Fast Breeder Reactor (FBR)

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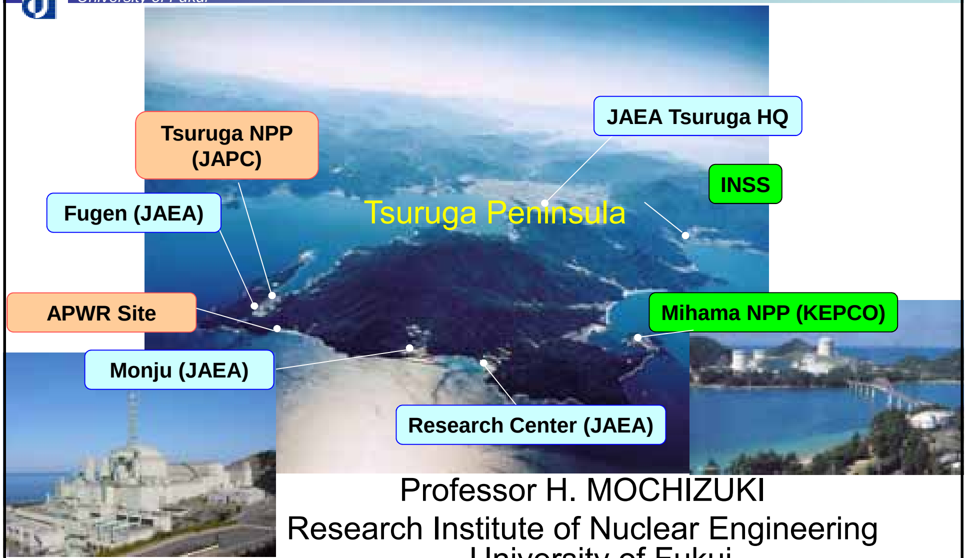

Professor H. MOCHIZUKI
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University of Fukui

1

Outline

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- Pu production and fuel cycle
- Comparison between LWR and FBR
- FBRs in the world
- Components of FBR
- Thermalhydraulic analysis of FBR

2

FBR and LWR

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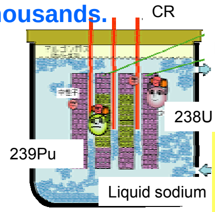
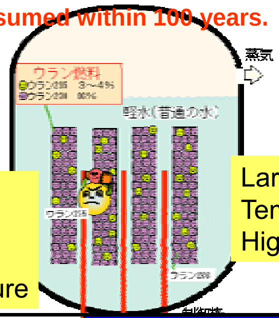
FBR: Breed nuclear fuel
($^{238}U \Rightarrow ^{239}Pu$.) We can utilize nuclear fuel for a couple of thousands.



Core is small.
Temp. is more than 500℃.
Atmospheric pressure

LWR：^{235}U of 0.7% in the uranium ore is consumed. Uranium ^{235}U will be consumed within 100 years.



Large core
Temp: ~300℃
High-pressure

FBR		LWR
Pu(~20%)+^{238}U(~80%) : MOX	Fuel	Slightly enriched uranium（3~4% ^{235}U)
Liquid sodium	Coolant	water
Non	Moderator	water
Fast neutron	Fission	Thermal neutron

3

Fuel cycle

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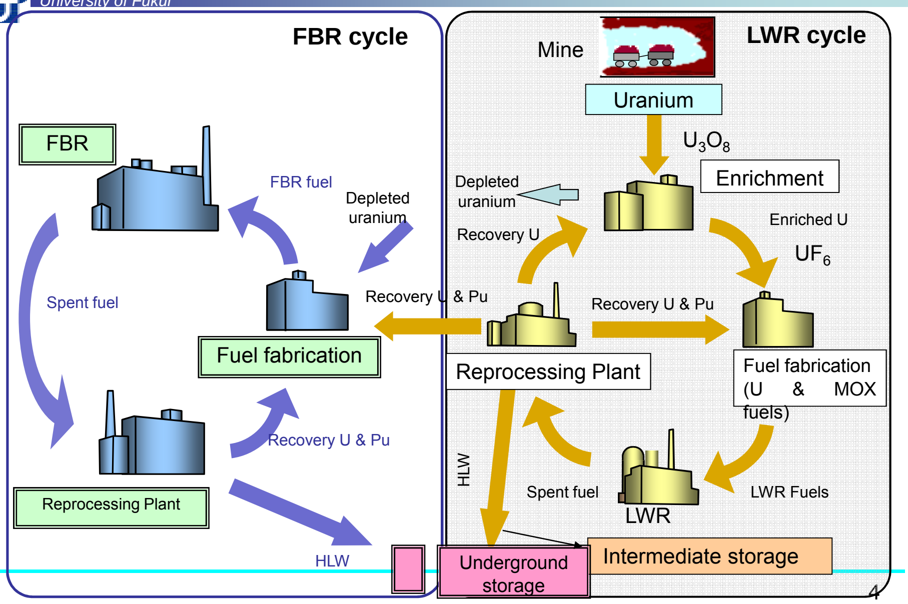

4

Fission in LWR or Graphite reactor

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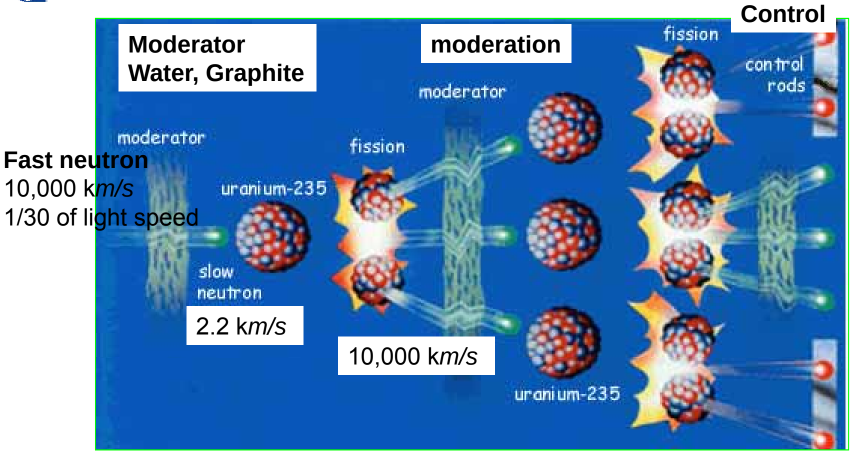

^{235}U has a large fission cross section to a thermal neutron. Some fast neutrons are absorbed in ^{238}U and produce ^{239}Pu.

5

Neutron irradiation chain of ^{238}U

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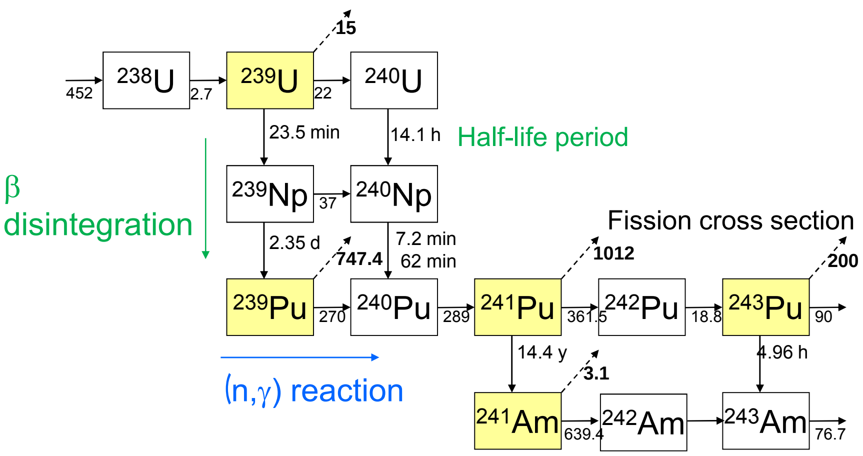

6

Microscopic cross section of ^{235}U & ^{238}U

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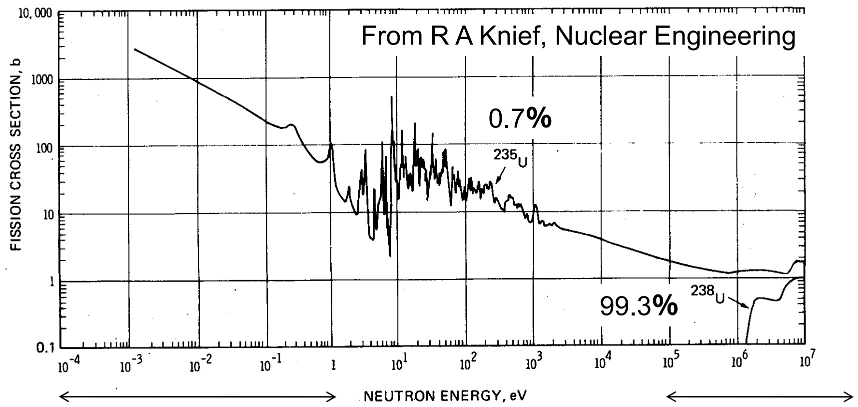
Easiness of fission



Thermal neutron
Fission cross section is large for thermal neutron.

Fast neutron
Fission cross section is small for fast neutron.

7

Cross section of neutron capture of ^{238}U

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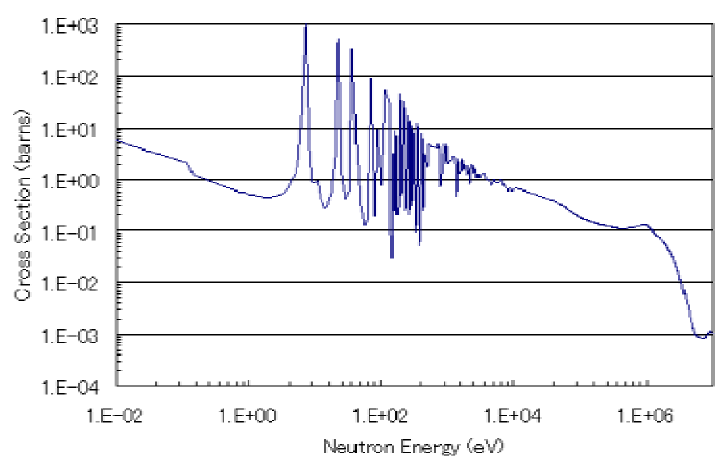

U-238 capture cross section (by JENDL-3.3)

8

Number of neutrons produced by one fission

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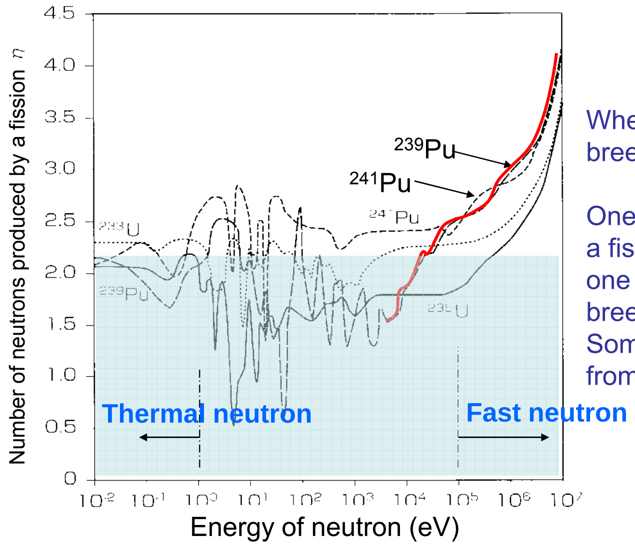

When η is less than 2, breeding is impossible.

One must be used for a fission, and the other one should be used for breeding.
Some of them escape from the reactor.

9

Characteristics of FBR

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- FBR can produce nuclear fuel more than consumption. Configuration of FBR is different from LWRs.
- Neutrons are not moderated in order to breed nuclear fuel efficiently.
- Enrichment of fuel is higher than that of LWR in order to raise fission probability.
- Fuels should be cooled by good heat transfer coolant (sodium) because power density is high.

10

Comparison of reactor vessel between FBR and LWR

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Monju
238MWe

Reactor vessel is thin due to low system pressure

Mihama Unit-3
826MWe

Reactor vessel is thick due to high system pressure

11

Comparison of fuel arrangement between FBR and LWR

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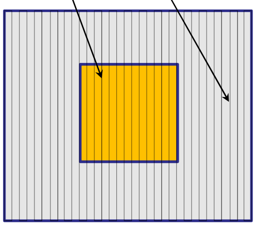
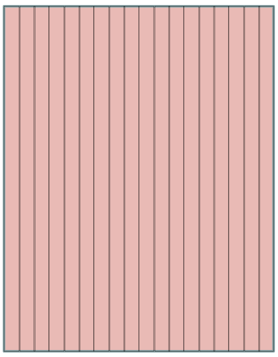
^{238}U+Pu(20%〜30%)
Driver fuel

Blanket fuel of ^{238}U is placed in the peripheral, upper and lower region of the core in order to breed effectively.

Example：^{238}U (96%) ＋ ^{235}U (4%)



- **Small core**
- **Short fuel**
- **Small diameter fuel**



- **Large core**
- **Long fuel**
- **Large diameter fuel**

Enrichment is high in the outer region of the core in order to flatten the power distribution.

12

Comparison of fuel assembly

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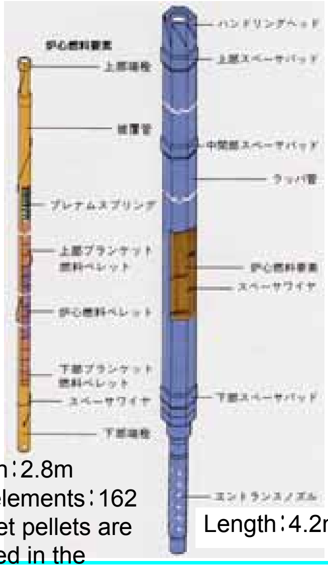

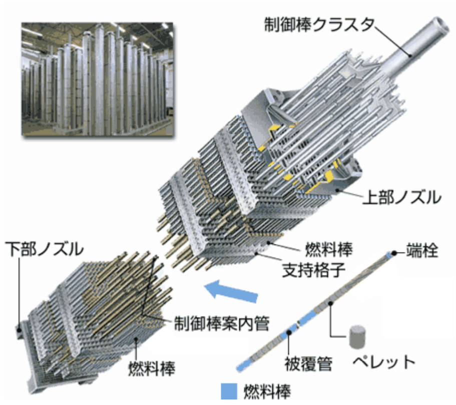

Length：2.8m
Feul elements：162
Blanket pellets are inserted in the cladding.

Length：4.2m

Length：approx. 4m
Effective length：Approx. 3.6m
Weight：670kg (17×17)

13

Comparison of turbine system

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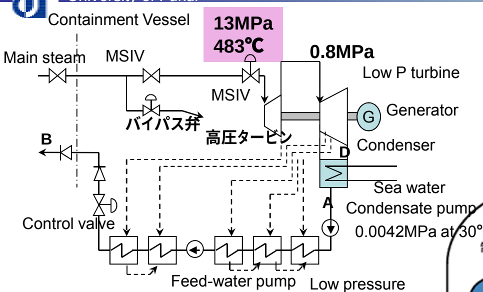

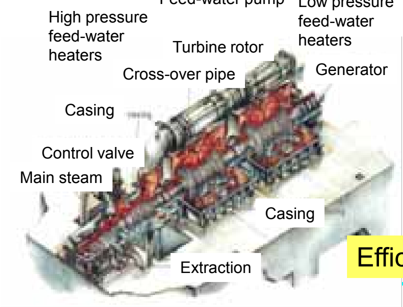

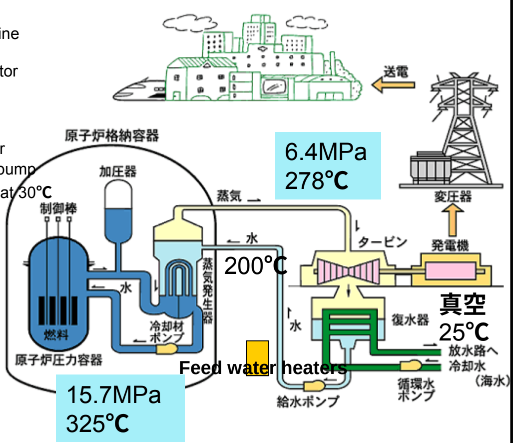

Efficiency: ≈40%

Efficiency: ≈32%

14

FBR & LWR

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	FBR	LWR
Neutron life time	10^{-7} seconds	10^{-5} seconds
Ratio of delayed neutron	0.34〜0.37%	0.55〜0.7%
Mean free path	long	short
Coolant	Sodium (low corrosive)	Water (high corrosive)
Fuel	UO_2, PuO_2 (Enrichment 〜 20%)	UO_2 (Enrichment 3〜 4%)
Cladding	S.S.	Zircaloy
Dia. of fuel pellet	4〜6mm	Approx. 1cm
Outlet coolant temperature	500〜550℃	280〜320℃
Temperature difference	130〜150℃	15℃ (B)〜35℃ (P)
System pressure	Atmospheric	7MPa (B)、15MPa (P)
Power density	Approx. 300kW/*l*	Approx. 90kW/*l*
Burn-up	100,000MWd/t	30,000〜60,000MWd/t
Efficiency	Approx. 40%	Approx. 32%

15

Characteristics of sodium

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◆ Sodium is alkali metal which is soft and has metallic color.
Weight of sodium is 0.97 times of water at 20 °C.
◆**Melting point is 98°C** (**97.8 °C**) .
◆**Boiling point is 881.5°C at atmospheric pressure.**

Sodium is lighter than water.

Easily cut by a knife

Liquid sodium

16

Reaction of sodium with water and air

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◆When sodium reacts with water, hydrogen gas and NaOH are produced.
$2Na + 2H_2O \rightarrow 2NaOH + H_2$ (Hydrogen) + Heat

Therefore, sodium must be separated from water.

◆Leak speed of sodium is slow due to atmospheric system pressure. However, sodium reacts with air as shown in photos, and produces a lot of white alkali aerosol.

17

Blow-down of high-pressure and high-temperature coolant

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Blow-down:
Discharge of high-temperature and high-pressure light water

ECC water injection in order to cool down the heat-up fuel

Even a small amount of steam leak, a jet is very dangerous. This is a different point compared to a leak of sodium.

18

Reason of superiority of Na among liquid metal

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	Na	K	NaK (70/30)	Li	Pb	Bi	Pb/Bi (eutectic)	Hg
Melting point(°C)	97.5	62.3	40	186	327.4	271.3	125	-38.9
Boiling point(°C)	881	758	825	1317	1737	1477	1670	357
Vapor pressure(600°C)(mmHg)	26	128		5×10^{-2}	3×10^{-4}	6×10^{-4}		22(atm)
Neutron absorption cross section								
Thermal neutron (barns)	0.505	2.07		71	0.17	0.034		380
Fast neutron (100eV)(mb)	1.1	5(400eV)		1000	4	3		60
Half-life period	15hr.	12.5hr.		0.8sec.	3.3hr.	5days		5.5min.
Thermal conductivity (600°C)(cal/cm/sec/°C)	0.15	0.084		0.07	0.036	0.037		0.02
Specific heat(600°C)(cal/g/°C)	0.3	0.183		1.0	0.038	0.038		0.03
Density (600°C)(g/cm^3)	0.81	0.7		0.47	10.27	9.66		12.2
Heat transport capability (4in.φPipe)(C.H.V./ft^2°Csec.)	3.4	1.9	1.2	8.8	1.2	1.3	1.2	1.4
Pumping forth ($1/\rho^2c^3$)	47	29.2	78	4.2	178	238	233	169
Price (£/ft^3)	3	42	16	120	40	500	300	730

19

Sodium cooled fast reactors

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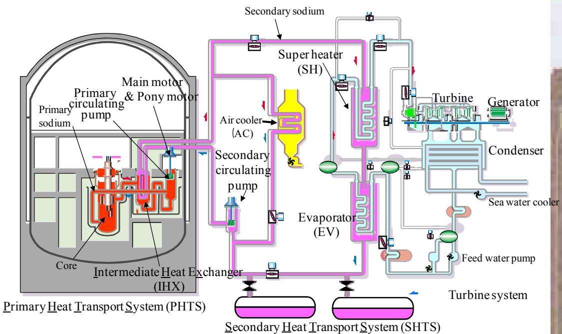
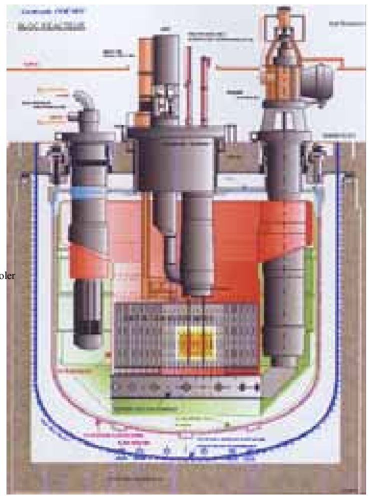
Loop type FBR "Monju"



Tank type FBR "Phénix"



20

FBR around the world

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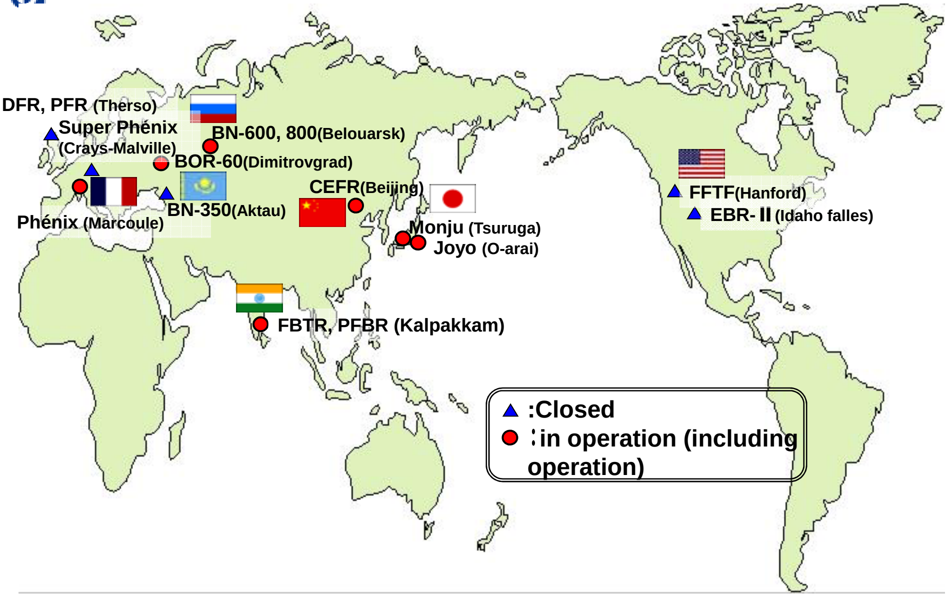

First power plant in the world (USA)

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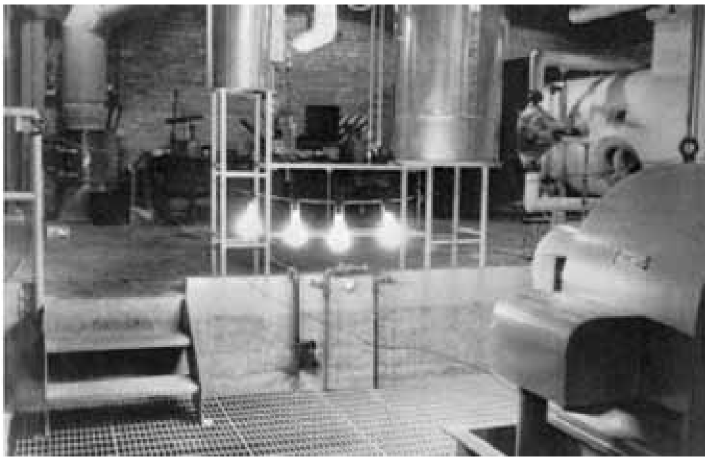
EBR−I (Experimental Breeder Reactor)
Coolant was NaK. Four light bulbs were lit up on 20 December 1951.



22

Donreay Fast Reactor, PFR (UK)

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Rating: 60 MWt/15MWe
Coolant: Na-K
Loops: 24

Prototype Fast Reactor

23

Phénix (France)

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Oldest power reactor in France.

Rating: 565MWt/255MWe
Coolant: Na
Loops: 3

24

Tank-type FBR (Phénix)

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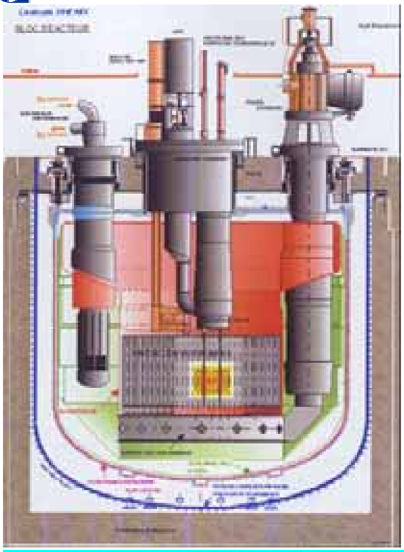

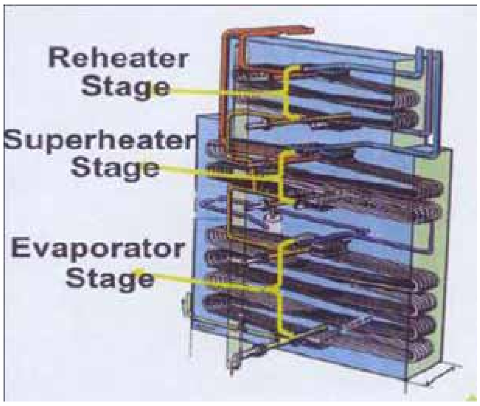

25

Super-Phénix (France)

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Electrical power:
1200MWe

Demonstration
plant in France

- Super-Phénix was sacrificed by Prime minister Jopspin on 2 February 1998 in order to have a coraboration between Socialist party and green party.

26

Super-Phénix

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Photo shoot in side the plant was allowed after the workshop at SPX. This might be the first and the last chance.

27

FBTR (India)

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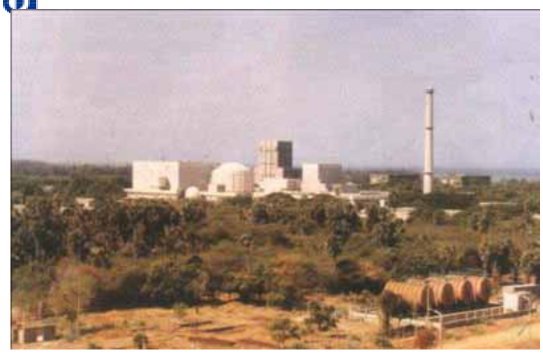

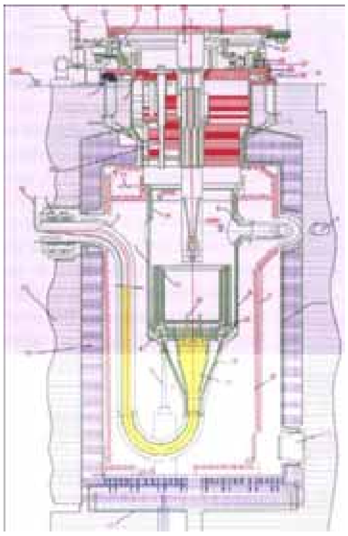

40 MWt /13.2 MWe
Fuel

Mark I (25 Nos.)	70% PuC + 30% UC
Mark II (13 Nos.)	55% PuC + 45% UC
PFBR test SA	29% PuO_2 + 71% UO_2

From IAEA-TECDOC-1531

28

PFBR (India)

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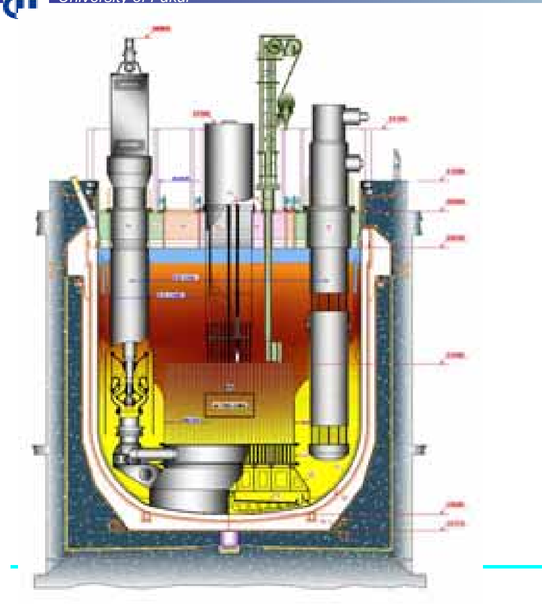

01	Main Vessel
02	Core Support Structure
03	Core Catcher
04	Grid Plate
05	Core
06	Inner Vessel
07	Roof Slab
08	Large Rotating Plug
09	Small Rotating Plug
10	Control Plug
11	CSRDM / DSRDM
12	Transfer Arm
13	Intermediate Heat Exchanger
14	Primary Sodium Pump
15	Safety Vessel
16	Reactor Vault

PFBR in 2008

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Erection of safety vessel on 24th June 08: An important milestone

30

BN600 (Russia)

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Beloyarsk NPP is close to Ekaterinburg.

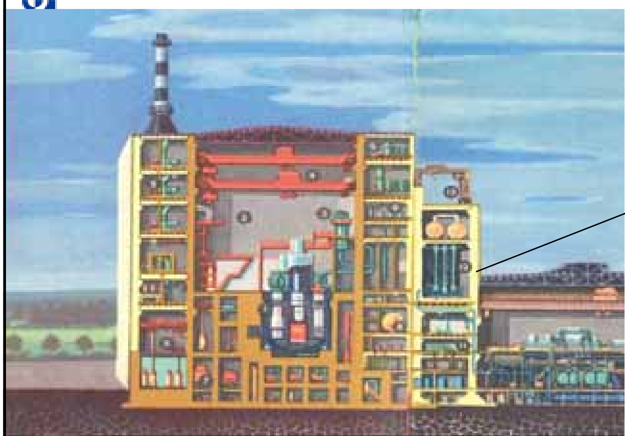
Pressure tube type reactor

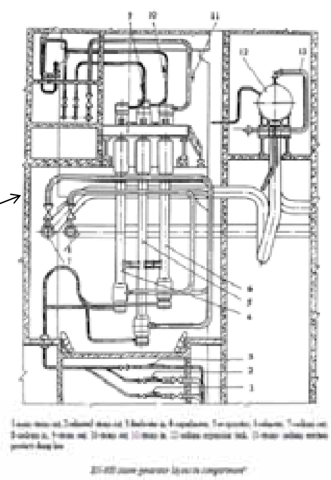
Site for BN800

BN600

BN600

University of Fukui





Modular type steam generator
Irradiation of vibro-pack fuel (Dismantled War head was used.)

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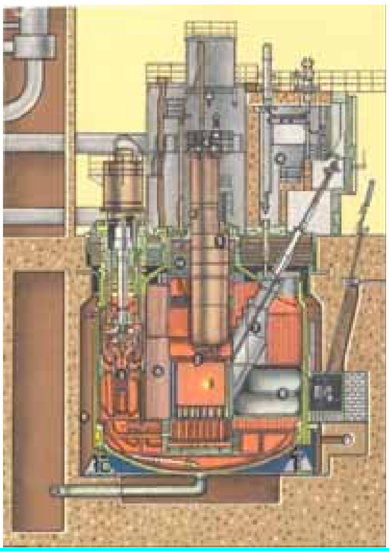
BN600



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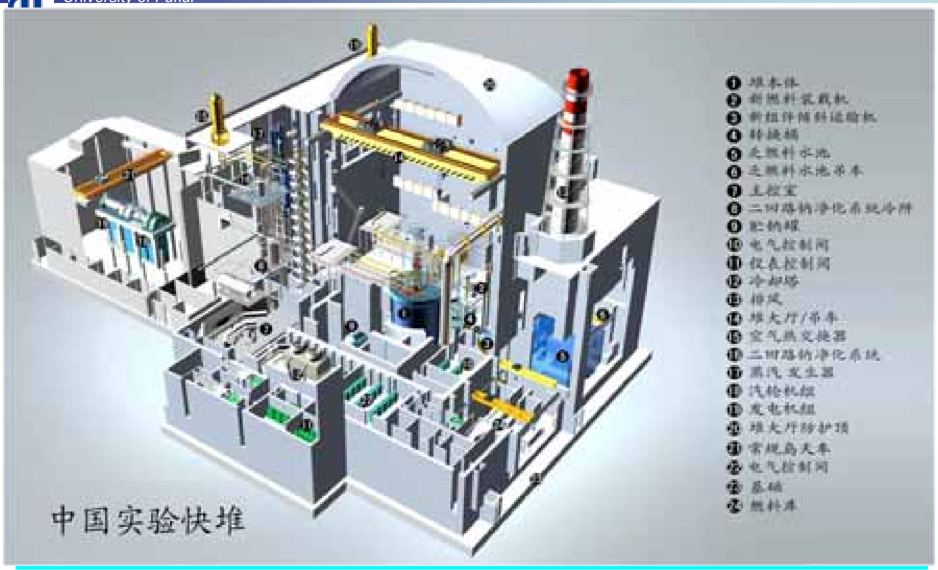
CEFR(1/3)



CEFR(2/3)

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35

CEFR(3/3)

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36

Core of "Monju"

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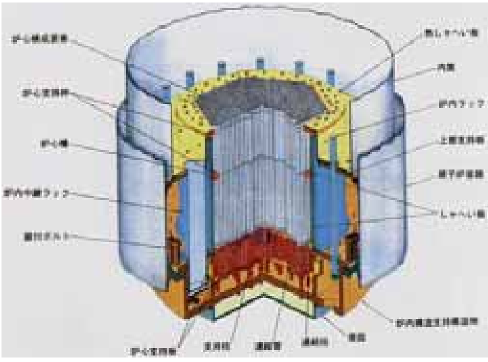

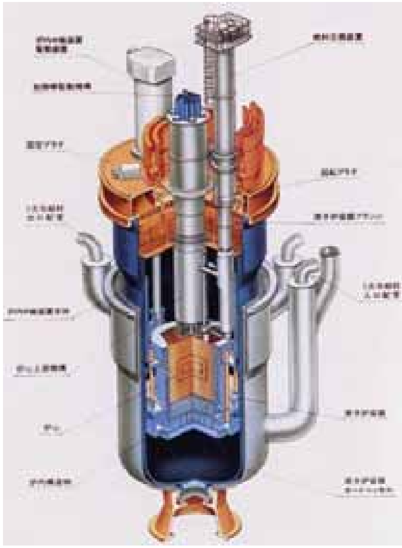

37

Fuel subassembly

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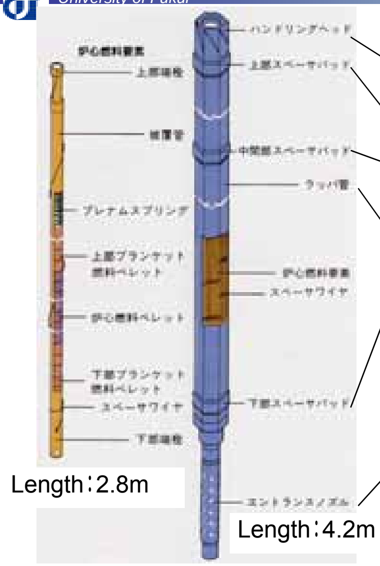

- Handling head: for the gripper of refueling machine
- Spacer pad: keep clearance to the adjacent wrapper tube
- Wrapper tube: keep flow rate and protect fuel subassembly
- Entrance nozzle: adjusting flow rate. Many orifices to prevent blockage

38

Shielding plug

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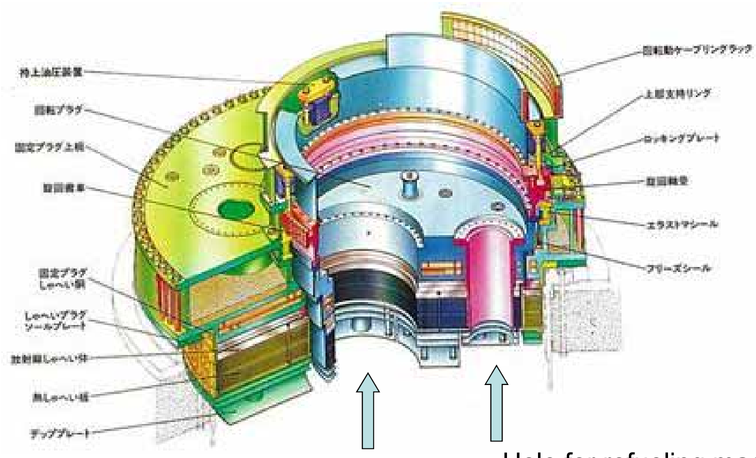

Hole for upper core structure

Hole for refueling machine

39

UIS and refueling machine

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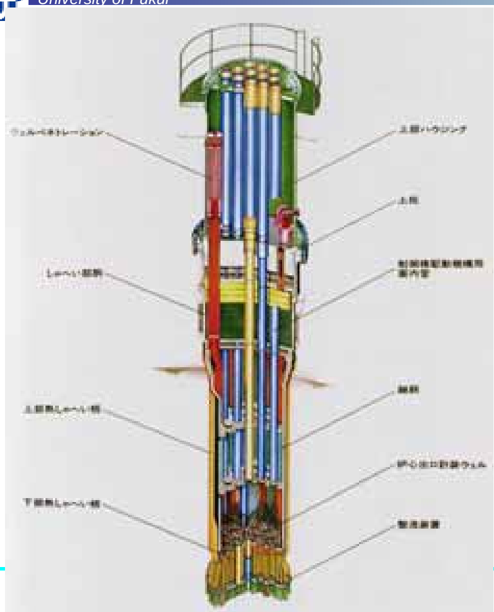

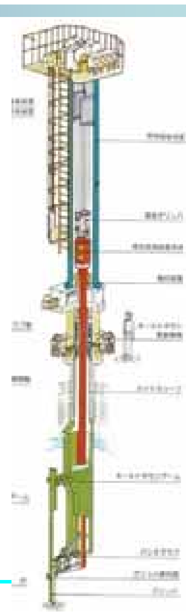

40

Arrangement of initial core

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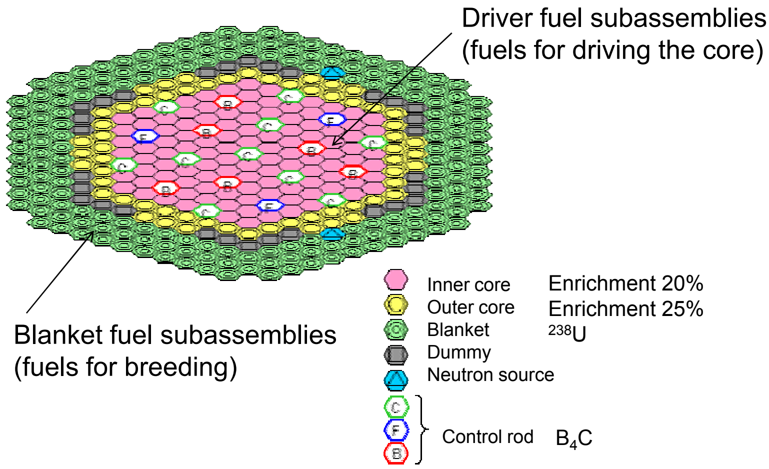

41

Flow distribution mechanism

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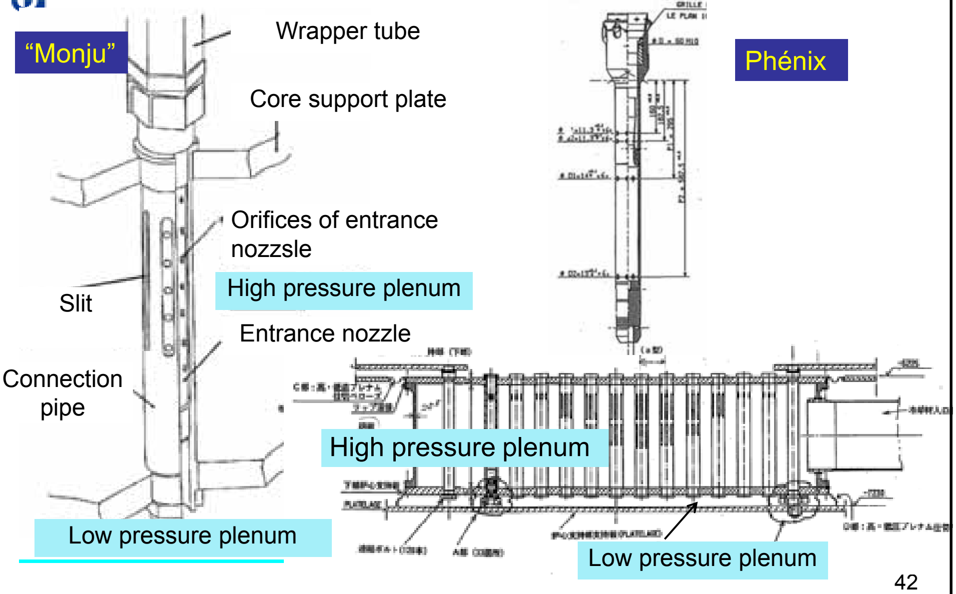

42

Fuel subassembly of Fermi reactor

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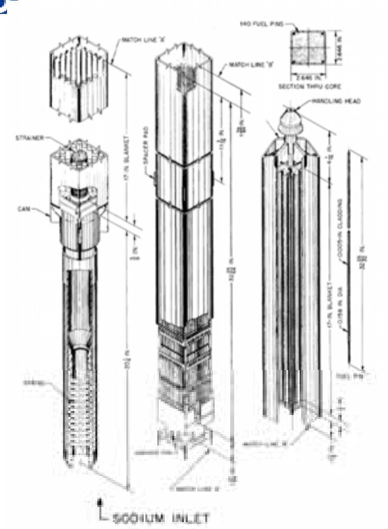

Fermi fuel subassembly details (2 of 3).

A fuel melt accident occurred in October 1966. A part of a fuel structure fell down at the inlet of the fuel assembly and blocked the entrance.

⇩

Orifices were provided in order to prevent total blockage. This is a lesson learned from the accident.

43

Piping of primary heat transport system

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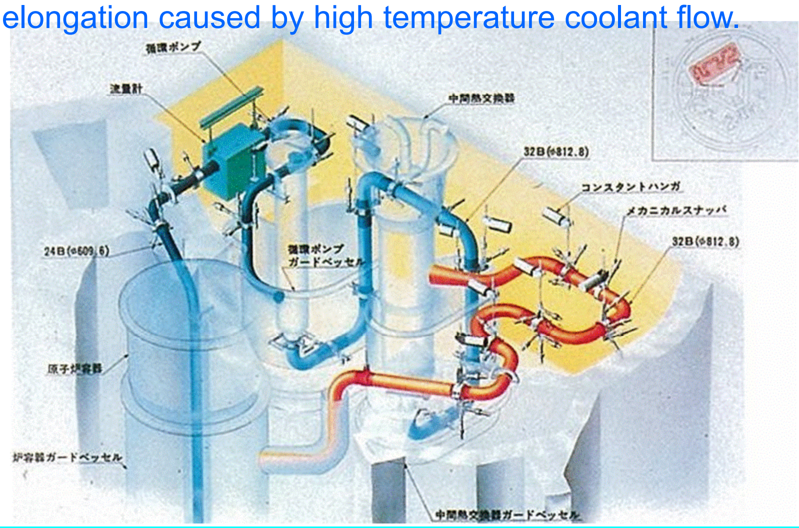
Piping is winding in order to absorb stress due to elongation caused by high temperature coolant flow.



44

Anti-seismic supporting mechanism

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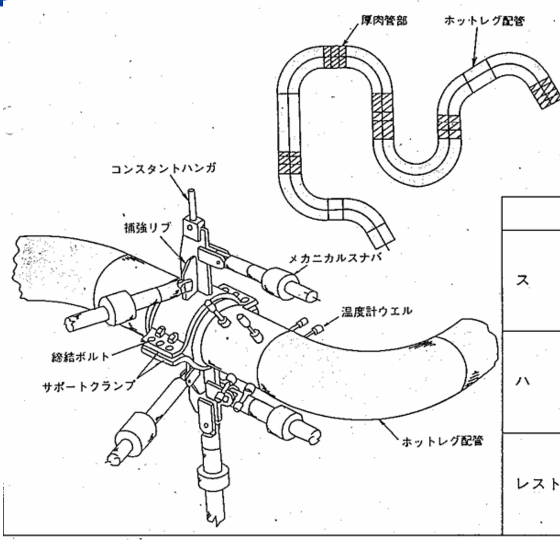

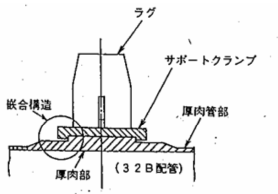

支持位置及び条件決定の考え方	
ス　ナ　バ	熱膨張による変位が大きい方向を、耐震設計上の要求から拘束する場合に用いる。
ハ　ン　ガ	熱膨張による鉛直方向変位が大きい箇所で、配管の自重を支持する目的から拘束する場合に用いる。
レストレイント	自重の支持あるいは耐震設計上剛性を高めるため配管を拘束する場合に用いる。

45

Intermediate heat exchanger

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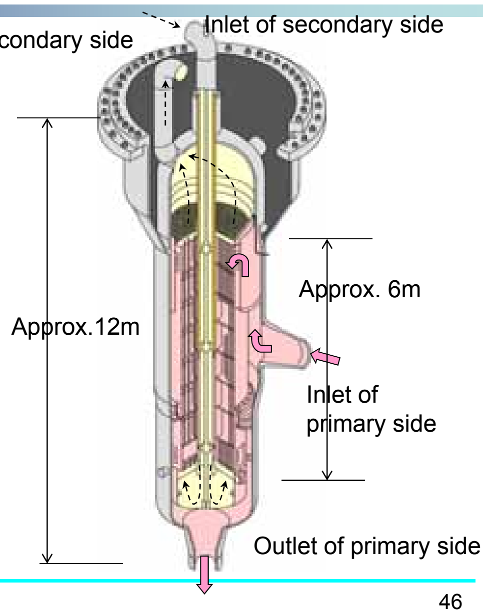
	Primary	Secondary
Flowrate	5120t/h	3730t/h
Inlet temp.	529℃	325℃
Outlet temp.	397℃	505℃
Configuration of heat transfer tube	OD 21.7mm, thickness:1.2mm, length:6.07m	
Number of HT tubes	3294	
Rating	238MW	
Height	12.1m	



46

Heat transfer in IHX

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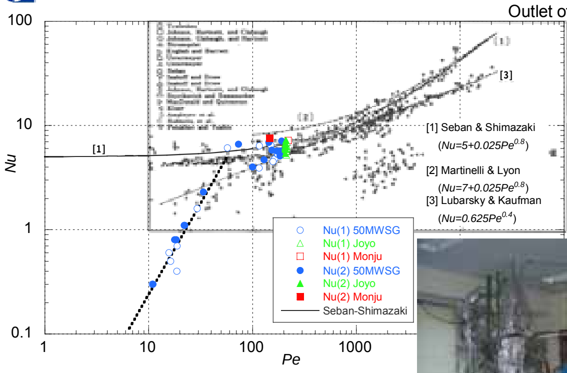

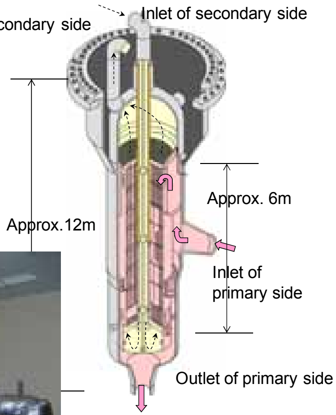

47

Internals of IHX

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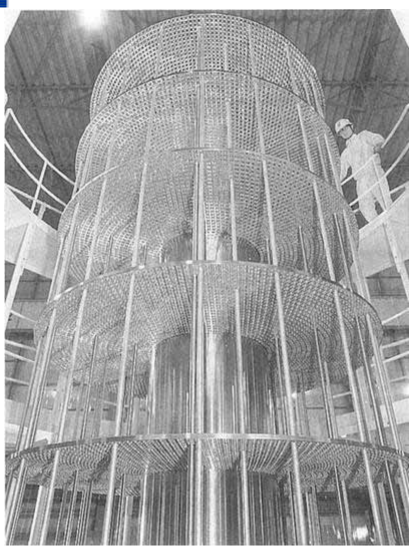
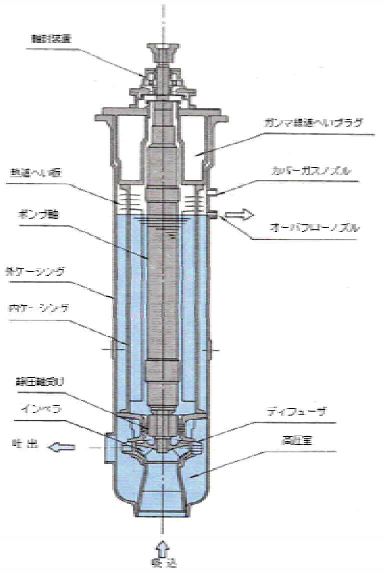


48

Primary main pump

University of Fukui



Intake pressure should be positive in order to prevent cavitation.

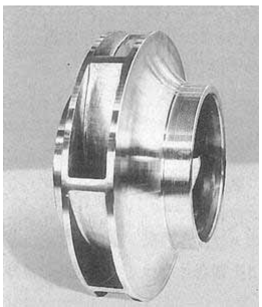
Liquid surface is formed inside the casing of the pump. Height of the pump is restricted by this surface height.

49

Primary main pump

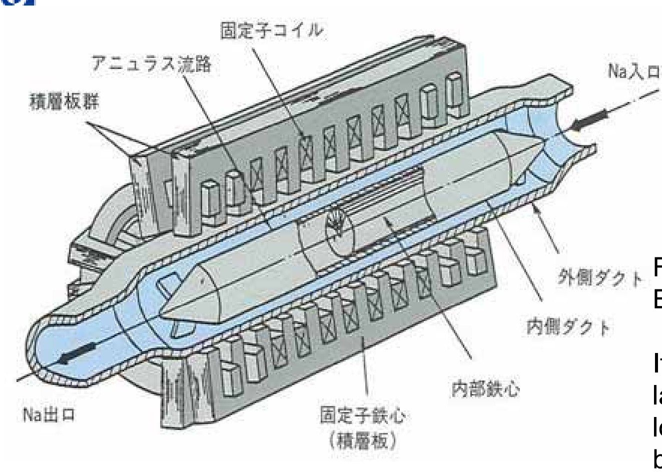
University of Fukui

Impeller blade



50

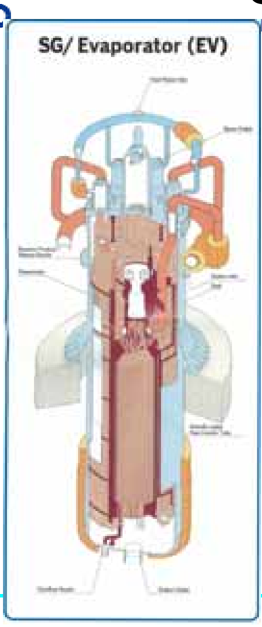
Electoro-magnetic pump

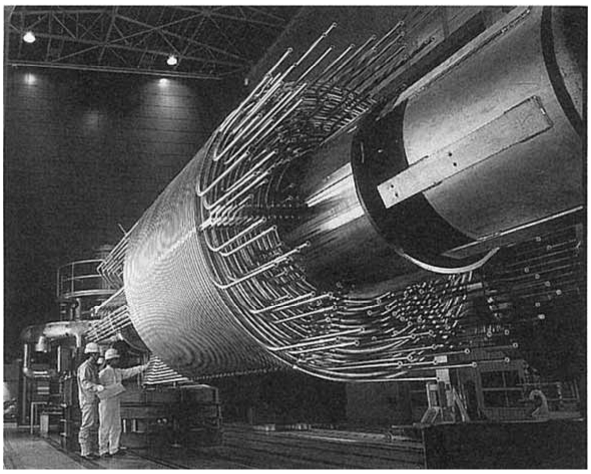


Fabrication of a large EM pump is difficult.

If one can fabricate a large EM pump, the location problem will be solved. Maintenance becomes easy.

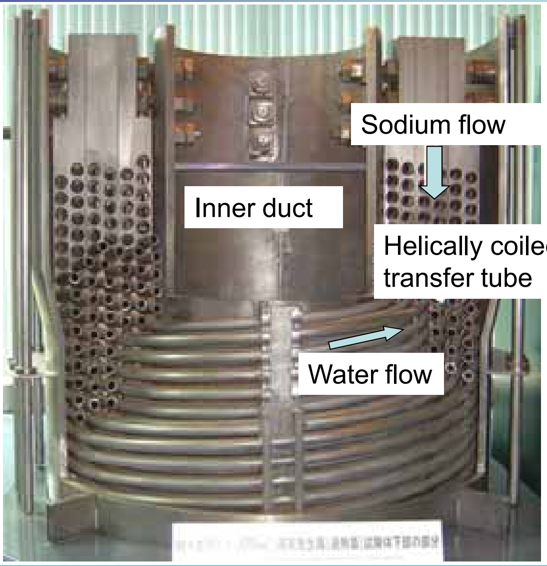
Steam generator





Super heater used at 50MW SG facility

University of Fukui



Air cooler for auxiliary system

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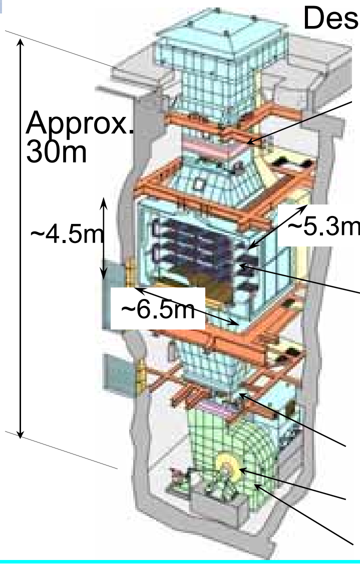
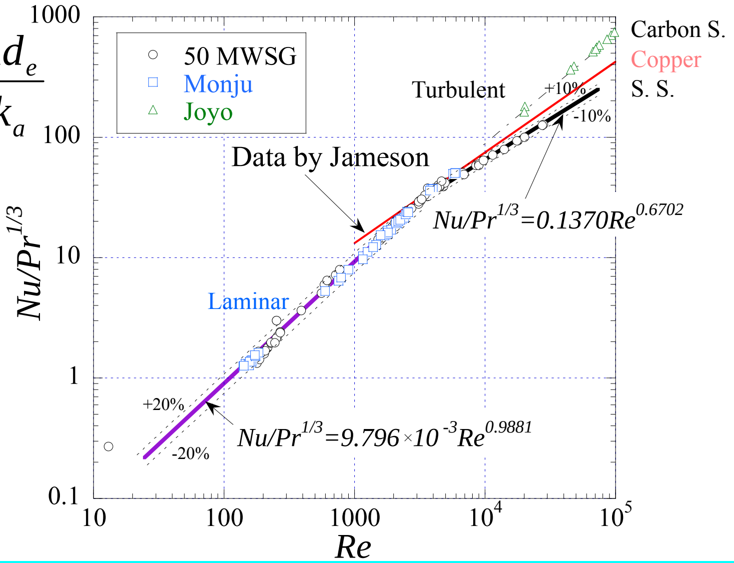
Design: 15MW, Real rating :20MW



H.T. C. of Finned Heat Transfer Tube

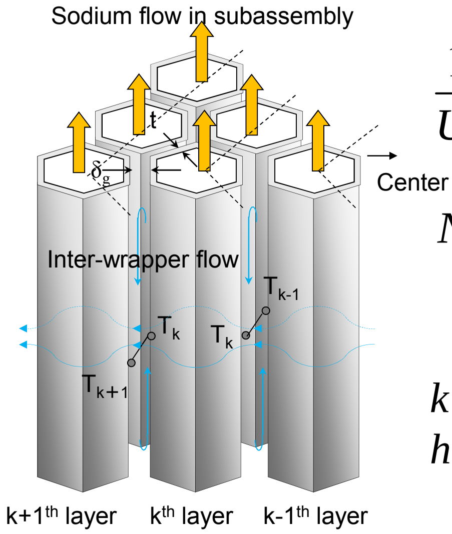
University of Fukui

$$Nu = \frac{hd_e}{k_a}$$



Inter-subassembly Heat Transfer Model

University of Fukui



$$\frac{1}{U} = \frac{\delta_g}{\left(k_{liq} + h\delta_g\right)} + \frac{t}{k_s}$$

$$Nu = \frac{hd_e}{k_{liq}} = 5 + 0.025Pe^{0.8}$$

k: thermal conductivity
h: heat transfer coefficient

Heat Transfer to the Concerned Channel

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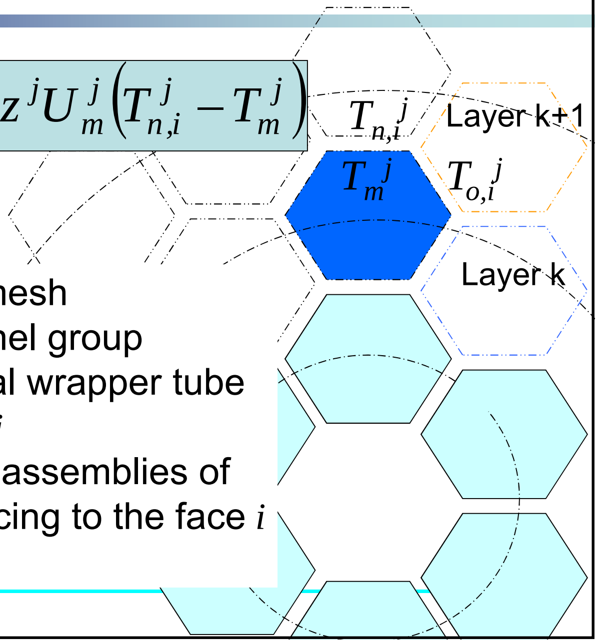
$$Q_m^j = \sum_{i=1}^{6} N_{m,i}^{n} l \Delta z^j U_m^j \left(T_{n,i}^j - T_m^j \right)$$



j: concerned axial mesh
m: concerned channel group
l: width of hexagonal wrapper tube
Δz^j: length of mesh j
$N_{m,i}^{n}$: number of subassemblies of channel group n facing to the face i of channel m

Exit temperature of 3rd Layer Subassembly

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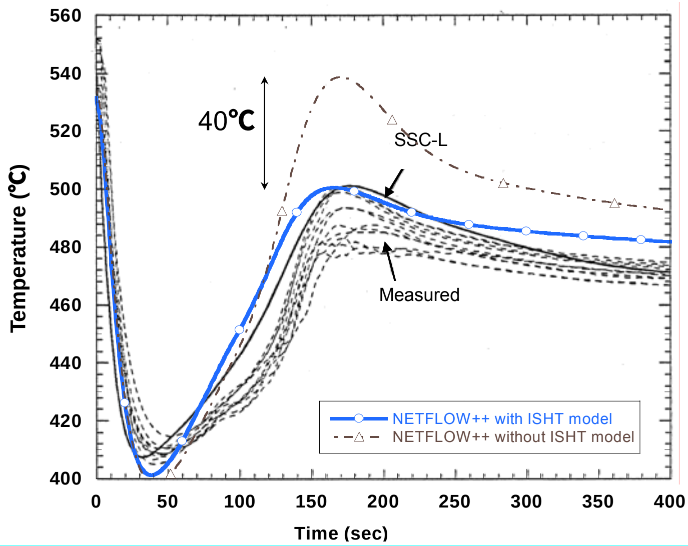

58

Downsizing of FBR

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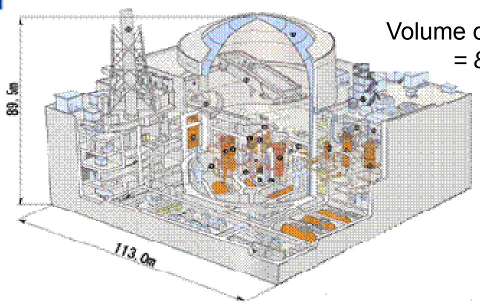
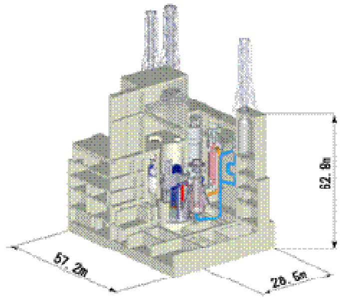


Volume of reactor building
= *810,000 m³*



***Prototype FBR* "Monju"**
Thermal output *714 MWt*
Electrical output *280 MWe*

Gen-IV FBR (JSFR)
Thermal output *3570 MWt*
Electrical output *1500 MWe*

Combined IHX and pump

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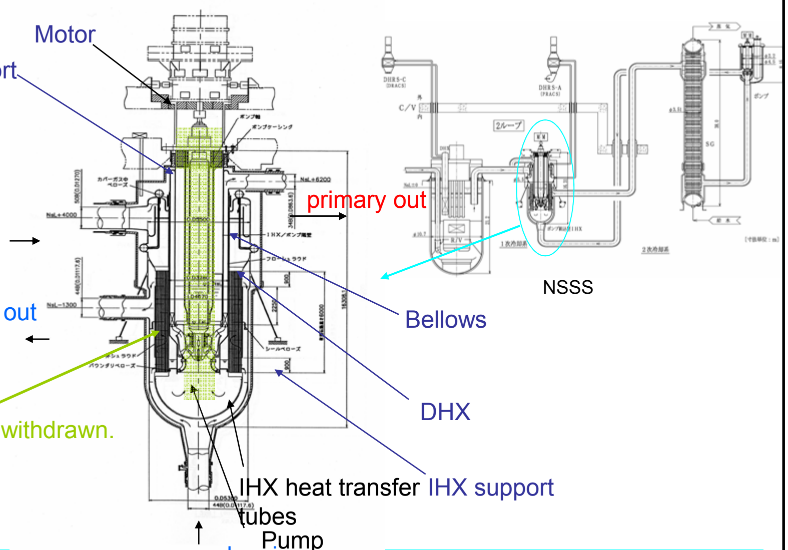
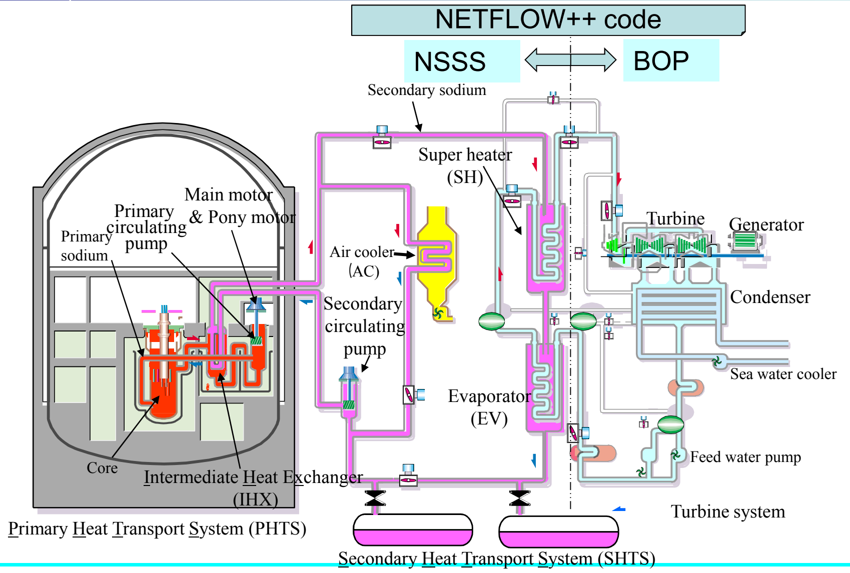


Heat Transport Systems of Monju

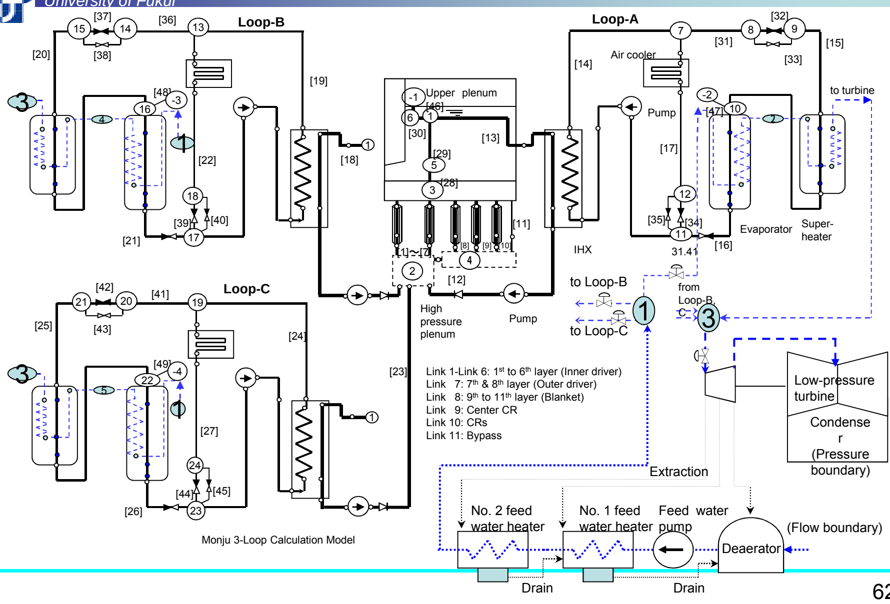
University of Fukui



61

Calculation model of whole heat transport systems

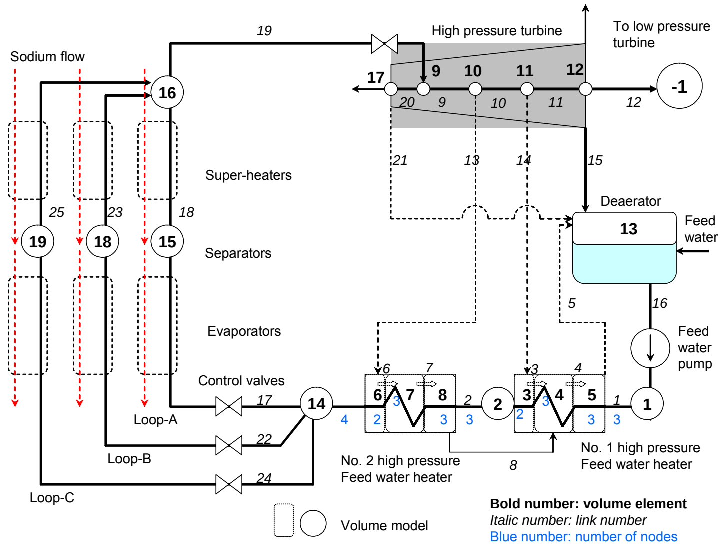
University of Fukui



62

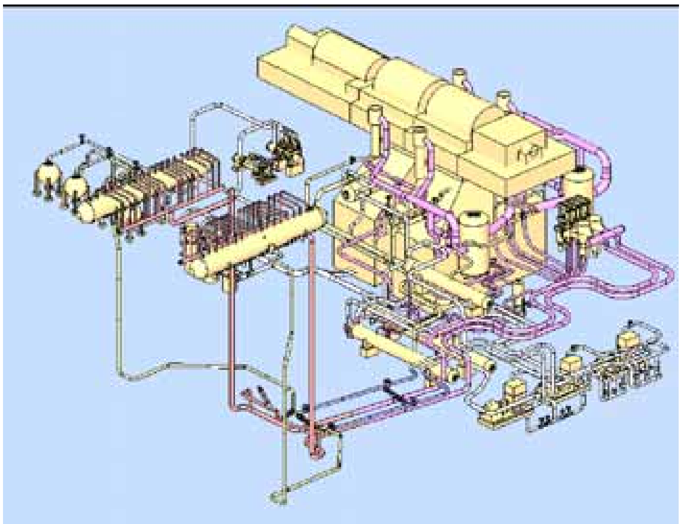
Analytical Model of Turbine and Feedwater Systems

University of Fukui



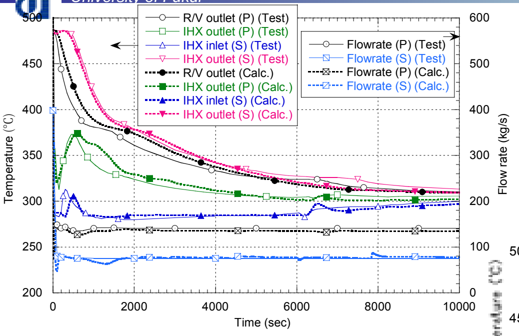
Calculation of turbine and feed water system

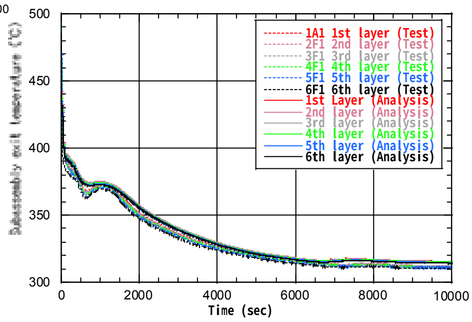
University of Fukui



Simulation of turbine trip test conducted at “Monju”

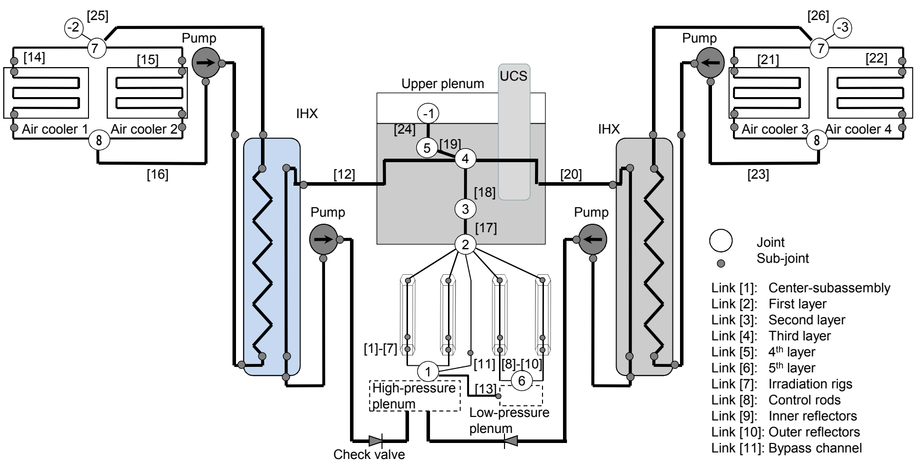
University of Fukui





Whole heat transport system model of “Joyo”

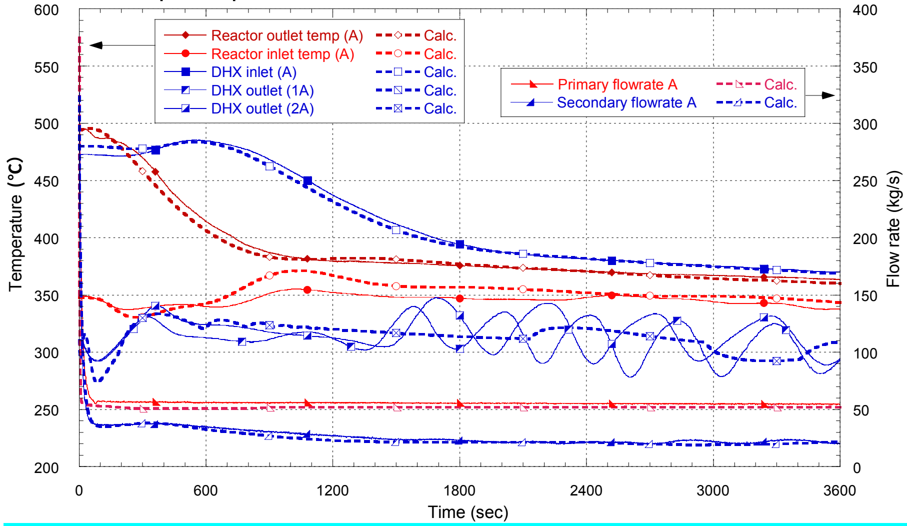
University of Fukui



Natural circulation after plant trip at "Joyo"

University of Fukui

Initial plant power: 140MW



67

Education of nuclear engineering at U-Fukui

University of Fukui

- Education of nuclear engineering for under graduate students
- Graduate School of Nuclear Power and Energy Safety Engineering
- Research Institute of Nuclear Engineering (start in Apr. 2009)

Left side of 2F
RINE

Start of education for graduate school student: from April 2011
- Basic Nuclear Engineering
- Nuclear Engineering
  - Fast Reactor
  - Advanced reactors
  - Fuel and Materials
  - Research for decommissioning
- Medical physics・Chemistry
- Disaster prevention Engineering

68