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IAEA International Atomic Energy Agency

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Joint ICTP-IAEA Course on Science and Technology of Supercritical Water Cooled Reactors

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SCWR CORE DESIGN 2: LWR TYPE

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SCWR Core Design 2: LWR Type

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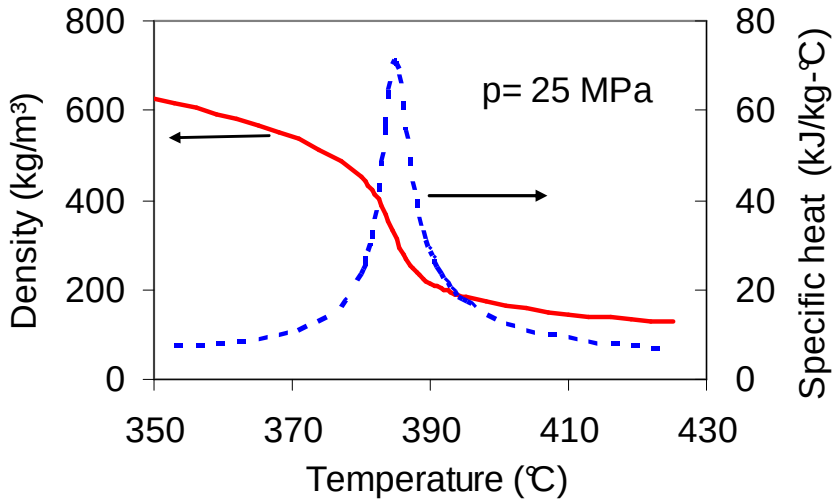
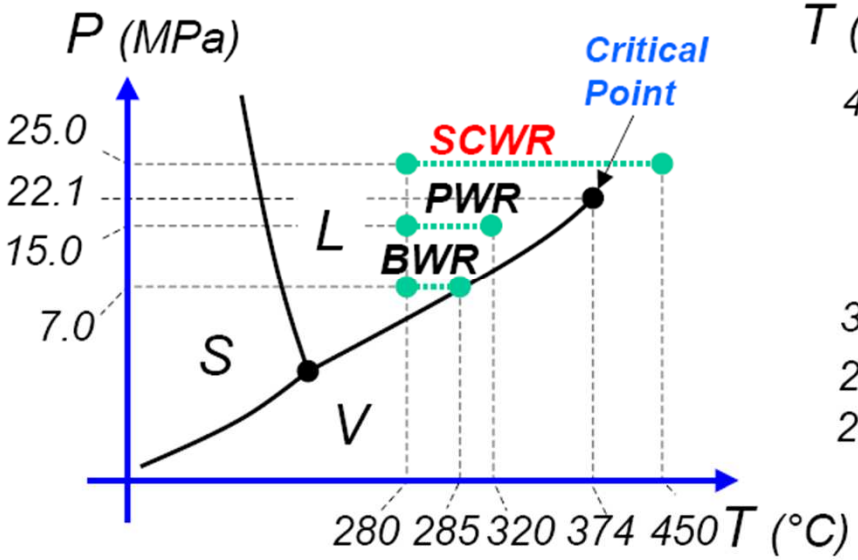
Shanghai Jiao Tong University

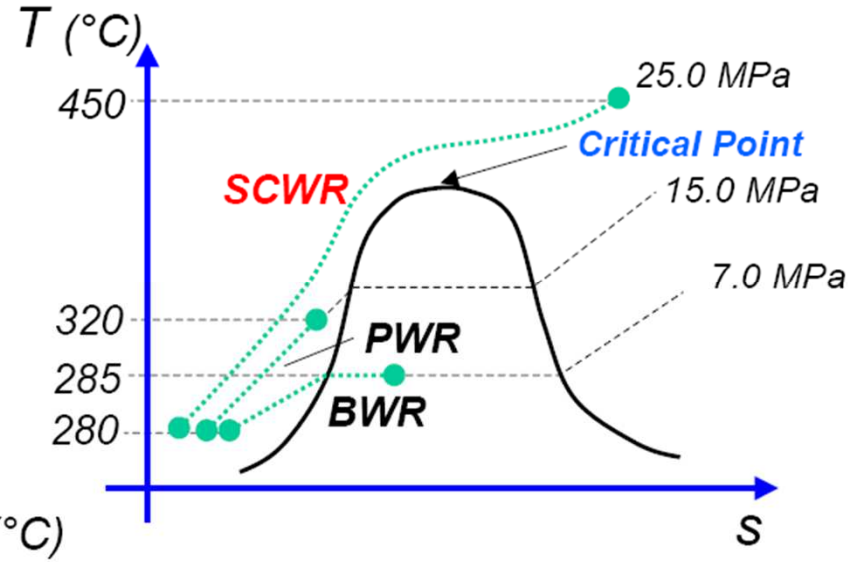
Objectives

- Contrast and compare with existing LWR designs
- Introduce various SCWR designs based on LWR technology
- Compare a thermal-, fast-, and mixed-neutron spectra cores

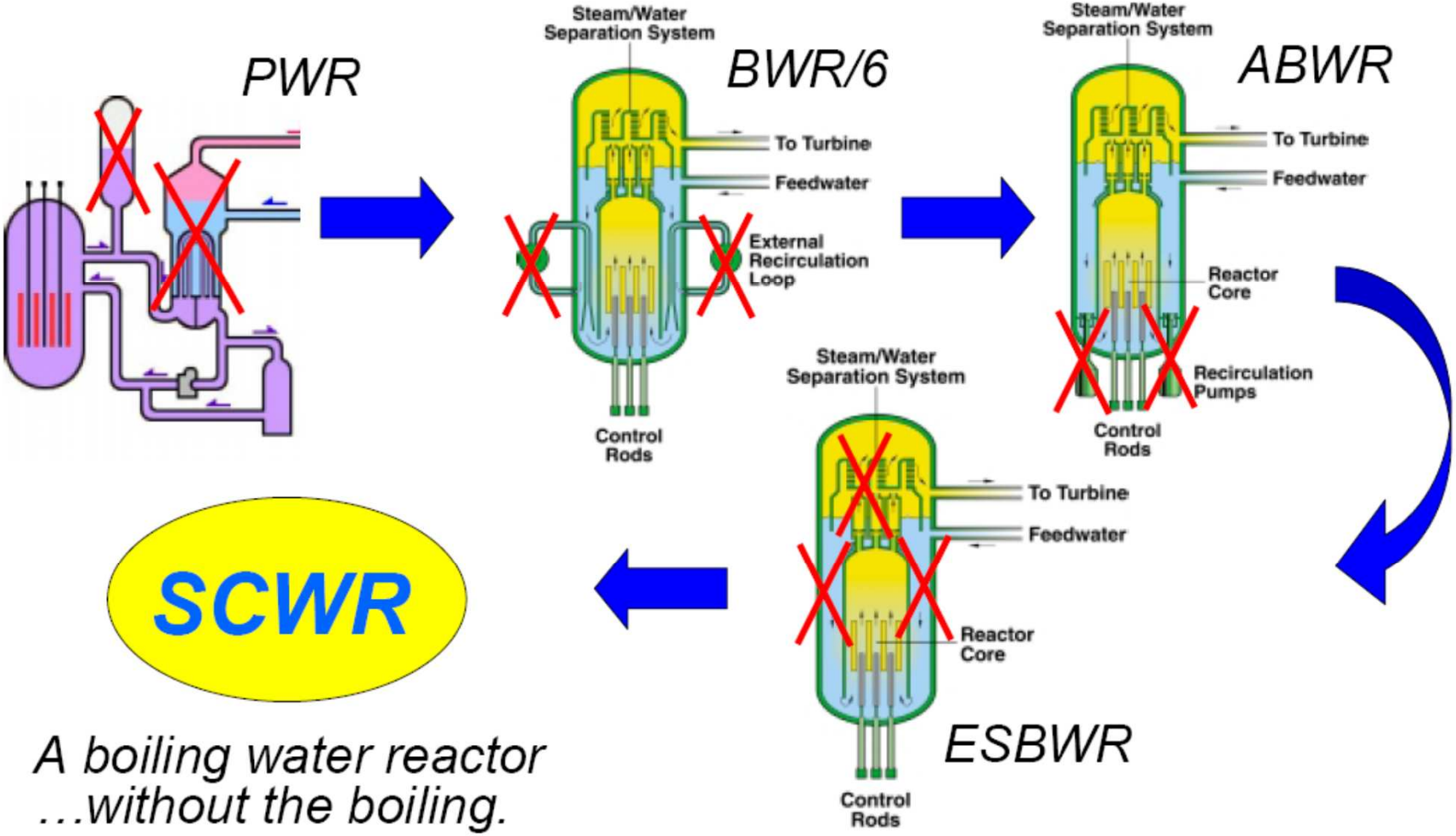
Supercritical water character







Comparing to the current LWR

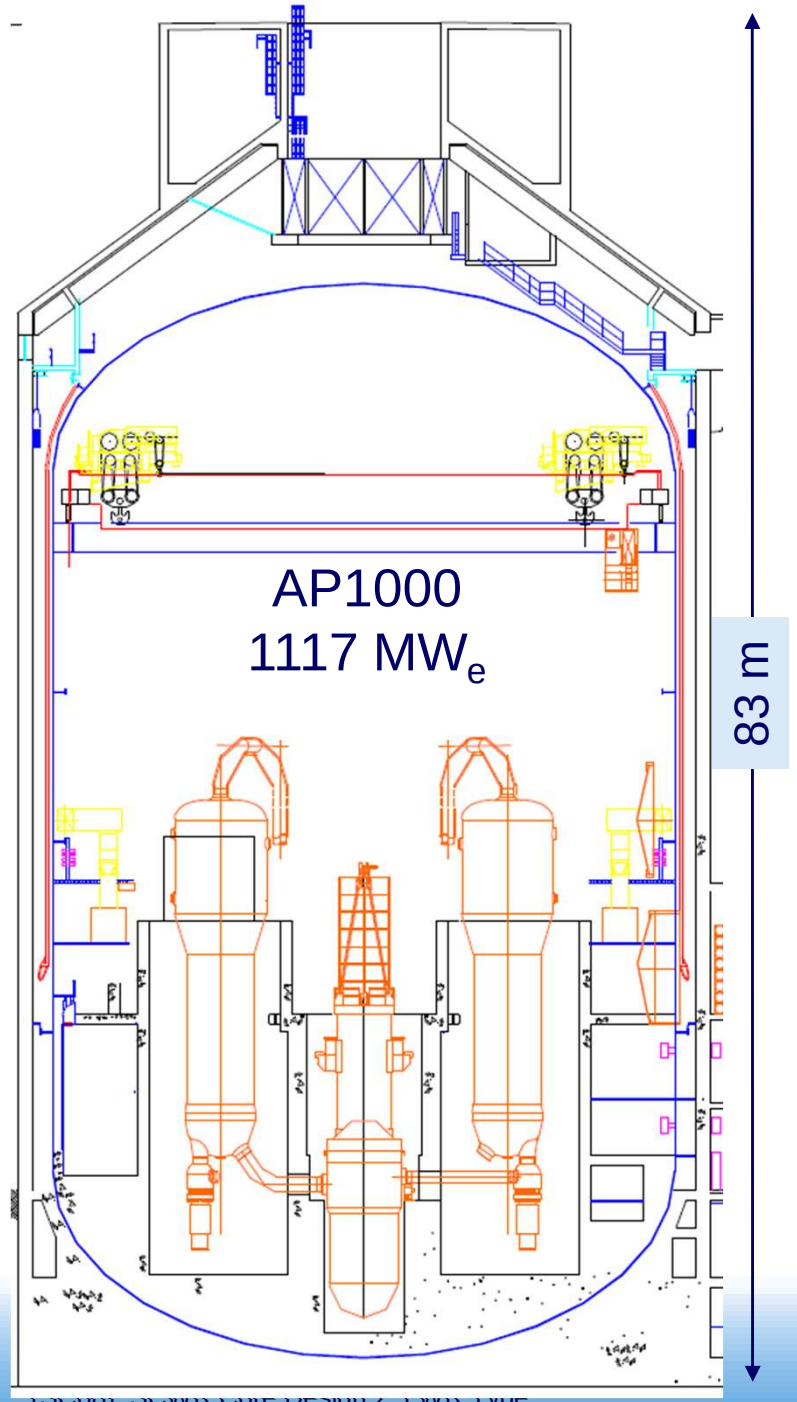


A boiling water reactor
…without the boiling.

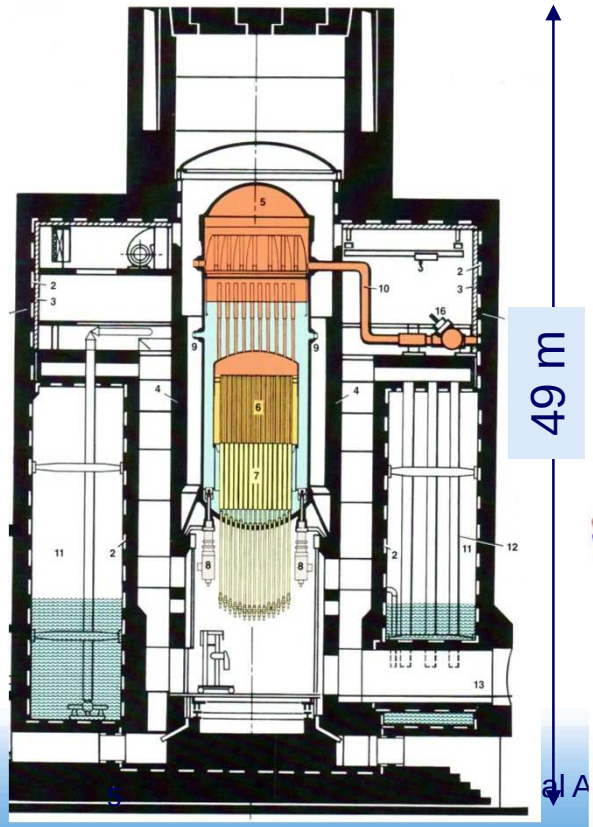
Advantage: Lower Costs

Comparison of Containment Size

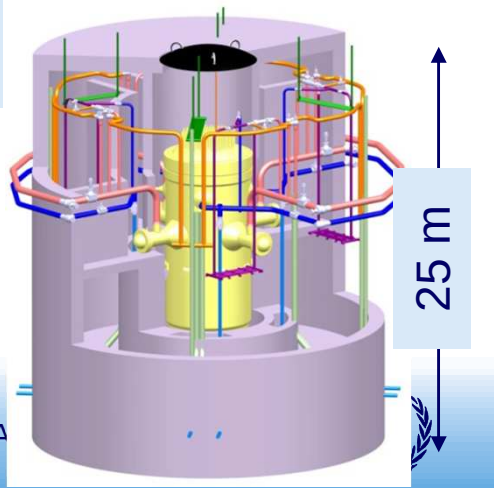
- same scale -



BWR
1284 MW$_e$



SCWR
1000 MW$_e$



Comparing to the current LWR

- Simple & compact plant systems
- No water/steam separation
- Low flow rate(1/10), high enthalpy coolant
- High temperature & thermal efficiency (510 C, ~44%)
- Flexibility of the neutron spectrum, increase the utilization of the fuel
- Utilizations of current LWR and Supercritical FPP technologies
- Major components are used within the temperature range of past experiences

Comparing to the current LWR(FA)

Parameter \ Type	AP1000	EPR	ESBWR	SCWR*
Fuel diameter (mm)	9.5	9.5	10.26	10.2
Pitch (mm)	10.8	12.6	12.95	11.2
Cladding thickness (mm)	0.57	0.625	3.2	0.63
Cladding material	ZIRLO™	Zircaloy	Zircaloy-2	Stainless Steel
Fuel arrangement	17×17 square	17×17 square	10×10 square	25×25 square
Fuel rod No./ FA	264	264	92	300
Average linear heat (w/cm)	188	154.9	151	180
FA assembly size (mm)	210	215.04	-	292.2
Fuel enrichment (%)	0.74-4.235	-5%:UO2 -7.4%:MOX	-	4.0-6.2
Active height (m)	4.27	4.2	3.0	4.2

Comparing to the current LWR (Core)

Parameter \ Type	AP1000	EPR	ESBWR	SCWR*
Fuel bundle number	157	241	1132	121
Core diameter (m)	3.04	3.767	5.883	3.73
Thermal power (MW)	3400	4250	4500	2744
Electricity power (MW)	1090	1500	1600	1200
Pressure (MPa)	15.51	15.5	8.62	25
Coolant flow rate (t/h)	48488	75347	34453	5104.8
Coolant inlet temp. (C)	279.4	295.3	269-272	280
Coolant outlet temp. (C)	322.3	328.2	288	500

**Japan thermal design Kamei, et al., ICAPP'05, Paper 5527*

Challenges of SCWR

- Extreme operating conditions

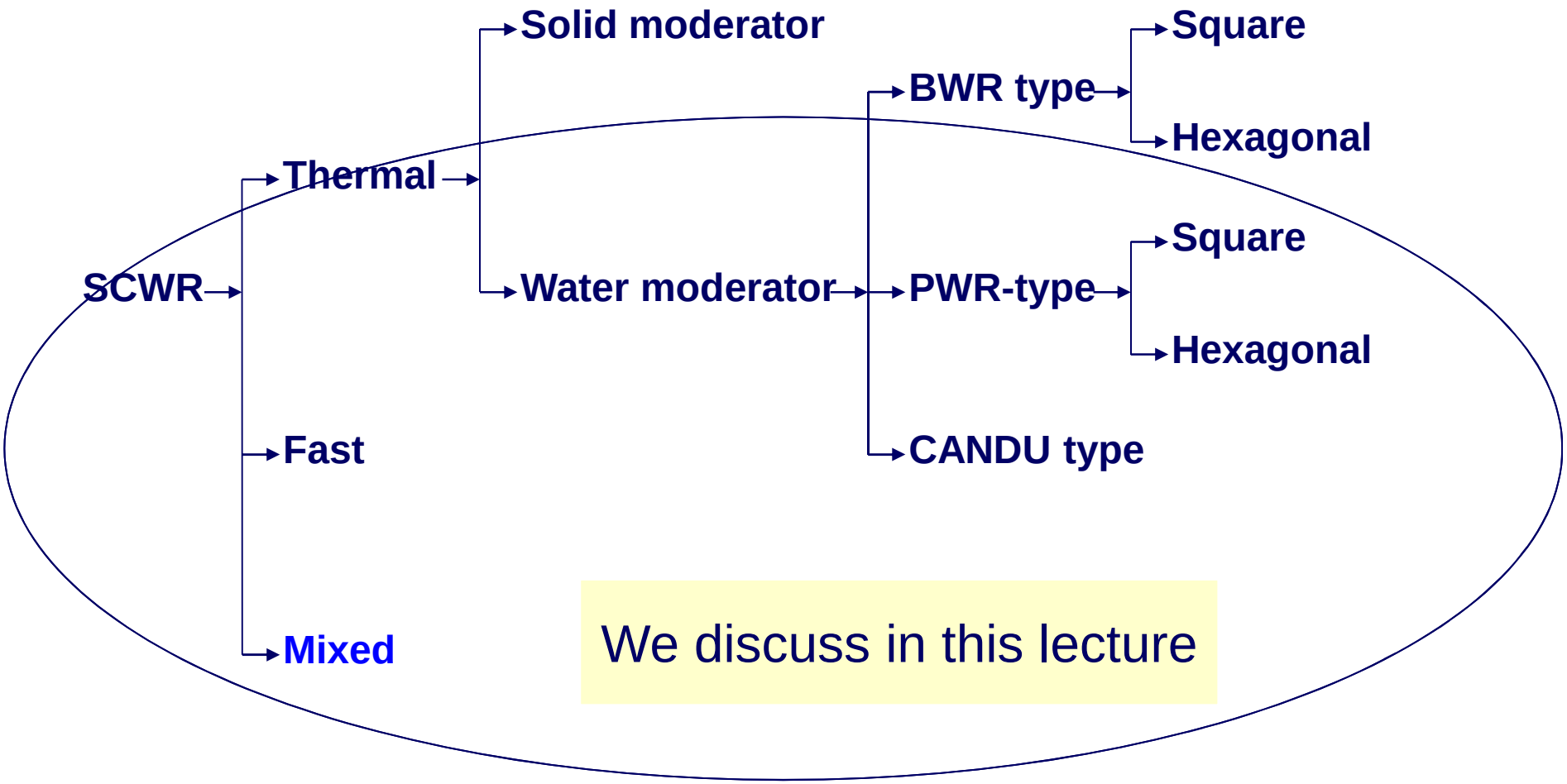
- High pressure
- high temperature
- high heat flux
- neutron irradiation

- Challenges in core/fuel assembly design

- Large property variation
- non-uniformity of moderation
- sensitive to hot channel factor
- non-uniformity of local heat transfer
- upper limit of cladding temperature

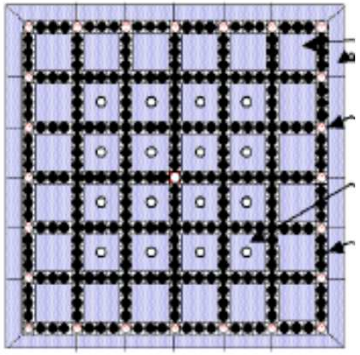
Large number of FA and Core designs

FA design summary

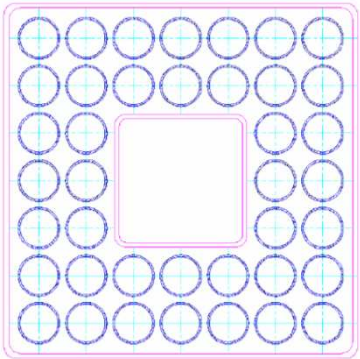


We discuss in this lecture

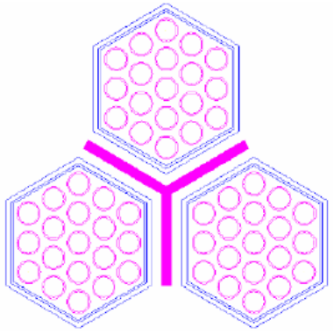
SCWR FA design examples



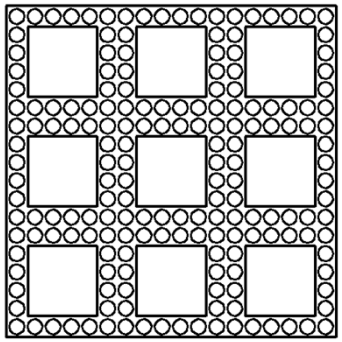
Japan



Europe

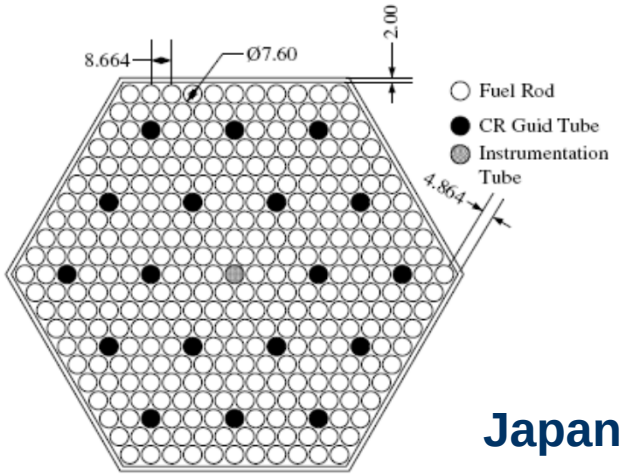


USA

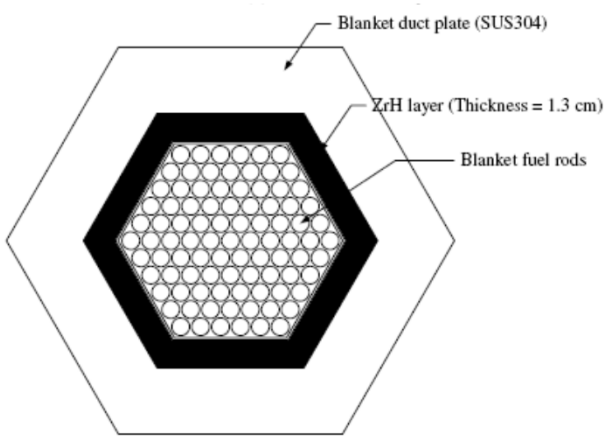


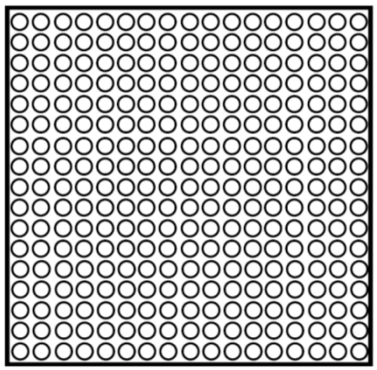
China

Thermal design



Japan



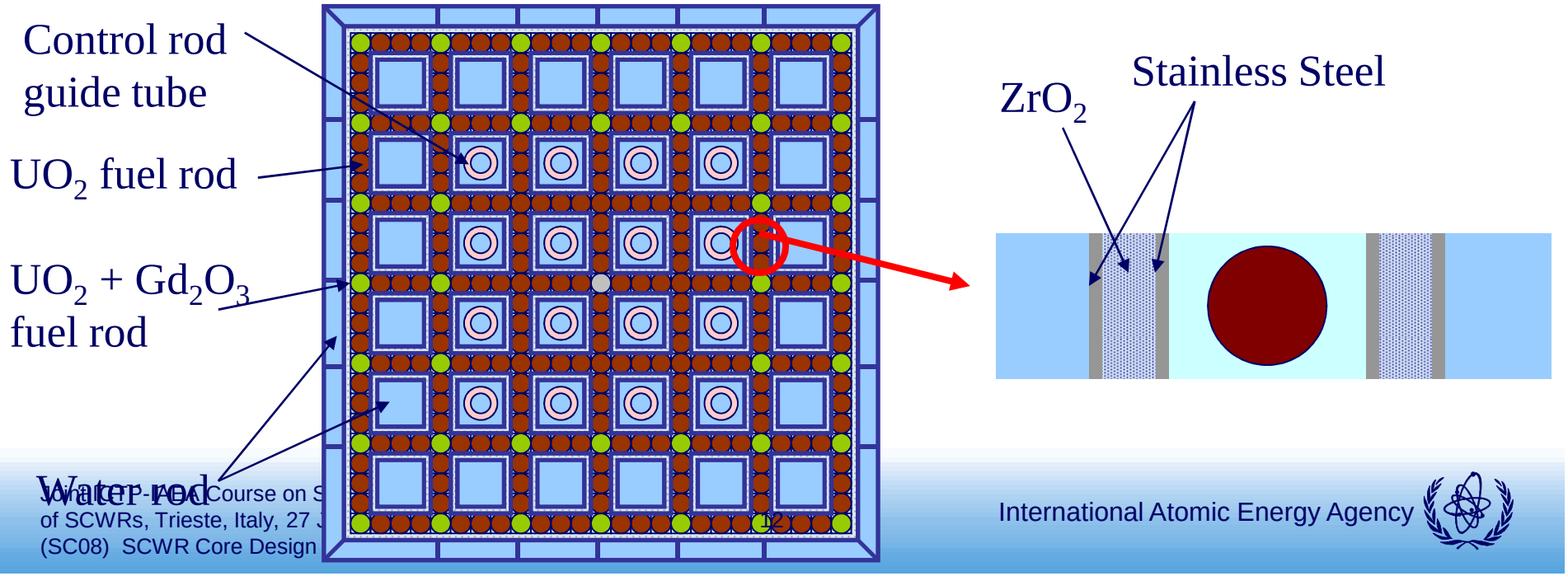


China

Fast design

SCWR core design examples FA design

Design requirements →	Solution
Low flow rate per unit power (< 1/8 of LWR) due to large ⊿T of once-through system	Narrow gap between fuel rods to keep high mass flux
Thermal spectrum core	Many/Large water rods
Moderator temperature below pseudo-critical	Insulation of water rod wall
Reduction of thermal stress in water rod wall	
Uniform moderation	Uniform fuel rod arrangement

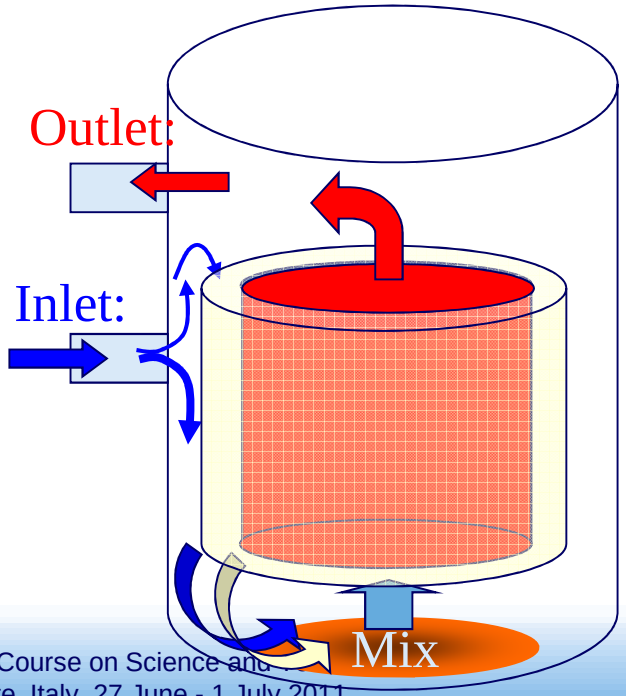


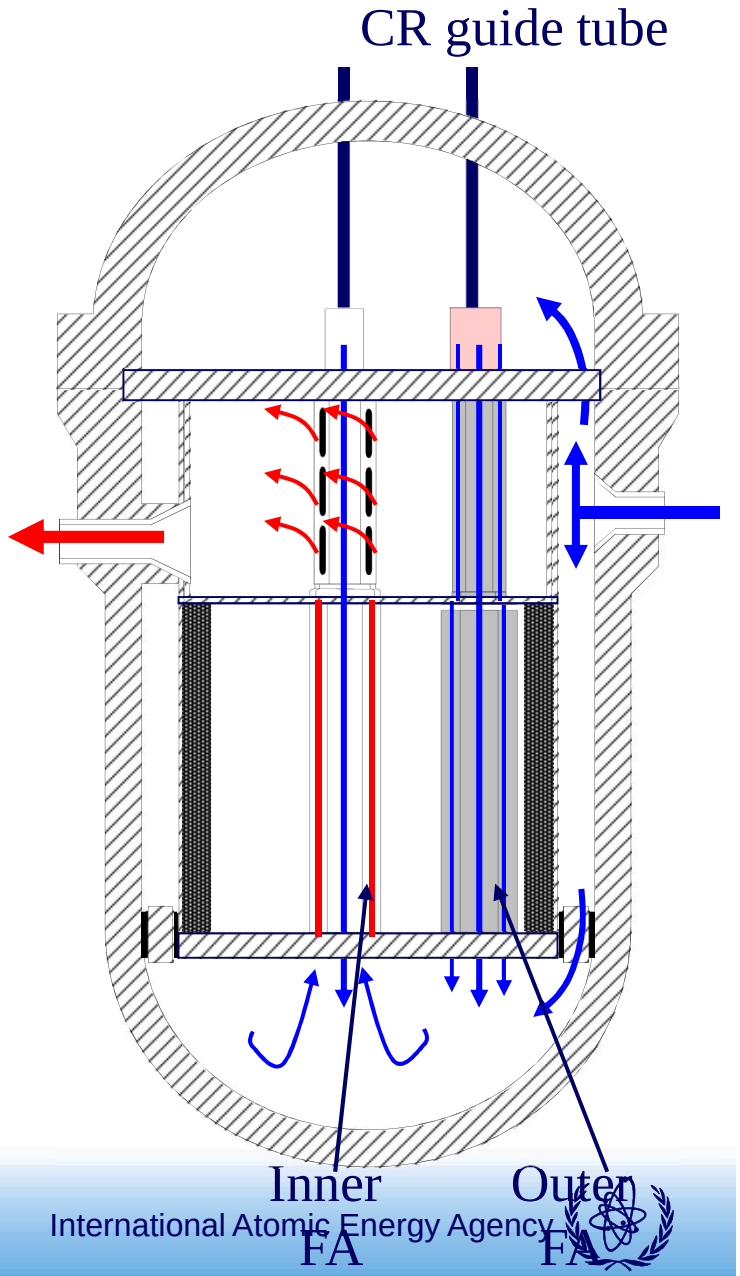
SCWR core design examples Coolant flow scheme

Flow directions

	Coolant	Moderator
Inner FA	Upward	Downward
Outer FA	Downward	Downward

To keep high average coolant outlet temperature



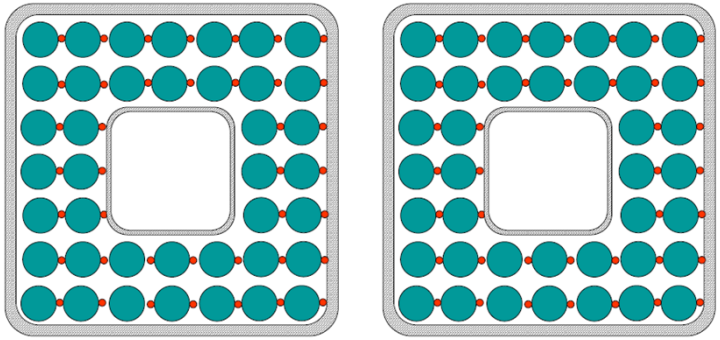


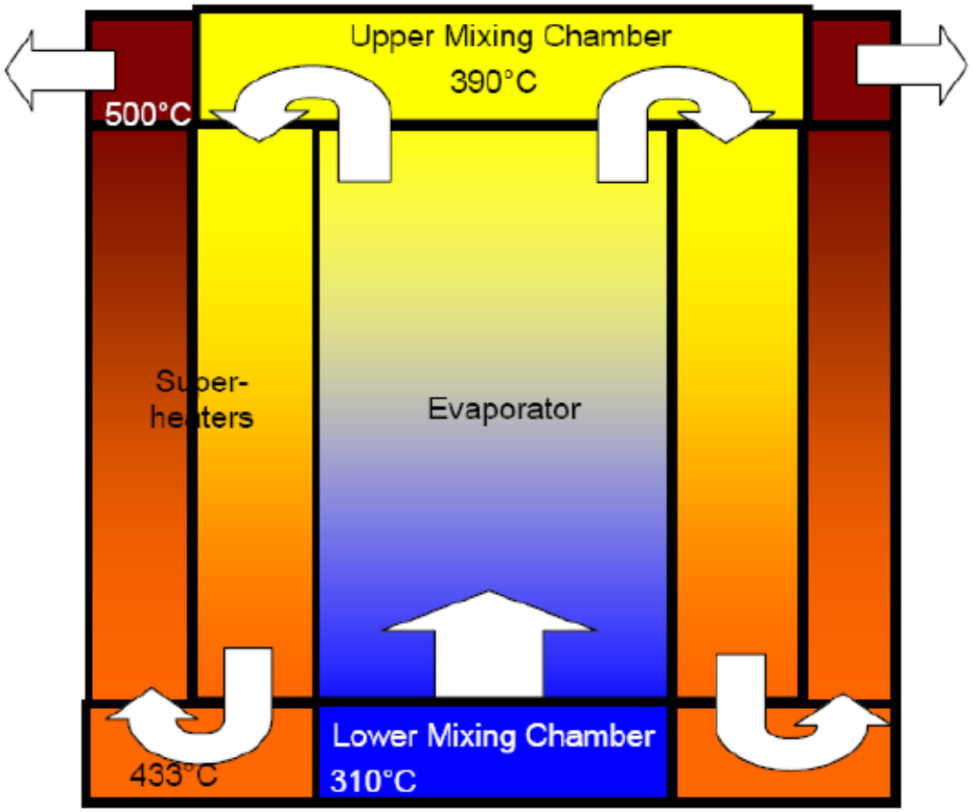
SCWR core design examples

SCWR Design Concepts in Europe:

The High Performance Light Water Reactor (HPLWR)

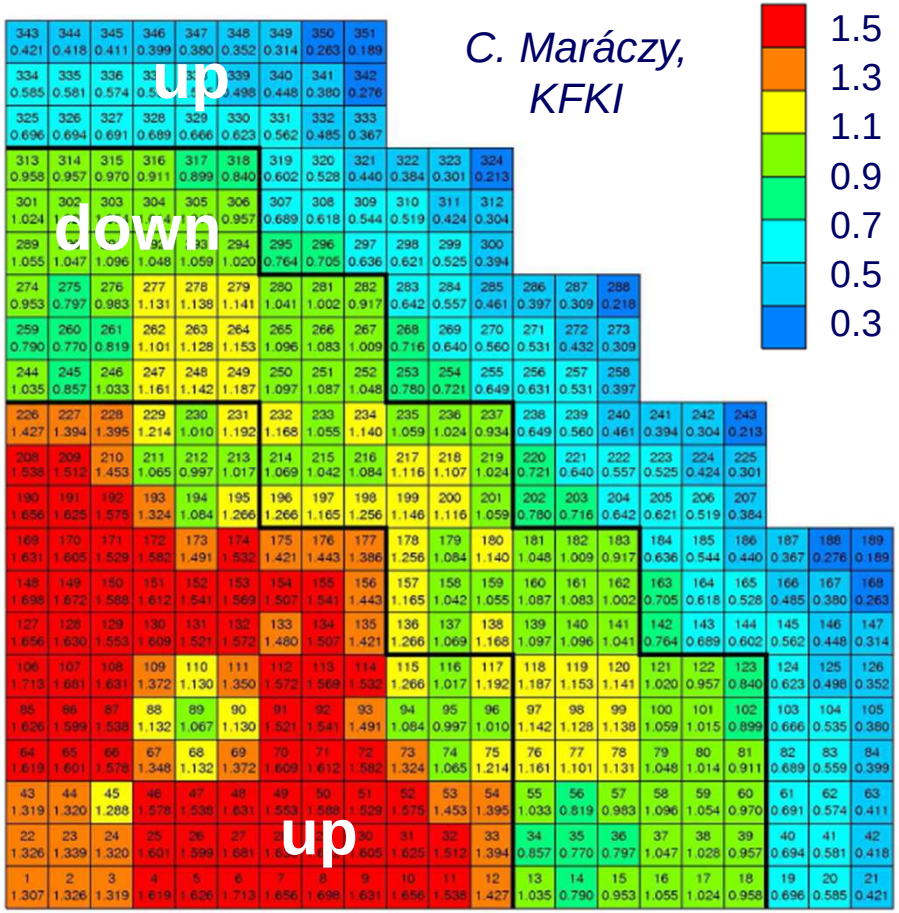
Assembly design





- Thermal neutron spectrum
- Three heat-up steps

HPLWR Core Design Analyses



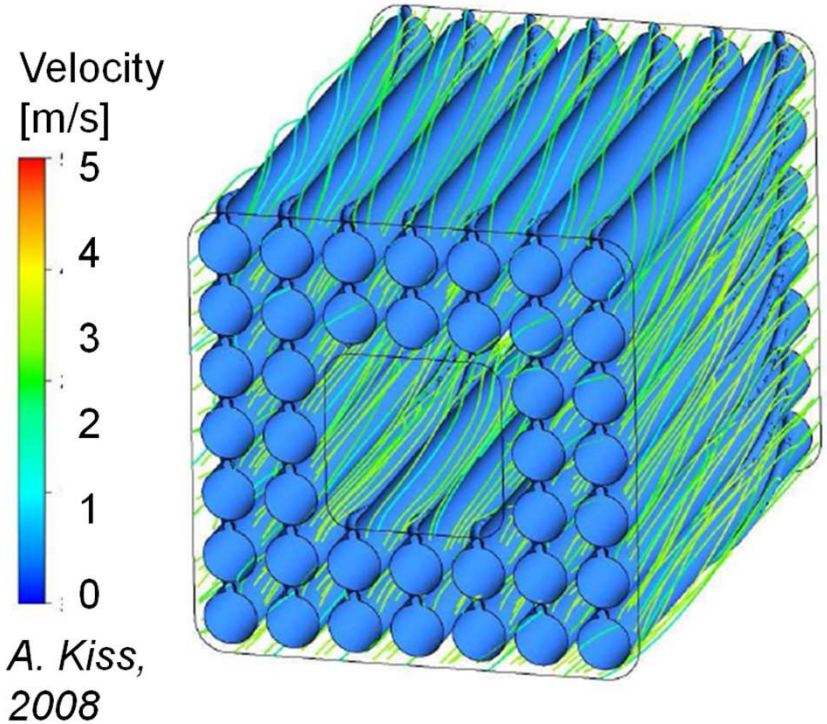
C. Maráczy, KFKI

Rel. power in ¼ core at beginning of an equilibrium cycle

Coupled neutronic / thermal-hydraulic analyses of

- Core power distribution
- Burn-up analyses
- Optimization of fuel shuffling
- Effect of control rods and burnable poisons
- Coolant mixing inside assemblies
- Uncertainties
- Single fuel rod predictions

Analyses of Coolant and Moderator Flow



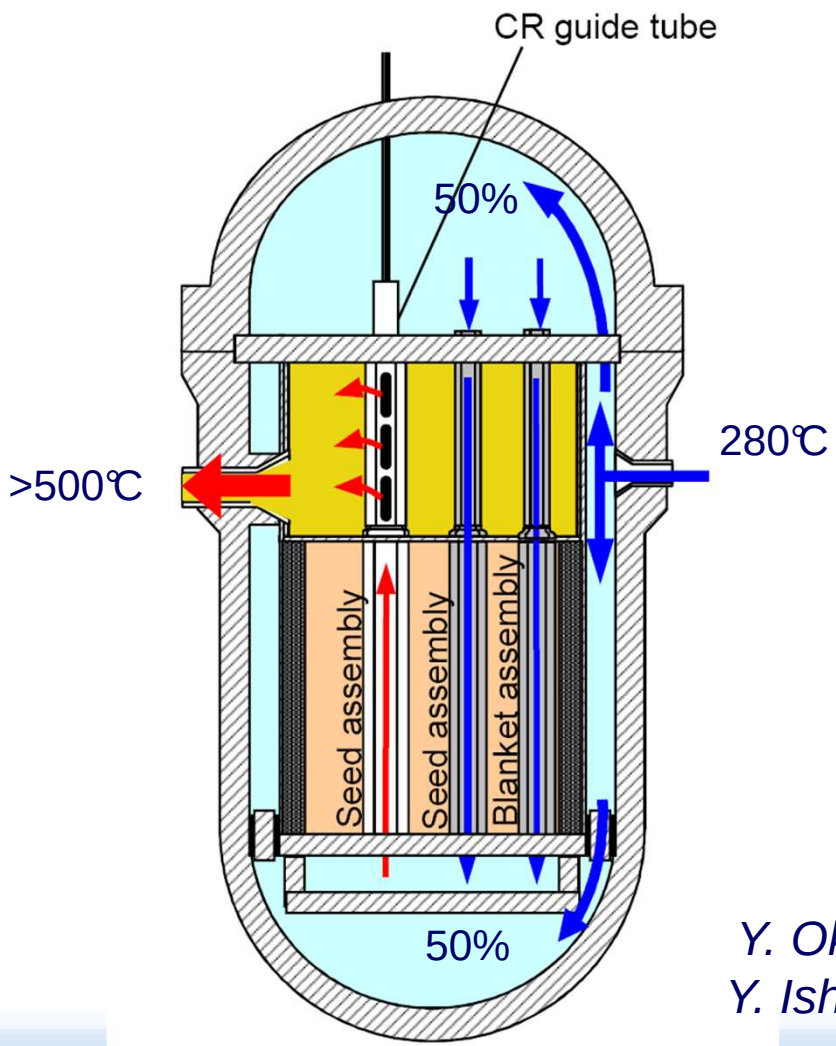
Twisted streamlines caused by wire wrap spacers

CFD-Analysis

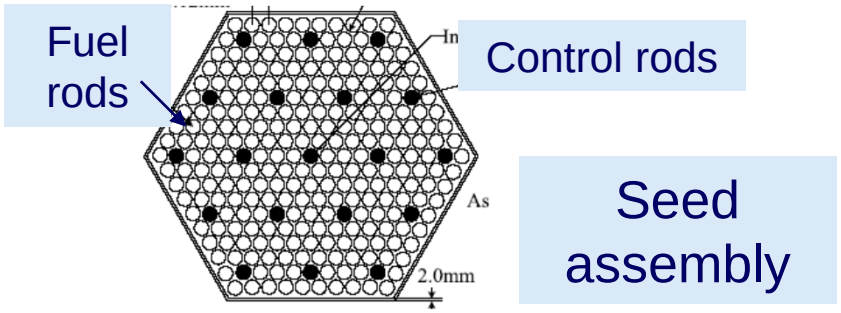
CFD and system code analyses of

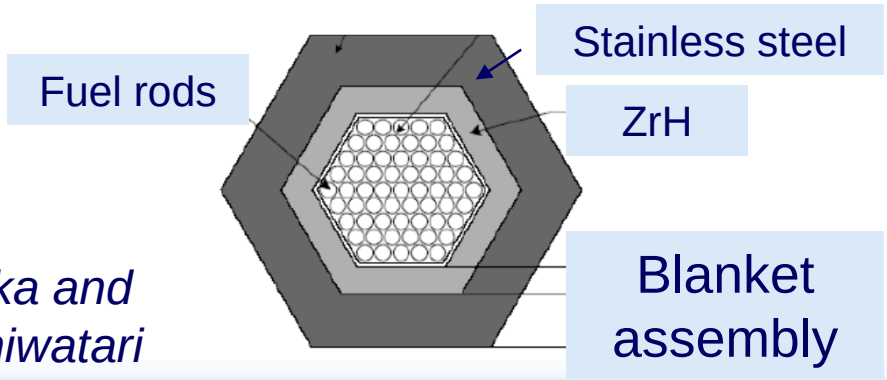
- Heat transfer and flow inside assemblies
- Mixing in plenums above and below the core
- Feedwater flow and heat transfer inside the pressure vessel

SCWR Core Design Concepts: The Super Fast Reactor, Japan



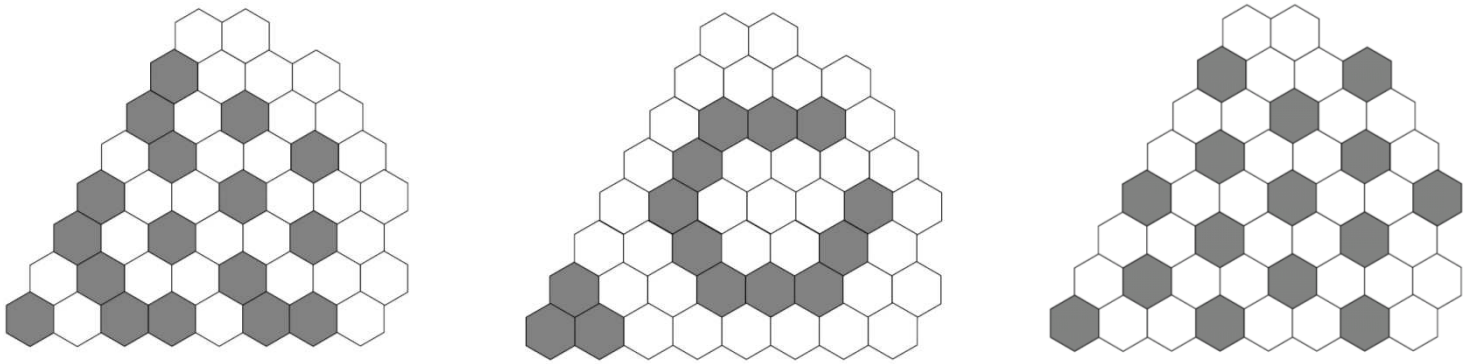
- Two heat-up steps
- Fast neutron spectrum

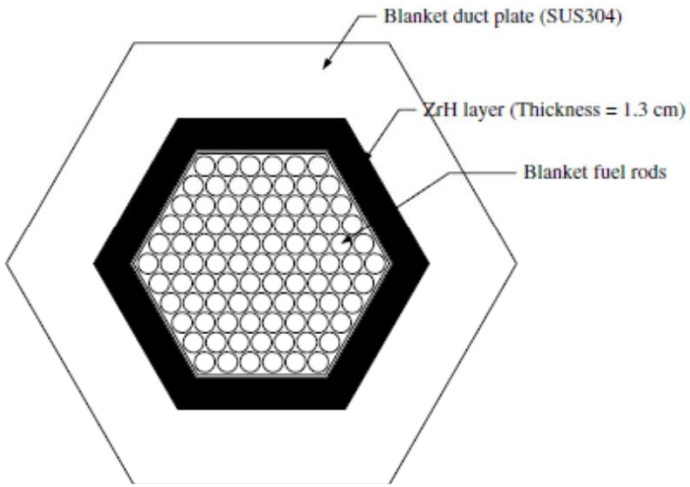


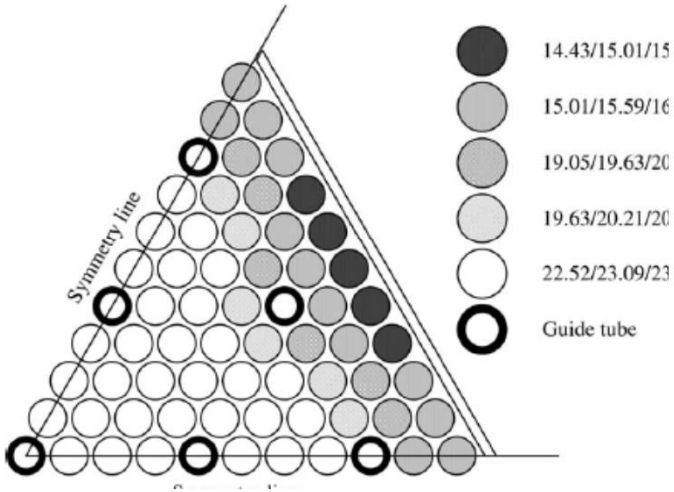


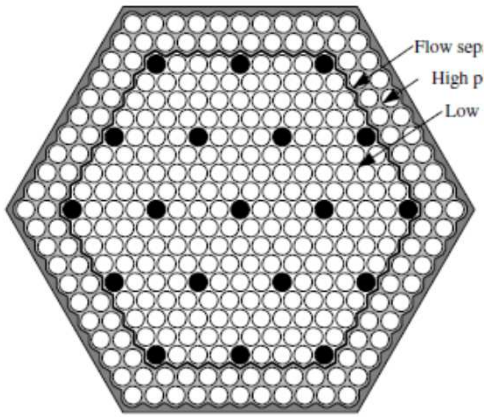
Y. Oka and Y. Ishiwatari

Reduce void reactivity and the local power peaking







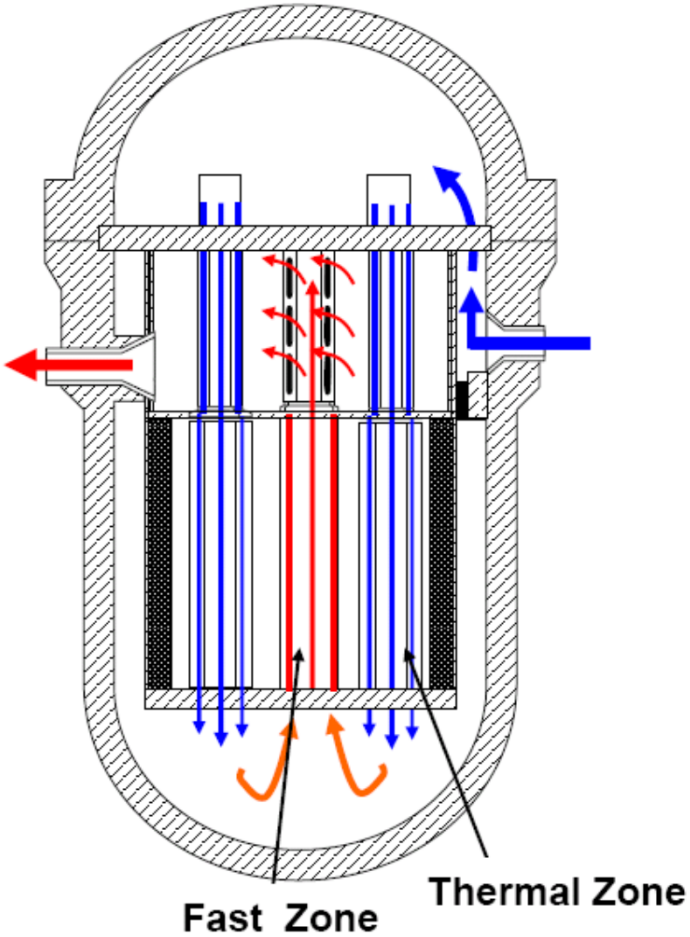


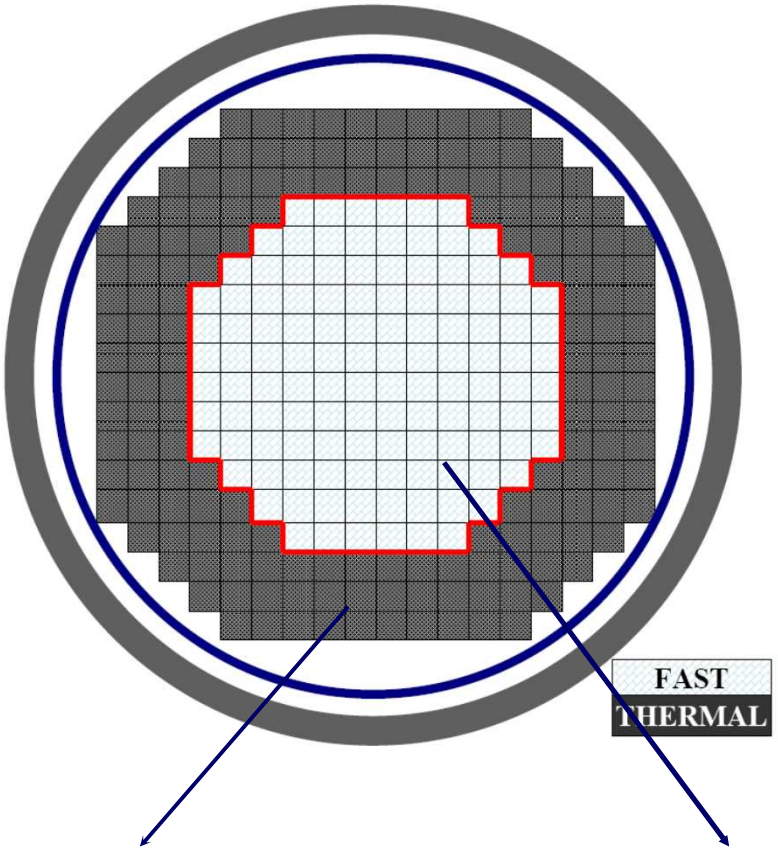
Proposal of SCWR-M Core

	Thermal core	Fast core
Core & FA design (mechanical)	X	√
Cladding temperature	X	√
Heterogeneity (hot channel factor)	X	√
Void reactivity feedback (safety)	√	X
Water storage in RPV (safety)	√	X
Enrichment	√	X
Conversion ratio (sustainability)	X	√
Power density	X	√

Mixed core

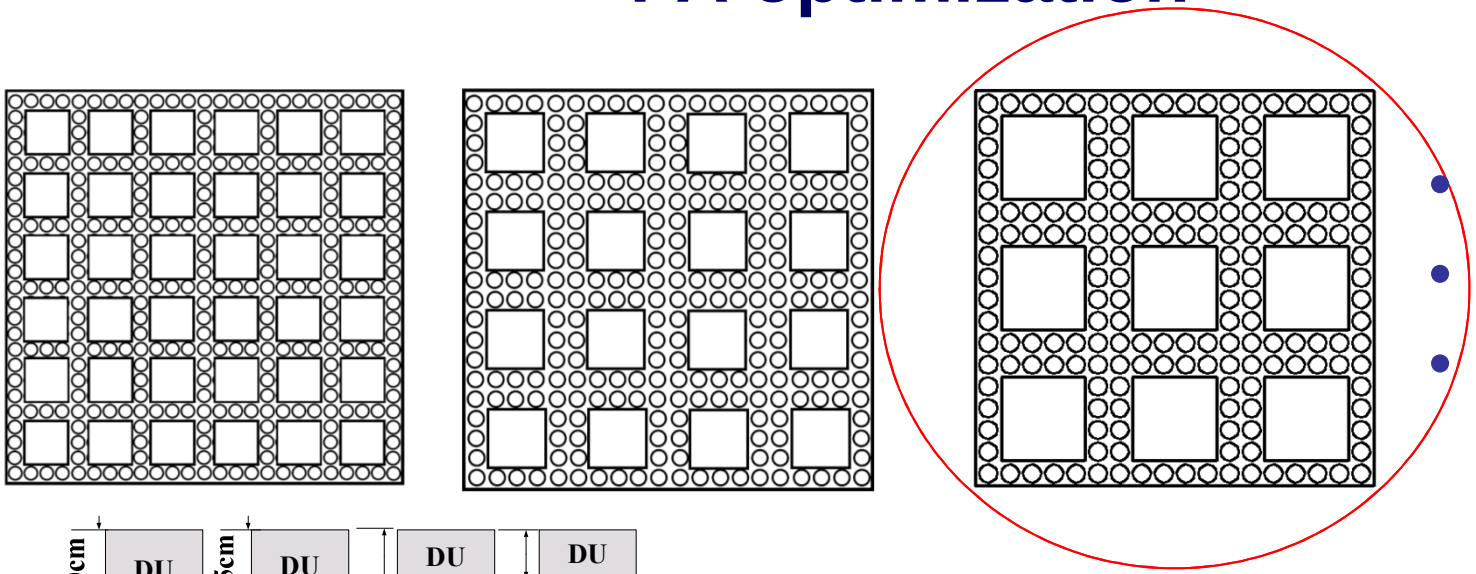
SCWR-M Core Structures (SJTU)



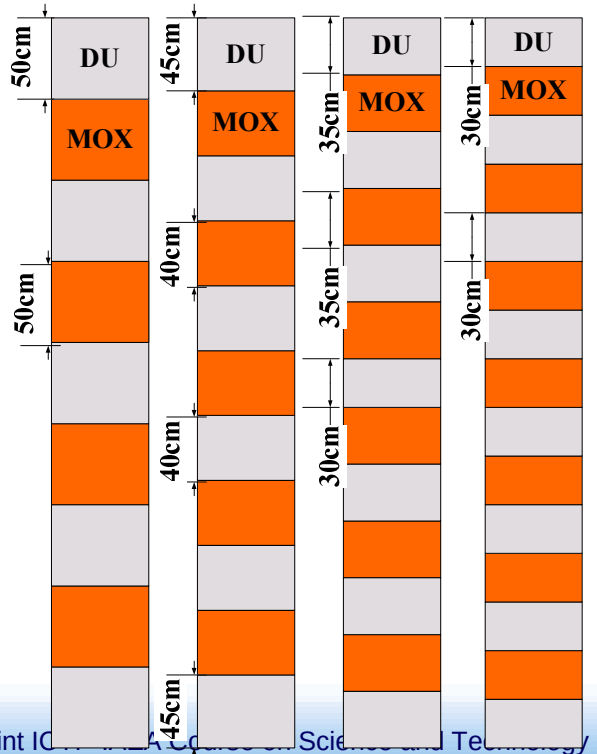


Thermal zone **Fast zone**

FA optimization



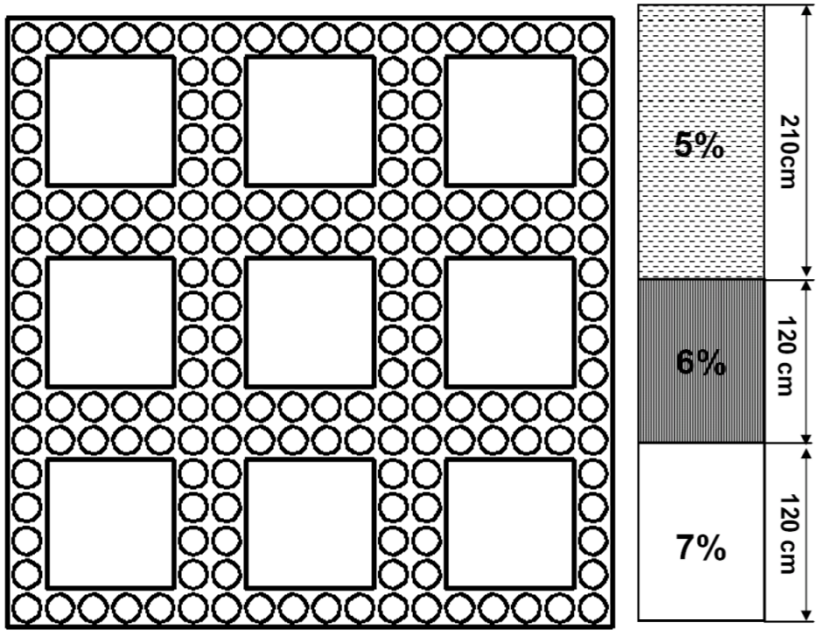
- P/d
- Diameter
- wall clearance



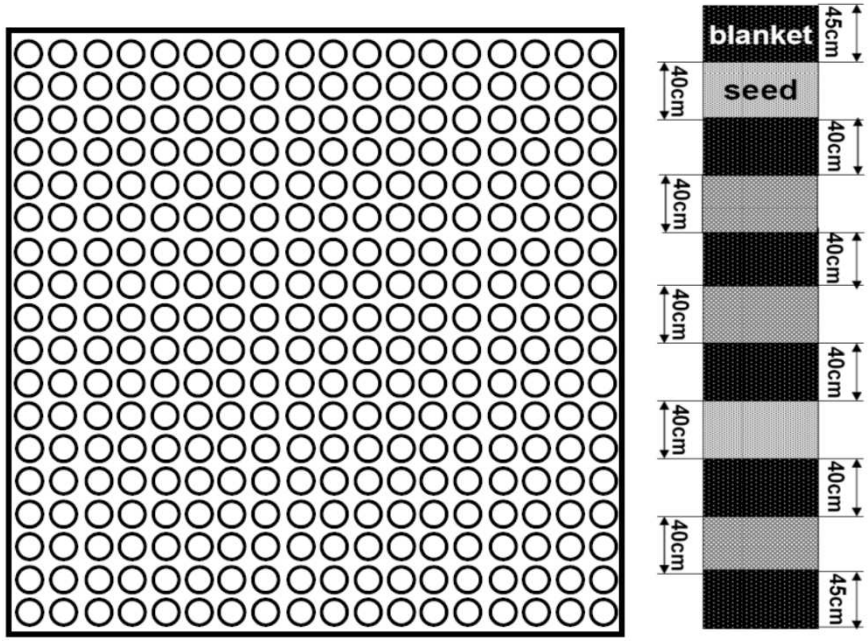
(a) 9层 (b) 11层 (c) 13层 (d) 15层

- Thermal FA two-row fuel assembly design (uniform moderation)
- Axial multilayer fuel assembly to flat the power profile and increase the conversion ratio

FA Structures



Multilayer FA (thermal)



Multilayer FA (fast)

FA Parameters

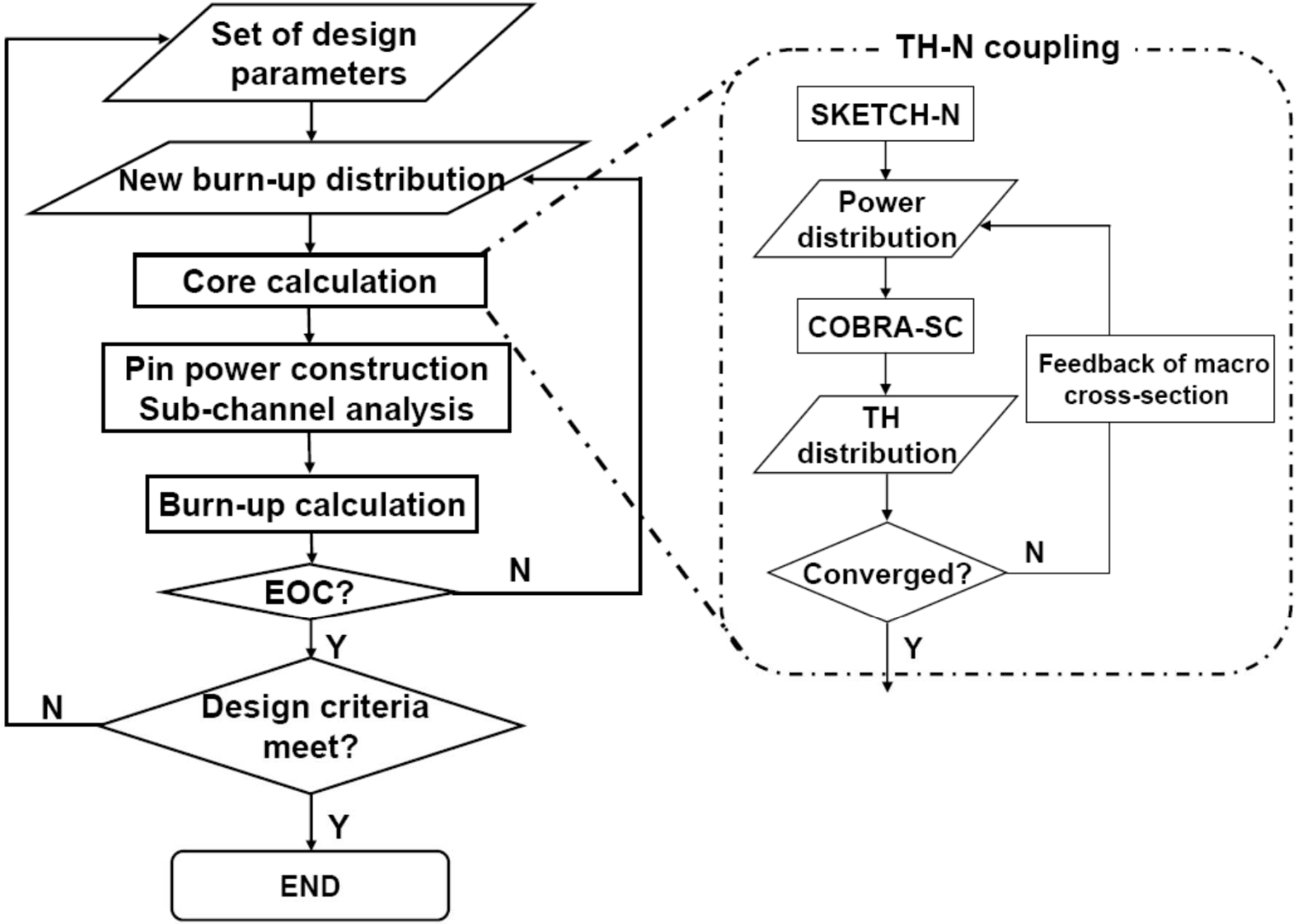
Design parameter	Thermal FA	Fast FA
Diameter of fuel pins, mm	8.0	8.0
Pitch-to-diameter ratio,-	1.20	1.20
Assembly side, mm	177.2	177.2
Fuel composition, -	UO_2	MOX
Fuel enrichment, %	5.0; 6.0; 7.0	24.0
Conversion ratio, -	0.6	1.01
Fuel temperature reactivity coefficient, 10^{-5}/K	- 1.72	- 2.65
Coolant reactivity coefficient*, 10^{-5}/K	- 27.9	- 5.20
Moderator reactivity coefficient, 10^{-5}/K	-100.0	--

* Change the water temperature in the coolant and moderator channel respectively to get the reactivity coefficient.

SCWR-M Core Parameters

Design parameter	Thermal	Fast	Whole core
Thermal power (MW)	2400.0	1400.0	3800.0
Electrical power (MW)	—	—	1650.0
Core height (m)	4.5	2	—
Equivalent diameter (m)	3.4	2.14	3.4
No. of fuel assembly (-)	164	120	284
Power density (MW/m^3)	100.89	75.74	90.26
Moderator fraction (%)	20.0	—	—

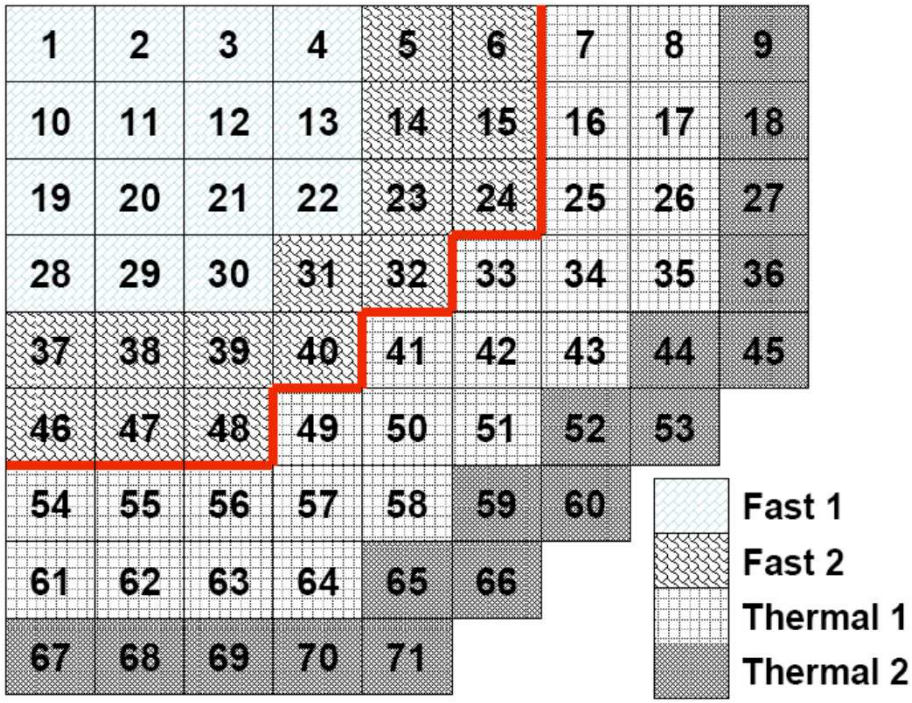
Coupling Analysis Method



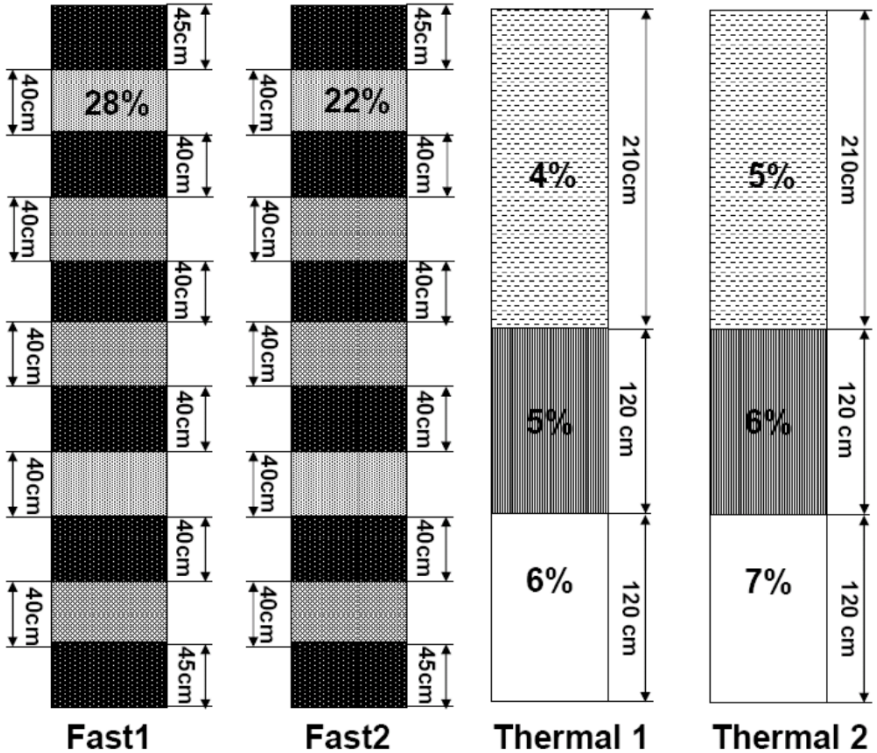
Measures to improve the SCWR-M

- The fast and thermal zones are divided into 2 parts with different enrichment.
- Increase the mass flow rate in the fuel assemblies, which have higher power density and non-uniform pin-power distributions
- Reduce the moderator mass fraction from 25% to 20%, to provide a higher coolant mass flux to reduce the peak cladding temperature.
- Enlarge the clearance of the peripheral fuel rod to 1.5mm, to provide a better coolability of the fuel rods near the assembly wall.

SCWR-M Core Optimization Results



radial distribution



axial distribution

FA Power and Flow Distribution

0.958	0.956	0.956	0.956	0.853	1.086	1.125	1.063	0.822
0.956	0.956	0.956	0.958	0.860	1.096	1.125	1.059	0.815
0.956	0.956	0.958	0.972	0.916	1.279	1.135	1.042	0.793
0.956	0.958	0.972	0.915	1.262	1.137	1.216	0.992	0.733
0.853	0.860	0.916	1.262	1.152	1.280	1.130	0.968	0.629
1.086	1.096	1.279	1.137	1.280	1.166	1.062	0.797	
1.125	1.125	1.135	1.216	1.130	1.062	0.839		
1.063	1.059	1.042	0.992	0.968	0.797			
0.822	0.815	0.793	0.733	0.629				

Power distribution

1	2	3	4	5	6	7	8	9
10	11	12	13	14	15	16	17	18
19	20	21	22	23	24	25	26	27
28	29	30	31	32	33	34	35	36
37	38	39	40	41	42	43	44	45
46	47	48	49	50	51	52	53	
54	55	56	57	58	59	60		
61	62	63	64	65	66			
67	68	69	70	71				

1.00	0.80
0.91	0.88
1.06	1.16
1.23	1.66

Flow distribution

Sub channel scale results

Results	Thernal(FA56)	Fast (FA32)
Max. linear heat rate (kW/m)	36.18	42.09
Max. coolant temperature (°C)	614.43	542.44
Hot channel factor (-)	1.264	1.563
Max. moderator temperature (°C)	368.10	—
Max. cladding temperature (°C)	725.12	708.90
Max. fuel temperature (°C)	1688.08	2089.93

Conclusions

- Big potential advantage of SCWR comparing to LWR
- A technical review of the LWR-SCWR: Japan and Europe, Thermal and fast spectrum
- The development and character of the SCWR-M

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…Thank you for your attention!

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