Materials Challenges for the Supercritical Water-cooled Reactor (SCWR)

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Outline of Talk

- *Introduction*
  - *Talk aimed at interested professionals, not experts*
- *Part I: The SCWR*
- *Part II: Thermo-Physics of SCW*
- *Part III: Materials Challenges*
  - *General Review*
  - *Canadian and International Efforts*
- *Conclusion*

Introduction

Critical Drivers in the Nuclear Renaissance

- **<u>Economics</u>**
  - **Reduced costs (especially capital costs)**
    - **Need Modularity, Scale, Simplified Core and Plant**
  - **Reduced financial risk (licensing uncertainty / construction time / capped cost)**
  - **Better Thermal and Fuel Use Efficiency**

- **<u>Safety and Reliability</u>**
  - **Operations safety**
  - **Protect against core damage (reduce likelihood & severity)**
  - **Eliminate offsite radioactive release potential**

- **<u>Sustainability</u>**
  - **Efficient fuel utilization**
  - **Waste minimization/management**

Introduction (Cont'd)

Critical Drivers in Nuclear Renaissance (Cont'd)

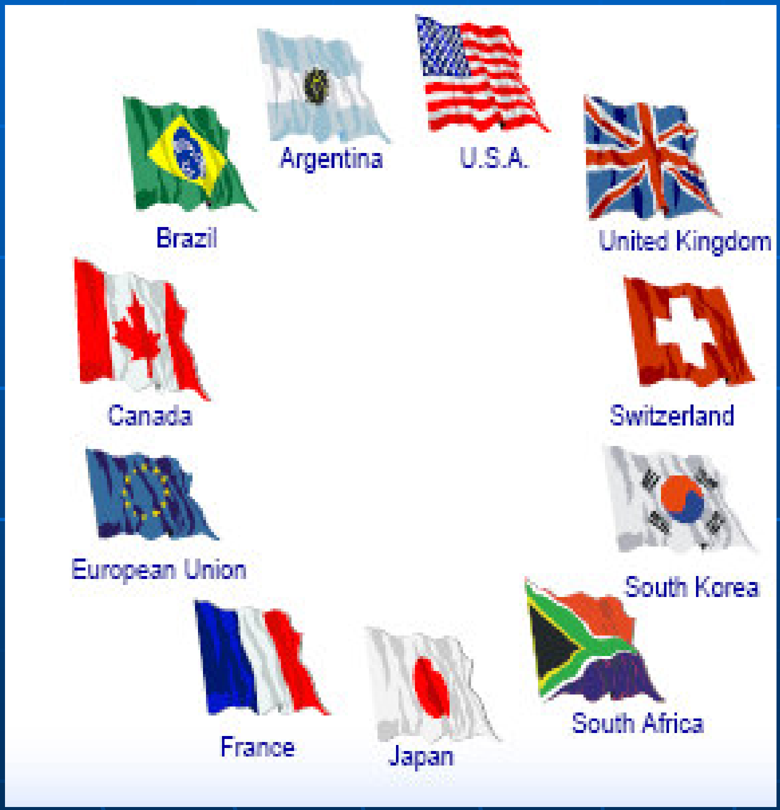
- ***Proliferation-resistant fuel cycles***
- ***Climate Change***
    - Greenhouse-gas emission free
    - Hydrogen Production
    - Process Heat
- ***Security***
    - Environmental threats (EQ)
    - Physical threats (plane crashes etc)

Introduction (Cont'd)

The Generation-IV Program is intended to develop Reactor Systems to fulfill these goals

- *Six Reactor Systems selected for R&D out of ~100 proposed, 2000-02:*
  - *Very High Temperature Reactor (**VHTR**) (He)*
  - *Gas-cooled Fast Reactor (**GFR**) (He)*
  - *Lead-cooled Fast Reactor (**LFR**) (Pb/Pb-Bi)*
  - *Sodium-cooled Fast Reactor (**SFR**) (Na)*
  - *Molten Salt Reactor (**MSR**) (Graphite core, Na-Zr-U-F fuel)*
  - *Supercritical Water-cooled Reactor (**SCWR**)*

Introduction (Cont'd)



Generation-IV International Forum (GIF):

Agreement on Goals

Led by diff countries

- Canada: SCWR

Sharing of Expertise

Progress Reviews

Deployment 2030 AD

IAEA/Euratom/OECD -NEA

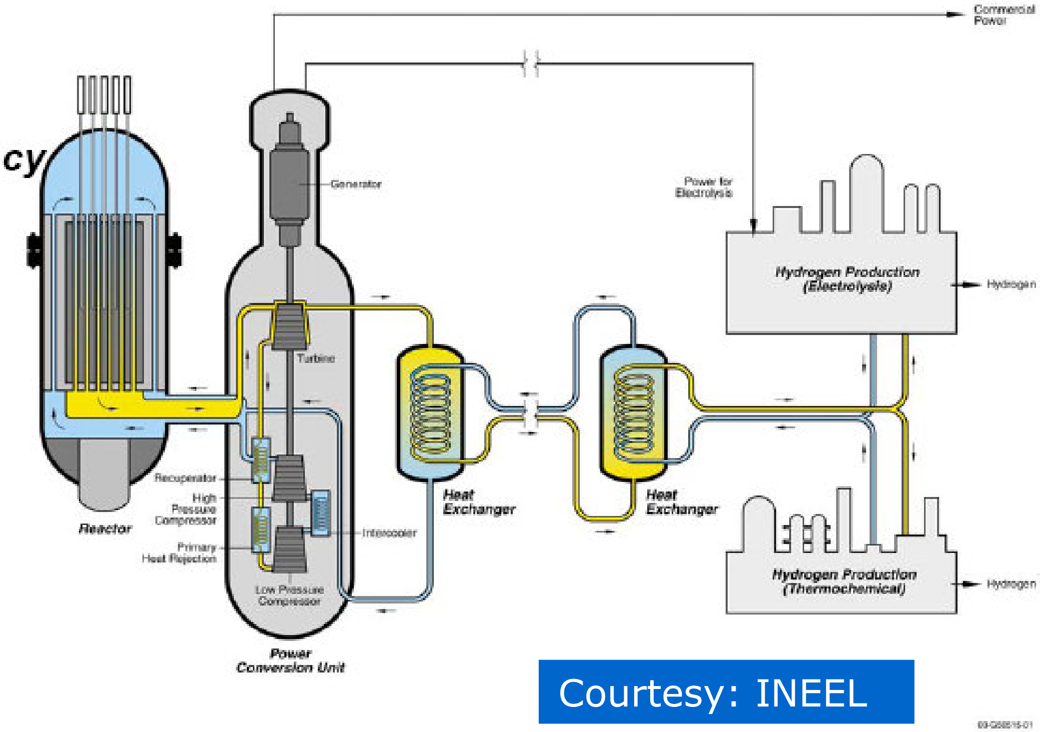
Introduction

Other International Initiatives with similar goals:

- INPRO (IAEA)
  - International Project on Innovative Nuclear Reactors and Fuel Cycles
- RAPHAEL (Euratom)
  - Reactor for Process Heat and Electricity
- I-NERI
  - International Nuclear Energy Research Initiative (Bilateral with US DOE)
- GNEP
  - Global Nuclear Energy Partnership – US coordinated

Very High Temperature Reactor (VHTR) US-led

- *Greatly Simplified Modular (150-300MWe) Design Lowers Capital Cost*
- *High Outlet Temperature Improves Thermal Efficiency (850-950°C)*
- *Hydrogen Production Potential Opens New Markets*
- *Graphite-Ceramic Core Materials Improve Safety*
- *Passively Safe to Loss of Coolant Accident*
- *Coated Particle Fuel*



Canada's Participation in Gen-IV

- *Leads R&D on the SCWR*
  - *PT design*
  - *SCW Light water coolant with Heavy-water moderator (SC**H**WR)*
- *SCWR variants pursued by other GIF members*
  - *SC**L**WR*
  - *Solid moderator (Korea, ZrH_2)*
  - *RPV design*
- *Also motivated by Canada-specific applications:*
  - *Tar Sands, Desalination, Process Heat, NHP by Cu-Cl*
  - *US variant SCLWR only electricity*
- *Canada also participates in VHTR under GIF*
  - *NHP, HTE development*
  - *Materials Development Synergies with SCWR*

Canada's participation in Gen-IV and SCWR

- Leadership role recognizes:
  - *Considerable work AECL undertook on SCW coolant*
  - *Facilities and expertise available in Canada to advance the R&D on the concept*
  - *Complementarity: CANDU design and SCW concept*
    - *Calandria-pressure tube separation decreases SCW Impact on neutronics*
    - *Pressure-tube design may handle higher pressures better than RPV*
- *US, EU, Japan, Korea, Russia, China, India also active in SCWR development*
- *IAEA has a Cooperative Research Program (CRP) on SCWR issued late 2006 – accepting Proposals*

Introduction (Cont'd)

- *Gen-IV Reactors will have*
  - Higher Core and Outlet Temperature
  - Higher Hydraulic Pressure in coolant loop
    - For better efficiency – make coolant SCW
    - Higher specific enthalpy, lower thermal conductivity, viscosity, density
    - Smaller balance of plant
  - Higher Radiation Dosage
    - Upto 150 dpa for fast spectrum vs 15 dpa for thermal
    - Coolant interaction with fast spectrum flux
    - Cladding interaction with fast spectrum flux
  - Novel Coolants and/or Moderators and/or Fuel media
    - Supercritical Water
    - Liquid Sodium / Lead
    - Gaseous Helium
    - Solid ZrH_2 moderator
    - Molten Zr/U/Na –Fluorides as fuel (MSR)
  - **Longer Design Life (60 yrs vs 20-40 yrs)**

Introduction (Cont'd)

- *So Gen-IV systems will face higher*
  - *Hydrostatic Stress*
  - *Thermochemical Stress*
  - *Radiolytic Stress*

  Than current generation reactors

  *Creates **Materials Challenges***

  Shared across all Gen-IV Reactor Systems

  Details differ: Cross-Cutting Integrated Materials Program

  Some Materials Challenges also shared with NHP, Breeder reactors, Fusion Reactor Concepts

Introduction (Cont'd)

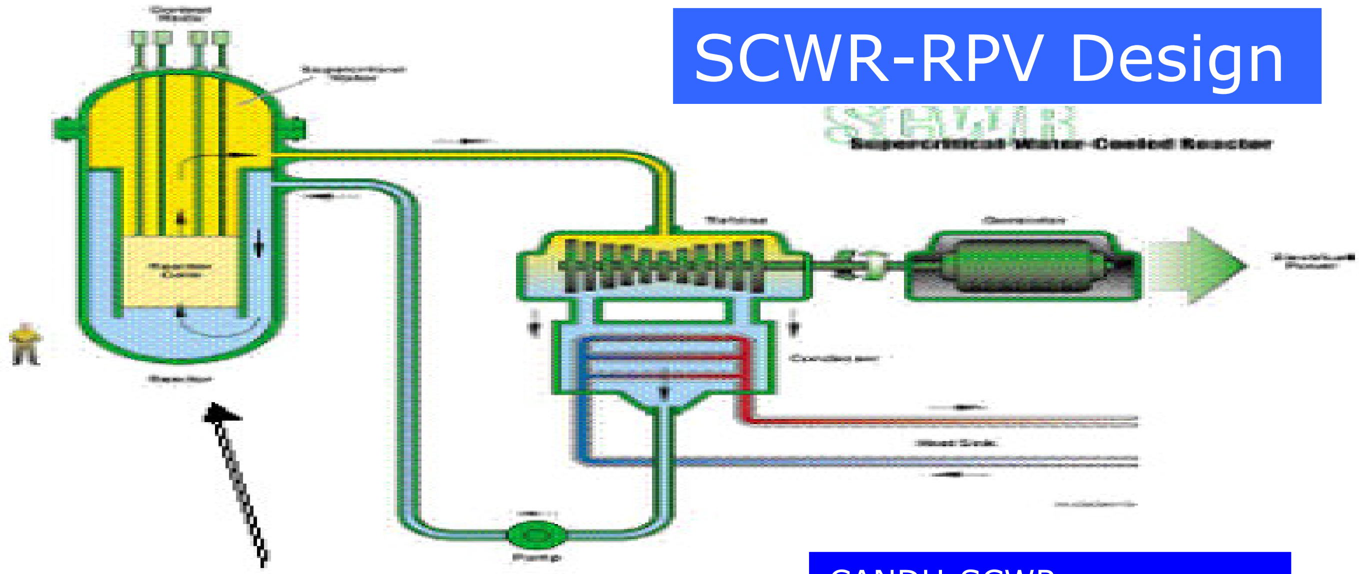
- The SCWR GIF Partners: Three Overall Projects
- **Materials and chemistry:** Select materials for use both in-core and out-of-core and for both the Canadian pressure tube (PT) and US reactor pressure vessel (RPV) designs. Build Water Chemistry database: based on materials compatibility and radiolysis behavior.
- **Design and integration**— Develop reference design meeting Generation IV requirements. Achievable outlet temperature based on materials, fuel performance, and linkages to proven steam cycles in SCW FFPs.
- **Basic thermal-hydraulic phenomena, safety, stability, and methods development** — Gaps exist in the heat transfer and critical flow database for the SCWR.

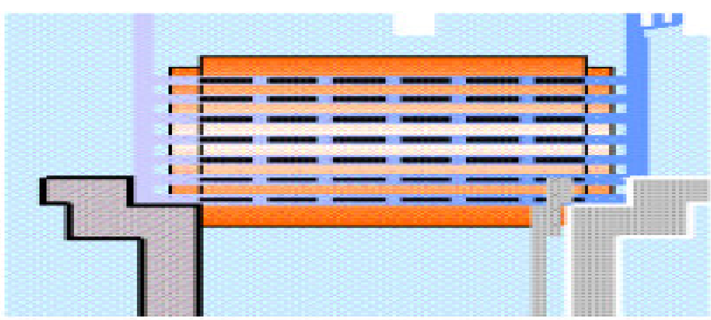
Introduction (Cont'd)

- *SCWR:*
  - *Combined radiological and SCW stress on core materials – no precedent.*
  - *This stress more acute for fast spectrum variants. (Other challenges also exist for SCW fast spectrum variant…need more moderator etc)*
- *No SCW **nuclear** plants have been built (though FF boilers with SCW have been operating for a while)*

The Supercritical Water-cooled Reactor – Preliminary Designs – CANDU and RPV

SCWR-RPV Design





CANDU-SCWR uses horizontal PT, Calandria, also to be modified from previous CANDU (Khartabil Chow 2007)

Sadhankar, et al 2007

CANDU-SCHWR

Preliminary Design Specifications

(Khartabil & Chow 2007)

Spectrum	Thermal
Moderator	Heavy water
Coolant	Light water
Thermal Power	2540 MW
Flow Rate	1320 kg/s
Number of Channels	300
Electric Power	1220 MW
Efficiency	48%
Fuel	UO_2 / Th
Enrichment	4%
Inlet Temperature	350°C
Outlet Temperature	625°C
Cladding Temperature	< 850°C
Calandria Diameter	4 m

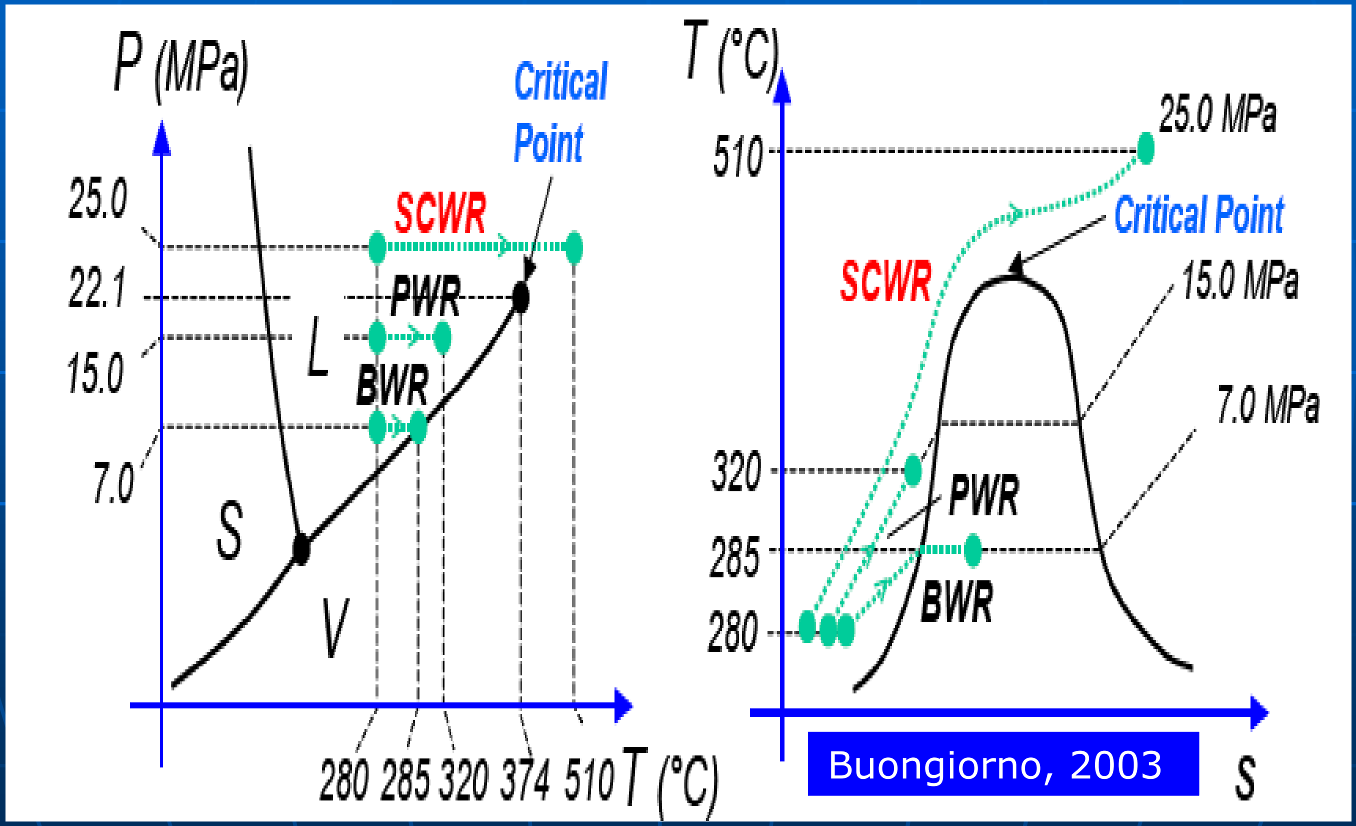
State-of-the-art FFP SCW boilers: 610 C and 25 MPa

SCWR – other specifications

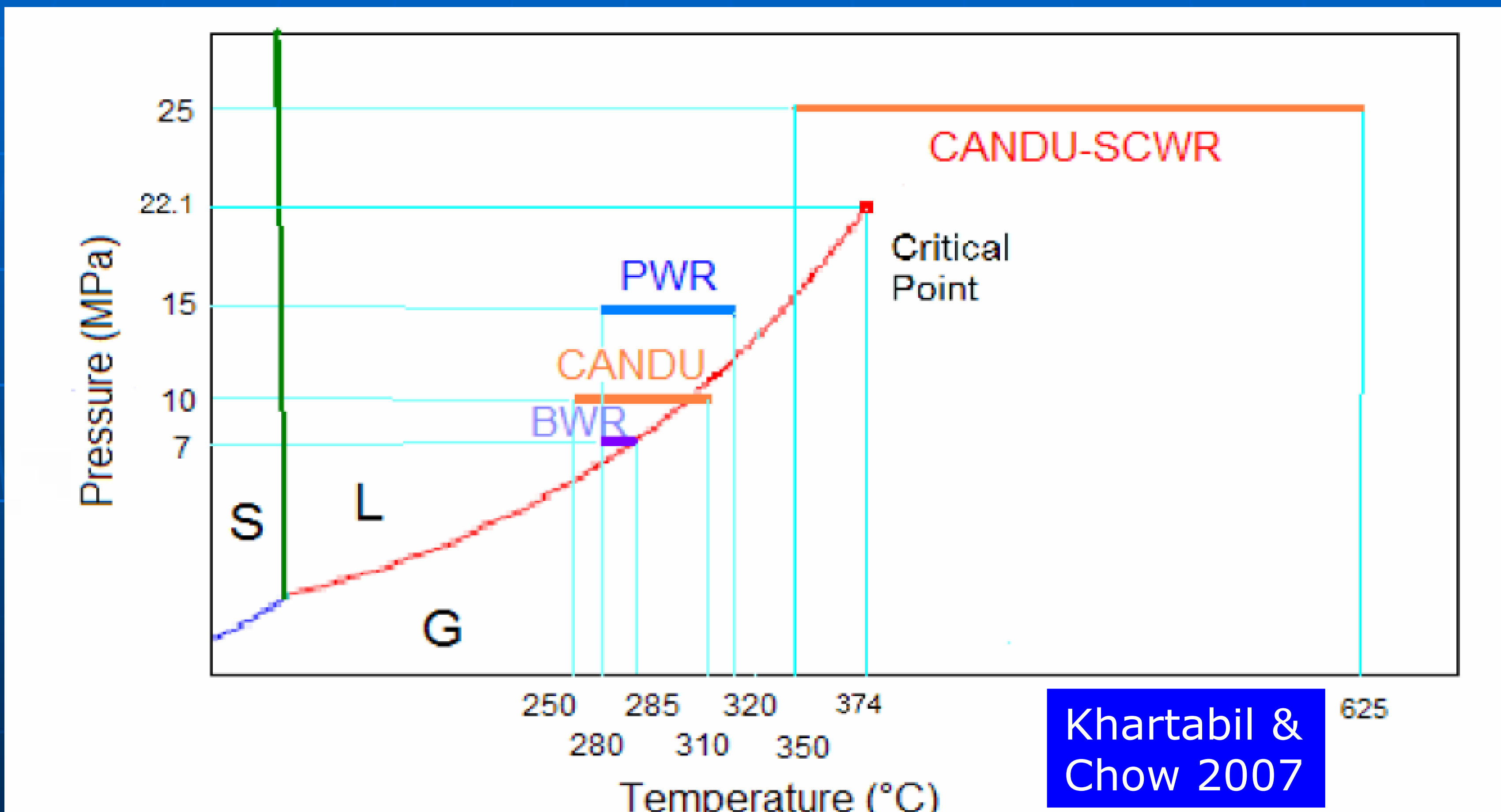
- *Light Water moderated thermal spectrum (SC**L**WR) – Japanese design basis for reference*
- *Solid moderator (Zr/H) Korea*
- *Pebble-bed fueling (SiC-UO_2)*
- *Variations of RPV Design*
- *Fast spectrum variant (many other challenges)*

Have their own materials challenges

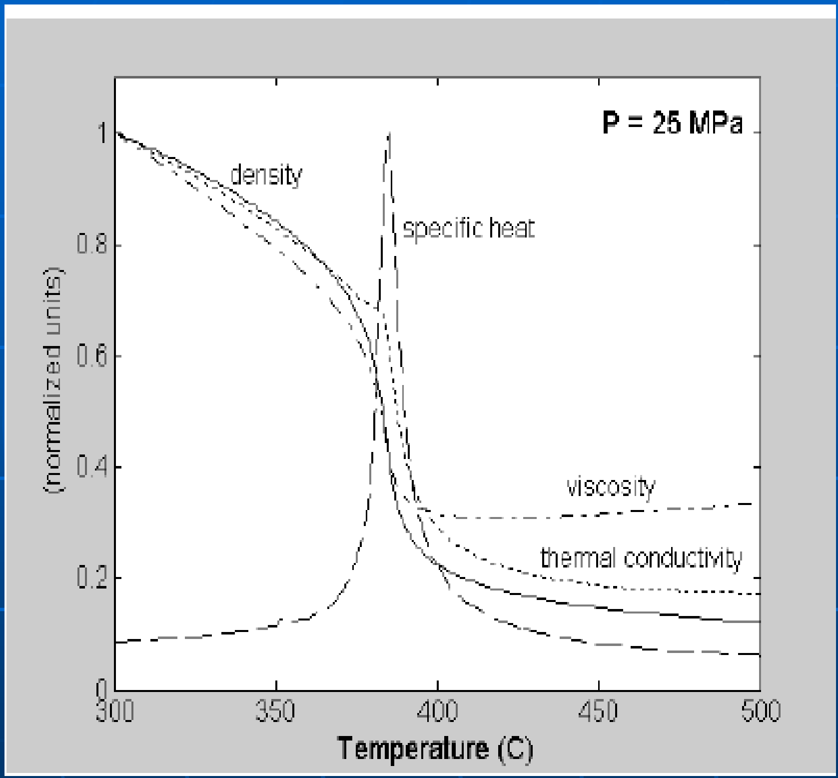
Contrasting SCWR-RPV Operating Conditions with PWR and BWR

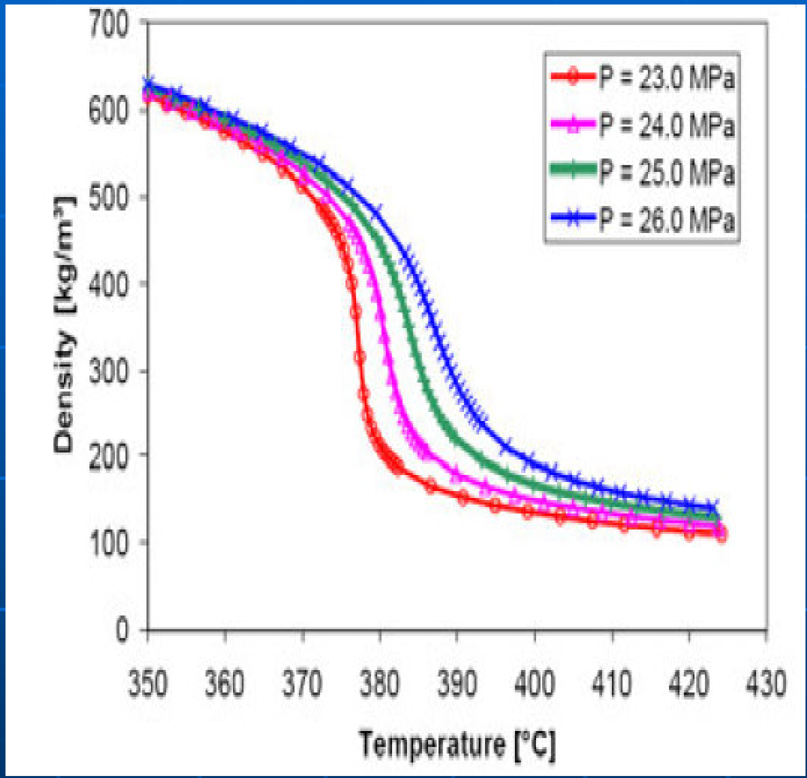


CANDU-SCWR Operating Regime



Thermo-Physics of Supercritical Water (Cont'd)





Above the critical point, SCW behaves like a dense gas with transport properties tunable by Pressure and Temperature, but can be highly corrosive to reactor materials. Organics dissolve in SCW but inorganics don't, reverse of ordinary water

Materials Challenges for SCWR

- *What conditions are relevant, and what phenomena are critical to model to obtain predictive understanding?*
  - *High Temperatures*
  - *High Pressures*
  - *Thermochemical Environment of SCW*
  - *Irradiation Flux (even worse for fast-spectrum variant)*
  - *Combination*

Materials Challenges for SCWR (Cont'd)

- Material Phenomena at High Temperatures and Pressures
  - Creep: Slow plastic deformation under constant stress – depends on T
  - Irradiation Swelling: Isotropic expansion under irradiation
  - Irradiation Creep: Creep under constant radiative stress; can occur at low T
  - Embrittlement:
    - Hardening from microstructural movement of dislocations
    - Grain boundary weakening

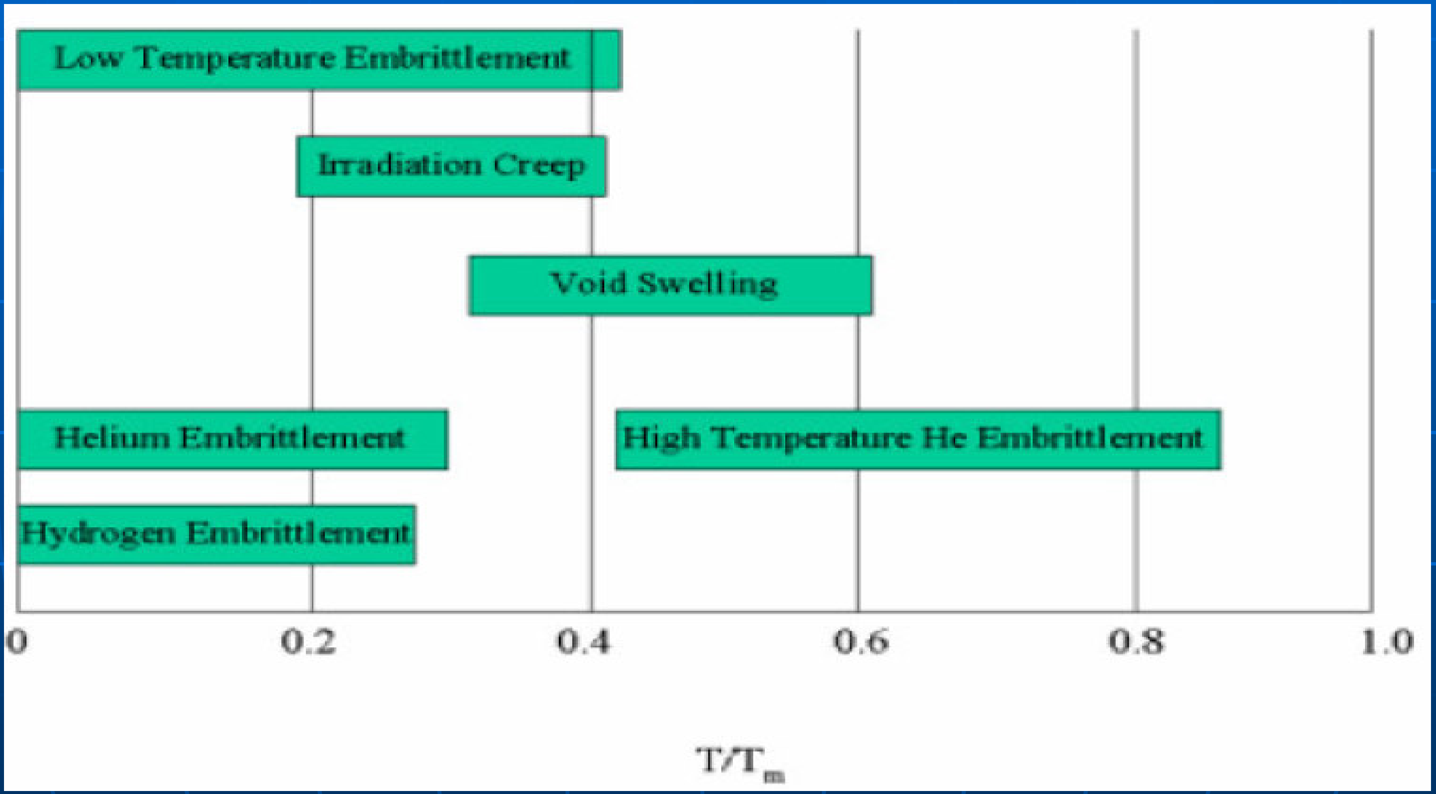
Materials Challenges for SCWR

- Materials chosen for reactors must have acceptable:
  - Dimensional Stability:
    - Void Swelling
    - Thermal Creep
    - Irradiation Creep
    - Stress Relaxation

    } Materials phenomena

  - Strength, Ductility, Toughness
  - Resistance to Creep Rupture, Fatigue Cracking, Creep-Fatigue Interaction, He Embrittlement
  - Chemical Compatibility and Corrosion Resistance (SCC and IASCC) with coolant (esp SCW, most important)
    (Corwin, 2006)

Materials Challenges for the SCWR



Damage Regimes as a function of Homologous Temperature, T/T_m where T_m is the melting temperature

Materials Challenges for SCWR

- For design, use, codification and regulatory approval, also need:
  - Validated models of structure-property relationships
  - Ability to predict long-term material behavior
  - Physical models of critical radiation phenomena - both FCC and BCC alloy systems
  - These needs are cross-cutting across all Gen-IV systems
    - Data obtained from irradiation experiments
    - Theoretical basis for interpolations and extrapolations
    - SCW interactions with materials critical to understand
      - (Corwin 2006)

Materials Challenges for SCWR (Cont'd)

Table 3. Summary of stress-strain and cracking results for benchmark and reference tests

Tests	Alloys	Yield strength (MPa)	Maximum strength (MPa)	Rupture strain (%)	Fracture mode	Crack density (#/mm^2)	Crack length (μm)	Crack depth (μm)
Benchmark	304L	185	420	36.8	IG+ductile	59.3	46.8	49.9
	316L	190	370	36.6	ductile	23.3	46.8	23.0
	625$^+$	335	960$^+$	60.7$^+$	IG+ductile	504.9	15.5	13.6
	690	215	475	41	IG+ductile	19.8	32.6	27.7
Reference	304L*	120	340*	25*	Did not fail	39.4	32.2	51.4
	316L	140	350	33	ductile	38.1	28.5	24.9
	625	270	675	47	IG+ductile	137.1	42.4	84.2
	690	174	455	42	Granular +ductile	32	24.9	33.1

Mechanical and Cracking Results From: Was, Teysseyre, Peng (2005)

Materials Challenges for SCWR (Cont'd)

- Water Chemistry of SCW under radiation and its impact on corrosion of materials:
  - Intergranular stress corrosion cracking (IGSCC)
  - Irradiation-assisted Stress Corrosion cracking (IASCC)
    - Metallurgical Structure: phase morphology, Cr depletion
    - Irradiation Effects on Grain boundary segregation
    - Oxidizers and Reducers in water
  - SC Water chemistry under irradiation is the <u>most important unknown</u> likely to affect materials properties for SCWR
  - Supercritical fluids may behave like two-phase fluids due to instabilities near the critical point, could impact corrosion.
  - Knowledge base for predicting SCC and IASCC under SCW does not currently exist

Materials Challenges for SCWR

Candidate Materials

- Mechanically alloyed materials: **Oxide Dispersion Strengthened (ODS) Steels** hold great promise for meeting materials requirements: fcc or bcc structure provides swelling resistance, while dispersed-Y provides enhanced high Temperature strength.
- Austenitic, Ferritic and Ferritic-Martensitic steels
- Models of processing-microstructure-property relationships → could lead to alloys with excellent:
  - *High-temperature creep strength*
  - *Microstructural Stability*
  - *Resistance to Void Swelling*
  - *Retain properties on off-scale temperature variations*

Materials Challenges for SCWR (Cont'd)

- Two-track approach:
  - Experimental work.
    - Supercritical Water: high T, high P: expensive
    - Surrogate fluids: Supercritical CO_2
    - Actual coolant in some reactor concepts
    - Is relevant also to CCS
  - Computation and simulation.

Conclusion

- *SCWR most promising water-cooled reactor in Gen-IV concepts. Great potential increases in thermal efficiency, simplified BoP, and superior economics.*
- *CANDU-SCHWR envisaged as evolution trajectory of CANDU→ 2060*
- *CANDU-SCHWR: desalination, oil sands heat, NHP*
- *CANDU-SCHWR: materials challenges in SCW + irradiation + high T, high P; thermo-hydraulics; design & integration*
- *Address challenges by*
  - *Experiment*
  - *Simulation*
- *Effort already well under way. E.g., (Khartabil and Chow, 2007) present data on candidate materials for pressure tubes, insulators, cladding for alternative designs SCHWR. Irradiation data still required.*