Nuclear power and the nuclear fuel cycle

The basic science, technology and economics nuclear power

Dr Benjamin Heard, August 2019

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FRAZER-NASH CONSULTANCY

Nuclear power and the nuclear fuel cycle

Part 1: Nuclear update – global status

Part 2: Nuclear power and fuel cycle – what is it? How does it work?

Part 3: Briefly examining cost

Part 3: Newest nuclear developments

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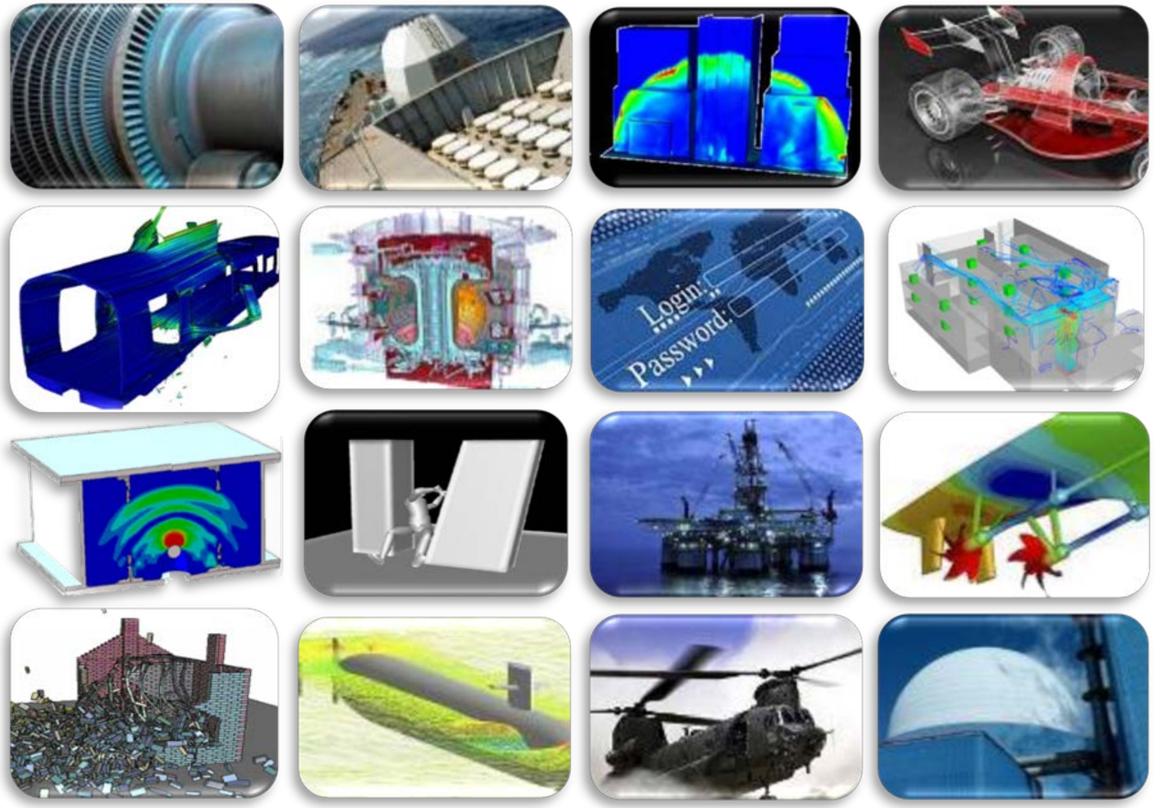
Who we are

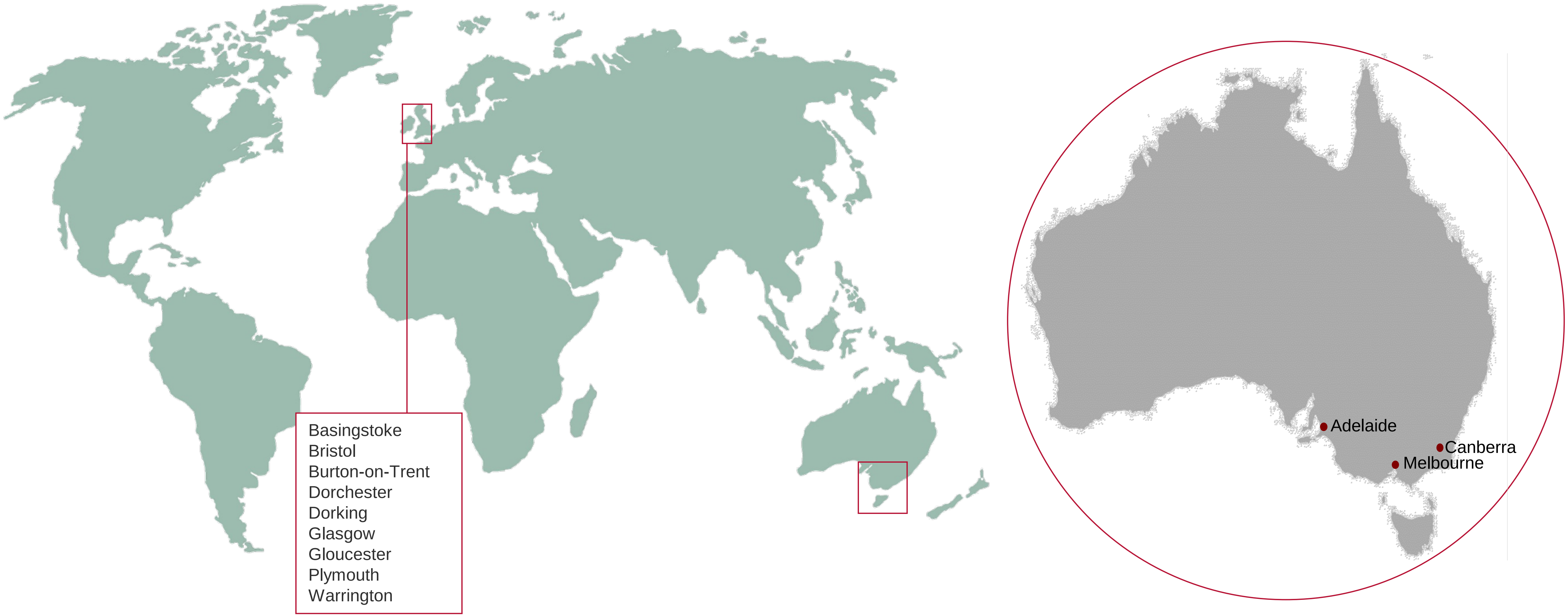
- Frazer-Nash is a leading systems and engineering technology company.
- Using our Systems Approach we excel at solving some of today's most complex engineering challenges.
- Our consultants apply their expertise and know-how to develop, enhance and protect our clients' critical assets, systems and processes.
- We use advanced engineering techniques to help clients improve safety, efficiency and performance. And provide independent advice to provide assurance, minimise risk and reduce costs and liabilities.

Who we are

- We're well known for our work across the aerospace, transport, nuclear, marine, defence, energy and oil and gas sectors; and for our security and resilience expertise.
- Our experience of working in diverse industries enables us to transfer skills across different markets to benefit our clients.
- We provide independent, impartial advice to government, regulators and commercial clients.
- With over 700 employees, Frazer-Nash operates from a network Australian and UK offices.



Where we are


Basingstoke
Bristol
Burton-on-Trent
Dorchester
Dorking
Glasgow
Gloucester
Plymouth
Warrington
Adelaide
Canberra
Melbourne

Frazer-Nash in Australia

In 2010, Frazer-Nash opened its office in Adelaide to support programmes in defence, natural resources, rail and aerospace. Since then our strategic aim has been to develop a business which is fully integrated with our UK business, active in the majority of our markets and offering all of our services.

Energy and resources
- Conventional power
- Mining
- Oil and gas
- Sustainable energy
- Water

Transport and industry
- Aerospace
- Automotive
- Marine
- Rail and metro

Defence
- Air systems
- C4ISTAR
- Defence facilities
- Land systems
- Submarines
- Surface ships
- Weapons systems

Some of our local team

Jonathan Armstrong - Adelaide

Head of Australian Business. Physicist. Previous AV 1 qualified expert. Technical oversight for Waste Acceptance Criteria for NRWMF

Dr Mark Wakelam - Canberra

Specialist in handling and transportation in the nuclear industry. Designer of prototype SMR for UK-based developer

Dr Janet Wilson – Adelaide

Civil and structural engineer, specialized in seismic qualification of nuclear facilities

Stuart Taylor – Canberra

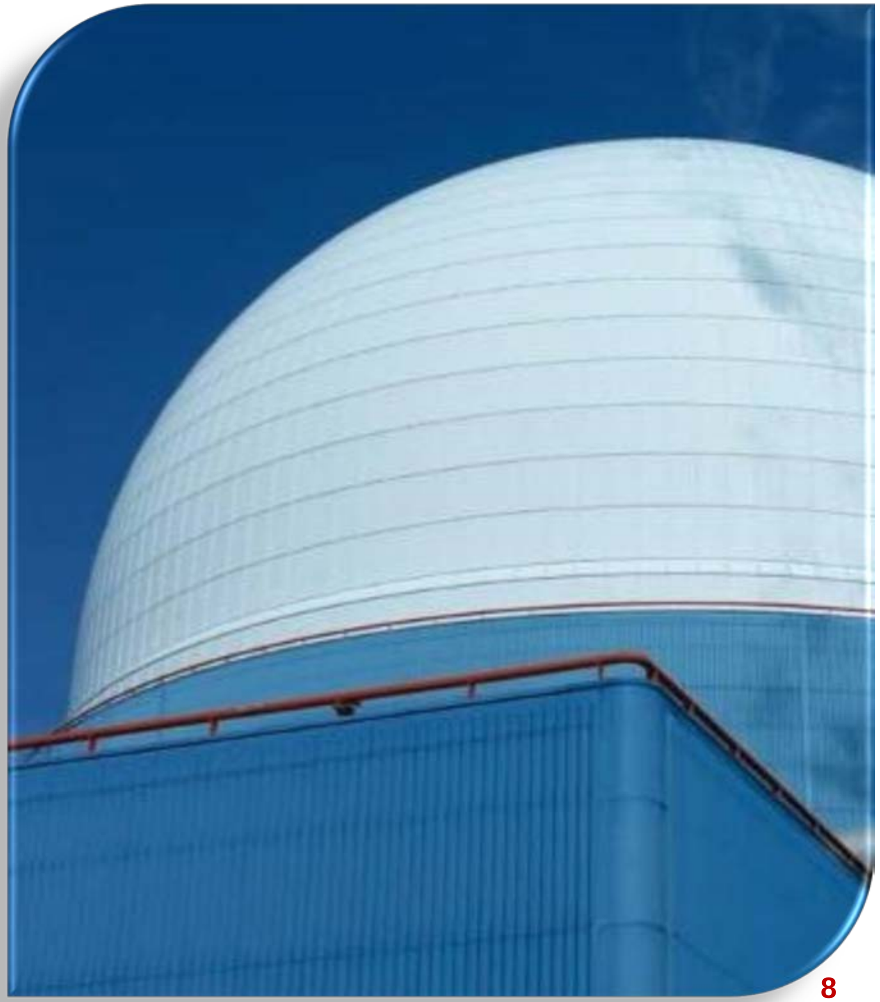
Requirements and acceptance management. Experienced in strategy development for Office of Nuclear Regulator and Nuclear Decomissioning Authority

Nigel Doyle – Adelaide

Safety case development, fuel handling and nuclear material tracking, 15 years experience in UK nuclear industry

Frazer-Nash in Nuclear

- Our support to the nuclear industry spans over **30 years**.
- Approximately **35%** of all the work Frazer-Nash does has a nuclear application.
- Our capability extends to some **400 people with nuclear experience**.
- Our skills are relevant and widely applied to the nuclear lifecycle from research and development, through reactor design, safety substantiation (GDA), commissioning, operation and decommissioning to green field.
- We hold major contracts with the UK regulator, operators, new build developers, reactor vendors, decommissioning companies and Tier 1 supply chain companies.
- We have supported all the new build programmes in the UK and are a respected Tier 1 professional services partner to **UK New Nuclear Developers**.



Part 1 – Nuclear update, global status

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How much nuclear is in use today?

As of 1 August 2019

- 443 *operable* reactors (NB *operable* does not mean *operating*)
- >395 GWe capacity (recent global highest in history of the technology)
- 2,563 TWh per year (>10x total Australian consumption)
- **10.3 % of global** electricity consumption
- **Second largest source** of GHG-free generation (after hydro electricity)
- 55 GWe (55 new units) under construction.
- Highly reliable – the ~100,000 MMe US nuclear fleet operates with average cf ~91%.

In a nutshell: Remains a major part of global electricity, and a massive pillar of clean energy supply.

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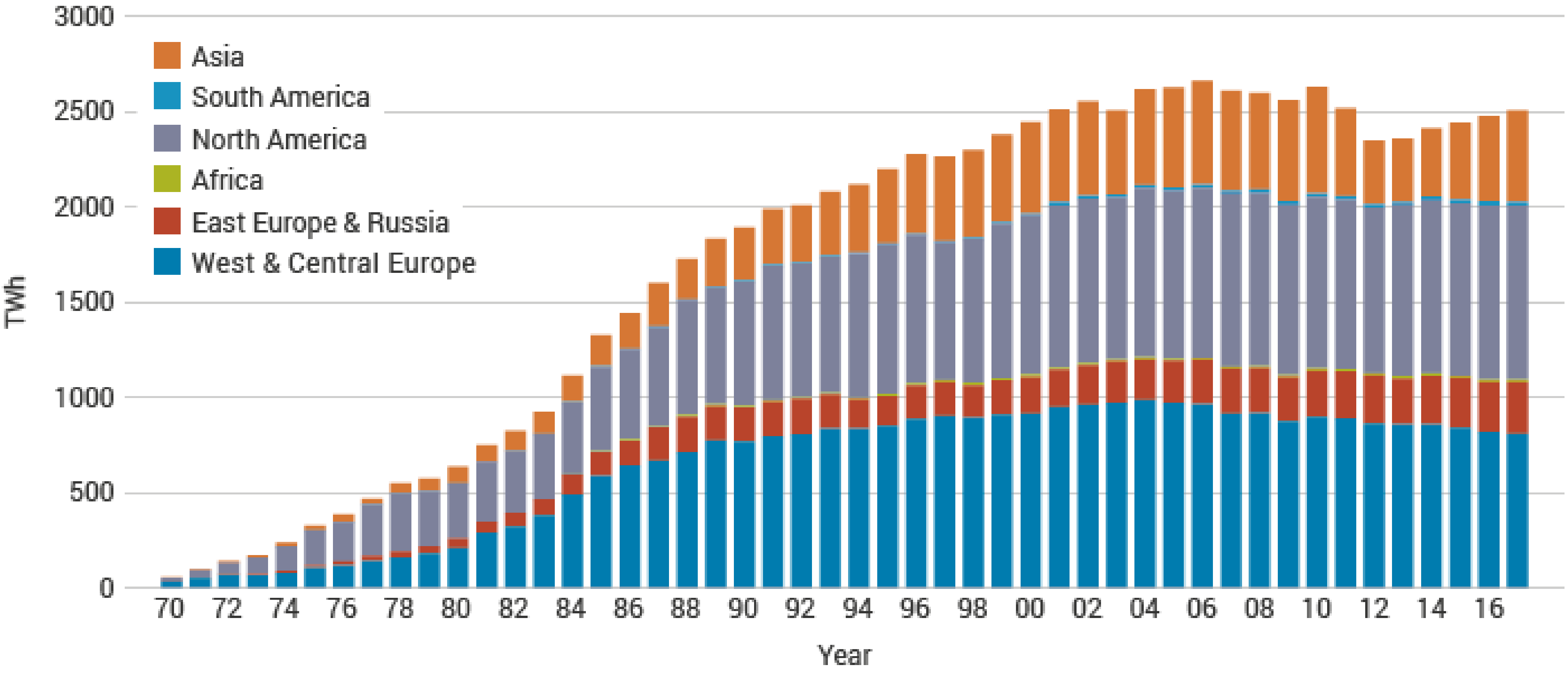
Fine…but how is it *really* going?

- Declined from peak proportion ~17 % global electricity (early 1990s)
- Output currently growing, but moderated by:
  - Japanese fleet shut down , slow progress on restart (*operable*…but not *operating*)
  - German premature closures (Energiewende policy)
  - Scheduled decommissioning of aging fleets
  - Economic pressures in USA – subsidised renewable and very cheap gas
  - Construction delays USA and Western Europe

In a nutshell… globally steady, slowly growing, stable share, uneven regional growth

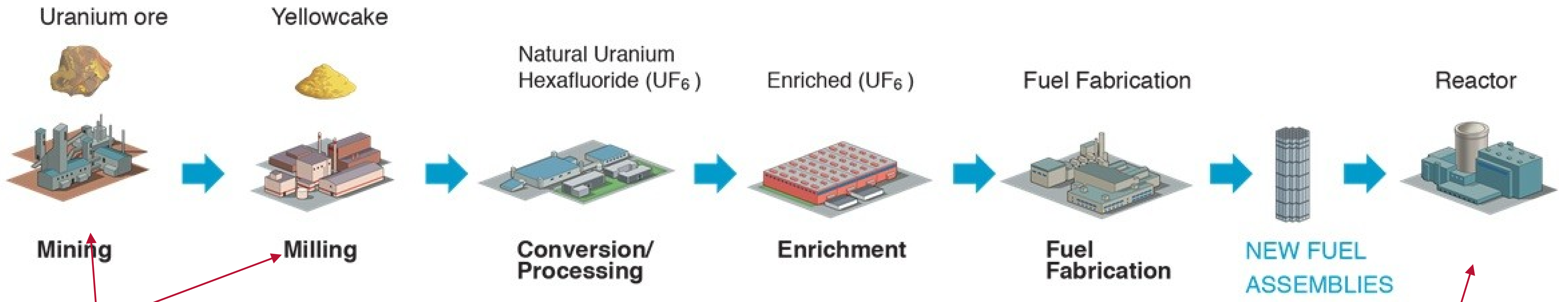
Slowly growing, uneven regional growth



Source: IAEA PRIS

Part 2 – Nuclear power and fuel cycle – what is it? How does it work?

Nuclear Fuel – From Mine to Reactor



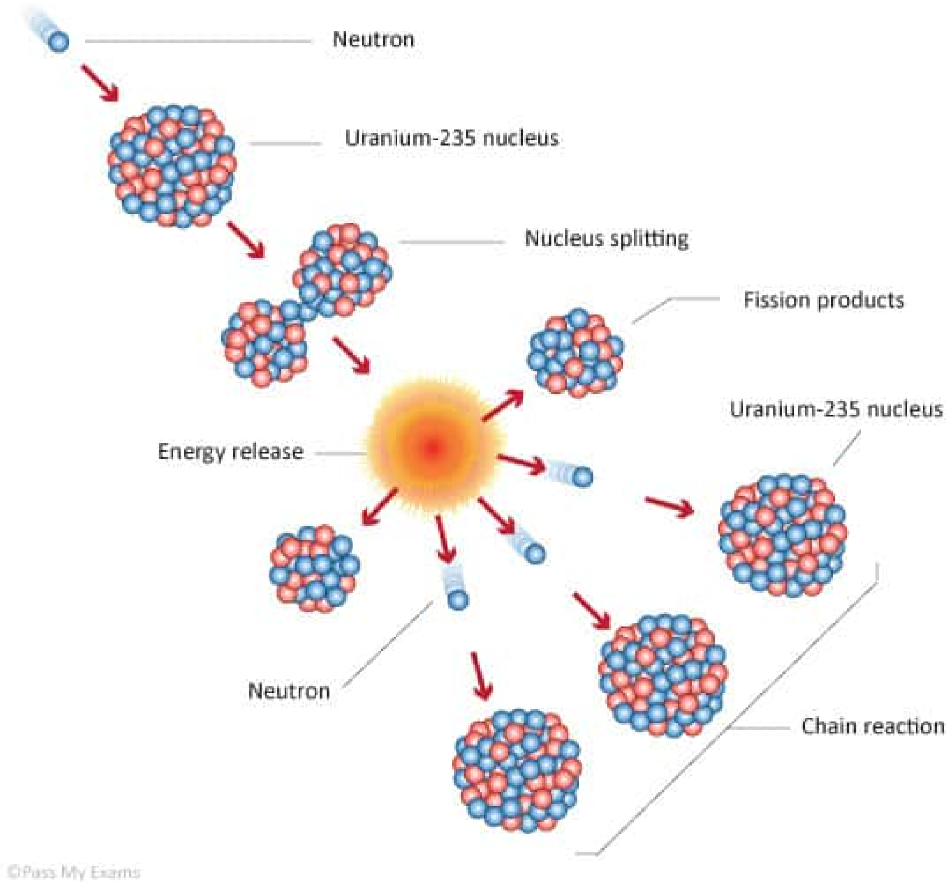
You are here!

Australia is a major player
Large share of total value

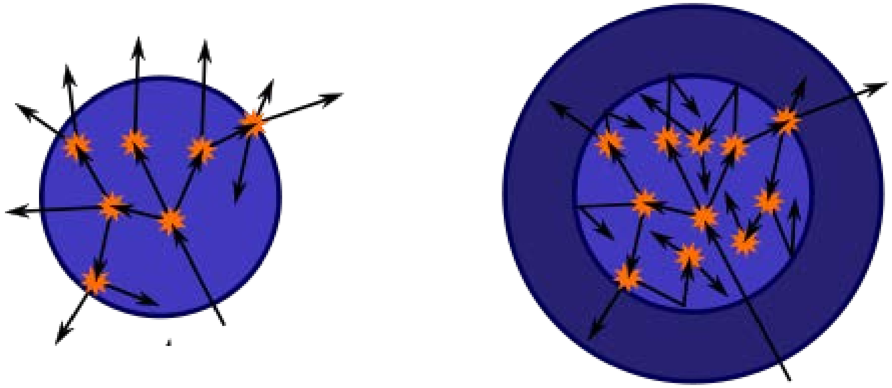
Ample capacity here (for foreseeable future)

What role for this?

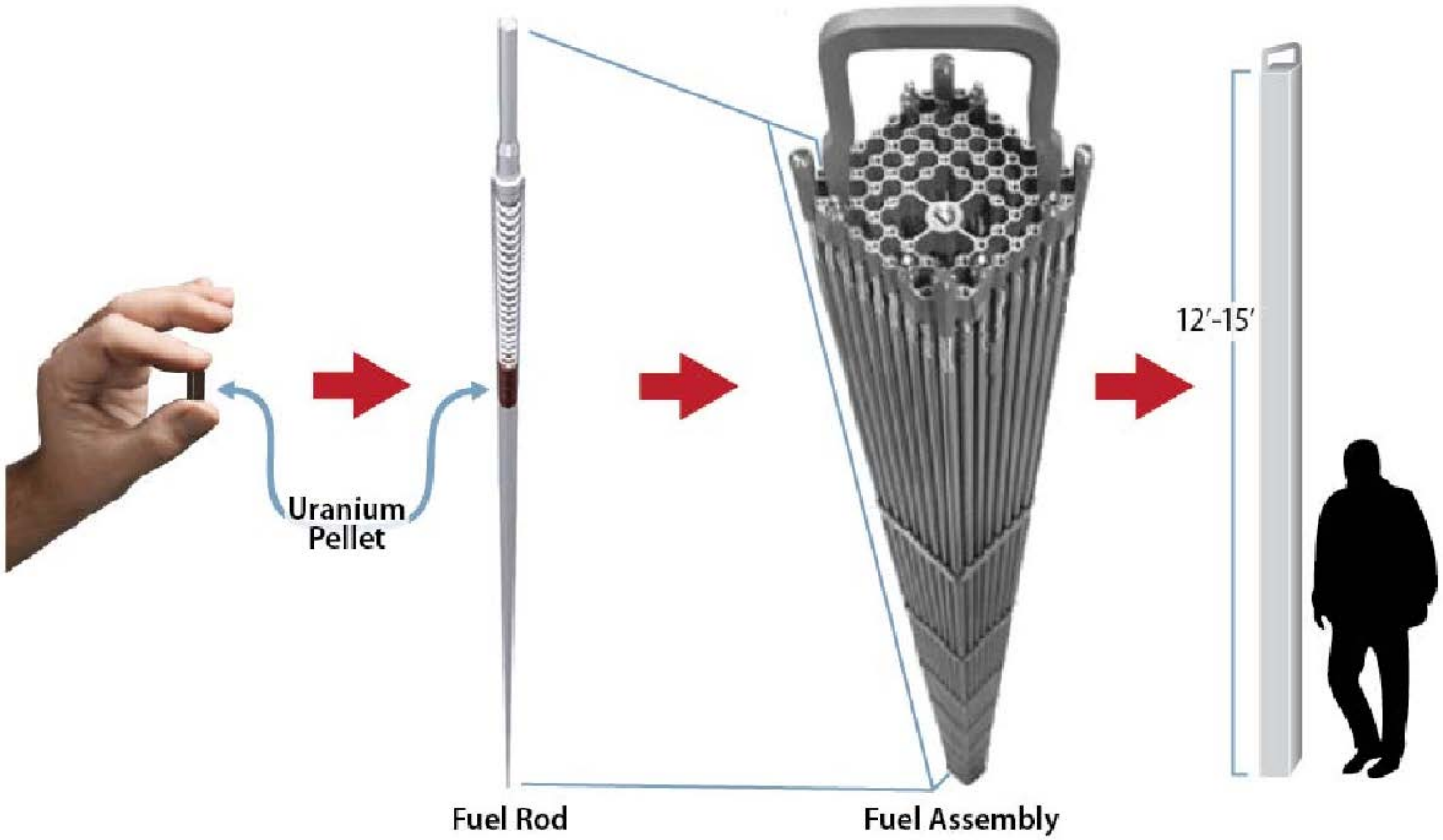
How does nuclear fuel work?



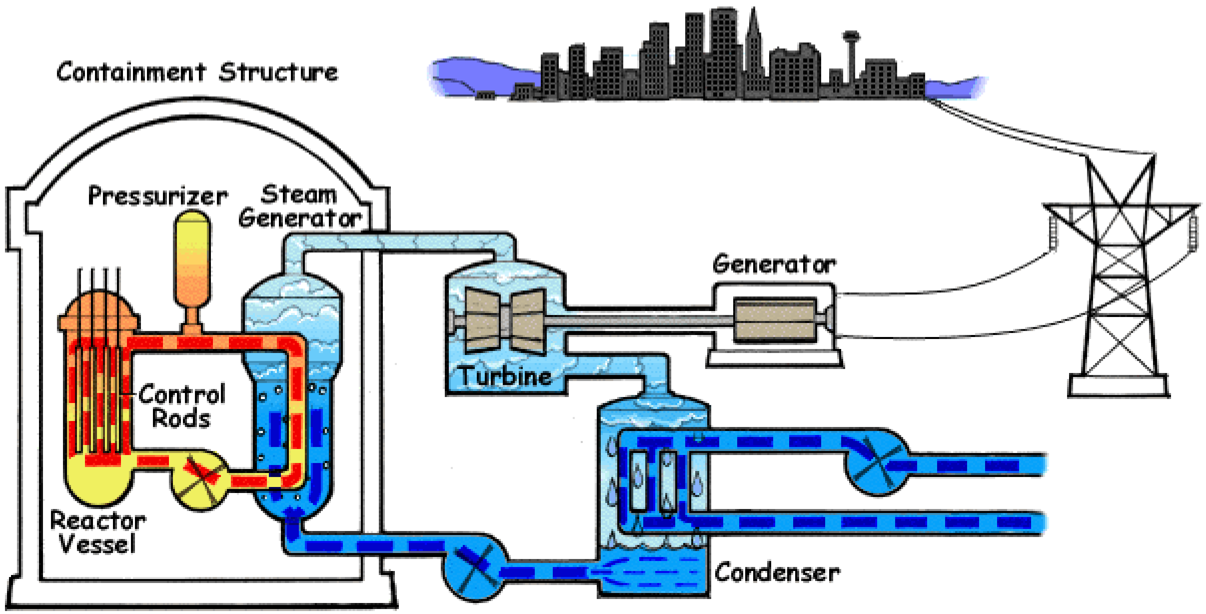
Keep the neutrons in!



What does nuclear fuel look like?



How does the power plant work?



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Why is this even interesting?
1. Energy density

FUEL	DENSITY	COMPARED TO BLACK COAL
Petrol/gasoline	44-46 MJ/kg	2
Diesel fuel	42-46 MJ/kg	2
Crude oil	42-47 MJ/kg	2
Liquefied petroleum gas (LPG)	46-51 MJ/kg	2
Natural gas	42-55 MJ/kg	2
Hard black coal (Australia & Canada)	c. 25 MJ/kg	1
Sub-bituminous coal (Australia & Canada)	c. 18 MJ/kg	1
Lignite/brown coal (Australia, electricity)	c. 10 MJ/kg	0
Firewood (dry)	16 MJ/kg	1
Natural uranium, in LWR (normal reactor)	500,000 MJ/kg	20,000
Natural uranium, in LWR with U & Pu recycle	650,000 MJ/kg	**26,000**
Natural uranium, in FNR	28 000,000 MJ/kg	1,120,000
Uranium enriched to 3.5%, in LWR	**3,900,000 MJ/kg**	**156,000**

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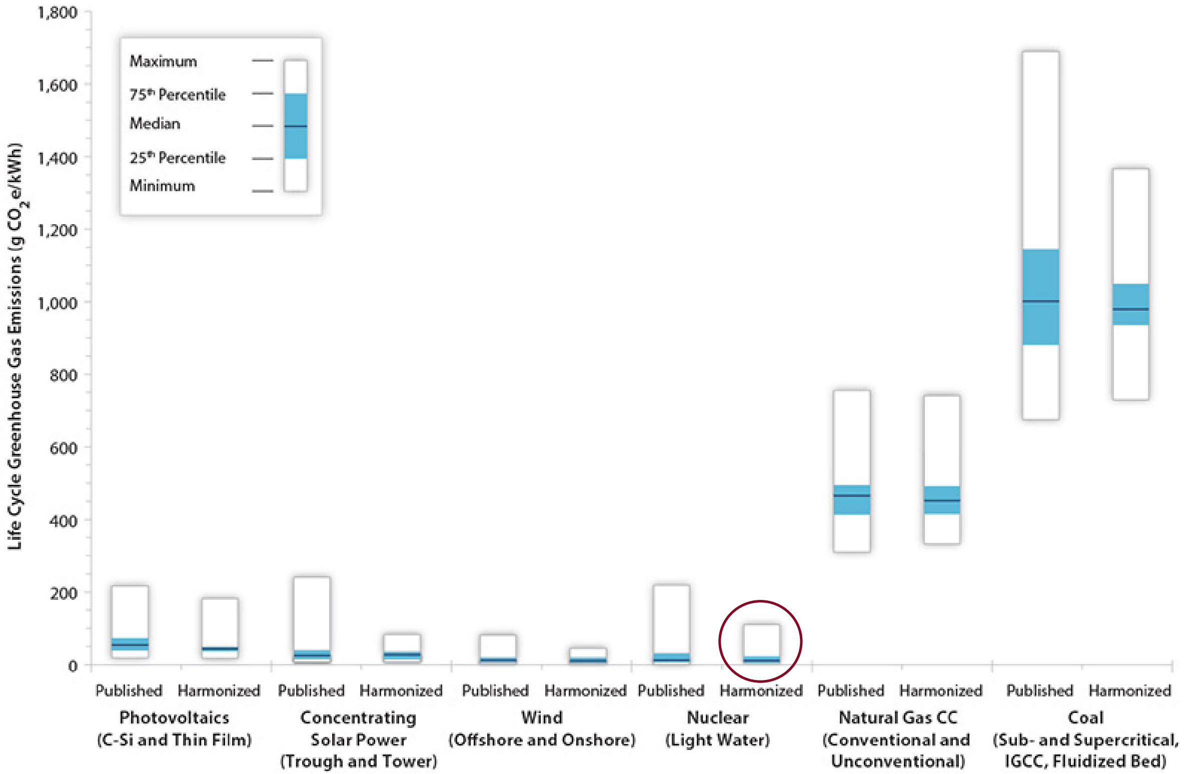
Why is this even interesting?
2. Across the lifecycle, very low greenhouse gas



	Photovoltaics	Concentrating Solar Power	Wind	Nuclear	Natural Gas CC	Coal
Estimates	46	36	126	99	61	164
References	17	10	49	27	45	53

*CC = combined cycle

99 estimates

27 references

Median of **12 g CO_2-e per kWh**

National Renewable Energy Laboratory (2013) *Lifecycle Assessment Harmonization*, as cited by Intergovenmental Panel on Climate Change

Why is this even interesting?
3. Across time, stable and reliable clean power supply

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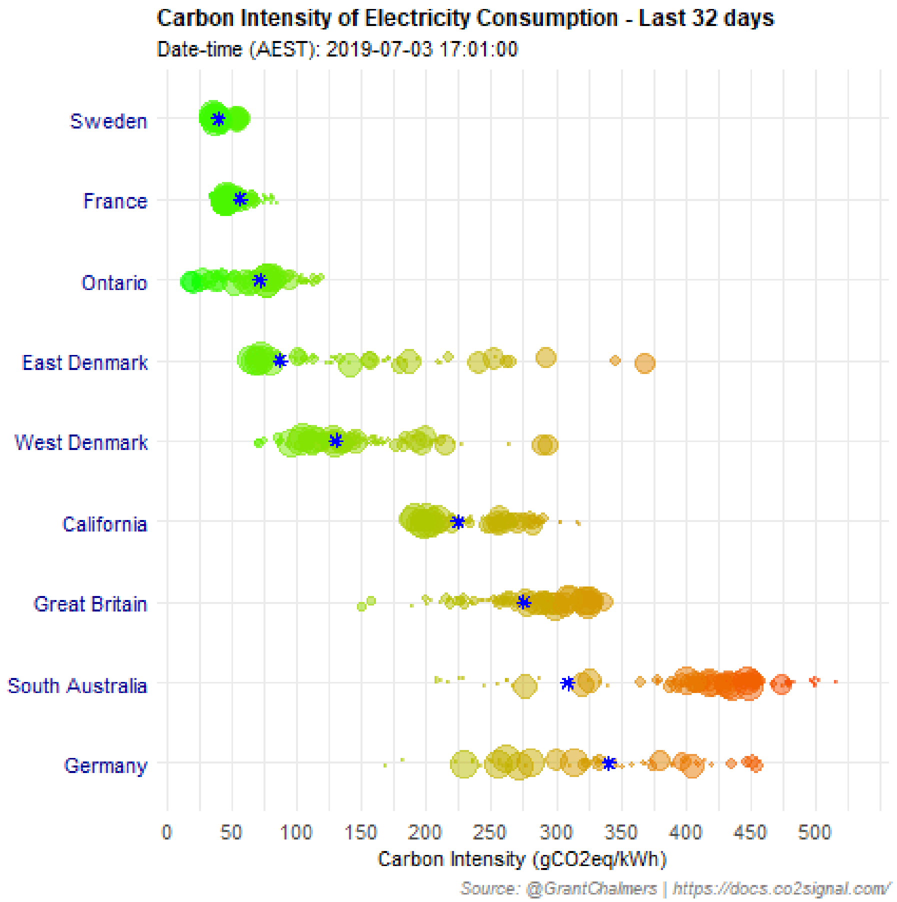
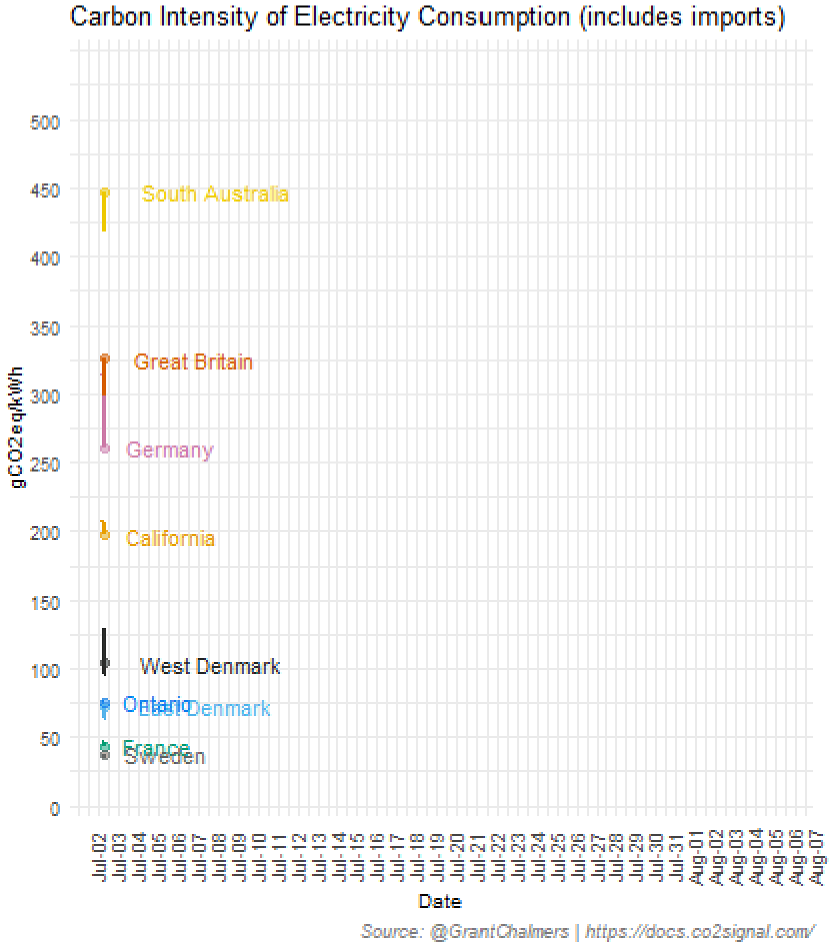
3. Across time, stable and reliable clean power supply





What's left is Used nuclear fuel / nuclear (?) waste

Uranium Fuel

Spent Fuel

Visually, the same as when it went in.
Virtually all the mass is still there.

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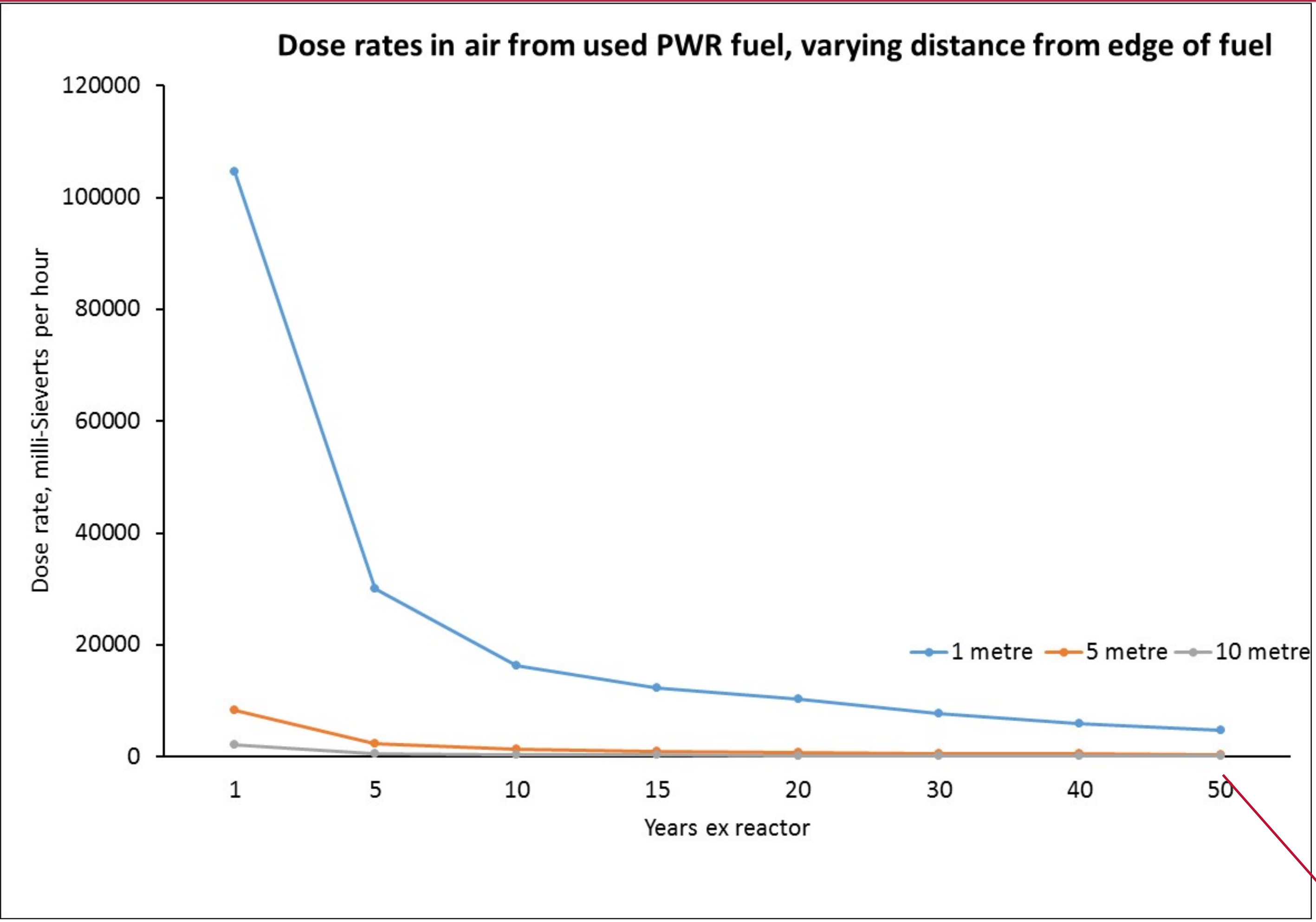
The **hazard** of used nuclear fuel



- The dose from unshielded used nuclear fuel:
  - Can easily be deadly
  - Falls swiftly with time
  - Decreases markedly with distance
- The management of this hazard is
  - Shielding
  - Distance
  - Time
- The hazard is **HIGH**
- The hazard management is **uncomplicated**

100 mSv – lowest dose as which evidence supports increased cancer risk, still present after 50 years at 1 hour of exposure from 10 metres

Data: Lloyd et al, 1994, Dose Rate Estimates from Irradiated Light-Water-Reactor Fuel Assemblies in Air.
Chart by Frazer-Nash Consultancy

Dry cask storage – interim management

Shielding, distance and time underpins safe management of used nuclear fuel

Shielding and distance means the hazardous Mujambi the lion is a popular attraction at Adelaide Zoo

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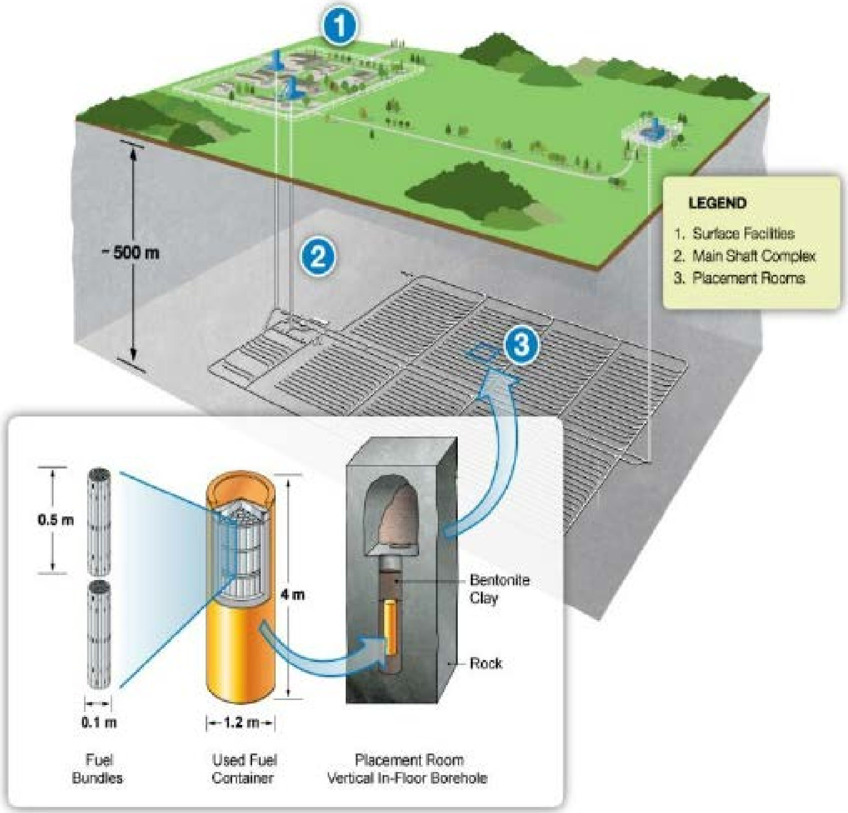
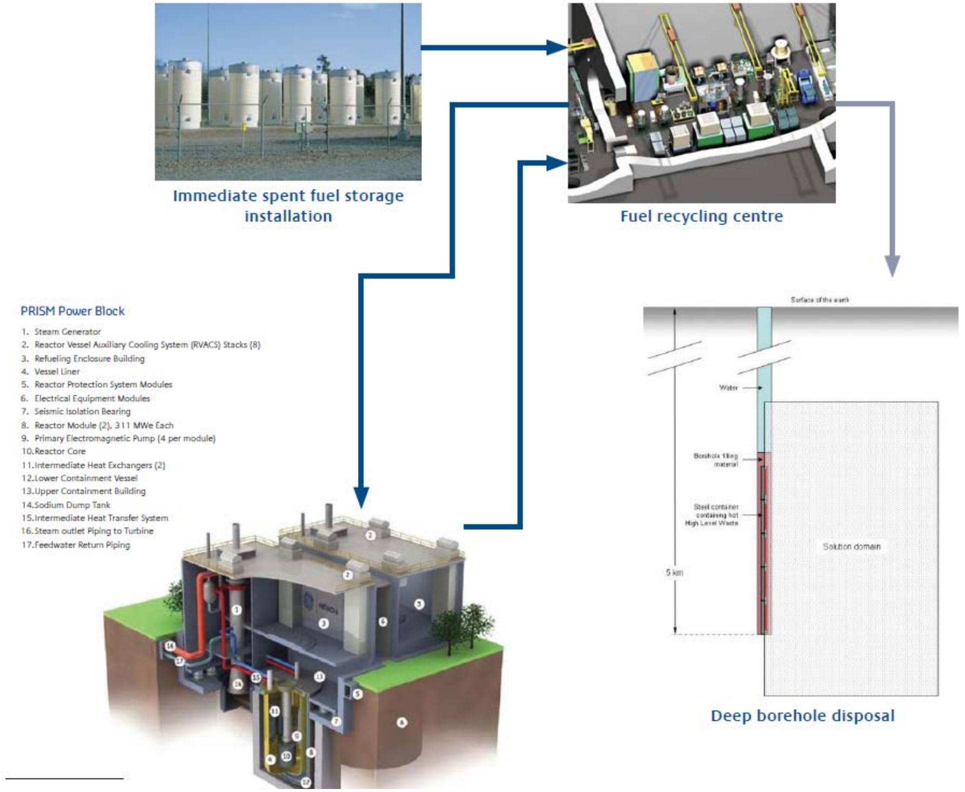
Ultimately, disposal is required. Of what?

Industry standard: Whole used fuel assemblies



Innovative alternative – fission products only



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Part 3 – Briefly examining cost

How is the cost of nuclear electricity determined?

Variant	Base	Lower discount	Lower capex	Shorter build
asset life (Amortisation)(years)	40	40	40	40
capacity factor (base assumption) (%)	91	91	91	91
fixed O&M ($m MWe)	0.344	0.344	0.344	0.344
variable O&M ($ MWh^{-1} sent out)	14.7	14.7	14.7	14.7
fuel cost ($ GJ HHV^{-1})	0.75	0.75	0.75	0.75
thermal efficiency (%)	34	34	34	34
energy conversion (GJ MWh^{-1})	3.6	3.6	3.6	3.6
discount rate (real, pre-tax weighted average cost of capital) (%)	**7**	**5**	**5**	**5**
capital cost ($ m MWe^{-1})	**5.558**	**5.558**	**5.000**	**5.000**
construction period (years)	**6**	**6**	**6**	**3**
levelised cost of electricity ($ MWh^{-1} sent out)	**89**	**73**	**68**	**65**

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Part 4: Newest nuclear developments

Advanced nuclear – an umbrella term

- **S**mall **M**odular **R**eactors **(SMR)**
- **L**iquid **F**uel **T**horium **R**eactor **(LFTR)**
- **P**ower **R**eactive **I**nnovative **S**mall **M**odule **(PRISM)**
- **I**ntegral **M**olten **S**alt **R**eactor **(IMSR)**
- **H**igh-**T**emperature **G**as-cooled **R**eactor **(HTGR)**
- **And more…!**

Advanced nuclear general refers to one or several of the following:

- **Smaller** generating units.
- **Advanced fuels** (metallic alloy solid fuel, liquid fuel salts, thorium-based fuels, uranium pebble fuel).
- **Passive or inherent safety** (incapable of over-power events, or passively cools in that event).
- **Higher outlet temperatures** (500 - >1,000 º C).
- Greater **fuel efficiency.**
- Geared toward **fuel recycling** and near-total uranium/transuranic consumption.

Advanced nuclear – presumed benefits

Cost reduction:

- Inherently safe = lesser engineering, complexity and materials.
- Smaller units = manufacturing paradigm over construction paradigm.
- Lower fuel costs
- Spread capital, bring forward revenue flow, lower risk.

Faster ramping

- Better integration with VRE; or…
- Full-day load-following?

Versatility

- High temperatures for crucial, non-electricity industrial applications.
- Electricity + (heat service).

Connectivity: Smaller single generating units, better suited to

- 'Long' grids (National Electricity Market).
- Weak grids (developing world).
- Off-grid (e.g. mines, remote communities).

Waste reduction

- More efficient use of mined uranium.
- Recycling of existing used fuel.

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Advanced nuclear – notes of caution

New generation of reactors is not commercially available today.

- Road to market with a new nuclear product: Long, expensive, difficult – expect attrition.
- Must fill order books, build manufacturing facilities, train and retain work force…
- Then deliver, succeed, repeat!
- Consider Tesla: battery gigafactories and Model 3 - the space between excitement and delivery.

Infographic from NuScale illustrates the challenge in commercialising new nuclear in the US.

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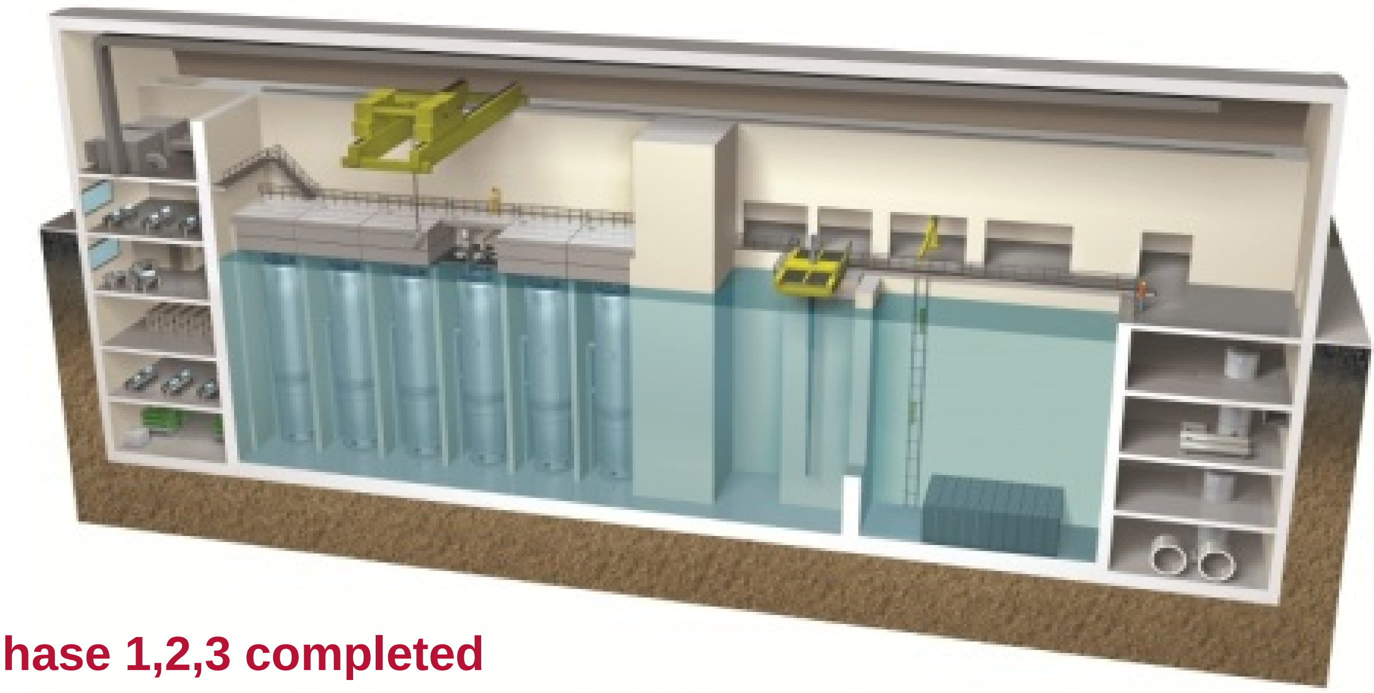
Advanced Nuclear - NuScale

- **Light water SMR**
  - Oxide fuel
  - Water cooled and moderated
  - Very small units (60 MWe)
  - Very nimble for load-following
- **Safety profile**
  - Total passive cooling and natural circulation, including submersion in heat sink



- **Status**
  - Design certification application with US NRC, **phase 1,2,3 completed**
  - **NO** emergency planning zone required
  - **NO** emergency back-up power required
  - Selected BWX Technologies as manufacturer (September 2018)
  - **Change to NRC regulations imminent to recognize new safety paradigm**

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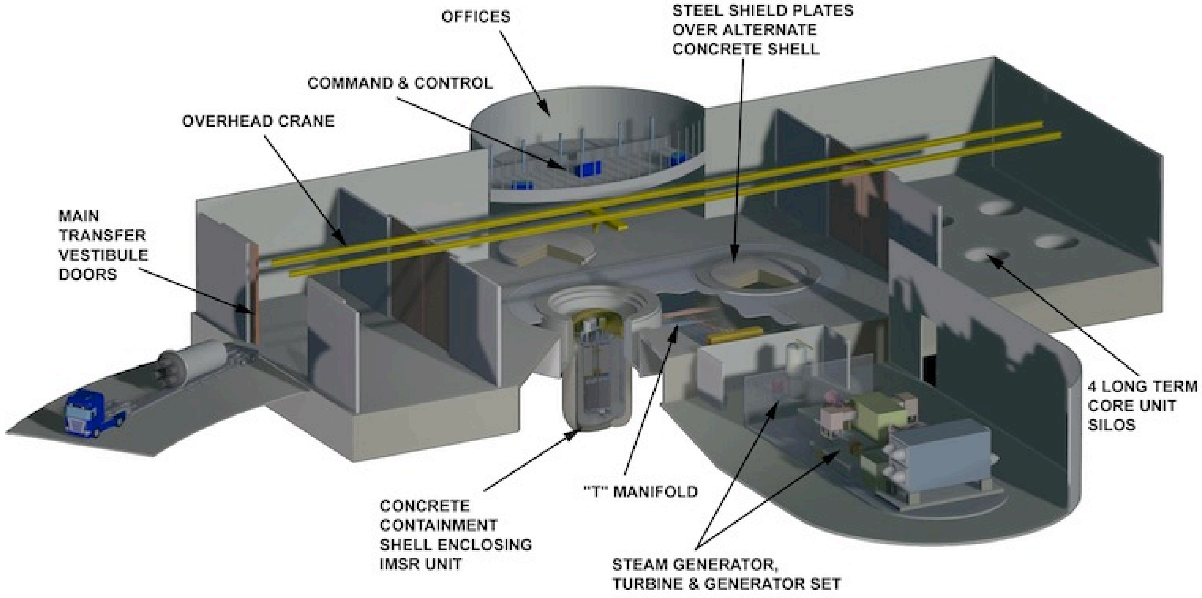
Advanced Nuclear – Terrestrial Energy

- **Integral Molten Salt Reactor**
  - Liquid fuel salt
  - Integrated reactor unit, 7-year life, designed for swap-and-replace
  - 6x fuel efficiency compared standard LWR
  - 190 MWe units, ~600 º C outlet – industrial grade heat
  - Very nimble for load following
- **Safety profile**
  - *Inherent* safety – liquid fuel cannot melt; temperature rise reduces chain reaction – ‘walk away safe’
  - No water – no steam – no hydrogen production
- **Status**
  - Commenced Stage 2 Pre-Licencing Vendor Design Review (October 2018)
  - Teaming with Southern Company and National Labs for business case in hydrogen production



Question and Answer

- Nuclear is steadily growing and not booming
- Nuclear power is very high energy density, very low lifecycle emissions and highly reliable.
- A pellet of nuclear fuel is equivalent to a ton of black coal
- Used nuclear fuel is a serious hazard with uncomplicated management, and highly recyclable
- The cost of nuclear electricity is driven by capex, discount rate and build time
- Advanced nuclear reactors present major, not minor, improvements on the current sector

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