R&D on Fast Reactors and their Fuel Cycles in NNL

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UK Fuel Ambition: Development of Fuels with Enhanced Sustainability, Safety & Economics using Indigenous UK R&D Skill & Facility Base

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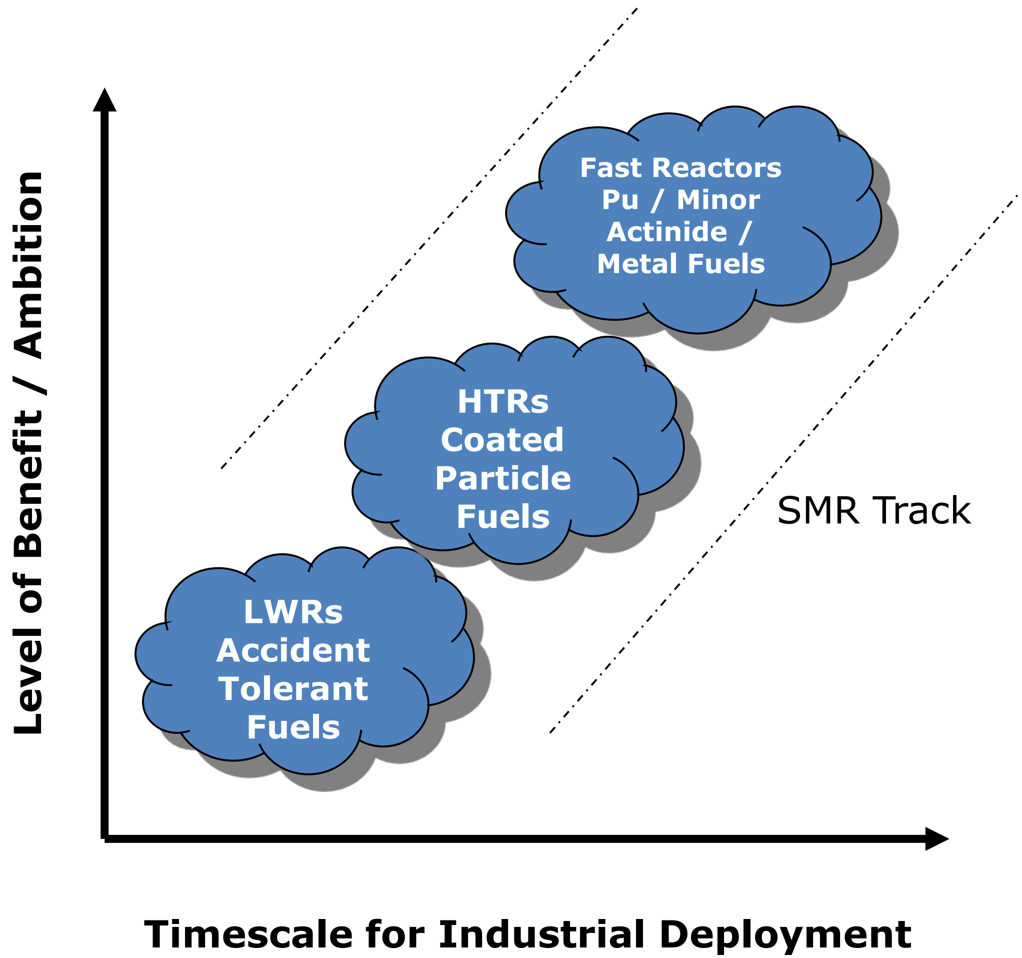
Enhanced Sustainability and Economics

- Improved Burn Ups
- Re-use of Recycled Fissile Materials
- Recycle of minor actinides
- Better Operational Flexibility
- Better Manufacturability

Enhanced Safety During Accident Conditions

- Lower Fuel Temperatures in Normal Operation Leading To Increased Margins in Accident Conditions
- Low or Zero Hydrogen Production and Associated Chemical Heating of the Cladding.
- Enhanced Fission Product Containment
- Enhanced Fuel Retention within Cladding



Nuclear Fuel Centre of Excellence

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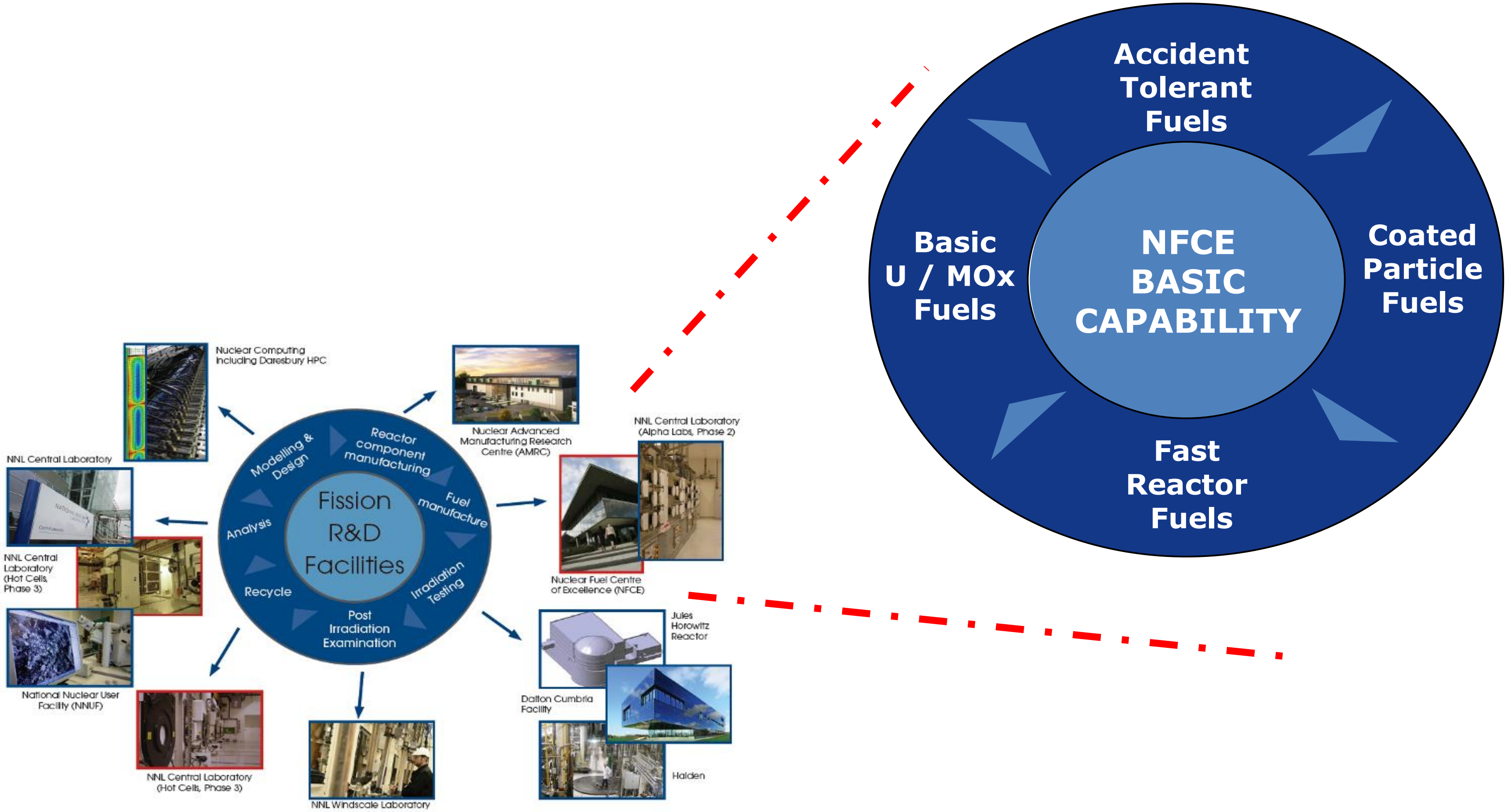

European Commission Funded Projects on Fast Reactor Systems

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- MARISA (FP7)
  - Project to build an international research consortium around the MYRRHA accelerator driven system (ADS)
- ESNII+ (FP7)
  - WP1 Leader, Contributions to WP2, WP3, WP4 and WP5
  - WP6 – ALLEGRO Core Physics Benchmarks
  - WP7 - Development of high Pu content fast reactor fuels and understanding the safety of fuel manufacturing processes.
- DEMOCRITOS (H2020)
  - Development of small gas or liquid-metal cooled fast reactor for space nuclear-electric propulsion systems

Fuel cycle scenario modelling

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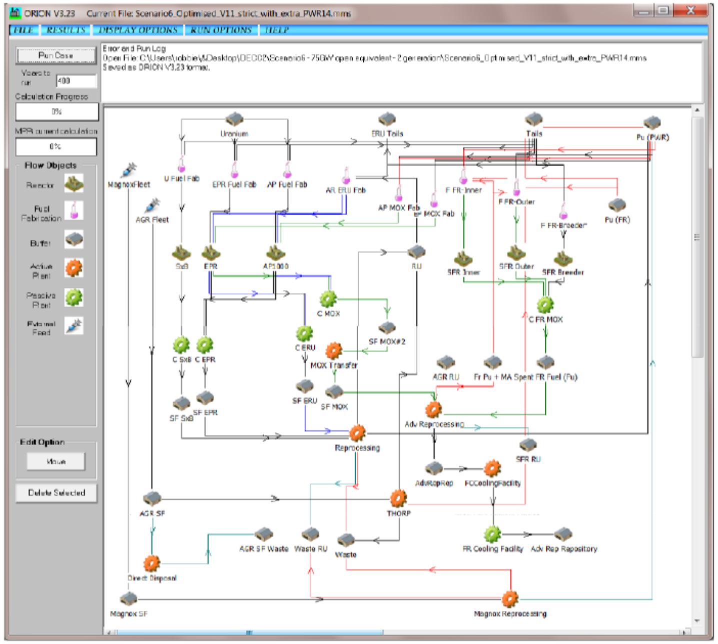
- Fuel cycle simulation computer programs are used to assess the impacts that different fuel cycle scenarios may have on:
  - Uranium ore requirements,
  - Ability to start a sustainable fast reactor fleet,
  - Time at which feed of natural uranium is no longer required
  - Packing density and inventory of a geological repository under different partitioning scenarios
  - The practicalities of handling fresh minor-actinide bearing nuclear fuel
  - Processing of spent nuclear fuel
  - Requirements for high level waste immobilisation technologies

NNL's ORION code has been used to assess the impacts of the alternative partitioning and transmutation scenarios



Generating capacity - transition from LWRs to fast reactors - Scenario (a)

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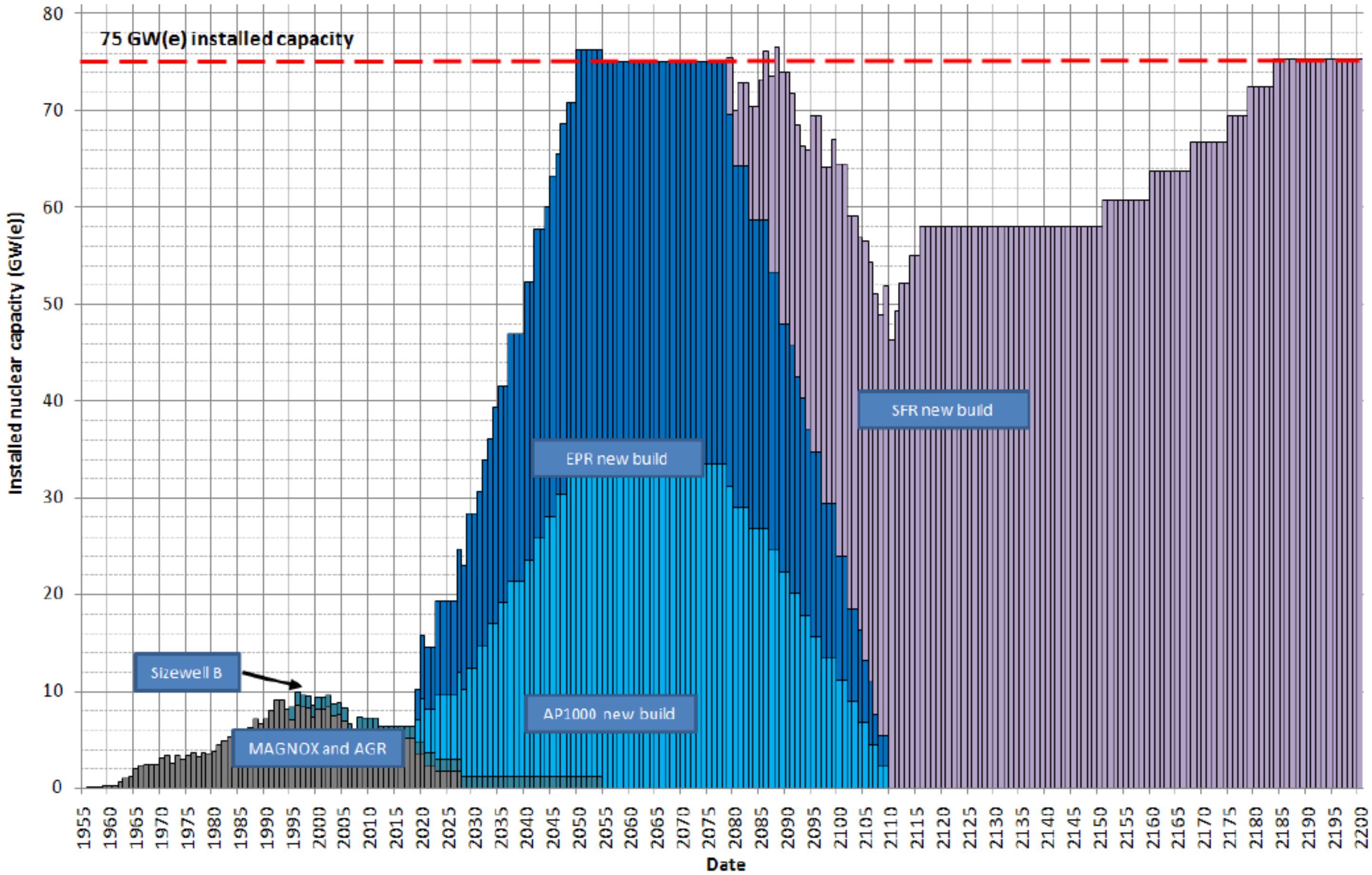

- 75 GWe target installed capacity
- FRs introduced at same rate as LWRs retire
- LWRs fuelled on mixture of UO_2 and MOX

Generating capacity - transition from LWRs to fast reactors - Scenario (b)

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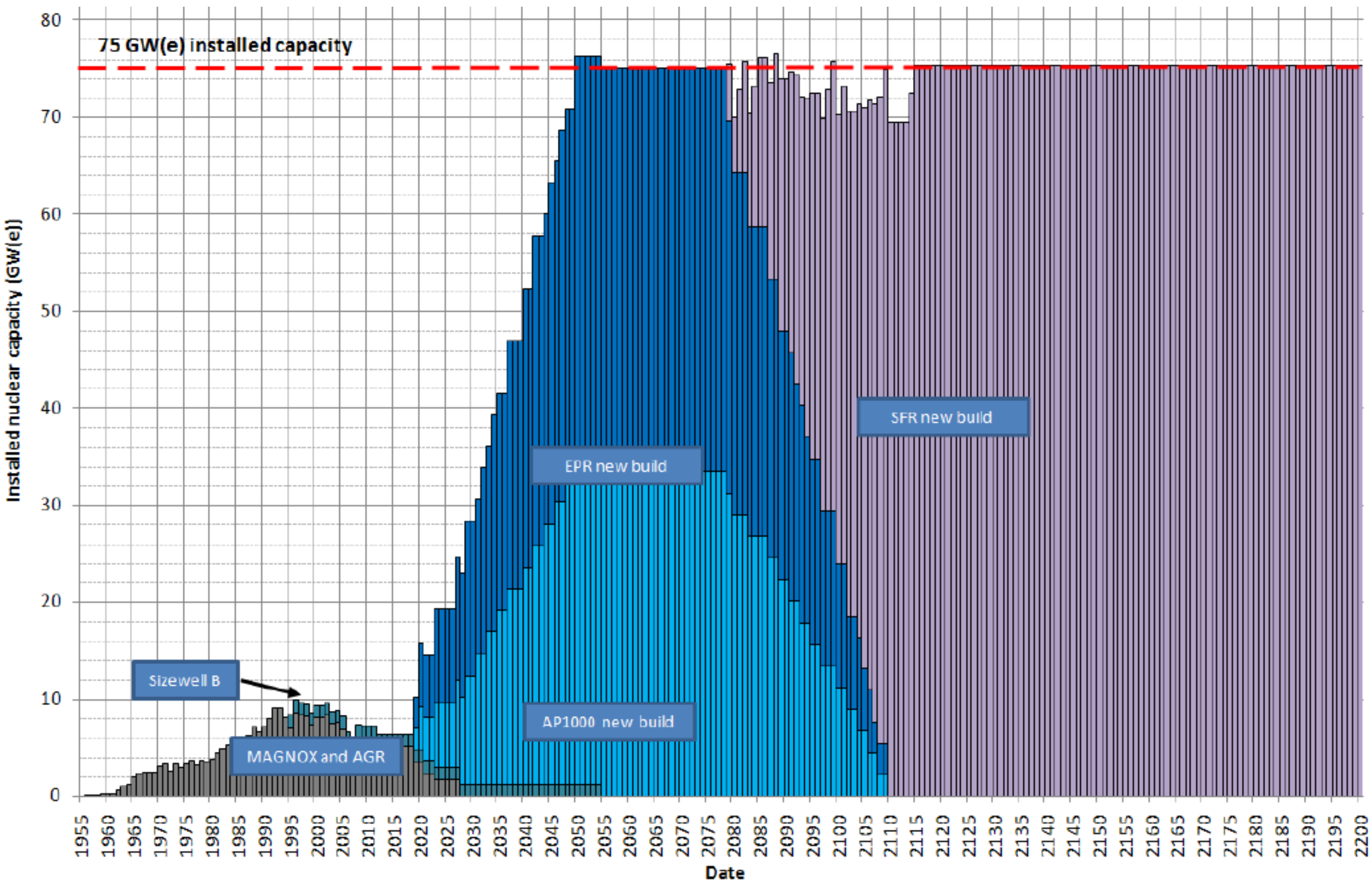

- 75 GWe target installed capacity
- FRs introduced at same rate as LWRs retire
- LWRs fuelled only with UO_2

Heat loading on a geological repository

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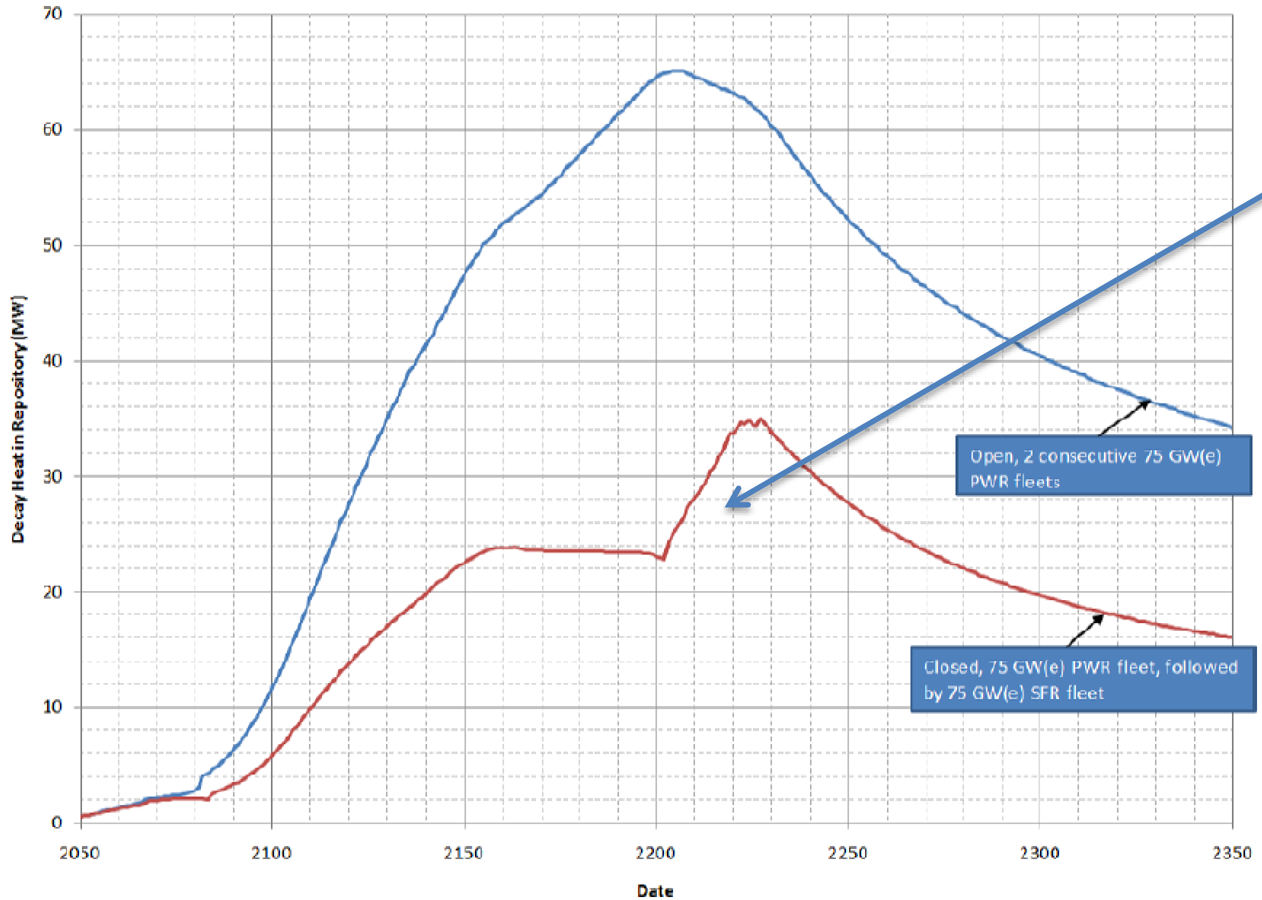

Retirement of SFR fleet when all fuel elements sent to repository intact

- Blue curve - two successive 75 GWe LWR fleets
- Red curve - a 75 GWe PWR fleet followed by a 75 GWe SFR fleet

Post Irradiation Examination of Historical Fast Reactor Core Components and Materials

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- CEA Programme – Phenix Treasure
  - CEA has a programme to carry out PIE on fuels and components irradiated in Phenix.
  - Possibility to examine some of these materials in the UK.
  - Transport of these materials is very difficult … so UK contribution is ….
- PFR Treasure
  - Identification of stored interesting components and materials irradiated in PFR
    - 1st Stage – Identification
    - 2nd Stage – Storage at Sellafield
    - 3rd Stage - PIE

Remaining PFR Fuel

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	No of Sub assemblies	No of pins	Burn-up (%)		Pu enrichment		Cladding
			Min	Max	min	max	
Sub-assemblies	71	20,369	2.2	19.6	15.9	33.8	M316, PE16, HL548
Radial breeders	14	1,226	0.1	2.4	-	-	M314, PE16, FV448
Clusters	33	553	0.2	11.9	0.0	33.2	M314, PE16, FV548
Loose pins		133	0.3	23.2	12.5	33.6	M314, PE16, FV548
Carbide	2 clusters, 5 mixer breeder sub-assemblies and 8 radial breeder sub-assemblies						

Data Available

- Fuel listing data include:
  - Assembly/pin identity
  - Assembly type
  - Design report
  - Drawing number
  - Pin diameter and length
  - Cladding material
  - No of grids
  - Grid materials
  - Core location
  - Irradiation cycle discharged

Other Materials

- Unirradiated fuel assemblies
  - air stored
- Carbide fuel
  - irradiated and
  - unirradiated
- Structural components
  - core and
  - primary circuit

Fast-track development of NNL's fast reactor fuel performance capability

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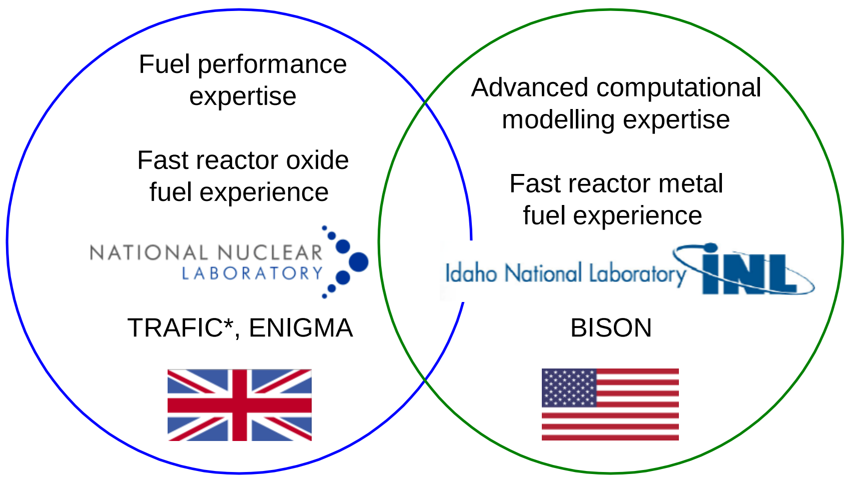
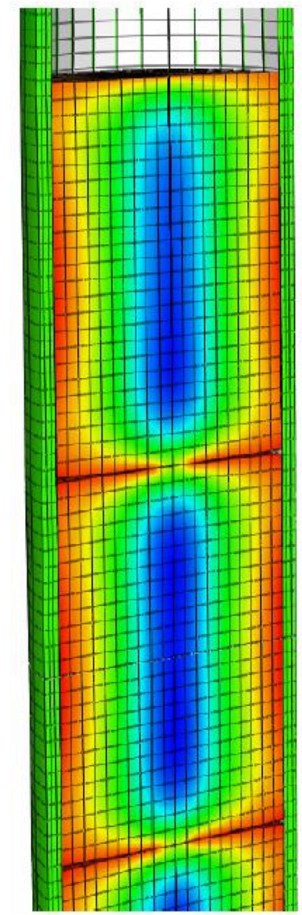
Developing a state-of-the-art capability for fast reactor fuel performance modelling

- Collaboration with INL
- NNL will develop BISON for fast reactor oxide fuel
- INL will develop BISON for fast reactor metal fuel
- Oxide fuel capability will be benchmarked against TRAFIC



- Strategic fit with UK nuclear energy R&D roadmap
- Underpins design & licensing of UK fast reactors and their fuel
    - including PRISM



Example visualisation of BISON fuel rod temperature distribution predictions

Fast Reactor Core Neutronics (ERANOS)

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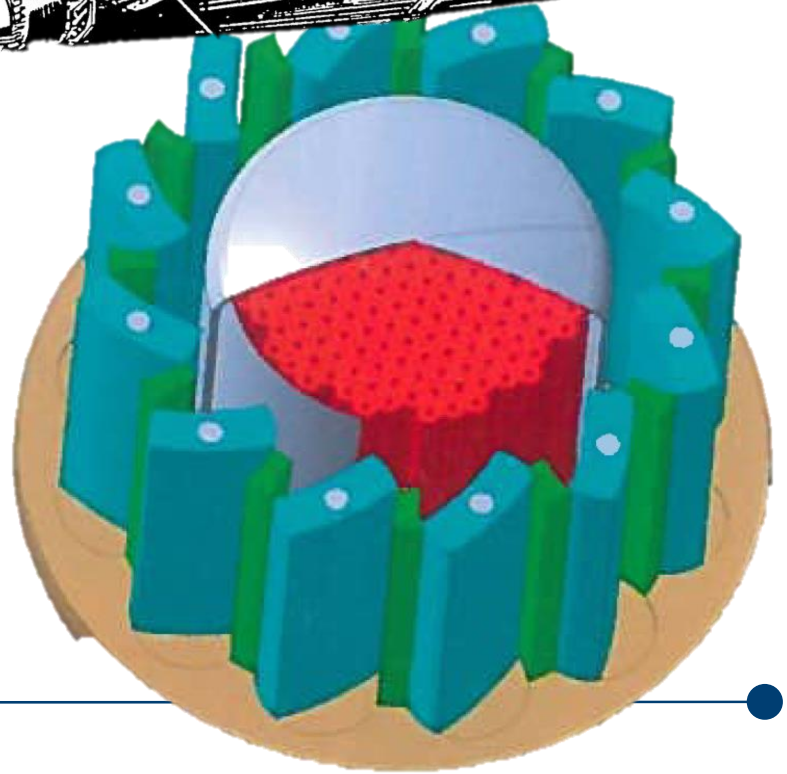
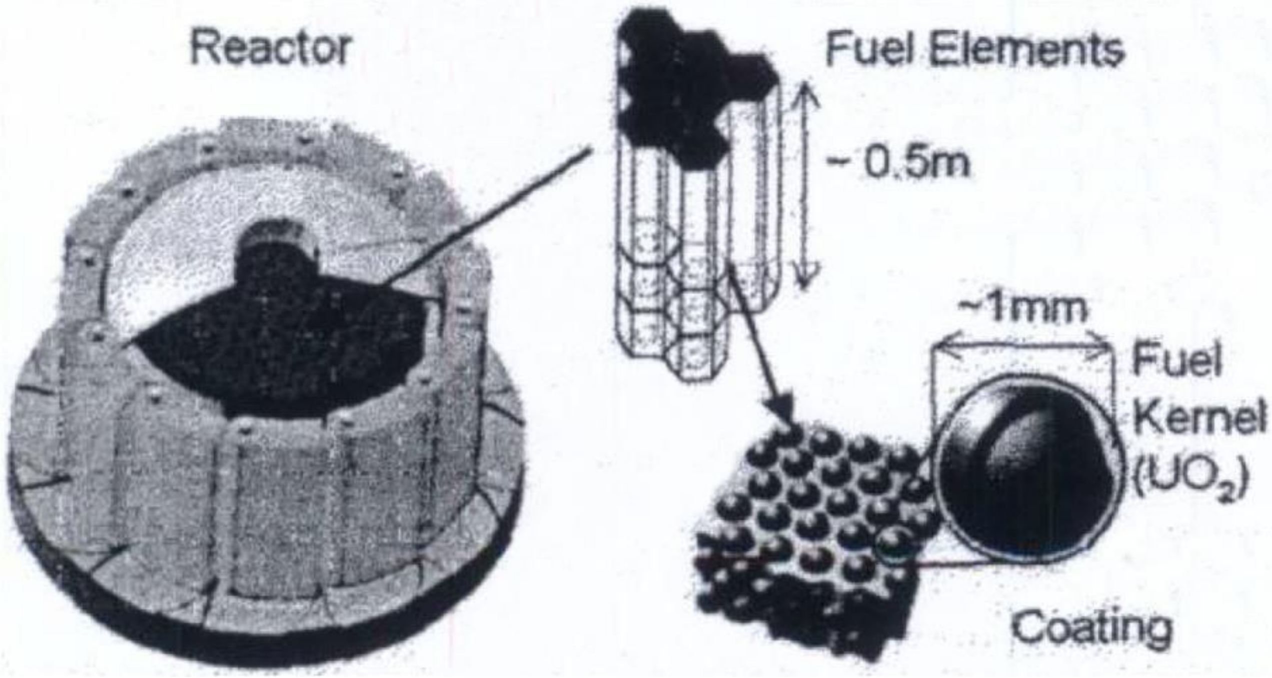
- IR&D Project – PRISM Core Neutronics Model
  - Objective – to form an independent view of the ability of the PRISM reactor to burn the UK's civil plutonium stockpile
- ALLEGRO
  - Benchmark calculations of the ALLEGRO start-up core as part of ESNII+ WP6
- OPUS
  - Assessment of the CEA gas-cooled space fast reactor.
  - Exploration and potential scale-up to 1MWe
- SP-100
  - USDOE/NASA concept for a liquid lithium cooled space fast reactor
- Molten Salt Fast Reactors
  - Independent calculations to inform our input into the debate

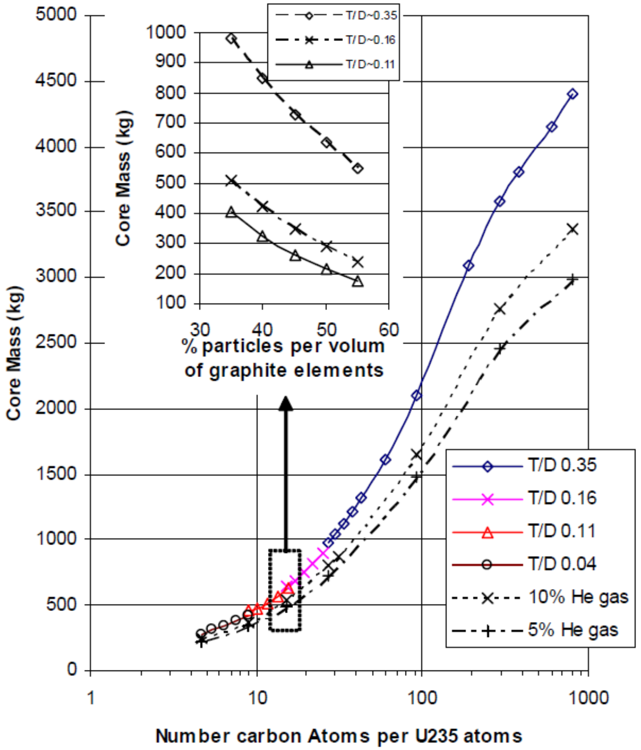
Starting 'workhorse' space reactor concepts – DEMOCRITOS project

- SP-100 core concept
  - $1b USSDI/USDOE/NASA joint project
  - 1300-1400K core outlet temperature
  - Small electrical output
  - Liquid metal cooled
- OPUS core concept
  - Significant CEA/CNES project
  - 1300K core outlet temperature
  - Small thermal & electrical output
  - Gas cooled
- (Other concepts exist. Chosen based on availability of data)



OPUS - core

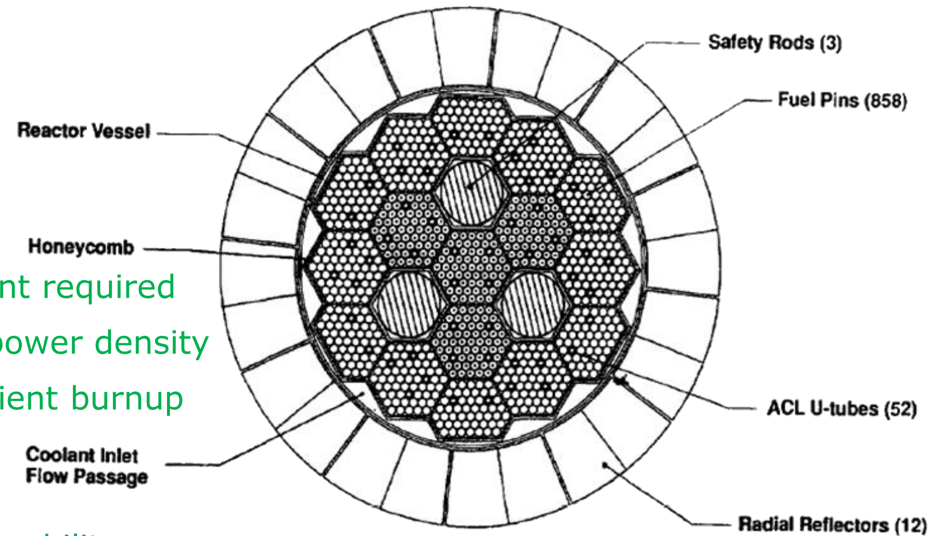


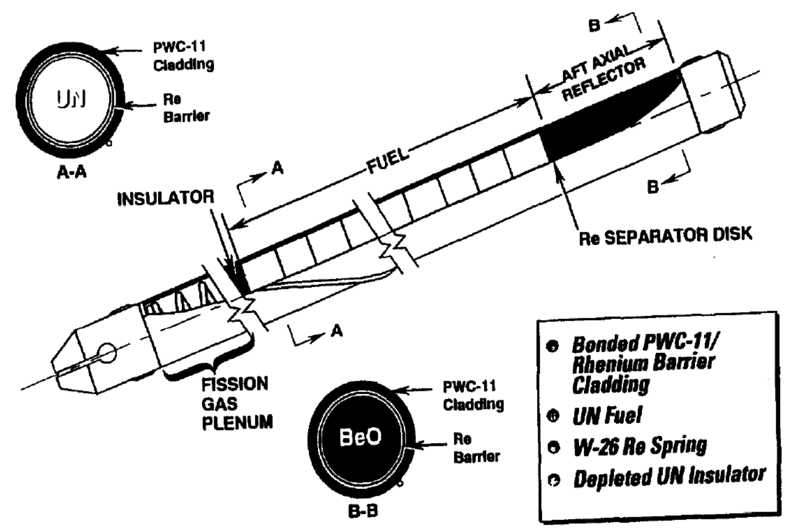


- Very high packing fraction (>> a normal HTR)
- 3cm across flats hexagonal prismatic fuel elements
- 1cm diameter coolant channel
- Most temperature rise due to poor heat transfer coefficient at coolant:graphite boundary. Relatively small temperature increase through block

SP100 – fuel and core

- 858 fuel pins arranged to form cylindrical core
- Uranium nitride pellet stack
  - High heavy metal density (x1.4) ⇨lowers enrichment required
  - Good thermal conductivity (x6 at high T) ⇨higher power density
  - Good fuel swelling characteristics (cf oxide) ⇨sufficient burnup
- PWC-11 + rhenium liner
  - Strong Doppler from cladding ⇨helps load follow capability
  - High degree of structural integrity ⇨grace period during ac
- Axial BeO reflector
  - Improves neutron efficiency ⇨lowers enrichment required
  - Thermalises spectrum at top of core
  - Moderates neutrons leaving core towards biological shield





Nuclear Electric Propulsion System Layout

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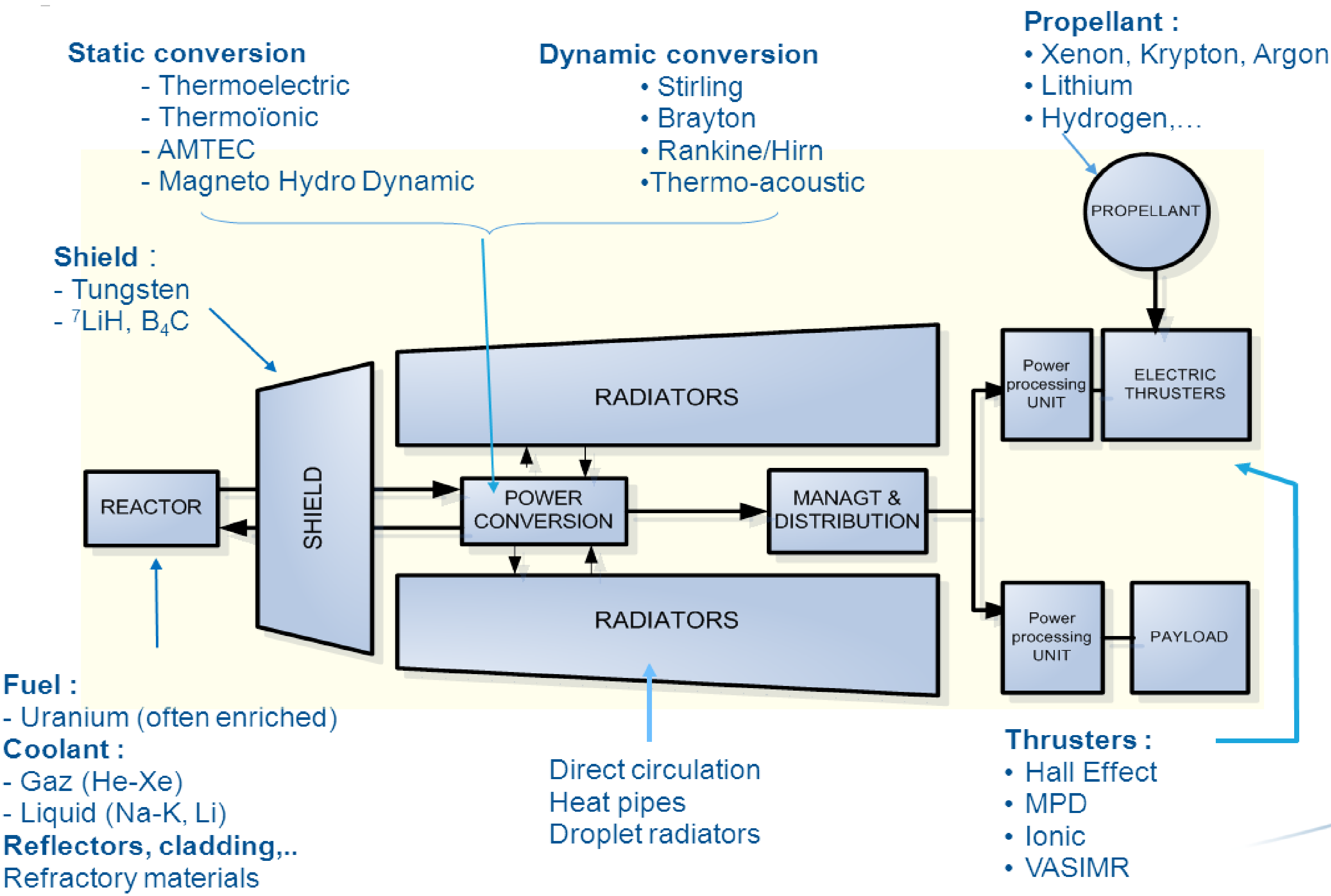

NEP – The Radiator Problem

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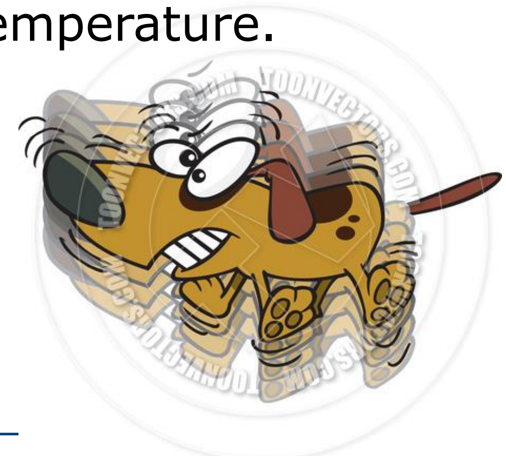
- For a system thermal efficiency of about 33%
  2 MW of heat will be rejected for 1 MWe generated.
- The radiator is the main contributor to the mass of the system so there is a strong driver to reduce the radiator area and hence radiator mass.
- For a given temperature the radiator area is proportional to the amount of heat rejected.
- For a given amount of heat rejected the radiator area is inversely proportional to T^4
  - » There is a conflicting requirement to both maximise thermal efficiency and maximise the temperature at which heat is rejected. Need to maximise the reactor outlet temperature.

Tail wagging the dog ? - legitimate in this case

Reactor design is driven by the need to optimise radiator performance.



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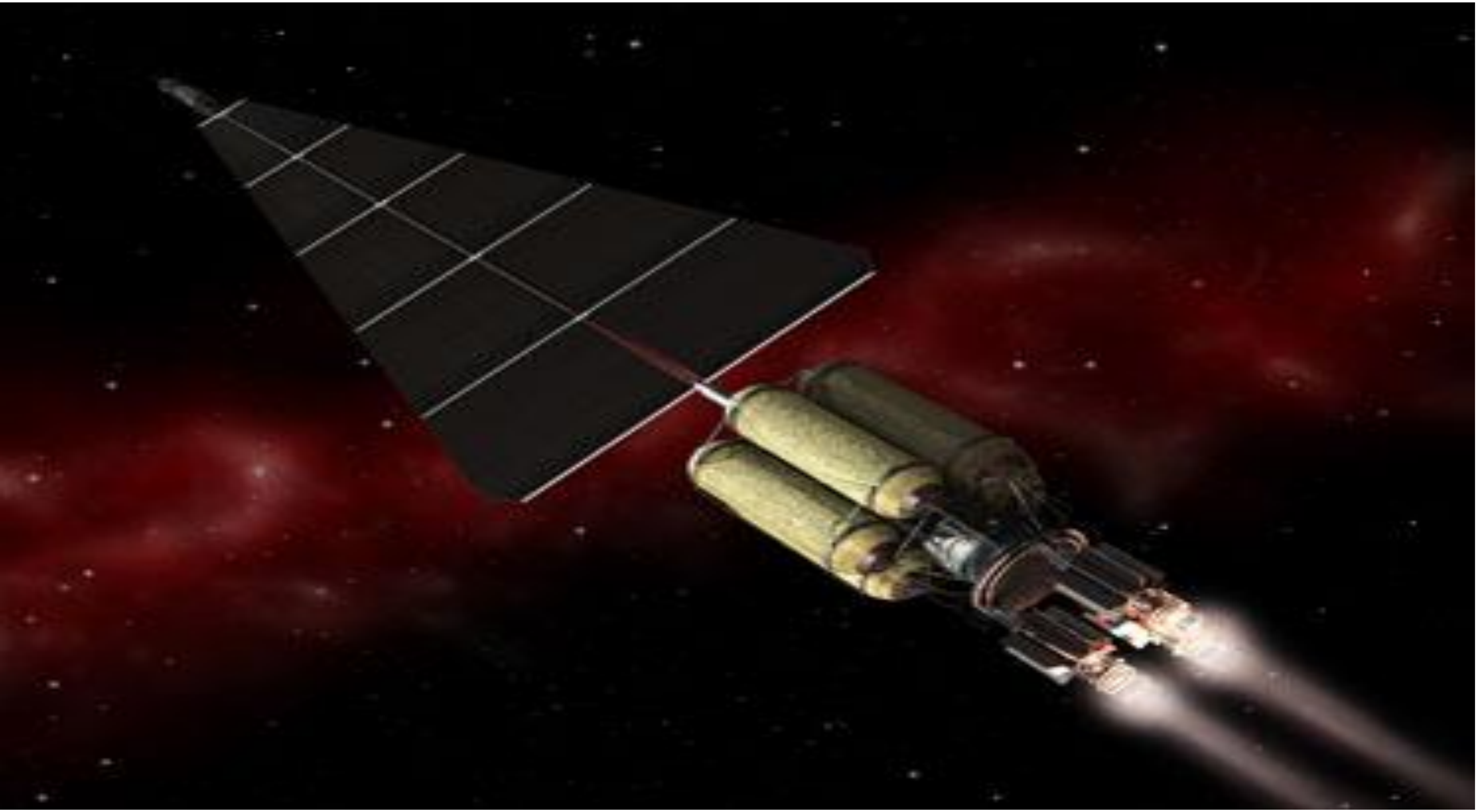
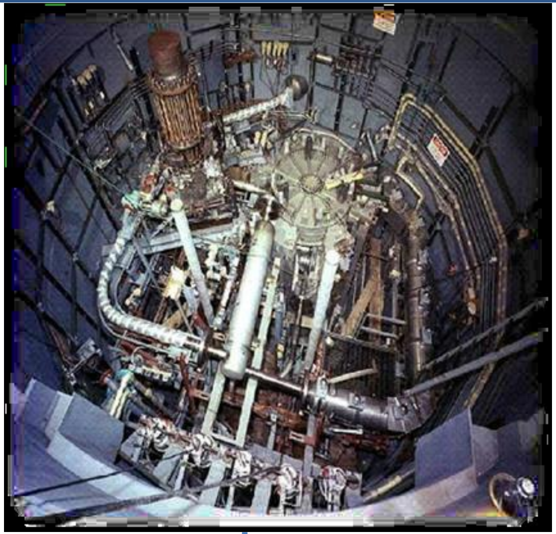
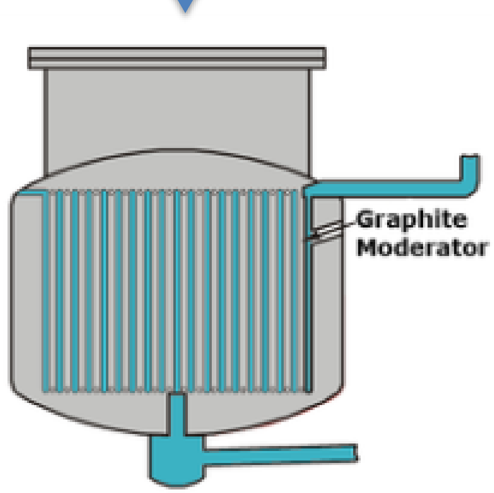


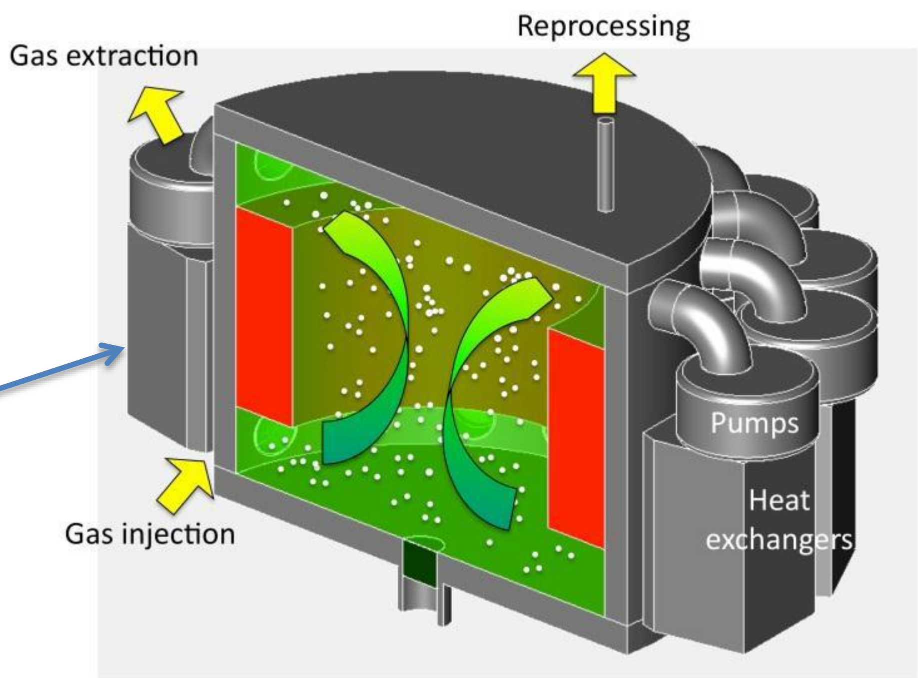
Molten Salt Fast Reactors



Molten Salt Reactor Experiment – Oak Ridge, US, 1960s



Delete the graphite moderator



Gen IV Molten Salt Fast Reactor MSFR

Images courtesy of Gen IV MSR System Steering Committee