IGD-TP WG4 Report
2016-10-26

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WG 4

- SNETP
- SPIRE
- DISCO
- SAEXFUEL
- Other presentations
- Structural suggestions and comments
- Conclusions

WG 4 Characterisation of spent fuel

SNETP introduction

- Waste issues Generation IV
- Relax requierements for geological disposal by minimising actinides in the fuel waste by the closed fuel cycle; reduce criticality issues
- Hambley: SNETP interface to the fuel field, burn-up, heat generation, even gen 2 not fully known how they will look like in 20-30 yrs, new fuels ATF, impact on (final) disposal, storage of present fuel for the foreseeable future.

- Continued meetings beetween IGD-TP and SNETP

WG 4

- SPIRE – characterisation of spent nuclear fuel for geological disposal
- Main topic
- Several presentations on the need to devepol the methods to characterise the fuel in terms of decay heat, radionuclide inventory, criticality, radiology, etc. with higher accuracy
- Gamma techniques, passive and active
- Neutron techniques, passive and active
- Large economic impact for the optimastion iof the repository (order of billions of Eu)
- Considered to be unique
- Support requested from the platform

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

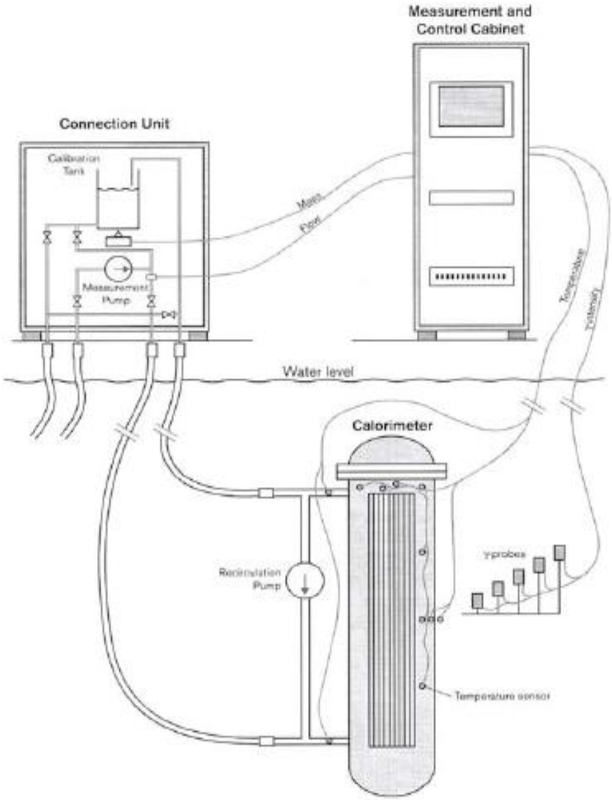
Safegaurds – amount of fissile material

(Fissile gases etc.)

Compare other projects such as Disco

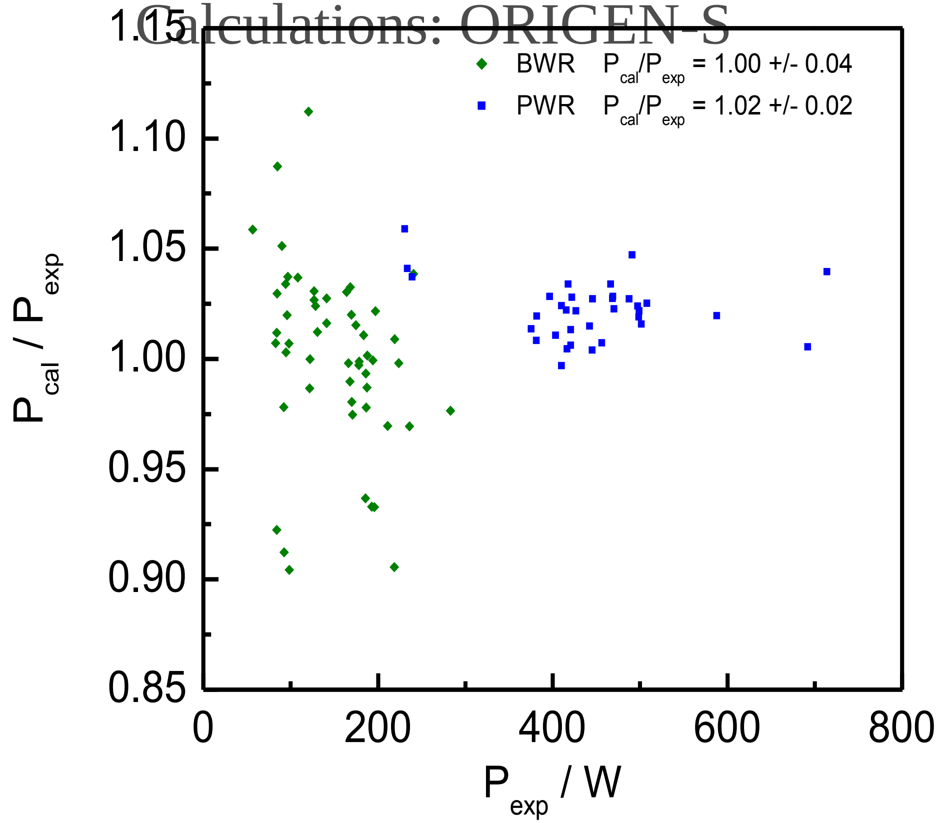
Present status : e.g. decay heat

Calorimeter at CLAB



Experiments at CLAB (2003 - 2004)

Calculations: ORIGEN-S



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SAEXFUEL

- Dealing with extended interim dry storage; more than 100 years
- Laboratory work intended in hot cells
- Modeling
- Should synchronise with other similar projects, e.g. by IAEA

WG 4

DISCO

- Discussed at last meeting
- Dealing with dissolution rates of the fuel etc.
- Considered to be unique

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Others

- Finocchiaro: Monitoring radiation measuring device (Neutrons and gammas): compact and low cost
- Winsley: UK inventory, diverse; heat, criticality, approaches; done for a number of concepts and host rock types; TDT; criticality
- Caruso: Swiss fuels, model validation, MIRAM Nagra model database, problem of canisters not filled, decay power, burn-up
- Nachmilner/Miksova: Russian type of rectors, SNF composition, cladding; differences of codes results for heat comp. SPIRE; cladding high burn up, contaminants, etc, international team created; many similarities to SPIRE

WG 4

Structural and organisational

- Need for integrated approach in the fuel area
- Full analysis of fuel issues that should be addressed
- Integration of different aspects of the fuel understanding such as chemistry, physics, technology, radiology etc. – often same thing looked at in different fields with little communication, such as radionuclide inventory
- Important to syncronise with other organisations such as IAEA, NEA, and others
- Endorsement needed from IGT-TP for certain projects
- The fuel group itself should be preserved and maintained and active
- WMO:s interaction important
- Next meeting: need for a next meeting in one year's time on the fuel area, independent of the development of joint programming

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General issues in the European fuel area

- Infrastructure theathened (hot cells, laboratories generally etc.)
- Getting young people into the field; secure competence
- Other issues mentioned:

Cladding as a barrier, high burn-up fuels, radiotoxity, inventory in different countries – legacy waste, criticality safety case, thermal modeling, spent fuel integrity (corrosion etc.), encapsulation

Codes mentioned: Scale/Origin, Triton, Arianne, Miram, Malibu, Protheus, Casmo, SNF, MCNPX, Aleph…

Decay heat fundamental parameter for geological disposal

Uncertainties: general issue, safety margins…

Dry cask and canister evolution

WG 4

Conclusions

1. Many fuel research topic remain open and are critical
2. Group very motivated and involved
3. High degree of consensus
4. SPIRE, DISCO and Saexful should be endorsed
5. Integrated approach for common proposals suitable in the fuel area for EU programmes
6. SNETP and IGD-TP should continute to have joint meetings and exchange

WG 4

- SNETP introduction Massimimo link SNETP – IGD_TP final disposal optimisation
- Waste issues Generation IV
- Minimise the waste, also FP
- Discussion where problems and risks come from
- SPIRE – characterisation of spent nuclear fuel for geological disposal
- What do we mean by characterisation
- Hambley: Burn-up, heat generation, even gen 2 not fully known how they will look like in 20-30 yrs, new fuels ATF, impact on (final) disposal, storage of present fuel for the foreseeable future.
- Miksova: SNF composition, cladding; differences of codes results for heat; cladding high burn up, contaminants, etc, team international created

WG 4 cont

- Winslow: UK inventory, diverse; heat, criticality, approaches; done for a number of concepts and host rock types; TDT; criticality
- Caruso: Swiss fuels, model validation, MIRAM Nagra database, canisters not fulled, decay power, burn-up
- Fiarcchiaro: monitoring, gamma and neutron detectors, low cost, compact,
- Jansson: Spire project structure
- Schillebeeckx: Spire WP 2 and 4,
- Kalorimeter plots
- Rochman/Seidl: Spire WP 5, Eon authorities Germany
- Cobos: Saexfuel; extended dry storage of SNF, stability of fuel over 100 yrs, ageing studies, modeling, labscale

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

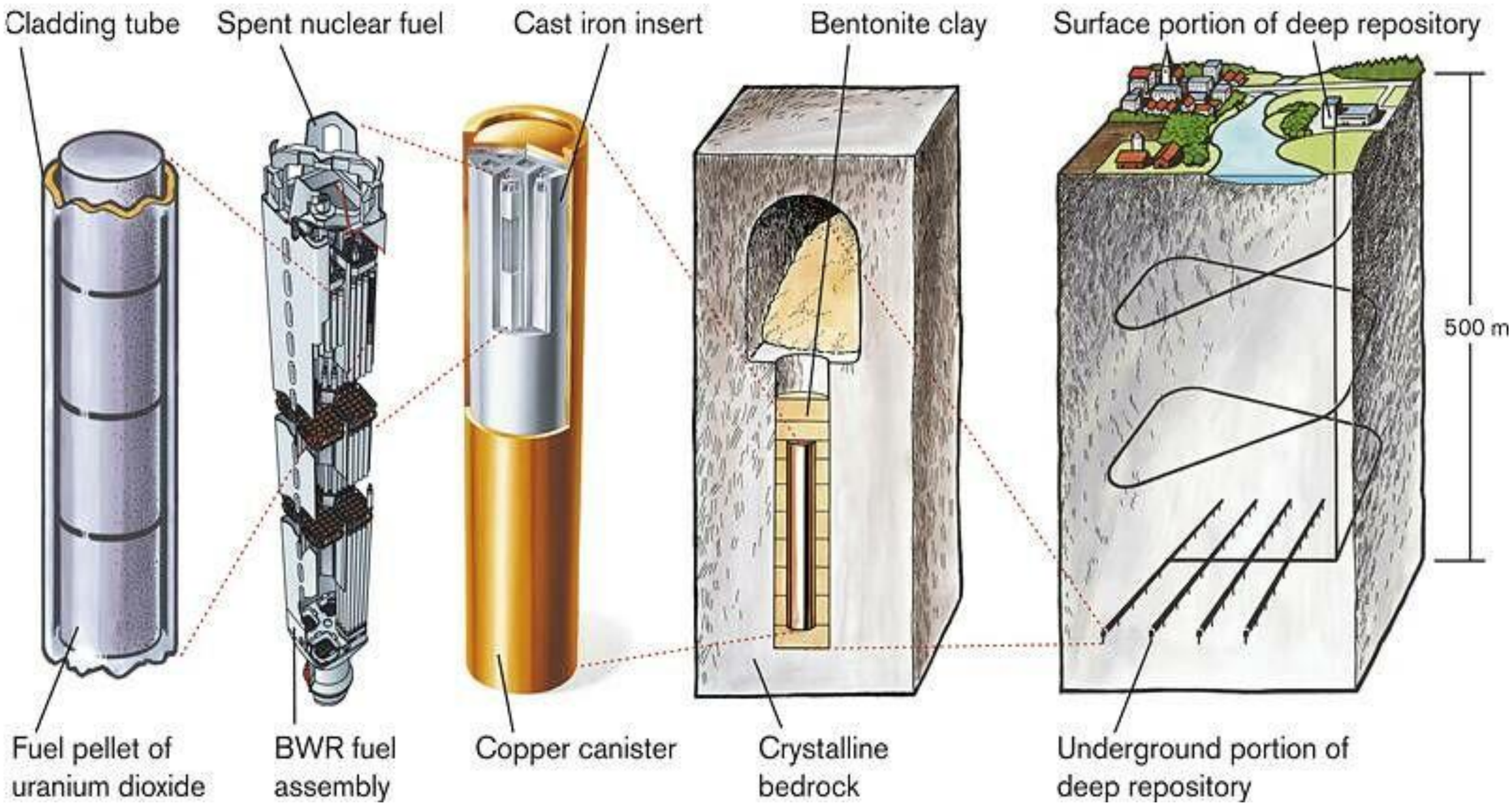
- Many issue general for different repository concepts – all have temperature requirements e.g.

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



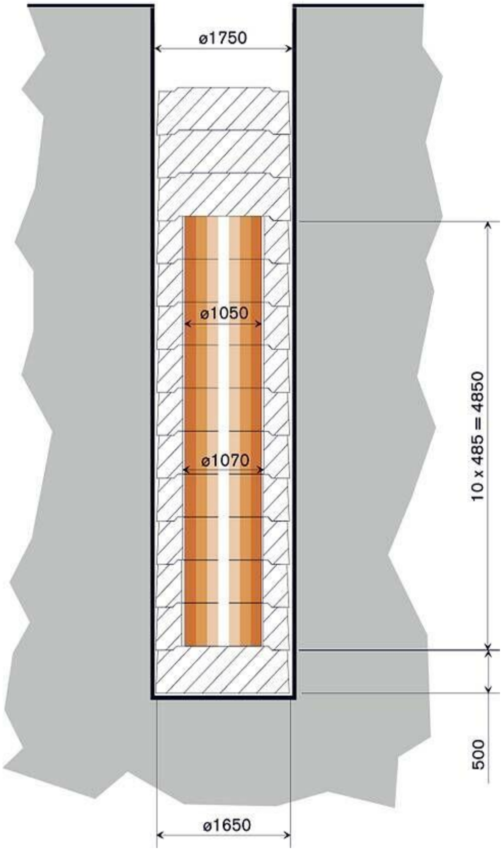
Cladding tube
Spent nuclear fuel
Cast iron insert
Bentonite clay
Surface portion of deep repository
500 m
Fuel pellet of
uranium dioxide
BWR fuel
assembly
Copper canister
Crystalline
bedrock
Underground portion of
deep repository

Canister in deposition hole

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

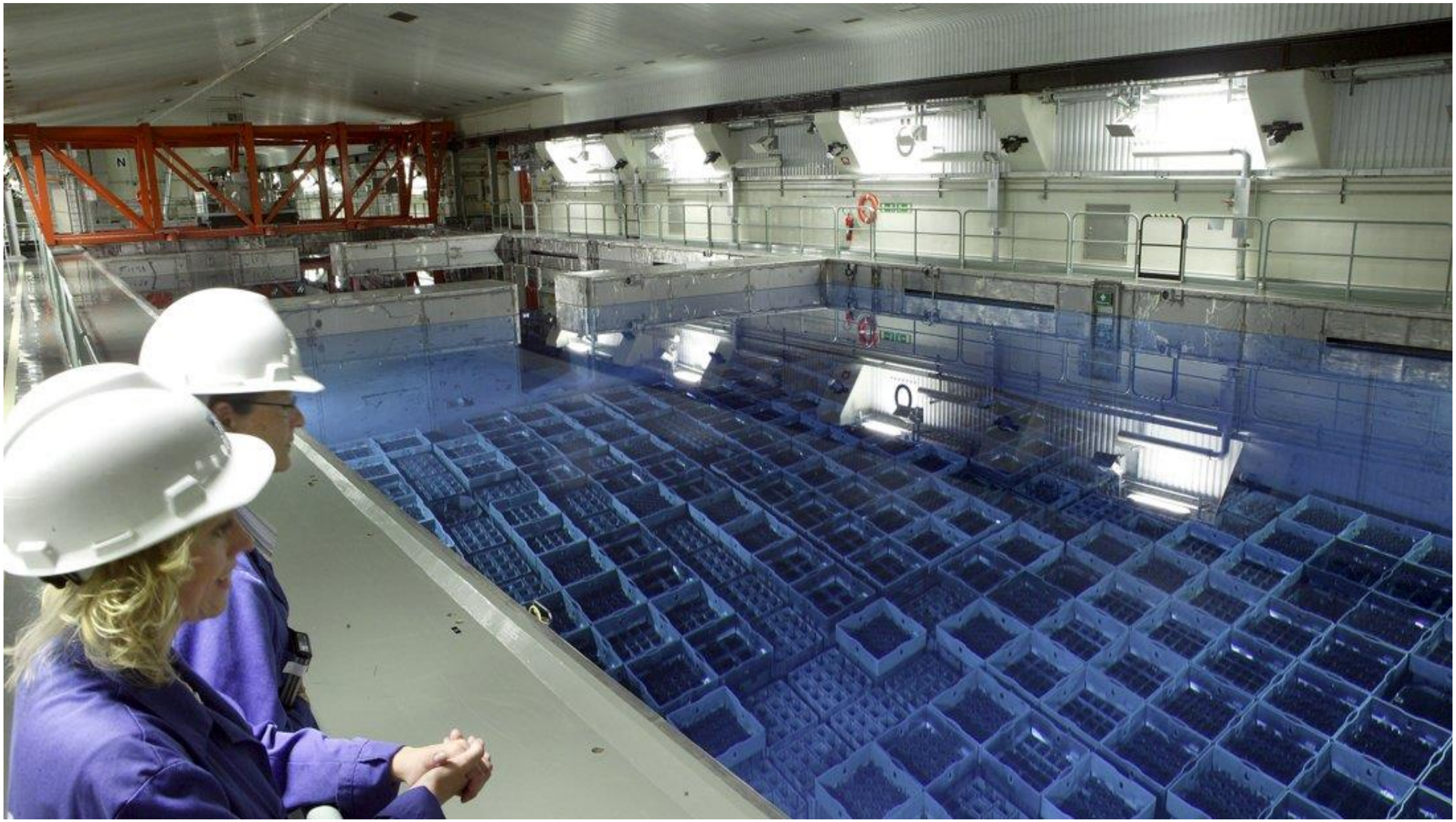
Montmorillonite (around 80%) + secondary minerals

Swedish bedrock:
More than 900 million years old



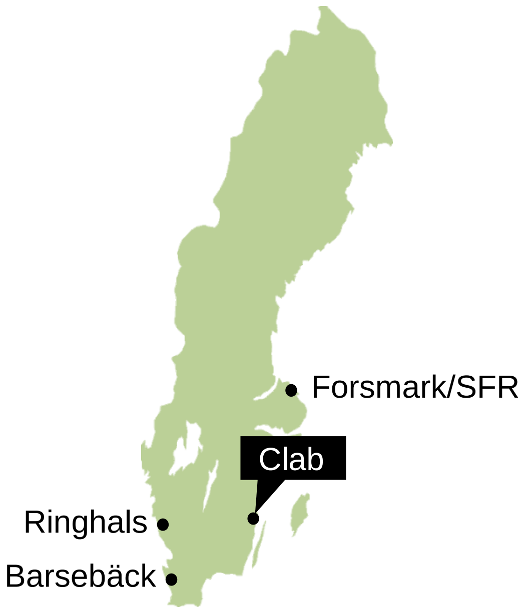
Clab – Central Interim Storage Facility for Spent Nuclear Fuel

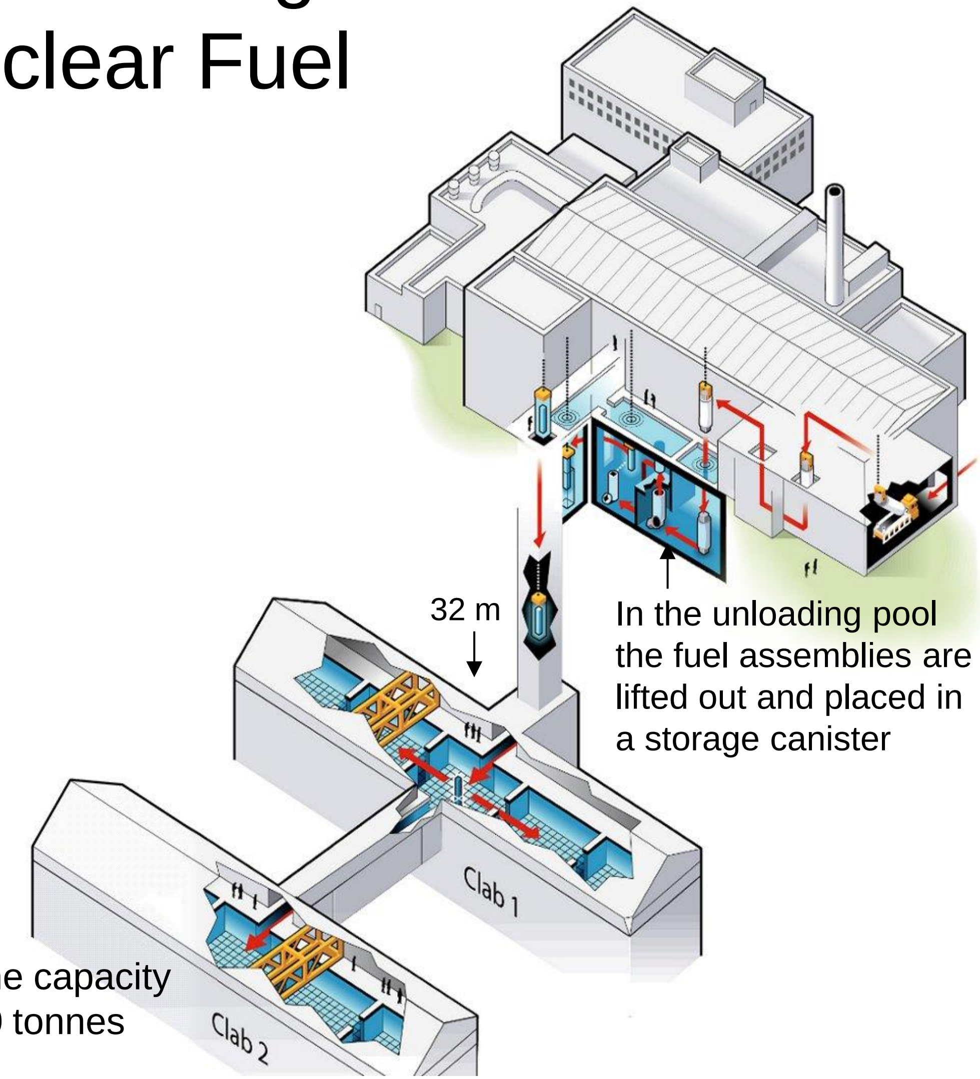
Clab: Water is an effective radiation screen



SKB

Clab – Central Interim Storage Facility for Spent Nuclear Fuel



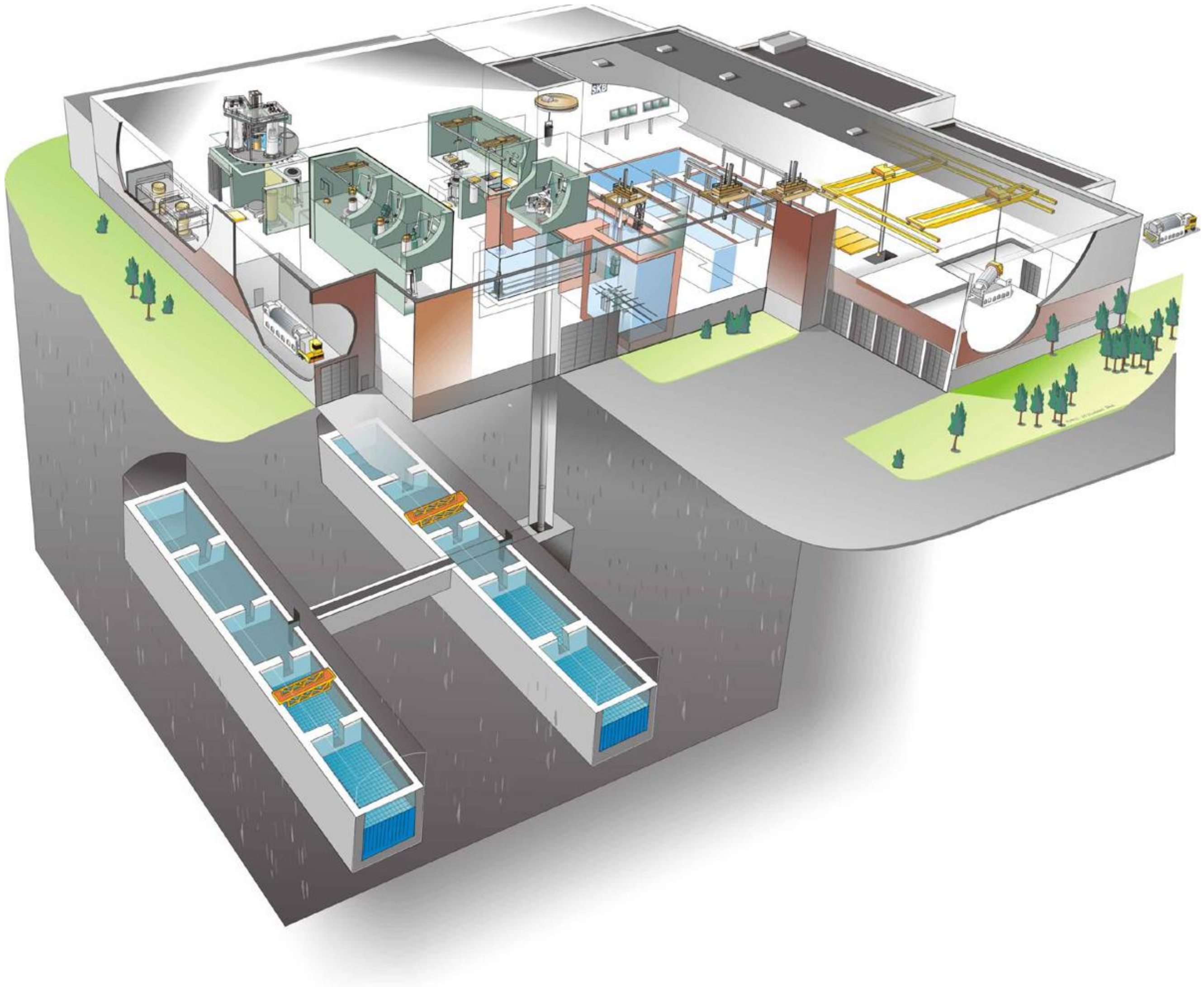


Clab 2 increases the capacity from 5,000 to 8,000 tonnes

Graphic art: Mats Jerndahl

Encapsulation plant

Clink – An integrated encapsulation and interim storage facility

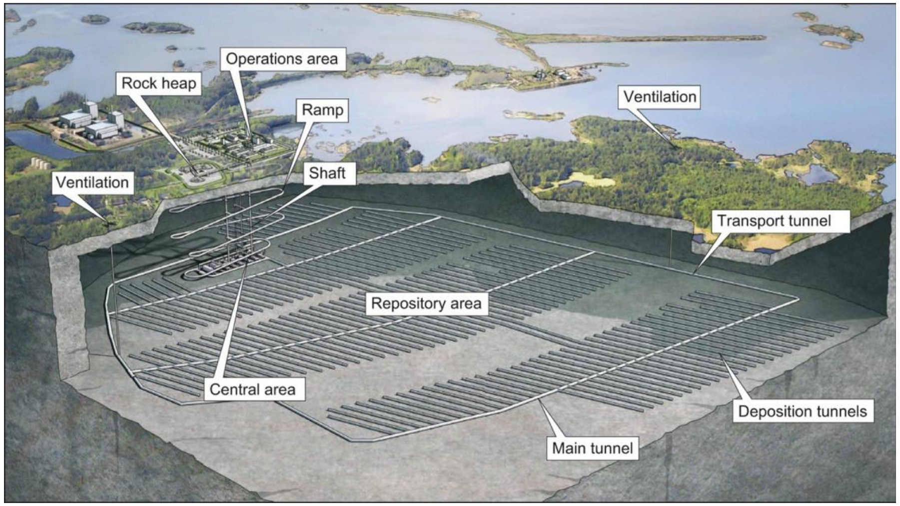


SKB

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

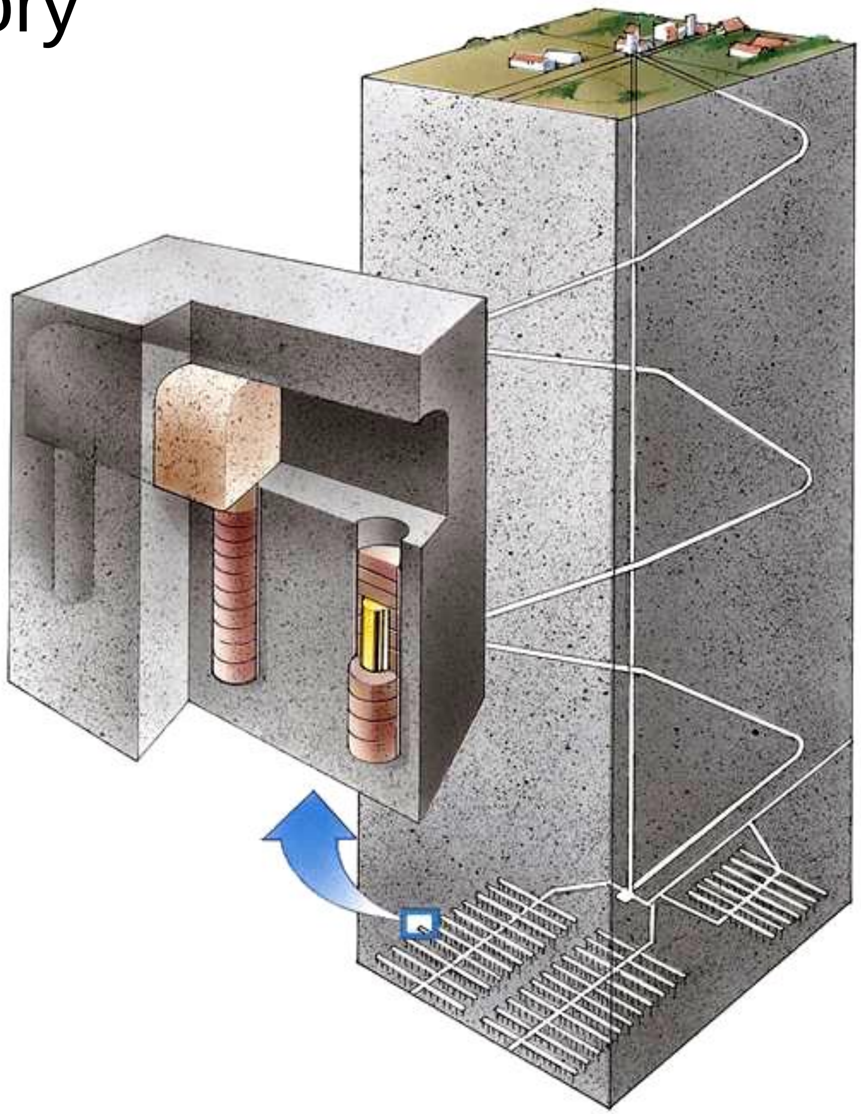
Planned surface facilities at Söderviken, Forsmark



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

The future final repository

- Depth: 400–700 m
- Rock requirements: 2–4 km^2
- 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 chalorimetric (’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 respository:

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 cansiters 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 unambigeous 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

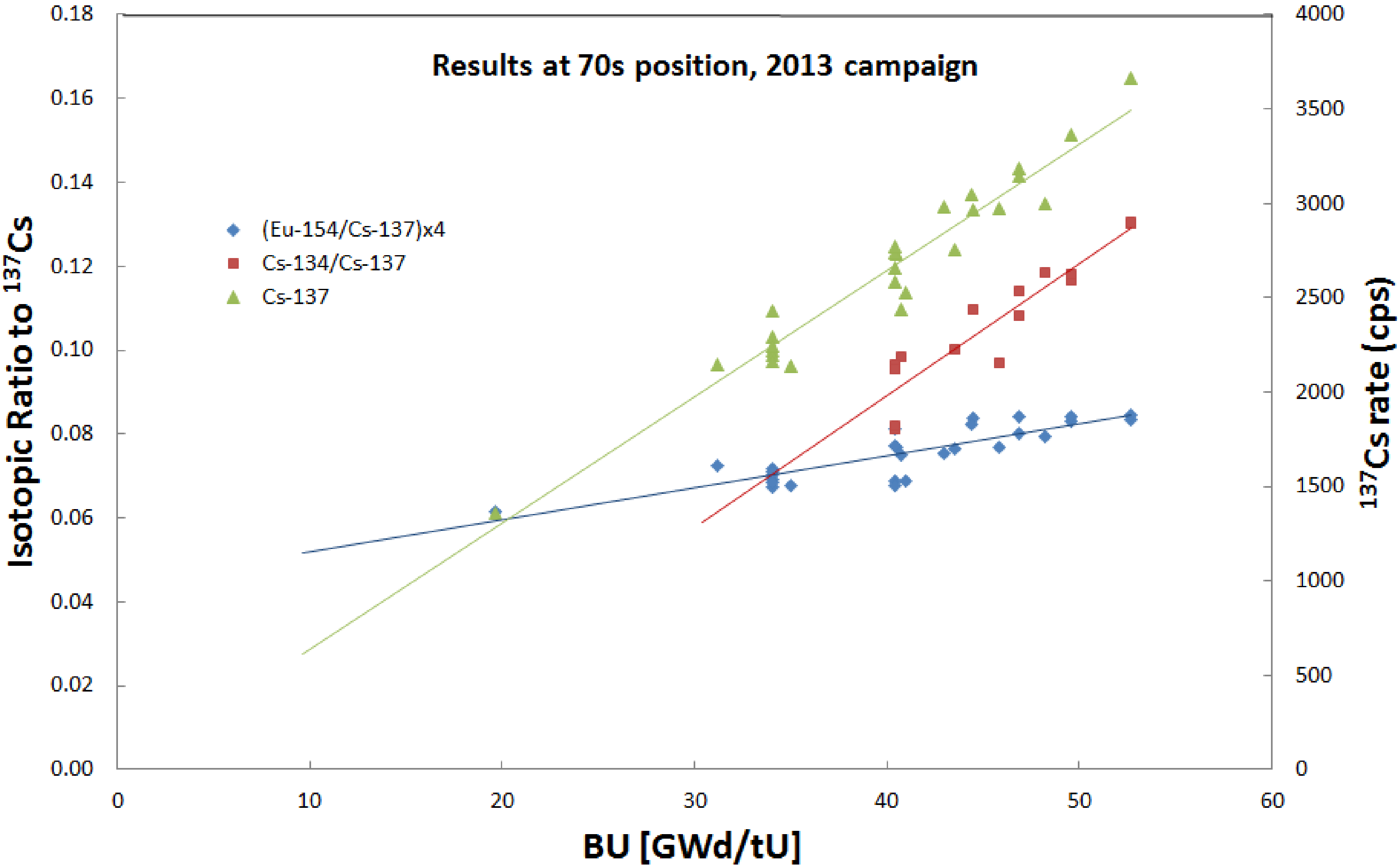
- SKB has had for decades one of the few (if not the only) calorimeter that can measure whole fuel assemblies, and have published lots of measurements
- Calorimetry has the potential to be accurate; in the order of 2-3 %
- Problem: requires long measurement times for each assembly several days for highest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

Wide collaborations to attack these issues

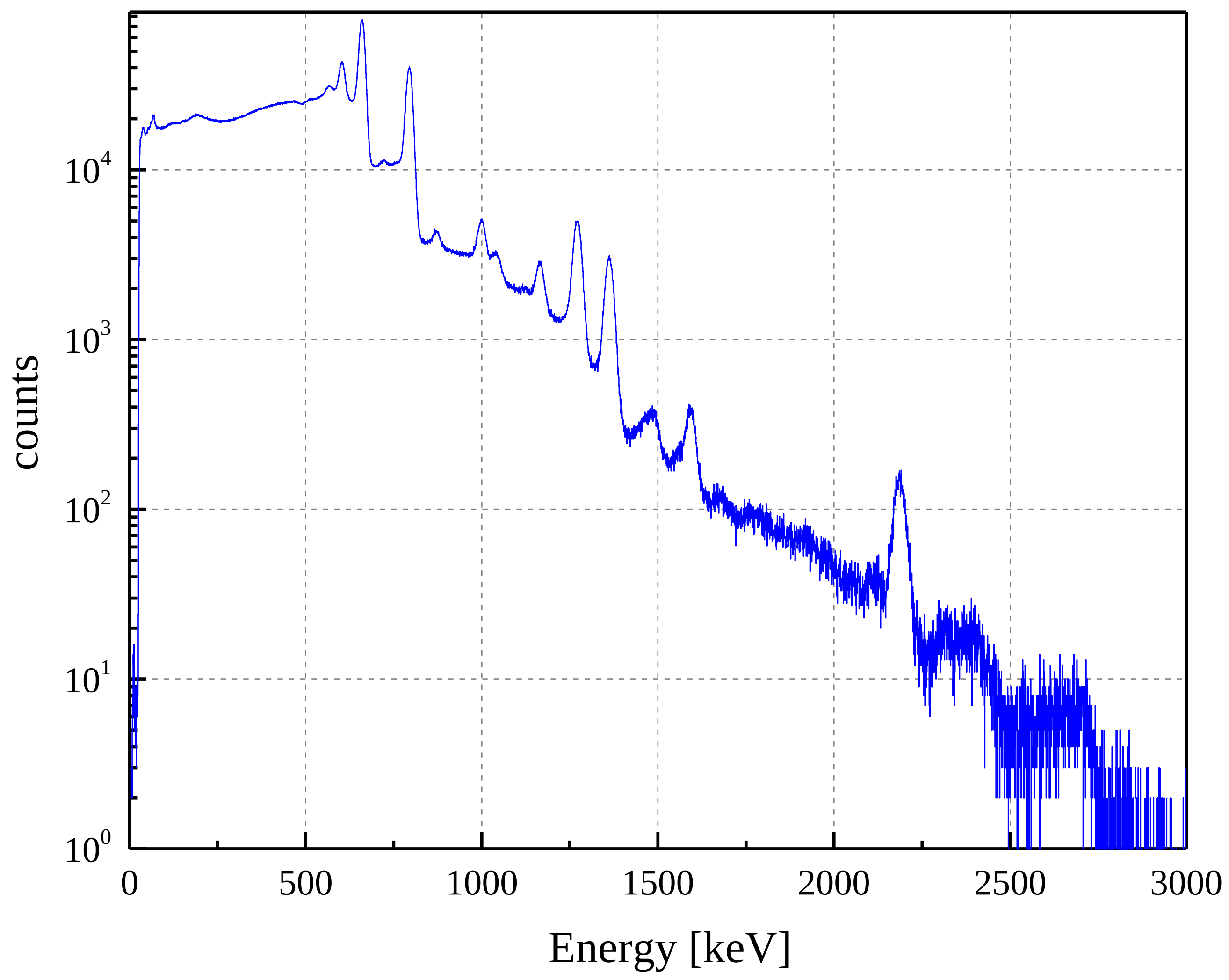
- Sweden (SKB), USA (DoE, LANL, ORNL, LLNL and more) , Euratom, Belgium, Japan, Korea

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


Results at 70s position, 2013 campaign
(Eu-154/Cs-137)x4
Cs-134/Cs-137
Cs-137
Isotopic Ratio to 137Cs
137Cs rate (cps)
BU [GWd/tU]
0.18
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
4000
3500
3000
2500
2000
1500
1000
500
0
0
10
20
30
40
50
60

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

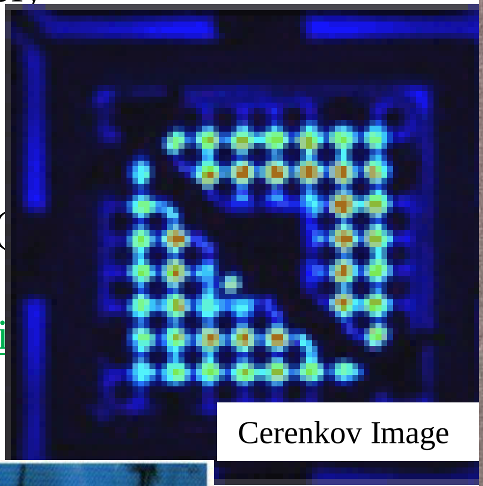
Euratom

OAK RIDGE NATIONAL LABORATORY
MANAGED BY UT-BATTELLE FOR THE DEPARTMENT OF ENERGY

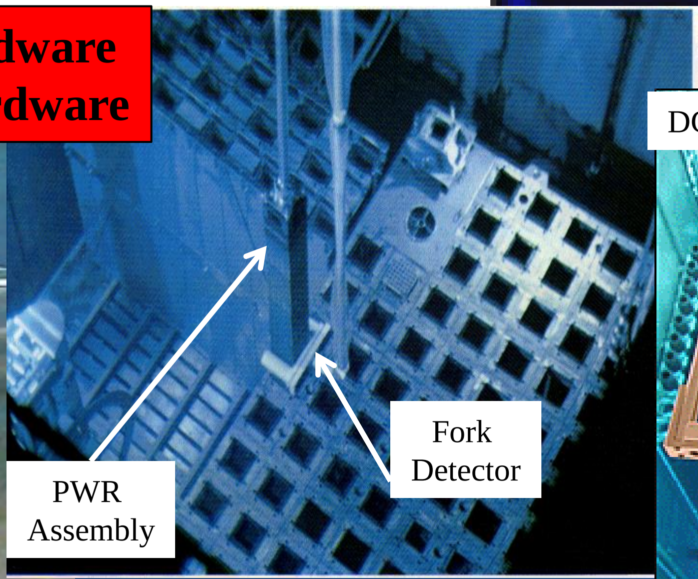
SKB

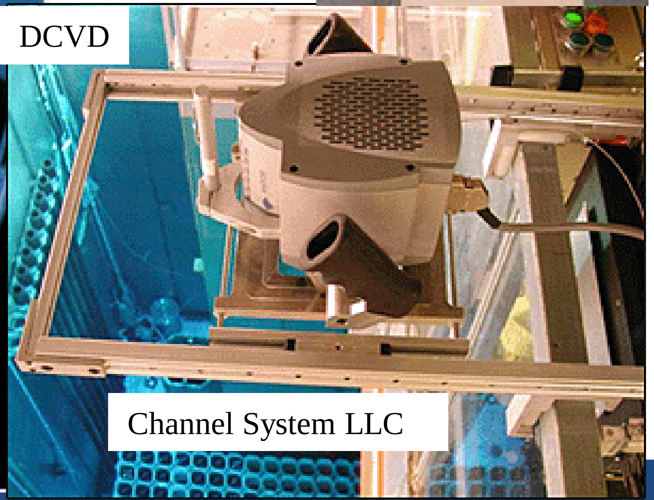
State-of-the-practice in spent fuel NDA

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

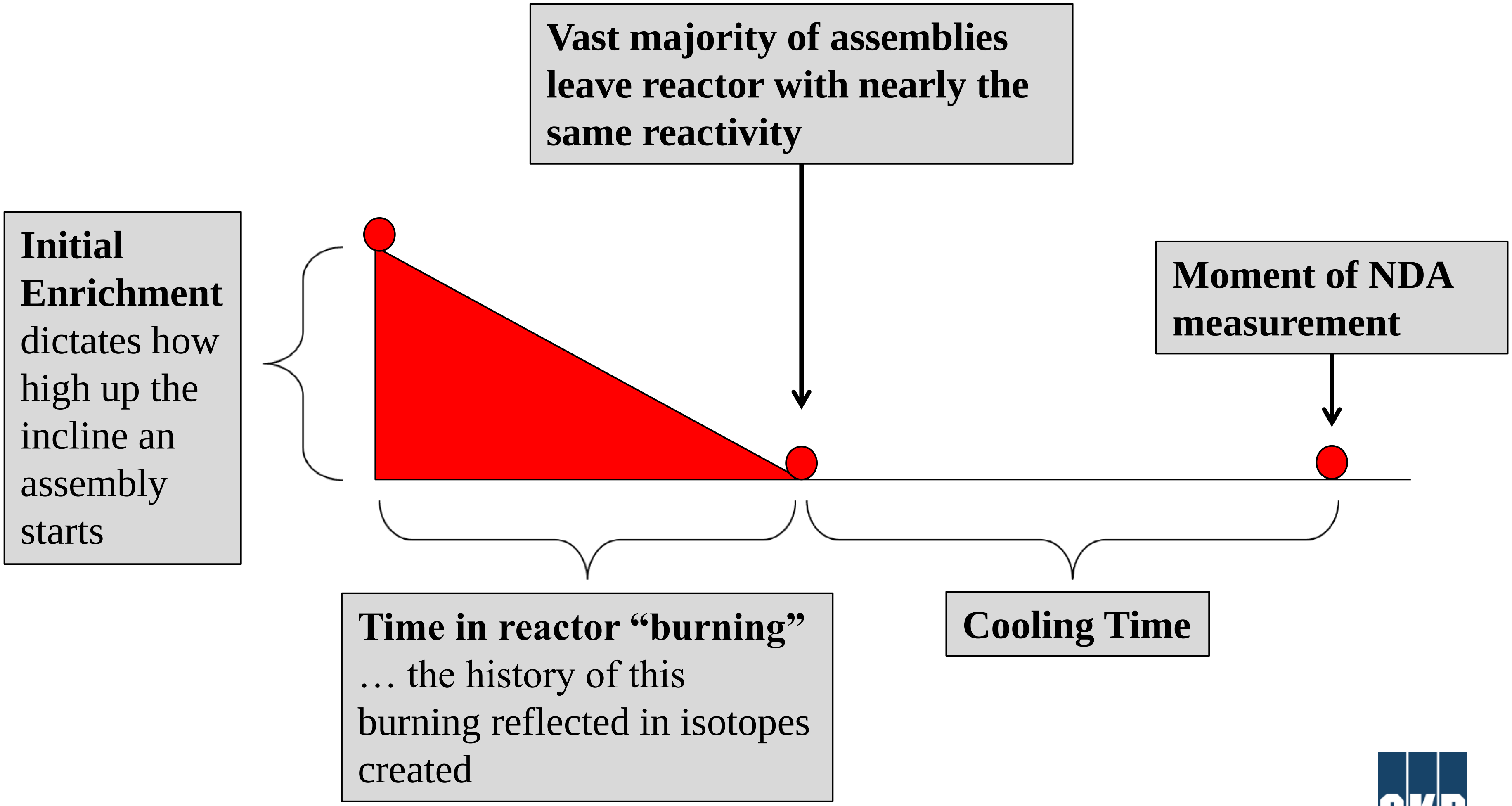


Inspection hardware vs. installed hardware





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}U, ^{239}Pu, ^{238}U	Majority of the fissile material
30 years	^{137}Cs	Dominant gamma source term
18 years	^{244}Cm	Dominant neutron source term
14 years	$^{241}Pu \rightarrow {}^{241}Am$	Fissile material → neutron absorber, noticeably f(t) in century after reactor
8.6 years	^{154}Eu	Second most enduring gamma source
4.7 years	$^{155}Eu \rightarrow {}^{155}Gd$	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.

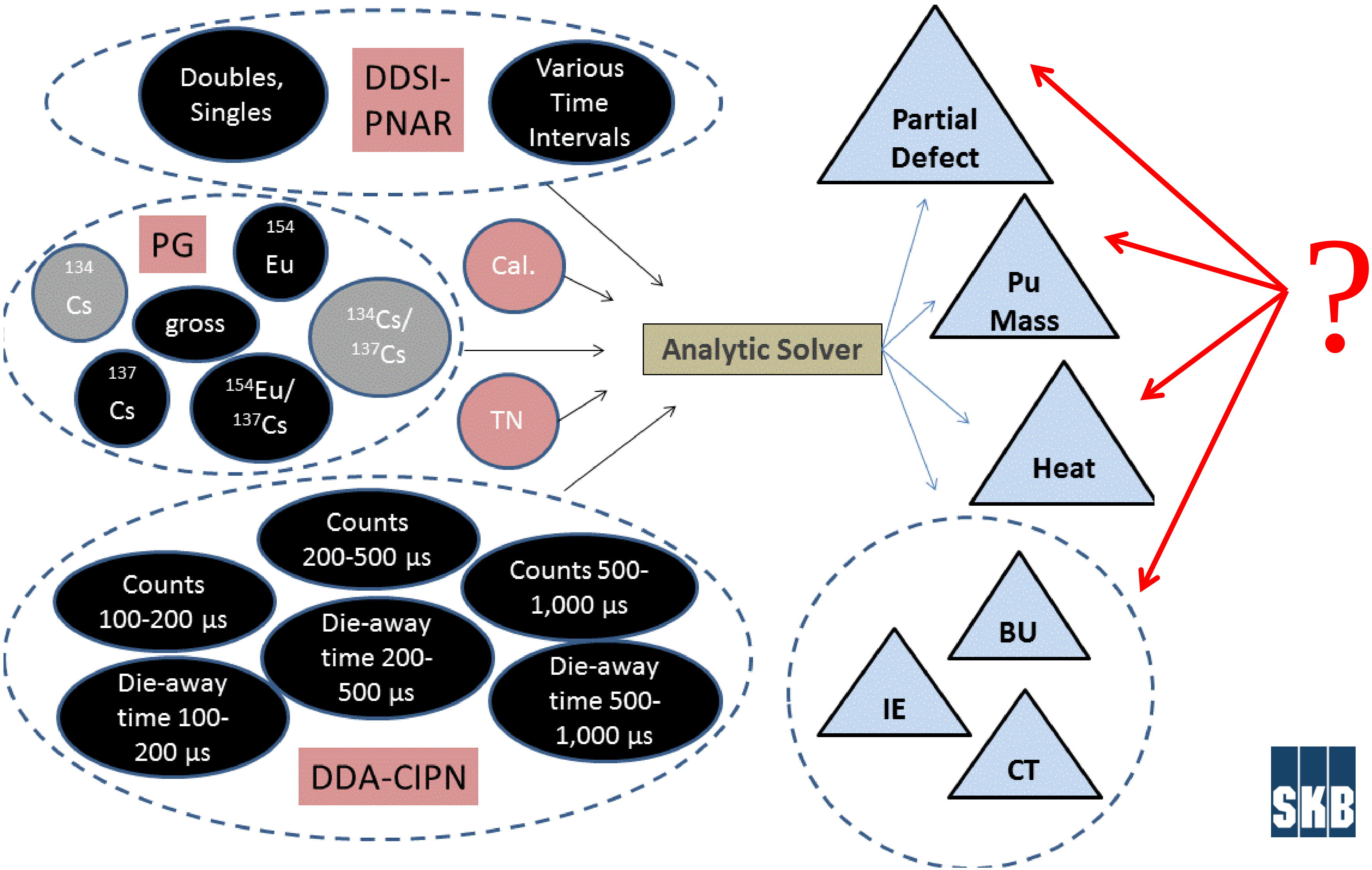
SKB

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** ($^{239}Pu_{effective}$, etc.) as well as any **declared data** deemed appropriate for use.

SKB

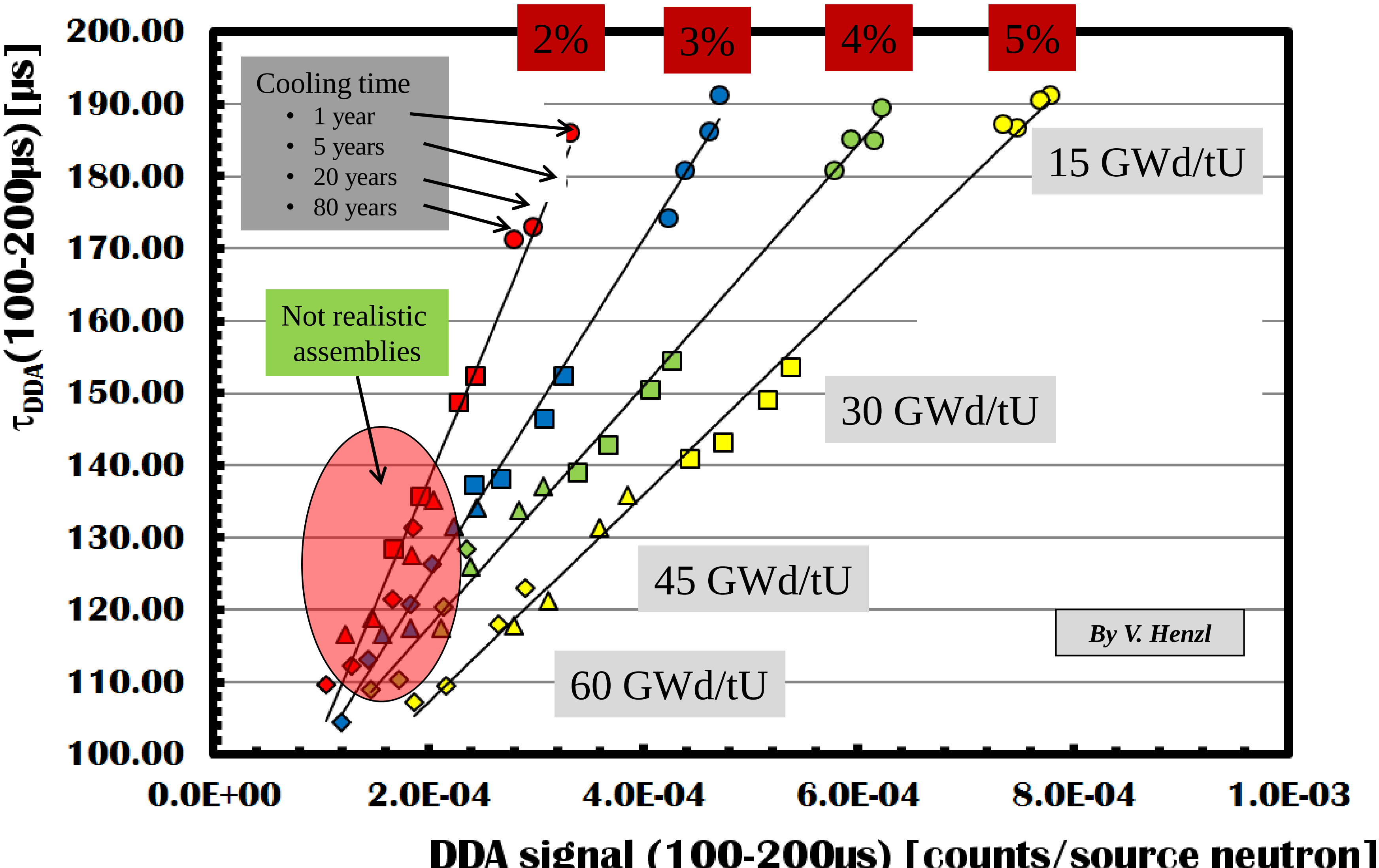
The analytic solver connects the measured signature to the quantity to be estimated, but …



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 ^{137}Cs count rate and the $^{154}Eu/^{137}Cs$, $^{134}Cs/^{137}Cs$, $^{106}Ru/^{137}Cs$, and $^{144}Ce/^{137}Cs$ 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, $LaBr_3$ detector.*

accepted for publication in NIM A.