Realistic and achievable sample representativeness for the environmental sampling during an OSI

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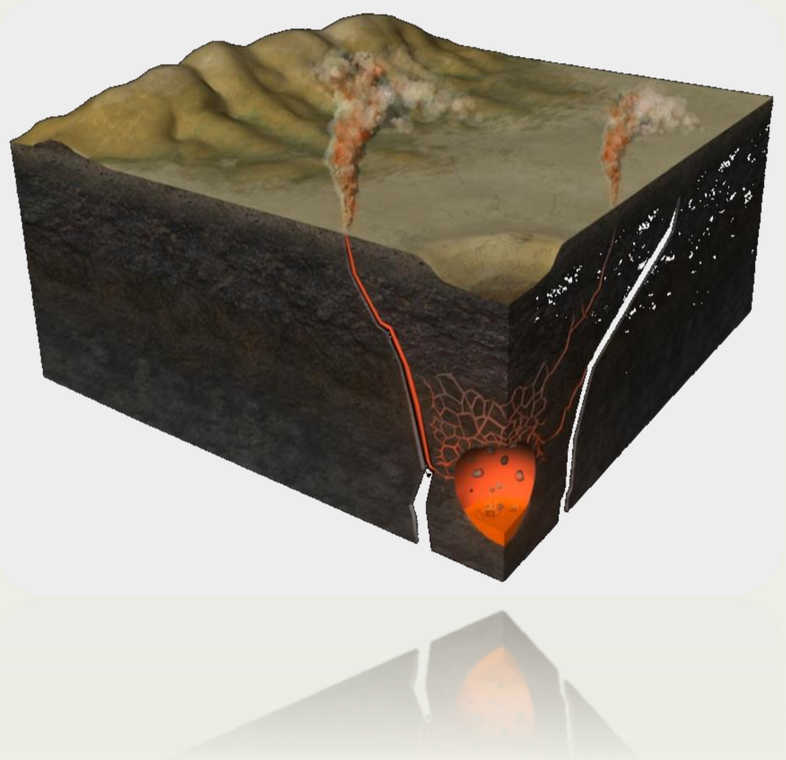
CONSTRAINS OF ENVIRONMENTAL SAMPLING IN AN OSI

- An underground nuclear explosion (UNE) presents quite a unique and complex scenario for post-detonation environmental monitoring
- A well contained UNE may not vent radioactive atoms to the surface at all.
- When a release does occur, it may be delayed, intermittent, or localized to a small seepage.
- Complex geological formations, such as those fractured by a nuclear explosion, represent a significant challenge for transport modelling.
- Furthermore, a nuclear explosion's energy alters the rock, creating new fractures and rubble zones.
- Data from a radionuclide plume often show a skewed distribution.



We acknowledge the support of the Italian Ministry of Foreign Affairs contributing to the activities of the National Data Centre – RN component

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IN THE CONTEXT OF AN OSI…

1) Does your **sample** give you the most reliable picture of the phenomena you are observing?

2) Does your **analysis** give you the most accurate picture of the sample you are measuring?
3) How many samples are you able to measure?

Photograph by Microgen Images/science Photo Library - Pixels

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WHAT TO CONSIDER

- The physics of radionuclide production and transport (pre-requisites)
- The quantity of material available for detection (IMS, external data…)
- The statistical methods for sample size calculation
- The number of measurements needed to achieve a desired level of confidence
- The practical considerations of field sampling and laboratory analysis (logistical constraints of the mission).

Ref.
Miley HS, Eslinger PW, Friese JI (2021) Examining nuisance aerosol detections in light of the origin of the screening process. Pacific Northwest Nation

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ANOMALY DETECTION

An anomaly in OSI can be defined as a localized area/materials of residual activity concentration of OSI relevant radionuclides that exceeds a predetermined threshold or that is not expected in that area.
The objective of the OSI environmental sampling and lab measurements is to confidently detect these areas of anomaly.

This detection :

- depends on the difference between the anomaly's concentration and the ambient background activity concentration of the OSI relevant radionuclides
- depends on the specific detected OSI relevant radionuclide
- is heavily influenced by the sensitivity of the instruments used for measurement

Ref.
Miley, H.S., Eslinger, P.W., Bowyer, T.W. *et al.* In the nuclear explosion monitoring context, what is an anomaly?. *J Radioanal Nucl Chem* **333**, 1681–1697 (2024). https://doi.org/10.1007/s10967-024-09411-y

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STATISCAL ERRORS IN HYPOTHESIS DECISION

Every survey design must balance two types of potential statistical errors. Lowering the chance of one often increases the chance of the other.

I. **Type I Error:** The probability of incorrectly attribute an anomaly or a suspicious detection (a false positive), leading in an OSI to:
   - Early ending of the inspection
   - Wrong attribution of the violation/violator
   - Loose of credibility of the OSI

I. **Type II Error:** The probability of incorrectly concluding that a no anomaly has been detected (a false negative), leading in an OSI to:
   - Extension of time of the inspection and related costs
   - Wrong conclusion
   - Loose of credibility of the OSI

	The Null Hypothesis is	TRUE	FALSE
DECISION (based on sampling and measurements)	Rejected	Type I error False Positive Probability = α	Correct Decision True Positive Probability = 1- β
	Not Rejected	Correct Decision True Negative Probability = 1- α	Type II error False Negative Probability = β

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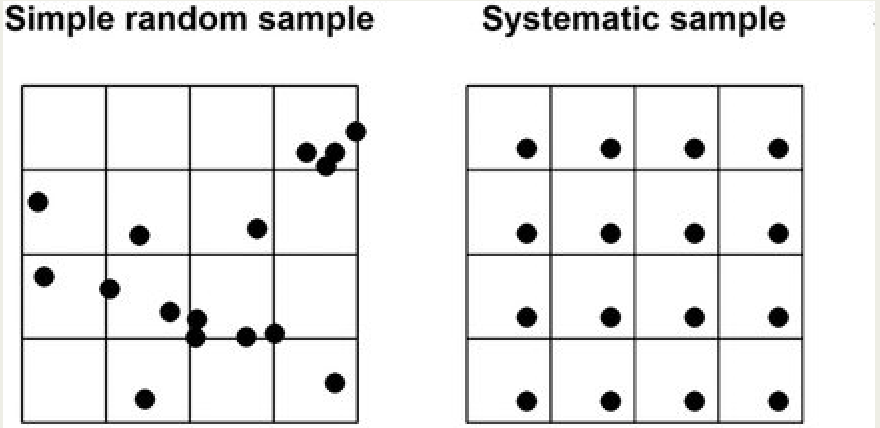
TYPE OF SAMPLING

Systematic Grid-Based Sampling: for large-area surveys (i.e. Chernobyl)
Simple Random Sampling (SRS): every member of the population has an equal chance of being selected.
Judgemental or Biased Sampling: This is a non-statistical method where samples are chosen based on expert judgment.

A purely random or systematic approach is often impractical or inefficient



Picture from Wills, Skye & Roecker, Stephen & Williams, Candiss & Murphy, Brian. (2018). Soil sampling for soil health assessment. 10.19103/AS.2017.0033.18.

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SAMPLING PLAN

Parameter	Description	Role in Sample Size Calculation
MDA	Minimum Detectable Activity. A measure of instrument sensitivity.	Determines the concentration that can be reliably measured. MDA is a function of background, efficiency, area, and time.
Threshold Concentration	The radioactivity concentration that corresponds to a significant hotspot concentration.	Used as the target concentration in the true hypothesis test
LC	A statistical threshold that determines whether a measured value is truly due to radioactivity or simply represents random background fluctuations	the critical level influences the acceptable statistical risk, directly impacting the required sample size by affecting the confidence level and the magnitude of the difference
Type I Error (α)	The probability of a false positive	A pre-defined value that must be considered when determining the sample size.
Type II Error (β)	The probability of a false negative	A pre-defined value that directly impacts the number of samples required to achieve the desired confidence

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Parameter	Description	Effect on Sample Size
Desired Confidence (1−α)	The probability of lowering level of interest of the search zone the	Increase
Desired Power (1−β)	The probability of raising the level of interest of the search zone	Increase
Width of tolerance (Δ)	The range of concentrations around the anomaly level where decision uncertainty is greatest.	Decrease
Site Variability (σ)	The estimated standard deviation of activity levels across the site.	Increase
Required LLD	The minimum concentration of a radionuclide that must be detectable.	Increase

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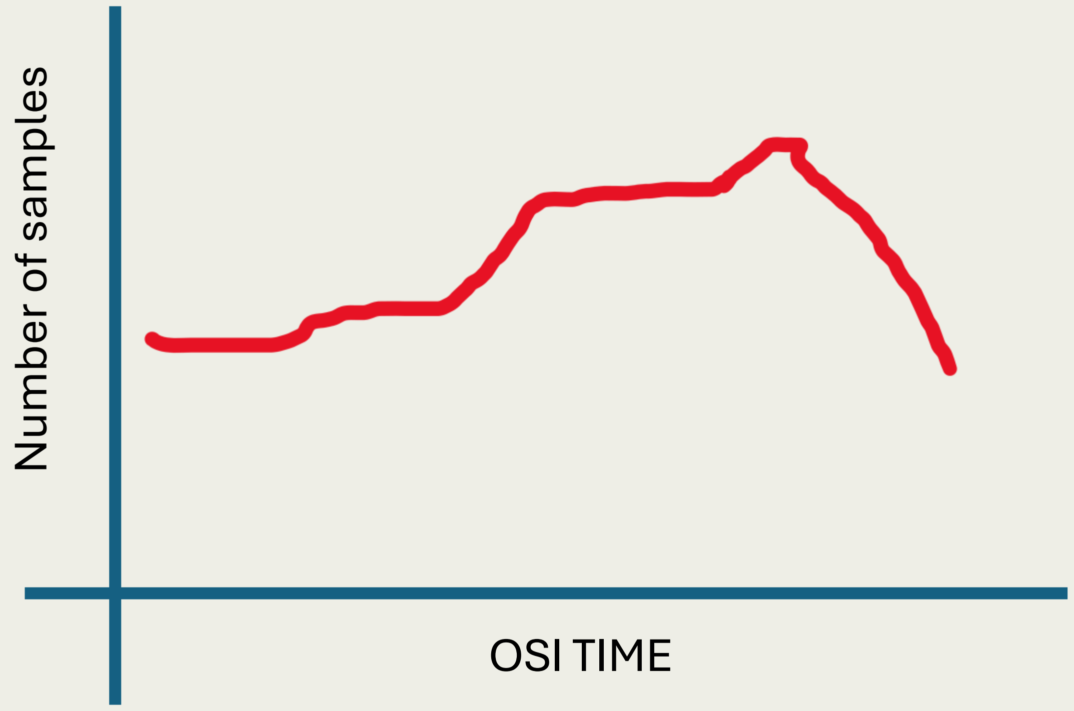
SEARCH LOGIC IN OSI

Scoping Sampling: preliminary assessments to identify search zone and to assign level of interest: limited number of scans and samples to provide an initial assessment of the radiological hazards.

Characterization Sampling: when anomalous detection is identified, a more detailed characterization survey is performed: greater number of samples to further narrow down the search zone.

Final Sampling: the ultimate sampling and measurements to demonstrate the detection: more samples from the same zone to obtain statistical tests.



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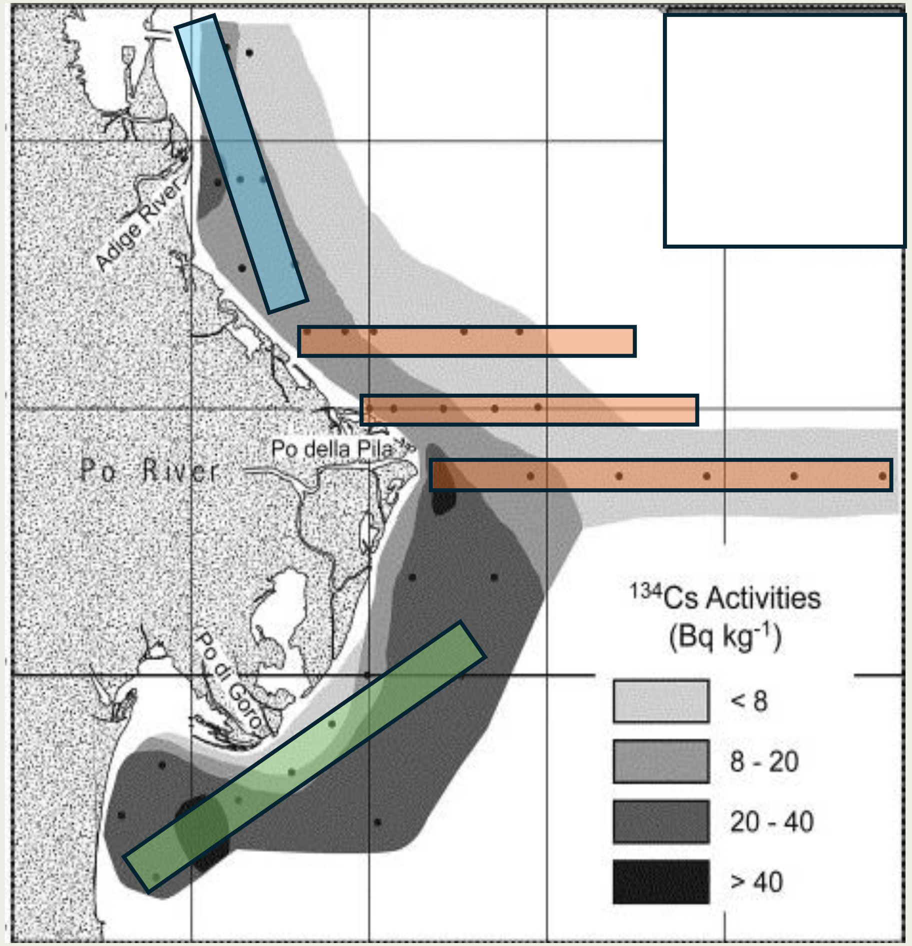
CASE STUDY: SAMPLING WITH KNOWN SOURCE TERM

- Define the objective – measure the activity concentration of the Cs137
- Choose the sampling method – random + judgmental
- Evaluate the sample size – 40 samples
- Check the sample characteristics – same sample
- Evaluate the sample quantity (considering lab requirements) – 100 g
- Measurements and evaluation of results



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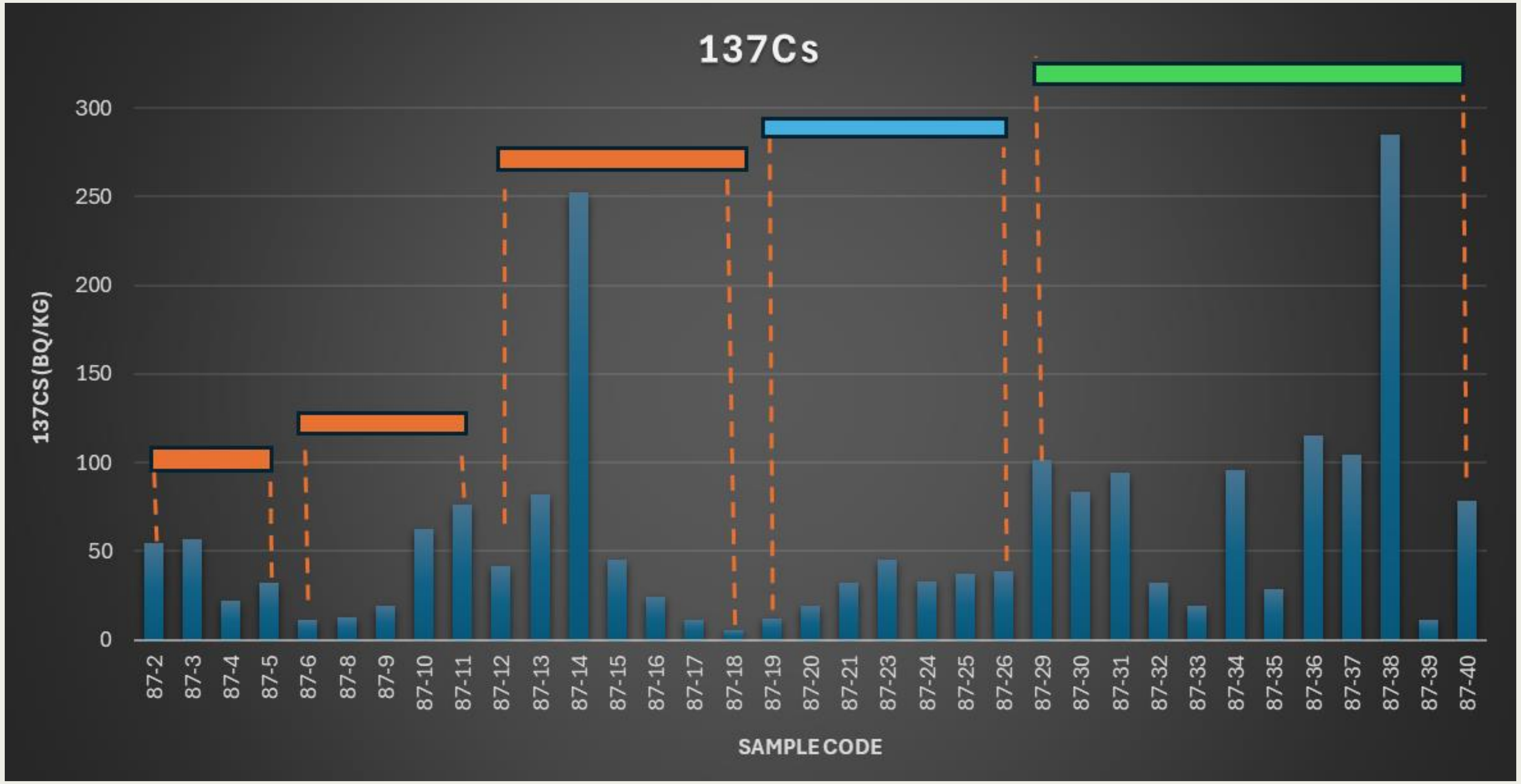
RANDOM + JUDGEMENTAL SAMPLING



- Source location was known
- 2 different sampling strategy (radial and linear)
- Random + Judgemental sampling
- N. of samples calculated according to the objectives
- Large lab capability

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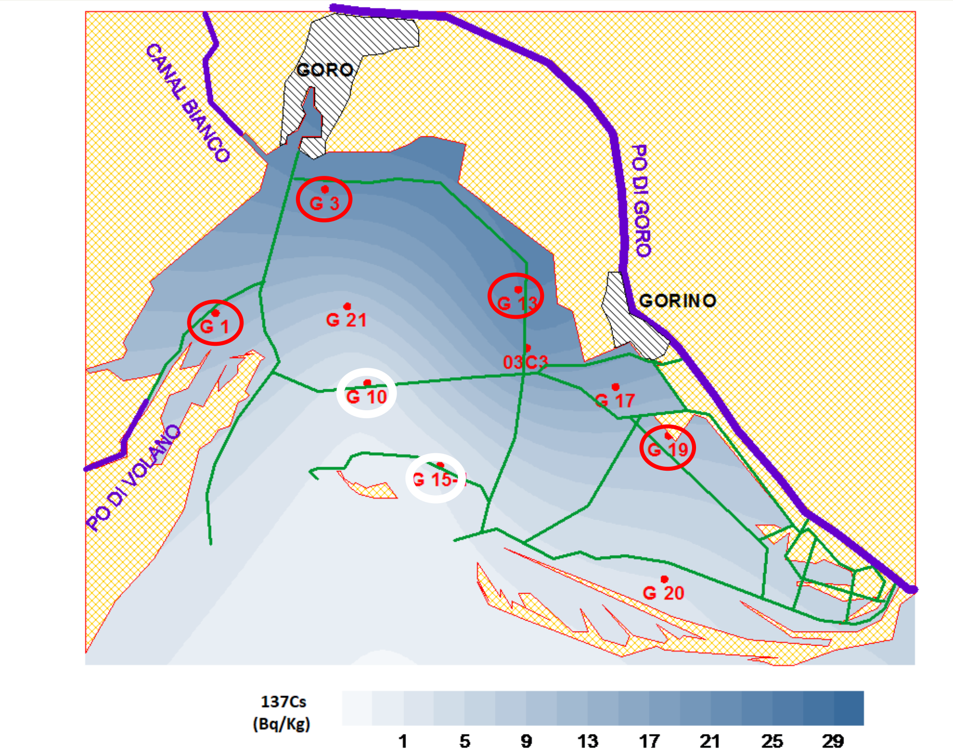
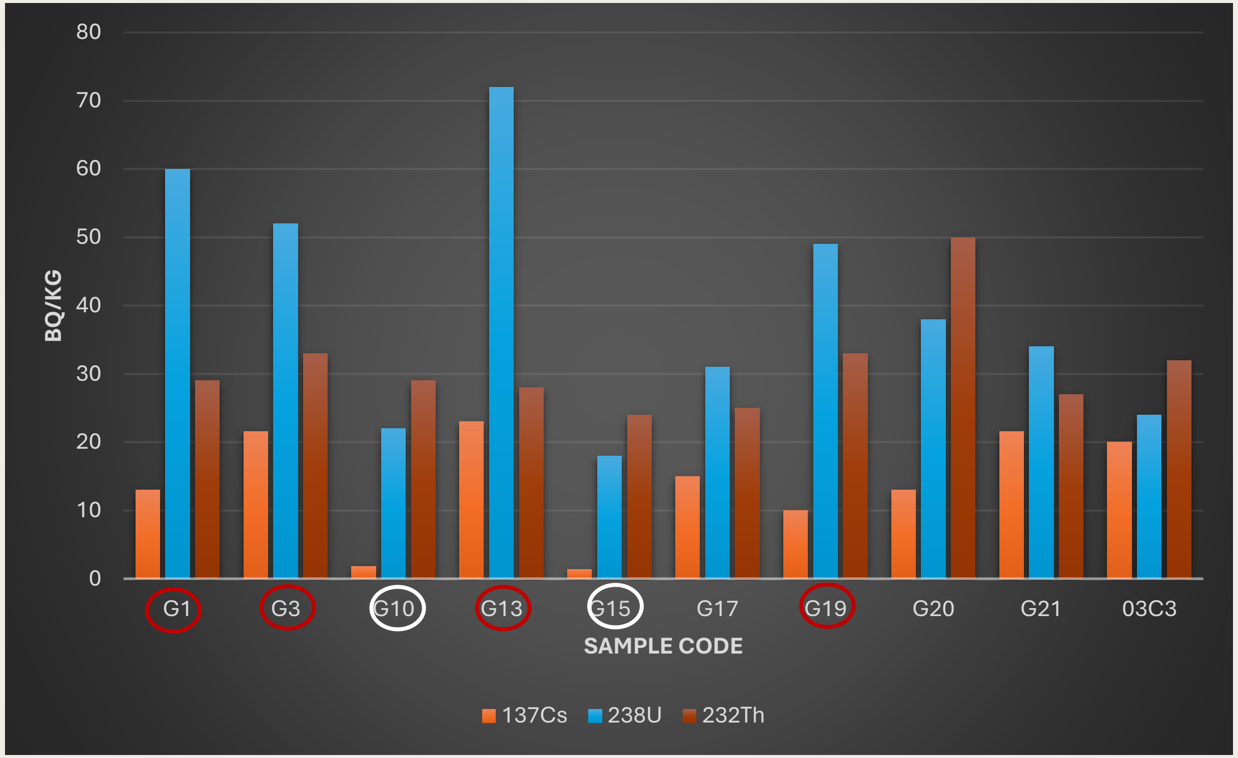
JUDGEMENTAL SAMPLING





- Choice of the mission objective – verify the Cs source term
- Sampling strategy – judgemental , hypothesis oriented
- N. of samples chosen by time constrain, significance, costs, lab capacity (10)

Ref. Telloli C, Rizzo A, Bertelli L, Bartolomei P, Marrocchino E, Vaccaro C. (2019) "Evaluation of the radionuclide concentration in the sediments of the Sacca di Goro (Italy)". Environmental Analysis & Ecology Studies, 4(5), 1-4.
DOI: http://doi.org/10.31031/EAES.2019.04.000598

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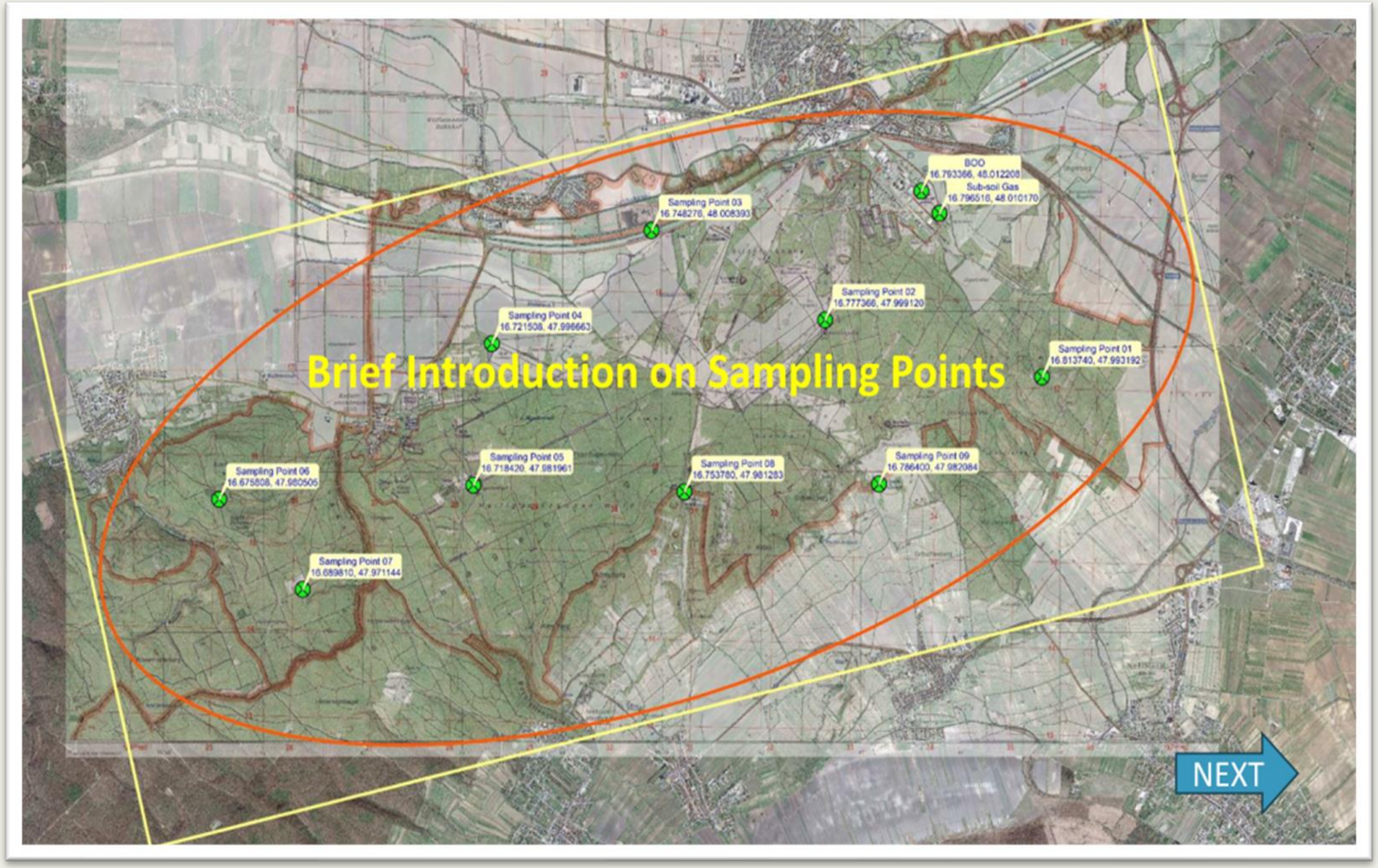
DIRECTED EXERCISE DE23

- 9/10 particolate samples
- 6 In situ
- Small lab capability
- Nearly Systematic grid sampling
- Scoping sampling (narrowing down search logic, identify search zone)



Map ref. Presentation DE23-debreifing by PTS

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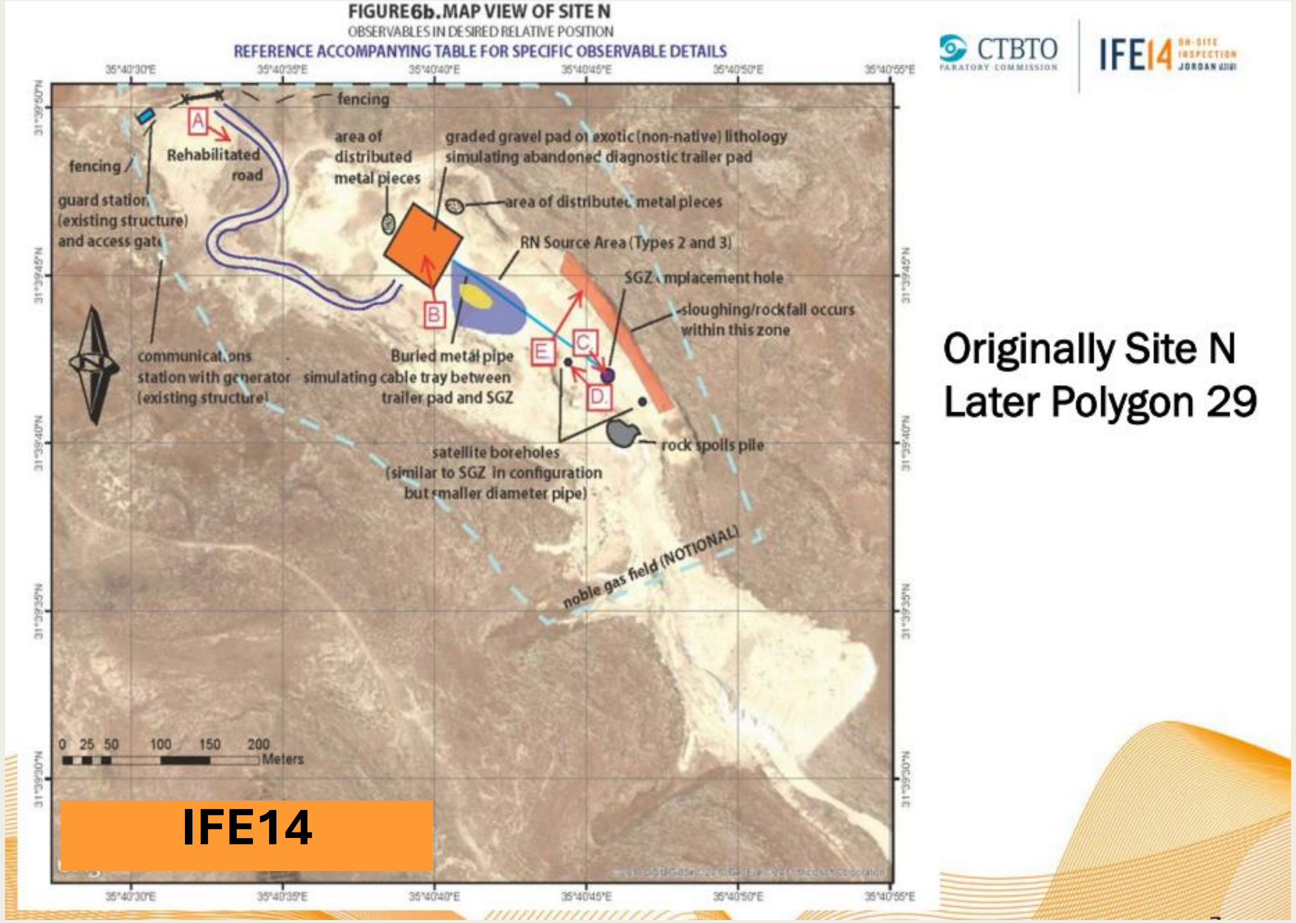
INTERGRATED FIELD EXERCISE IFE14



Narrowing down the area from $1000\ km^2$ to $300\ m^2$

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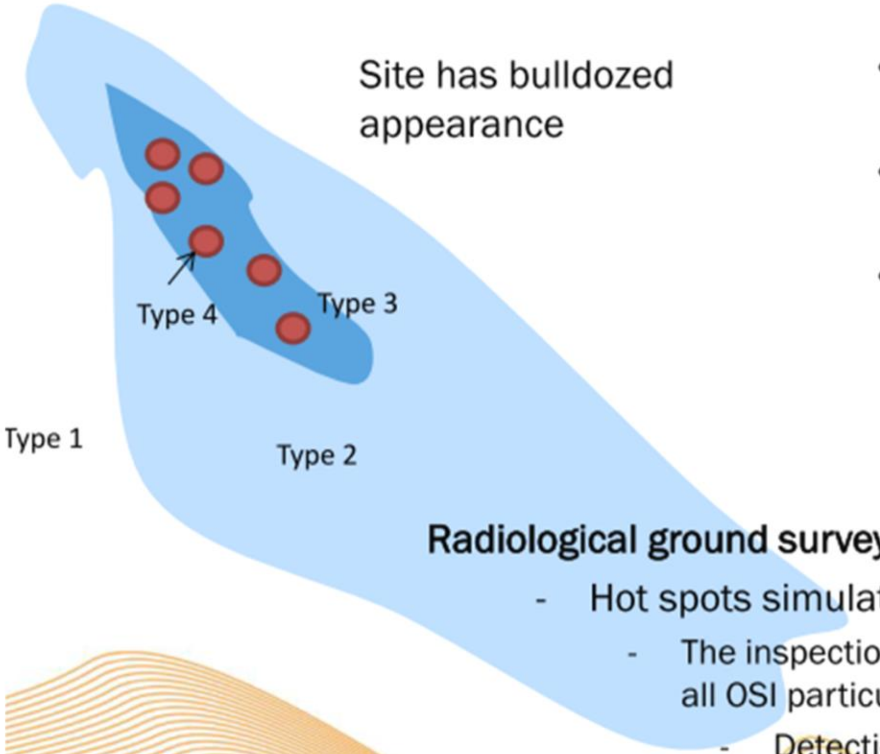
Detected radioisotope is I-131 Surrogate Ag-110m (type 2,3) or Co-60 (type 4)



- Type 1
  - Background (no inject)
- Type 2
  - Weak iodine surrogate
- Type 3
  - ~10x type 2
- Type 4
  - Hot spots: Detectable using ground-based survey (or in-situ gamma spec if used)

Radiological ground survey and in situ gamma spectroscopy

- Hot spots simulated by buried sources (10 x 40 MBq)
  - The inspection team provided with an equivalency table for all OSI particulate relevant radionuclides
    - Detection of x is detection of y
    - Only one actual surrogate was used
    - To use actual I-131 is risky for H&S reasons
- Sources contained in Aluminum pipe

Ref. Presentation IFE 14 Briefing –Dec. 2014 by Gordon MacLeod

- ➢ 130 particolate samples
- ➢ ca 150 analysis
- ➢ 31 In situ
- ➢ Good lab capability
- ➢ Scoping sampling, then judgemental sampling

With 130 samples, we were able to exclude some search zone, characterise others and detect the anomaly.
The workload of the lab was intense but affordable.

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CONCLUSION

I. **Source-Term Analysis:** study the phenomena to calculate the expected radionuclide production and surface concentration. This step is foundational, as it provides the threshold concentration, for the statistical models.

II. **Define Risk and Objectives:** Determine the acceptable Type I (α) and Type II (β) errors based on mission objectives and risk tolerance. This crucial step is a strategic decision that directly influences the number of samples required.

III. The **MDA** provides the technical boundary of what is detectable.

IV. The **LC** provide the input for the statistical sample size

V. The **statistical framework may** be applied since the beginning driven by predefined levels of confidence and acceptable decision errors

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CONCLUSION

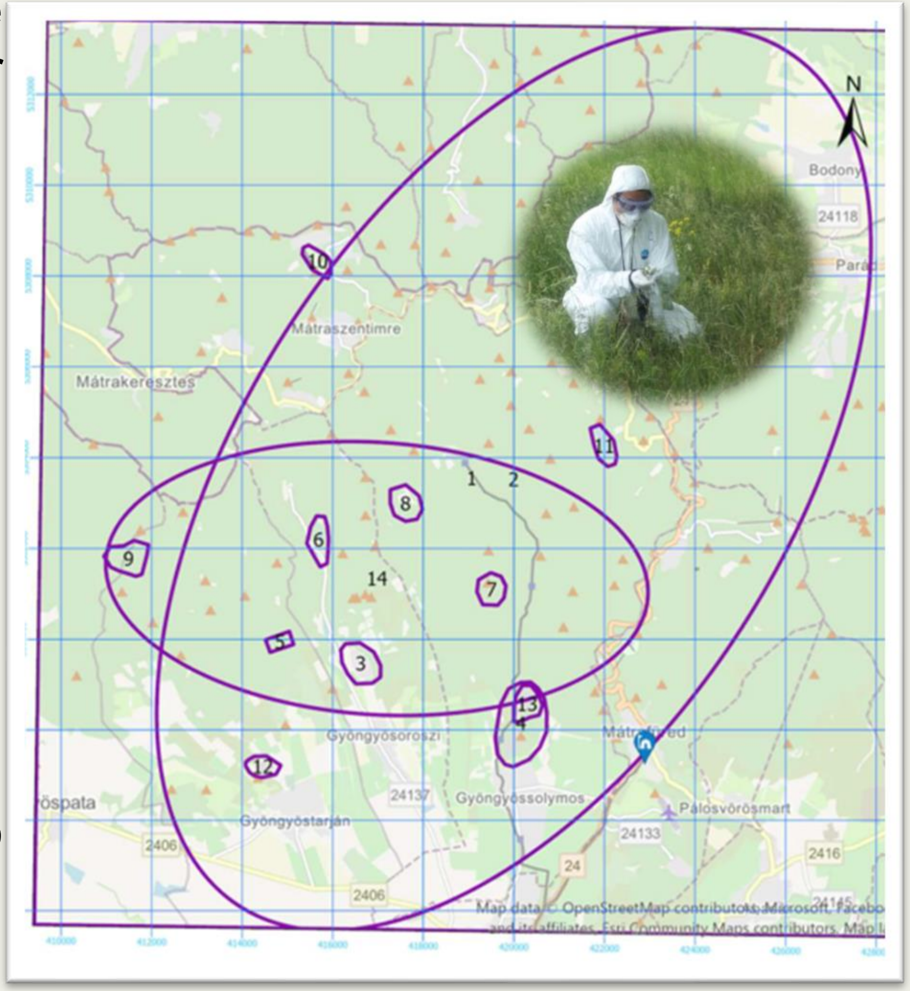
VI. Design Sampling Strategy: Choose the most appropriate methodology, such as a systematic grid for broad coverage or a geostatistical approach for greater efficiency.

VII. Calculate Sample Size:

- Use equations from the most suitable statistical methods to determine the minimum number of samples required to meet the defined objectives.
- If not possible, start the sampling and apply in due course, considering the results of the search logic
- As a rule of thumb **5-8 samples** for day are **realistic** and **achievable** (100-160 samples in the first 25 days of inspection)

VIII. Plan for lab:, including the number of replicates and blanks, to ensure **data quality**.

IX. The **expertise** of the inspectors and the applied **procedures** can improve the efficiency and accuracy of the entire campaign



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THANK YOU

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