Journey from Gen III/III+ to Gen IV Reactors

Dr Adi Paterson
Australian Nuclear Science & Technology Organisation

EA Nuclear Engineering Panel: 22 November, 2017
<table>
<thead>
<tr>
<th>ANSTO Putting Science to Work</th>
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<tr>
<td><strong>OPAL Research Reactor</strong></td>
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<td><strong>Centre For Neutron Scattering</strong></td>
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<td><strong>Nuclear Materials Research</strong></td>
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<td><strong>Advisor to Government</strong></td>
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EBR-1 First Nuclear Electricity - December 20 1951
GIF Timeline (Australia)

• Intention to apply in April 2007
• Application halted (change in Government) in late 2007
• Government supports bid to join the GIF in March 2015 with bi-partisan support
• Petition presented to GIF Policy Group in October 2015
• GIF Policy Group Delegation visit to Australia in Feb 2016

From Lyndon Edwards: Australia’s Participation in the Generation IV International Forum (GIF)
Australia accedes to the GIF Framework Agreement

On 14 September 2017, Australia deposited its instrument of accession to the Generation IV International Forum (GIF) Framework Agreement. Australia became the 14th member of the GIF on 22 June 2016 when it signed the GIF Charter.

Acceding to the Framework Agreement will allow Australia to become actively engaged in R&D projects related to Generation IV systems, particularly in R&D projects on advanced materials.
International Context

Instruments for Australia in Nuclear Power

- IAEA/NEA (Fission): Small Modular Reactors
- Fusion: **ITER** and **INTERNATIONAL TOKAMAK PHYSICS ACTIVITY (ITPA)**
- Generation IV International Forum
- China: SINAP partnership (renewal?)

= Towards a strategic research and technology framework?
Generations of Nuclear Energy

Generation I
- Early Prototypes
  - Shippingport
  - Dresden
  - Magnox
  - PWRs
  - BWRs
  - CANDU

Generation II
- Commercial Power
  - Advanced LWRs
  - CANDU 6
  - System 80+
  - AP600

Generation III
- Evolutionary Designs
  - ABWR
  - ACR1000
  - AP1000
  - APWR
  - EPR
  - ESBWR

Generation III+
- Revolutionary Designs
  - Safe
  - Sustainable
  - Economical
  - Proliferation Resistant and Physically Secure


Gen I | Gen II | Gen III | Gen III+ | Gen IV

http://www.gen-4.org/Technology/evolution.htm
Tree of Nuclear Power Reactors

From G. Cognet: The different generations of nuclear reactors From Generation-1 to Generation-4
Gen III Objectives

- ABWR 1996
- Active Safety – reduced core damage frequency
- Improved Fuel Technology
- Design Life Extension 60-100 years
- Thermal efficiency
- Standardisation
Gen III+ Objectives

- VVER-1200/392M 2017
- Superior Thermal Efficiency
- Passive safety systems
  - Gravity fed cores, convective cooling and condensation
- Standardised designs “modularity”
- Accident tolerant fuel
- Operational design life 50 to 100 years
III/III+ to IV Global Nuclear Capacity

• Significant shifts since 2013
• The “models” are changing
• The countries are changing
• New insights:
  – Predictable supply chains (the Russian model)!
    • Lifecycle contracts with spent fuel return
  – SMRs spin or substance?
Reactors planned, under construction and operational

Turkey: 6 Operational, 2 Under construction, 6 Planned
Jordan: 2 Operational, 0 Under construction, 0 Planned
Saudi Arabia: 16 Operational, 3 Under construction, 0 Planned
Iran: 0 Operational, 1 Under construction, 1 Planned
UAE: 4 Operational, 3 Under construction, 0 Planned
Pakistan: 22 Operational, 6 Under construction, 19 Planned
India: 24 Operational, 3 Under construction, 2 Planned
Bangladesh: 0 Operational, 0 Under construction, 2 Planned
China: 37 Operational, 20 Under construction, 40 Planned
Taiwan: 6 Operational, 2 Under construction, 0 Planned
Japan: 42 Operational, 2 Under construction, 9 Planned
South Korea: 24 Operational, 3 Under construction, 2 Planned
Generations of Nuclear Energy

Older Reactors (no more builds)
- Generation I: Early Prototypes
  - Shippingport
  - Dresden
  - Magnox
- Generation II: Commercial Power
  - PWRs
  - BWRs
  - CANDU

New Reactors (current builds)
- Generation III
  - Advanced LWRs
  - CANDU 6
  - System 80+
  - AP600
- Generation III+
  - Revolutionary Designs
- Generation IV
  - Evolutionary Designs

Advanced reactors
- Gen III+
  - Integral-PWRs
  - Gen IV
  - HTGRs
  - MSRs
  - SFRs
  - LBFRs

Timeline:
- 1950
- 1960
- 1970
- 1980
- 1990
- 2000
- 2010
- 2020
- 2030

http://www.gen-4.org/Technology/evolution.htm
My view in 2013
Design maturity and regulators

- Global integrated nuclear industry
  - United States
  - France
- Mature nuclear program
  - South Korea
  - Russia
  - UK
- Mainstream nuclear
  - Japan
- Transformational nuclear
  - China
- Small nuclear nation
  - Finland
  - United Arab Emirates
  - United Arab Emirates
  - Turkey, Vietnam
- First concrete
- New entrants
2017

Aspiration: Design maturity and regulators

- Global integrated nuclear industry
  - Russia

- Mature nuclear program
  - South Korea
  - China

- Mainstream nuclear
  - France
  - United States

- Transformational nuclear
  - UK

- Small nuclear nation
  - Japan

- First concrete
  - Finland
  - United Arab Emirates

- New entrants
  - Turkey, Jordan
  
- Design improvement
- Design evolution
- Design revolution
Genesis of Generation IV Concepts

- In 1999, low public and political support for nuclear energy
  - Oil and gas prices were low
- USA Proposed a bold initiative in 2000
  - The vision was to leapfrog LWR technology and collaborate with international partners to share R&D on advanced nuclear systems
  - Oil prices jumped soon thereafter
- Gen IV concept defined via technology goals and legal framework
  - Technology Roadmap released in 2002
    - 2 year study with more than 100 experts worldwide
    - Nearly 100 reactor designs evaluated and down selected to 6 most promising concepts
  - First signatures collected on Framework Agreement in 2005; first research projects defined in 2006

“This may have been the first time that the world came together to decide on a fission technology to develop together.”
William Magwood IV, First Chairman of the Generation IV International Forum

Generation IV Goals

• Safety and Reliability
  – Very low likelihood and degree of core damage
  – Eliminate need for offsite emergency response

• Sustainability
  – Long term fuel supply
  – Minimise waste and long term stewardship burden

• Proliferation Resistance and Physical Protection
  – Unattractive Materials diversion pathway
  – Enhanced physical protection against terrorism

• Economics
  – Life cycle cost advantage over other energy sources
  – Financial risk comparable to other energy sources
Generation IV reactors

Sodium Fast Reactor

Lead Fast Reactor

Very High Temperature Reactor

Gas-Cooled Fast Reactor

Super Critical Water Cooled Reactor

Molten Salt Cooled Reactor
Gen-IV Market Status Developments

- Terrestrial Integral Molten Salt Reactor (Canada)
- Terra-Power (US-China)
- HTR-PM in China (VHTR)
- BN-800 (Sodium Fast Reactor) Russia-China
# Gen-IV and the developmental risk space

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<th>Industry structure and capacity</th>
<th>Design improvement</th>
<th>Design evolution</th>
<th>Design revolution</th>
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**Current Nuclear Power**
- Large
- Slow to build
- Expensive upfront
Gen-IV Australia Ambitions

• First membership by a non-nuclear power country
• Nuclear materials focus
• Safety cases
• Economics
• …… more focus on Waste management
ANSTO – SINAP Collaboration

• Centre for Thorium Molten Salt Reactor (TMSR) systems
  – Initial $400M R&D investment
  – Non-active Demonstrator

• ANSTO-SINAP Joint Research Centre
  – Materials technology for Molten Salt Reactors
  – Molten salt corrosion
  – Radiation damage
  – High temperature properties
Generation IV Structural Materials R&D

- **Irradiation**
  - Neutron, ion damage studies

- **High temperature**
  - Creep testing
  - Creep/ Fatigue Analysis

- **Corrosion**
  - Testing in molten salt environments

- **Combined environments**
  - Irradiation + corrosion (MSR)
  - Corrosion + high temperature creep
  - Irradiation under high temperature

From Lyndon Edwards: Introduction to ANSTO and contributions to GIF with focus on VHTR Materials VHTR SSC 11-12 Nov 2016, Las Vegas, USA
Requirements of MSR structural materials:

- Operating Temperatures of 630-700°C
- Corrosive molten fluoride salt (FLiNaK; FLiBe)
- 200 dpa neutron radiation
- 0.6 MPa pressure
- 30+ years reactor design life
Micromechanical Tensile Testing

From Lyndon Edwards: Introduction to ANSTO and contributions to GIF with focus on VHTR Materials VHTR SSC 11-12 Nov 2016, Las Vegas, USA
Trends in Radiation Strengthening with Dose

- Ion irradiation provides useful qualitative information
- Current research linking micro to macro properties

From Lyndon Edwards: Introduction to ANSTO and contributions to GIF with focus on VHTR Materials VHTR SSC 11-12 Nov 2016, Las Vegas, USA
Effect of Radiation on Strain Rate Response

Engineering stress-strain plot for Nickel single crystal foil

**Unirradiated**
Tested in tension along
a) <100>
b) <110>
orientations at strain rates 5 and 500 n/ps.

Engineering stress-strain plot for Nickel single crystal foil

**Irradiated to 10^{17}He^+/cm^2**
Tested in tension along
c) <100>
d) <110>
orientations at strain rates 5 and 500 n/ps.

*Xu et al. unpublished work*

From Lyndon Edwards: Introduction to ANSTO and contributions to GIF with focus on VHTR Materials VHTR SSC 11-12 Nov 2016, Las Vegas, USA
Gen IV Structural Materials R&D

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From Lyndon Edwards: Introduction to ANSTO and contributions to GIF with focus on VHTR Materials VHTR SSC 11-12 Nov 2016, Las Vegas, USA
Creep resistance and material degradation of a candidate Ni-Mo-Cr corrosion resistant alloy. Shrestha et al. Materials Science and Engineering A, 674, pp.64–75

From Lyndon Edwards: Introduction to ANSTO and contributions to GIF with focus on MSR Related Materials, MSR pSSC 23-24 January PSI, Switzerland, USA
MSR and VHTR Creep/Fatigue Analysis

- RemLife Software –
  - Simulator to calculate the effects of unit cycling on the accumulation of creep and creep-fatigue damage on components and estimate the associated economical impact

From Lyndon Edwards: Introduction to ANSTO and contributions to GIF with focus on MSR Related Materials, MSR pSSC 23-24 January PSI, Switzerland, USA
Modelling/Predicting Creep Rupture

• FEA prediction of in-service materials performance
• User-defined material models for creep strain/damage

Prediction (via FEA) of creep rupture during an accelerated creep test in ex-service AISI 316H stainless steel using a Strain Energy Ductility Exhaustion (SEDE) creep damage model

From Lyndon Edwards: Introduction to ANSTO and contributions to GIF with focus on MSR Related Materials, MSR pSSC 23-24 January PSI, Switzerland, USA
Predicting Weld Residual Stress

- ANSTO has developed models of microstructure and stress around single- and multi-pass welded joints
- Including international round-robin programmes
  - NeT (AISI 316, Inconel 600, A508)
  - USNRC (DMW)
- Used to support plant maintenance and design decisions

From Lyndon Edwards: Introduction to ANSTO and contributions to GIF with focus on VHTR Materials VHTR SSC 11-12 Nov 2016, Las Vegas, USA
Typical Weld Simulation: A 508 EB Weld

Temperature Distribution

Stress Distribution

Martensite Formation

Bainite Formation

Courtesy A. Vasileiou, University of Manchester

From Lyndon Edwards: Introduction to ANSTO and contributions to GIF with focus on VHTR Materials VHTR SSC 11-12 Nov 2016, Las Vegas, USA
2020s Nuclear Value Proposition

- Baseload
- Low-carbon
- Low fuel cost
- Extended Plant Life
- Safer
- Replaces Coal
- Could replace Gas and Oil
- But.................
But………

• Do we understand anything about the energy state of the planet?
• And electricity is only a small part of this!
Breaking the link
Energy and CO₂ emissions

Source: Thom Mason, ORNL
Energy growth in non-OECD nations

World electricity consumption, 1990-2040

Trillion kWh

Year

1990  2000  2010  2020  2030  2040

Energy Information Administration, USA.
Electricity use per capita: asymmetrical..
Australia in global perspective

- Problem: confusing electricity with energy!
- Solution: Clean energy consensus

- Problem: ignoring emerging economies
- Solution: Global perspective essential

- Problem: CO₂
- Solution: Clean Fuels

- Option: Nuclear
- Solution: SMR, then GEN IV
New to Nuclear Countries

- Regulator
- Public engagement
- Workforce
- Financing
- Sovereign risk
- Credit agency
- Fuel disposal
- Risk mitigation

ANSTO making sense of nuclear
Thank You
Carbon Intensity Notes

- Electricitymap.org
- 21/11/17 AEDT
- From about 8:30pm

- Nuclear and Hydro lead the charge!
Denmark
November 21, 2017 8:29 PM

Carbon Intensity: 524 g CO₂e/kWh
Low-carbon: 27%
Renewable: 25%

Electricity production | Carbon emissions
by source
- wind
- solar
- hydro
- hydro storage
- geothermal
- biomass
- nuclear
- gas
- coal
- oil
- unknown

Carbon intensity in the last 24 hours
- DE
- NO
- SE

Updated 7 minutes ago
Australia (Tasmania)
November 21, 2017 8:29 PM

Carbon Intensity: 103 gCO₂eq/kWh
Low-carbon: 83%
Renewable: 83%

Electricity production and Carbon emissions by source:
- wind: ?
- solar: ?
- hydro: ?
- hydro storage: ?
- geothermal: ?
- biomass: ?
- nuclear: ?
- gas: ?
- coal: ?
- oil: ?
- unknown: ?

AUS-VIC

Carbon intensity in the last 24 hours
Get historical data and forecast API

Origin of electricity in the last 24 hours

Carbon intensity (gCO₂eq/kWh)
Australia (Queensland)

Carbon Intensity: 770 gCO₂eq/kWh
- Low-carbon: 1%
- Renewable: 1%

Carbon intensity in the last 24 hours
- Origin of electricity in the last 24 hours