Introduction to ANSTO and contributions to GIF with focus on MSR Related Materials

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Molten Salt Reactor Workshop
Paul Scherrer Institut, Switzerland
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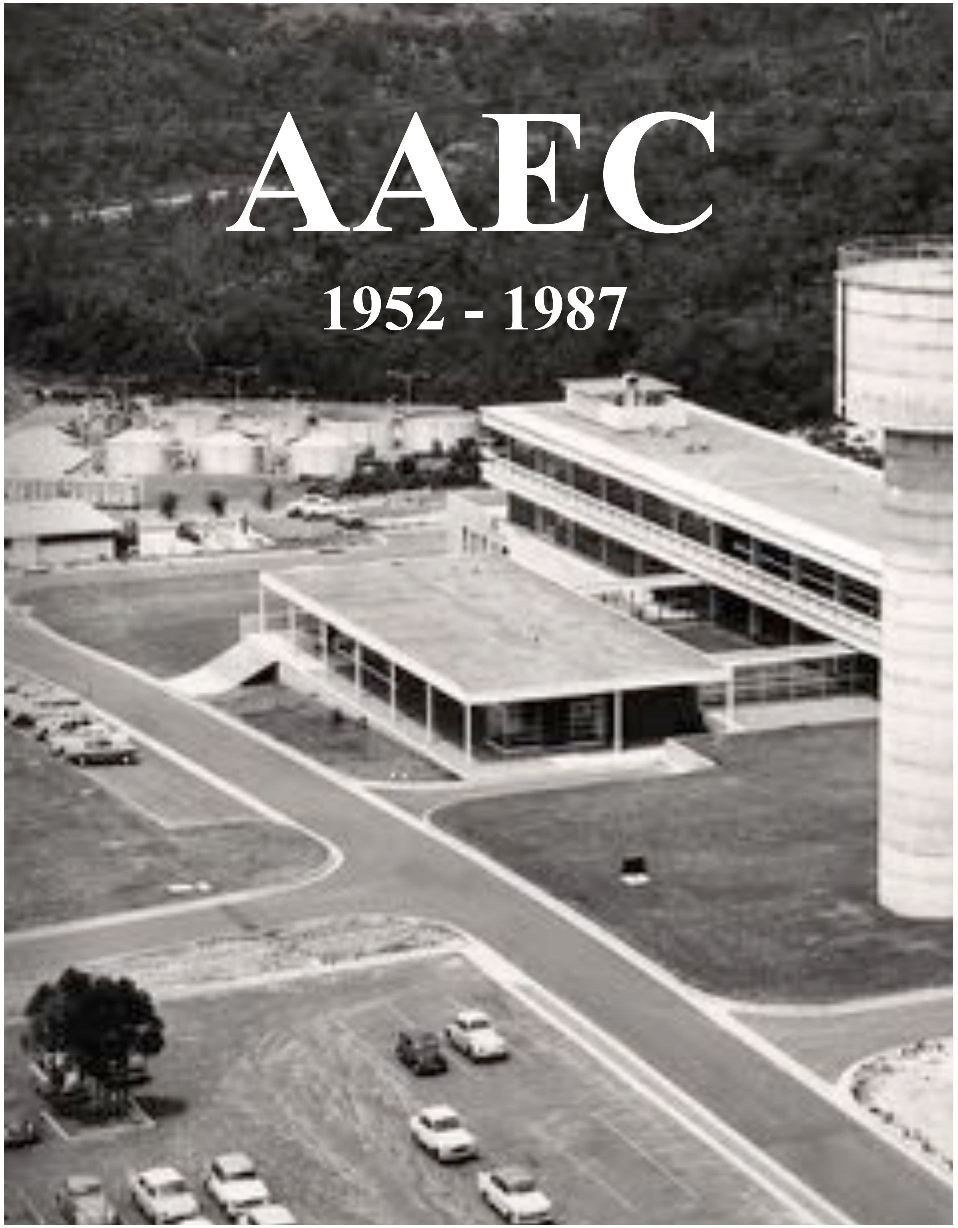
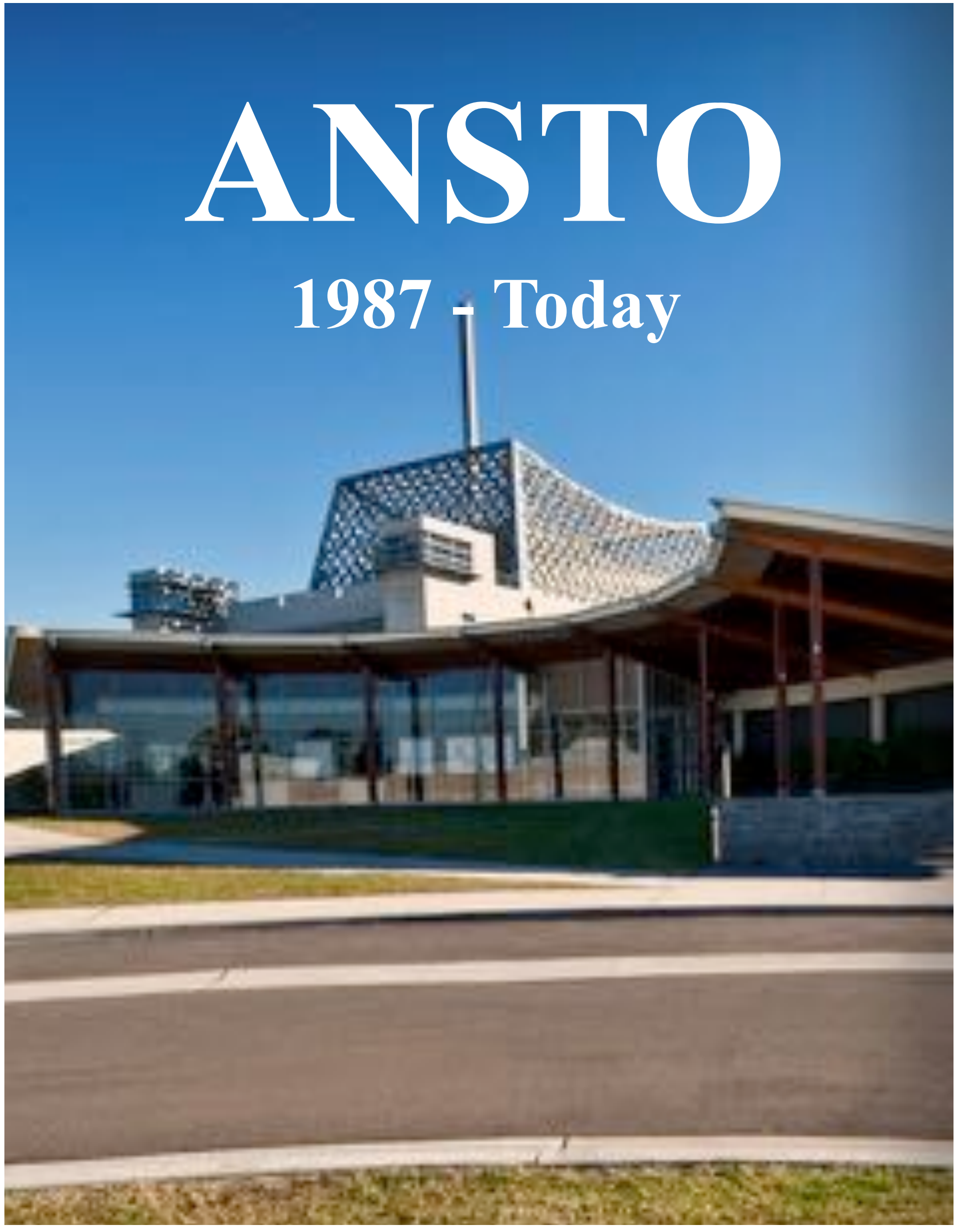
Australia and the Nuclear Fuel Cycle

- ***Australia involved in NFC since its inception…***
- ***Has, arguably, the world's largest Nuclear Fuel Cycle Materials resources.***
- ***Uranium produces 25% of Australian energy exports***
- ***Is considering middle and back-end NFC activity***

Australia's National Nuclear Lab for 60 years





ANSTO today

OPAL Research Reactor	Center for Neutron Scattering
Centre for Accelerator Science	Australian Synchrotron
Advisor to Government	Gateway to Australian Universities
Nuclear Fuel Cycle Research	Nuclear Materials Research

Uranium in Australia

- ***Has the world's largest reserves of uranium (>25% of the world total)***
- ***Is the world's third-ranking producer behind Kazakhstan and Canada***
- ***In 2015 Australia produced 6689 tonnes of oxide concentrate (U_3O_8)***
- ***Exports only to countries who have signed the Nuclear Non-Proliferation Treaty.***

Source: Geoscience Australia

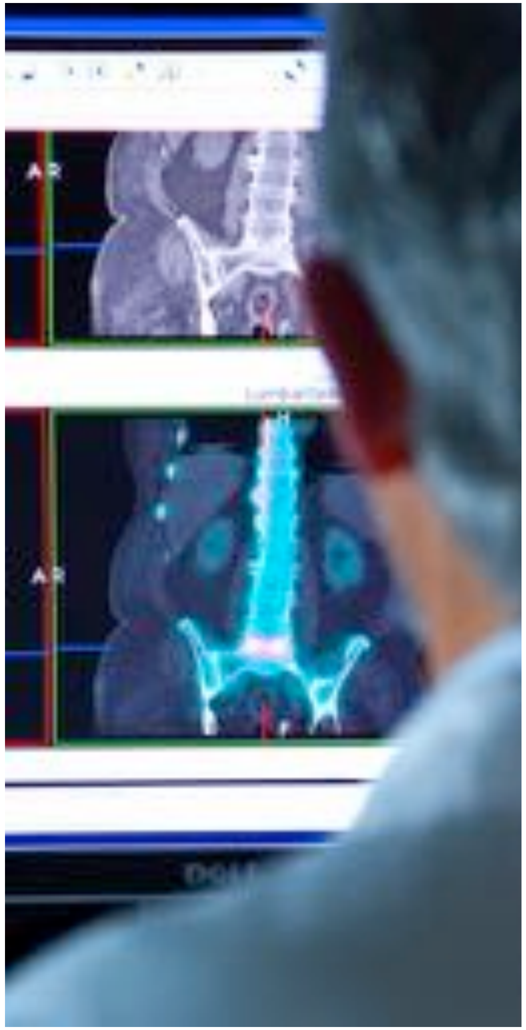
Thorium in Australia

- Carbonatite, Placer depositions, Vin-type deposits, Alkaline rocks: World resources: ~ 6 mil tons.
- Australian thorium resources estimate ~0.5 mil tons.
- ~ 9% of total world resources
- No current production of thorium in Australia

Source: Geoscience Australia

ANSTO Nuclear Medicine Project (ANM)

- *80% of all nuclear medicine procedures use Mo-99/Tc-99m*
- *Diagnosing heart disease, cancer, neurological disorders and more.*
- *40 million patients per year*
- *Global market of US$550 million per annum*
- *Potential critical worldwide Mo-99 shortage*
- *A new Australian Mo-99 production facility*
- *Mo-99 production capacity to allow for increased exports*
- *First full scale operational Synroc facility in the world*



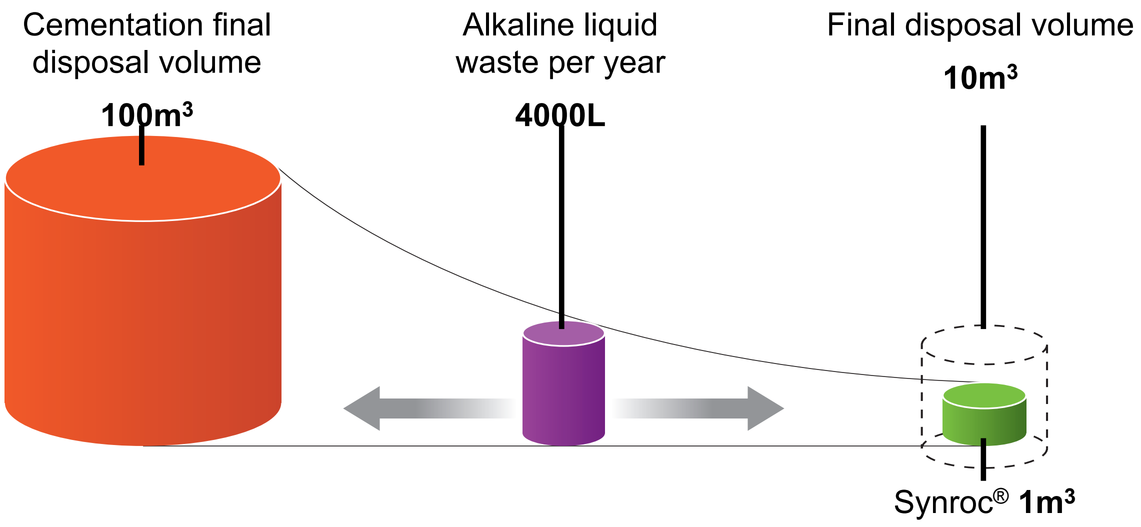
Mo-99/Tc-99m Supply chain

OPAL Reactor	Processing Plant (ANM)	Global distribution	Local distribution of finished goods	Hospital and Pharmacy	Clinical Imaging	Health Outcomes
LEU U^{235} targets irradiated in OPAL	Mo-99 separated and purified	Bulk Mo-99 Shipped to meet global demand	Tc-99m Generators dispensed and	Tc-99m eluted and combined with cold kits	Product administered to patients for	Imaging helps diagnosis & leads to appropriate
3-12 days	1 day	1 day	1 day	5 minutes	-	-

Challenging supply chain

The ANSTO Nuclear Medicine Facility

Synroc: the Nuclear Waste solution



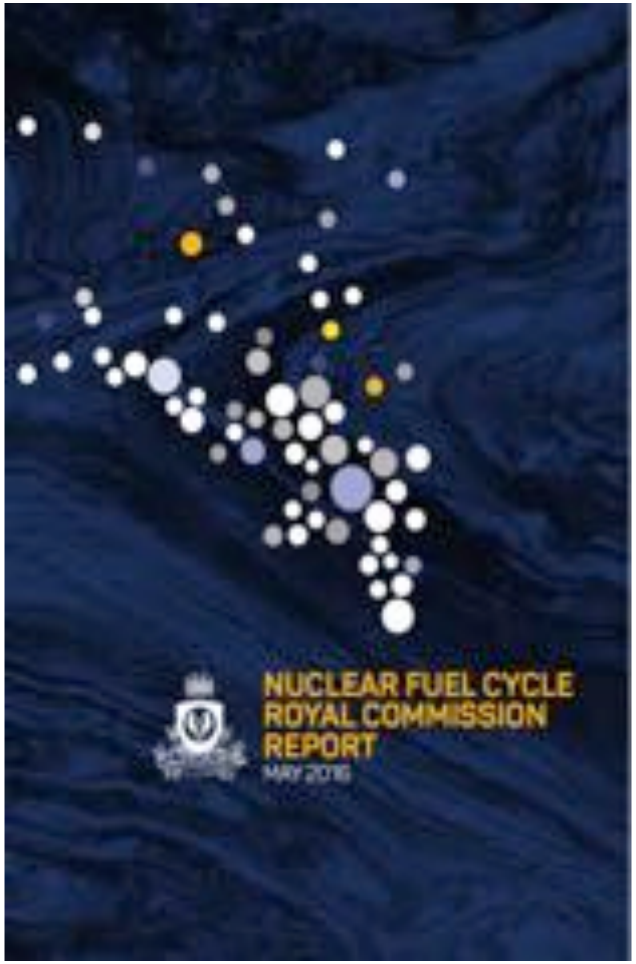
- *Intermediate Level Liquid Waste, ILLW, will be managed using this technology*
- *Synroc conceived in Australia and technology developed at ANSTO as safe and economic method for dealing with waste*
- *Potential to treat radioactive wastes world wide including high level waste*

South Australian Royal Commission.

In 2015, a Royal Commission was established by the South Australian (state) Government investigating Nuclear Fuel Cycle risks and opportunities.

Royal Commission Key Findings

- ***Expansion of uranium mining may be beneficial***
- ***Conversion, enrichment, fuel fabrication not viable at present***
- ***Fuel leasing likely to be more commercially attractive***
- ***Nuclear power in South Australia not compatible with current market***
- ***Community consent is essential, no sites investigated***



Australia and the Gen IV International Forum

- ***Independently, in 2015, the Australia Federal Government petitioned to join the Generation IV International Forum***
- ***Petition presented to GIF Policy Group in Oct 2015***
- ***GIF Policy Group Delegation Visit to Sydney in Feb 2016***
- ***GIF Policy Group unanimously endorsed Australian membership in April, 2016***
- ***ANSTO signed the GIF Charter in June 2016 initiating Australia's membership into the Forum***

GIF Policy Group Delegation to Australia, February 2016

Generation IV Reactor Systems

	System	Neutron Spectrum	Fuel /Fuel Cycle	Coolant Temp. (C)	Power (MWe)	Plant Effici. (%)	Applications
	Sodium Cooled Fast Reactor (SFR)	Fast	MOX, Metal /Closed	500 - 550	50 300-600 1500	42	Electricity, Actinide Recycle
✔	**Very High Temperature Reactor (VHTR)**	Thermal	Coated particles /Open	900 -1000	250	> 47	Electricity, Hydrogen Production, Process Heat
	Gas-Cooled Fast Reactor (GFR)	Fast	Carbides /Closed	850	200-1200	45 - 48	Electricity, Hydrogen Production, Actinide Recycle
	Supercritical Water Reactor (SCWR)	Thermal, Fast	UOX, MOX /Open; Closed	510 - 625	1500	Max. 50	Electricity
	Lead-Cooled Fast Reactor (LFR)	Fast	Nitrides; MOX /Closed	480 - 570	50-150 300-600 1200	42 - 44	Electricity, Hydrogen Production
✔	**Molten Salt Reactor (MSR)**	Thermal, Fast	Fluorides salts /Closed	700 - 800	1000	Max. 45	Electricity, Hydrogen Production, Actinide Recycle

A Technology Roadmap for Generation IV Nuclear Energy Systems, December 2002
GIF R&D Outlook for Generation IV Nuclear Energy Systems, August 2009

Australian GIF capability overview

- ***Reactor risk and safety analysis***
- ***Radiation damage***
- ***Creep, creep fatigue and code development***
- ***Molten salt corrosion and testing***
- ***Atomistic and molecular modelling***
- ***Structural Integrity and weld modelling***

Also some expertise on GIF relevant:

- ***Education and Training***
- ***Economic Modelling: from Univ. New South Wales (UNSW)***

Australia's intended GIF Research

Following its success in gaining membership of GIF, Australia is proposing to join:

- ***The VHTR SA***
- ***The MSR pSSC***
- ***The VHTR Material (MAT) PA***
- ***The Risk and Safety Working Group.***

In addition, with our University partners we are exploring how we might make contributions to:

- ***The GIF Education and Training Working Group***
- ***The Economic Modelling Working Group***

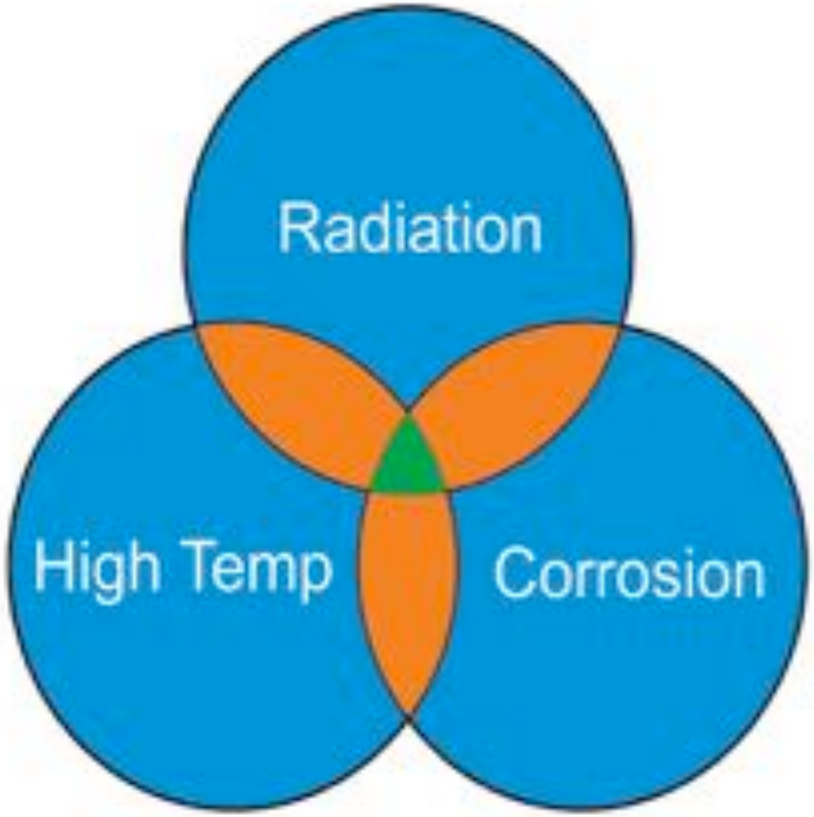
- ***A substantial proportion of our capability and intended research in these areas is capable of supporting all of the other Gen IV reactor systems e.g. SFR, LFR, SCWR, GFR***

Australian Nuclear Fuel Cycle R&D

- *Fuel/cladding interactions*
  - *Use of atomistic modelling (e.g. DFT)*
- *Structural materials performance under extreme conditions*
  - *Irradiation, corrosion, high temperatures and/or deformation*
- *Separation science*
  - *Synthesis and analysis of titania frameworks for separation of U, Pu*
- *Wasteform fabrication*
  - *Construction of a Synroc waste treatment plant to reduce volume of ANSTO nuclear by-products by 99%*

Generation IV Structural Materials R&D

- ***Irradiation***
  - *Neutron, ion damage studies*
- ***High temperature***
  - *Creep testing*
- ***Corrosion***
  - *Testing in molten salt environments*
- ***Combined environments***
  - *Irradiation + corrosion (MSR)*
  - *Corrosion + high temperature creep*
  - *Irradiation under high temperature*



ANSTO/SINAP Joint Materials Research Centre

- ***Shanghai Institute of Applied Physics (SINAP), Chinese Academy of Science (CAS)***
- ***Australia/China Science and Research Fund Grant 2013-2016***
- ***ANSTO-SINAP Joint Materials Research Centre***
- ***Materials technology for Molten Salt Reactors***
  - » ***Molten salt corrosion***
  - » ***Radiation damage***
  - » ***High temperature behaviour***

Materials Studied:

1. GH3535, a Chinese variant of Alloy N with the nominal composition of Ni–16Mo–7Cr–4Fe.
2. Other potentially Ni-based materials

Generation IV Structural Materials R&D

- ***Irradiation***
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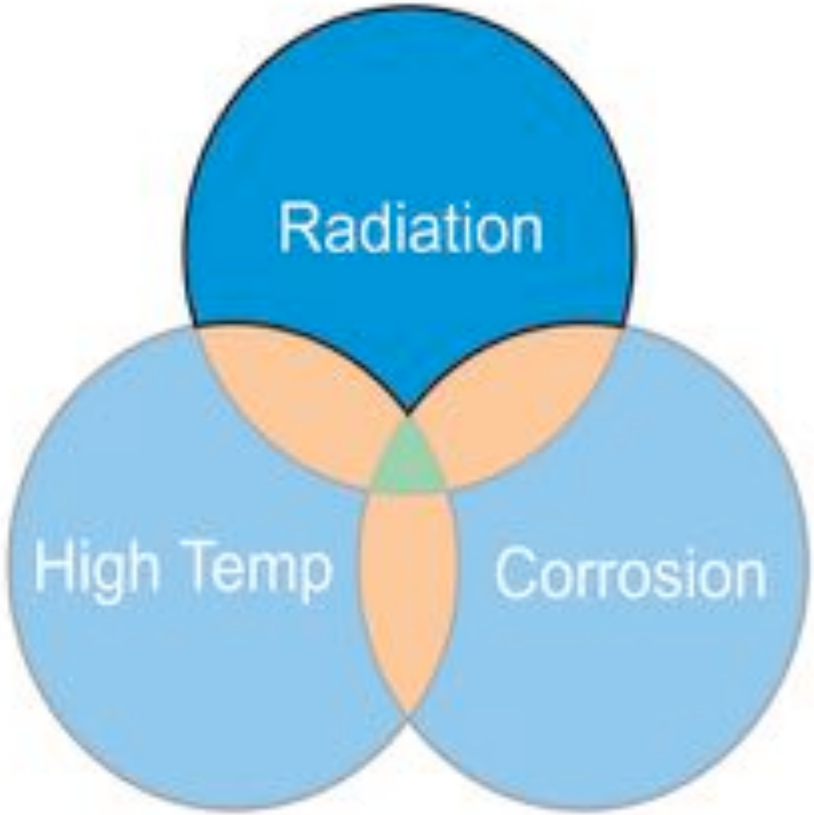


Radiation Damage Test Environments at ANSTO

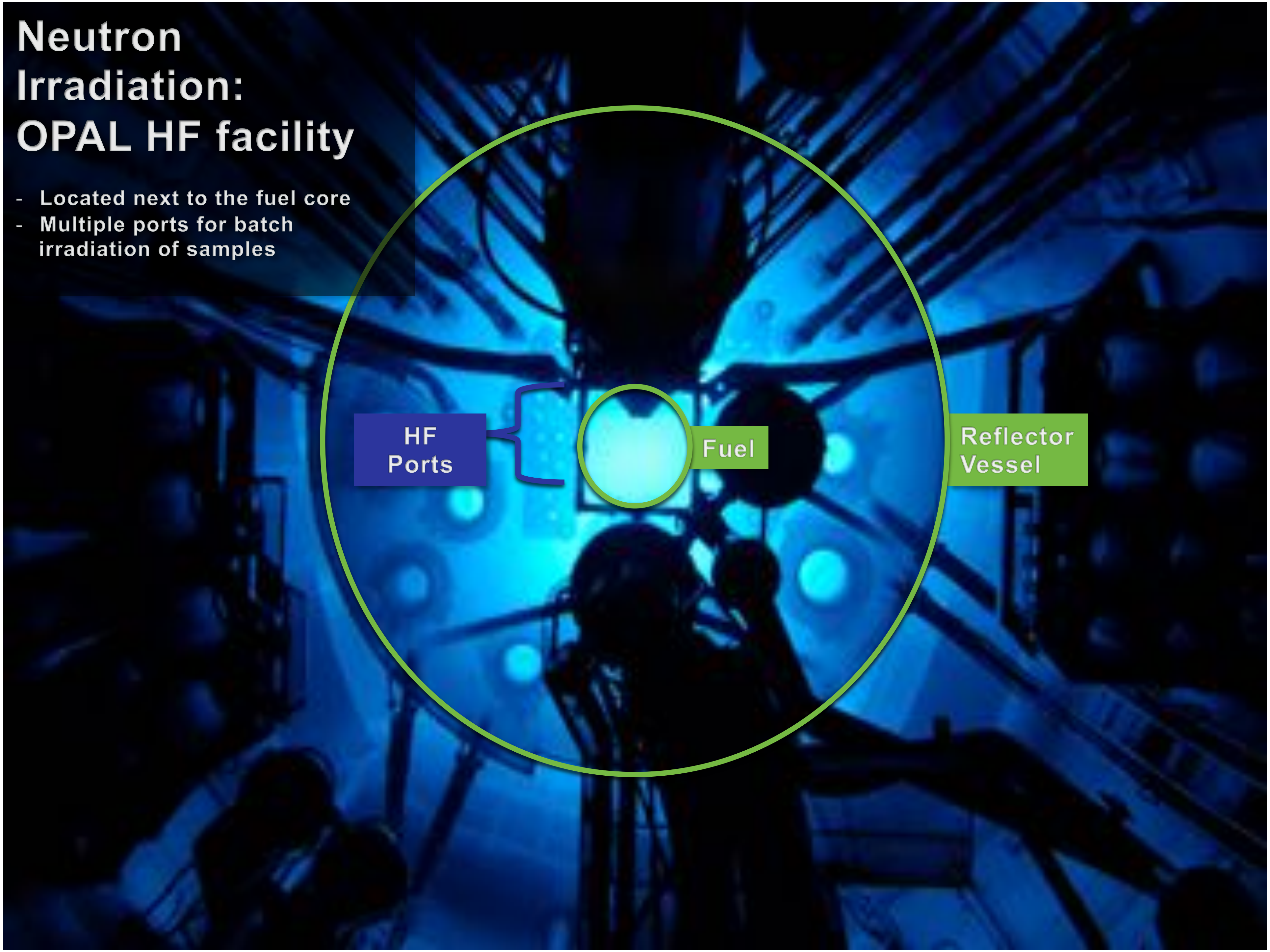
OPAL Research Reactor

Accelerators

- ***1MV VEGA accelerator***
- ***2MV STAR tandetron accelerator***
- ***6MV SIRIUS tandem accelerator***
- ***10MV ANTARES tandem accelerator***

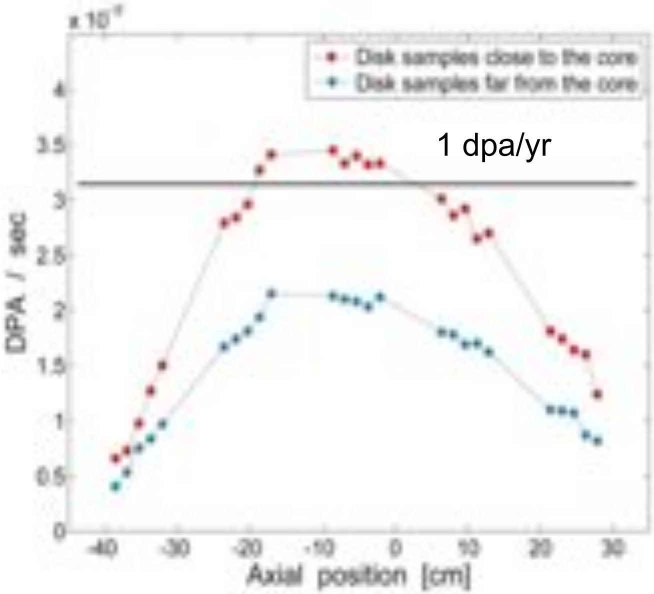
Neutron Irradiation: OPAL HF facility

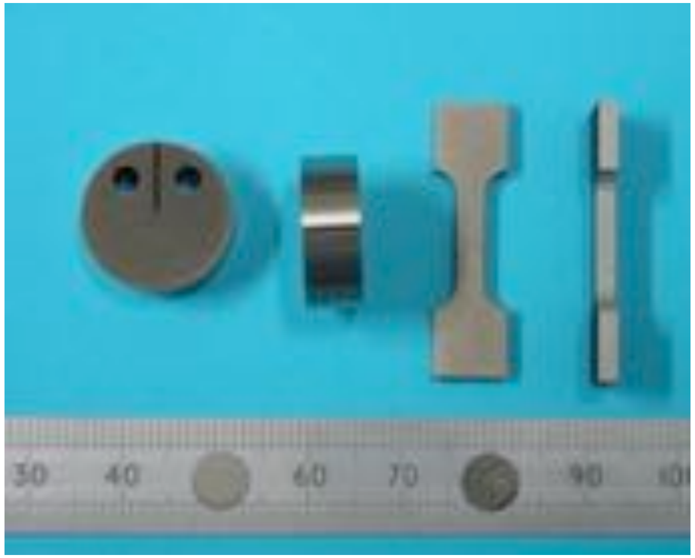
- Located next to the fuel core
- Multiple ports for batch irradiation of samples



Neutron Irradiation Specimens

- *Miniature dog-bone samples*
- *Small punch discs*
- *Compact tension discs*
- *Quarter-size Charpy samples*
- *Corrosion samples*

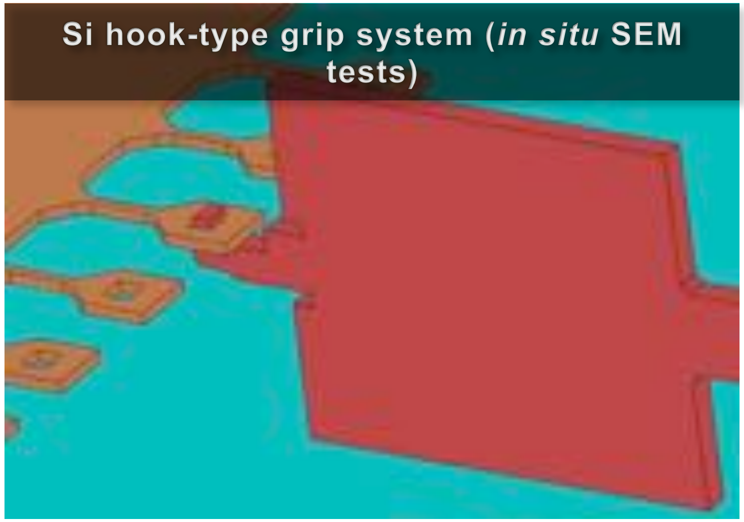


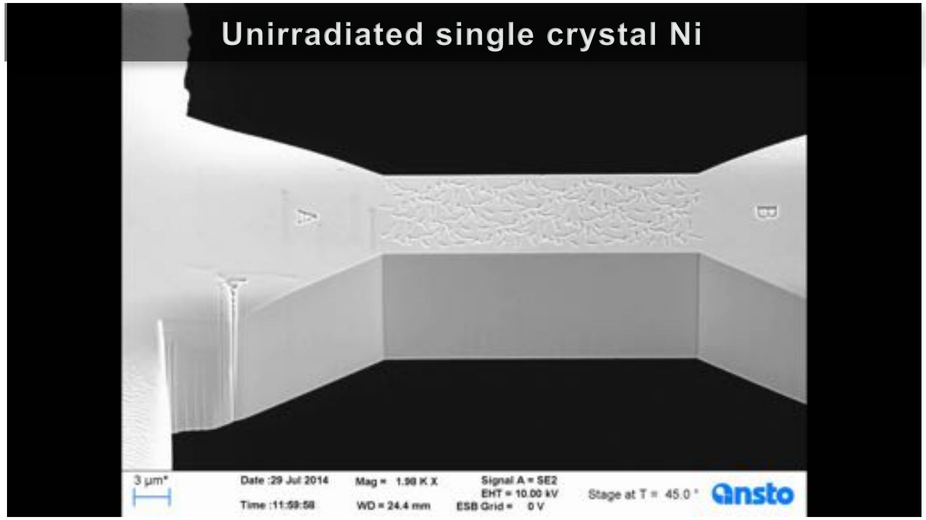


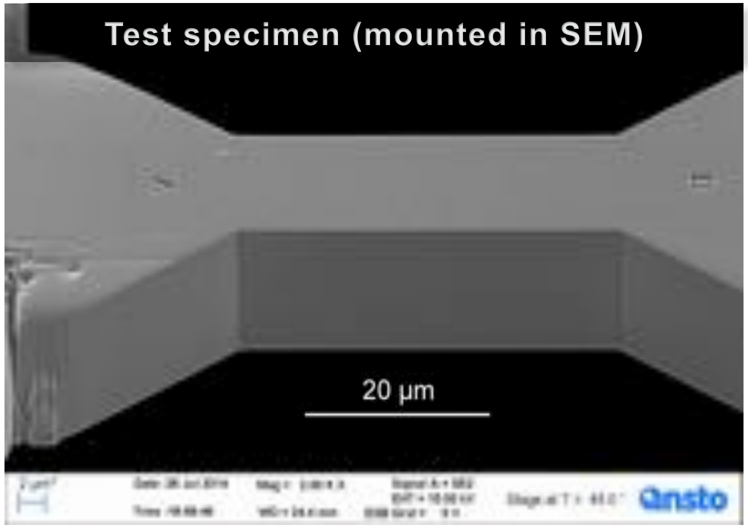
The Role of Ion Irradiation

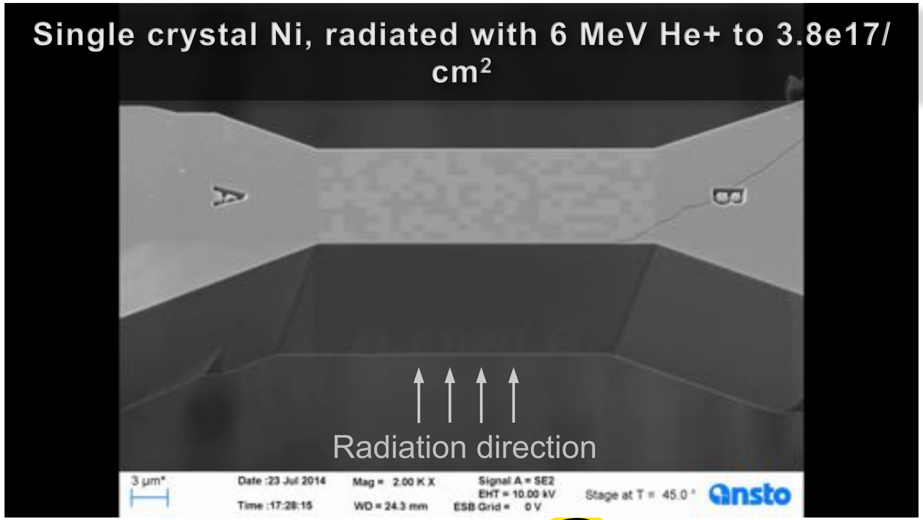
- *Current limitations on neutron fluence*
- *Ion irradiation allows for higher dpa*
  – *Proton and alpha damage of thin samples*
  – *Self irradiation of energetic heavier ions*
- *Must be accompanied by modelling of the processes to enable correlation of ion vs. neutron damage*
- *Useful for preliminary qualification of nuclear structural materials*

Micromechanical Tensile Testing

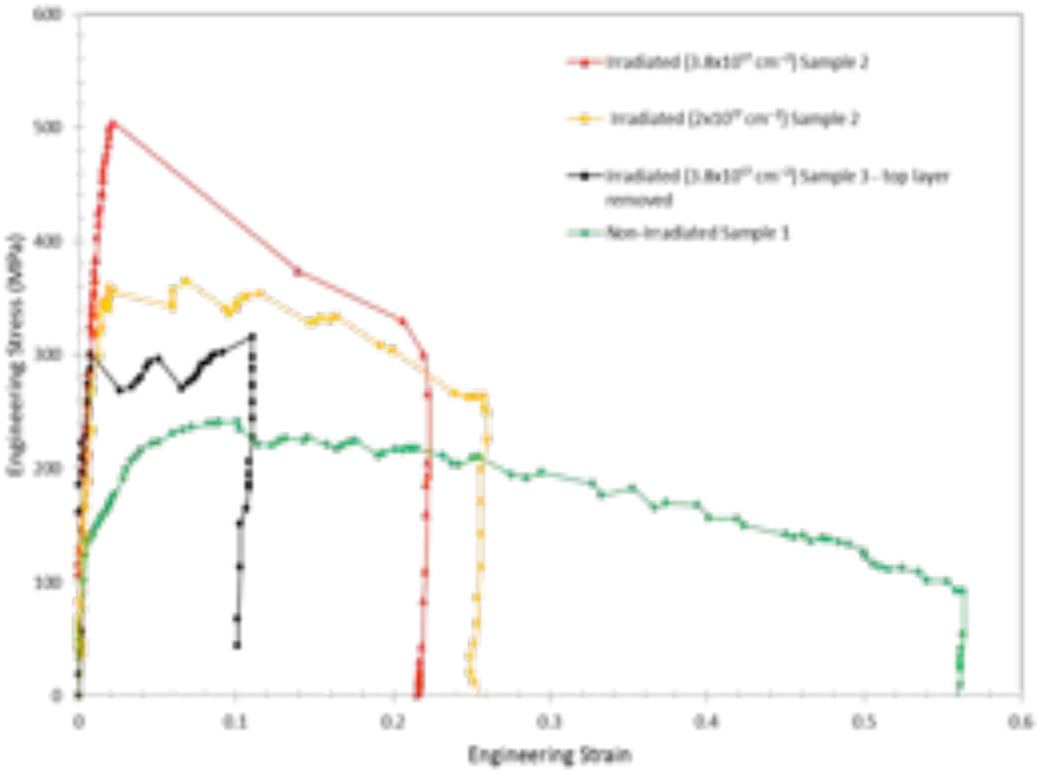


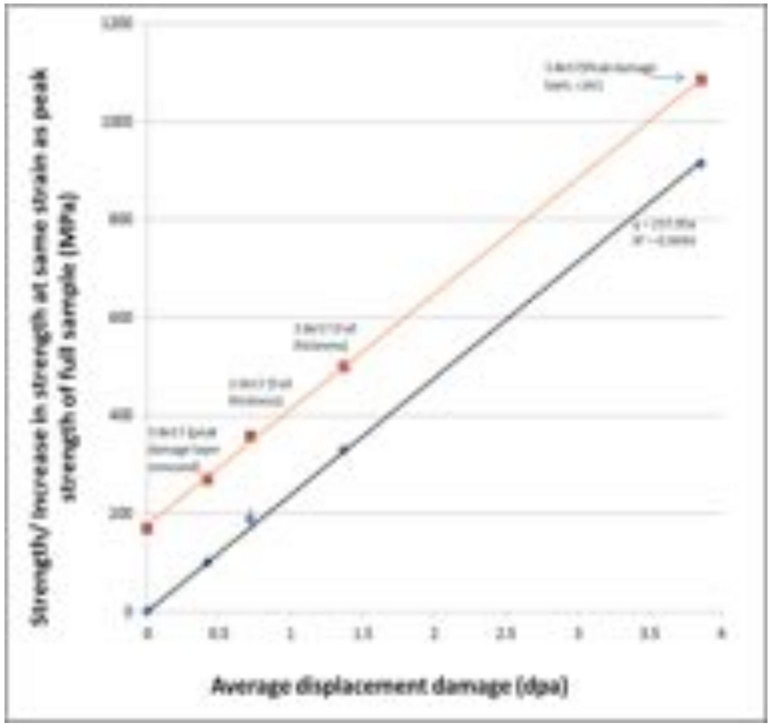






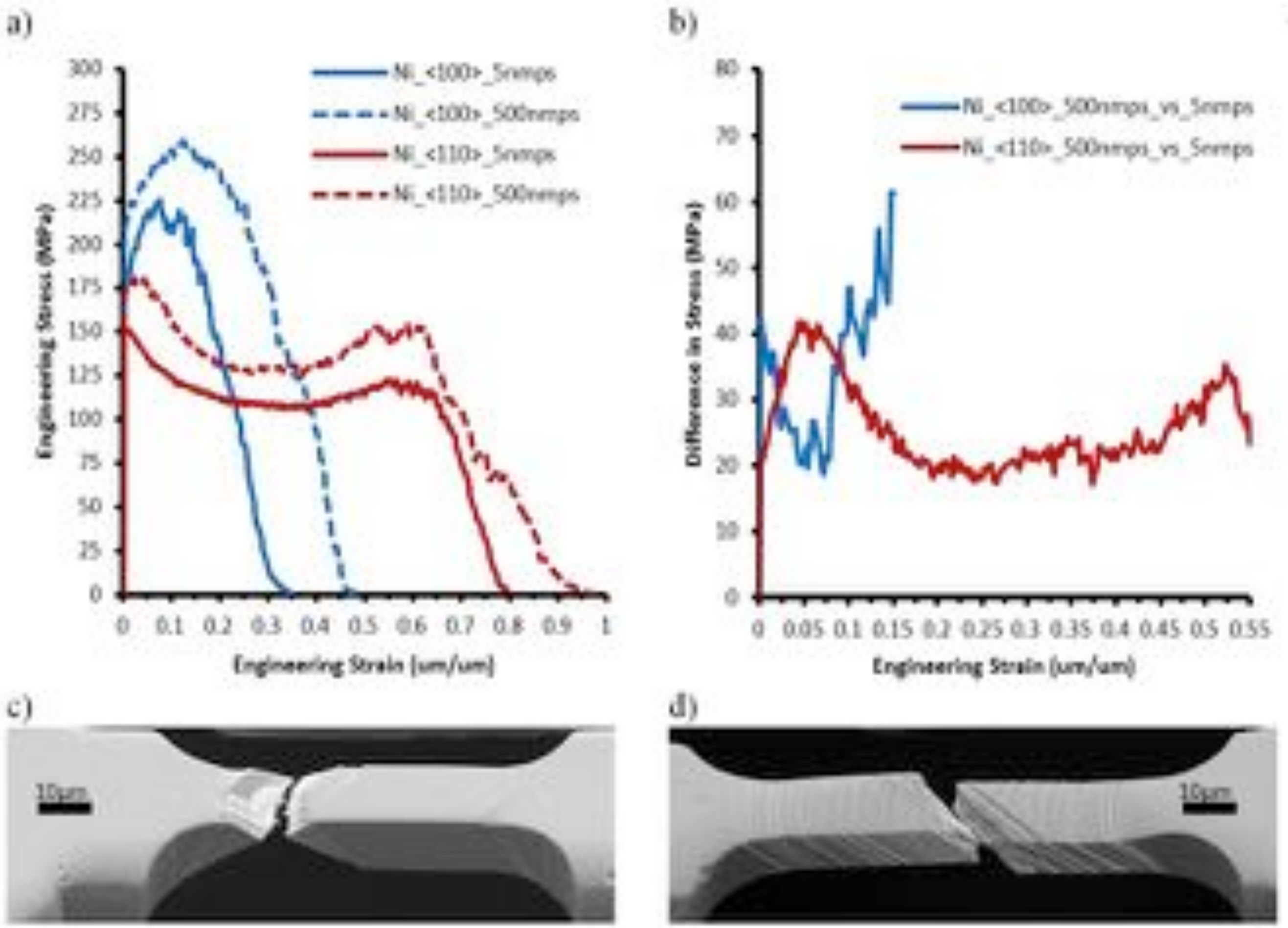
Trends in Radiation Strengthening with Dose





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

Effect of Strain Rate



Xu et. al. unpublished work

a) Engineering stress-strain plot for Nickel single crystal foil tested in tension along <100> and <110> orientations at strain rates 5 and 500 nm/s.

b) Difference in engineering stress between 500 and 5 nm/s strain rate tests for Ni foil oriented along <100> and <110> orientations.

c) 20kV SEM image of <100> oriented Ni foil after necking failure in tension

d) 20kV SEM image of <110> oriented Ni foil after necking failure in tension.

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

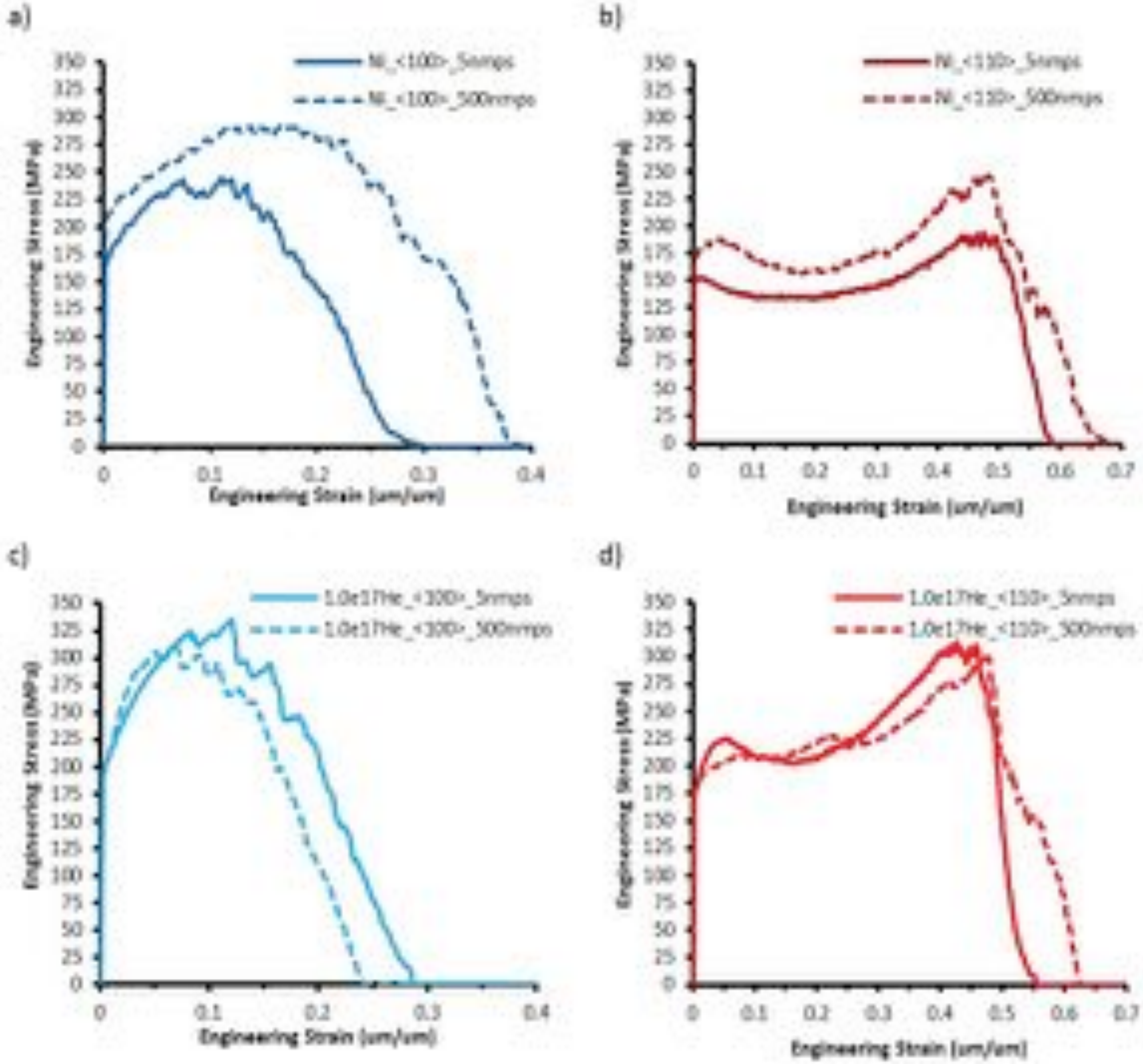
Irradiated to $10^{17}He^{+}/cm^{2}$

Tested in tension along

c) <100>

d) <110>

orientations at strain rates 5 and 500 n/ps.



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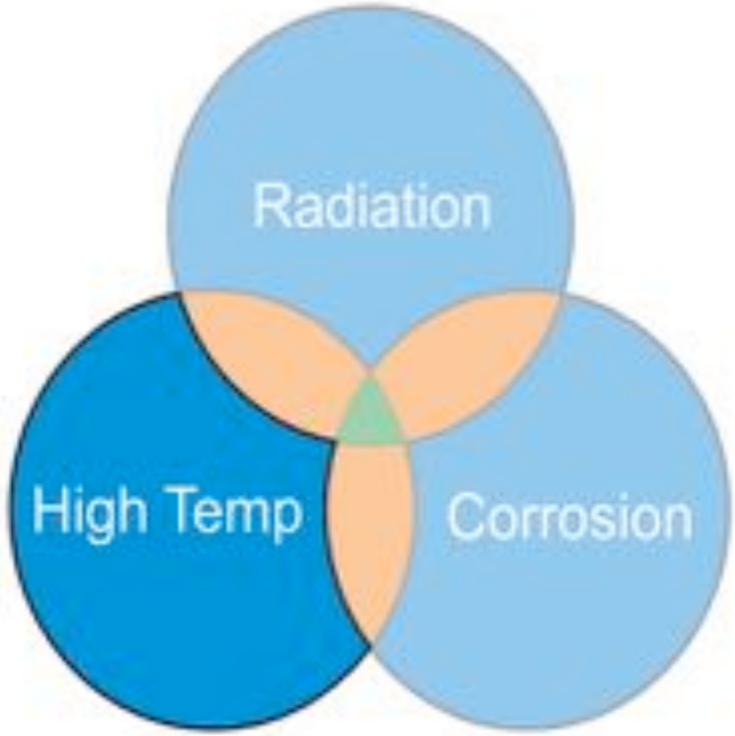
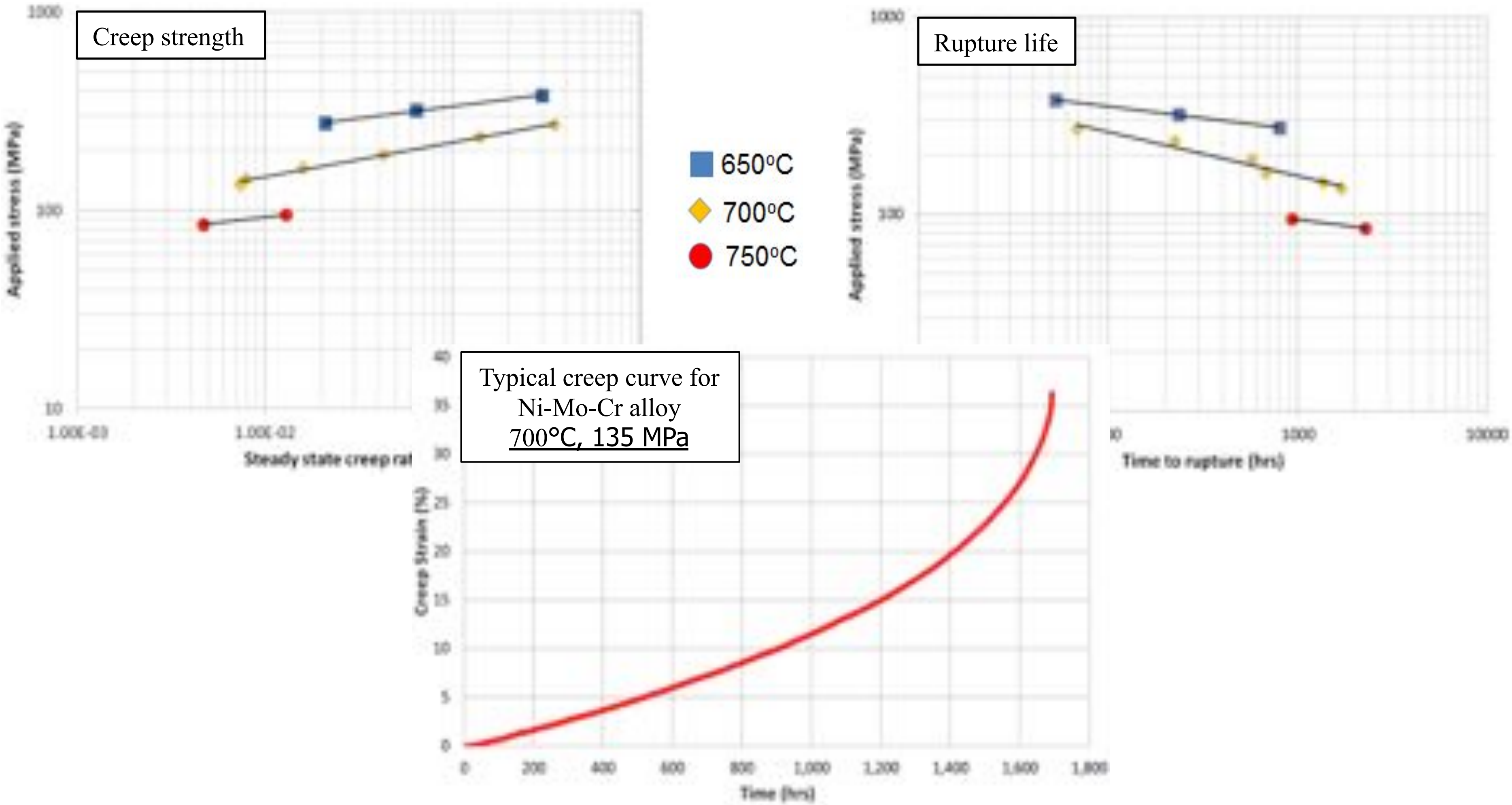
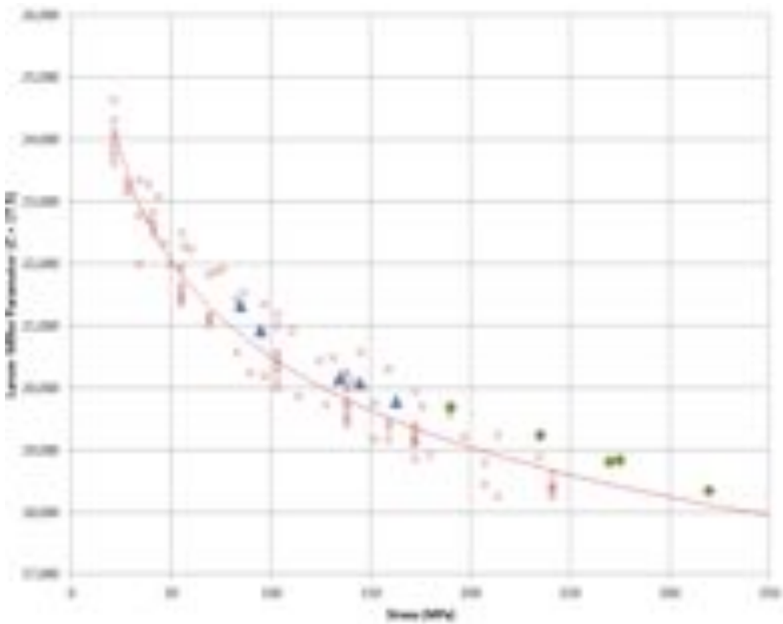


ANSTO/SINAP Creep testing GH3535



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

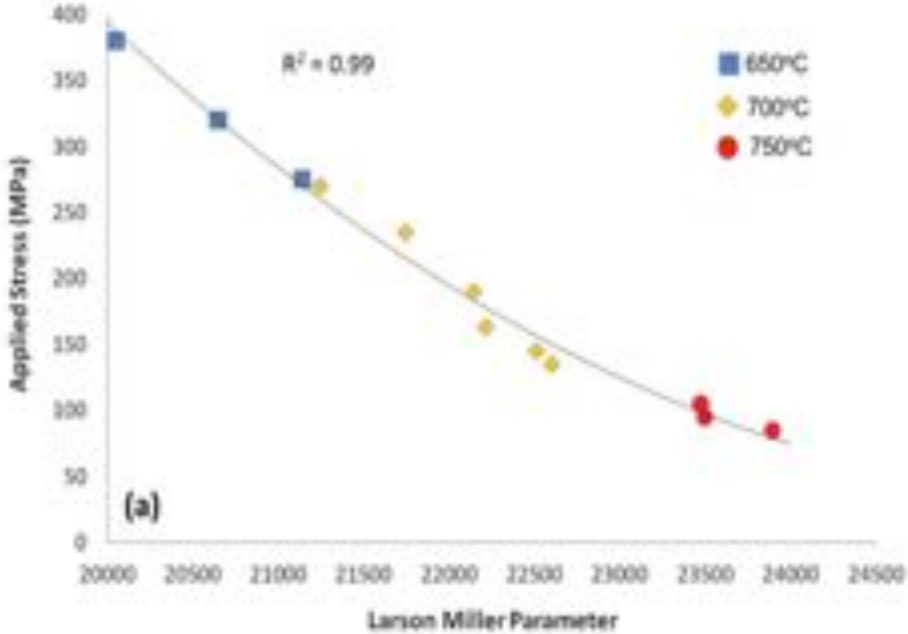
GH3535 vs Hastelloy N



<u>Larson Miller Parameter (LMP)</u>

LMP = T [log (t_r) + C]

T - temperature (°K)
t_r - time to rupture (hrs)
C - constant (17.5)



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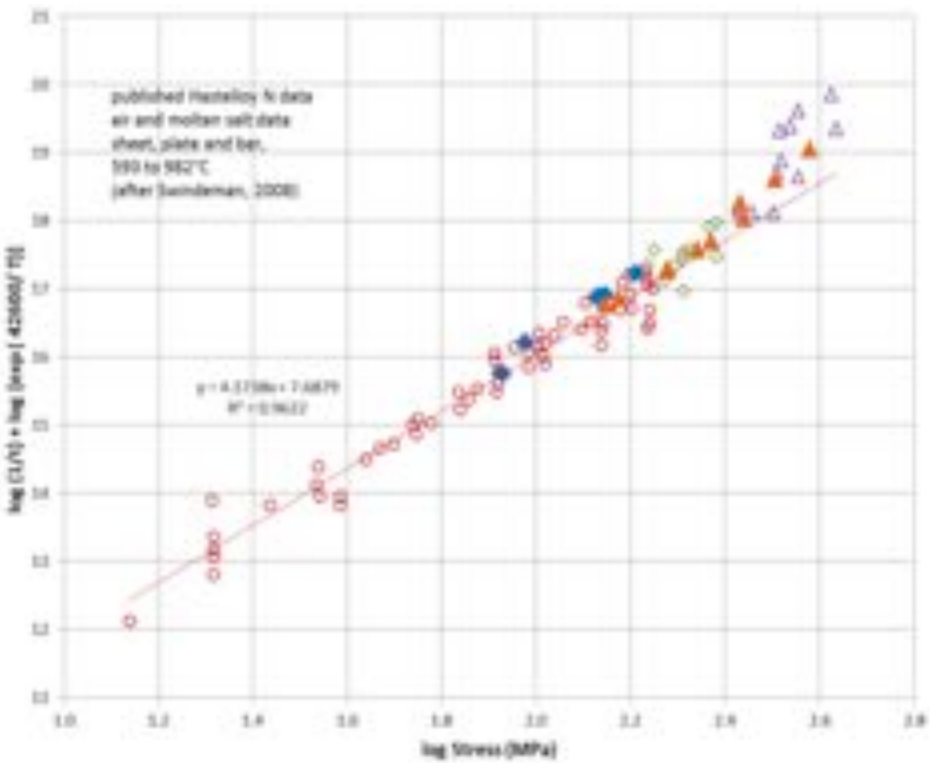
GH3535 vs Hastelloy N

Time to 1% creep strain data

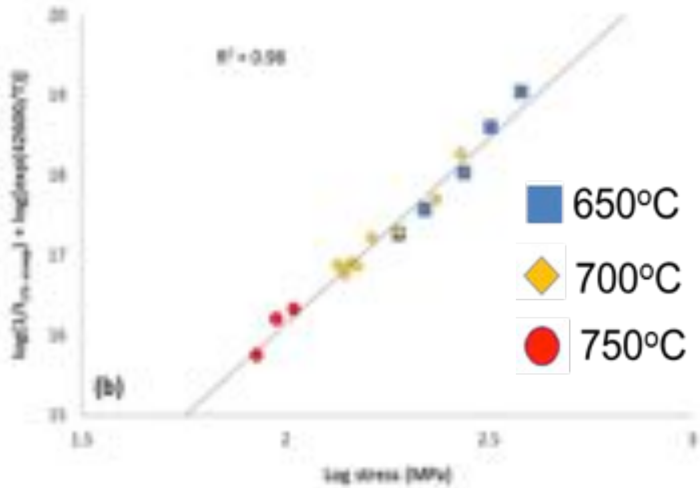


<u>Dorn-Shephard Parameter for 1% creep</u>

$\mathrm{Log}(1/\, t_{1\%creep}) + \mathrm{Log}(\exp(42600/T))$

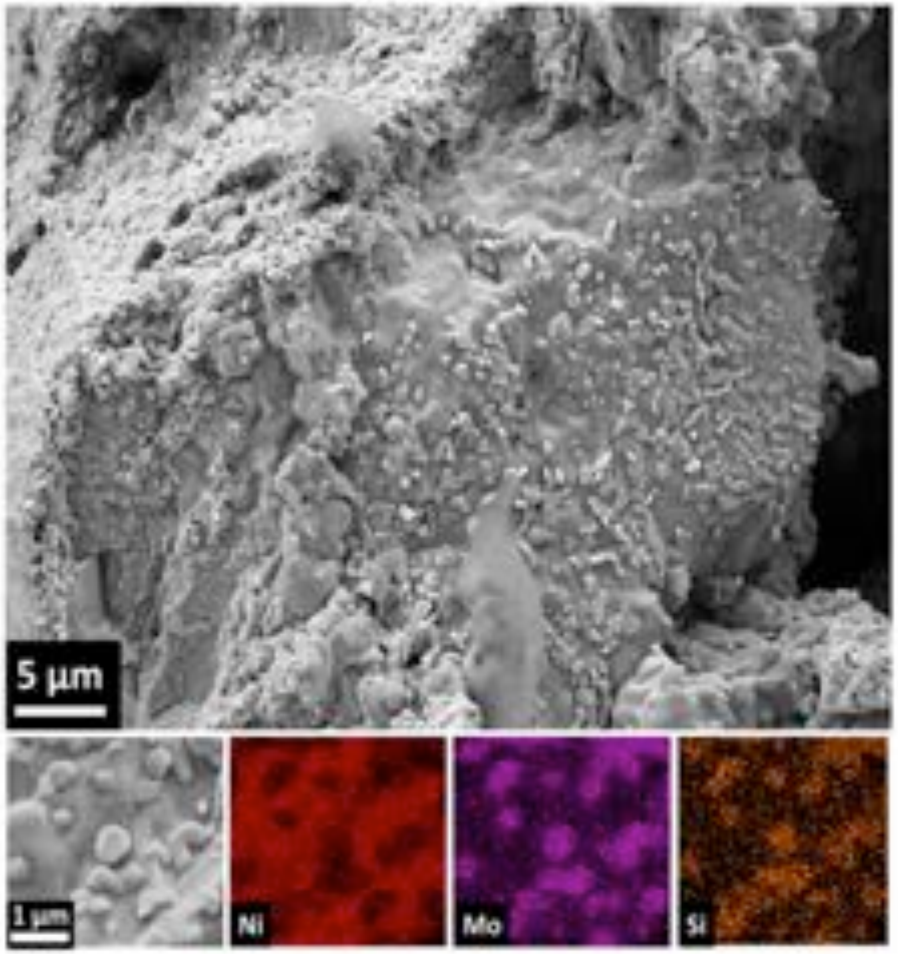
T - temperature (°K)
$\mathbf{t_{1\%creep}}$ - time to 1% creep strain (hrs)

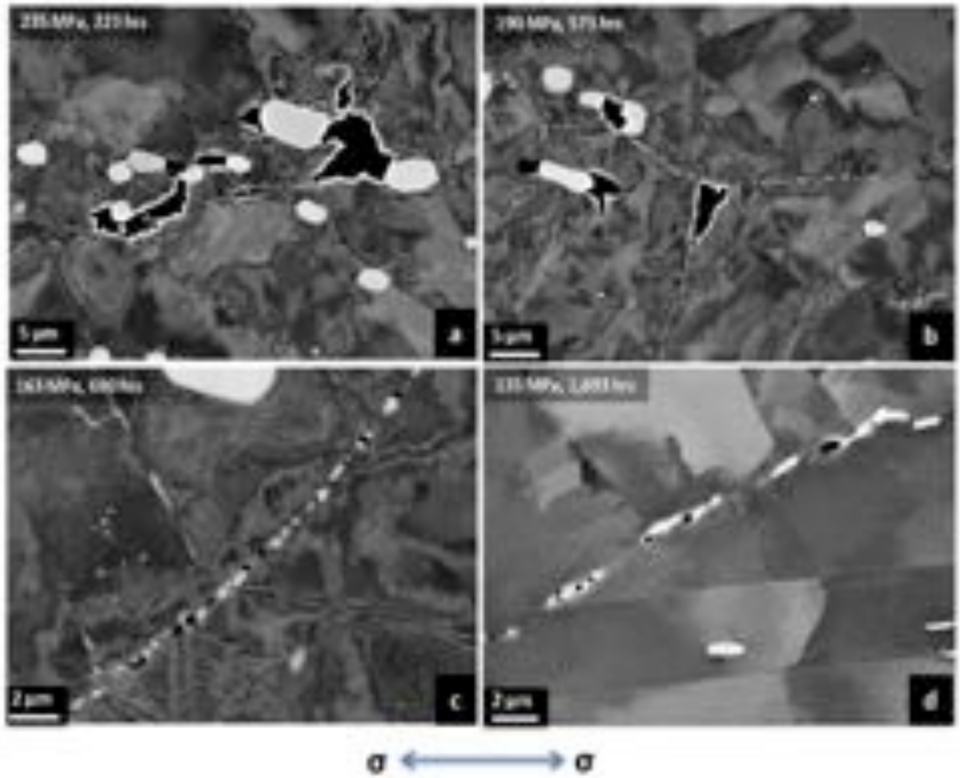
Creep exponent
n = 4



Creep resistance and material degradation of a candidate Ni-Mo-Cr corrosion resistant alloy. Shrestha et al. Materials Science and Engineering A, <u>674,</u> pp.64–75

Importance of second phase particles





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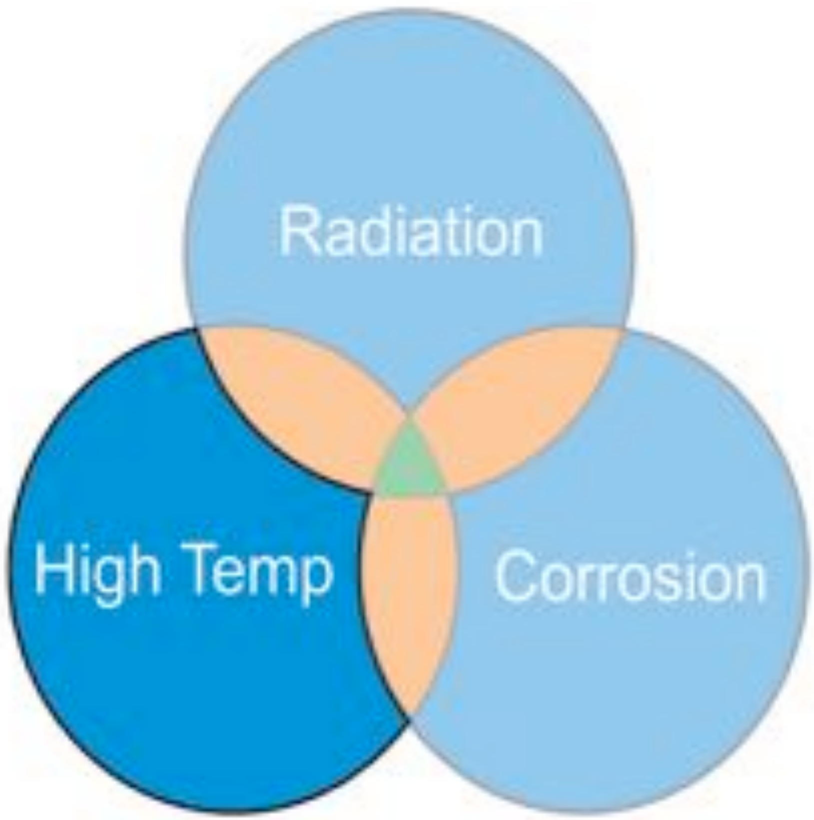
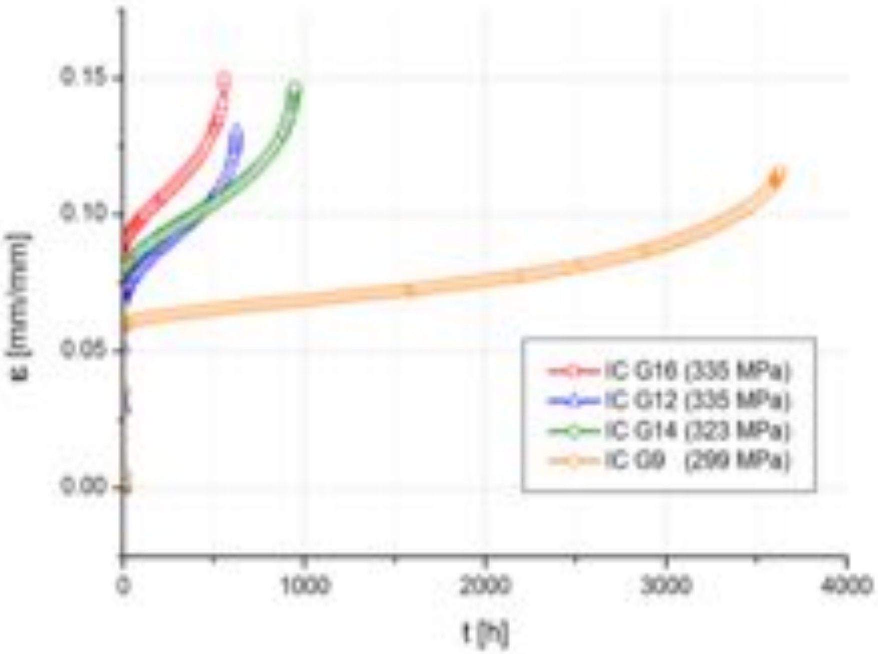
Generation IV Structural Materials R&D

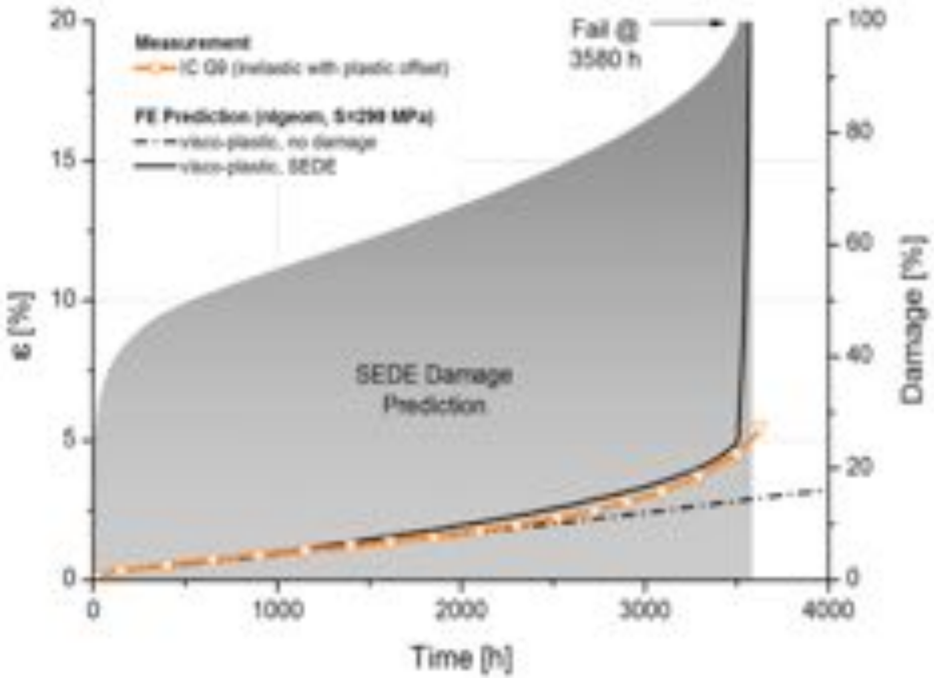
- *Irradiation*
  - *Neutron, ion damage studies*
- ***High temperature***
  - ***Creep testing***
  - ***Creep/Fatigue Analysis***
- *Corrosion*
  - *Testing in molten salt environments*
- *Combined environments*
  - *Irradiation + corrosion (MSR)*
  - *Corrosion + high temperature*
  - *Irradiation under high temperature*



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

RemLife Software

- ***RemLife is a simulator that calculates the effects of unit cycling on the accumulation of creep and creep-fatigue damage on components and estimates the associated economic impact***

- ***Used in conventional power stations and advanced gas combined cycle heat steam recovery boilers but can also be used for heat exchanger and the conventional side of nuclear plants***

- ***The software bridges the gap between “back-of-the-envelope” calculations for base rupture and fully detailed finite element analysis for creep-rupture and combined creep-fatigue analyses***

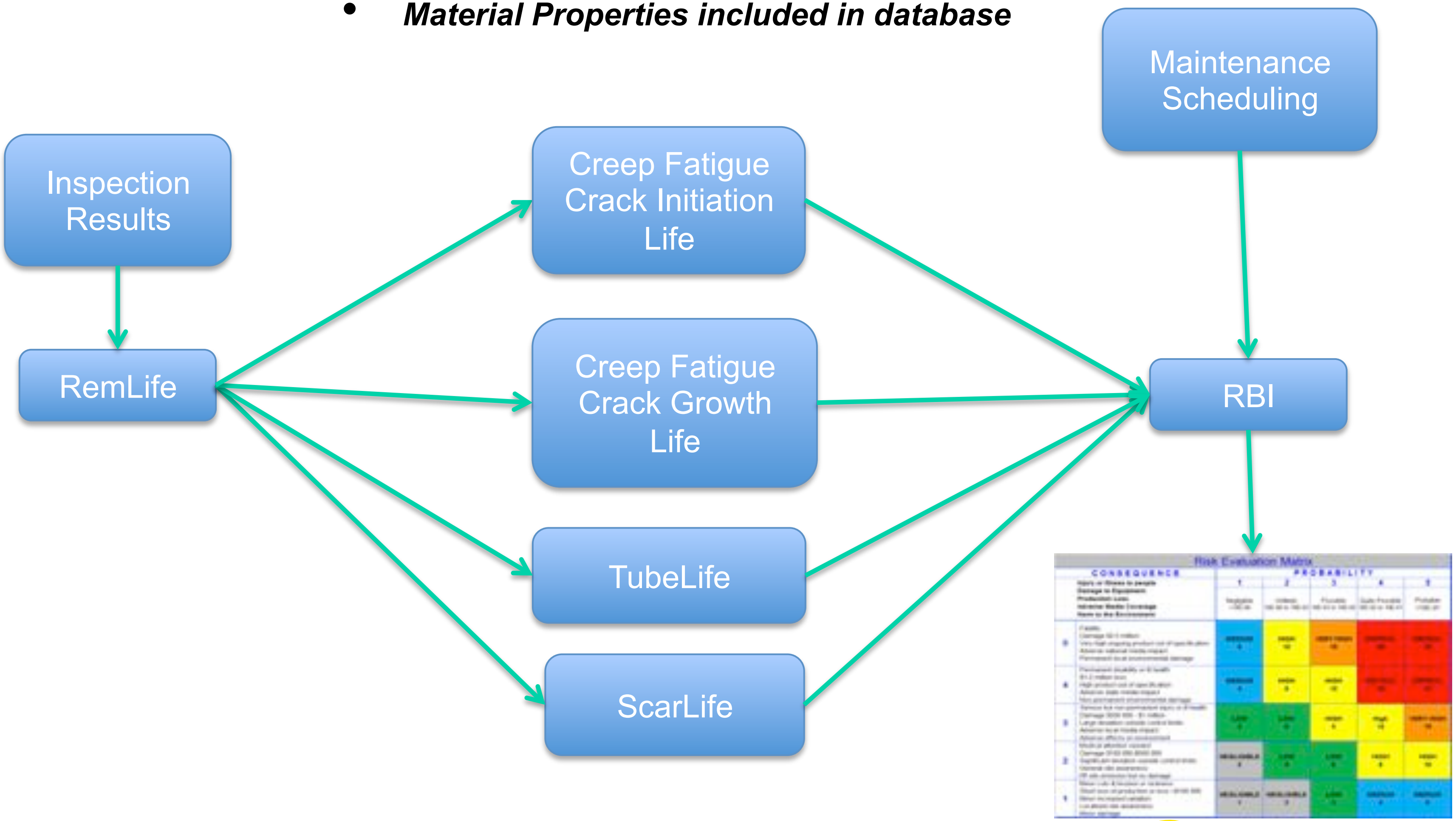
- ***Software commercialised for non-nuclear plants through sale to ALS Industrial Power Services Pty Ltd; an Australian ASX 200 company***

- ***ANSTO retains rights for use of software in Nuclear Science and Engineering fields.***

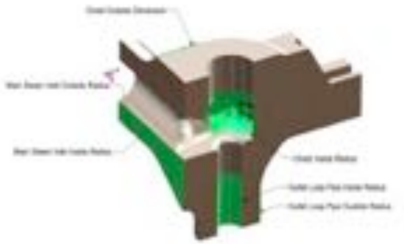
RemLife

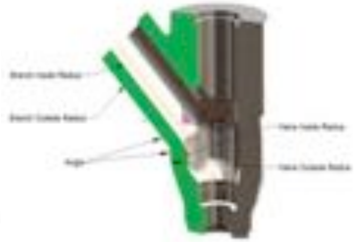
- ***Creep-fatigue cycling***
- ***RBI Assessment***
- ***Crack Growth***
- ***Material Properties included in database***

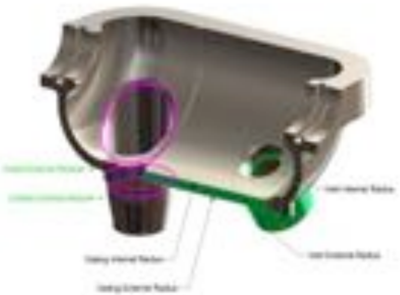
RemLife is a simulator that calculates the effects of unit cycling on the accumulation of creep and creep-fatigue damage on components

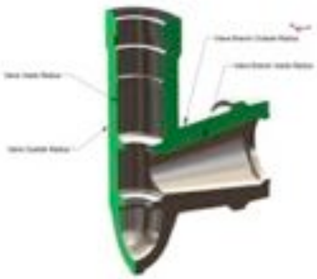


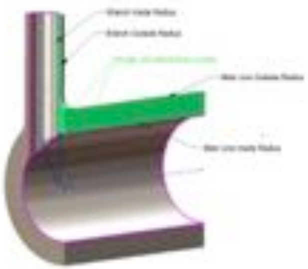
Generic Components

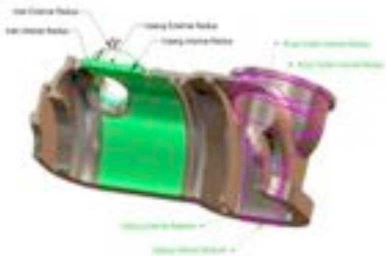


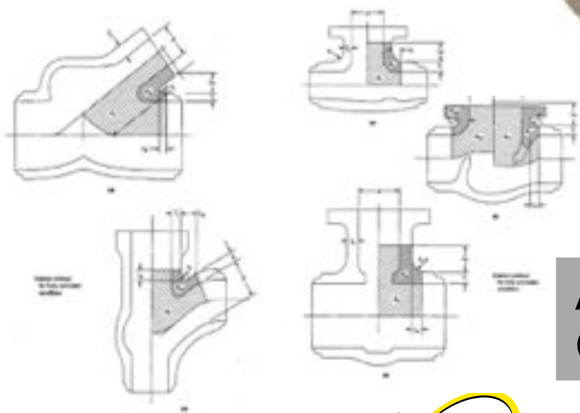












Also user defined Components

Creep-Fatigue Materials Database

Developed materials database for creep-fatigue performance

Full C-F Model

1Cr0.5Mo (P12)	1.25Cr0.5Mo (P11)	2.25Cr1Mo (P22)
0.5Cr0.5Mo0.25V (CMV)	1Cr1Mo0.25V (CMV)	1.25Cr1Mo0.25V (CMV)
P9	X10CrMoVNb (P91)	9Cr0.5Mo1.8WVNbB (P92)
AISI 304	AISI 316	25Cr35NiNbMa (HK40)
X20CrMoV12-1	7-9Cr2WV	P23
Hastelloy XR	Fe0.75Ni0.5MoCrV	Fe2.25Cr1Mo0.25V

Under Development

What about MSR Materials?

Remlife Design & Remaining Life Codes

Design Standards

- ***AS4041***
- ***AS1210***
- ***AS1228, BS1113***
- ***BS5500***
- ***EN13445***
- ***ASME III NB-NC***
- ***EN12593***
- ***ASME B31.1***
- ***ASME VIII Div I***
- ***ASME VIII Div II***
- ***TRD301***

Remaining Life Codes

- ***R5 high temperature code (EDF/British energy)***
- ***API 579 ASME FSS (USA)***
- ***RCC-MR (European)***

Remlife Design & Remaining Life Codes

Design Standards

- ***AS4041***
- ***AS1210***
- ***AS1228, BS1113***
- ***BS5500***
- ***EN13445***
- ***ASME III NB-NC***
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Remaining Life Codes

- ***R5 high temperature code (EDF/British energy)***
- ***API 579 ASME FSS (USA)***
- ***RCC-MR (European)***

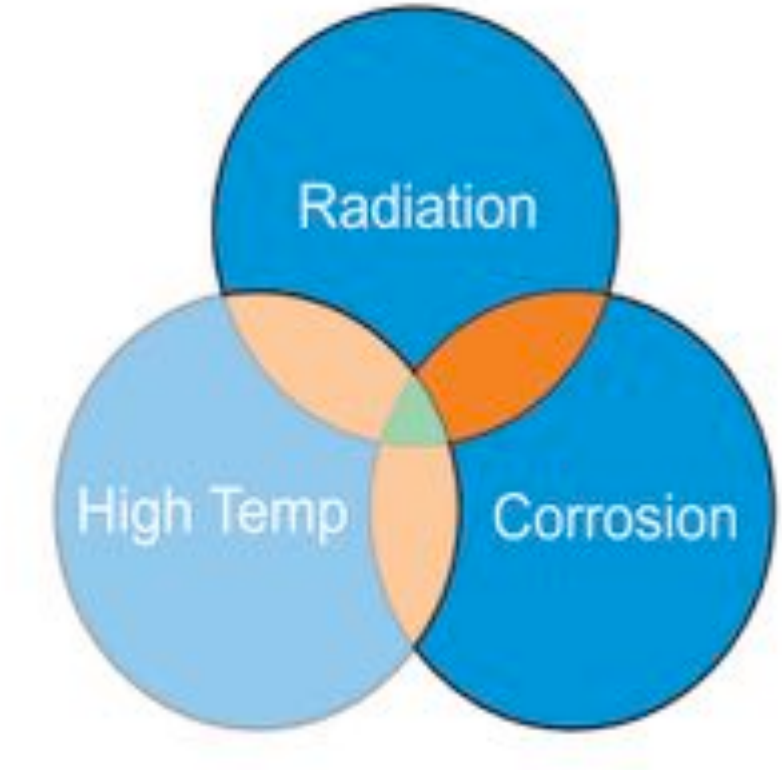
➢ ***Planning to incorporate radiation damage effects***

➢ ***Will enable Remlife to be used as first stage concept/detail design tool***

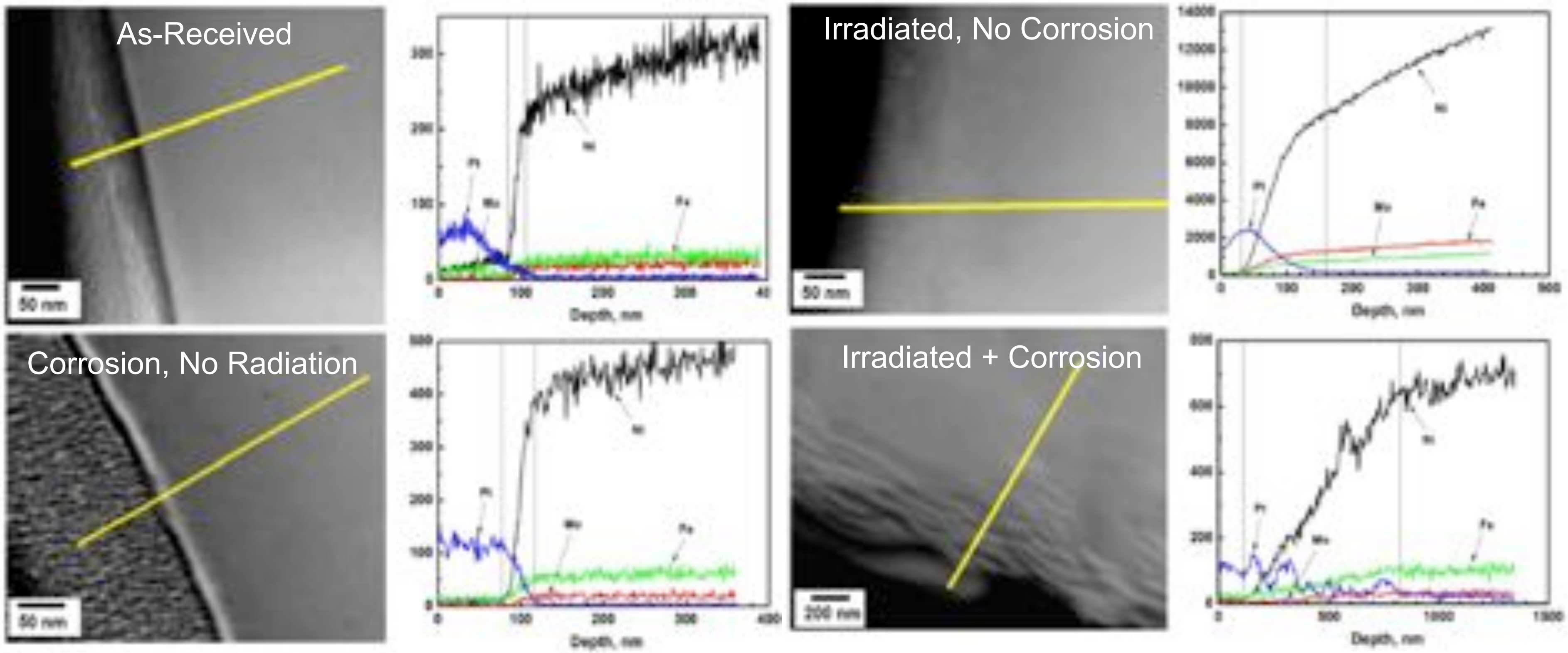
➢ ***What are the MSR needs?***

Generation IV Structural Materials R&D

- *Irradiation*
  - *Neutron, ion damage studies*
- *High temperature*
  - *Creep testing*
- *Corrosion*
  - *Testing in molten salt environments*
- ***Combined environments***
  - ***Irradiation + corrosion (MSR)***
  - *Corrosion + high temperature*



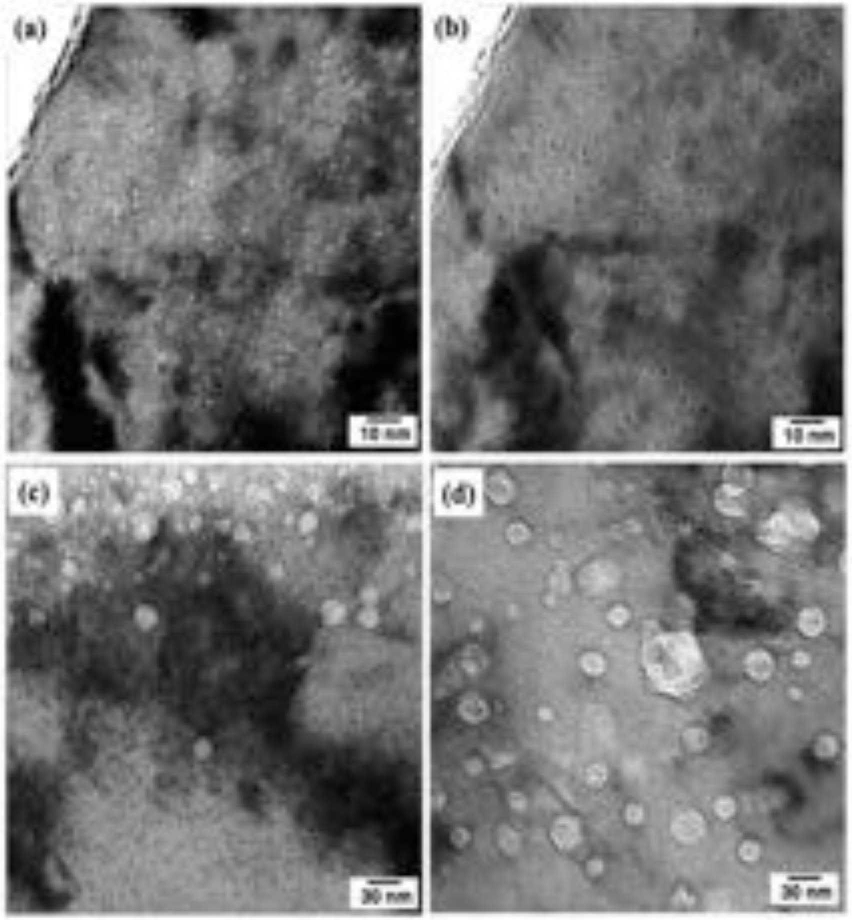
Effect of Ion Irradiation on Corrosion



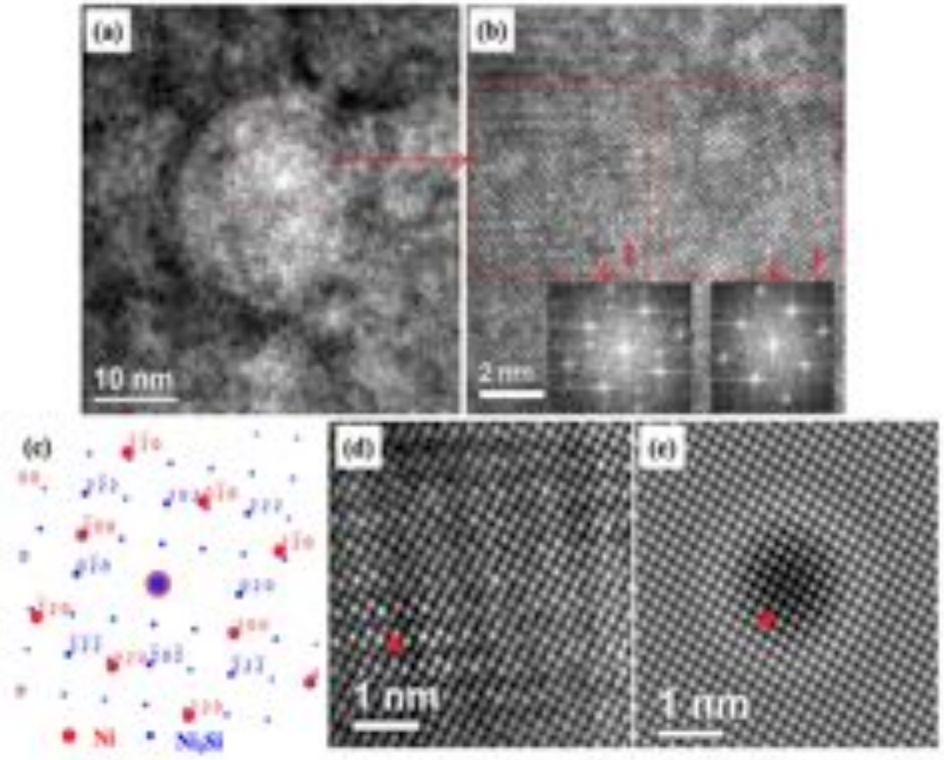
- ***GR3535 alloy, FLiNaK salt, 10^{17} ions/cm^2 He+***
- ***Helium ion irradiation increases the thickness of the corrosion layer in the irradiated and corroded sample by more than 30 times***

High-temperature corrosion of helium ion-irradiated Ni-based alloy in fluoride molten salt Zhu et al. Corrosion Science, 91, pp. 1-6.

Structural changes with corrosion time



Irradiated alloy after corrosion for 10, 100 and 200 hours at 750°C



- HRTEM images of a helium bubble in 200h sample
- Nano-scale Ni_2Si precipitate shown by the arrowheads.

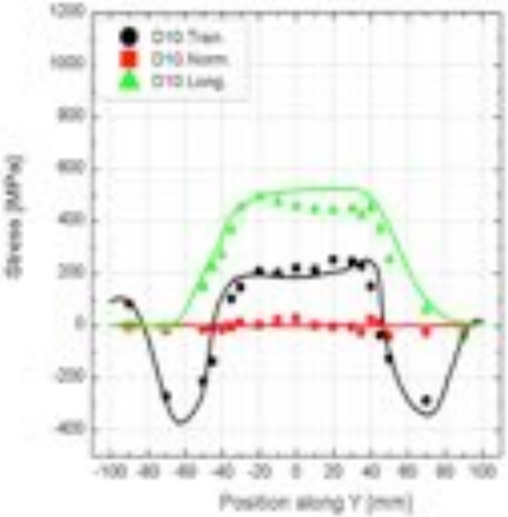
Zhu et al. unpublished work

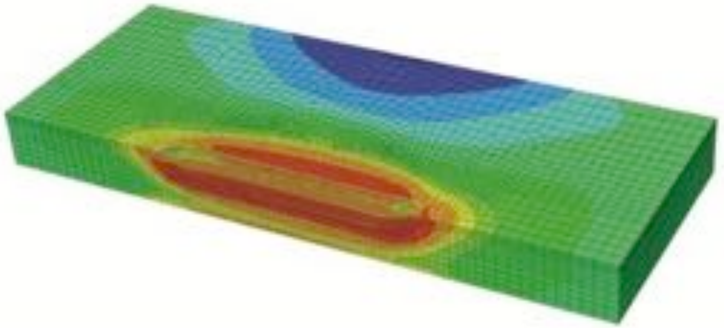
ANSTO/SINAP MSR Materials Papers

- ***De Los Reyes, M., Edwards, L., Kirk, M.A., Bhattacharyya, D., Lu, K.T., & Lumpkin G.R.', Materials Transactions, 55, (2014) pp. 428-433***
- ***He, Z.T., Gao, L.N., Qi, W., Zhang, B.L., Wang, X., Song, J.L., He, X.J., Zhang, C., Tang, H., Holmes, R., Xia, H.H. and Zhou, X.T, Carbon, 84, (2015) pp. 511-518***
- ***Zhu, H., Holmes, R., Hanley, T., Davis, J., Short, K & Edwards, L., Corrosion Science, 921 (2015) pp. 1-6***
- ***He, Z., Gao, L., Qi, W., Zhang, H., Wang, X., Song, J., He, Xiujie, Zhang, C., Tang, H., Holmes, R., Huihao, X., Zhou, X., Carbon, 84 (2015) pp. 511-518***
- ***Shrestha S. L., Bhattacharyya, D., Yuan, G., Li, Z.J.,Budzakoska-Testone, E. , De Los Reyes, M. Drew, D. and Edwards, L., 674, (2016) pp.64–75***
- ***Li, J., Shrestha, S.L., Long, Y., Li, Z.J. and Zhou, X.T., Materials and Design, 93, (2016) pp.324-333***
- ***De Los Reyes, M., Voskoboinikov, R., Kirk, M.A., Huang, H., Lumpkin, G., Bhattacharyya, D., Journal of Nuclear Materials, 474 (2016), pp. 155-162***
- ***Yang, C., Muránsky, O., Zhu, H., Thorogood, G.J., Huang, H , and Zhou,. X., Materials and Design 113 (2017) pp. 223–231***

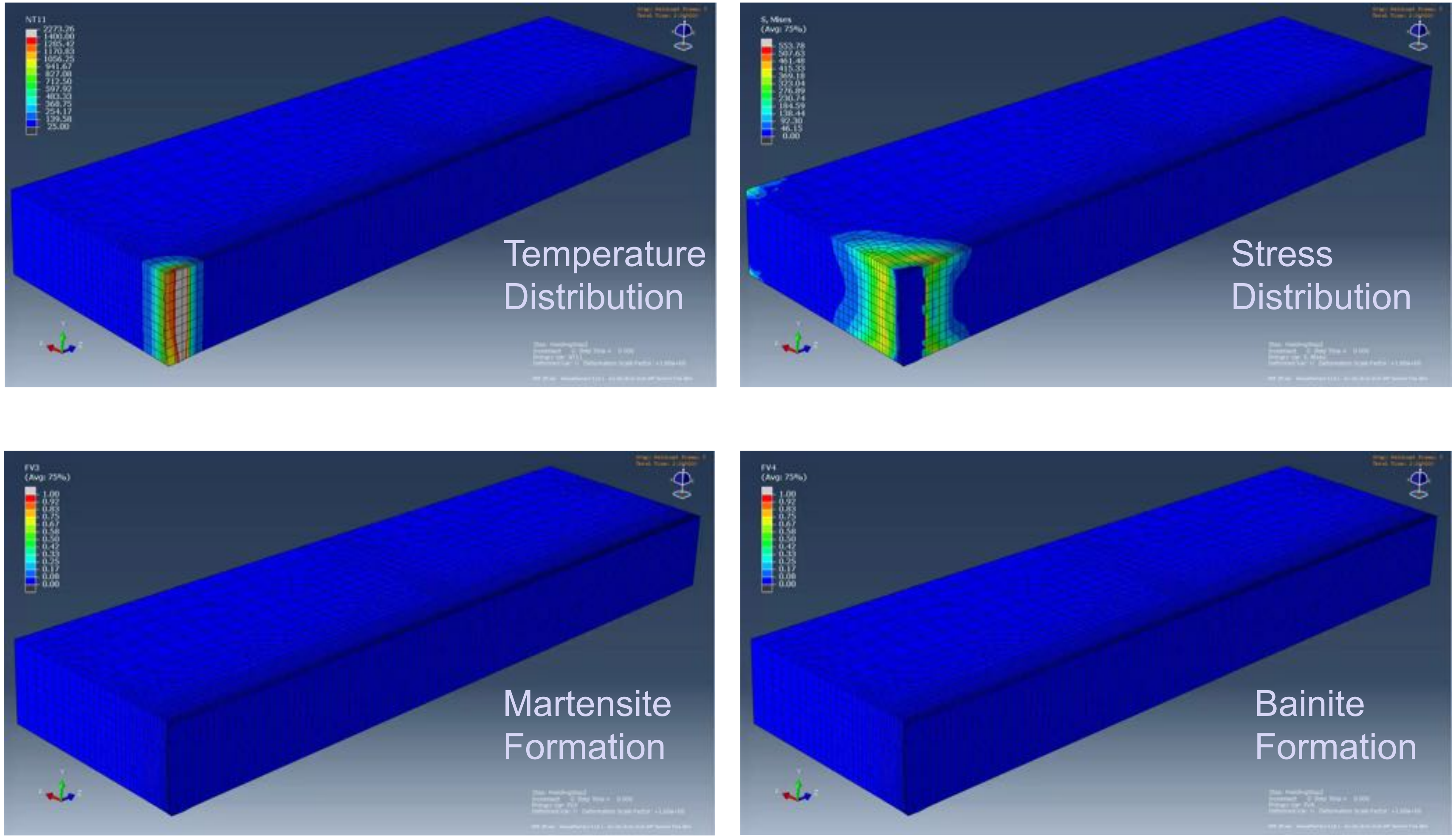
Understanding and Predicting Weld Residual stress

- ***ANSTO has developed complex models of microstructure and stress state 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***



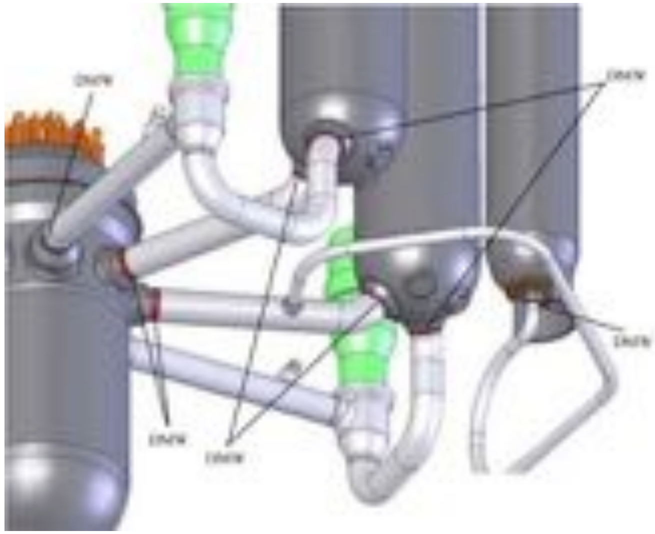


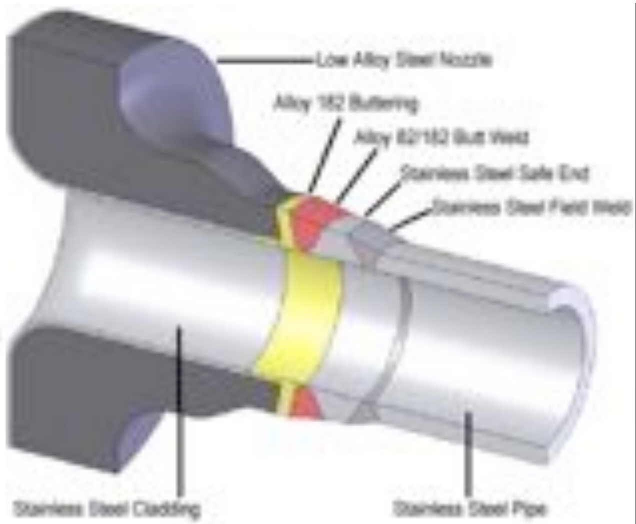
Typical Weld Simulation: A 508 EB Weld



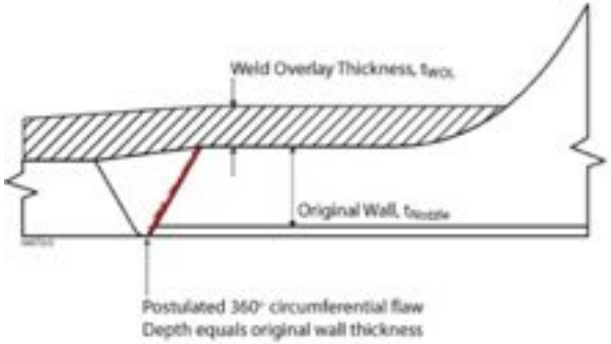
Courtesy A. Vasileiou, University of Manchester

Stress Corrosion Cracking in PWR Dissimilar Material Welds

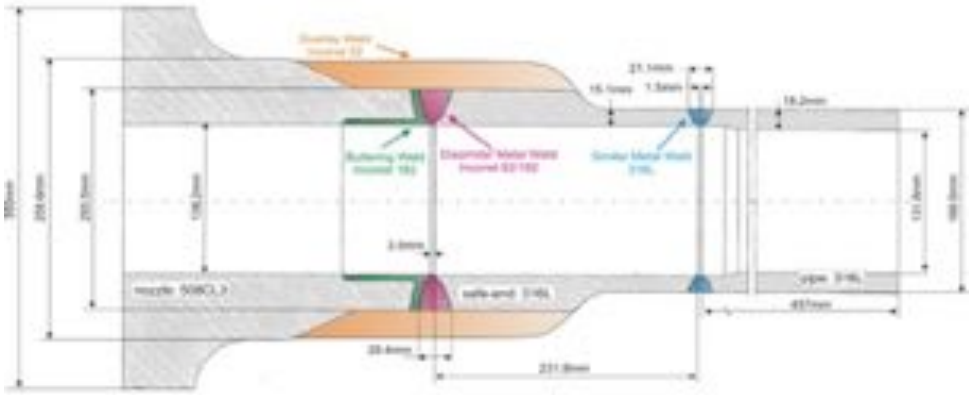


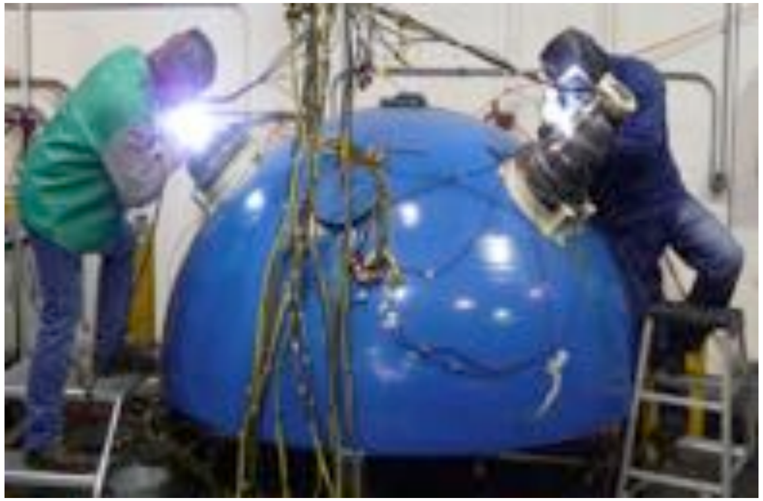


- Since 2000, 19 cracks found at dissimilar metal welds
- Engineering solution is full structural weld overlays
- Structural Integrity assessment needs weld stresses
- ANSTO worked with Nuclear Regulatory Commission (US) and EDF/British Energy (UK) to develop validated weld modelling of dissimilar metal welds

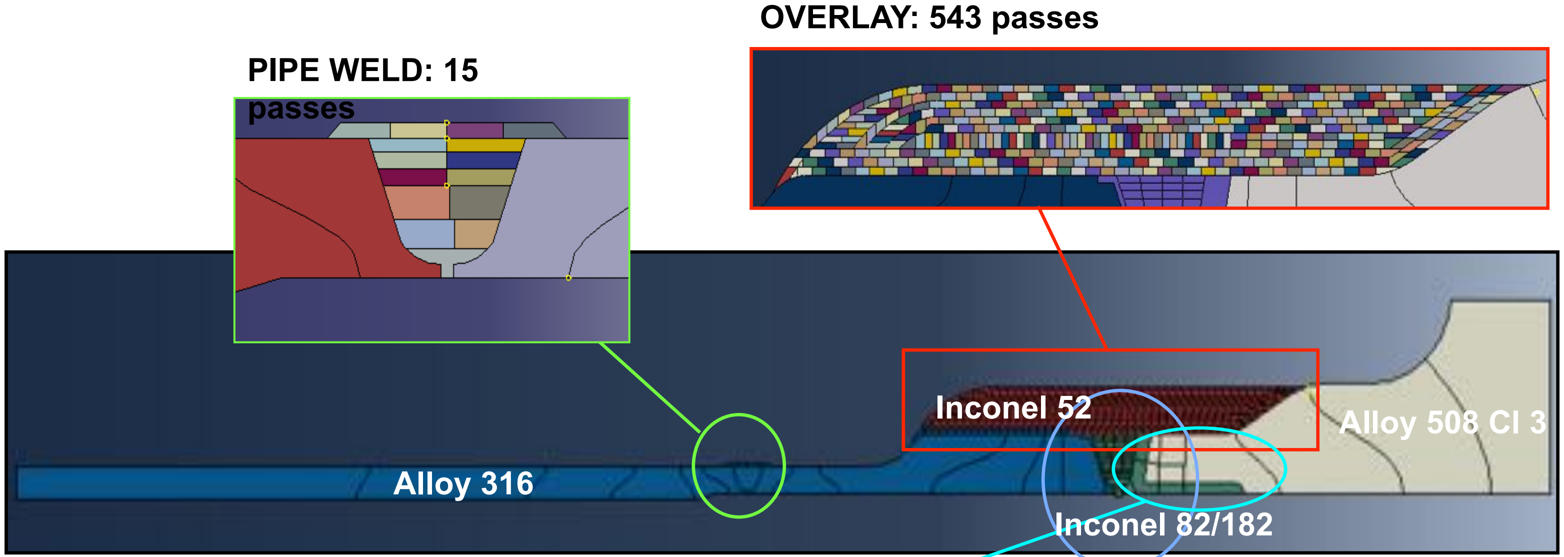


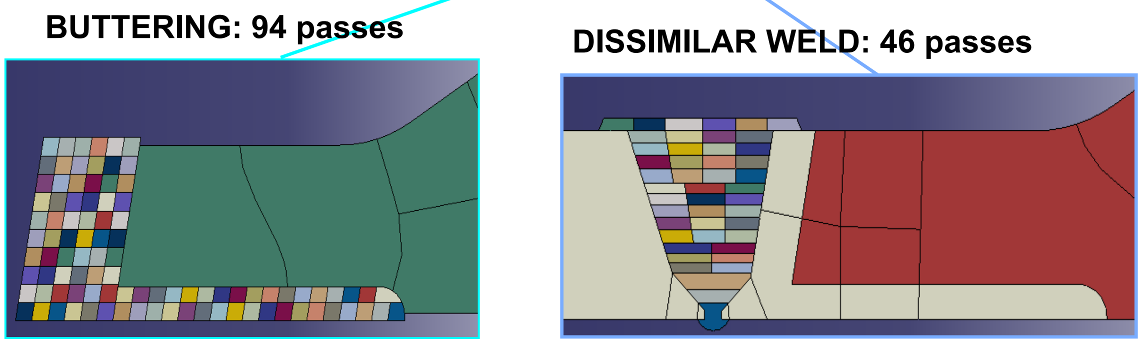
Validation using full scale mock ups.





Modelling of Nuclear Dissimilar Weld Overlays

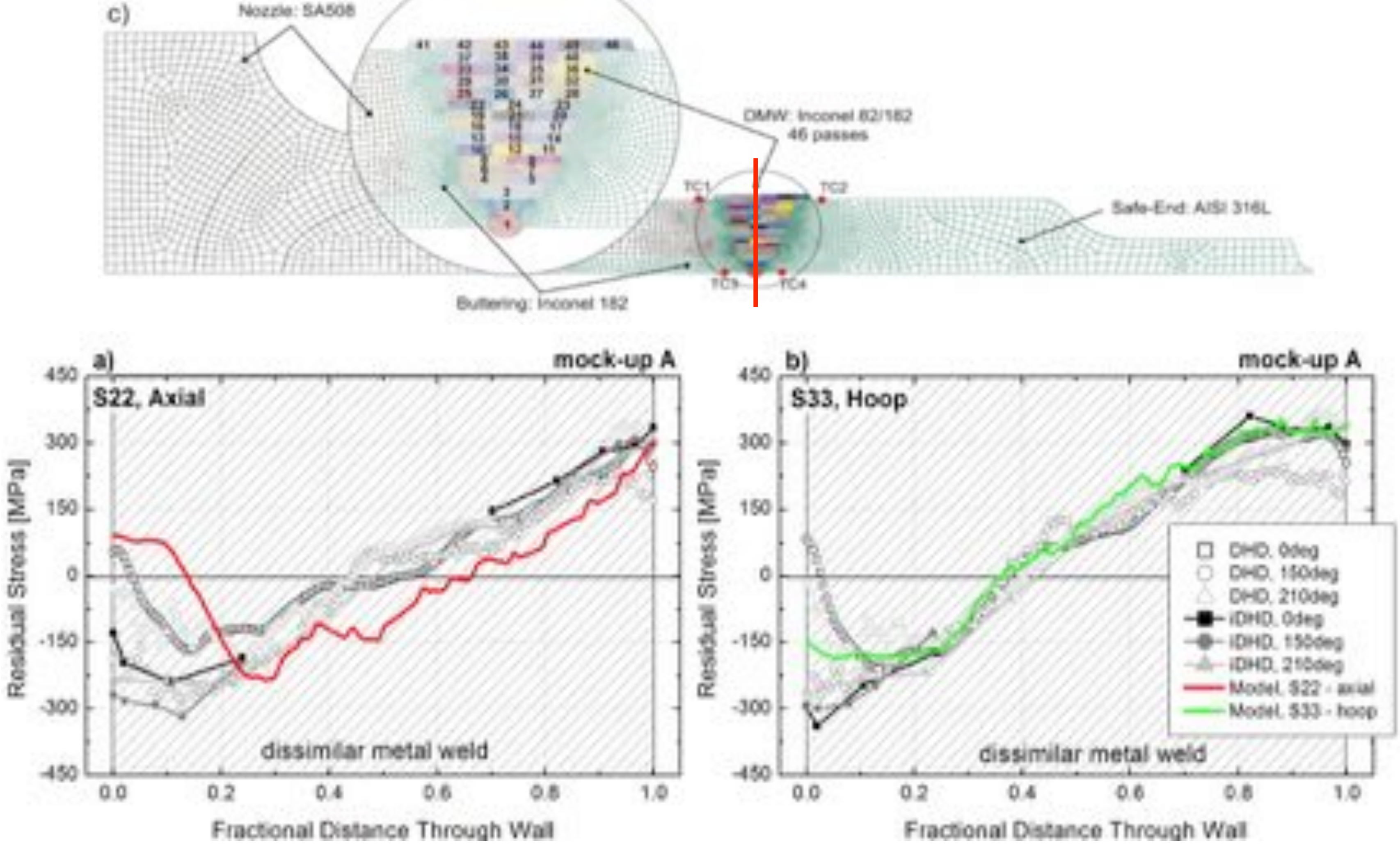




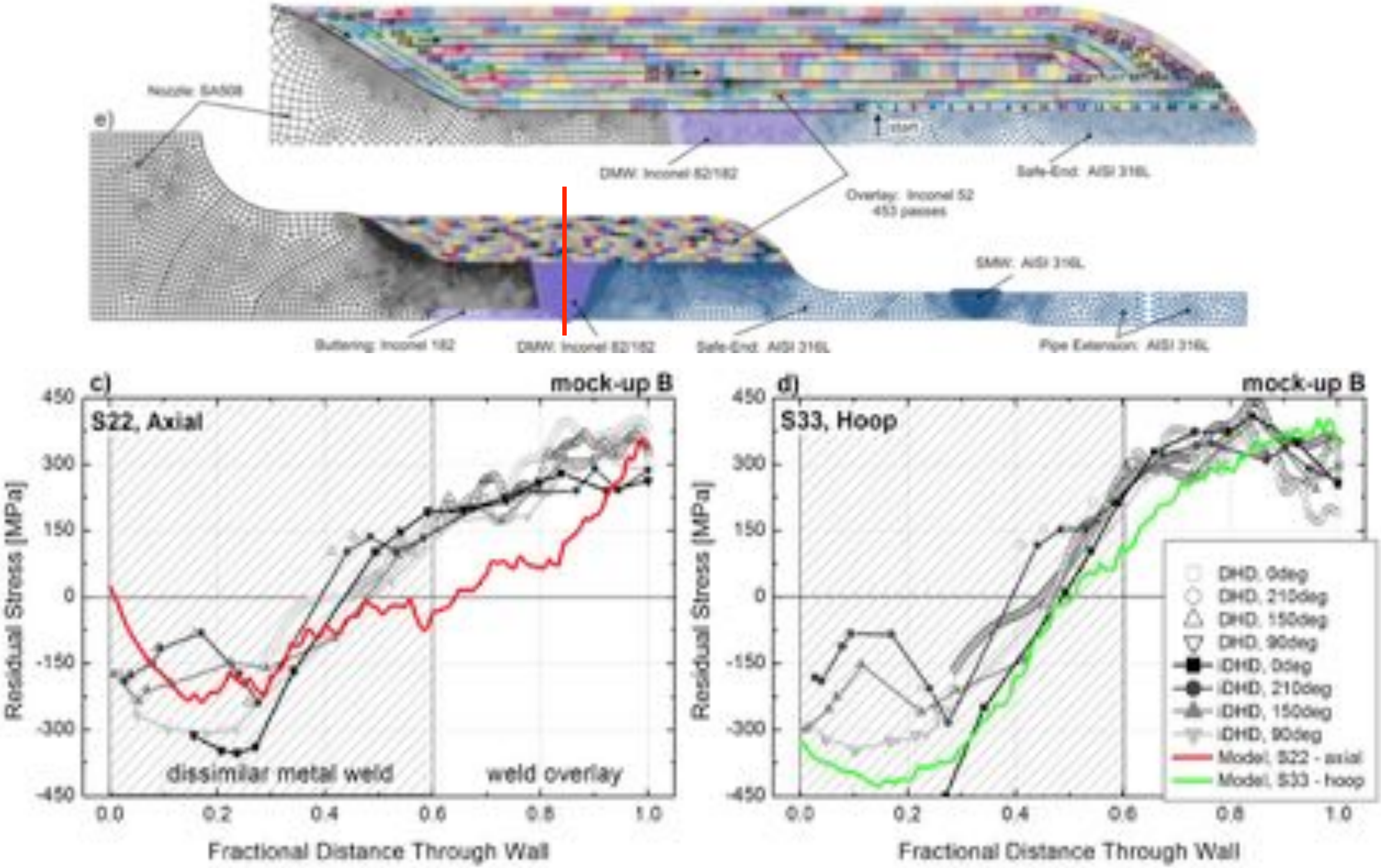
INSTRUMENTED MOCK UP

Full axi-symmetric model of instrumented mock up containing 598 weld passes in four different alloys

Residual Stresses (without overlay)



Residual Stresses (with 453-Pass Overlay)



Admiral Hyman Rickover (USN)

An academic reactor or reactor plant almost always has the following basic characteristics:

(1) It is simple.
(2) It is small.
(3) It is cheap.
(4) It is light.
(5) It can be built very quickly.
(6) It is very flexible in purpose.
(7) Very little development will be required. It will use off-the-shelf components.
(8) The reactor is in the study phase. It is not being built now.

Admiral Hyman Rickover (USN)

On the other hand a practical reactor can be distinguished by the following characteristics:

(1) It is being built now.

(2) It is behind schedule.

(3) It requires an immense amount of development on apparently trivial items.

(4) It is very expensive.

(5) It takes a long time to build because of its engineering development problems.

(6) It is large.

(7) It is heavy.

(8) It is complicated.

Admiral Hyman Rickover (USN)

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In Nuclear, materials are usually in this category of "*mere technical details*"

Questions

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