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OVERVIEW OF GLOBAL DEVELOPMENT OF SCWR CONCEPTS

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Overview of Global Development of SCWR Concepts (SC04)

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Joint ICTP-IAEA Course on Science and Technology of SCWRs, Trieste, Italy

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AECL EACL

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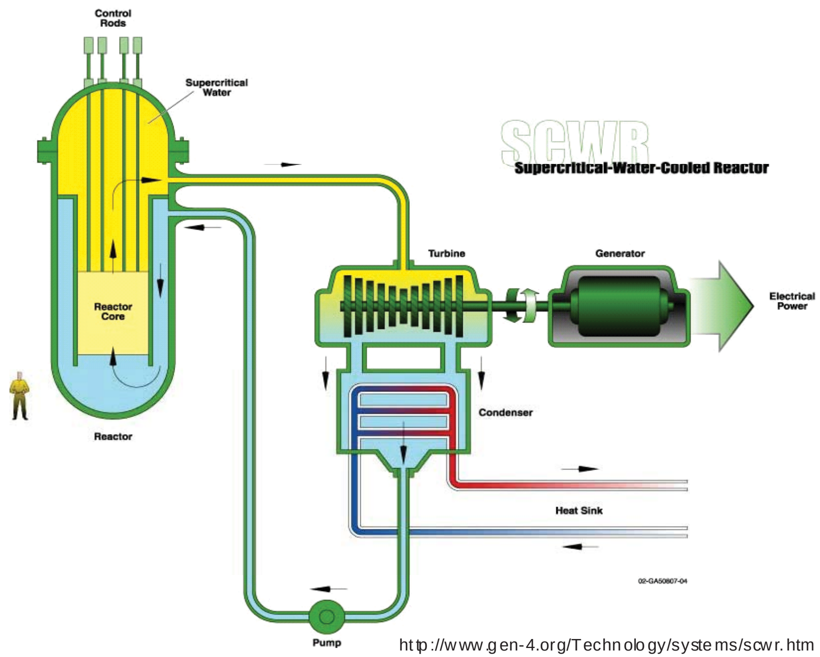
Objective

- To introduce global development of SCWR concepts in
  - Canada
  - China
  - European Union
  - Japan
  - Korea
  - Russia
  - United States
- Focusing on
  - Thermodynamic cycle
  - Core design
  - Fuel design
  - Safety system

Introduction

- A number of SCWR design concepts have been pursued
  - All evolved from the current fleet of reactors
    - Boiling-water reactors – vessel type
    - Pressurized-water reactors – vessel type
    - Pressurized heavy-water reactors - channel type
  - Each concept is at different design stages
  - Some concepts have been terminated
- GIF SCWR concepts focus on achieving four design goals improving
  - Safety, economic, sustainability and proliferation resistance



http://www.gen-4.org/Technology/systems/scwr.htm

Design Parameters for SCWR Concepts

Parameters	Unit	Canadian SCWR	SCWR-M	HPLWR	JSCWR	Super Fast Reactor	SCWR-SM	VVER-SCP	US SCWR
Country	–	Canada	China	EU	Japan		Korea	Russia	US
Organization	–	AECL	SJTU	EU-JRC	Toshiba/U. of Tokyo	U. of Tokyo	KAERI	OKB "Gidropress", IPPE	INEEL
Reactor type	–	PT	RPV	RPV	RPV	RPV	RPV	RPV	RPV
spectrum	–	Thermal	Mixed	Thermal	Thermal	Fast	Thermal	Fast-resonance	Thermal
Power thermal	**MW**	2540	3800	2300	4039	1602	3182	3830	3575
linear max/ave	**kW/m**		39/18	35/14, 8, 4.5 (a)	-/13.5		39/14.26	-/15.6	39/19.2
Thermal eff.	**%**	48	~44	43.5	42.7	~44		43-45	45
Pressure	**MPa**	25	25	25	25	25	25	24.5	25
T_{in} coolant	**°C**	350	280	280	290	280	280	290	280
T_{out} coolant	**°C**	625	510	500	510	508	510	540	500
Flow rate	**kg/s**	1320	1927.0	1179	2105	820		1890	1843
Active core height	**m**	5.0	4.5	4.2	4.2	2	3.66	4.05	4.27
Equiv. core diameter	**m**	~4.5	3.4	3.8	3.34	1.86		3.6	3.93
Fuel	–	Pu-Th	UO_2/MOX	UO_2	UO_2	MOX	UO_2	MOX	UO_2
Cladding material	–	SS	SS	316SS	310SS	SS		austenitic alloy (ChS-68, EP-172)	SS
# of FA		336	284	1404	372	162/73	193	241	145
# of FR in FA		78	180/324	40	192	252/127	316	252	300
D_{rod}	**mm**	7/12.4/12.4 (b)	8	8	7	5.5	9.516	10.7	10.2
Pitch	**mm**	vary	9.6/9.6	9.44		6.55	11.5	12	11.2
Moderator	–	D_2O	H_2O/---	H_2O	H_2O	-/ZrH	ZrH_2	H_2O	H_2O

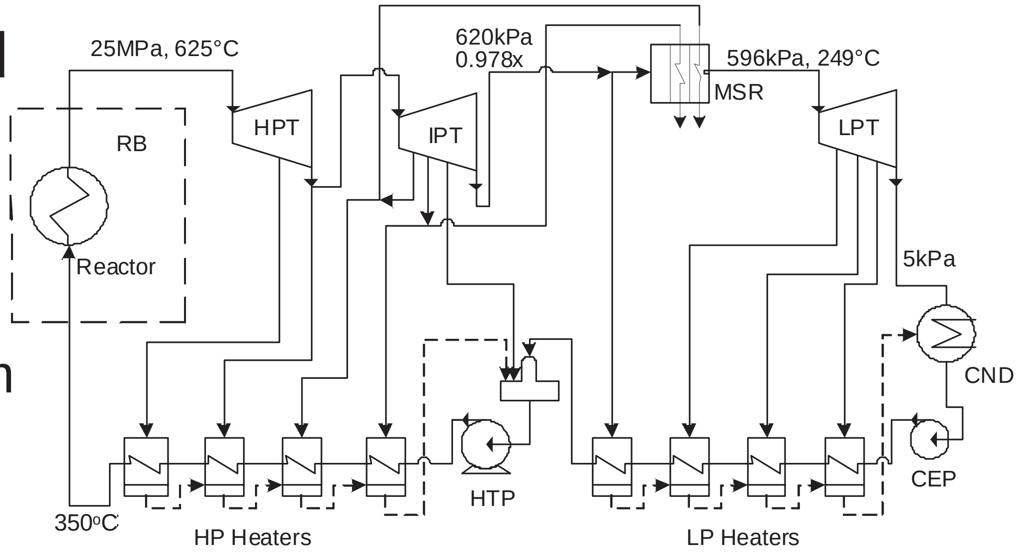
(a) Evaporator, Superheater 1, Superheater 2 (b) Outer, Middle, Inner rings

Canada's SCWR Concept

- Main CANDU features are retained
  - – Modular fuel channels
  - – Heavy water moderator
- Supercritical light water coolant
  - – Pressure of 25 MPa
  - – Outlet temperatures up to 625^{o}C
- Advanced fuel channel design
- Enhanced passive safety
  - – Separation between moderator and coolant is unique to CANDU reactors
  - – Moderator (heavy water) acts as a passive heat sink
- Advanced fuel cycles
- Non-electricity applications

Canada's SCWR Thermodynamic Cycle

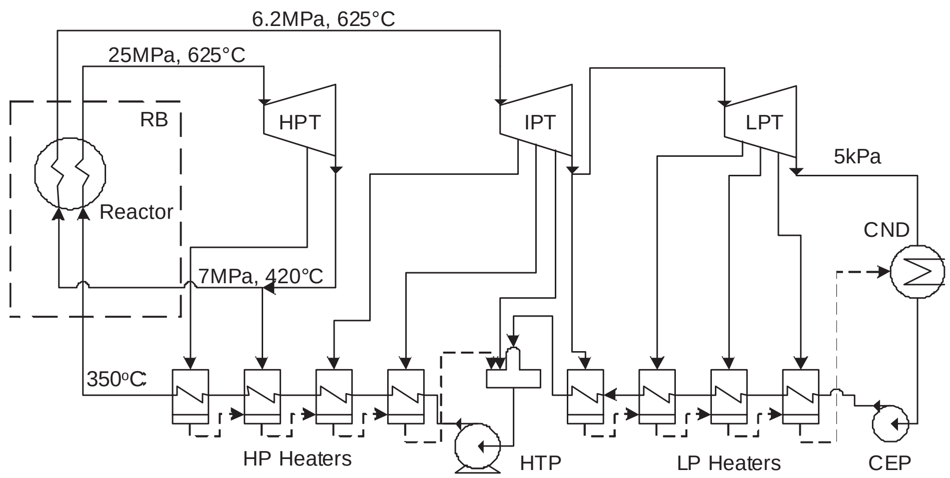
- Matches closely the current advanced turbine configuration of a SC fossil power plant
- High-pressure "steam" fed directly into the steam turbines (direct-steam cycle)
  - Improved efficiency
  - Plant simplification (no steam generator)
- A moisture separator reheater is installed to reduce the steam moisture inside the low pressure turbines



M. Yetisir et al., 2011

Reheat Option for Canada's SCWR Thermodynamic Cycle

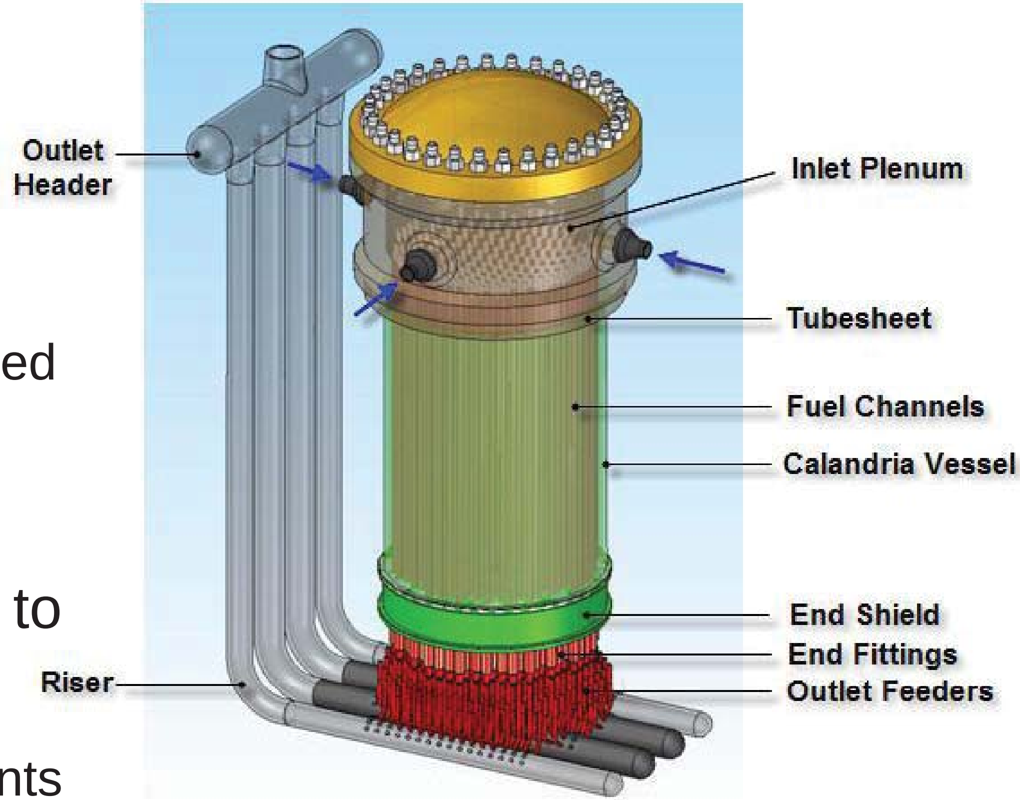
- Most high pressure turbines in fossil-power plants are designed for steam reheat
  - All turbines will have the same cabability in 5-10 years
- Reheat option can be implemented into the Canadian SCWR
- Steam from the high-pressure turbine is returned to the core, reheated, and then fed to the intermediate-pressure turbine.
- Benefits:
  - Raise the efficiency further
  - Eliminates the moisture separator reheater



M. Yetisir et al., 2011

Canada's SCWR Core Design

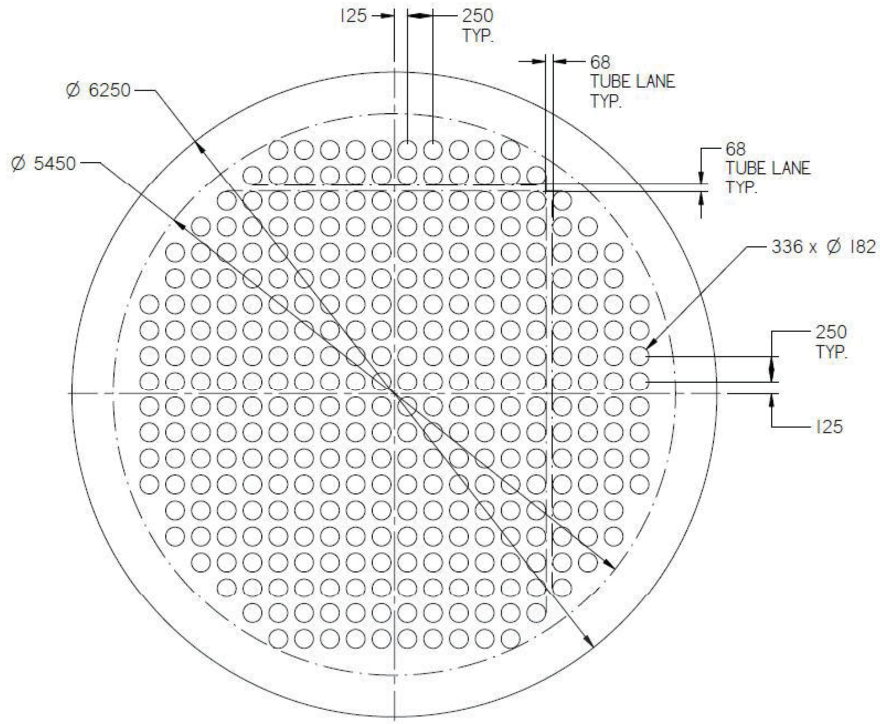
- Vertical channels
- High-pressure inlet plenum
  - Simplify refueling process
  - Reduce lattice pitch
  - Relatively low temperature (350ºC)
  - Individual channel closure design is still being investigated
- Low-pressure moderator
  - Passive moderator cooling circuit (not shown)
- Channel outlets connecting to header
  - Small diameter reducing material thickness requirements



M. Yetisir et al., 2011

Fuel Channel Layout in Canada's SCWR Core

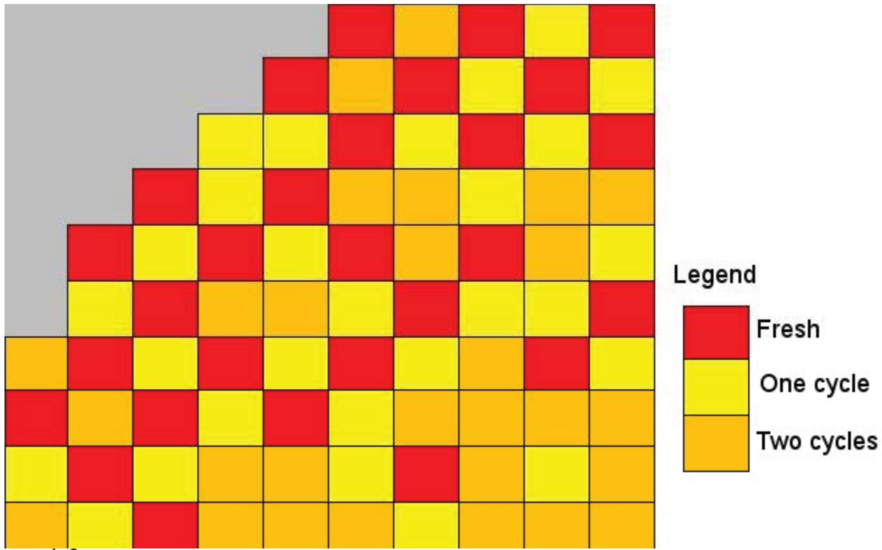
- Thermal power of 2540MW (electric power of 1200MW, based on 48% efficiency)
- A total of 336 fuel channels (average channel power is 7.5 MW(t))
- Core radial power factor is about 1.28
- Lattice pitch is 250 mm (to achieve a negative void coefficient and high fuel burnup)
- Each channel houses a 5m long bundle assembly

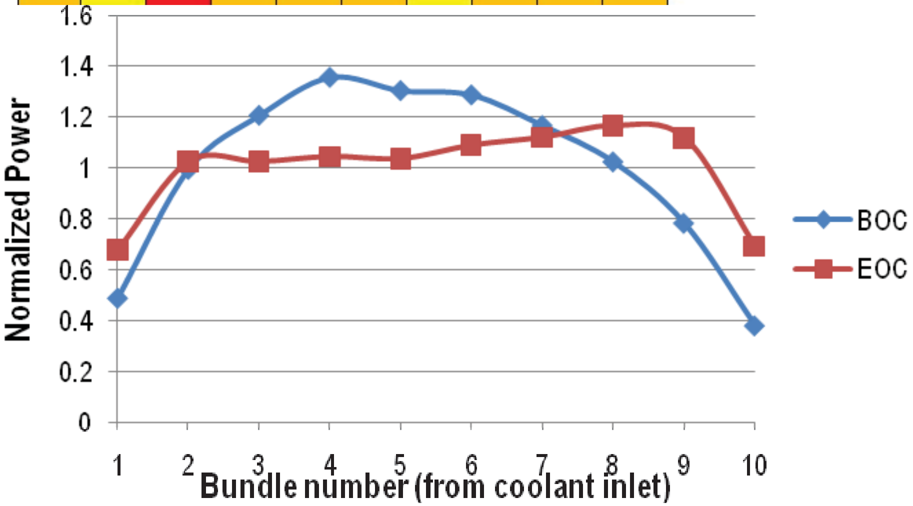


M. Yetisir et al., 2011

Advanced Fuel Cycle for Canada's SCWR

- Thorium fuel cycle to meet all GIF design goals
  - Enhanced safety
  - Resource sustainability
  - Economic benefit
  - Proliferation resistance
- Plutonium is mixed uniformly with thorium
- 3-batch refuelling scheme
  - Ensure even power distribution radially across the core
- Axial power profiles established for BOC and EOC fuels
- Further refinements of refuelling scheme are in progress

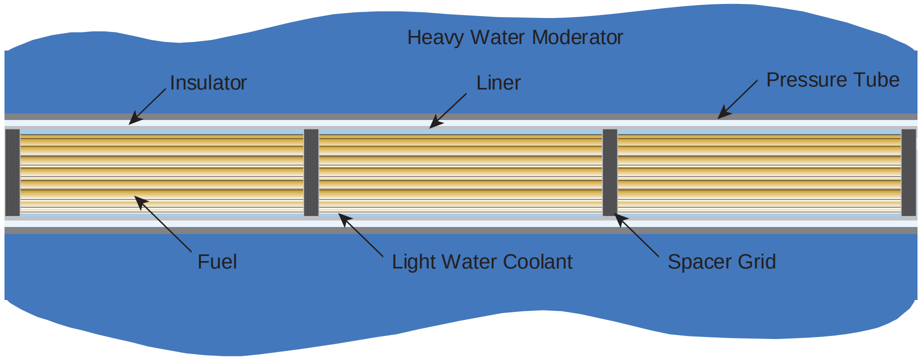


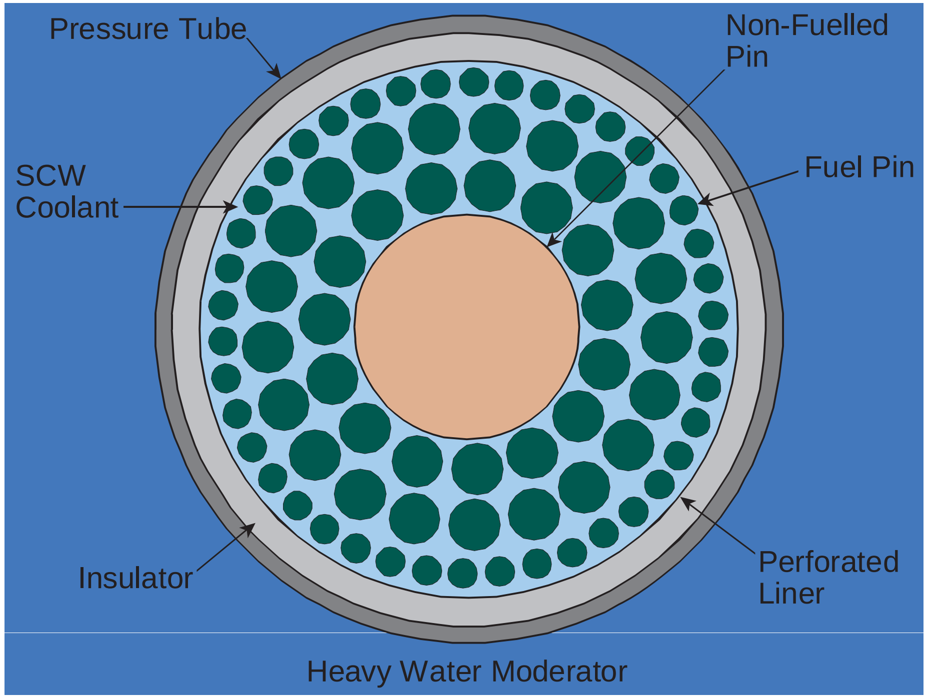


M. McDonald et al., 2011

Canada's SCWR Fuel Channel Design

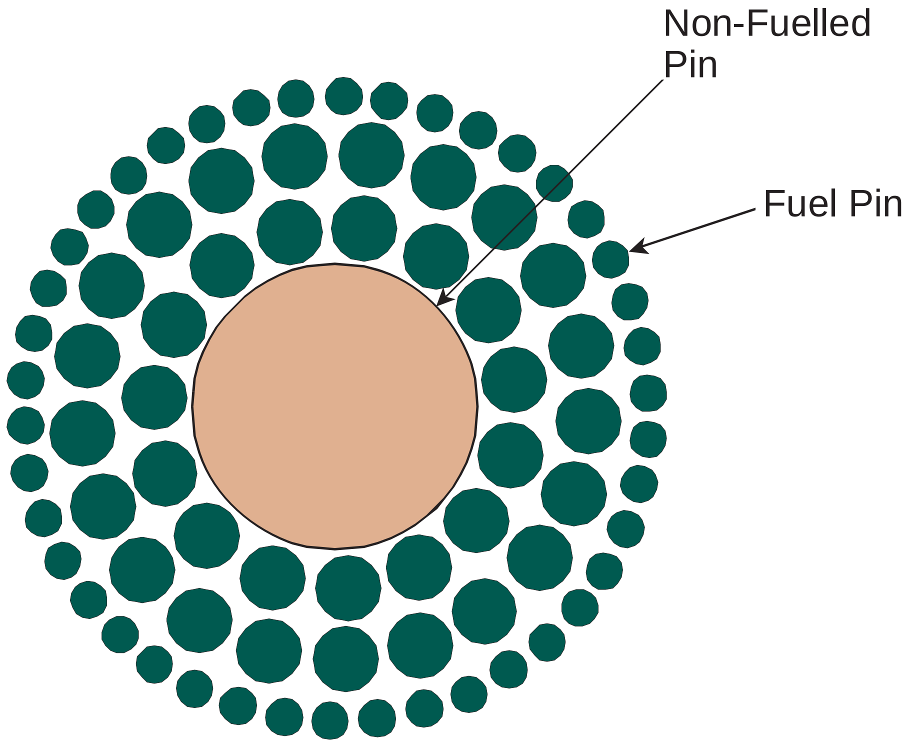
- Insulate pressure tube on the inside
- Remove calandria tube
- Insulator thickness optimized to obtain
  - Usual heat loss by conduction/convection to the moderator under normal operation
  - Sufficient heat rejection by radiation/conduction/ convection under accident conditions
- Refer to as the high efficiency channel (HEC)





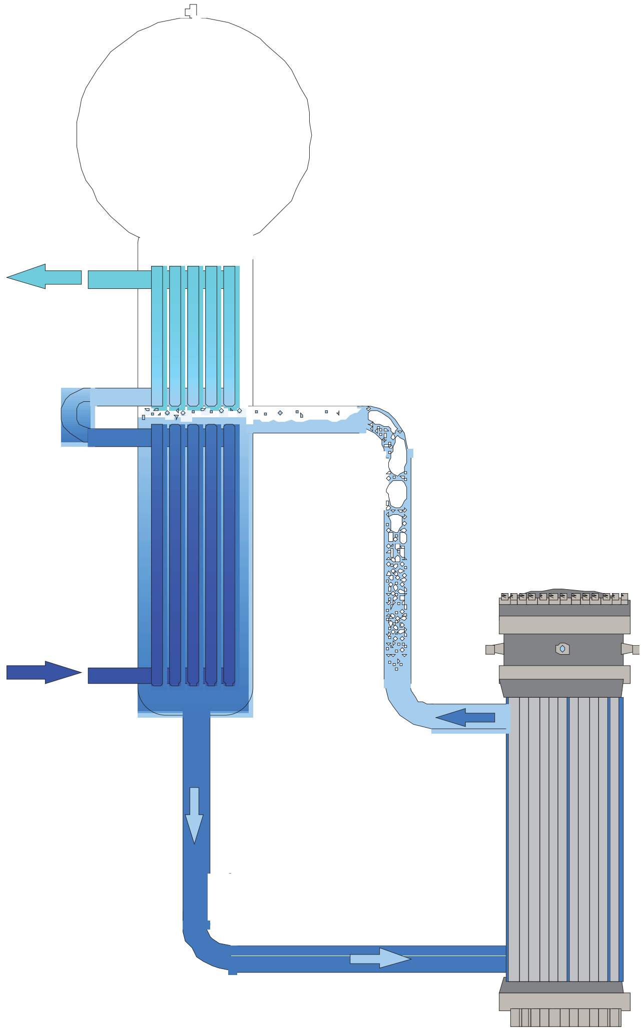
Canada's SCWR Fuel Design

- Three concentric rings of fuel with 15, 21, and 42 fuel elements
  - Fuel composition is 13% plutonium in thorium
  - Graded enrichment option is being examined
- A large non-fuelled element in the centre
  - Zirconia surrounded by cladding
  - Reduces coolant void reactivity
- Fuel cladding option
  - Austenitic stainless steel
  - Ferritic / martensitic steel
  - Oxide dispersion strengthened steel



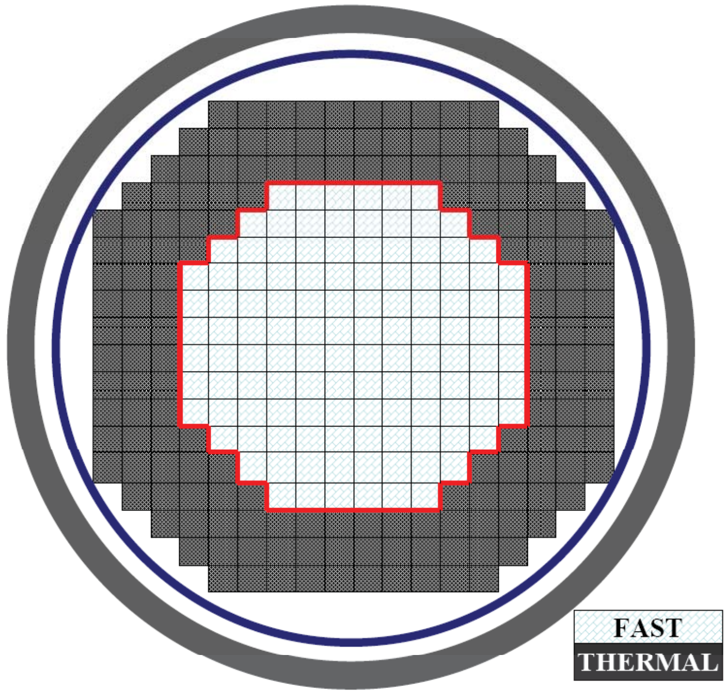
Canada’s Passive Moderator Cooling Concept

- Enhances safety
- Design for normal and emergency operation
- Two-phase flow in hot leg generated by flashing
- Advanced fuel channel design allows moderator to operate close to saturation
- Heat removed by radiation and convection
- “Walk away safety” with no core melt



China's SCWR Concept

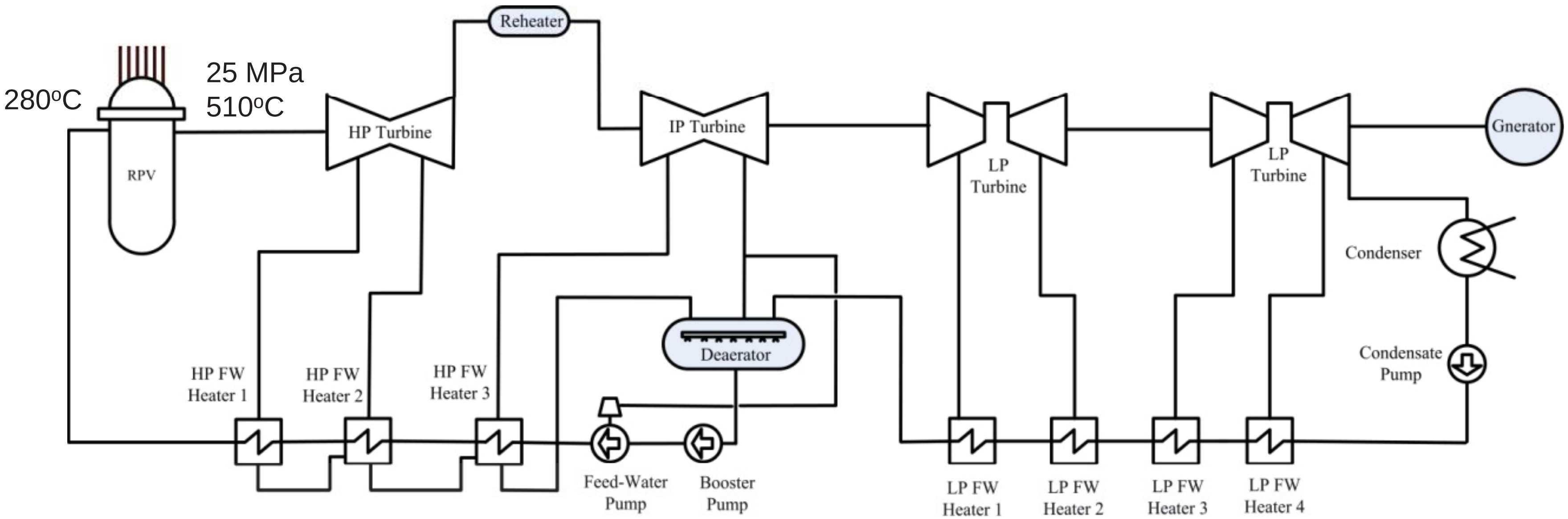
- Pressure vessel type
  - Thermal power of 3800 MW
  - Electric power of 1650 MW
- Mixed core design with multi-layer fuel assembly
  - Two zones
    - Thermal neutron spectrum in the outer zone with 164 fuel assemblies
    - Fast spectrum in the inner zone with 120 fuel assemblies
  - Achieve a high temperature at the reactor exit



X. Cheng et al., 2007

China's SCWR Thermodynamic Cycle

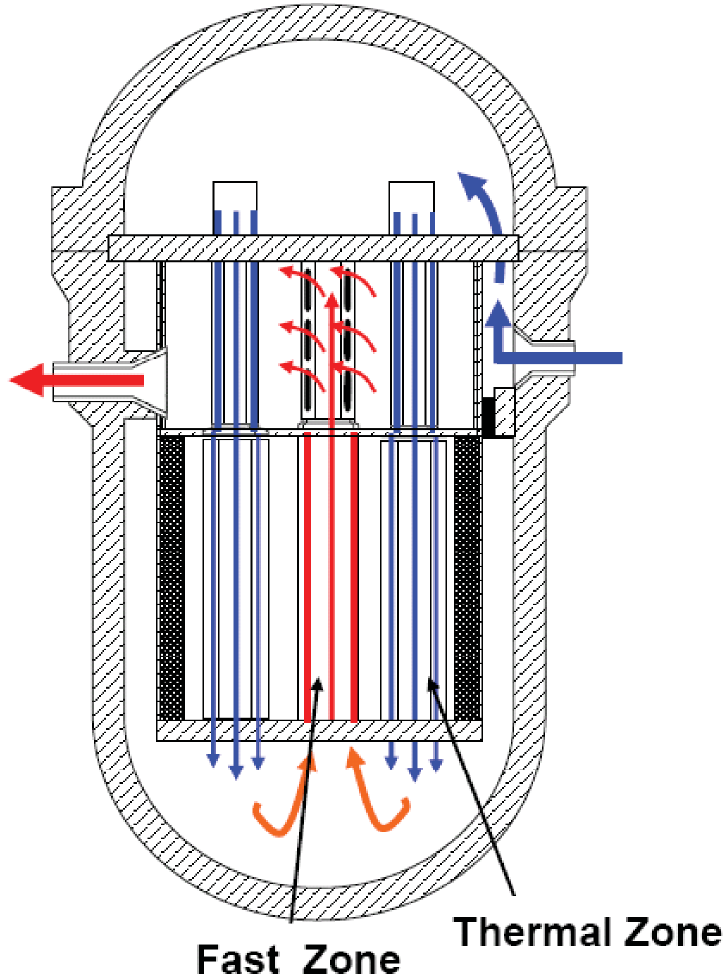
- Based on BWR conception and supercritical pressure fossil-fired power plant
- Steam from the reactor is supplied to the high pressure turbine, then through the re-heater, and enters the intermediate-pressure turbine and low pressure turbines.



X. Cheng et al., 2007

China's SCWR Core Design

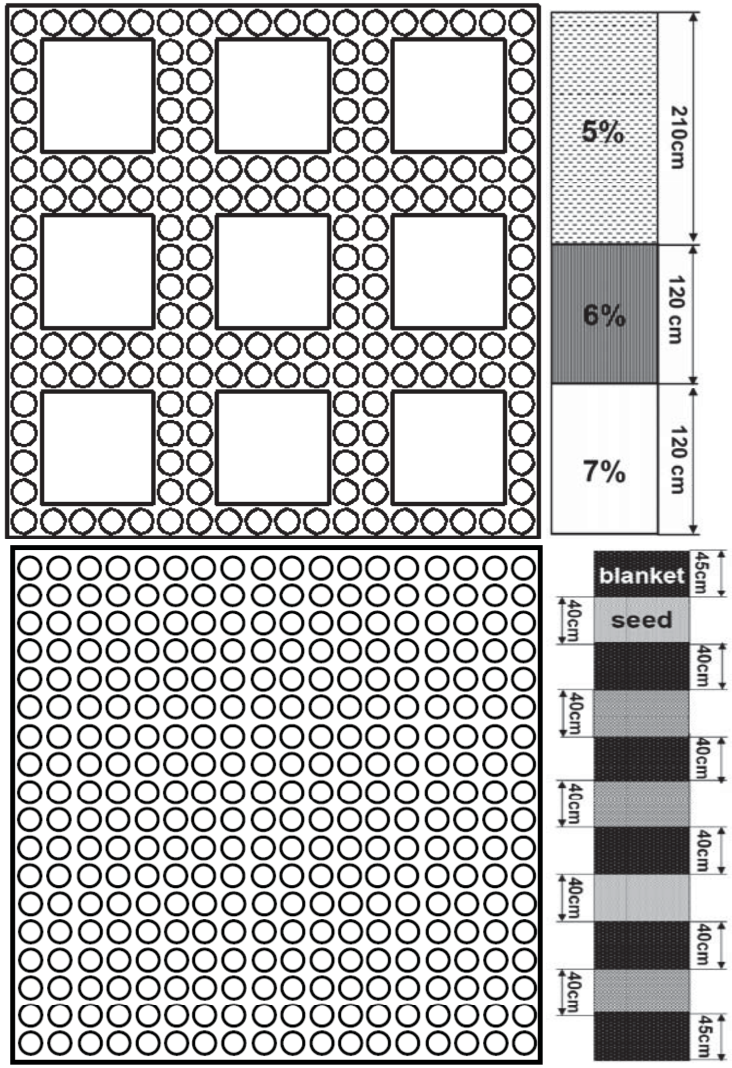
- Equivalent core diameter is 3.4m
- Thermal spectrum zone
  - Co-current downward flow mode
  - Exit temperature over the pseudo-critical point
  - Active height is 4.5 metres
- Fast spectrum zone
  - Upward flow mode
  - A hard neutron spectrum with a wide lattice structure
    - Mitigating the non-uniformity of the circumferential heat transfer at the cladding surface
    - Ensuring a large inventory of water
  - The multi-layer fuel assembly can lead to a conversion ratio close to 1
  - Active height is 2 metres



X. Cheng et al., 2007

China's SCWR Fuel Design

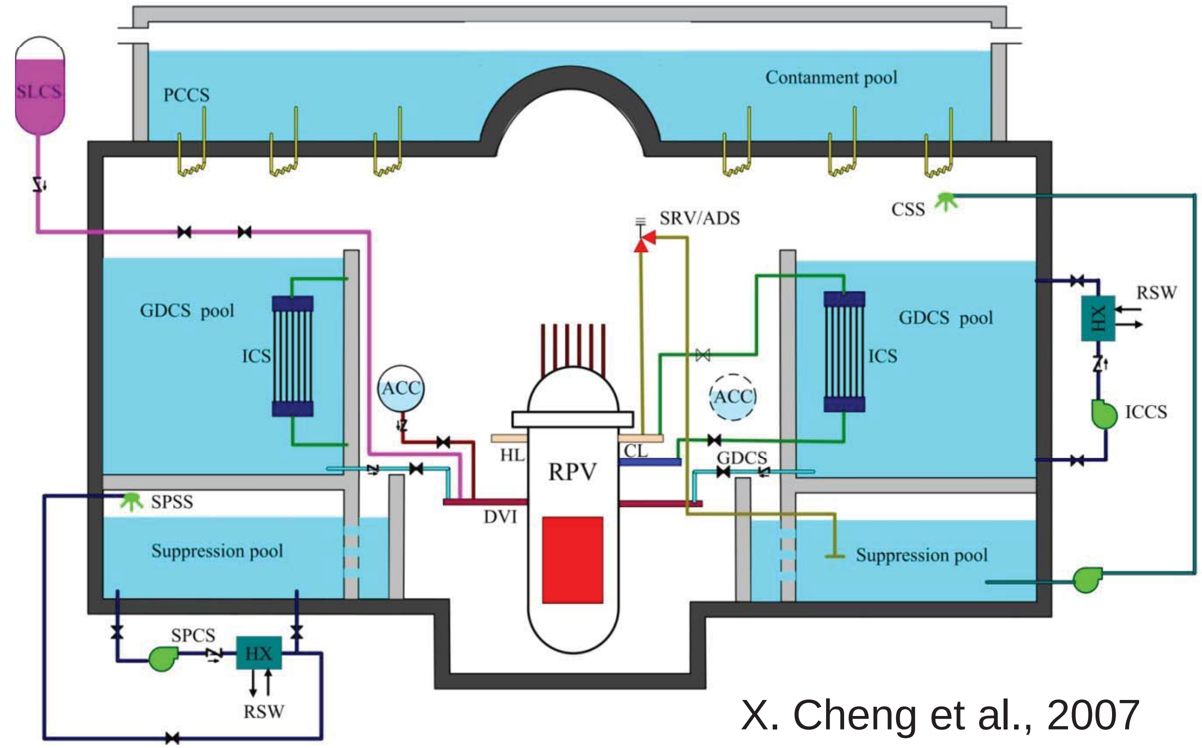
- Thermal zone
  - 180 8-mm rods
  - UO_2 fuel
  - Multi-layer enrichment of 5, 6, and 7%
- Fast zone
  - 324 8-mm rods
  - MOX fuel of 24% enrichment
  - 11 layers of seed and blanket materials
    - Short seed core to increase neutron leakage for negative void reactivity coefficient
    - Axial blankets with depleted uranium to increase the conversion ratio and reduce void reactivity coefficient



X. Cheng et al., 2007

China's SCWR Safety System

- Based on the design of advanced water reactors
- Passive concept from the ESBWR and AP1000



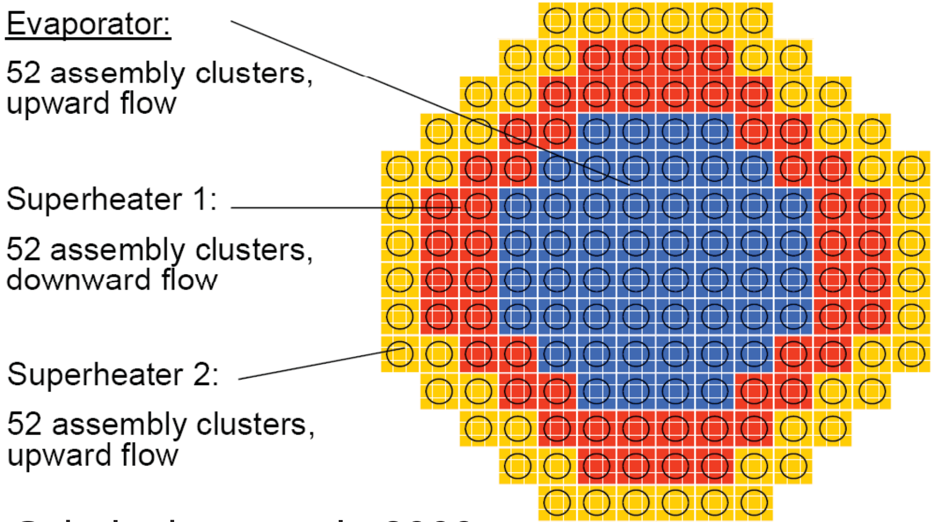
List of Acronyms

RPV:	Reactor Pressure Vessel
ACC:	Accumulator
GDCS:	Gravity Driven Cooling System
ICS:	Isolation Condenser System
SRV:	Safety/Relief Valves
ADS:	Automatic Depressurization System
SLCS:	Standby Liquid Control System
CSS:	Containment Spray System
SPCS:	Suppression Pool Cooling System
SPSS:	Suppression Pool Spray System
ICCS:	ICS Cooling System
RSW:	Reactor Service Water
DVI:	Direct Vessel Injection
HX:	Heat Exchanger
HL:	Hot Leg
CL:	Cold Leg

X. Cheng et al., 2007

European Union's SCWR Concept

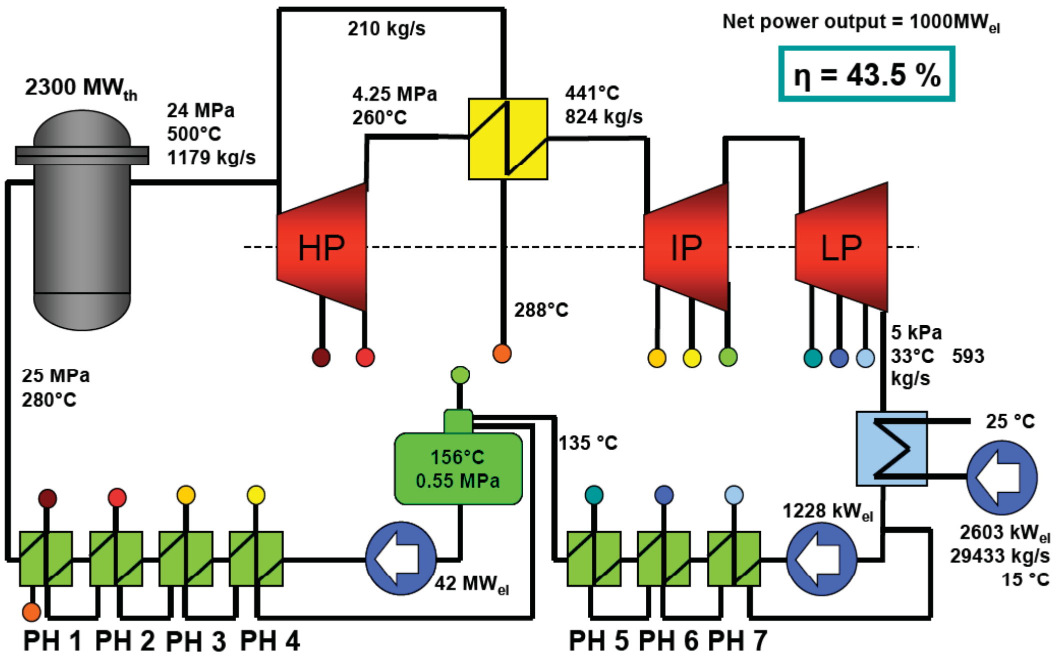
- High Performance Light Water Reactor (HPLWR)
- Pressure vessel type
  - Thermal power of 2300 MW
  - Electric power of 1000 MW
- Operating conditions
  - Pressure at 25 MPa
  - Core exit temperature at 500^{o}C
- Three-zones core
  - Evaporator
  - Superheater 1
  - Superheat 2



T. Schulenberg et al., 2009

European Union's SCWR Thermodynamic Cycle

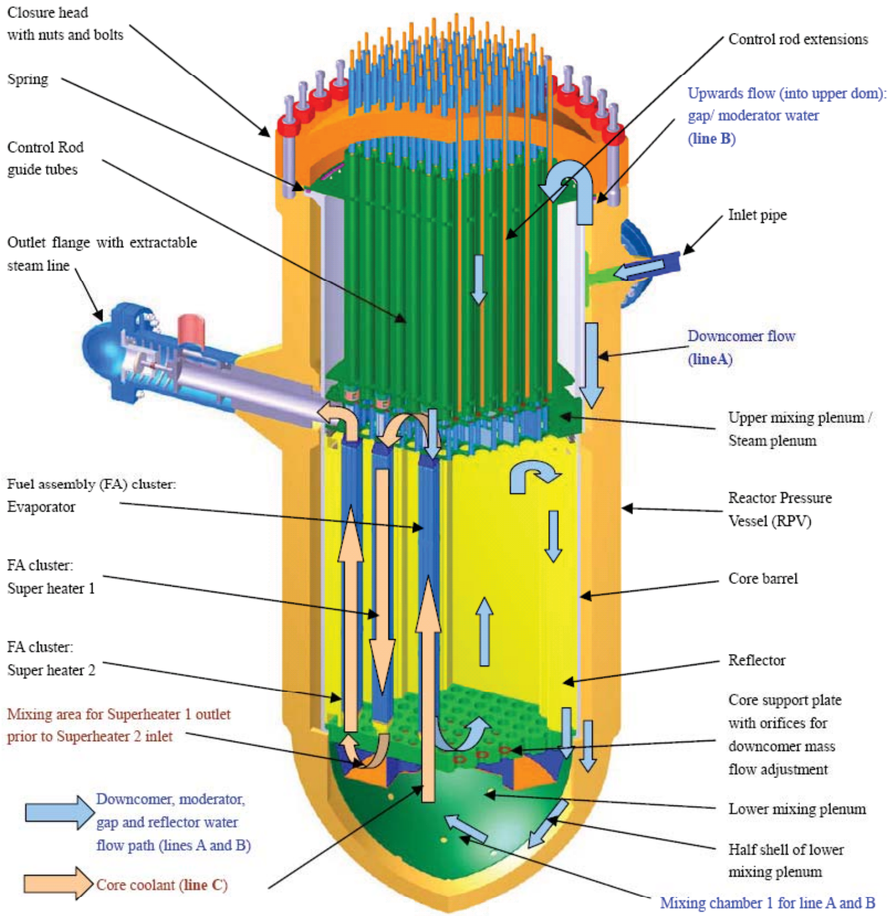
- Based on BWR concept and supercritical pressure fossil-fired power plant
- Steam from the reactor is supplied to the high pressure turbine, then re-heat using part of the extracted steam, and enters the intermediate-pressure turbine and low pressure turbines.



M. Brandauer et al., 2009

European Union's SCWR Core Design

- Equivalent core diameter is 3.8m
- Inlet flow splits
  - Upward to cool the dome and down through the gap between assemblies
  - Downward to lower plenum at temperatures from 280 to 310ºC
- Three heat-up steps with coolant mixing between steps to eliminate hot streaks
  - Upflow in evaporator at temperatures from 310 to 390ºC
  - Downflow in superheater-1 at temperatures from 390 to 433ºC
  - Upflow in superheater-2 at temperatures from 433 to 500ºC

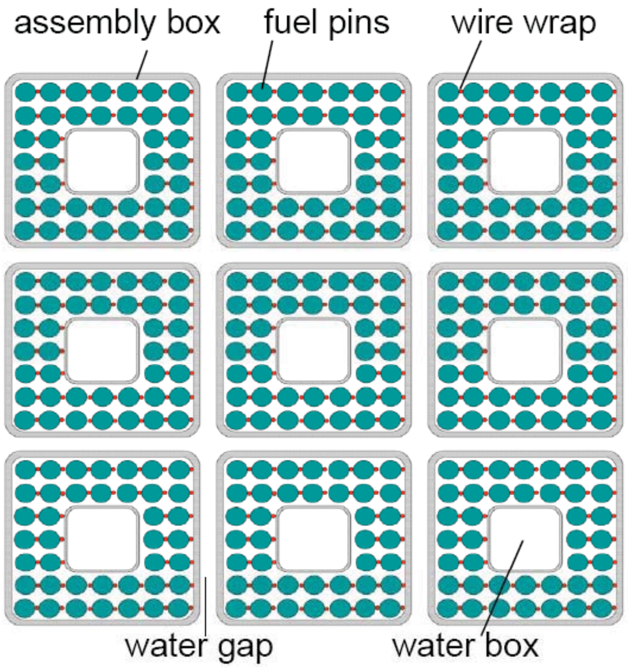


T. Schulenberg et al., 2008

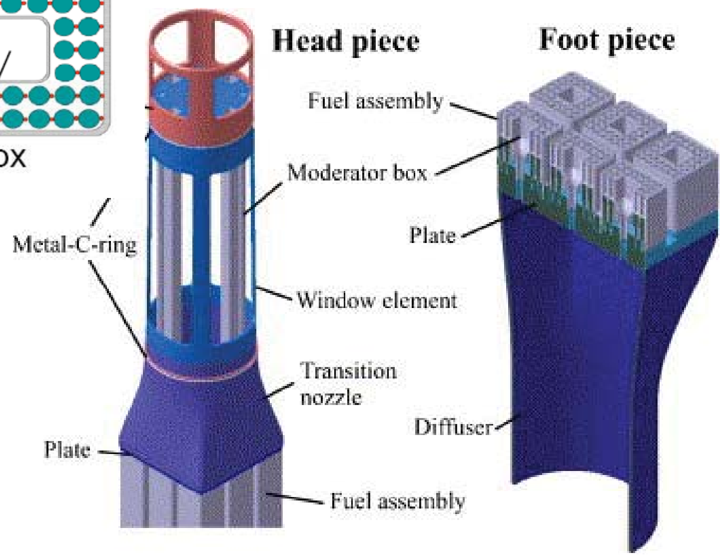
European Union's SCWR Fuel Design

Assembly Design Data:

Fuel pin diameter	8mm
p/d	1.18
wire wrap diameter	1.34mm
fuel pins per assembly	40
active length	4200mm
assembly box size	67.5mm
assembly box length	4851mm
water box	26.9mm
box material	SS 347

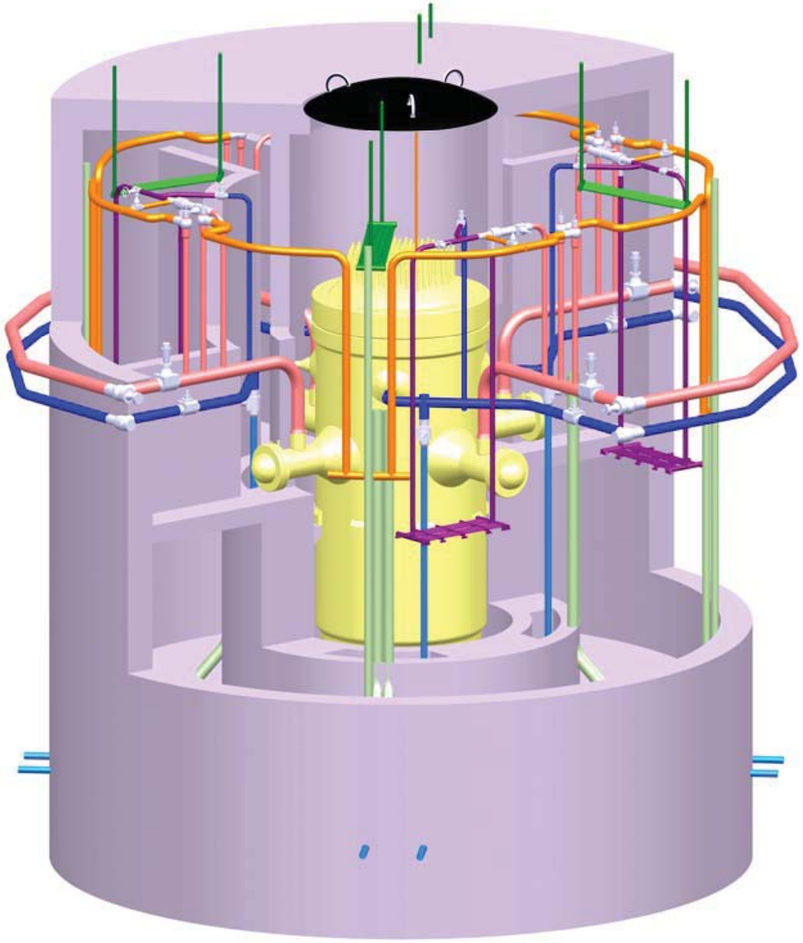


J. Hofmeister et al., 2007



European Union’s SCWR Safety System

- Based on the design of the boiling water reactors
  - No primary pumps (direct cycle)
- Feedwater or steam line breaks
  - Feedwater and steam lines closed with two containment isolation valves inside and outside of the containment
  - Reactor is shutdown while the depressurization valves open releasing the steam into upper pools
  - Residual heat is removed until one coolant injection pump is available
- Long term passive residual heat removal from the containment using containment condensers to the spent fuel pool



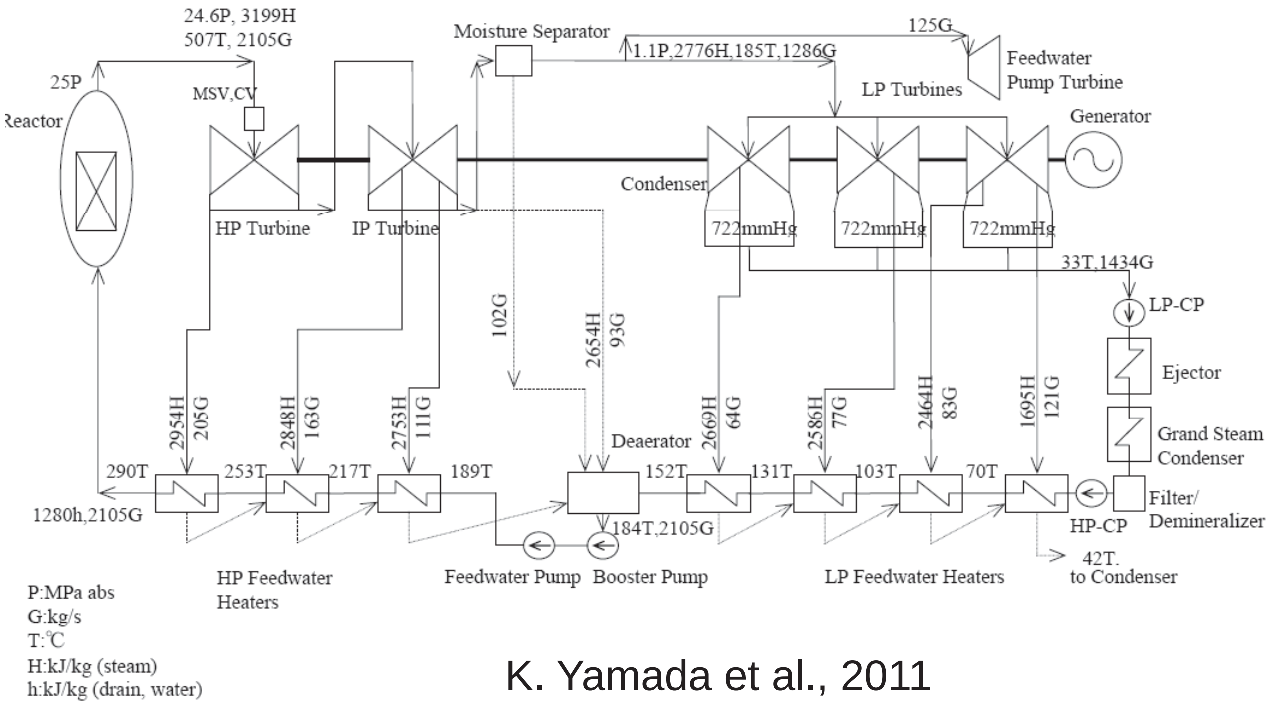
Japan’s Thermal SCWR Concepts

- Japan SCWR (JSCWR)
- Pressure vessel type
  - Thermal spectrum
  - Thermal power of 4039MW
  - Electric power of 1725MW
  - Light water cooled
  - Light water moderated
- Operating conditions
  - Pressure at 25 MPa
  - Feedwater temperature at 290°C
  - Core exit temperature at 510°C

K. Yamada et al., 2011

Japan's Thermal SCWR Thermodynamic Cycle

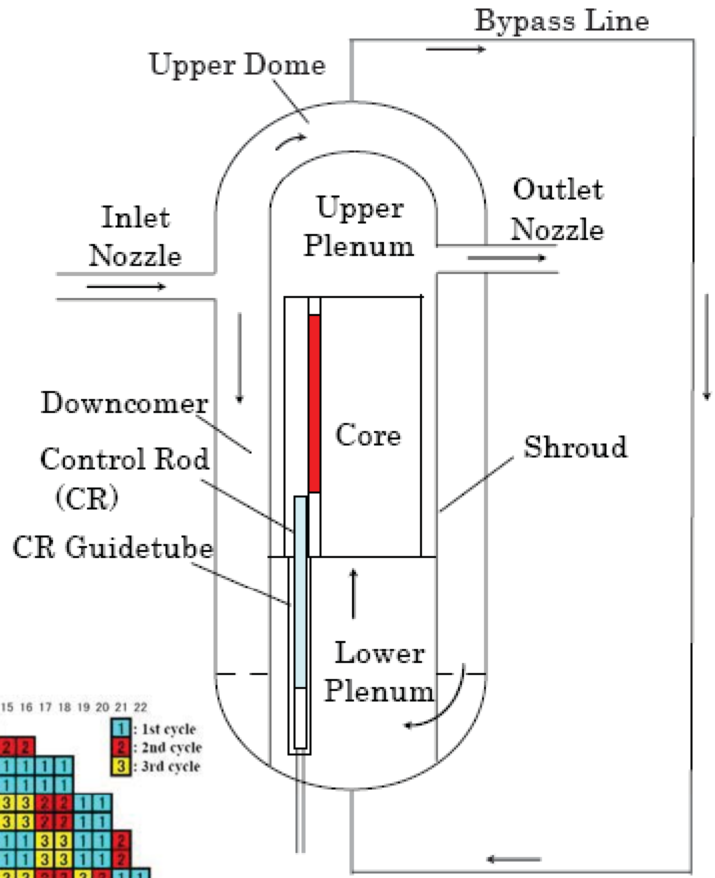
- Steam from the reactor is supplied to the high pressure turbines, then the intermediate-pressure turbines, through the moisture separator, enters the low pressure turbines
- Eight-stage system of feedwater heating consisting of mixing heaters: four low-pressure heaters, deaerator, three high-pressure heaters

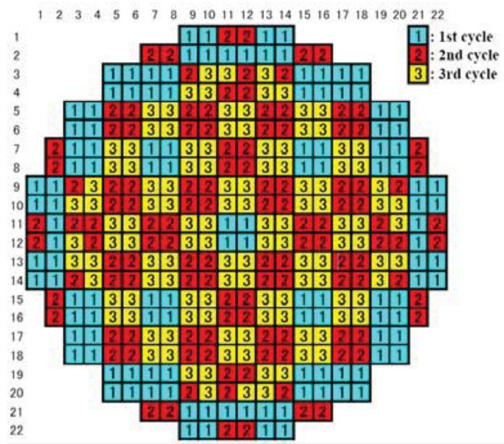


K. Yamada et al., 2011

Japan's Thermal SCWR Core Design

- Core diameter is 4.8 m
- Inlet flow splits
  - Upward to cool the dome and down to lower plenum through the gap at the other side of the core
  - Downward to lower plenum
- Single pass
  - Double-pass option
- 87 Control rods inserted from the bottom
- 372 fuel assemblies
- Three-batch fuelling

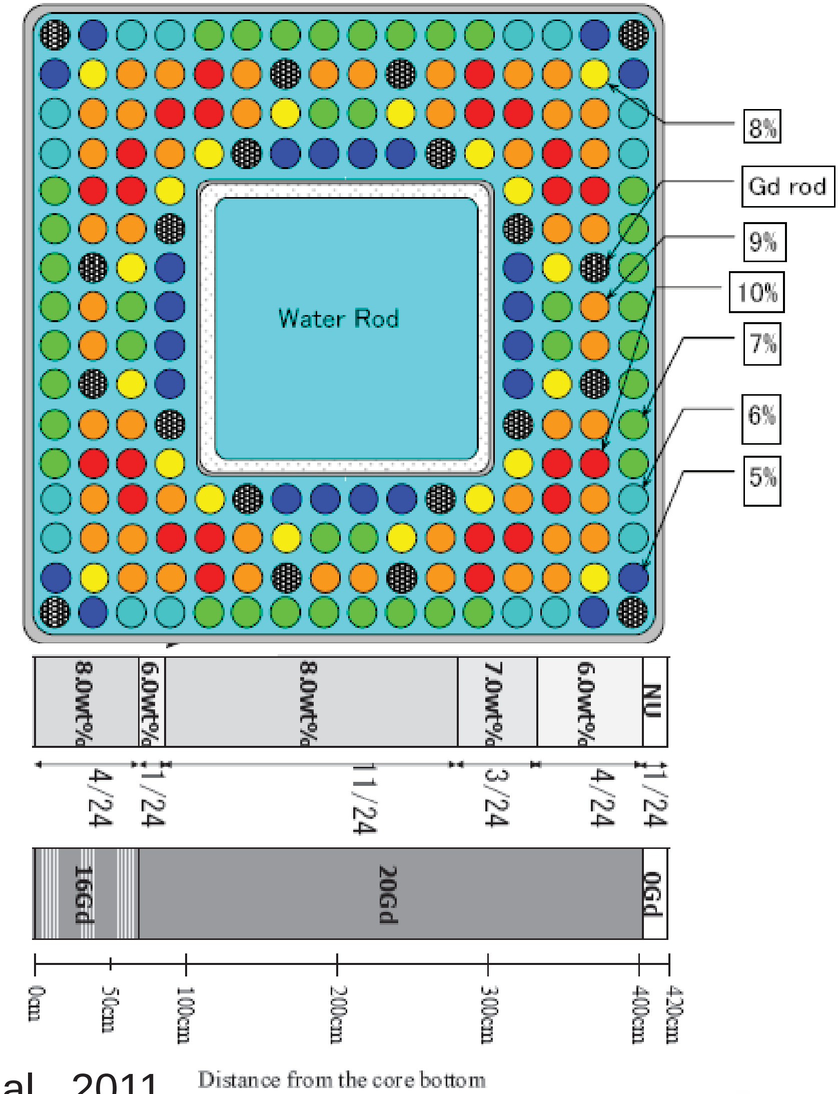




K. Yamada et al., 2011

Japan's Thermal SCWR Fuel Design

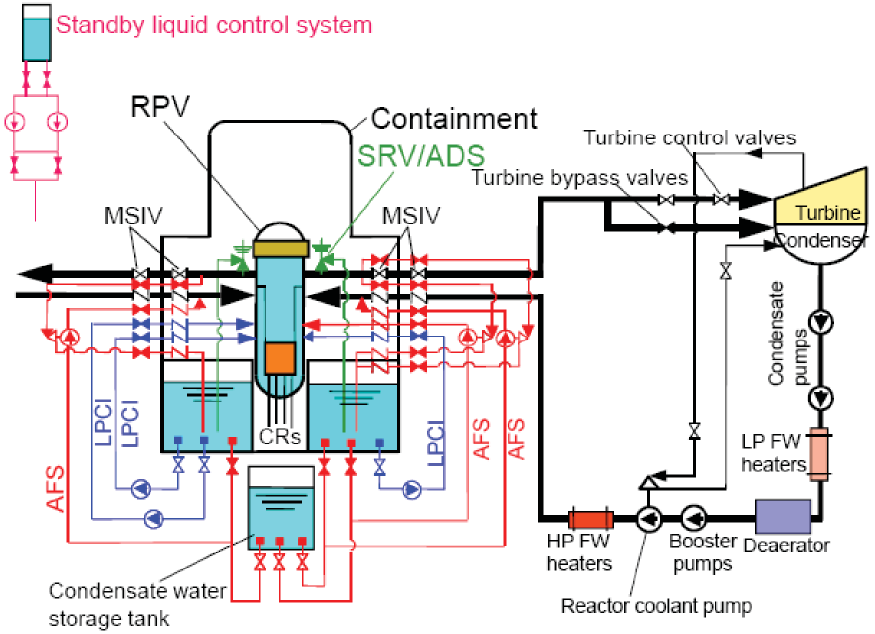
- Square-array fuel assembly
  - 137-mm by 137-mm
  - 192 7-mm fuel rods
  - 20 Gadolinia rods
  - Central square water rod
  - Graded enrichment
- Fuel rod
  - Active fuel length 4.2 m
  - UO_2 pellets
  - Graded enrichment (axial)
  - Stainless-steel "316" cladding



S. Sakurai et al., 2011

Japan's Thermal SCWR Safety System

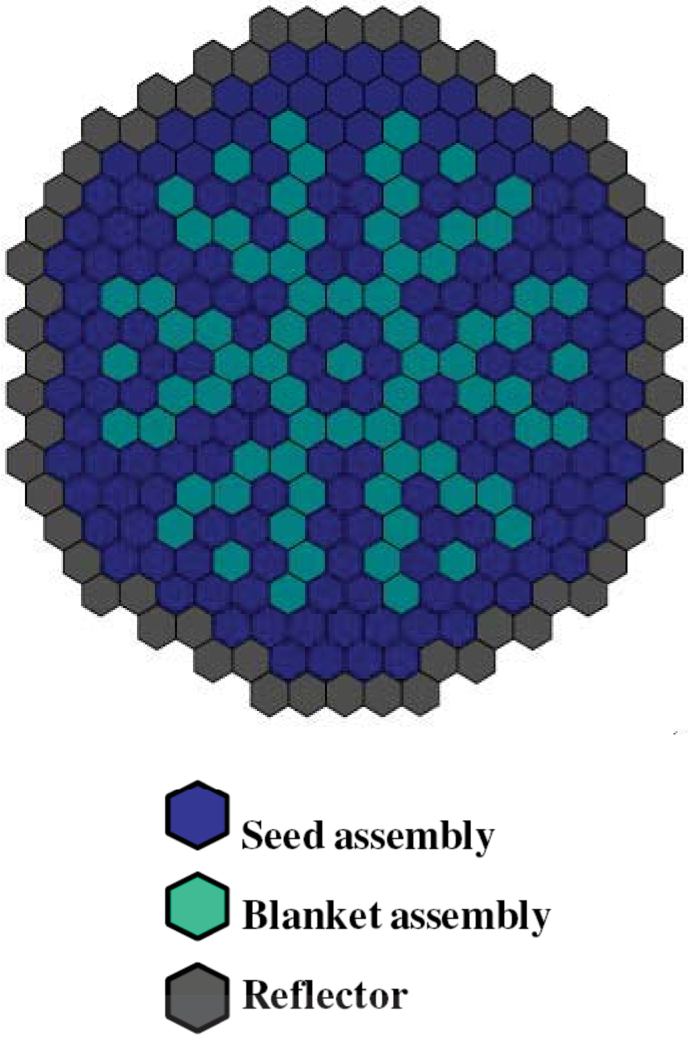
- Based on the design of the advanced boiling water reactors
- Emergency Core Cooling Systems
  - Auxiliary Feedwater System
  - Low Pressure Core Injection System
  - Automatic Depressurization System
- Reactor Shutdown System
  - Standby Liquid Control System for backup
- Coolant Supply System



Y. Ishiwatari et al., 2011

Japan's Fast SCWR Concept

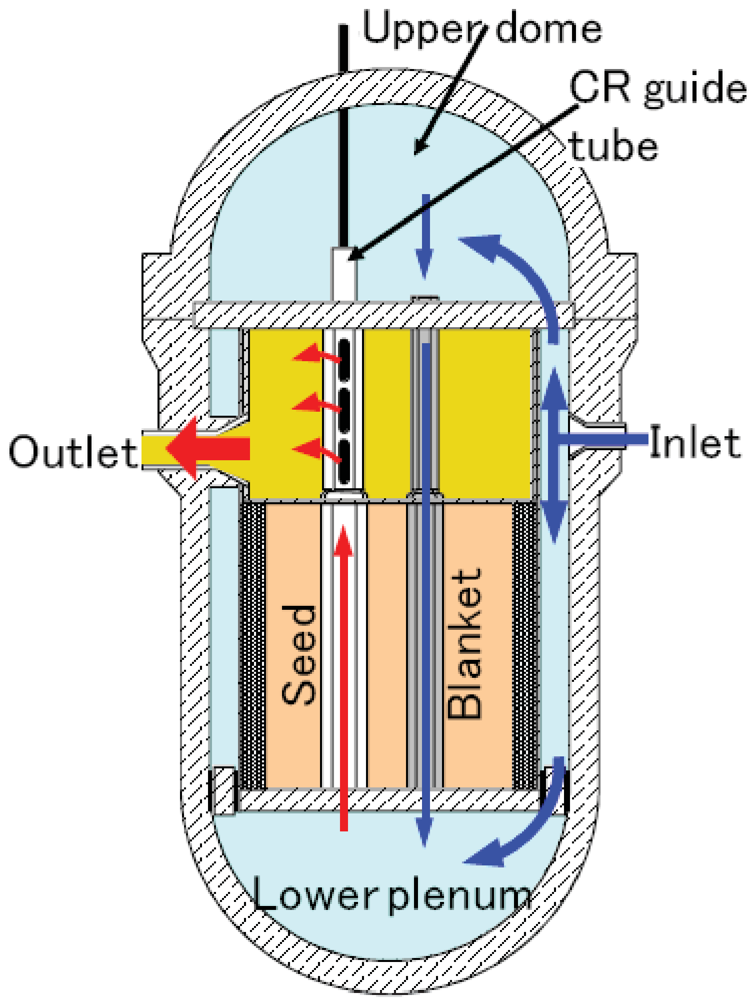
- Super Fast Reactor (Super FR)
  - High power rating and no moderator
  - Capital cost reduction
- Pressure vessel type
  - Fast spectrum
  - Thermal power of 1602 MW
  - Electric power of 705 MW
  - Light water cooled
- Operating conditions
  - Pressure at 25 MPa
  - Feedwater temperature at 280°C
  - Core exit temperature at 508°C
- Same plant systems as the JSCWR



T. Nakatsuka et al., 2010

Japan's Fast SCWR Core Design

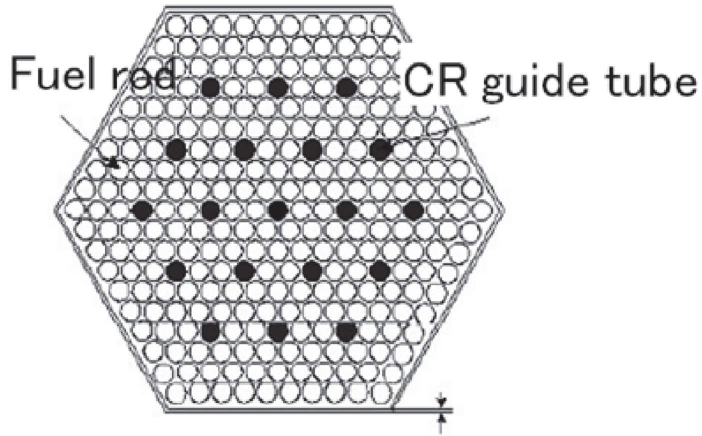
- Equivalent core diameter is 1.86 m
- Inlet flow splits
  - Upward to cool the dome and down to lower plenum through the blanket assemblies
  - Downward to lower plenum
- Flow mixed in the lower plenum and travelled upward through the seed assemblies to outlet
- 162 seed and 73 blanket assemblies



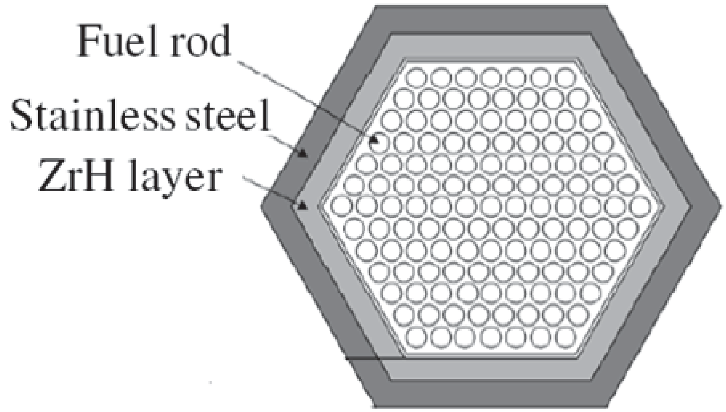
T. Nakatsuka et al., 2010

Japan's Fast SCWR Fuel Design

- Hexahedral assemblies
- Seed assemblies
  - 252 5.5-mm fuel rods
  - MOX fuel
  - 19 0.55-mm control rods
- Blanket assemblies
  - 127 5.5-mm fuel rods
  - Depleted uranium fuel
  - Solid moderator in blanket
- Active fuel length is 2 m
- Stainless steel cladding



(a) Seed fuel assembly

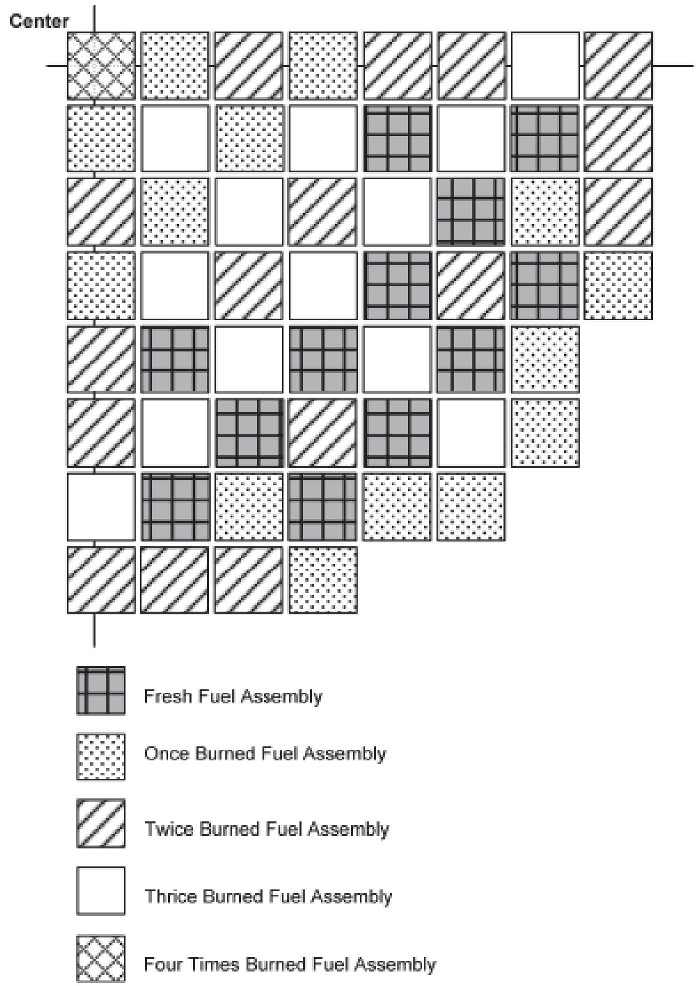


(b) Blanket fuel assembly

T. Nakatsuka et al., 2010

Korea's SCWR Concept

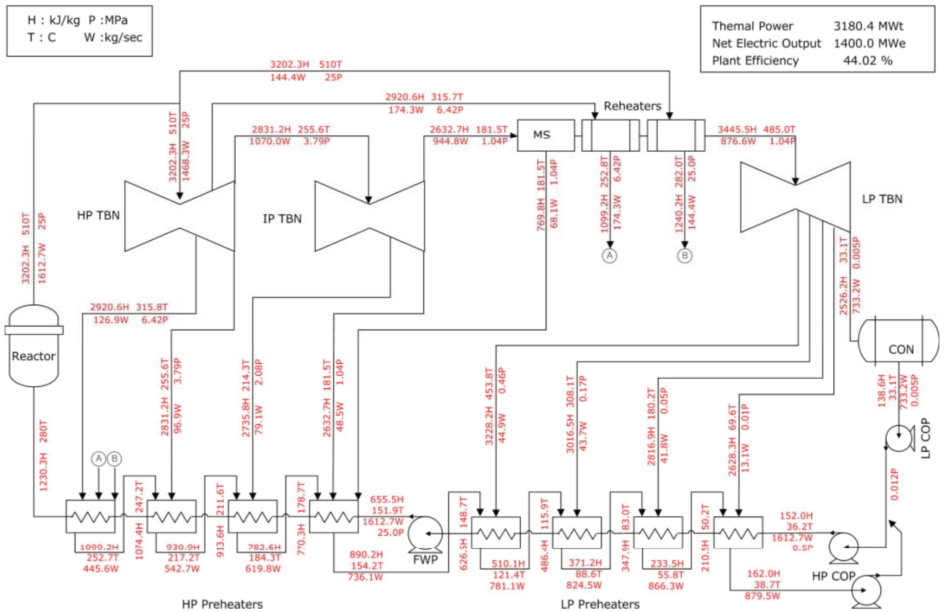
- Pressure vessel type
  - Thermal power of 3182MW
  - Electric power of 1400MW
- Operating conditions
  - Pressure of 25 MPa
  - Core outlet temperature 510^{o}C
- 193 fuel assemblies
  - Four-batch fuel loading
- Solid moderator rods
- Development has been discontinued



K. M Bae et al., 2007

Korea's SCWR Thermodynamic Cycle

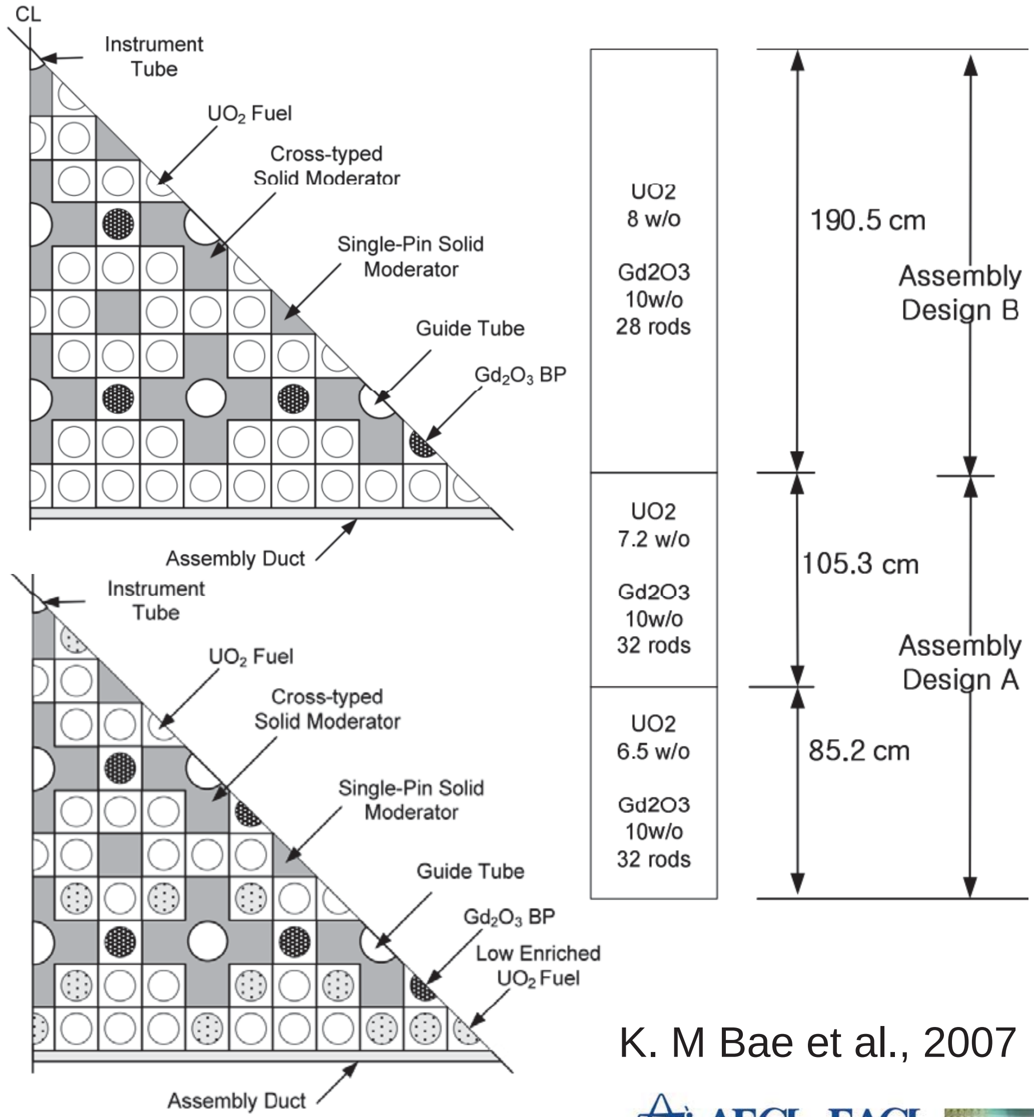
- Two-stage reheat and 8-stage regenerative system
- Steam from the reactor is supplied to the high pressure turbines, then the intermediate-pressure turbines, through the moisture separator and reheaters, enters the low pressure turbines.



K. M Bae et al., 2007

Korea's SCWR Fuel Design

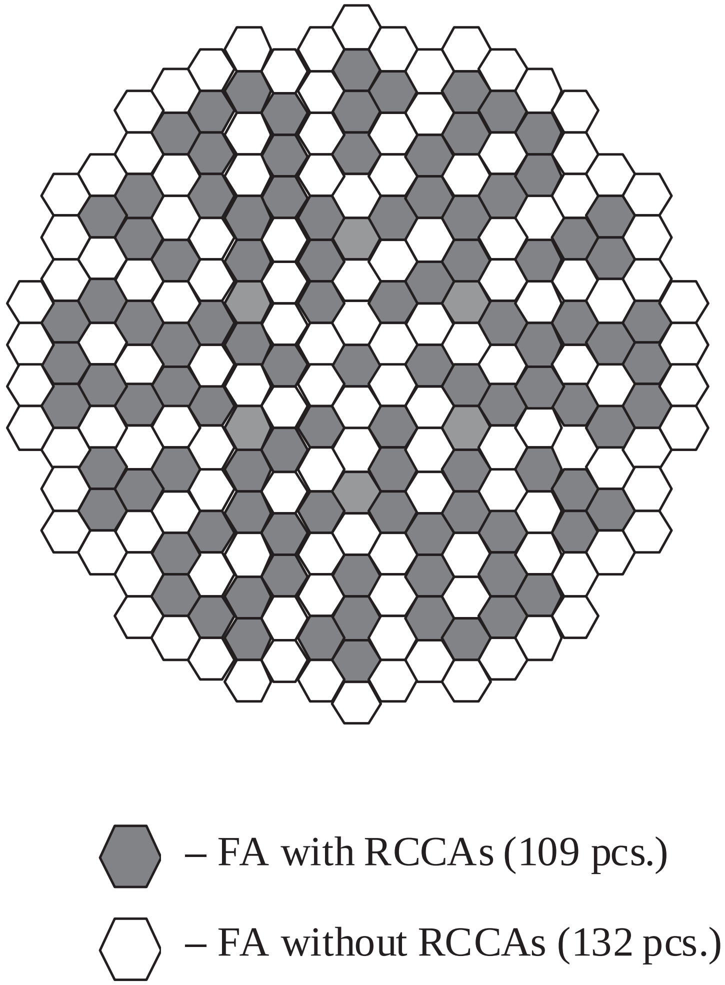
- 381 cm active length
- Comprises two assemblies
  - UO$_2$ fuel with 3 enrichments
- 21x21 rods array
  - 300 fuel rods
  - 25 cruciform-typed solid moderator pins
  - 16 single pins of the solid moderator
  - Gadolinium as burnable poison



K. M Bae et al., 2007

Russia's SCWR Concept

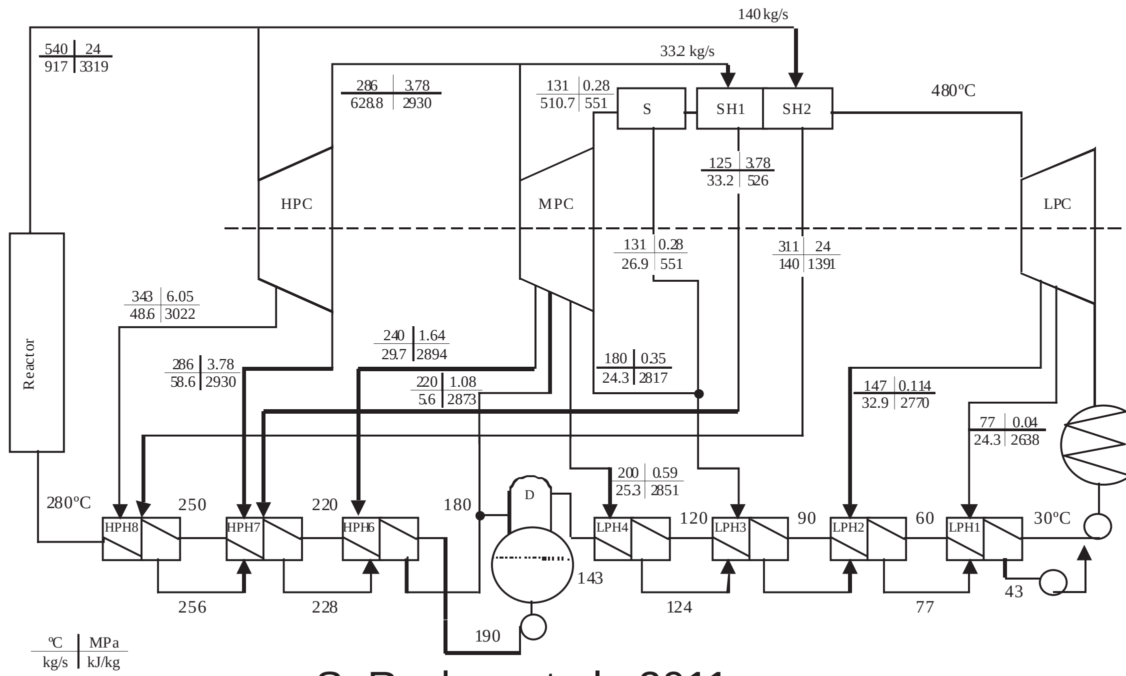
- VVER-SCP
  - Computational studies at SSC RF IPPE
  - Design efforts at OKB "GIDROPRESS"
- Pressure vessel type
  - Fast spectrum
  - Thermal power of 3830 MW
  - Electric power of 1890 MW
  - Breeding factor 0.9-1
- Operating conditions
  - Pressure at 24.5 MPa
  - Core exit temperature at 540^{o}C



S. Ryzhov et al., 2011

Russia's SCWR Thermodynamic Cycle

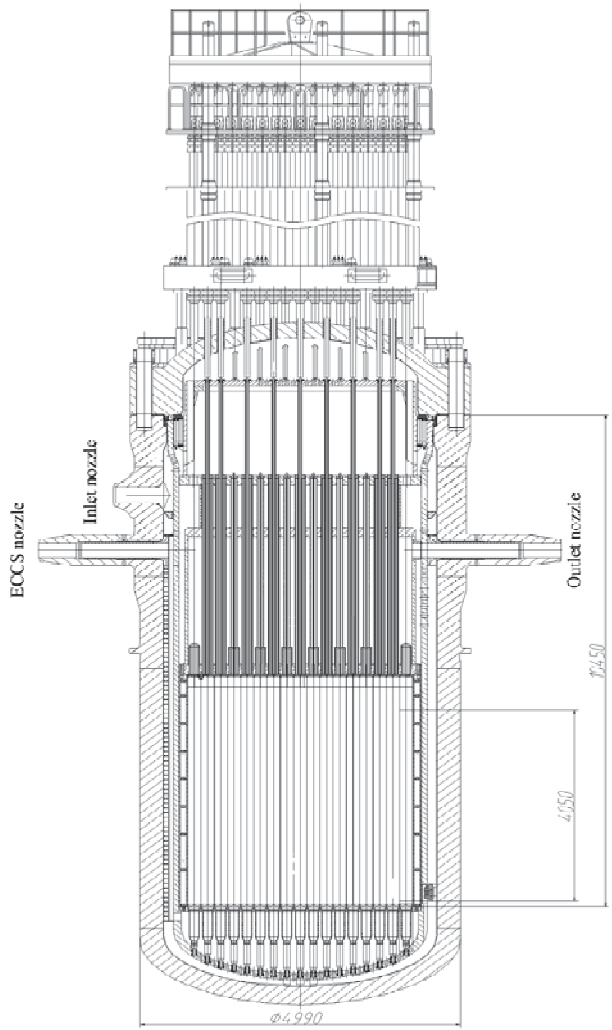
- Steam from the reactor is supplied to the high pressure turbines, then the intermediate-pressure turbines, through the moisture separator and reheaters, enters the low pressure turbines.
- Eight-stage system of feedwater heating that consists of mixing heaters: four low-pressure heaters, deaerator, three high-pressure heaters.



S. Ryzhov et al., 2011

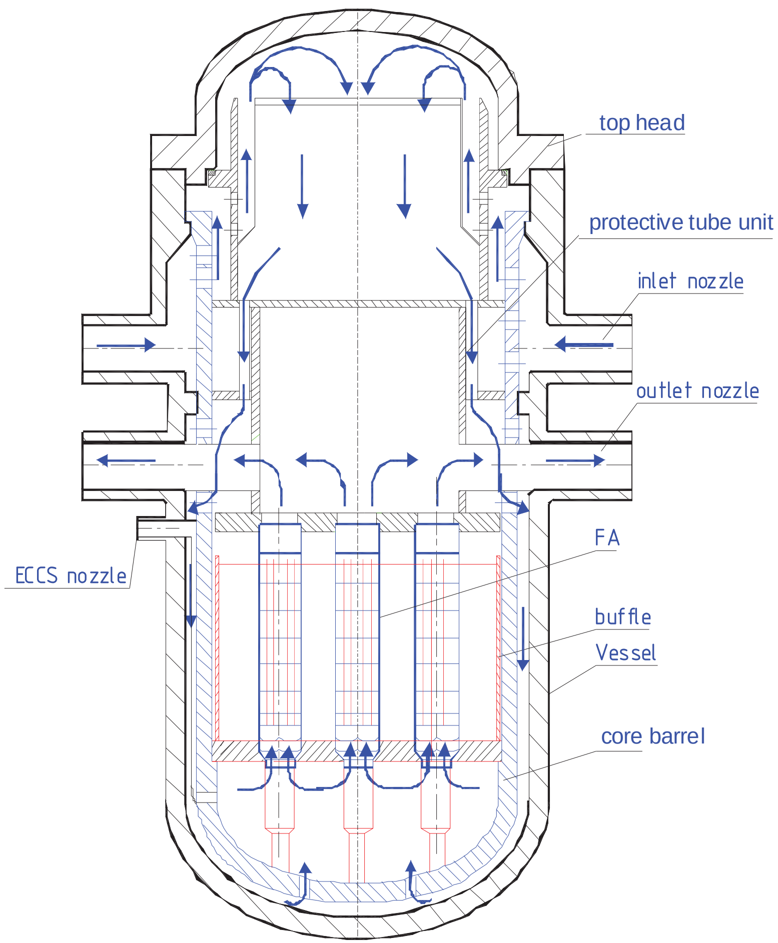
Russia's SCWR Core Design

- Equivalent core diameter is 3.6 m
- 241 fuel assemblies
- Two core flow-path options
  - Single pass
  - Double pass
- Single pass
  - Sandwich-type core with MOX-fuel layer (0.9 m) and mixed depleted uranium and zirconium hydride layer
  - avoid the positive void reactivity effect
- Double pass
  - Under development

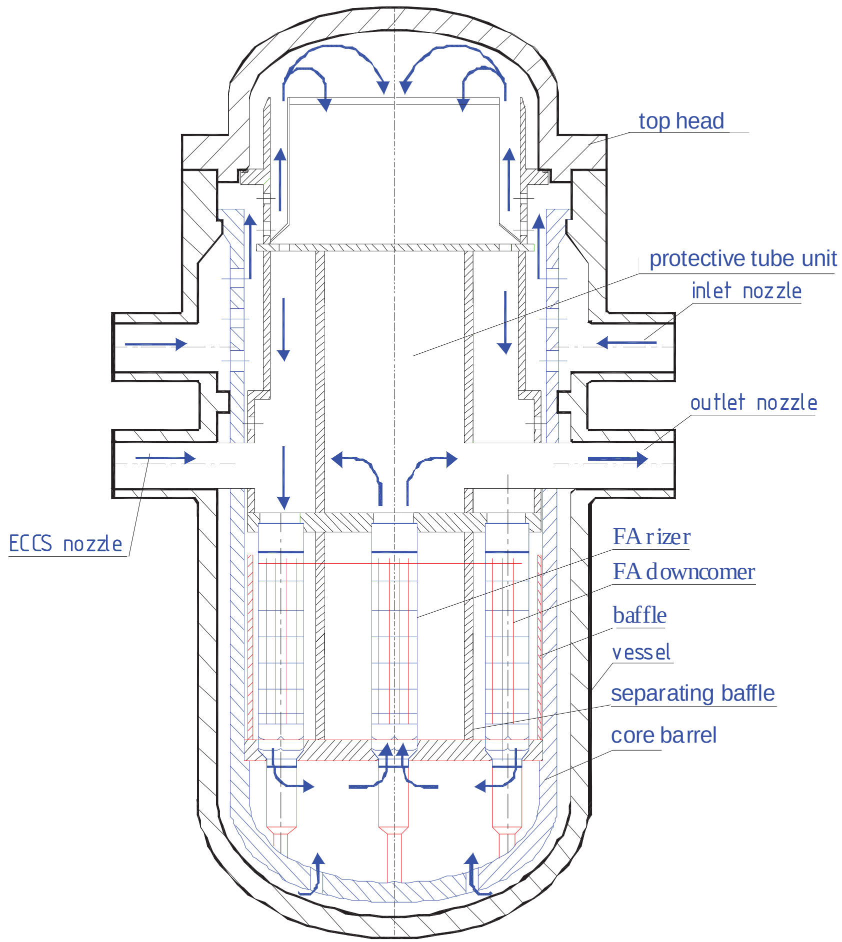


S. Ryzhov et al., 2011

Russia's SCWR Core Flow Path Options



Single-Pass Flow

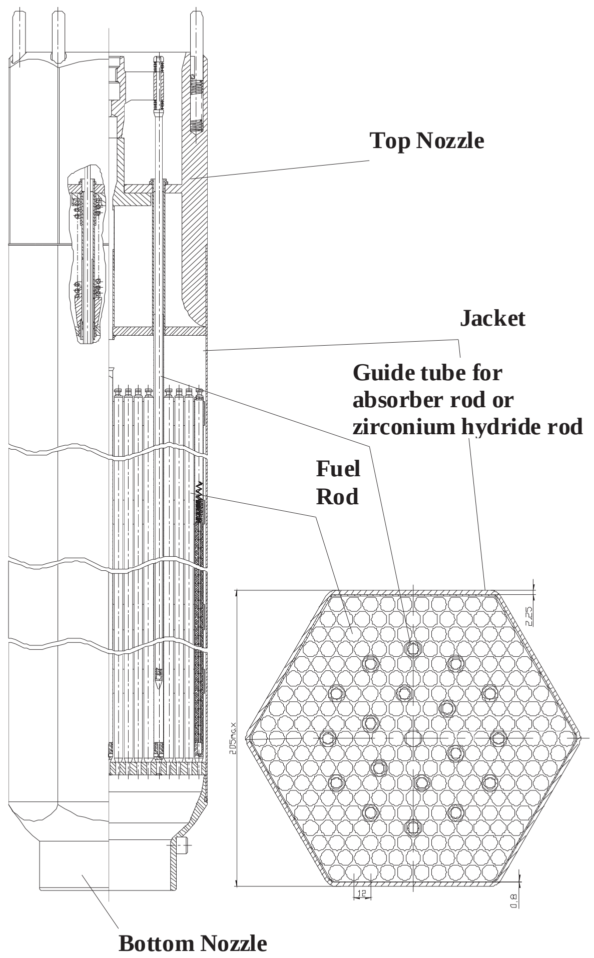


Double-Pass Flow

S. Ryzhov et al., 2011

Russia's SCWR Fuel Design

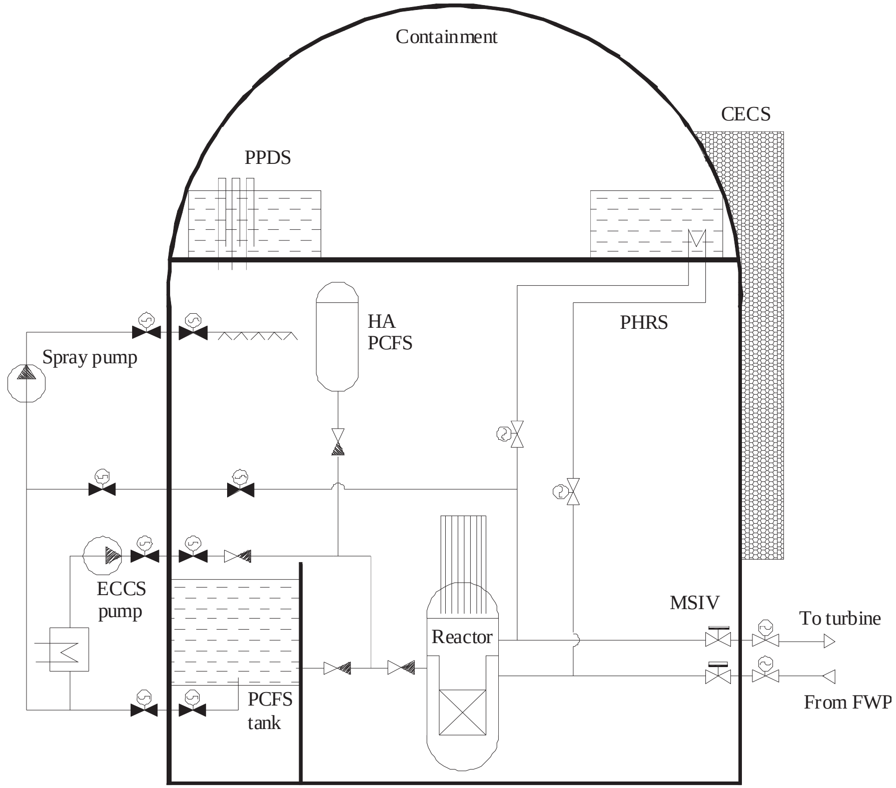
- Jacketed hexahedral fuel assembly
  - 252 10.7-mm fuel rods
  - 18 12-mm guide tubes for control rods of the rod cluster control assemblies (RCCA)
  - One 12-mm central tube
  - 2.25-mm jacket thickness
- Wire-wrapped spacing spirals
- Active fuel length
  - 4.07 m for single pass
  - 3.76 m for double pass



S. Ryzhov et al., 2011

Russia's SCWR Safety System (1)

- One of three coolant circulation loops and one channel of the safety system is shown for
  - Containment isolation (MSIV)
  - Passive residual heat removal from the core (PHRS)
  - Emergency core cooling system and reactor makeup (PCFS accumulators and tanks, ECCS pumps)
  - Prevention of pressure increase in the containment (PPDS, spray system)
  - Heat removal from the containment (CECS)



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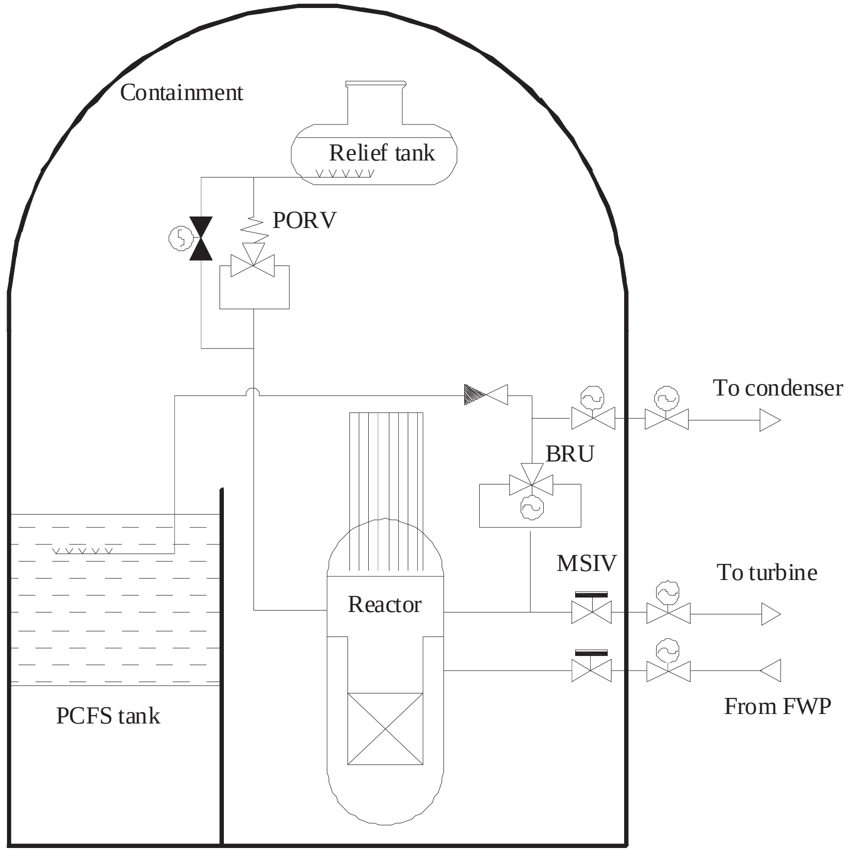
Russia's SCWR Safety System (2)

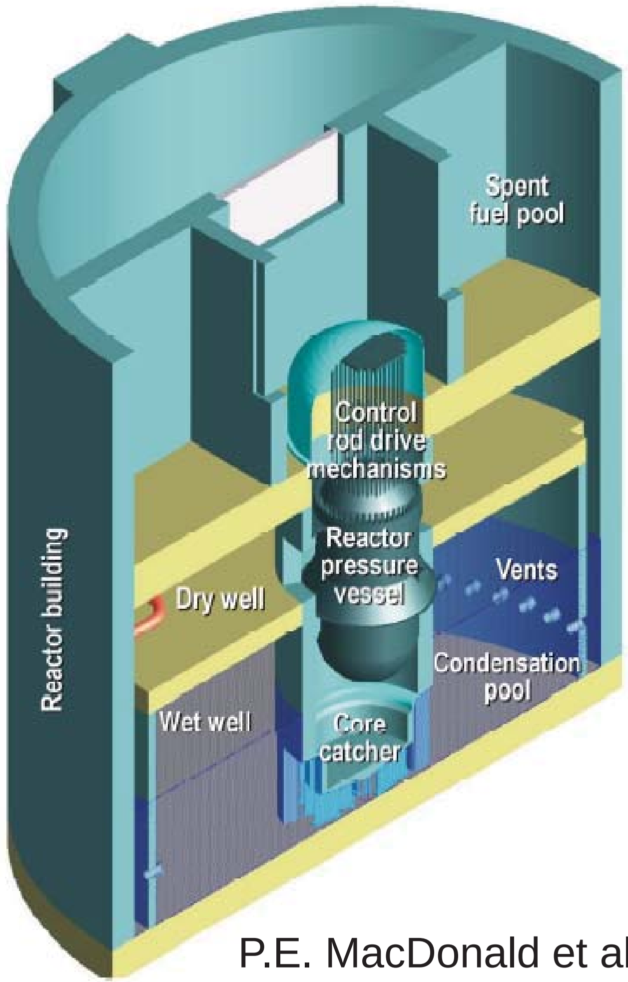
- One channel of the safety system is shown for
  - Pressure decrease system under emergency conditions (BRU)
  - Pressure limitation system in the reactor (PORV)



S. Ryzhov et al., 2011

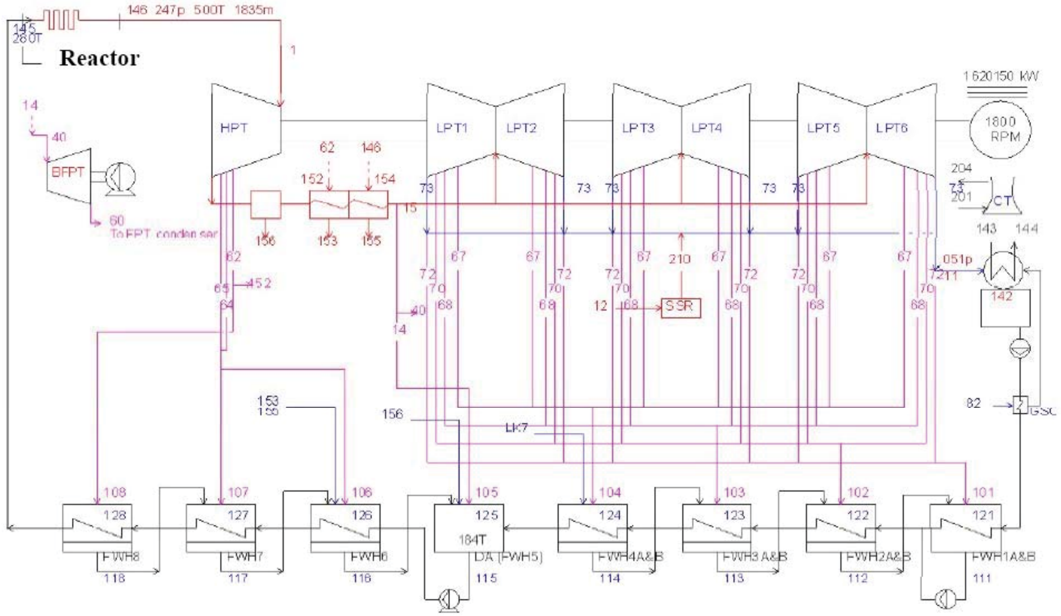
United States' SCWR Concepts

- Pressure vessel type
  - Thermal spectrum
  - Thermal power of 3575MW
  - Electric power of 1600MW
  - Light water cooled
  - Light water moderated
- Operating conditions
  - Pressure at 25 MPa
  - Feedwater temperature at 280^{o}C
  - Core exit temperature at 500^{o}C
- Program discontinued



P.E. MacDonald et al., 2005

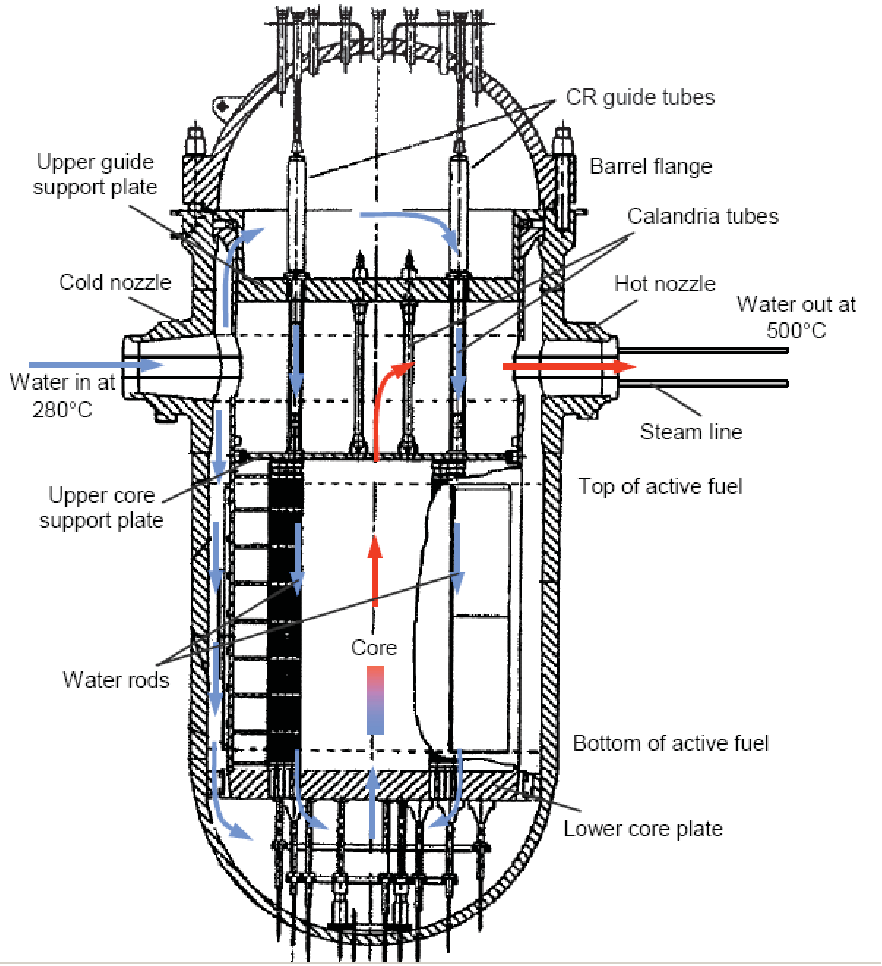
- Steam from the reactor is supplied to the high pressure turbines, through the moisture separator and reheaters, enters the low pressure turbines.
- Eight-stage system of feedwater heating that consists of mixing heaters: four low-pressure heaters, deaerator, three high-pressure heaters.



P.E. MacDonald et al., 2005

United States' Thermal SCWR Core Design

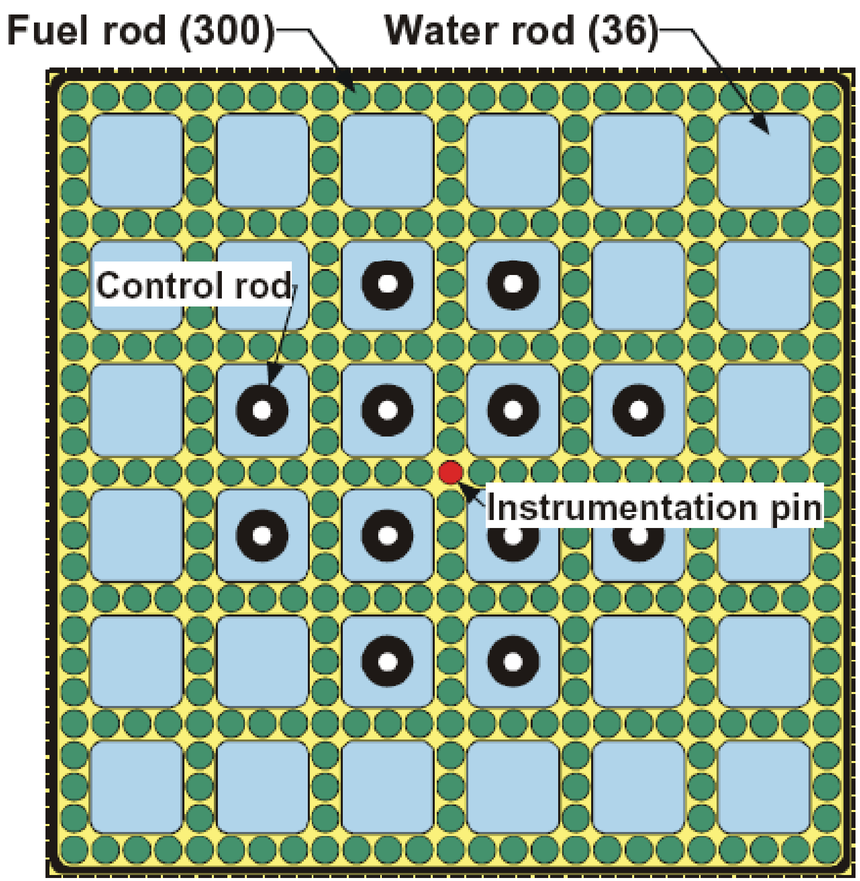
- Equivalent core diameter is 3.93 m
- Inlet flow splits
  - Upward to cool the dome and down through the gap between assemblies
  - Downward to lower plenum
- Flow mixed in the lower plenum and travelled upward through the fuel assemblies to outlet
- 16 control rods inserted from the top
- 145 fuel assemblies



P.E. MacDonald et al., 2005

United States' SCWR Fuel Design

- Square-array fuel assembly
  - 286-mm overall size
  - 300 10.2-mm fuel rods
  - 36 square water rods
  - Grid spacers (~14)
- Fuel rod
  - Active fuel length 4.27 m
  - UO_2 pellets
  - 5% enrichment
  - Gadolinium as burnable poison
  - Low swelling austenitic stainless-steel cladding



P.E. MacDonald et al., 2005

Conclusions

- 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 the thermal spectrum cores
- Design challenges, particularly cladding material selection
  - Improvement in heat-transfer prediction could ease the cladding material requirement

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