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SNETP : IGD-TP Interface
Spent Fuel Storage and Disposal

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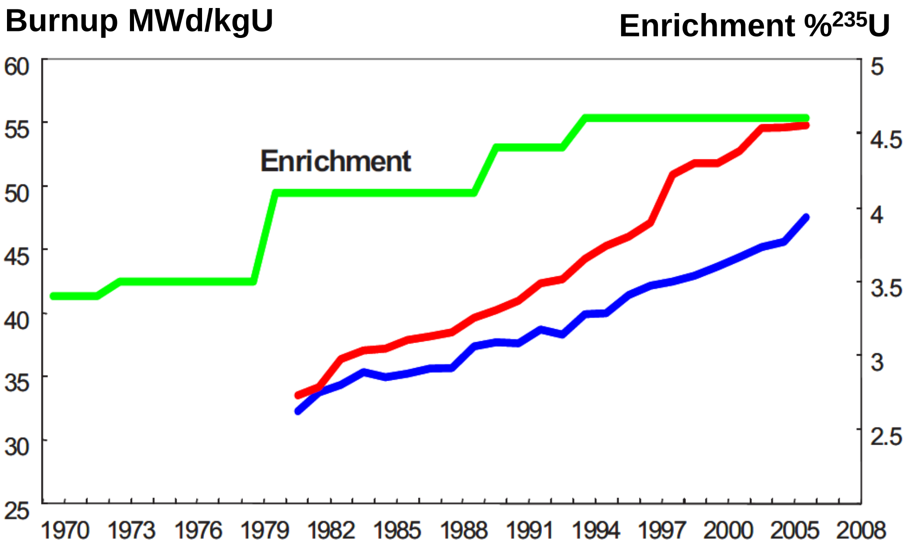
IGD-TP Exchange Meeting
Cordoba, Spain, October 2016

Overview

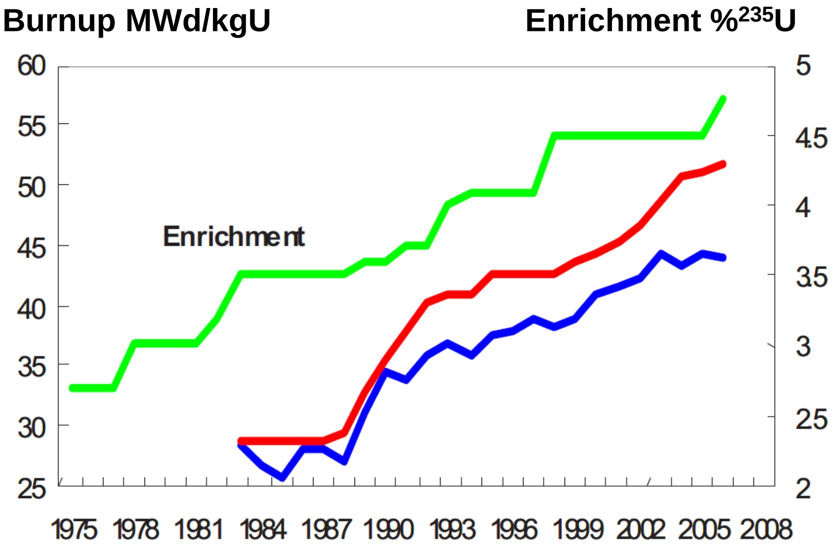
- Developments in Fuel Technology
  - ★Current Reactor Fuels
  - ★Advanced Fuels
  - ★Other Fuels
- Integrating the Back-end for Fuel
- SNETP : IGD-TP Interface

Burnup Trends

PWR Fuel



BWR Fuel



🟥 Burnup of peak reload batch

🟦 Average burnup of all discharged assemblies

IAEA Nuclear Energy Series NF-T-3.8

Effects of Higher Burn-up

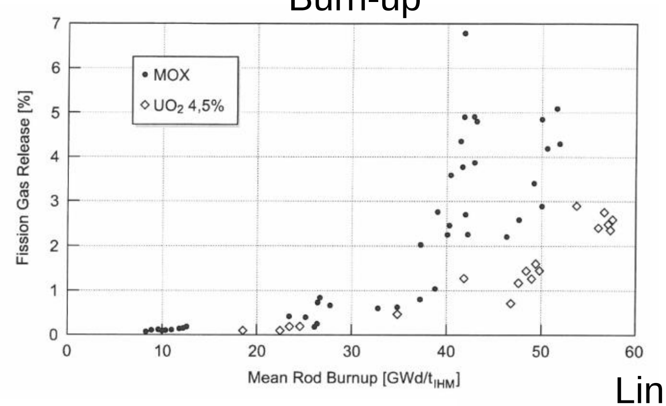
- Effects of burn-up
  - heat load
  - crud thickness
  - cladding oxide thickness
  - cladding hydride content
  - grain size
  - fuel fragmentation
  - porosity size and distribution
  - fission gas release

- Radionuclide Inventory
  - The fraction of residual ^{235}U and fissile Pu decreases
  - The fraction of Am decreases
  - The fraction of Np and Cm increases

Effects of Reactor Operations

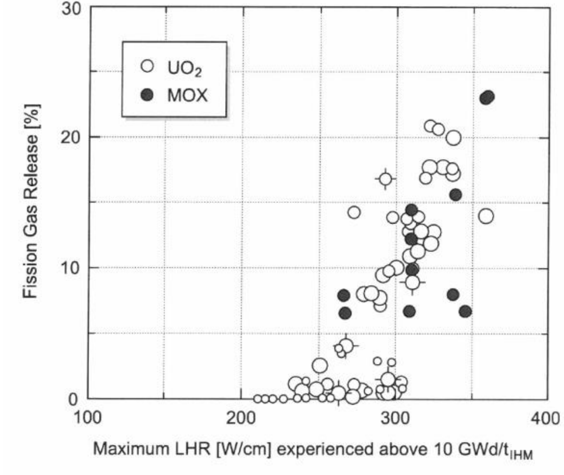
Burn-up is not the only parameter that can change as utilities maximise fuel utilisation. e.g. fission gas release:

Burn-up

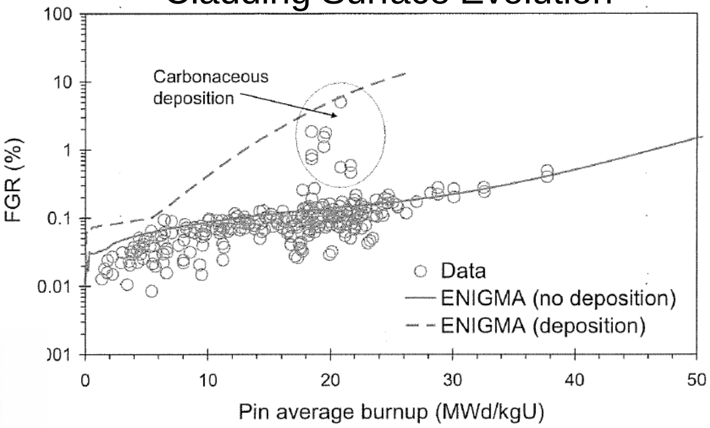


Johnson, LH. Partitioning of radionuclides in Swiss power reactor fuels. Nagra Report 02-07. 2002.

Linear Heat Rating



Cladding Surface Evolution

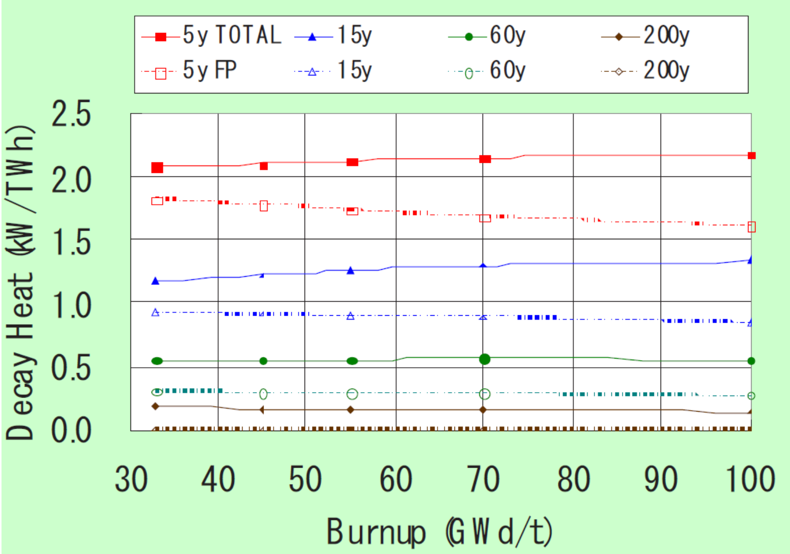


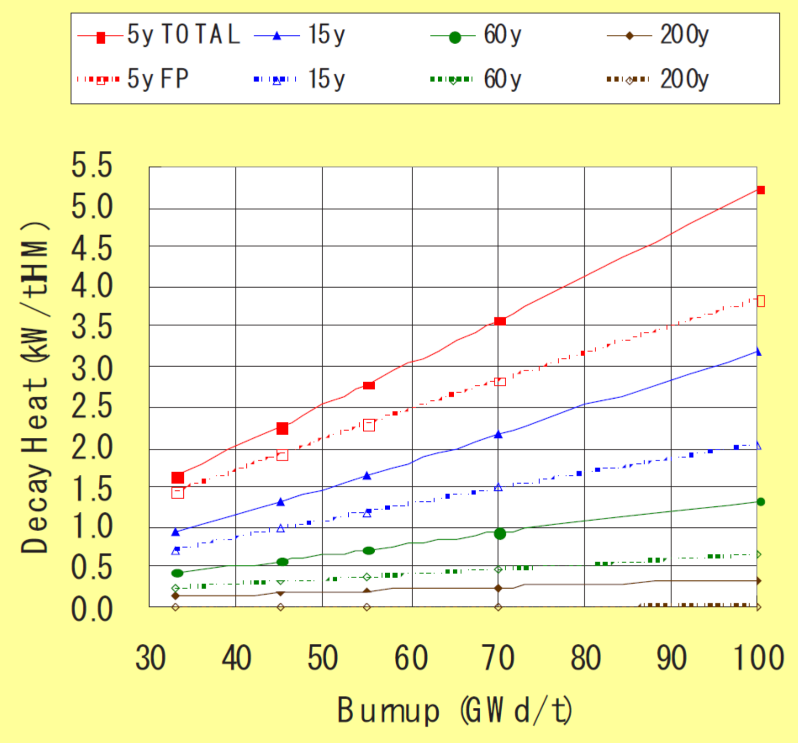
Barker, M et al. Analysis of fission gas in Advanced Gas-cooled Reactor fuel.
Top Fuel 2012.

Decay Heat Generation Effects

LWR UOX fuel

Solid line – total heat output
Dotted line – output from fission products





Decay heat per unit energy output increases slightly with burn-up

Decay heat per unit mass or volume increases strongly with burnup (important for transport and storage)

Changes to Current Fuels

- Manufacture
  - Increased sintering time -> marginal increased grain size
- Fuel composition
  - Cr -> grain size from 8-12 µm up to 45 µm, to reduce fission gas release e.g. GAIA by Areva, ADOPT by Westinghouse
  - Gd as a burnable poison
  - Surface coating ZrB_2, increases rod pressures
- Cladding
  - changes to composition: Zirlo, M5
  - changes to manufacturing processes, e.g. SWRA

- **Developments in Fuel Technology**
  - Current Reactor Fuels
  - **Advanced Fuels**
  - Other Fuels
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Drivers for Fuel Development

Enhanced Economics
- Better burn ups
- Better operational flexibility
- Better manufacturability

Enhanced Safety during Accident Conditions
- Enhanced containment at elevated temperatures
- Enhanced fuel retention within cladding
- Reduction in hazardous reaction products

Enhanced Sustainability
- replace Unat with Urep
- reduce repository burden

Principal Barrier to Adoption is Cost of Development and Licensing

Accident Tolerant Fuels

Fuel Development Experience

- ✓ Range of alternative claddings known
- ✓ Benefits of higher density fuels
- ✗ Large adoption barriers

Post Fukushima Analysis

- Increase time to fuel failure
- More robust cladding
- Higher density fuels proposed to off-set cladding cost

Utility Drivers

- Reduced accident risk
- No economic detriment

Summary of ATF options

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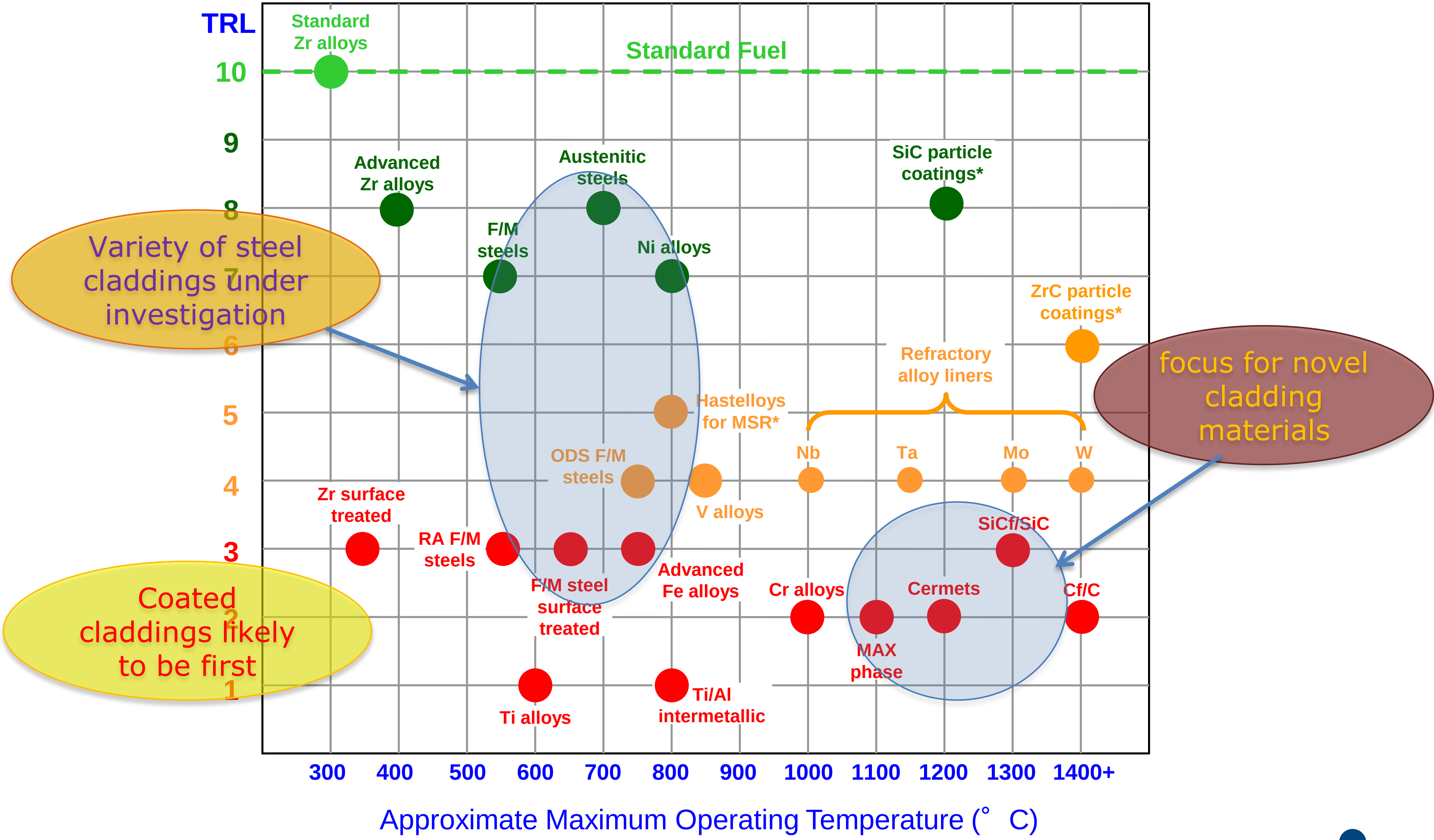
- Cladding modification
  (e.g. coated Zr alloys)
- Cladding replacement
  (e.g. FeCrAl)
- Cladding and fuel replacement
  (e.g. U_3Si_2 fuel with SiC composite clad)

Increasing resilience /performance

Increasing variation from current fuel/clad system

Candidate Cladding Developments



Variety of steel claddings under investigation

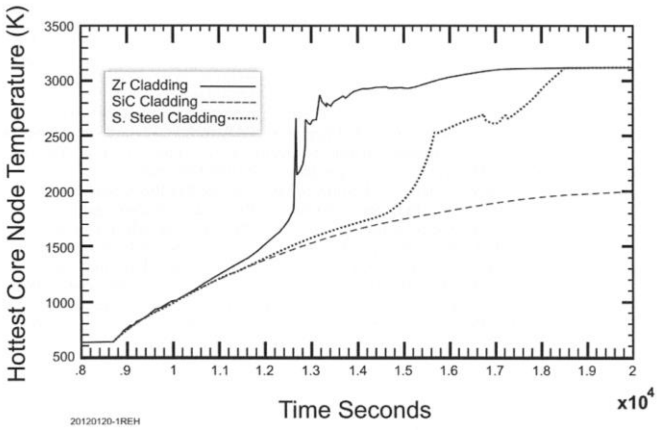
focus for novel cladding materials

Coated claddings likely to be first

Cladding properties

- Zirconium-alloy cladding currently used in all Light Water Reactors
- Zirconium-alloys have reasonable corrosion resistance at normal operating temperatures (<350ºC)
- At higher temperatures the oxidation rate accelerates;>500ºC gross oxidation can occur
- Results in the evolution of large quantities of hydrogen that can explode
- Surface coatings proposed to limit surface oxidation

- Ceramic cladding such as SiC has much greater resistance to oxidation in water and steam, even at high temperatures
- Good radiation stability
- Low neutron capture cross-section
- Greater mechanical strength at high temperatures.



Why Consider Fuel Matrix?

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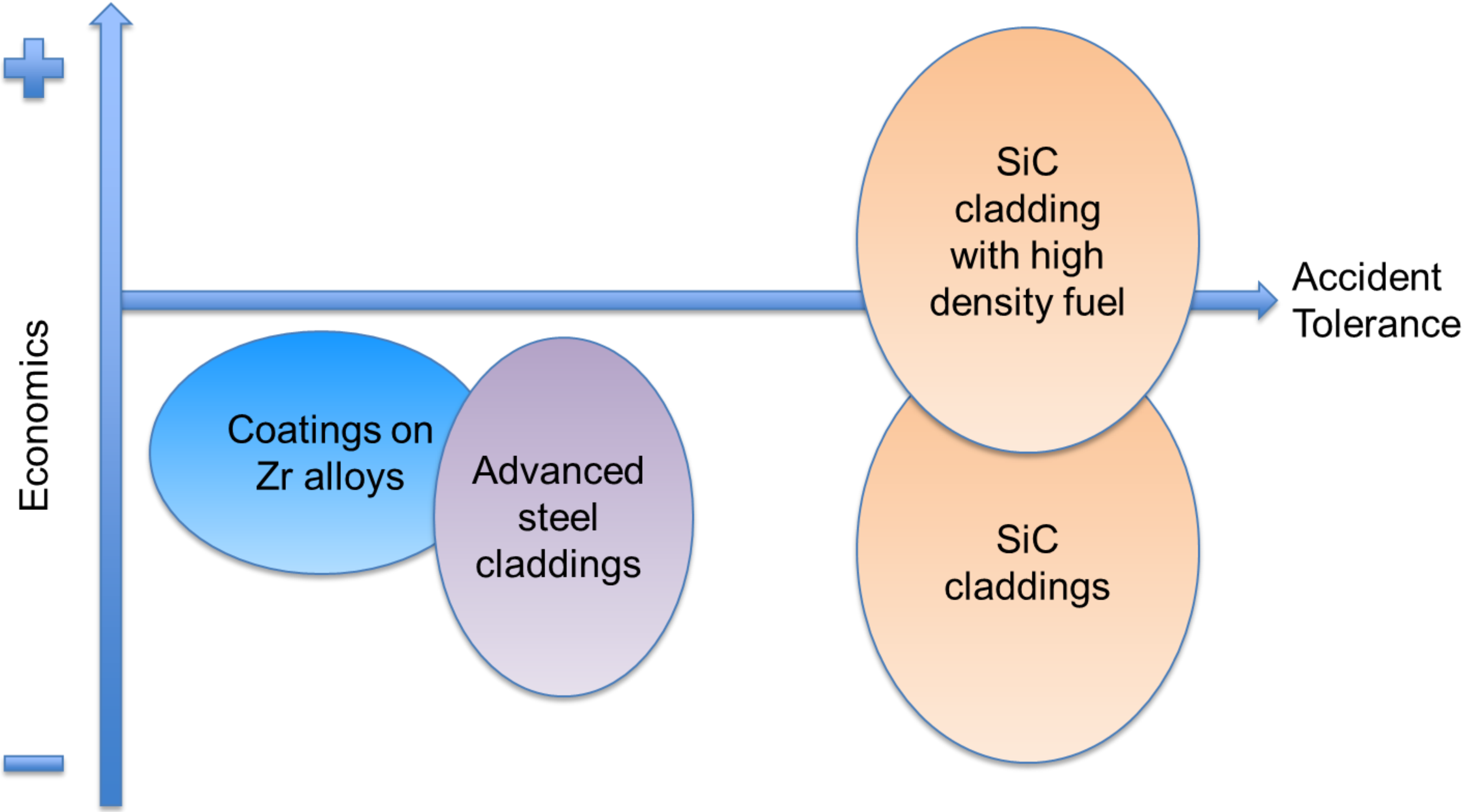
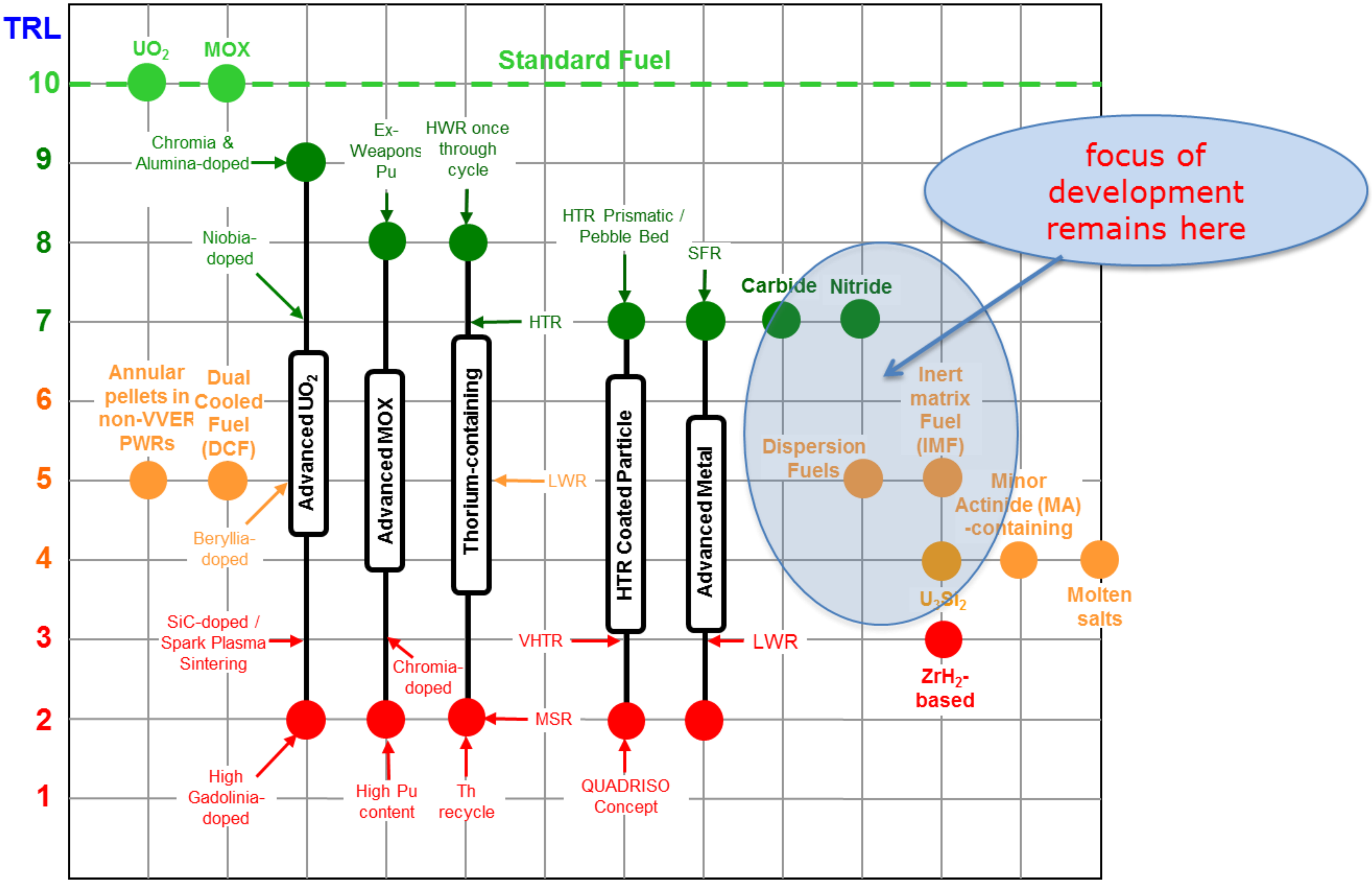
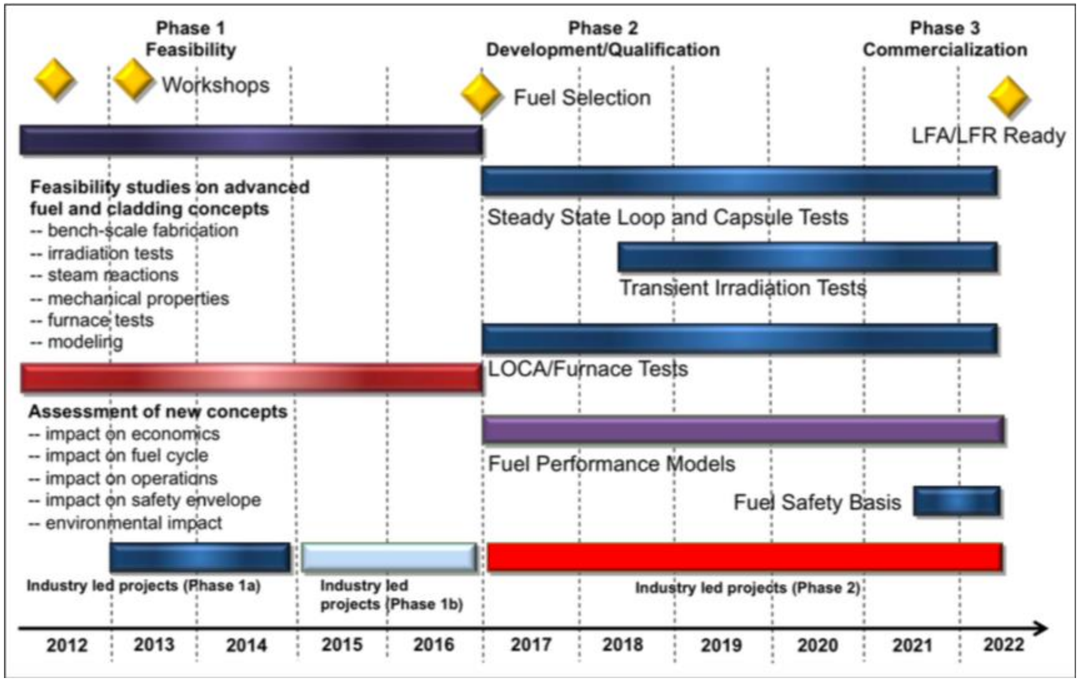


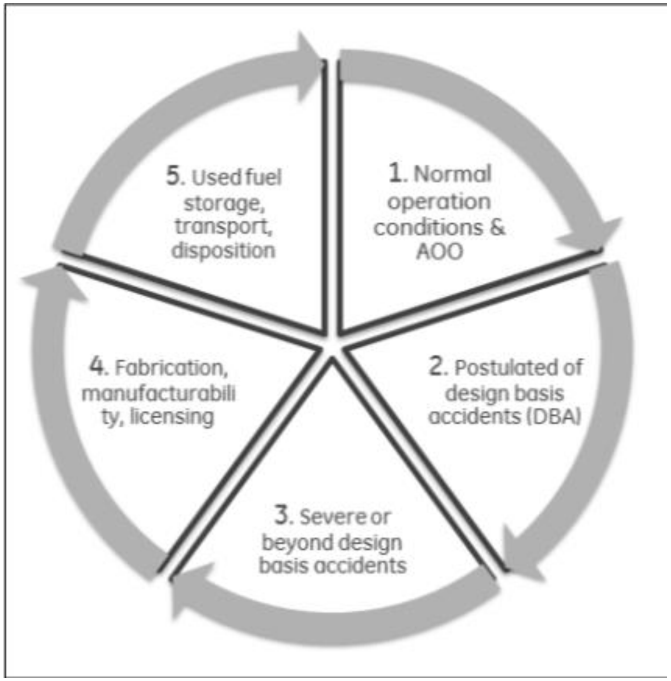
Candidate Fuel Developments



US DoE ATF Programme

Example showing timescales of a fuel development programme





Five Areas of Assessment for ATF

Recent Progress

Increased utility interest, particularly in US because of potential savings in O&M because reduced fuel failure risk will permit downgrading of some safety systems.

Enabling infrastructure improvements well underway, e.g. ATR and TREAT reactors.

Manufacturing of advanced claddings is progressing for a number of cladding types and test irradiation have started for some coatings

SiC composite clad tubes.
Courtesy of Westinghouse

Manufacturing of fuel for test irradiations progressing well.
e.g. for USi/UN fuels:

- First test reactor trials underway (ATR/Halden).
- Water reactivity trials underway.
- Fuel manufacturing trials and process development underway.

Down selection of options, e.g. in US DOE programme, still some way off.

Earliest availability of commercial fuels ~mid-2020s.

- **Developments in Fuel Technology**
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Other Fuels

- Old
  - Test reactor fuels and experimental fuels
  - Development/demonstration reactor fuels
  - Gen I/II reactors (e.g. gas-cooled)
  - Research reactors (U/Al)
  - Fuel residues
    - Post Irradiation Examination residues
    - Damaged and degraded fuels
    - Corium and test fuels
    - Fuel archives

- Gen III/III+ (see earlier)

- New
  - Small Modular Reactors
  - Gen IV experimental reactors

UK inventory

~5% of gas-cooled power reactor fuel for storage & disposal

- Developments in Fuel Technology
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Spent Fuel Management

Tactical Success

Strategic Failure ?

Spent Fuel Management

- Multi-decade storage will be required
  - ★ cooling required depends on fuel type, burn-up, etc.
  - ★ heat load limited by repository geology and design
  - ★ e.g. >100 years for 65 GWd/teU fuel in UK granitic rock

- High burn-up fuel disposal not yet constrained by delay in repositories

- Technologically fuel can be stored safely for decades to centuries
  - ★ repackaging is feasible with current technology
  - ★ but, not a sustainable solution

Our Challenge

If not reprocessed spent fuel is of zero current or future value. Management is therefore a cost to be minimised.

- Maintain robust safety margins by
  - ★Understanding underlying science and phenomena
  - ★Designing out likely failure modes
  - ★Keeping defence in depth approach
  - ★Utilising passive safety as far as possible
- Develop monitoring to provide confirmation of system performance
- Reduce total cost between discharge and disposition
- Maintain public confidence over generations

Current R&D

- Fuel evolution over decades-centuries
- Fuel cladding integrity after heating and cooling
- Focus on post storage transportation
- Degradation mechanisms and ageing management plans for cask storage
- Long term performance of cask seals
- Long term performance of cask neutron shielding
- Spent fuel pool severe accident assessment
- Drying behaviour of defective spent fuel

Future R&D I

Safety Margins

- Identification & underpinning of SCC-resistant materials / treatments for canister based storage
- Effects of radiolysis on containment corrosion for unshielded containment boundaries exposed to atmosphere

Monitoring

- Deployable monitoring systems to detect containment failure
- Development of improved monitoring for water carryover in fuel
- Monitoring/remediation of SFP containment cracks

Future R&D II

Reduce Costs

- Reduce uncertainties in quantities that drive costs
- Develop distributed power sources to power critical sensors
- Understanding of economic uncertainties and risks associated with different combinations of storage system, disposal system, SF inventory and timescales
- Optimise storage and disposal requirements

- Developments in Fuel Technology
  - Current Reactor Fuels
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- **SNETP : IGD-TP Interface**

SNETP : IGD-TP Interface

- Progress to date
  - Promotion of jointly relevant H2020 projects, e.g.
    - DISCO
    - SPIRE
  - Joint publicity
    - Joint factsheet published

DISCO

Modern Spent Fuel Dissolution and Chemistry in Failed Container Conditions

Two main motivations for DISCO:

1. enhance our understanding of spent fuel matrix dissolution under conditions representative of failed containers in reducing repository environments;
2. assess whether novel types of fuel (MOX, doped) behave like the conventional ones.

16 contributors from 9 countries.

Amphos 21 Consulting
Forschungszentrum Jülich GMBH
Fundacio CTM Centre Tecnologic
Joint Research Centre - European Commission
Karlsruher Institut Fuer Technologie
National Nuclear Laboratory Limited
Paul Scherrer Institut
Studsvik Nuclear AB
Svensk Kärnbränslehantering AB
Teknologian tutkimuskeskus VTT Oy
The University of Cambridge
The University of Sheffield
Studiecentrum voor Kernenergie/Centre d’Etude de l’Energie Nucléaire
Commissariat a l’Energie Atomique et aux Energies Alternatives
Association pour la Recherche et le Developpement des Méthodes et Processus Industriel
Centro de investigaciones energeticas, medioambientales y tecnologicas -CIEMAT

7 member end user group & 8 associated groups including NUGENIA platform

SPIRE

SPent fuel characterisation Program for the Implementation of REpositories

The motivation for SPIRE is to understand the dominant contributions to the source term uncertainties at different time scales and to minimise them.

Driver for the project is minimising uncertainties in heat generation as it affects geological disposal and dry storage criteria for spent fuel.

7 contributors from 6 countries.

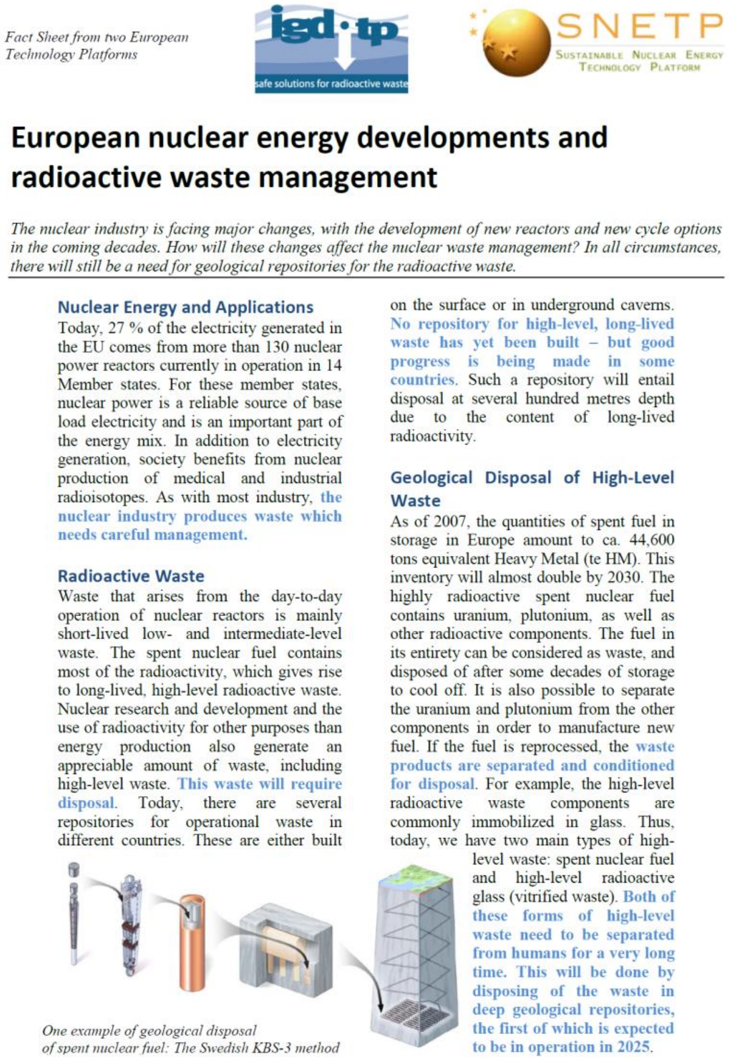
Studiecentrum voor Kernenergie/Centre d’Etude de l’Energie Nucléaire
Upsala University
Svensk Kärnbränslehantering AB
Culham Centre for Fusion Energy
EON
Joint Research Centre - European Commission IRMM
LGI Consulting

3 member end user group, plus collaboration with US National Laboratory

Joint Factsheet

- Collaborative publication
- Integration of production and disposal aspects and perspectives
- Presents key aspects and drivers from both programmes
- Common message – importance of timely disposal facility development

www.igdtp.eu/index.php/key-documents/doc_download/385-igd-tp-snetp-factsheet



Fact Sheet from two European Technology Platforms

igd-tp safe solutions for radioactive waste

SNETP Sustainable Nuclear Energy Technology Platform

European nuclear energy developments and radioactive waste management

The nuclear industry is facing major changes, with the development of new reactors and new cycle options in the coming decades. How will these changes affect the nuclear waste management? In all circumstances, there will still be a need for geological repositories for the radioactive waste.

Nuclear Energy and Applications

Today, 27 % of the electricity generated in the EU comes from more than 130 nuclear power reactors currently in operation in 14 Member states. For these member states, nuclear power is a reliable source of base load electricity and is an important part of the energy mix. In addition to electricity generation, society benefits from nuclear production of medical and industrial radioisotopes. As with most industry, **the nuclear industry produces waste which needs careful management.**

Radioactive Waste

Waste that arises from the day-to-day operation of nuclear reactors is mainly short-lived low- and intermediate-level waste. The spent nuclear fuel contains most of the radioactivity, which gives rise to long-lived, high-level radioactive waste. Nuclear research and development and the use of radioactivity for other purposes than energy production also generate an appreciable amount of waste, including high-level waste. **This waste will require disposal.** Today, there are several repositories for operational waste in different countries. These are either built on the surface or in underground caverns. **No repository for high-level, long-lived waste has yet been built – but good progress is being made in some countries.** Such a repository will entail disposal at several hundred metres depth due to the content of long-lived radioactivity.

Geological Disposal of High-Level Waste

As of 2007, the quantities of spent fuel in storage in Europe amount to ca. 44,600 tons equivalent Heavy Metal (te HM). This inventory will almost double by 2030. The highly radioactive spent nuclear fuel contains uranium, plutonium, as well as other radioactive components. The fuel in its entirety can be considered as waste, and disposed of after some decades of storage to cool off. It is also possible to separate the uranium and plutonium from the other components in order to manufacture new fuel. If the fuel is reprocessed, the **waste products are separated and conditioned for disposal.** For example, the high-level radioactive waste components are commonly immobilized in glass. Thus, today, we have two main types of high-level waste: spent nuclear fuel and high-level radioactive glass (vitrified waste). **Both of these forms of high-level waste need to be separated from humans for a very long time. This will be done by disposing of the waste in deep geological repositories, the first of which is expected to be in operation in 2025.**

One example of geological disposal of spent nuclear fuel: The Swedish KBS-3 method

SNETP : IGD-TP Interface

- Future Vision
  - Further collaboration for H2020 calls
  - Consider joint review/position statements, e.g.
    - Impact of fuel development on fuel disposal
    - Impact storage options on fuel disposal

The End

Thank you for your attention

Any questions ?

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SNETP
Sustainable Nuclear Energy Technology Platform

NUGENIA
NUclear GENeration II & III Association
www.nugenia.org

About the Presenter

- David Hambley works in the Spent Fuel Management Technology team of the Fuel Cycle Solutions Business of the National Nuclear Laboratory.
- He is the laboratory's Research Fellow for Spent Fuel Management and Disposal at the National Nuclear Laboratory. In this role, he is responsible for leading NNL's activities to support the interim storage of spent oxide fuels and the remediation and interim storage of legacy, mainly uranium metal, fuels. He is also actively involved in research into the behaviour of the UK's Advanced Gas-Cooled Reactor fuels in repository environments. David has 30 years of experience working in the nuclear power industry, including positions in/with the UK Atomic Energy Authority, AEA Technology and the Australian Nuclear Science and Technology Organisation. He is a Research Fellow at NNL and is involved in international activities on spent fuel storage at IAEA, WNA and with EPRI Enhanced Storage Collaboration Programme.
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