-7}$	$1.23*10^{-8}$
(F3,F4)	$4.07*10^{-8}$	$5.89*10^{-11}$
(F1,F2,F3,F4) (raw)	$5.30*10^{-8}$	$3.87*10^{-10}$

Statistical hypothesis test activities (2)

- Wilcoxon test
  - All the functions don't follow a normal distribution
    - t-test not applicable
    - Use the Wilcoxon test

H0 : no difference between the populations of the pairs (+2σ) and those of the four measurements (raw).

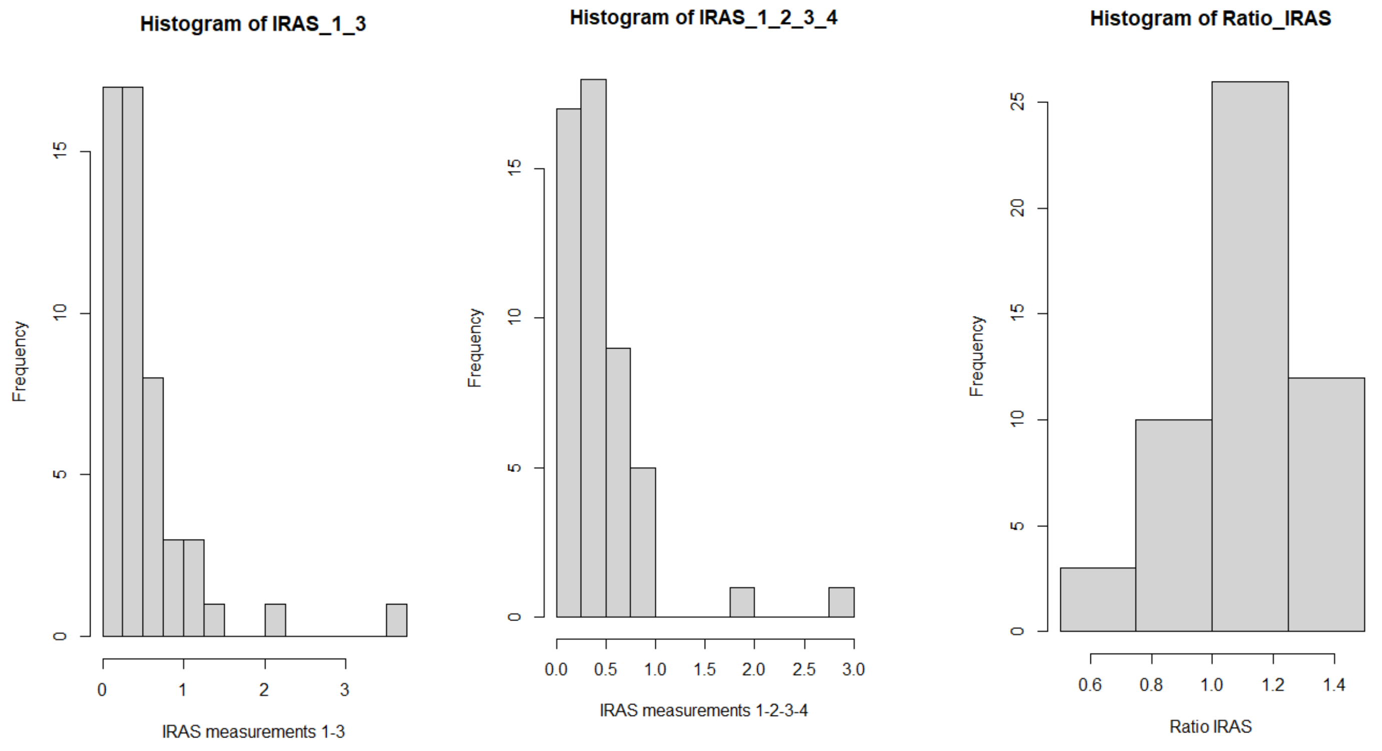
All the p-values > 0.05 → we can't reject the H0 hypotheses

Measurements	p-value	
	Na-22	Co-60
(F1,F2)	0.82	0.97
(F1,F3)	**0.53**	**0.63**
(F1,F4)	0.83	0.56
(F2,F3)	0.83	0.74
(F2,F4)	0.98	0.93
(F3,F4)	0.68	0.79

→ The (Fx-y) and F1-4 distributions are statistically identical for Co-60 and Na-22

IRAS

$$IRAS = \sum_i \frac{Am_i}{10^{\text{Classe } i}}$$



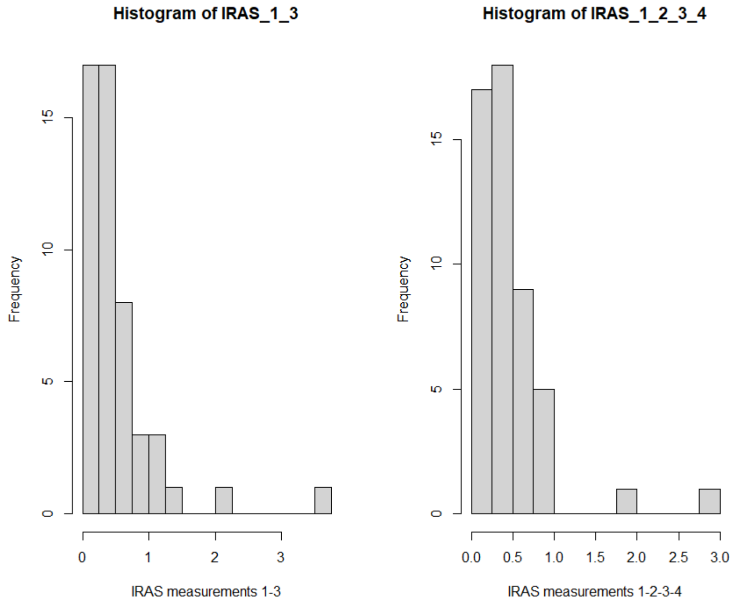
	Ratio
Values greater than 1	75%
Geometric mean	1.09
Median	1.11
1st quantile	1.00
5th percentile	0.76

Statistical hypothesis test IRAS (1)

- Normality test
  - Shapiro test

    H0 : Null hypothesis→ the function follows a normal distribution

    - IRAS(F1,F3) → p-value = $1.67 \cdot 10^{-9}$
    - IRAS(F1,F2,F3,F4) → p-value = $4.79 \cdot 10^{-9}$



Here IRAS(F1,F3) and IRAS (F1,F2,F3,F4) don't follow a normal distribution.

Statistical hypothesis test IRAS (2)

- Wilcoxon test
  - IRAS (F1,F3) and (F1,F2,F3,F4) don’t follow a normal distribution

H0 : no difference between the two populations

P-value = 0.64 > 0.05 → we can’t reject H0

→ The two distributions IRAS(F1,F3) and IRAS (F1,F2,F3,F4) are statistically identical.

Uncertainties

- Uncertainties at the 95% confidence interval (2σ):
  - Peak count, nuclear data, detector efficiency characterization
  - Efficiency calibration due to waste uncertainty (heterogeneity)
- The reported uncertainties do not include waste geometry uncertainties
- For which F we would have F*2σ → 5th percentile ratios ≥ 1
- For F = 6.5, we have the 5th percentile ratios for the ^{60}Co equal to 1
- We could multiply all our uncertainties by this factor to have 95% of our ratios above 1 for the ^{60}Co
- ANDRA TFA specifications do not require reporting activities at 95% C.L.

$$A = \frac{N_s}{\varepsilon(E).\Delta t} \times \frac{1}{I_\gamma}$$

```
********************** Radioprotection Group ****************************
*****   I N T E R F E R E N C E   C O R R E C T E D   R E P O R T   *****
*****                                                               *****
*************************************************************************
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Nuclide	Halflife	Conf.	Weighted Mean Activity (Bq /gram)		MDA
Na-22	2.603E+00 Y	1.000	1.121E-01 ±	7.5%	7.92E-03
Mn-54	3.121E+02 D	1.000	4.001E-02 ±	14.9%	1.65E-02
Co-57	2.717E+02 D	0.998	2.605E-02 ±	73.0%	5.56E-02
Co-60	5.271E+00 Y	1.000	1.022E+00 ±	3.3%	5.60E-03
Eu-152	1.354E+01 Y	0.834	9.249E-02 ±	12.1%	1.55E-02

? = nuclide is part of an undetermined solution
X = nuclide rejected by the interference analysis
@ = nuclide contains energy lines not used in Weighted Mean Activity

Errors quoted at 2.000 sigma

Conclusion and future work

- Analyzed 51 QC waste packages

- For IRAS and activity values, we can conclude that the measurements (F1,F3) are representative of the average of the measurements (F1,F2,F3,F4)

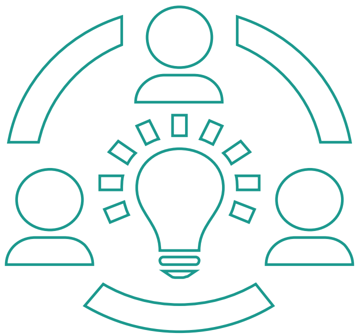
- The two distributions (F1,F3) and (F1,F2,F3,F4) are statistically identical. The values of (F1,F3) at 2σ are reasonably conservative with respect to (F1,F2,F3,F4)
  → The ANDRA TFA requirement is fulfilled as it concerns the waste batch

- Calculated a penalizing systematic uncertainty in order to have the 5th percentile of the distribution of the activity ratio (F1,F3)/(F1,F2,F3,F4) greater than 1.
  → Statistically speaking, for (F1,F3) to be systematically penalizing at the package level with e.g. 95% confidence. we would need to multiply values by 6.5.
  → However, this is not acceptable because it would lead to overly conservative activity declarations
  → Not required by ANDRA TFA specifications
- Future work: Qualify activity values of the "Hot" face at 2σ with respect to the (F1,F2,F3,F4) activities.

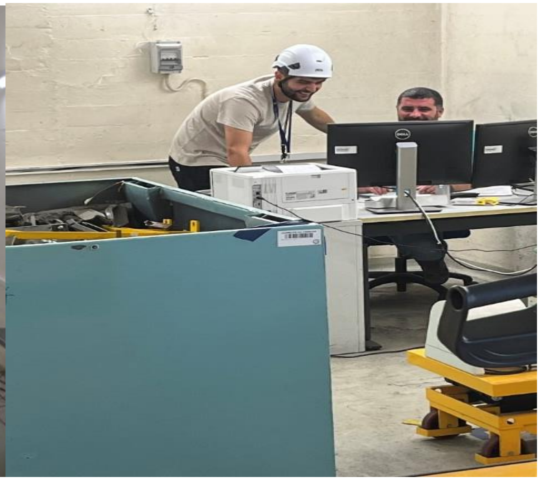
Other activities at CERN

- Learning R programming and Analysis software

- Teamwork → interaction engineer/technicians



- Carrying out characterization measurements of radioactive packages



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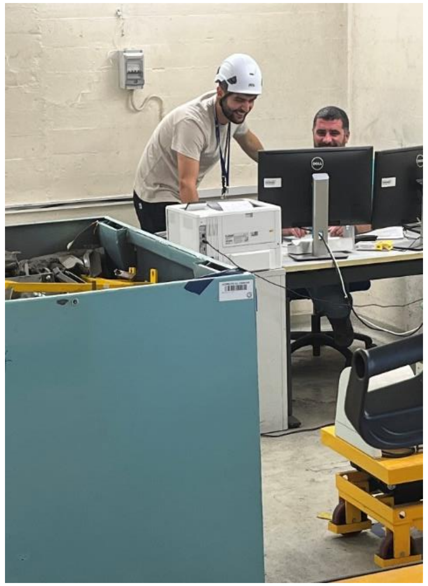
- This was a rich and empowering experience for me




Thank you!

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A new gamma spectroscopy methodology based on probabilistic uncertainty estimation and conservative approach

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Thomas Frosio *, Matteo Magistris, Nabil Menaa, Régis Michaud, Maeva Rimlinger, Chris Theis

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