SUPER-CRITICAL WATER-COOLED REACTORS

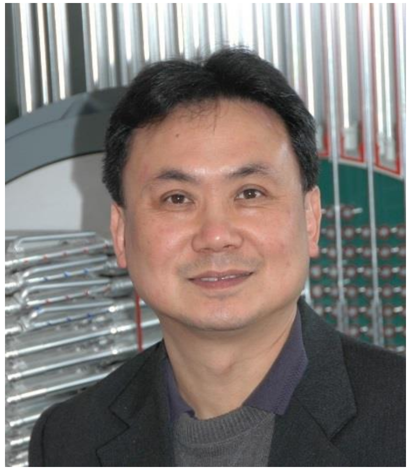
Laurence Leung

SCWR System Steering Committee

2017 March 28

Meet the presenter

Laurence Leung has been working at Canadian Nuclear Laboratories (formerly Chalk River Laboratories of Atomic Energy of Canada Limited) since 1987 in the field of thermal-hydraulics. He completed his Ph.D. degree at University of Ottawa, Canada, in 1994. Laurence is currently Manager of R&D Facilities Operations and is also responsible for the development of the Canadian Super-Critical Water-cooled Reactor (SCWR) concept. He received 13 awards from AECL (CNL) and external organizations, and delivered short courses on thermal-hydraulics and SCWRs. Laurence is one of Canada's representatives to the GIF SCWR System, and is the Co-Chair of the System Steering Committee and the Thermal-hydraulics and Safety Project Management Board.



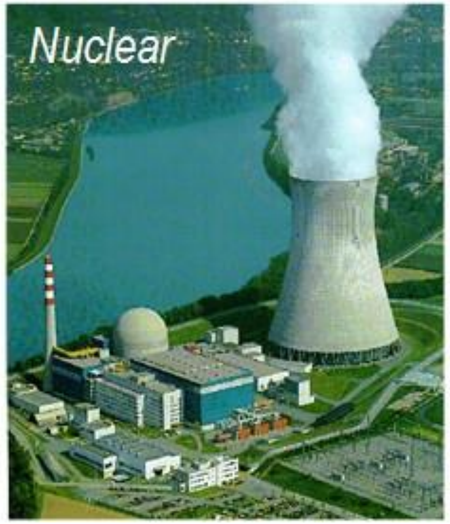
Email: Laurence.leung@cnl.ca

OUTLINE

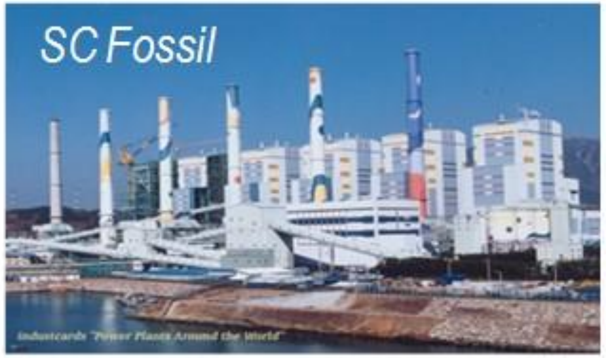
- Historical development
- System design/materials and fuels
- Specific applications
- Status
- Alignment to GIF Technical Goals
- Challenges
- Collaborations
- Summary

Why SCWR?

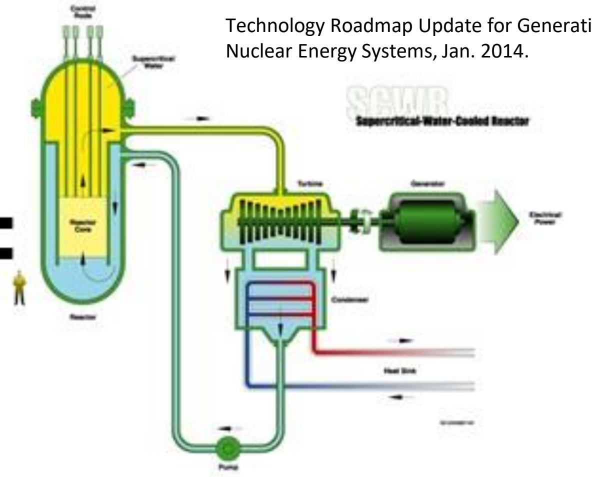
- Merging proven advanced technologies of nuclear and fossil-fuel power plants
- Many utilities operate both nuclear and supercritical fossil plants
- Many years of design and operating experiences



+



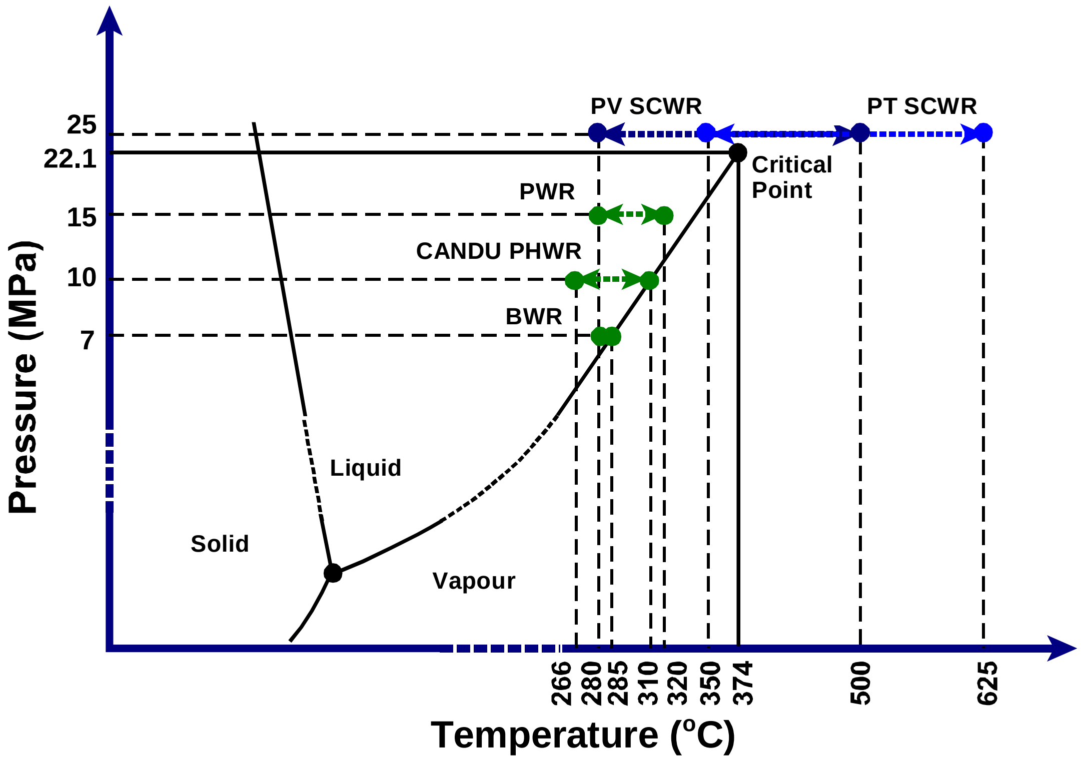
=



Technology Roadmap Update for Generation IV Nuclear Energy Systems, Jan. 2014.

SCWR Main Features

- High efficiency with supercritical pressures and temperatures at core outlet
  - Increasing the power output for the same fuel input (specific fuel utilization)
  - Reducing waste heat from turbines and condensers (environmental discharges)
  - Building fewer plants for meeting demand (capital and operating cost savings)
- Simplification of plant components and layout
  - Direct cycle eliminating heat exchangers, steam generators, steam dryers, and moisture separator reheaters
  - Reduction in capital and operational costs
- Design flexibility
  - Thermal or fast spectrum
  - Advanced fuel cycles and fuel design optimization
  - Reduction in electrical energy costs
  - Opportunities for co-generation



Historical Development

- Super-Critical Water-cooled Reactor (SCWR) concepts were studied during 1950s and 1960s
  - Westinghouse supercritical reactor
    - Thermal spectrum reactor of 70 MW_{th} for operation at pressure of 27.6 MPa and coolant outlet temperature of 538°C
  - Westinghouse supercritical once-through tube reactor (SCOTT-R)
    - Thermal spectrum reactor of 2300 MW_{th} for operation at pressure of 24.1 MPa and coolant outlet temperature of 566°C
  - General Electric Hanford supercritical reactor
    - Thermal spectrum reactor of 300 MW_{th} for operation at pressure of 37.9 MPa and coolant outlet temperature of 621°C
  - Babcock & Wilcox supercritical fast breeder reactor
    - Fast spectrum reactor of 2326 MW_{th} for operation at pressure of 25.3 MPa and coolant outlet temperature of 538°C
- Superheated steam reactors
  - Beloyarsk AMB-100 and AMB-200 reactors at ~510°C
  - Heissdampfreaktor at 457°C

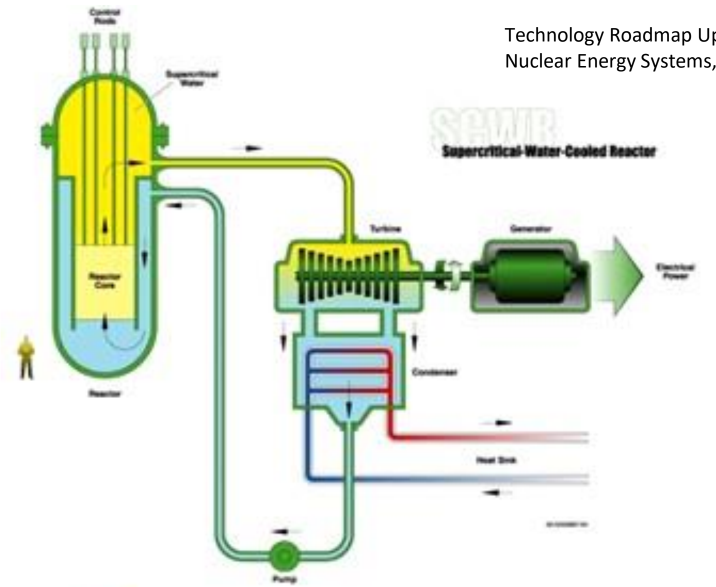
Renewed interest in 1990s

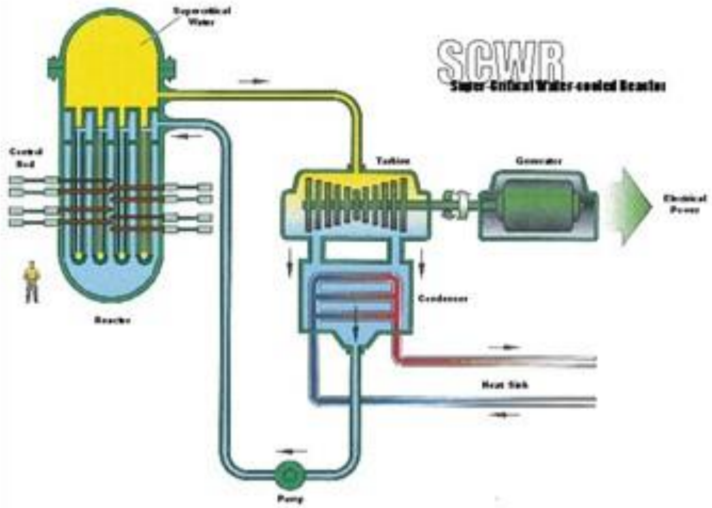
- Environmental concerns
  - Green-house gas emission
- Demand of stable energy supply
- Potential for cost reduction
  - Fuel cost is lower, but capital cost is higher, for nuclear than coal-fired power plants
  - Increase in steam temperature could simplify the nuclear system
- Advancement in boiler technology
  - Leverage development in the fossil-power industry reducing cost and risk
  - Net efficiency could reach ~50% at steam temperature of 700°C

SCWR Concept Development

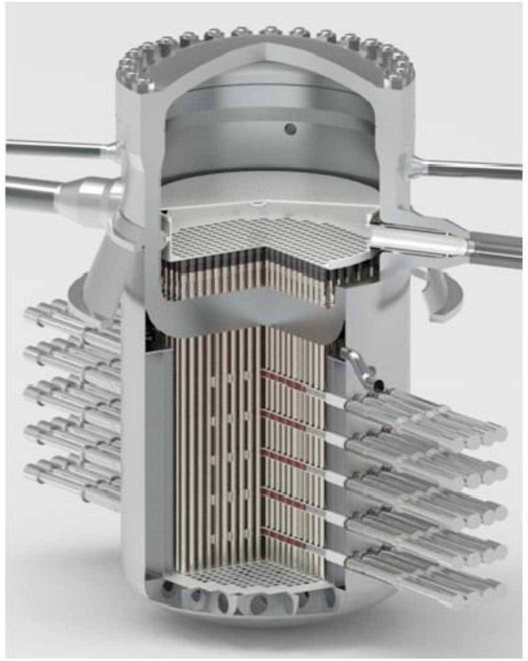
- Countries currently involve in SCWR concept development (GIF SCWR System Arrangement signatories)
  - Canada
  - China
  - EU
  - Japan
  - Russian Federation
- All concepts evolve from current fleet of nuclear reactors
  - Pressure-Vessel Type
    - Boiling-water reactors
    - Pressurized-water reactors
  - Pressure-Tube Type
    - Pressurized heavy-water reactors
- Most R&D is common
  - Opportunity to collaborate

Technology Roadmap Update for Generation IV Nuclear Energy Systems, Jan. 2014.

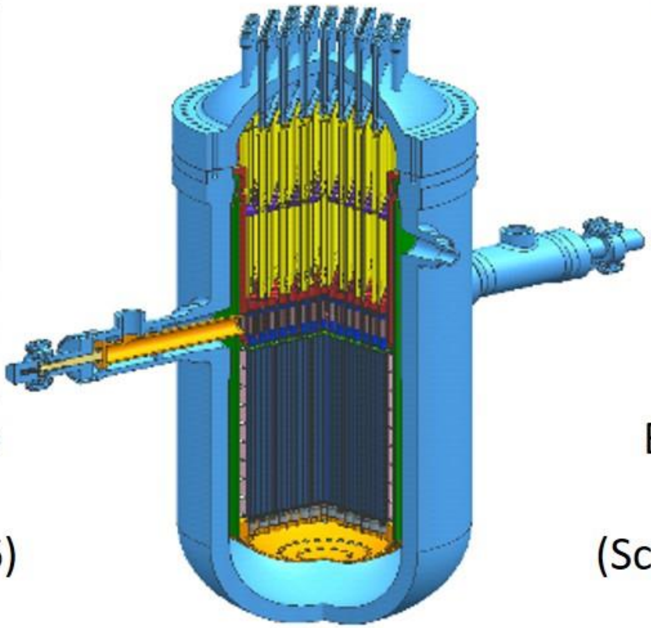




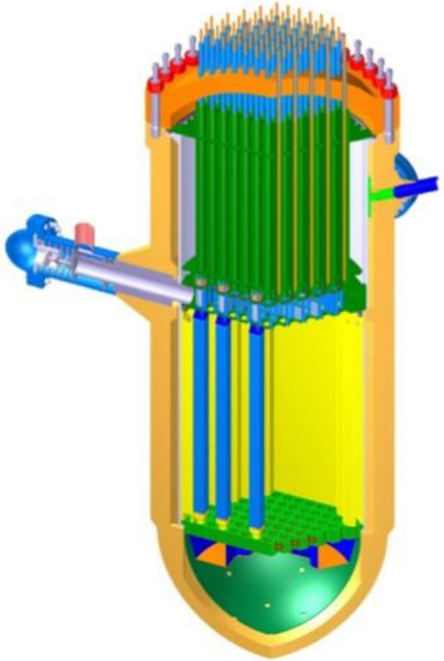
SCWR Core Concepts (Thermal Spectrum)



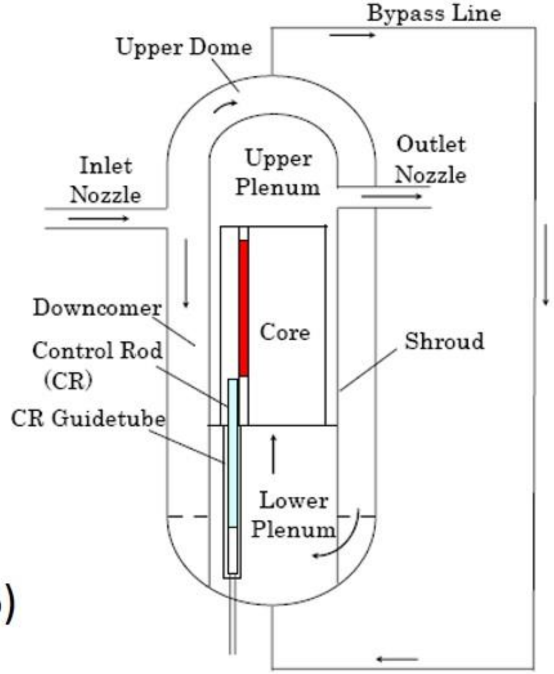
Canada's Pressure-Tube Type SCWR Core Concept (Schulenberg and Leung, 2016)



China's Pressure-Vessel Type SCWR Core Concept (IAEA, 2015)

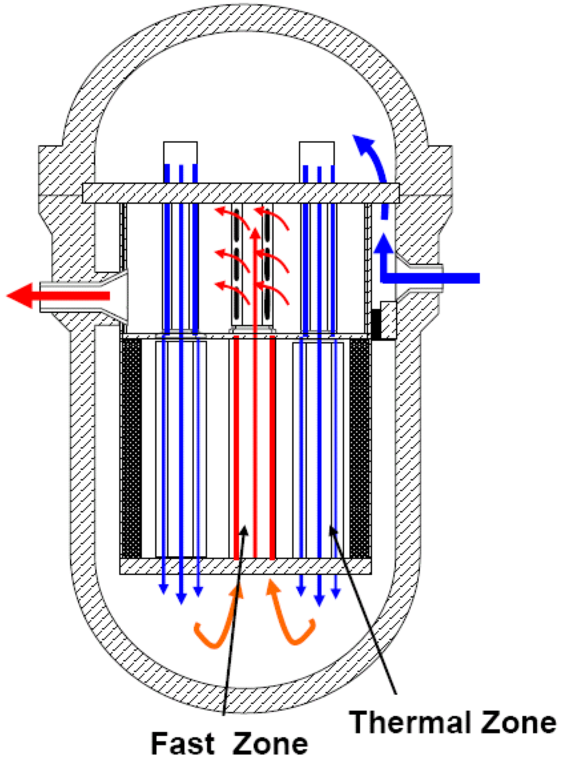


EU's Pressure-Vessel Type SCWR Core Concept (Schulenberg and Leung, 2016)

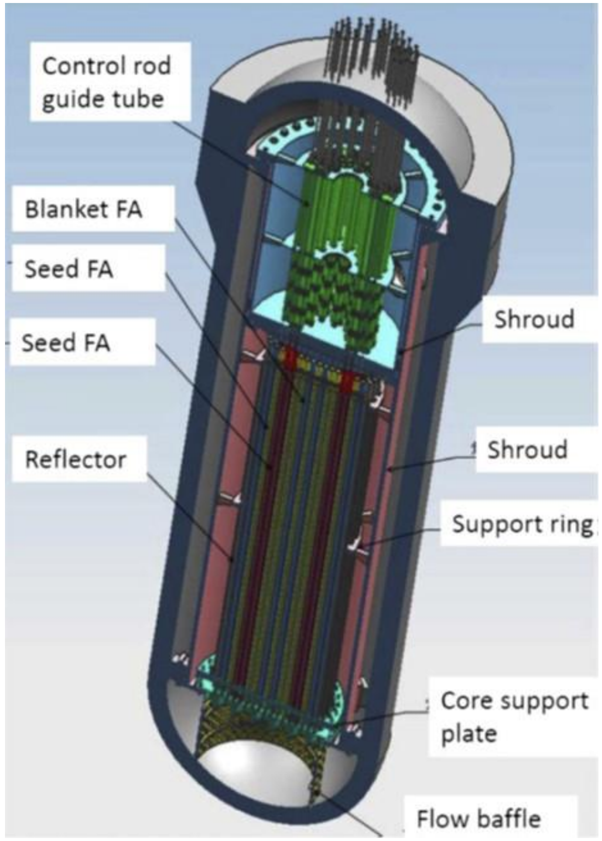


Japan's Pressure-Vessel Type SCWR Core Concept (Yamada et al., 2011)

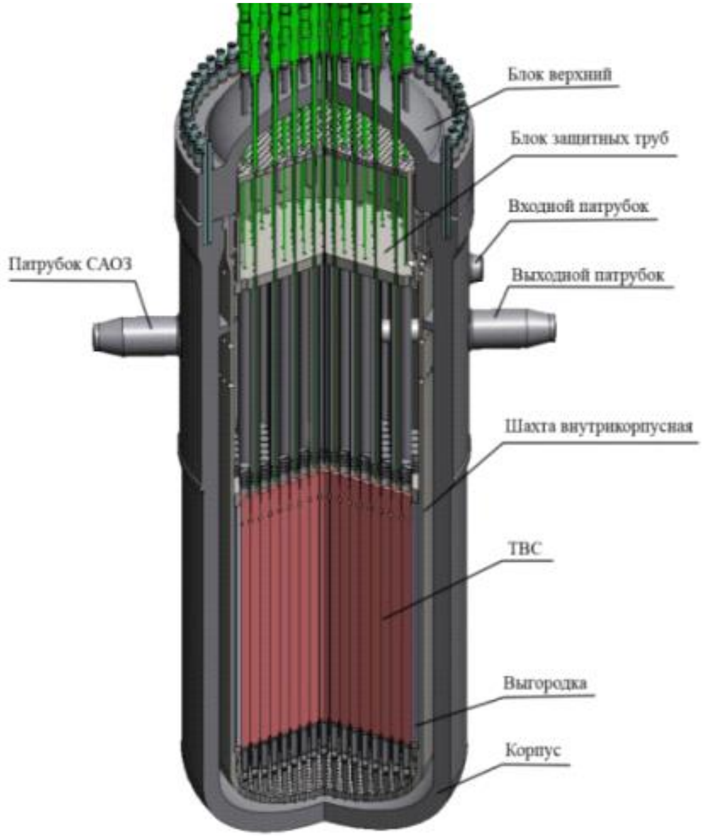
SCWR Core Concepts (Other Spectra)



China's Mixed-Spectrum SCWR Core Concept (Cheng et al., 2007)

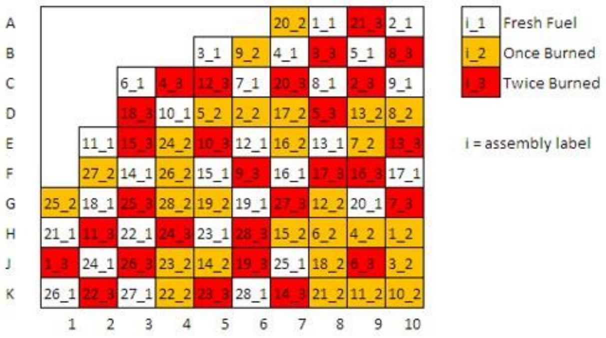


Japan's Fast-Spectrum SCWR Core Concept (Schulenberg et al., 2014)

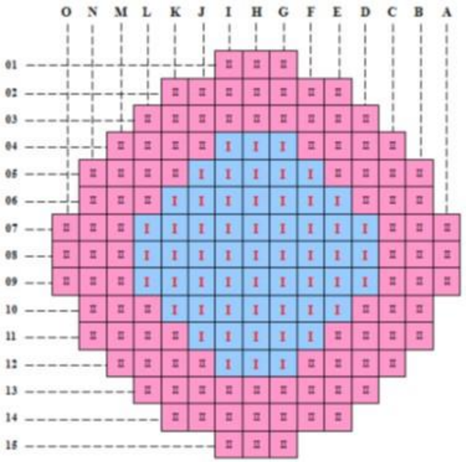


Russian Federation's Fast Spectrum SCWR Core Concept (Ryzhov et al., 2011)

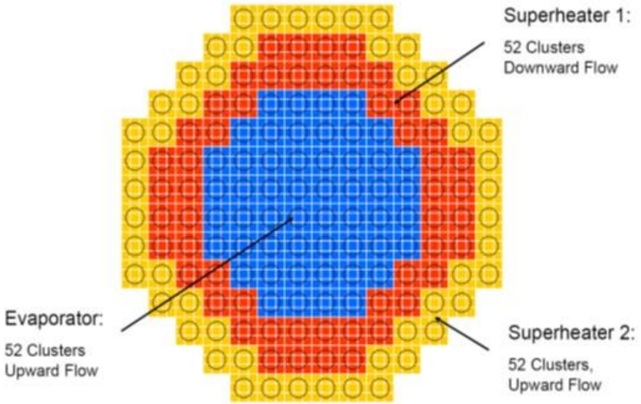
SCWR Core Maps



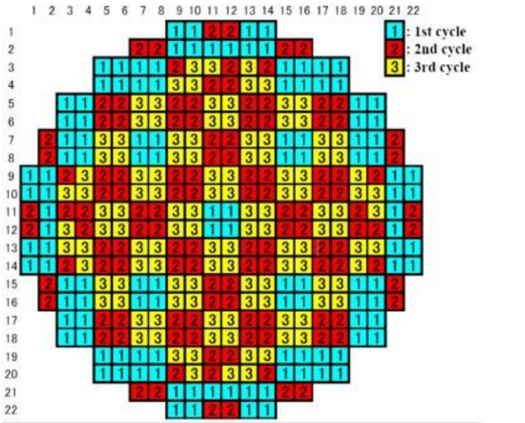
Canada's Thermal Spectrum SCWR Core Map (Pencer and Colton, 2013)



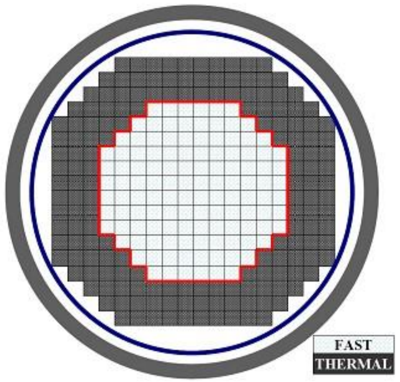
China's Thermal Spectrum SCWR Core Map (IAEA, 2015)



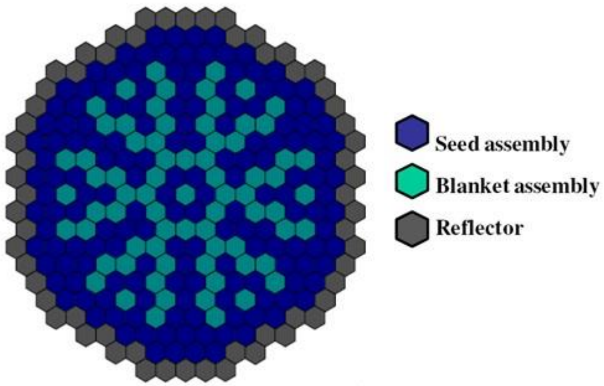
EU's Thermal Spectrum SCWR Core Map (Schulenberg and Leung, 2016)



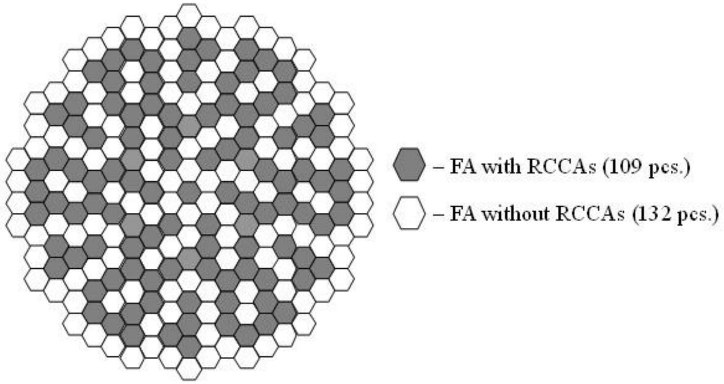
Japan's Thermal Spectrum SCWR Core Map (Yamada et al., 2011)



China's Mixed-Spectrum SCWR Core Map (Cheng et al., 2007)

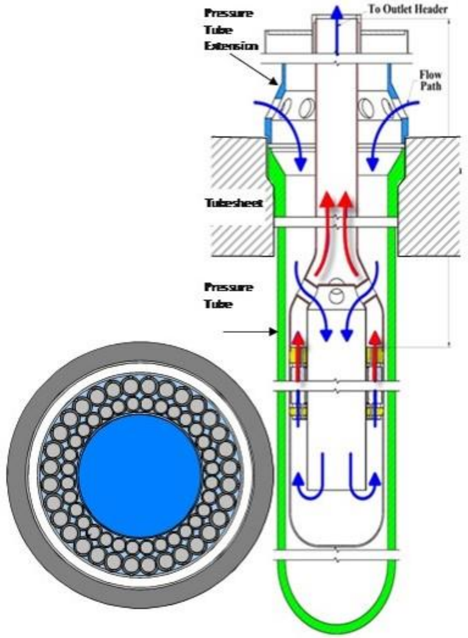


Japan's Fast Spectrum SCWR Core Map (Nakatsuka et al., 2010)

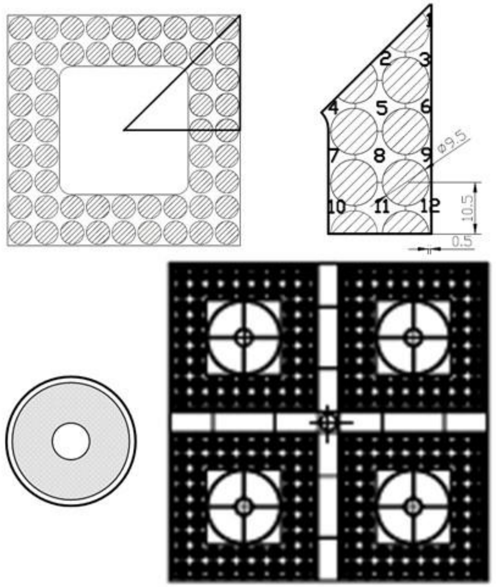


Russian Federation's Fast Spectrum SCWR Core Map (Ryzhov et al., 2011)

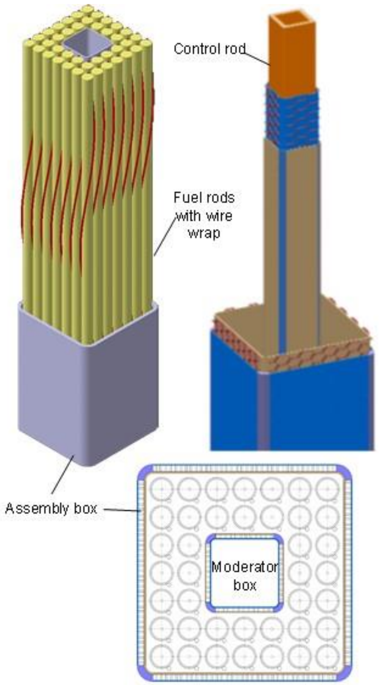
SCWR Fuel Concepts (Thermal Spectrum)



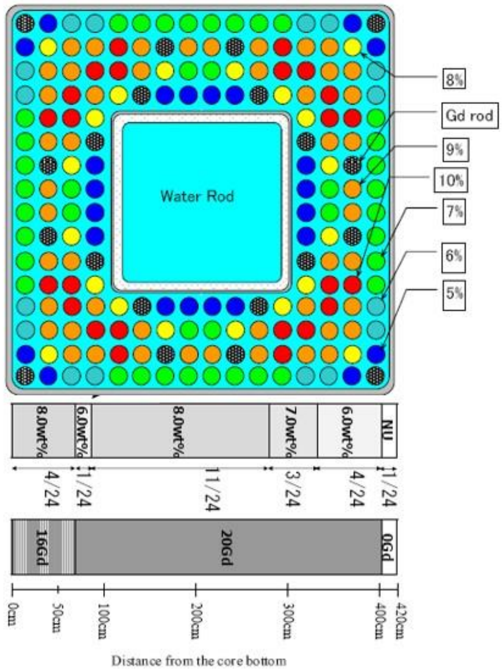
Canada's Pressure-Tube Type SCWR Fuel Concept (Schulenberg and Leung, 2016)



China's Pressure-Vessel Type SCWR Fuel Concept (IAEA, 2015)

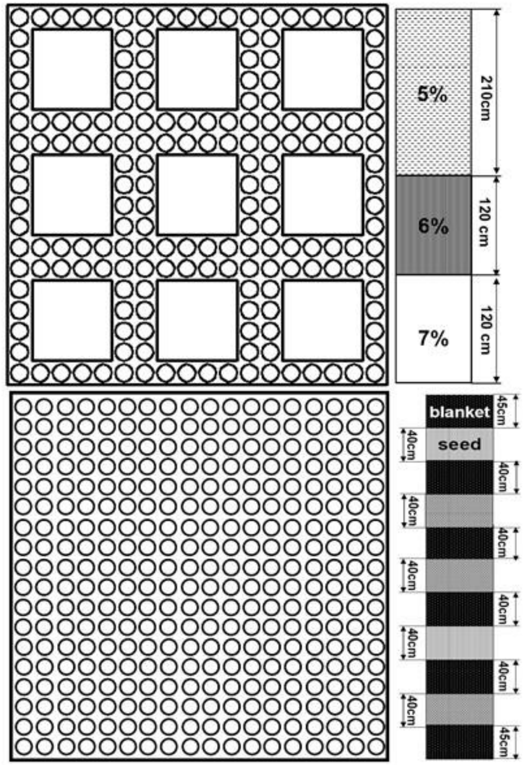


EU's Pressure-Vessel Type SCWR Fuel Concept (Schulenberg and Leung, 2016)

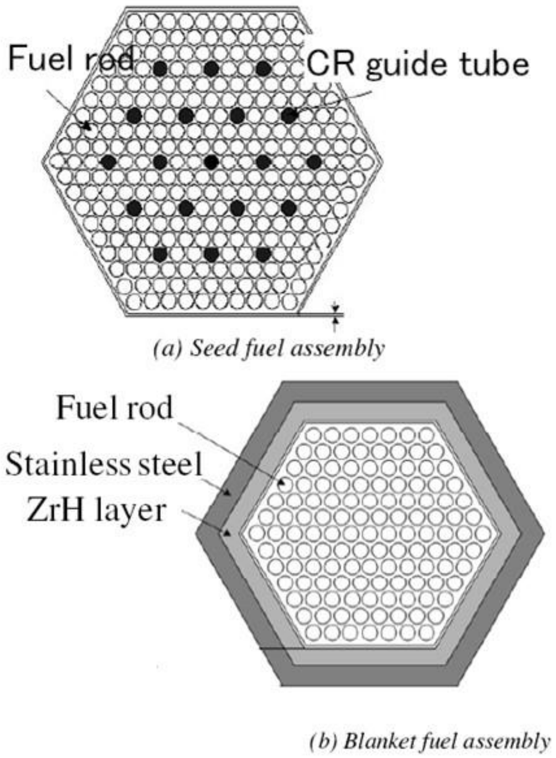


Japan's Pressure-Vessel Type SCWR Fuel Concept (Sakurai et al., 2011)

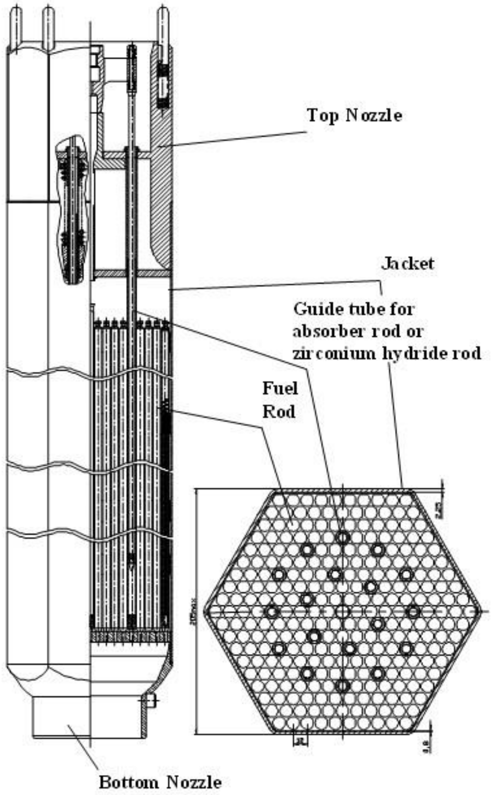
SCWR Fuel Concepts (Other Spectra)



China's Mixed Spectrum SCWR Fuel Concept (Cheng et al., 2007)

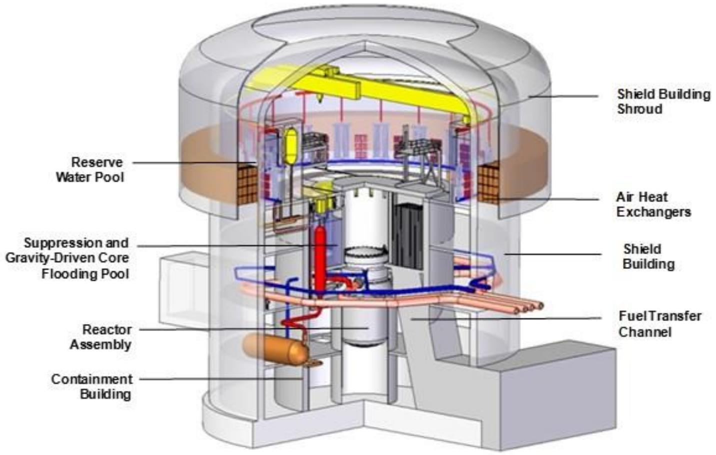


Japan's Fast Spectrum SCWR Fuel Concept (Nakatsuka et al., 2010)

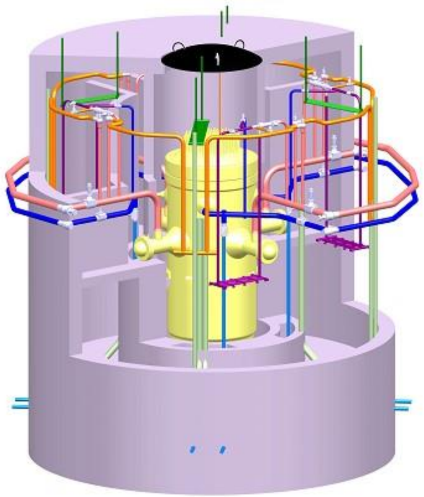


Russian Federation's Fast Spectrum SCWR Fuel Concept (Ryzhov et al., 2011)

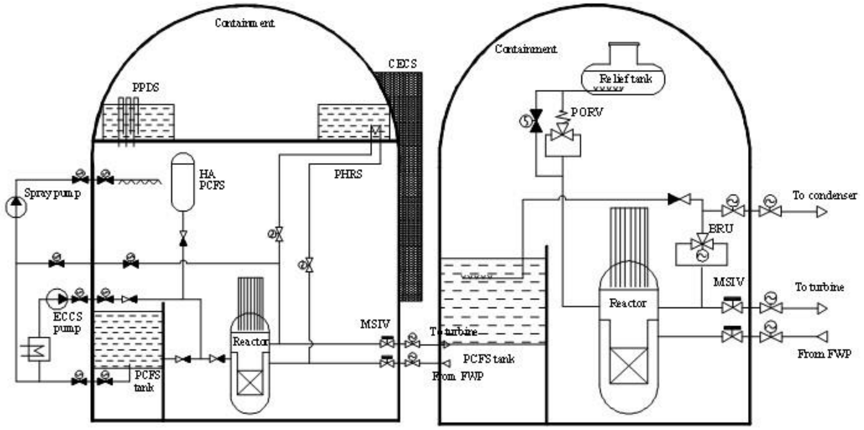
SCWR Safety System Concepts



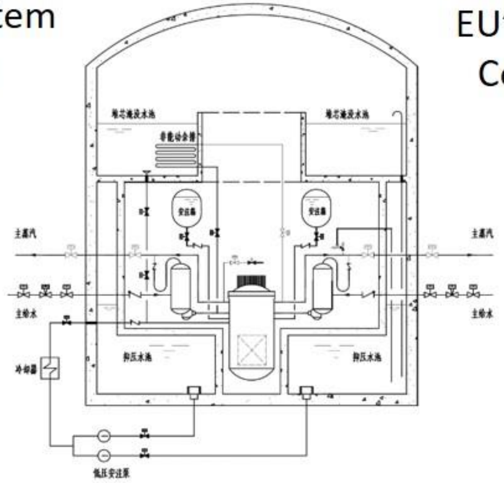
Canada's SCWR Safety System Concept (Schulenberg and Leung, 2016)



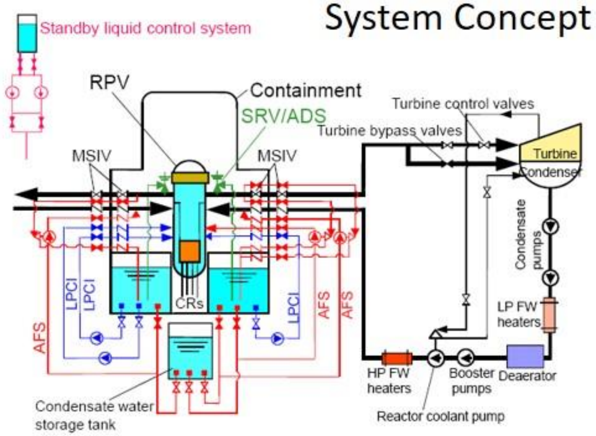
EU's SCWR Safety System Concept (Schulenberg and Leung, 2016)



Russian Federation's SCWR Safety System Concept (Ryzhov et al., 2011)

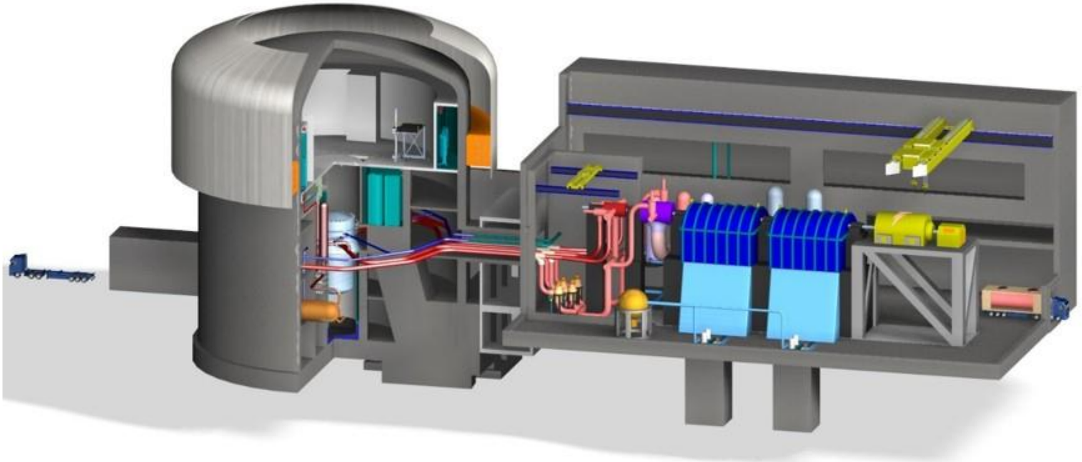


China's SCWR Safety System Concept (IAEA, 2015)

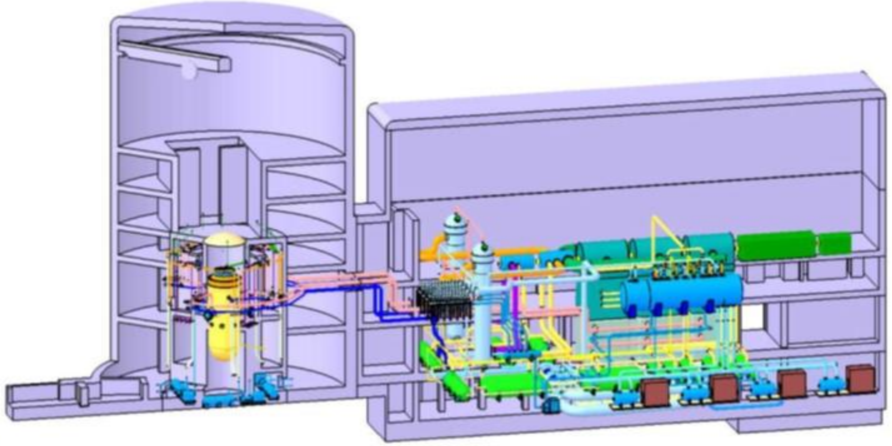


Japan's SCWR Safety System Concept (Ishiwatari et al., 2011)

SCWR Plant Concepts



Canada's SCWR Plant Concept
(Schulenberg and Leung, 2016)



EU's SCWR Plant Concept
(Schulenberg and Leung, 2016)

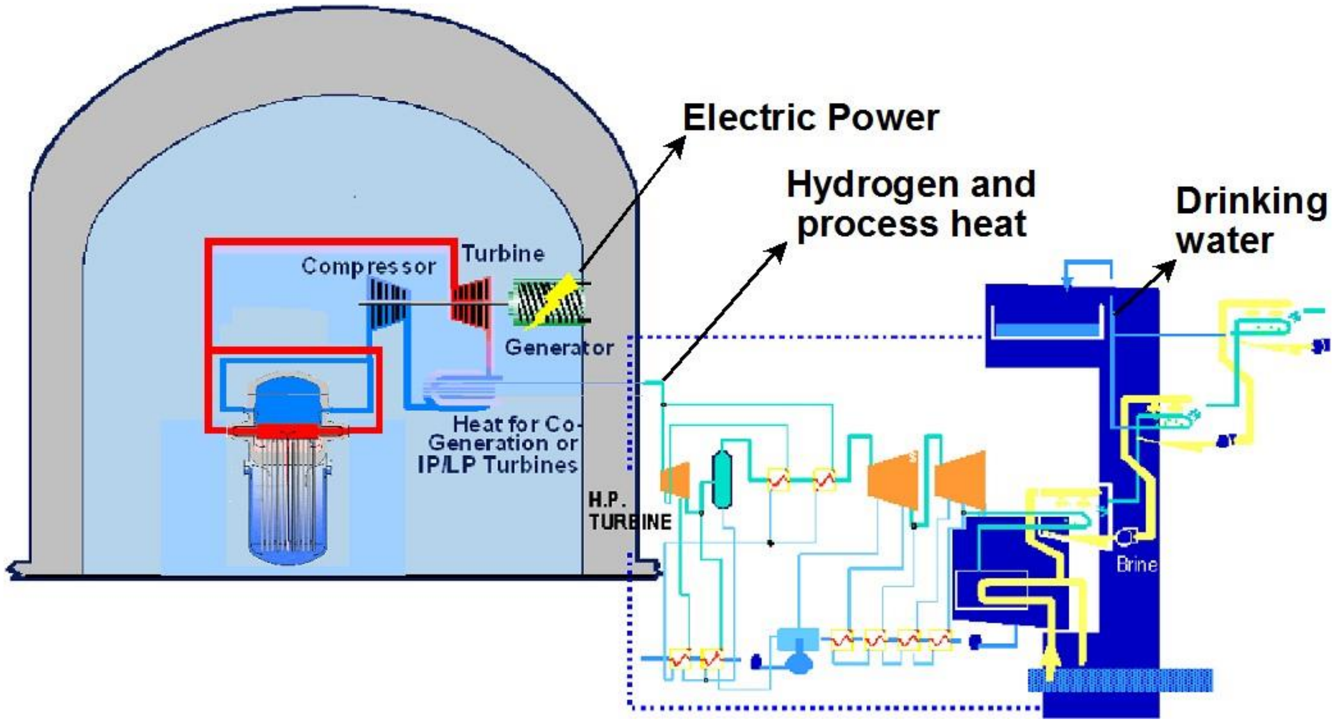
Japan's SCWR Plant Concept
(Yamada et al., 2011)

Key SCWR Parameters

	Canada	China		EU	Japan		Russian Federation
Type	PT	PV	PV	PV	PV	PV	PV
Spectrum	Thermal	Thermal	Mixed	Thermal	Thermal	Fast	Fast
Pressure (MPa)	25	25	25	25	25	25	24.5
Inlet Temp. (°C)	350	280	280	280	290	280	290
Outlet Temp. (°C)	625	500	510	500	560	501	540
Thermal Power (MW)	2540	2300	3800	2300	3794	1602	3830
Efficiency	48	43	44	43.5	46	44	45
Active Core Height (m)	5	3	4.5	4.2	4.2	2.4	4.07
Fuel	Pu-Th (UO_2)	UO_2	UO_2/MOX	UO_2	UO_2	MOX	MOX
Moderator	D_2O	H_2O	H_2O/-	H_2O	H_2O	-/ZrH	-
# of Flow Passes	1	2	2	3	1/2	1/2	1/2

SCWR Applications

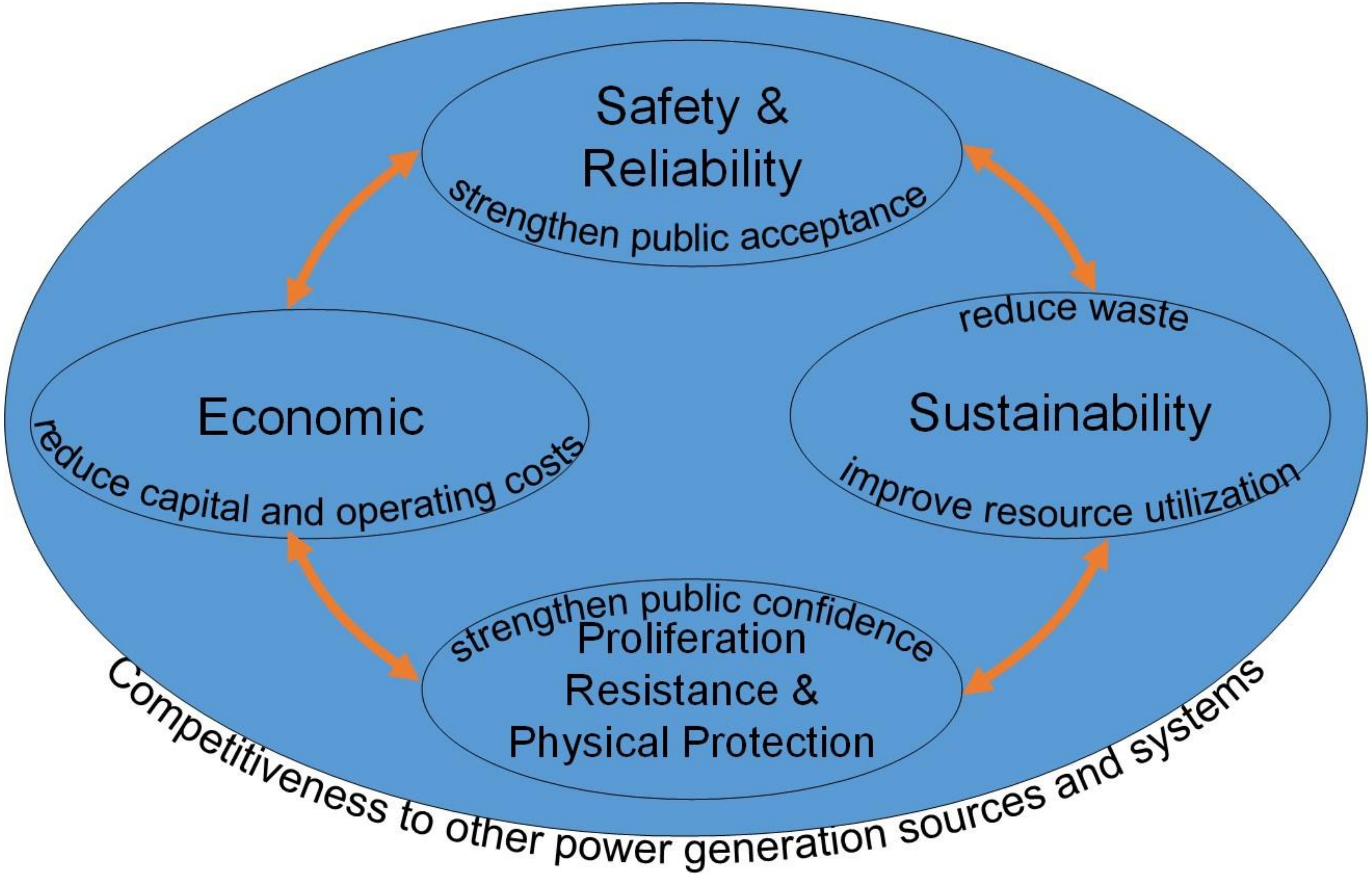
- Primarily for electric power generation
- Heat can be extracted for co-generation
  - Hydrogen production
  - Oil extraction (Steam-Assisted Gravity Drainage process)
  - Desalination
  - Process heat



SCWR Concept Development Status

- Canada, EU and Japan have completed the development of their concepts
  - International peers reviewed the concept and assessed viability
  - R&D to improve confidence on the developed concepts
- China and Russian Federation are working on completing of their concepts
  - China plans to host the review of their concept with international peers
- Preparation of a fuel irradiation test
  - Acquire design and licensing experience of in-reactor supercritical water system
  - Obtain in-reactor data on fuel, cladding material and thermal-hydraulics at supercritical pressures to improve understanding and for code validation
- Development of small SCWR concepts
  - Other than Japan's Super Fast Reactor, all SCWR concepts have been developed to generate electric powers at or greater than 1000 MW
  - Small remote communities require much less power
  - Adjustment of SCWR core size to meet local deployment needs (e.g., 10 to 300 MWe)

GIF Technology Goals

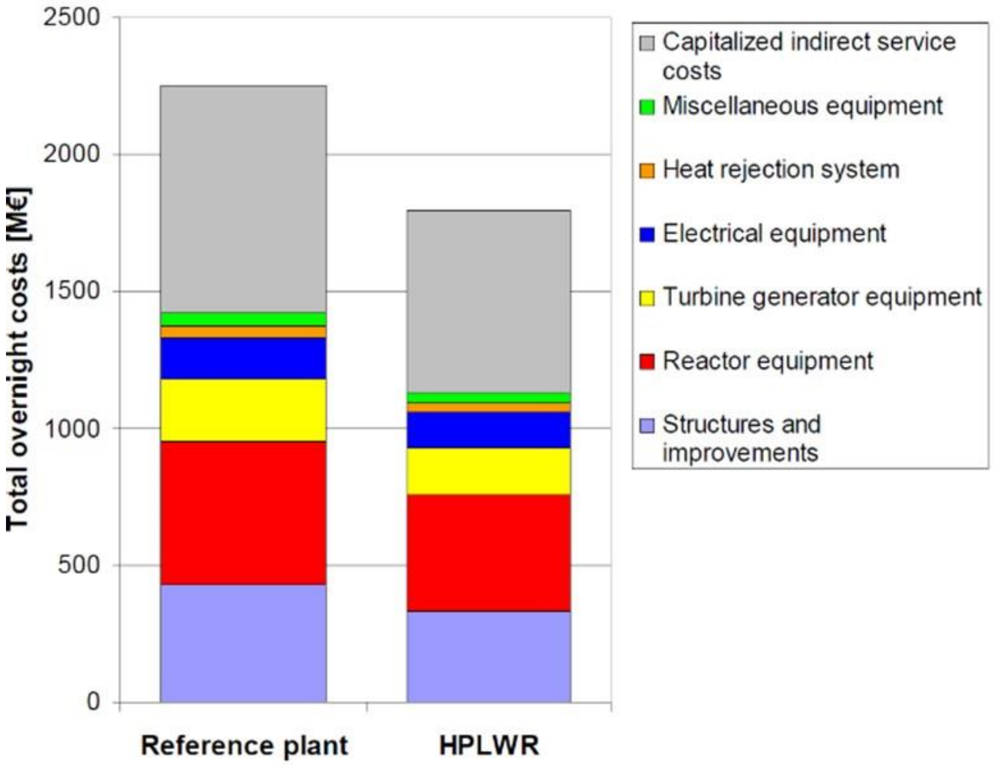


Economics

- GIF Economic Goals for Gen IV Systems
  - Have a life cycle cost advantage over other energy sources (i.e., lower levelized unit cost of energy on average over the lifetime)
  - Have a level of financial risk comparable to other energy projects (i.e., similar total capital investment and capital at risk)
- Cost Components
  - Capital, fuel, operation and maintenance costs
- Cost Evaluation
  - Total Capital Investment Cost (TCIC)
    - Overnight Capital Cost plus interest during construction
  - Levelized Unit Electricity Cost (LUEC)
  - Generally, there is a high degree of uncertainty surrounding economic estimates for advanced reactor concepts
- Efficiency Improvement
  - Fewer plants are needed to meet demand (i.e., capital and operating cost savings)

Pressure-Vessel-Type SCWR Economics

- Capital cost of the EU SCWR concept (HPLWR) has been assessed against that of an Advanced Boiling-Water Reactor
- GIF economic assessment guidelines were applied
- Total overnight cost for the HPLWR is about 20% lower
- Sensitivity of capital and fuel costs on electricity generation cost were analyzed
  - Capital-cost variation affects the electricity generation cost over a short term but its effect diminishes with time
  - Fuel-cost variation affects the electricity generation cost over the depreciation period and the difference is reduced with time



Schulenberg and Starflinger, 2012.

Pressure-Tube-Type SCWR Economics

- Compared to Advanced Boiling-Water Reactor proposed for the Tennessee Valley Authority Bellefonte Site
  - Cost information presented in 2005
- GIF economic modelling tool was applied
  - Including uncertainty
- Canadian SCWR
  - Comparable Total Capital Investment Cost (TCIC)
  - Higher Levelized Unit Electricity Cost (LUEC) due to higher fuel cost
  - Uncertainties are higher
- Economics could be improved if SCWR is used
  - as a burner for excess Plutonium
  - as a high-temperature heat source for co-generation

Reactor technology	TCIC ($/kWe)	Currency	In 2014 US$[a]
Canadian SCWR concept	3863	2007 US$	4411
Reference ABWR	3610	2007 US$	4122
AP 1000 regulatory filing estimate [13]	4210	2010 US$	4571
AP 1000 estimate[16]	4400	2011 US$	4632
Summer AP 1000 installation [17]	4675	2014 US$	4675
Vogtle AP 1000 installation [18]	3072	2014 US$	3072

[a]Escalation based on average annual consumer price index.

Reactor technology	LUEC ($/MWh)	Currency	In 2014 US$[a]
Canadian SCWR concept	51.40	2007 US$	58.69
Reference ABWR	38.78	2007 US$	44.44
Darlington (post-refurbishment) [19]	79.00	2013 CAN$	80.29
World Nuclear Association—OECD Europe [20]	50.00–82.00	2010 US$	54.29–89.04
World Nuclear Association—USA [20]	49.00	2010 US$	53.21
World Energy Council [21]	91.00–147.00	2012 US$	93.80–151.60

[a]Escalation based on average annual consumer price index.

Moore et al., 2016. (quoted references cited in original paper)

Safety and Reliability

- GIF Safety and Reliability Goals for Gen IV Systems
  - Excel in safety and reliability
  - Have a very low likelihood and degree of reactor core damage
  - Eliminate the need for offsite emergency response
- Integrated Safety Assessment Methodology
  - Applicable tools depending on the maturity of the design
    - Qualitative Safety-features Review (QSR)
    - Phenomena Identification & Ranking Tables (PIRT)
    - Objective Provision Tree (OPT)
    - Probabilistic Safety Assessment (PSA)
    - Deterministic and Phenomenological Analysis (DPA)

SCWR Safety and Reliability Characteristics

- Similar to current fleet of reactors
  - Pressure-vessel type SCWRs to pressurized or boiling water reactors (PWRs or BWRs)
  - Pressure-tube type SCWRs to pressurized heavy-water reactors (PHWRs) or BWRs (direct cycle)
- Safety requirements
  - Current fleet of reactors focus on maintaining coolant inventory in the core of PWRs and PHWRs or the reactor vessel of BWRs
  - SCWRs focus on maintaining coolant flow rate through the core

Pressure-Vessel-Type SCWR Safety and Reliability

- Safety analysis of Japan's Super LWR (Oka et al., 2010)
  - Deterministic analyses covering key postulated accident scenarios
    - 15% break of the loss of coolant accident is the limiting event
      - Predicted peak cladding temperature of ~1000°C (350°C above the steady-state value).
  - Simplified Probabilistic Safety Analysis
    - Core Damage Frequency is 5.1E-7 for Large-Break Loss-of-Coolant Accident
- Safety analysis of EU's HPLWR (Schulenberg and Starflinger, 2012)
  - Deterministic analyses covering selected postulated accident scenarios
    - Total loss of feedwater is the limiting event
      - Predicted peak cladding temperature of 910°C
    - Passive safety systems to enhance safety characteristic

Pressure-Tube-Type SCWR Safety and Reliability

- Qualitative Safety-features Review (QSR)
  - Five levels of defence-in-depth provisions assessed
- Phenomena Identification & Ranking Tables (PIRT)
  - 30 knowledge gaps identified; mainly related to new material (ceramic insulator) in the core
- Deterministic analyses covering key postulated accident scenarios
  - Coupled loss-of-coolant with loss of emergency core cooling accident is the most limiting cladding-temperature event
    - Peak cladding temperature at 1175°C
- Simplified Probabilistic Safety Analysis
  - Probability of core damage is at least one order of magnitude lower than other reactor systems

Status of Knowledge	Rank of Importance			
	H	M	L	I
4	3	2	1	10
3	67	37	4	242
2	25 (gap)	1 (gap)	8	21
1	4 (gap)	0 (gap)	0 (gap)	3

Outcome	Postulated Accident Scenario		
	Small-Break LOCA	Large-Break LOCA	Loss of Class-IV Power
No Core Damage	1.00×10^{-2}	1.00×10^{-4}	1.00×10^{-2}
Limited Core Damage	1.00×10^{-6}		2.10×10^{-8}
Core Damage	4.06×10^{-9}	4.06×10^{-11}	1.34×10^{-10}

Sustainability

- GIF Sustainability Goals for Gen IV Systems
  - Generate energy sustainably and promote long-term availability of nuclear fuel
  - Minimise nuclear waste and reduce the long term stewardship burden
- Assessment methodology
  - GIF has not established a common methodology for assessment at this point
- Nuclear energy
  - One of the lowest sources of green house gases (20 to 30 times less than fossil fuel sources including natural gas).

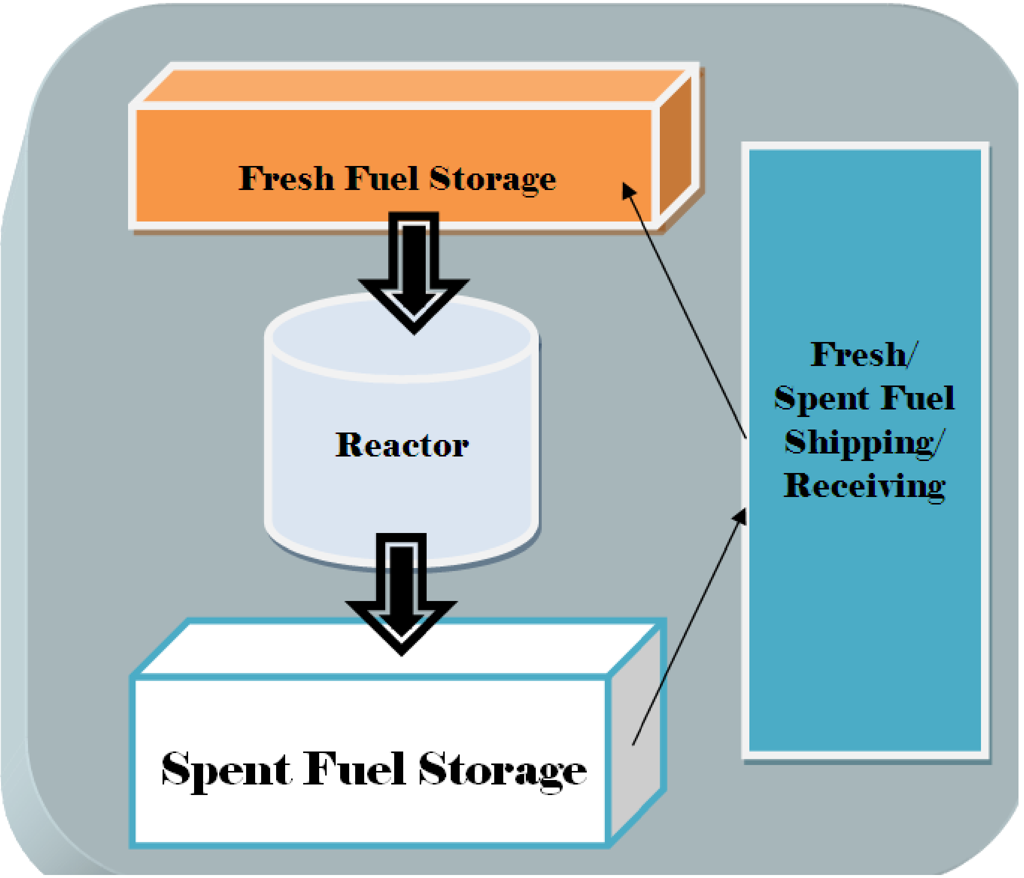
- Sustainability Metrics
  - Meets clean air objectives,
  - Promotes long-term availability of systems,
  - Promotes effective fuel utilization
  - Minimizes and manages nuclear waste,
  - Reduces the long-term stewardship burden of nuclear waste, and
  - Improves protection for the public health and the environment.

SCWR Sustainability Characteristics

- Efficiency improvement
  - Increasing the power output for the same fuel input
  - Reducing waste heat from turbines and condensers
  - Promotes effective fuel utilization, minimization of nuclear waste, long-term availability of systems and environmental protection
- Implementation of advanced thorium fuel cycle
  - Improved sustainability (thorium is more abundant than uranium in the world)
  - Use of plutonium / thorium fuel extends natural uranium resources (no additional uranium needed).
  - Use of thorium fuel produces future usable fissile inventory of U-233
  - Lower short-term gamma of used nuclear fuel
  - Reduction in the amount and the decay power of high level waste

Proliferation Resistance and Physical Protection

- GIF Proliferation Resistance and Physical Protection Goal for Gen IV Systems
  - Be a very unattractive route for diversion or theft of weapon-usable materials, and provide increased physical protection against acts of terrorism
- GIF Proliferation Resistance and Physical Protection Evaluation Methodology
  - Proliferation Resistance measures
  - Physical Protection measures

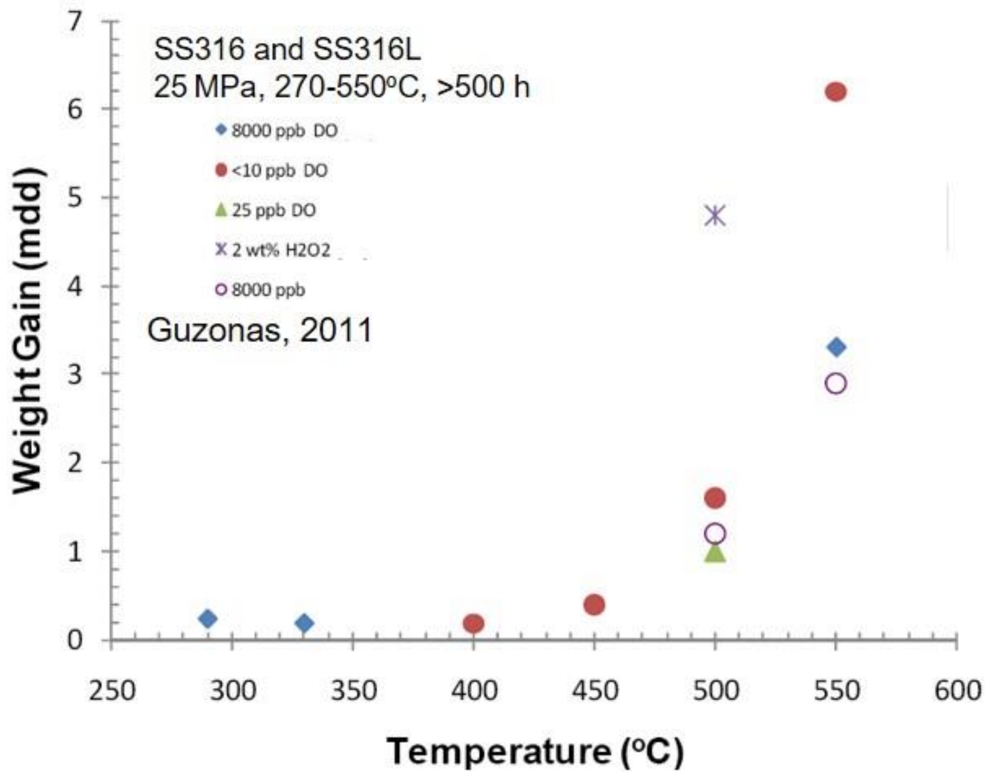


SCWR Proliferation Resistance and Physical Protection

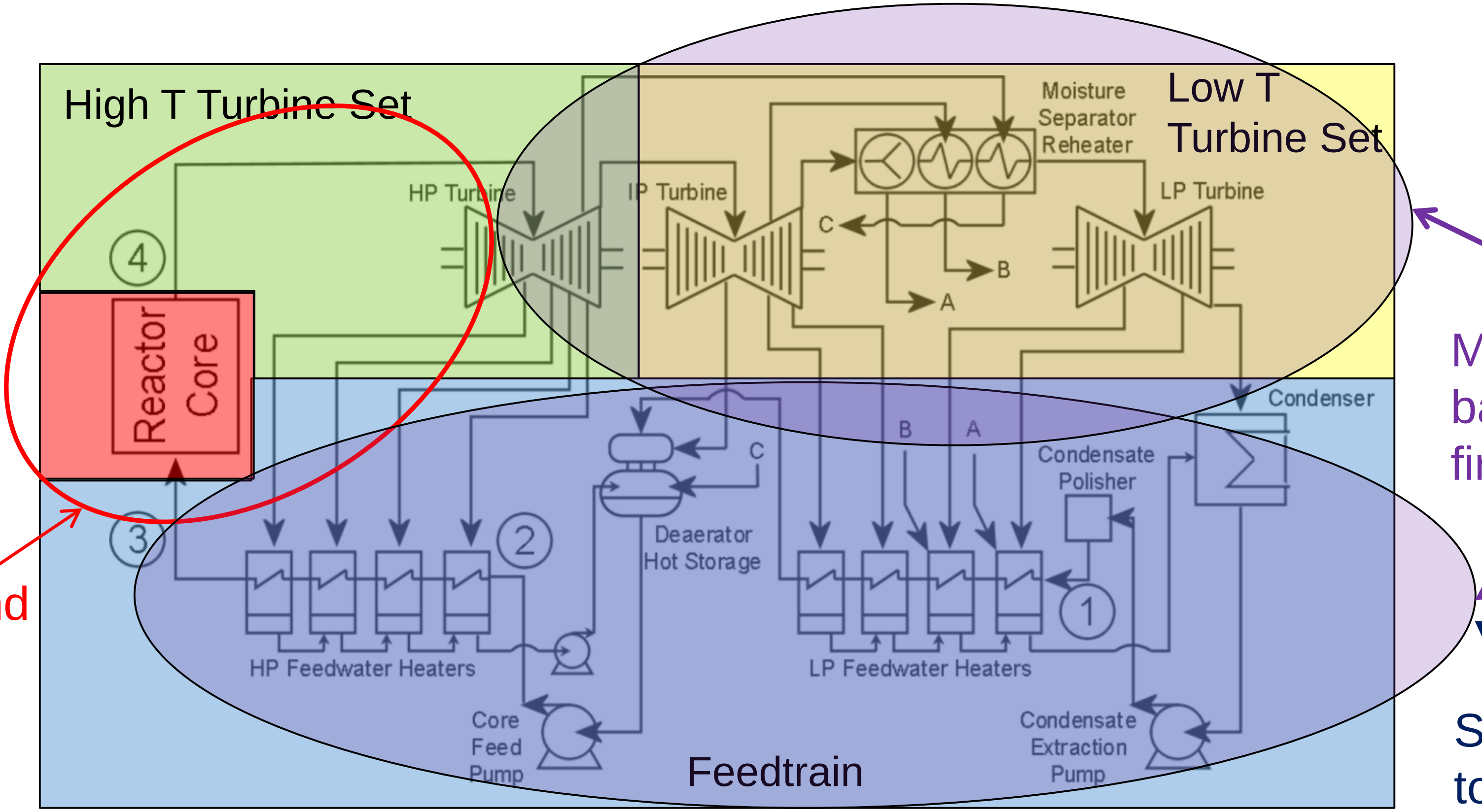
- Main Threats Identified
  - Proliferation Resistance Threats:
    - Diversion of fresh and/or spent fuel
    - Concealed production (misuse)
  - Physical Protection Threat:
    - Sabotage attempts to cause radiological release
- SCWRs have smaller footprint
  - Enhanced opportunities for physical protection
- Most concepts are based on "familiar" technology, from an international safeguards viewpoint:
  - Thermal spectrum
  - Batch-fuelled
  - Solid fuel
  - Light-water coolant
- Implementation of advanced thorium fuel cycle
  - Thorium is fertile, not fissile
  - Lower Plutonium production
  - Production of U-233 and U-238
    - Difficult to separate
  - Spent fuel contains deep-burn Plutonium and U-233 mixed with U-232
  - High level of radioactivity of the spent fuel
    - A large barrier to diversion of the spent fuel assemblies

SCWR Design Challenges: Materials

- In-core (except cladding) and out-of-core components
  - No single alloy with sufficient information to confirm its performance
  - Based on materials used in current fleet of reactors and fossil-fired power plants
  - Different acceptance requirements on corrosion for nuclear power plants
  - Need thermal and corrosion-resistant barrier
- Cladding
  - Zirconium-based alloys are not viable material
  - Stainless steel or nickel-based alloys are potential candidates
  - Demonstrate performance in key areas: Corrosion and stress corrosion cracking; strength, embrittlement and creep resistance; and dimensional and microstructural stability
  - Quantify irradiation effect
- Challenges
  - Testing at high pressures and high temperatures
  - Irradiation effect



Overview of SCWR Materials Selection



Outside the bound of current OPEX

Materials selection can be based on BWR and fossil-fired SCW plant OPEX

Some optimization needed to minimize impurity transport to the core

Ranking of Cladding Material Candidates

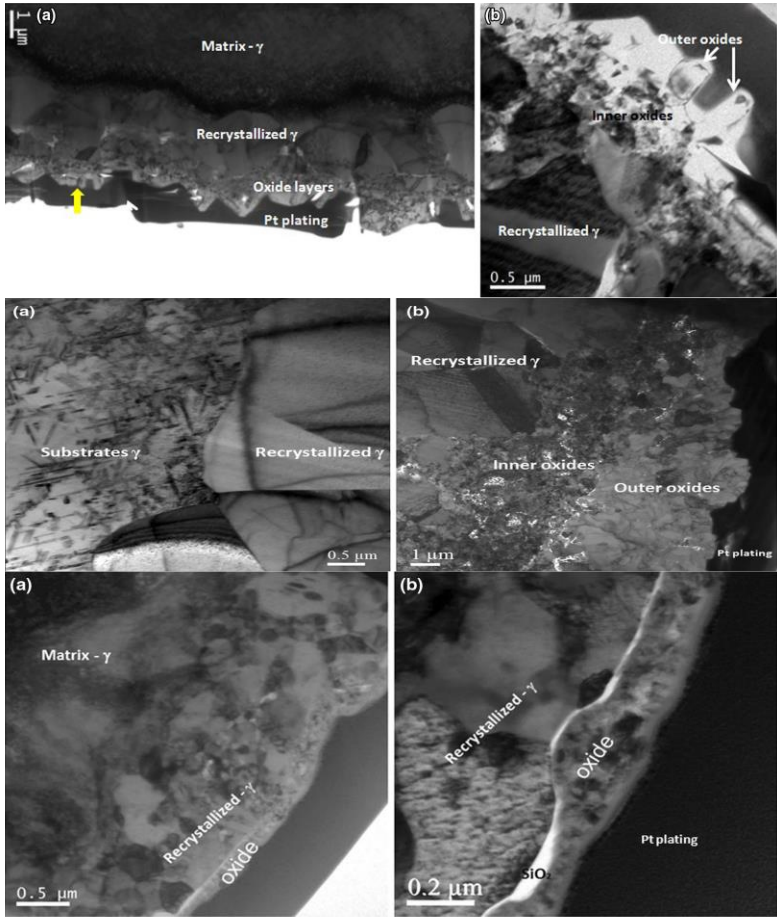
Alloy	Property							
	Corrosion	Oxide Thickness	SCC (un-irradiated)	IASCC	Creep	Void Swelling	Ductility (4% elongation)	Strength
800H								
310S								
625								
347								
214								

- GREEN – Available data suggest that this alloy meets the performance criteria under all conditions expected in the core
- YELLOW – Some (or all) available data suggest that this alloy may not meet the performance criteria under some conditions expected in the core
- RED - Some (or all) available data suggest that this alloy will not meet the performance criteria under some conditions expected in the core
- GREY – There are insufficient data to make even an informed guess as to the behavior in an SCWR core

(Guzonas et al., 2015)

Corrosion Tests at Low, Medium and Supercritical Pressures

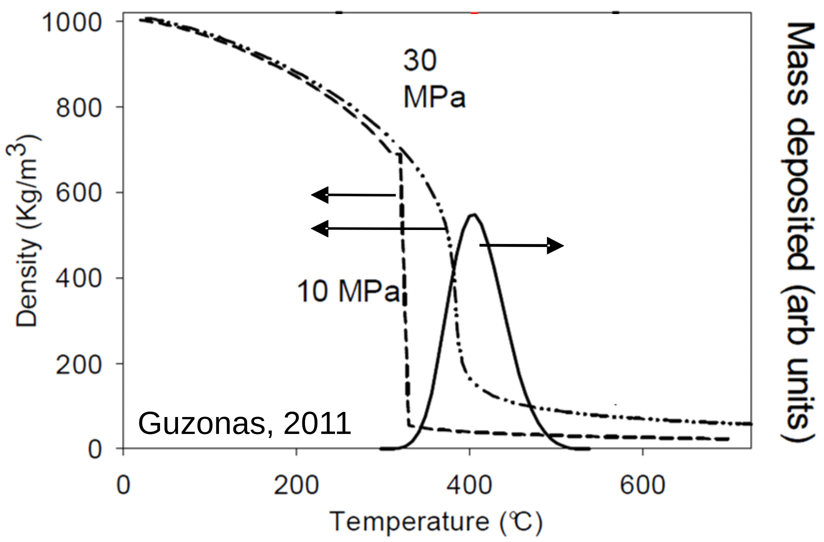
- Corrosion tests of austenitic stainless steels (SS) 310, 304, and Ni and Fe based A286
- Pressures of 0.1 MPa, 8 MPa, and 29 MPa at 625 ^{o}C for 1000 hours
- A single-layer oxide formed at 0.1 MPa and dual-layer oxides at 8 MPa and 29 MPa, followed by a Cr depleted region into the austenite substrate
  - Compositions of the inner oxides at 8 MPa and 29 MPa are Cr rich
  - Similar to those of the single-layer oxides at 0.1 MPa exposures
- Corrosion testing results in superheated steam agree qualitatively with those expected at 25 MPa
- Superheated steam at 0.1 MPa is a suitable surrogate for SCW corrosion testing



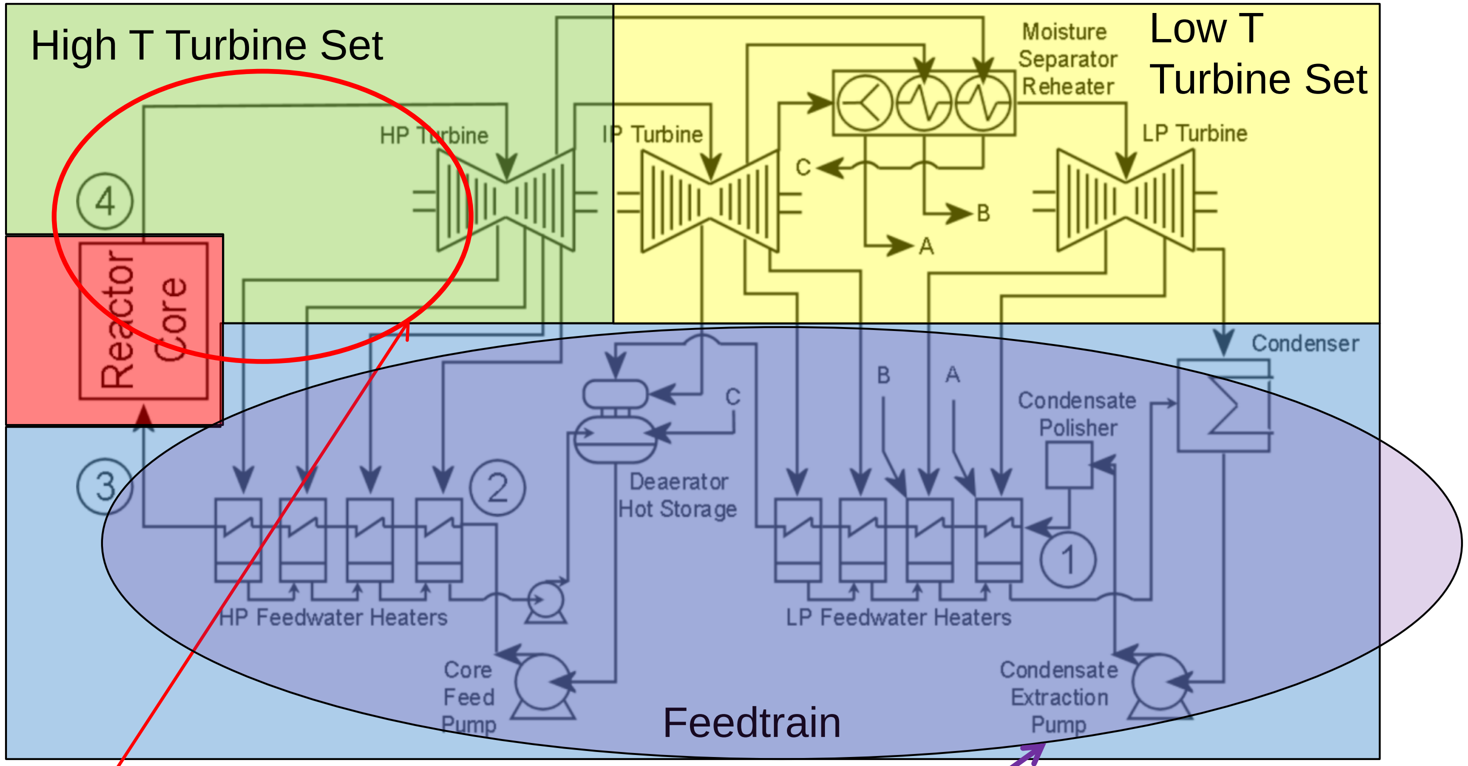
Li et al., 2015

SCWR Design Challenges: Chemistry

- Changes in chemical properties due to marked change in SCW density through the critical point
- SCWR In-core radiolysis is markedly different from those of conventional water-cooled reactors
  - Extrapolation of the behavior is inappropriate
  - Strong impact on corrosion and stress corrosion cracking
- Identification of an appropriate water chemistry to minimize
  - Corrosion rates
  - Stress corrosion cracking
  - Deposition of deposits on fuel cladding and turbine blades
- Establish a chemistry-control strategy



Chemistry Control

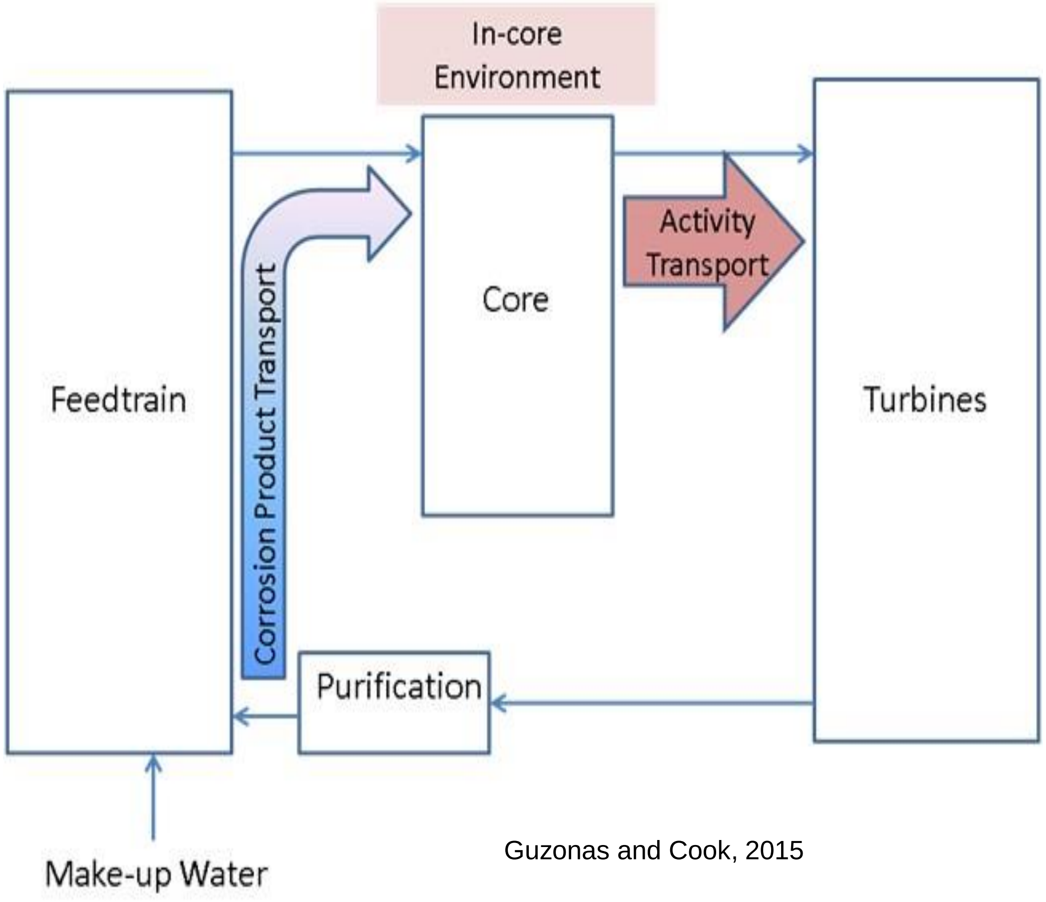


Only this part is supercritical

The chemistry **here** determines the concentrations of impurities entering the core.

Chemistry Control Strategy

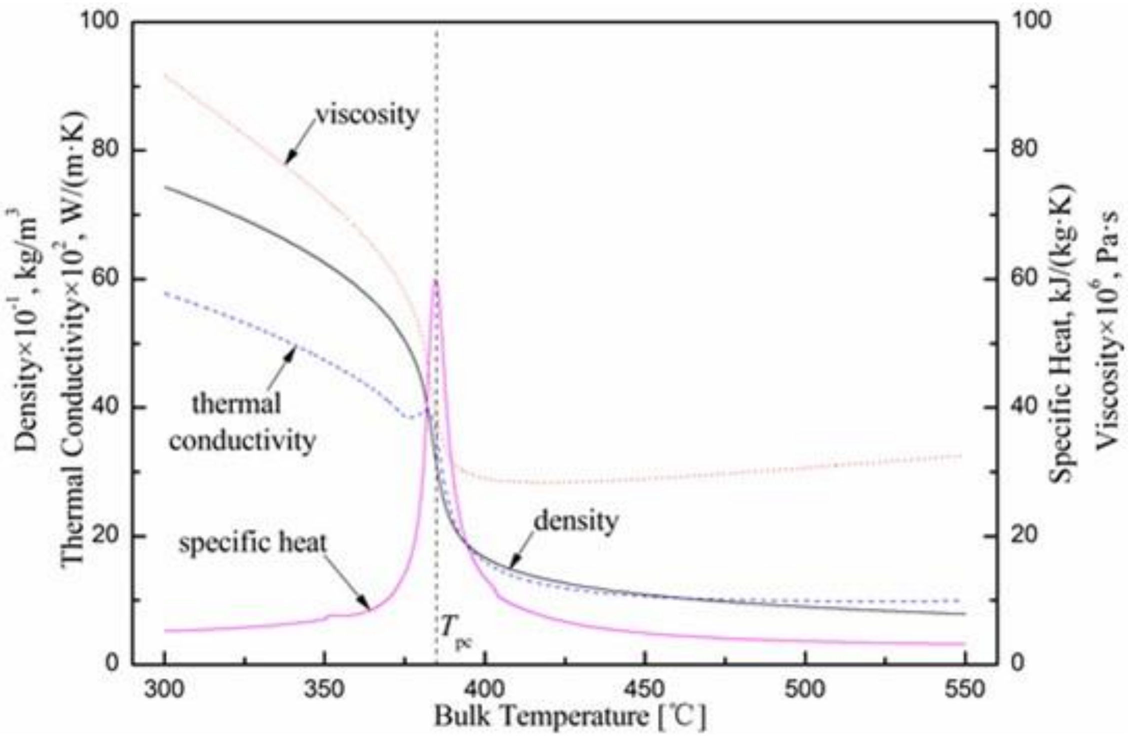
- Full flow condensate polisher (like BWRs)
  - To remove impurities
- Oxygenated Treatment (OT) for feedtrain
  - To minimize corrosion of the feedtrain and corrosion product transport to the core
- Possible hydrogen addition upstream of core
  - To control oxidizing species in-core and immediately downstream of the core



Guzonas and Cook, 2015

SCWR Design Challenges: Thermalhydraulics

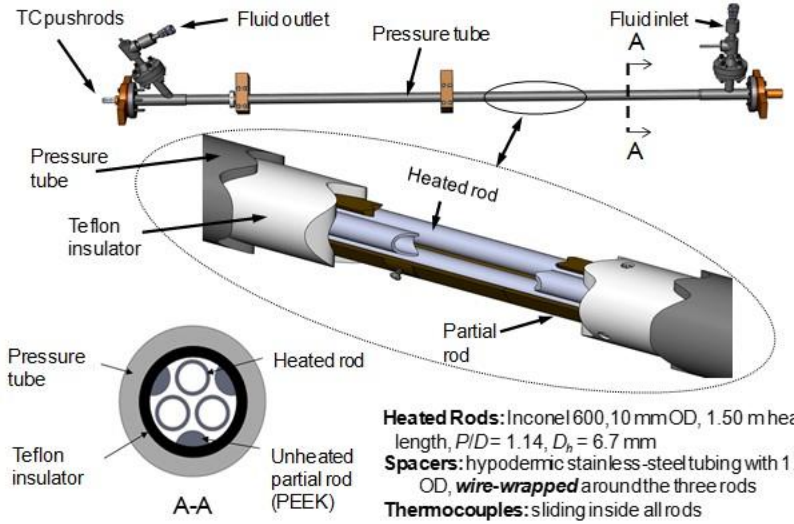
- Accurate prediction of heat transfer at supercritical pressures is essential to establish power output and safety margin
  - Support fuel design, fuel optimization and safety analysis
- Cladding temperature limits have been adopted as the design criteria
  - Traditional CHF criteria are no longer appropriate due to the lack of phase change
- Sharp variations in fluid properties at the pseudo-critical point
  - Significant impact to heat transfer
- Experimental heat transfer data are available for flow of water and surrogate fluids at supercritical pressures
  - Large amount of tube data
    - Those obtained for fossil-plant boilers are not directly applicable
  - Data of 3-, 4- and 7-rod bundle subassemblies
    - Tests with full-scale bundle assembly are considered premature
  - Lack of data on separate effects
    - Non-uniform power profiles



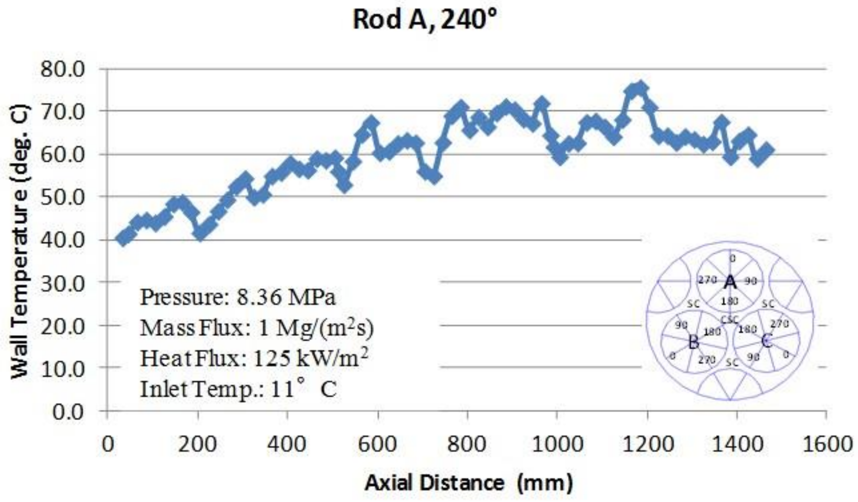
Samples of Experimental Database

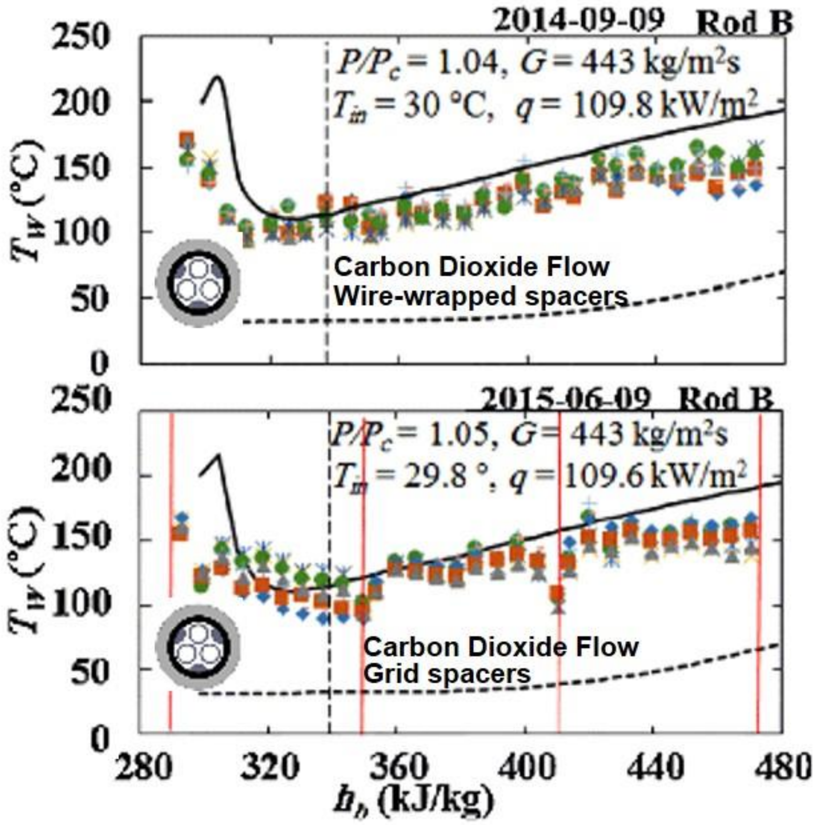
Experiments	Geometry	Fluid
Annuli	8-mm OD heated rod, 12- and 16-mm ID unheated shroud, 2-m heated length	Water (upflow and downflow)
Tubes	8- and 22-mm IDs, 2-m heated length	CO_2 (upflow)
Tube	12.5-mm ID, 2-m heated length	R-134a (upflow)
Annuli	10-mm OD heated rod, 18-mm ID unheated shroud, 2.244-m heated length	R-134a (upflow)
4-rod bundle	Four 8-mm OD heated rods, 20.3-mm square flow channel with rounded corners, 60-cm heated length	Water (upflow)
3-rod bundle	Three 10-mm OD heated rods, 1.5-m heated length	CO_2 (upflow)
7-rod bundle	Seven 7.4-mm OD heated rods, 27.9-mm ID unheated shroud, 2-m heated length	R-134a (upflow)

Heat Transfer Experiments with Bundle Subassemblies

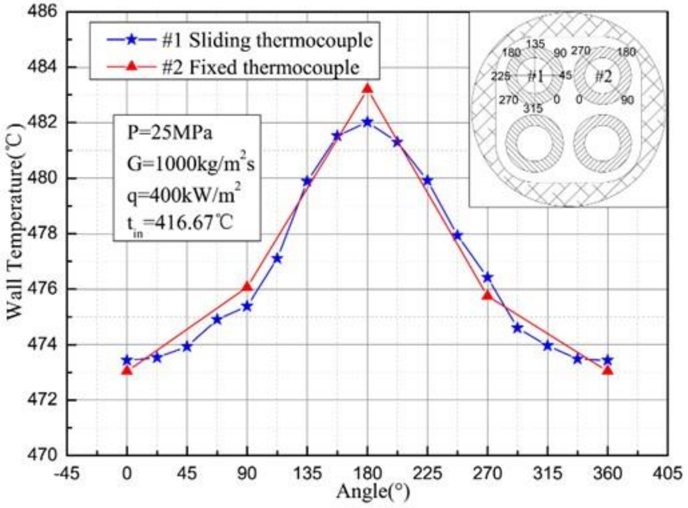


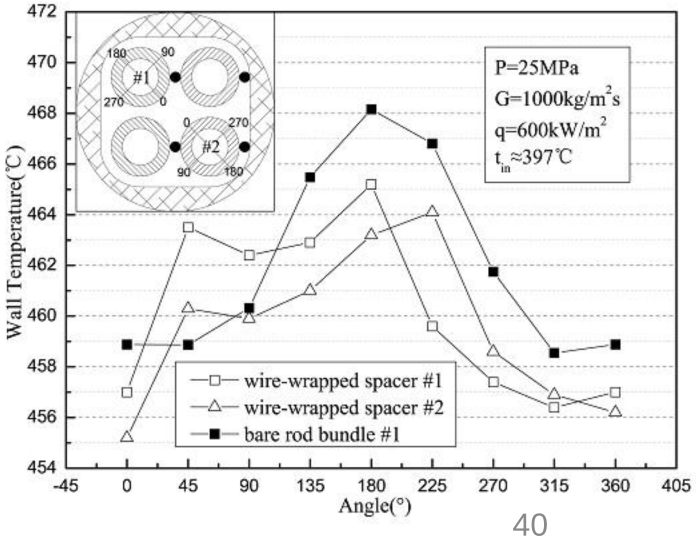
Heated Rods: Inconel 600, 10 mm OD, 1.50 m heated length, P/D = 1.14, D_h = 6.7 mm
Spacers: hypodermic stainless-steel tubing with 1.3 mm OD, ***wire-wrapped*** around the three rods
Thermocouples: sliding inside all rods





Eter et al., 2016.



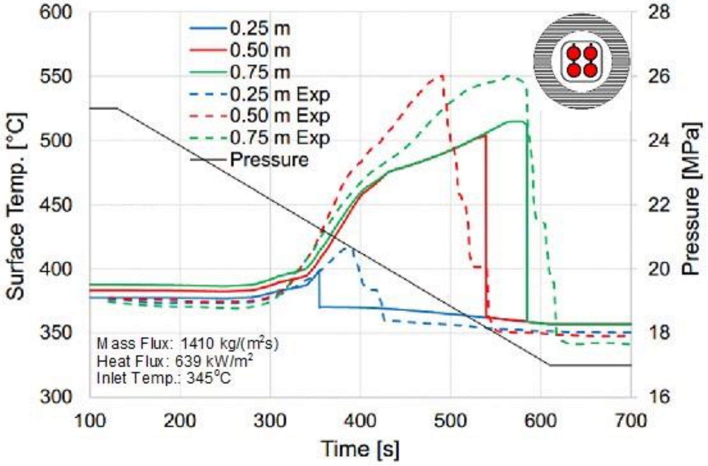


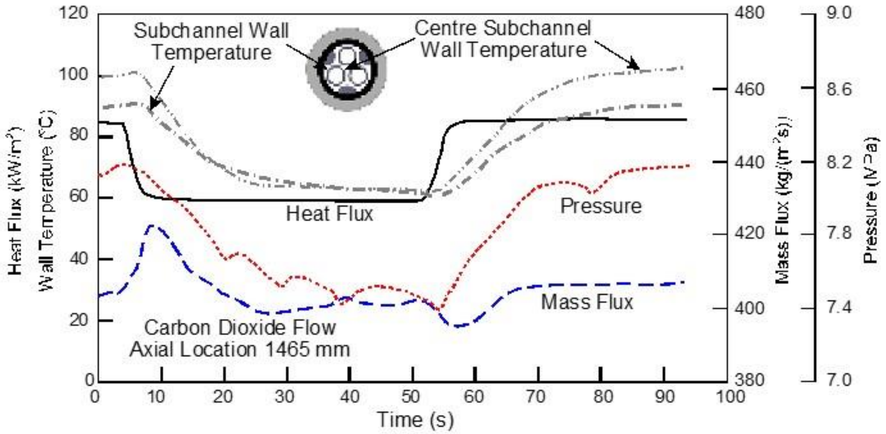
SCWR Design Challenges: Safety

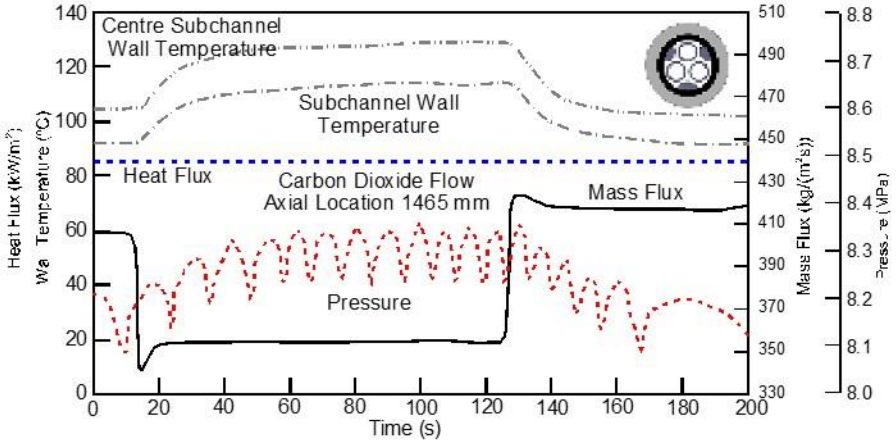
- Support safety system design and demonstration of its effectiveness
- Transient experimental data on supercritical heat transfer
  - Pressure transient through the pseudo-critical point
- Experimental SCW data on critical flow
  - Designs of safety/relief valve and depressurization system
  - Support of large break loss-of-coolant accident analyses
- Susceptibility to dynamic oscillations
  - Large variation of coolant density in the axial direction
  - Strong coupling of the neutronic and thermal-hydraulic behavior
  - Need experimental data and analytical model to predict the onset of instability
- Applicability of safety analysis code
  - Validations were performed for subcritical applications only
  - Need integral test data at supercritical conditions

Transient Experiments

- Understanding of heat-transfer characteristics during postulated accident scenarios
- Experiments simulating power, flow and pressure transients have been performed
  - Water flow through a 4-rod bundle
  - Refrigerant R-134a flow in a tube or through a 7-rod bundle
  - Carbon dioxide flow through a 3-rod bundle
- Power and flow transients
  - Wall temperatures respond rapidly to changes in power and flow
- Pressure transient
  - Wall temperature decreases slightly with increasing pressure at supercritical conditions
  - The rate of decrease is reduced at supercritical pressures
  - The trend reverses with decreasing pressure







SCWR Design Challenges: Physics

- Neutronic design has an impact on safety, economics, sustainability, proliferation resistance and security
  - Coolant changes from liquid-like to gas-like fluid over the core impacting absorption/moderation characteristics
- Similar to those of current fleet of reactors except for differences in geometry, temperatures and properties
  - Spectrum and cross-section effects
  - Strong coolant-moderator effects
  - 3D neutronic-thermal-hydraulics coupling calculation is needed
- Challenges
  - Accuracy of physics codes for harder neutronic spectrum at higher fuel and moderator temperatures
  - Validation of physics codes

Collaborations

- Leverage resources and expertise to expedite the development
  - Generation-IV International Forum (GIF)
  - International Atomic Energy Agency (IAEA)
  - Bilateral agreements
- Exchange of technical information
  - International Symposium on SCWRs
  - Information Exchange Meetings
  - IAEA Coordinated Research Projects and Technical Meetings

Summary

- Various SCWR design concepts are presented
  - Pressure Tube and Pressure-Vessel types
  - Direct thermal cycle that leads to design simplification and cost reduction
  - A range of thermal powers from 1600 to 4000 MW at thermal efficiencies higher than 43%
  - Thermal spectrum, fast spectrum, and mixed spectrum cores
  - UO_2, MOX, and thorium fuels
  - Light water, heavy water, and solid moderators
- Some similarities emerged for thermal spectrum cores
- Design challenges have been identified
  - Some have been resolved
  - Others are being addressed

References

- OECD Nuclear Energy Agency, "Technology Roadmap Update for Generation IV Nuclear Energy Systems", January 2014.
- T. Schulenberg and L. Leung, "Super-critical water-cooled reactors", Handbook of Generation IV Nuclear Reactors, Editor: I.L Pioro, Woodhead Publishing Series in Energy: 103, 2016.
- IAEA, "Status Report - Chinese Supercritical Water-Cooled Reactor (CSR1000)", IAEA Advanced Reactors Information System (ARIS) Database, December, 2015.
- K. Yamada et al., "Overview of The Japanese SCWR Concept Developed under The GIF Collaboration", Proc. 5th International Symposium on Supercritical Water-cooled Reactors, Vancouver, Canada, March 13-17, 2011.
- X. Cheng et al., "A Mixed Core for Supercritical Water-cooled Reactors", Nuclear Engineering and Technology, 40(2), pp. 117-126, 2007.
- T. Schulenberg et al., "Review of R&D for Supercritical Water Cooled Reactors Progress in Nuclear Energy", Progress in Nuclear Energy, Vol. 77, pp. 282-299, November, 2014.
- S. Ryzhov et al., "Concept of A Single-Circuit RP with Vessel Type Supercritical Water-Cooled Reactor", Proc. 5th International Symposium on Supercritical Water-cooled Reactors, Vancouver, Canada, March 13-17, 2011.
- J. Pencer and A. Colton, "Progression of the Physics Conceptual Design for the Canadian Supercritical Water Reactor", Proc. 34th Annual Conference of the Canadian Nuclear Society, June 09-12, 2013, Canadian Nuclear Society (2013).
- S. Sakurai et al., "Japanese SCWR Fuel and Core Design Study", Proc. 5th International Symposium on Supercritical Water-cooled Reactors, Vancouver, Canada, March 13-17, 2011.
- T. Nakatsuka et al., "Current Status of Research and Development of Supercritical Water-Cooled Fast Reactor (Super Fast Reactor) in Japan, Proc. IAEA Technical Meeting on Heat Transfer, Thermal-Hydraulics and System Design for Super-Critical Water-Cooled Reactors, Pisa, Italy, July 5-8, 2010.

References

- Y. Ishiwatari et al., “Safety Analysis of JSCWR”, Proc. 5th International Symposium on Supercritical Water-cooled Reactors, Vancouver, Canada, March 13-17, 2011.
- T. Schulenberg and J. Starflinger, High Performance Light Water Reactor (Design and Analyses), KIT Scientific Publishing, 2012.
- M. Moore, L. Leung and R. Sadhankar, “An Economic Analysis of the Canadian SCWR Concept Using G4-ECONS”, CNL Nuclear Review, Vol. 5, No. 2, pp. 363-372, 2016.
- D.A. Guzonas, “Materials and Chemistry for a Supercritical Water-Cooled Reactor-Progress and Challenges”, Proc. 5th Int. Sym. on SCWRs (ISSCWR-5), Vancouver, British Columbia, Canada, March 13-16, 2011.
- D. Guzonas, M. Edwards and W. Zheng, “Assessment of Candidate Fuel Cladding Alloys for the Canadian Supercritical Water-cooled Reactor Concept”, Proc. 7th Int. Sym. on SCWRs (ISSCWR-7), Helsinki, Finland, 15-18 March 2015.
- W. Li, O.T. Woo, D. Guzonas, J. Li, X. Huang, R. Garcia and C. Bibby, “Effect of Pressure on the Corrosion of Materials in High Temperature Water,” 2015 TMS Annual Meeting & Exhibition, Orlando, Florida, 15–19 March 2015.
- D. Guzonas and W. Cook, “Water Chemistry Specifications for the Canadian Supercritical Water-Cooled Reactor Concept”, Proc. 7th Int. Sym. on SCWRs (ISSCWR-7), Helsinki, Finland, 15-18 March 2015.
- Y. Oka et al, Super Light Water Reactors and Super Fast Reactors (Supercritical-Pressure Light Water Cooled Reactors), Springer Science+Business Media, 2010.
- A. Eter, D. Groeneveld and S. Tavoularis, “An experimental investigation of supercritical heat transfer in a three-rod bundle equipped with wire-wrap and grid spacers and cooled by carbon dioxide”, Nuclear Engineering and Design, Vol. 303, pp. 173–191, 2016.
- H. Wang, Q. Bi and L.K.H. Leung, “Heat Transfer from a 2×2 Wire-Wrapped Rod Bundle to Supercritical Pressure Water”, Int. J. of Heat and Mass Transfer, Vol. 97, pp. 486–501, 2016.

UPCOMING WEBINARS

27 April 2017	Fluoride Salt Cooled High Temperature Reactor	Prof. Per Peterson, UC Berkeley, USA
23 May 2017	Molten Salt Reactor	Dr. Elsa Merle, CEA, France
20 June 2017	Lead Fast Reactor	Prof. Craig Smith, US Naval Graduate School, USA