



# IGD-TP WG4 Introduction

## 2016-10-25

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# WG 4

- SNETP introduction
- Waste issues Generation IV
- SPIRE – characterisation of spent nuclear fuel for geological disposal

# Characterisation of the spent nuclear fuel

- Geological deposition – needed also for Gen IV reactors to some extent
- KBS-3 example
- (Also other need such as leaking and damaged fuel – not covered here)

# SPIRE

- Purpose and goal

To develop methods and procedures to have sufficient knowledge of each fuel element at the time of encapsulation for final disposal.

Great potential for optimisation of repositories – large economic impacts in the order of billions of euros.

Filling of canisters

Number of canisters – for Swedish case marginal cost of one canister around 1 MEu – total amount canisters around 6000

Distance between canisters

Distance between deposition tunnels

# SPIRE

- Umbrella generally for fuel characterisation:

Temperature requirement verification – decay power

(KBS-3: temperature requirement on bentonite 100 oC, on canister insert 125 oC)

Criticality

Radiation field

Radionuclide inventory

Safegaurds – amount of fissile material

(Fissile gases etc.)

Compare other projects such as Disco

# SPIRE

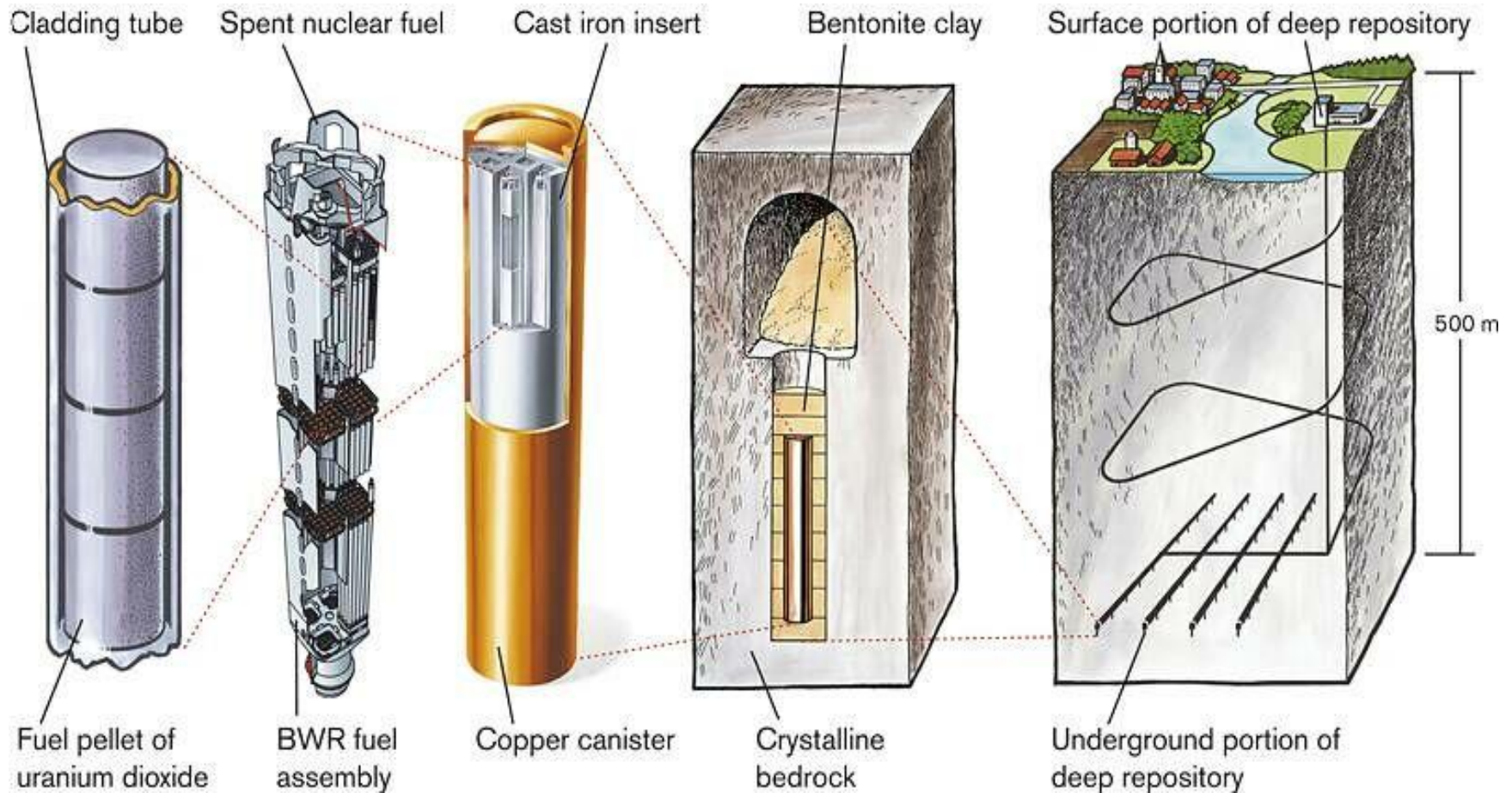
- Great need for collaborations as experiments and modelling is expensive and resources scarce
- Many issue general for different repository concepts – all have temperature requirements e.g.

Undervalued issue so far

# SPIRE

Need to integrate 'fuel physics' and 'fuel chemistry' – often look at the same issue from different perspectives, such as radionuclide inventory

# KBS-3





# Canister in deposition hole

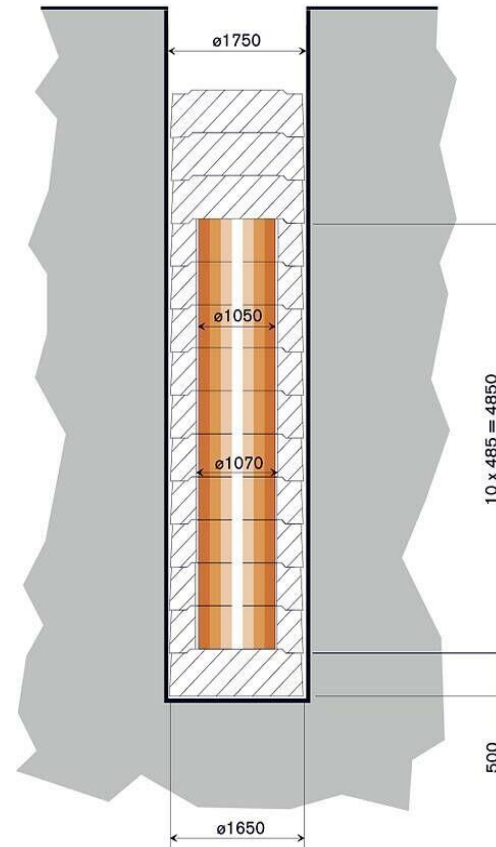
## Bentonite clay:

Natural clay with very special swelling properties (nano-material)

Montmorillonite (around 80%) + secondary minerals

## Swedish bedrock:

More than 900 million years old

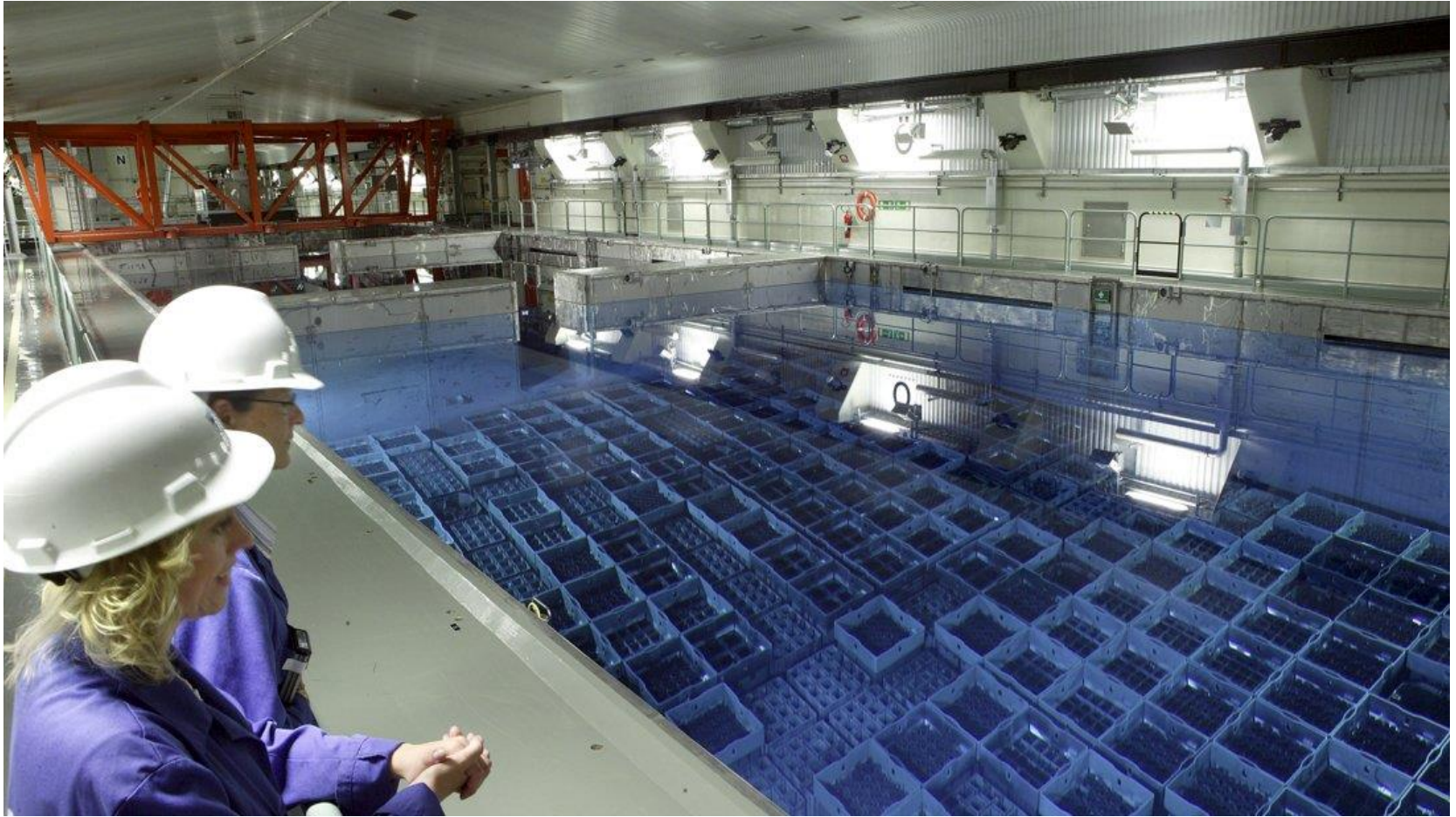


# Clab – Central Interim Storage Facility for Spent Nuclear Fuel





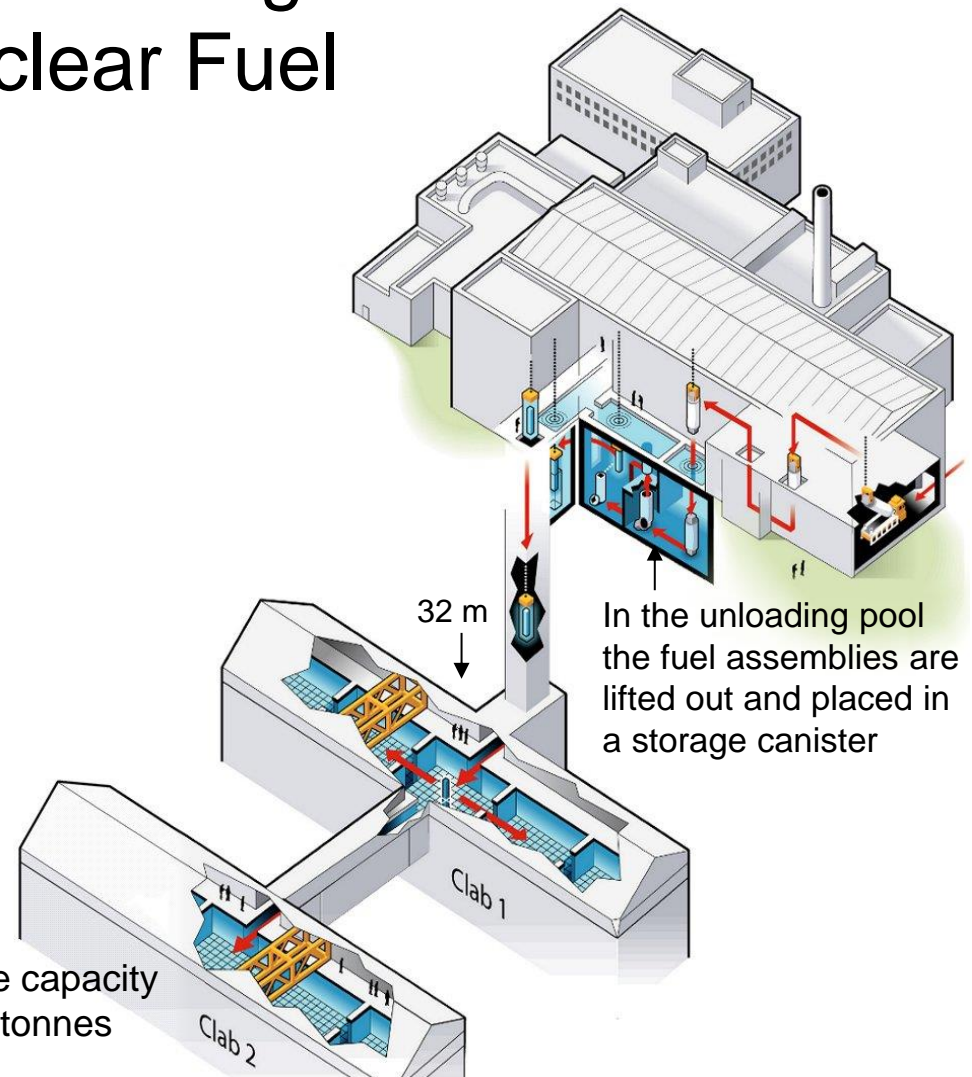
# Clab: Water is an effective radiation screen



# Clab – Central Interim Storage Facility for Spent Nuclear Fuel



**Clab 2** increases the capacity from 5,000 to 8,000 tonnes



Graphic art: Mats Jerndahl

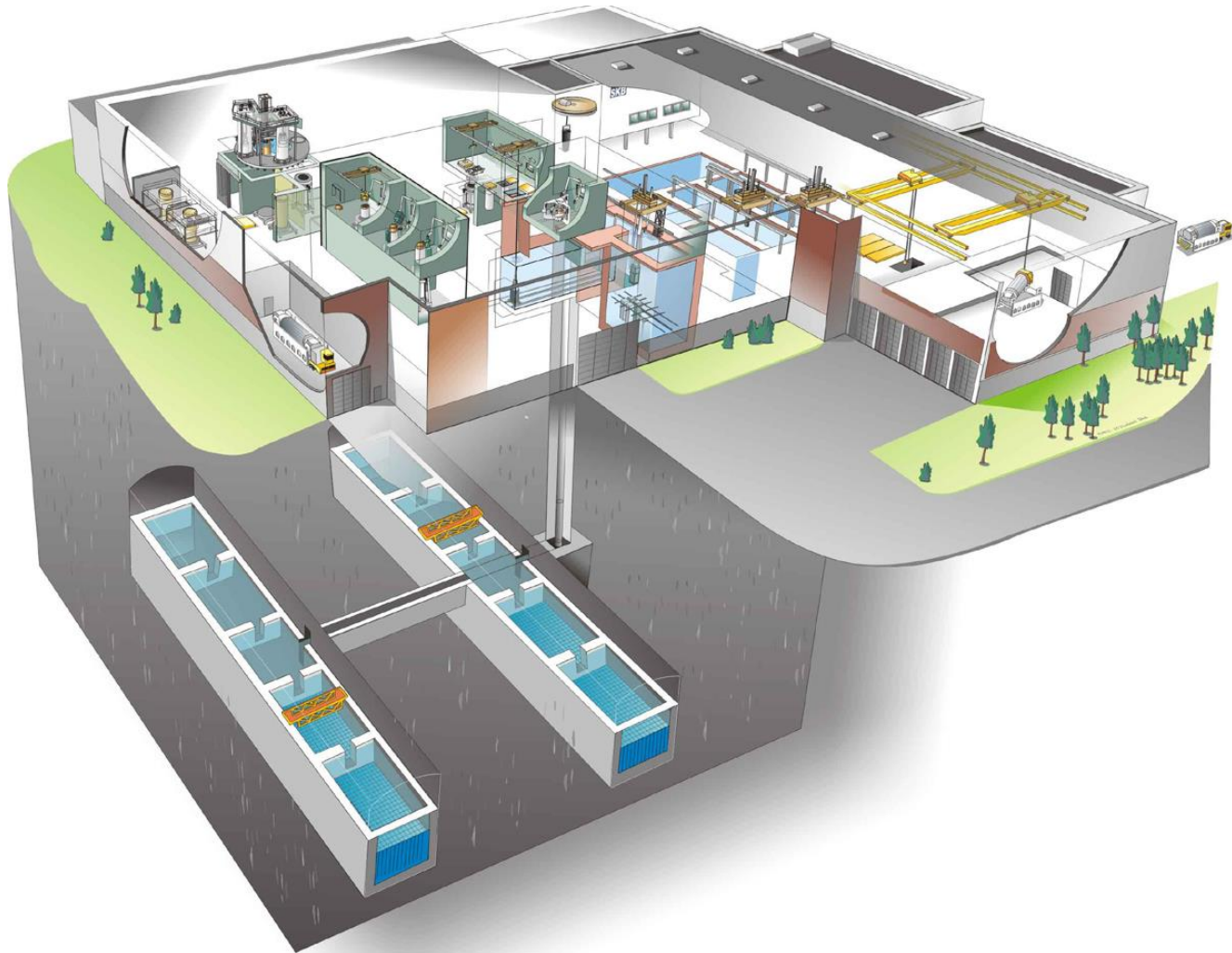




# Encapsulation plant



# Clink – An integrated encapsulation and interim storage facility



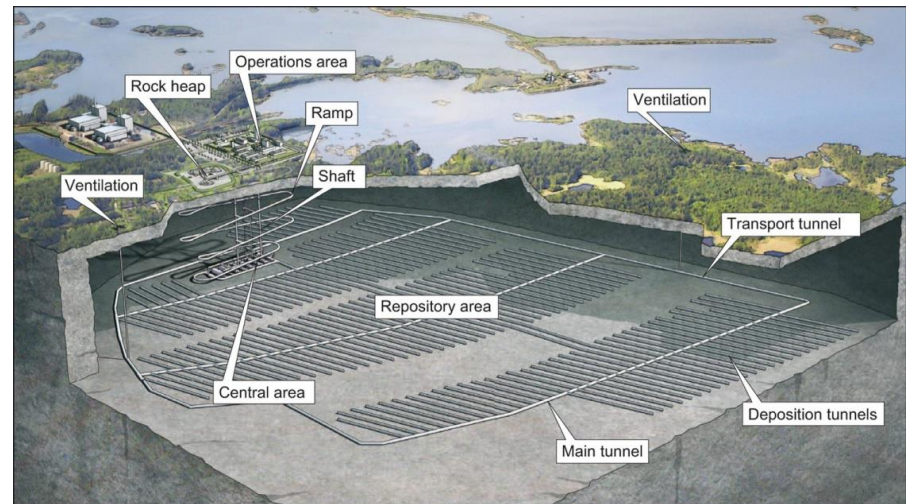


# The Nuclear Fuel Repository

- Final disposal of all spent fuel from the present Swedish nuclear energy programme
- Design capacity 6 000 canisters corresponding to 12 000 tonnes of spent fuel
- 15 years of planning, design, construction and commissioning
- 60 years of operation followed by decommissioning and closure



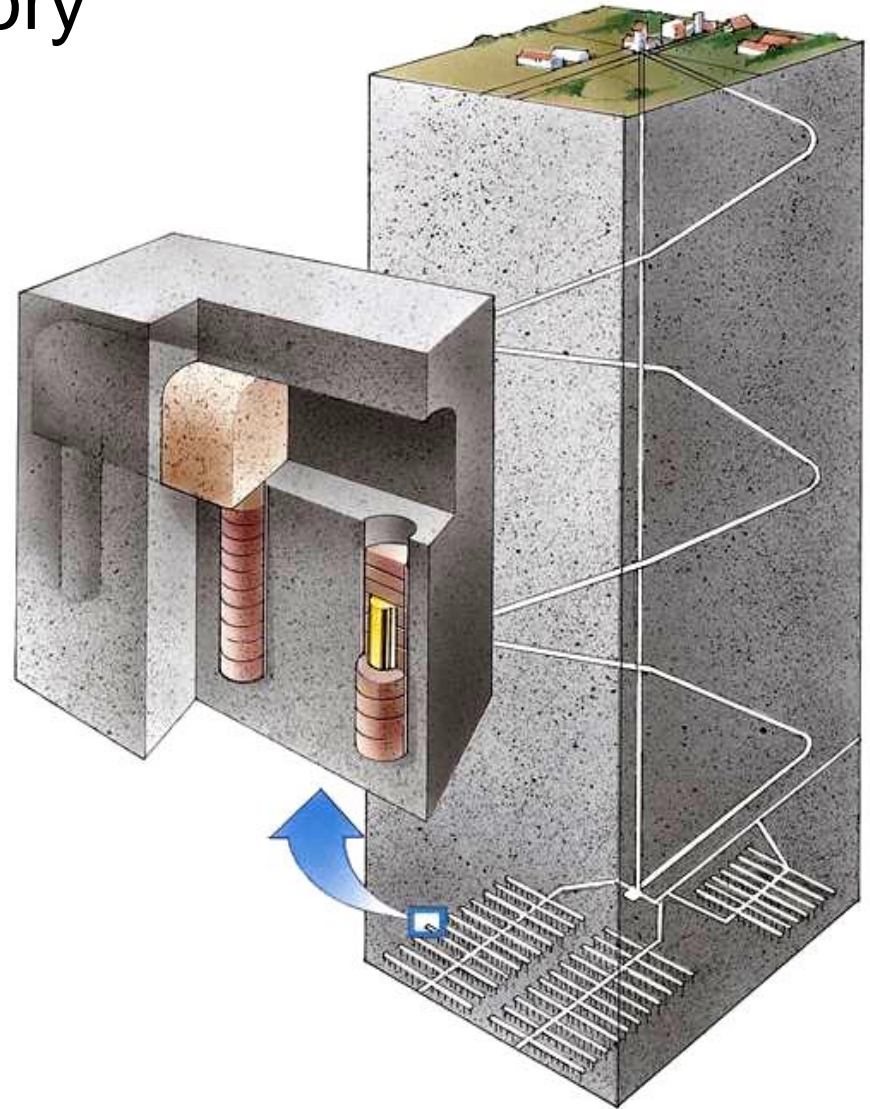
Planned surface facilities at Söderviken, Forsmark



The repository at 470 m depth, when fully built-out

# The future final repository

- Depth: 400–700 m
- Rock requirements:  
2–4 km<sup>2</sup>
- Around 4,500 canisters  
after 40 years reactor use





# IAEA Safeguards of nuclear material

- Normally an owner of nuclear material declares it, and then IAEA and other authorities can inspect that it is
- A final geological repository is different from other storages of nuclear material in that it cannot be inspected once it is deposited
- This means that the safeguards procedure before deposition will be strict: measurements will be necessary of each fuel assembly

# Fuel measurements

- Decay heat – fulfil temperature requirement on canister and bentonite; optimization of repository – general for all types of repository, including dry casks (comp. Germany)
- Safeguard: identify correct fuel, missing pins
- Contents of fuel – amount of fissile material
- Radionuclide inventory
- Burn-up (BU), Initial enrichment (IE), Cooling time (CT)
- Criticality – multiplicity
- Radiation doses: gamma and neutrons

# Fuel measurements

- All can ideally be determined with one joint measurement system together with modelling code and known history of the fuel
- Nuclear (gammas, neutrons) and calorimetric ('thermos') measured
- Important establish methods with sufficient statistics so they be general
- From a safeguard point-of-view, geological repositories are an anomaly in the sense that the nuclear material is not inspectable
- Hence requirement in principle by IAEA to measure on each fuel assembly

# Decay heat

- Geological repository:

Important for the design of canisters and repository

Strict temperature requirements on canister and bentonite (and on rock)

Important for the optimisation of canisters and repository (what fuels encapsulated, how far between canisters in the rock)

- Dry casks: comp. Germany where authorities do not accept present determination of decay heat for dry cask storage due to unknown uncertainties
- Fundamental parameter in codes such as Scale, where content (e.g. U, Pt) is determined
- Important parameter to evaluate in reprocessing: main argument for reprocessing economical, but then also cost of storage must be included

# Measurement system at encapsulation plant

- Present safeguards measurement devices: mobile, sampling (non-complete), for use in the field ('rough, unsophisticated'), low through-put etc.
- System at encapsulation plant: permanent, complete (all assemblies), robust, must give unambiguous results, complexity in principle acceptable, high through-put, low uncertainty

As there is sufficient information in the radiation field from the fuel, this is possible to achieve, but with significant method development

## Calorimetry

- SKB has had for decades one of the few (if not the only) calorimeter that can measure whole fuel assemblies, and have published lots of measurements
- Calorimetry has the potential to be accurate; in the order of 2-3 %
- Problem: requires long measurement times for each assembly several days for highest accuracy
- SKB has to determine around 12 assemblies per day
- This would then require hundreds of calorimeters, which would be very impractical

Wide collaborations to attack these issues

- Sweden (SKB), USA (DoE, LANL, ORNL, LLNL and more) , Euratom, Belgium, Japan, Korea

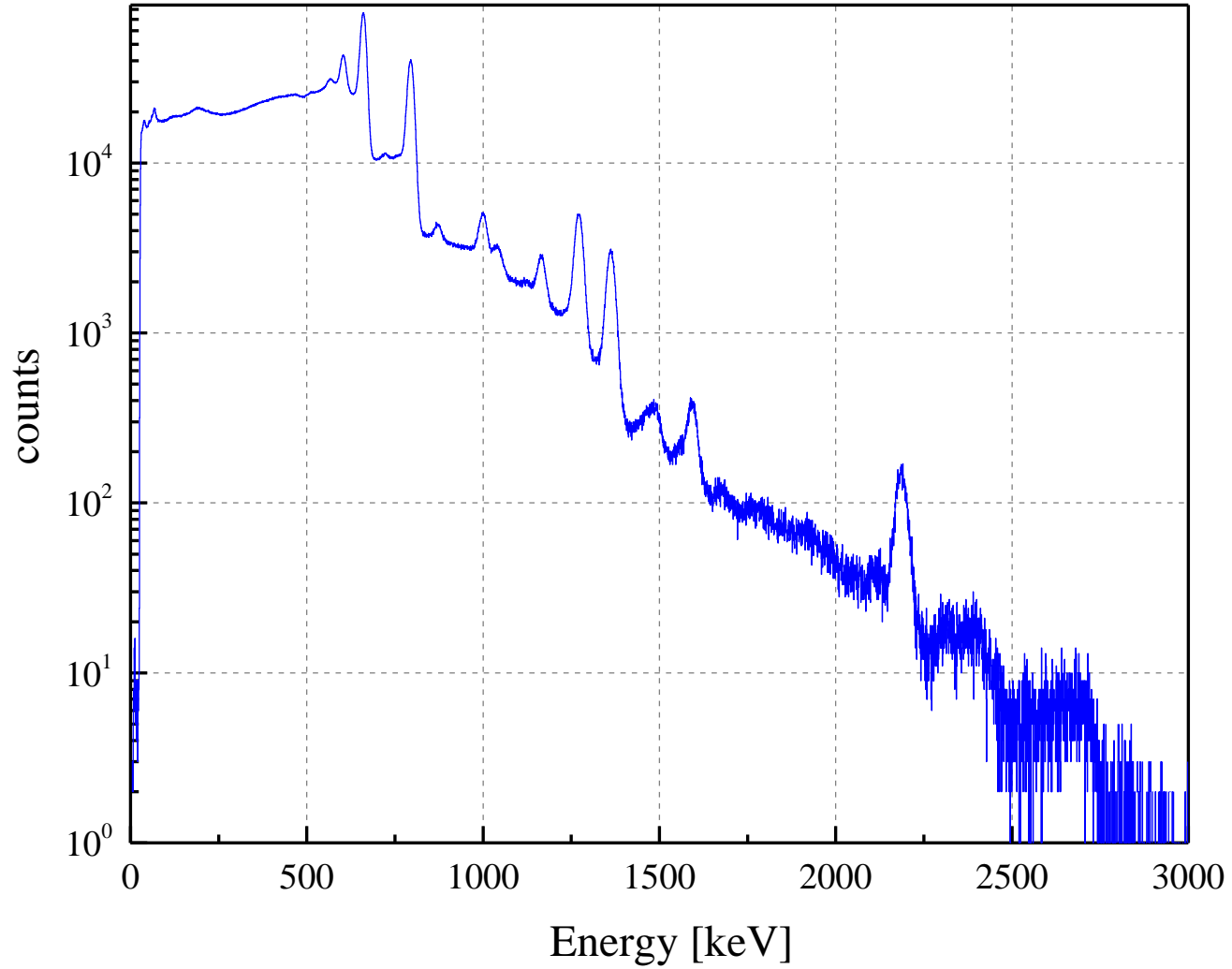
SKB-50: 50 fuel assemblies (25 PWR, 25 BWR) measured with a variety of techniques: gammas, calorimetry, neutron measurements, novel instruments etc.

- Europe: 'SPIRE' collaboration





# LaBr3 gamma detector



## Challenges

- Understand the fuel in terms of interpreting the signals from the radiation field
- Finding unambiguous relationships between e.g. decay heat and other measureable signals
- Decrease uncertainties substantially
- Few experts in each country
- Competence development and broadening vital
- Instrument development necessary

## Problems in the present

- Fairly high uncertainties on the methods and codes used at least 30 % - huge economic implications
- Codes based on known fuel history – status and quality of the fuel history is very varying and have seldom been recorded for the purpose of final deposition of the spent fuel
- Even if fuel history would be perfect, still large uncertainties due to lack of precise and complete cross sections etc.
- Variations over the fuel assembly itself
- Etc.

# Overview

- Description of research performed to date on spent fuel NDA: Next Generation Safeguards Initiative Spent Fuel Project.
- Non-Destructive Assay (NDA) analysis and research planned for CLINK
  - Analysis approach selected to match the inherent complexity
  - Experimental plans and time table



UPPSALA  
UNIVERSITET

SKB

 Lawrence Livermore  
National Laboratory



Sandia  
National  
Laboratories



MICHIGAN  
ENGINEERING  
UNIVERSITY of MICHIGAN

Euratom



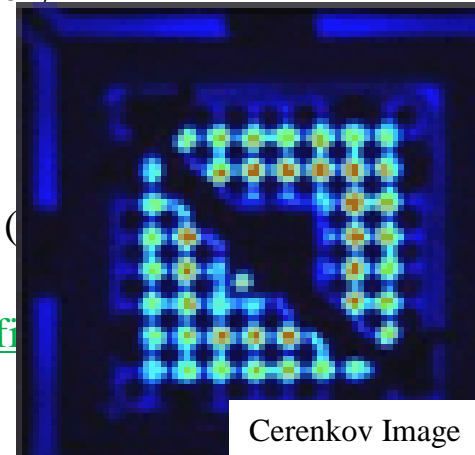
OAK RIDGE NATIONAL LABORATORY

MANAGED BY UT-BATTELLE FOR THE DEPARTMENT OF ENERGY

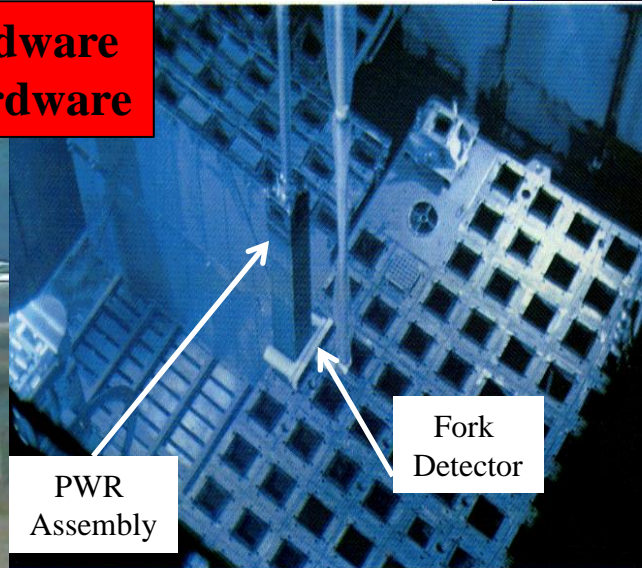
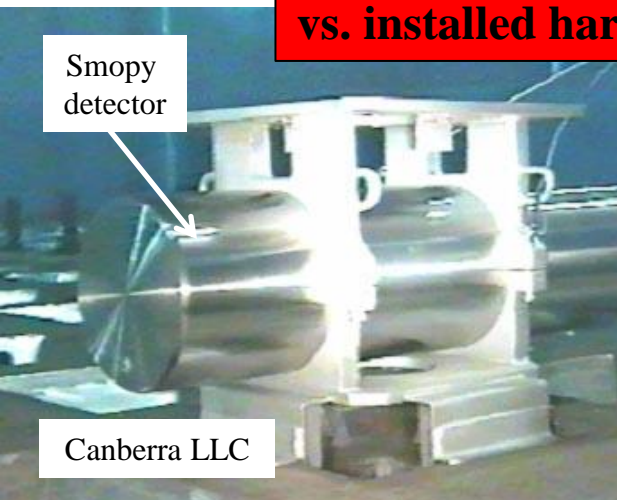


# State-of-the-practice in spent fuel NDA

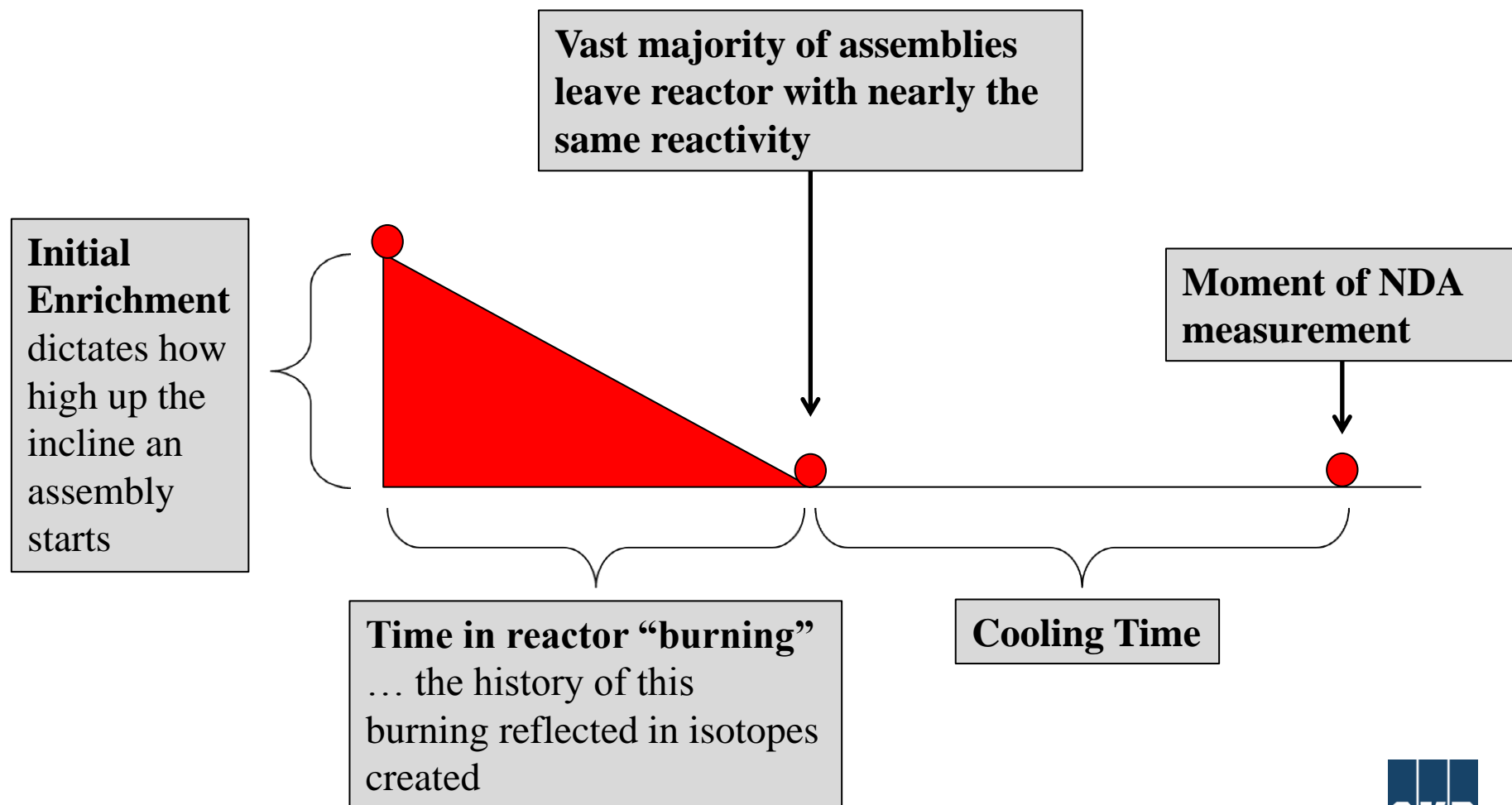
- Cerenkov Viewing Device (ICVD, DCVD)
  - Detects Cerenkov glow from water around assembly
- Spent Fuel Attribute Tester (SFAT)
  - $^{137}\text{Cs}$  is present
- FORK and SMOPY
  - Fission chambers  $\rightarrow$  total neutron ( $^{244}\text{Cm}$ )
  - Ion chambers and CdTe  $\rightarrow$  fragment gammas



**Inspection hardware  
vs. installed hardware**



# Thinking about the big picture: spent fuel assay from a potential energy perspective



# Variation in time: half-lives of a few key quantities of interest to CLINK (10 to 70 year time period)

Half-lives	Isotope(s)	Comments
effectively infinite	$^{235}\text{U}$ , $^{239}\text{Pu}$ , $^{238}\text{U}$	Majority of the fissile material
30 years	$^{137}\text{Cs}$	Dominant gamma source term
18 years	$^{244}\text{Cm}$	Dominant neutron source term
14 years	$^{241}\text{Pu} \rightarrow ^{241}\text{Am}$	Fissile material $\rightarrow$ neutron absorber, noticeably $f(t)$ in century after reactor
8.6 years	$^{154}\text{Eu}$	Second most enduring gamma source
4.7 years	$^{155}\text{Eu} \rightarrow ^{155}\text{Gd}$	Neutron absorber, noticeably $f(t)$ in century after reactor
effectively infinite	large number	Actinide and fission fragment neutron absorbers not already mentioned

Multiplication changes ~20% for a typical assembly as it ages from 5 to 80 years.



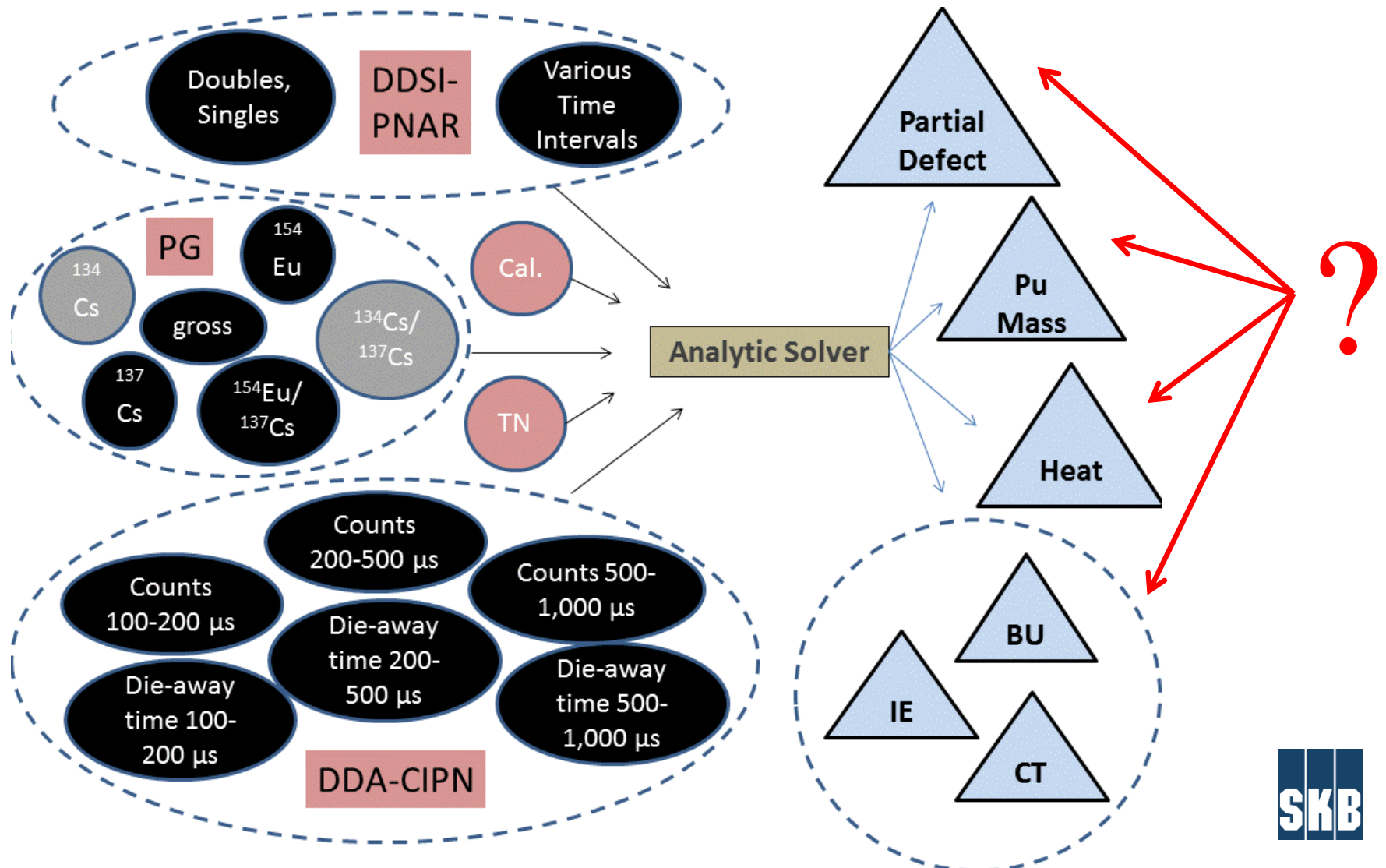
# What is meant by “data mining?” and “analytic solver?”

- **Data Mining** (Merriam-Webster): the practice of searching through large amounts of computerized data to “**find useful patterns or trends.**”
- **Analytic solvers** refers to **mathematical formulations** that enable data mining.
- With respect to spent fuel, the “large amounts of computerized data” include the **various NDA signals** or **derived quantities** ( $^{239}\text{Pu}_{\text{effective}}$ , etc.) as well as any **declared data** deemed appropriate for use.





# The analytic solver connects the measured signature to the quantity to be estimated, but ...

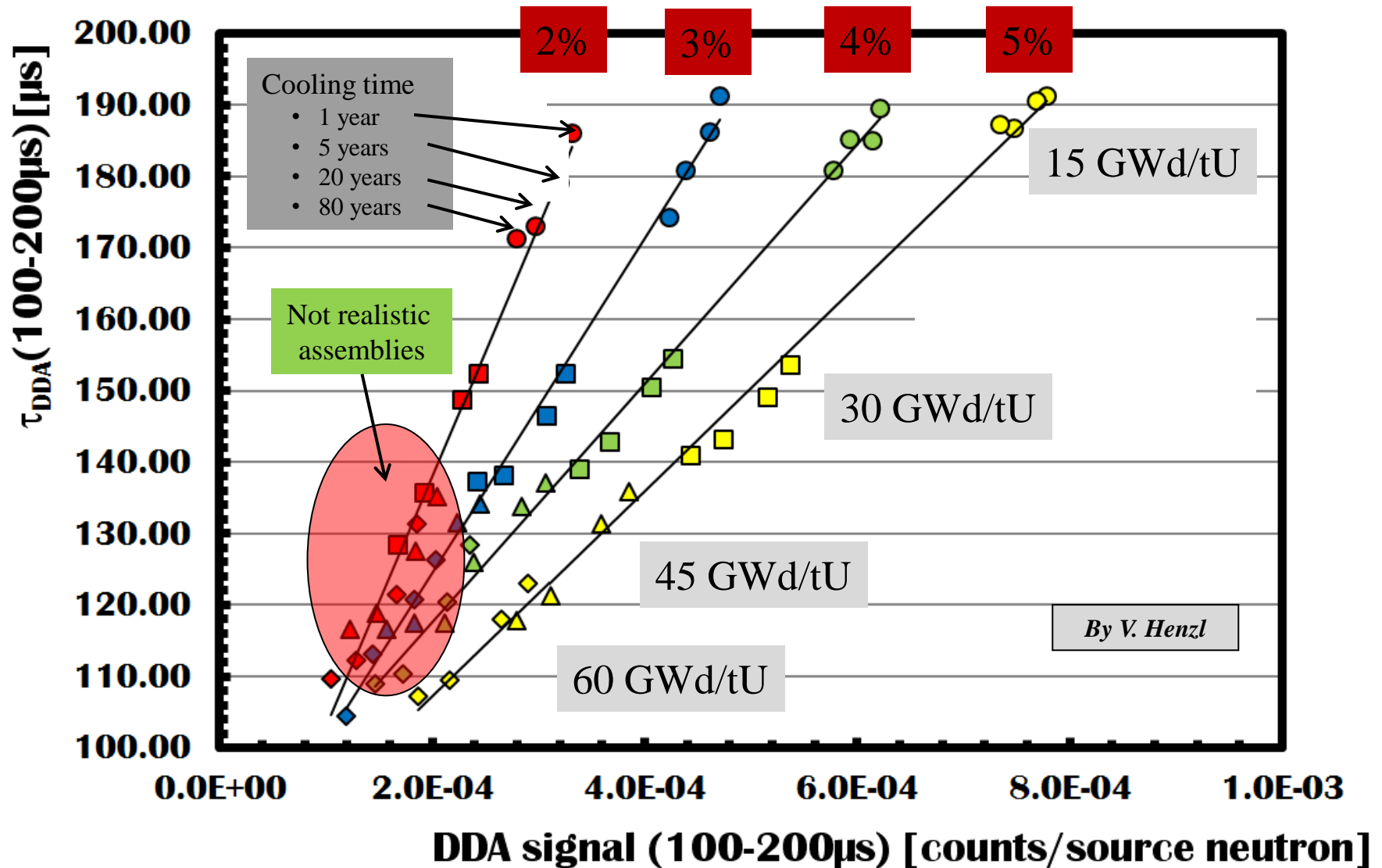


# Conclusions

- NDA spent fuel project (NGSI-SF) summary:
  - Recently completed measurements in ROK and Japan
  - An ambitious plan with 25 PWR and 25 BWRs is underway in collaboration with SKB, Euratom and DOE
- Data mining being applied to determine the optimal mathematical structure to match the complexity of spent fuel NDA signals and to enable a range of quantities to be estimated (heat, IE, BU, CT, Pu mass, partial defect)
  - Analysis being applied in a **systematic manner** (Fork through active techniques) in order to quantify capability for a range of assumptions (various quantities taken as “known”).



# Initial Enrichment, Burn-up and Cooling Time Estimation Promising



• **DETERMINING INITIAL ENRICHMENT, BURNUP, AND COOLING TIME OF PRESSURIZED-WATER-REACTOR SPENT FUEL ASSEMBLIES BY ANALYZING PASSIVE GAMMA SPECTRA MEASURED AT THE CLAB INTERIM-FUEL STORAGE FACILITY IN SWEDEN**

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• **ABSTRACT**

• The purpose of the Next Generation Safeguards Initiative (NGSI)–Spent Fuel (SF) project is to strengthen the technical toolkit of safeguards inspectors and/or other interested parties. The NGSI–SF team is working to achieve the following technical goals more easily and efficiently than in the past using nondestructive assay measurements of spent fuel assemblies: (1) verify the initial enrichment, burnup, and cooling time of facility declaration; (2) detect the diversion or replacement of pins; (3) estimate the plutonium mass [which is also a function of the variables in (1)]; (4) estimate the decay heat; and (5) determine the reactivity of spent fuel assemblies. Since August 2013, a set of measurement campaigns has been conducted at the Central Interim Storage Facility for Spent Nuclear Fuel (Clab), in collaboration with Swedish Nuclear Fuel and Waste Management Company (SKB). One purpose of the measurement campaigns was to acquire passive gamma spectra with high-purity germanium and lanthanum bromide scintillation detectors from Pressurized Water Reactor and Boiling Water Reactor spent fuel assemblies. The absolute <sup>137</sup>Cs count rate and the <sup>154</sup>Eu/<sup>137</sup>Cs, <sup>134</sup>Cs/<sup>137</sup>Cs, <sup>106</sup>Ru/<sup>137</sup>Cs, and <sup>144</sup>Ce/<sup>137</sup>Cs isotopic ratios were extracted; these values were used to construct corresponding model functions (which describe each measured quantity's behavior over various combinations of burnup, cooling time, and initial enrichment) and then were used to determine those same quantities in each measured spent fuel assembly. The results obtained in comparison with the operator declared values, as well as the methodology developed, are discussed in detail in the paper.

• **KEYWORDS:** *passive gamma, initial enrichment, burnup, cooling time nondestructive assay of spent fuel, germanium detector, LaBr<sub>3</sub> detector.*