Pb-Bi Cooled Direct Contact Boiling Water Small Reactor

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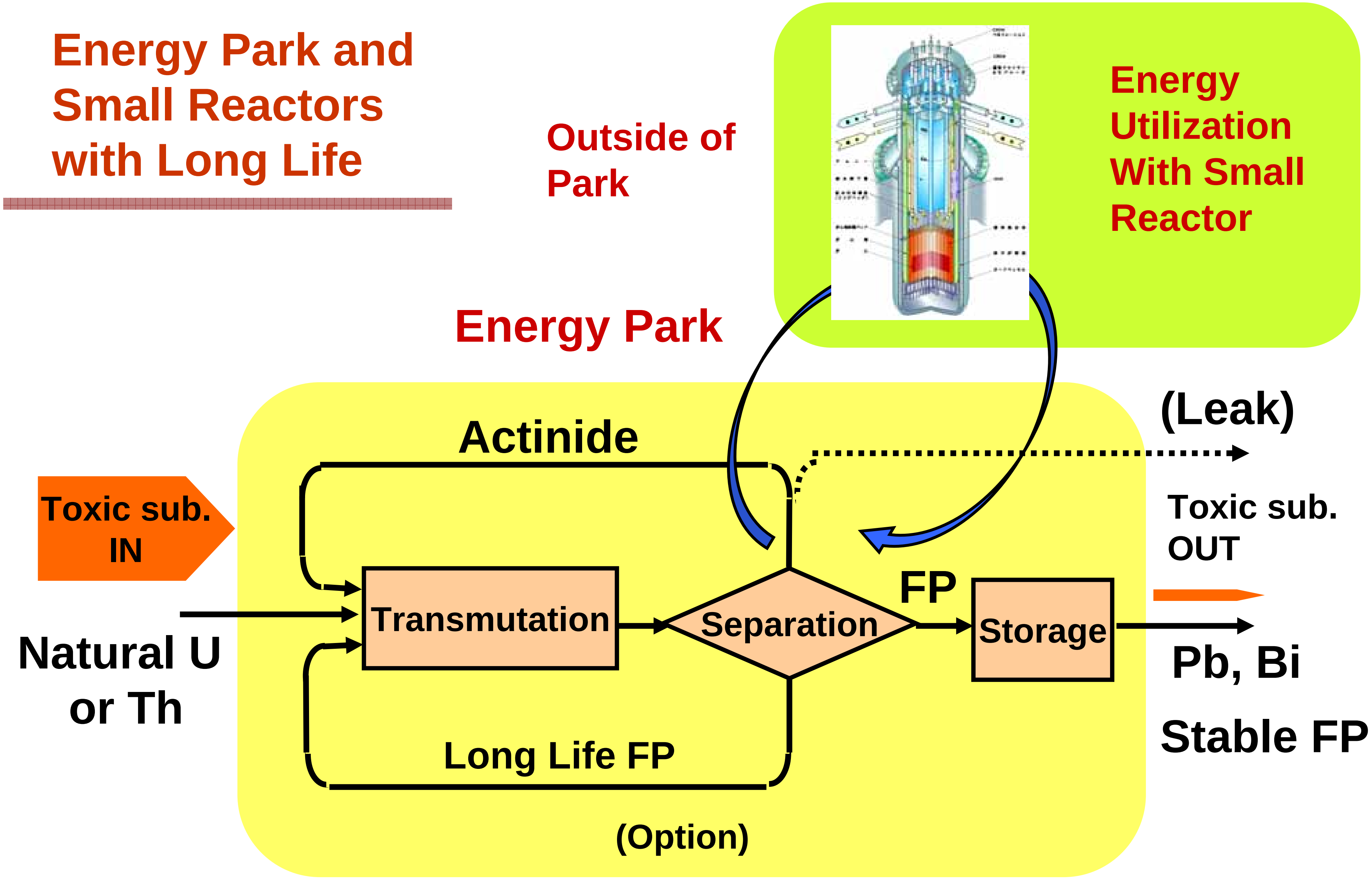
Energy Park and Small Reactors with Long Life



FP：Fission Products

Reactors in Park and Sites

Nuclear Energy Park

Large LFR
-Transmutation
-CANDLE Burning

Self-controllable Na-cooled Large FR

CO_2 Gas Turbine Medium Size Reactor

Transportation of Reactors

Outside of Park (Site)

Production of Electricity, Heat and Hydrogen

Long Life Small LFR
- **Forced Convection**
- **Gas Lift Pump**

Self-controllable Na-cooled Small FR

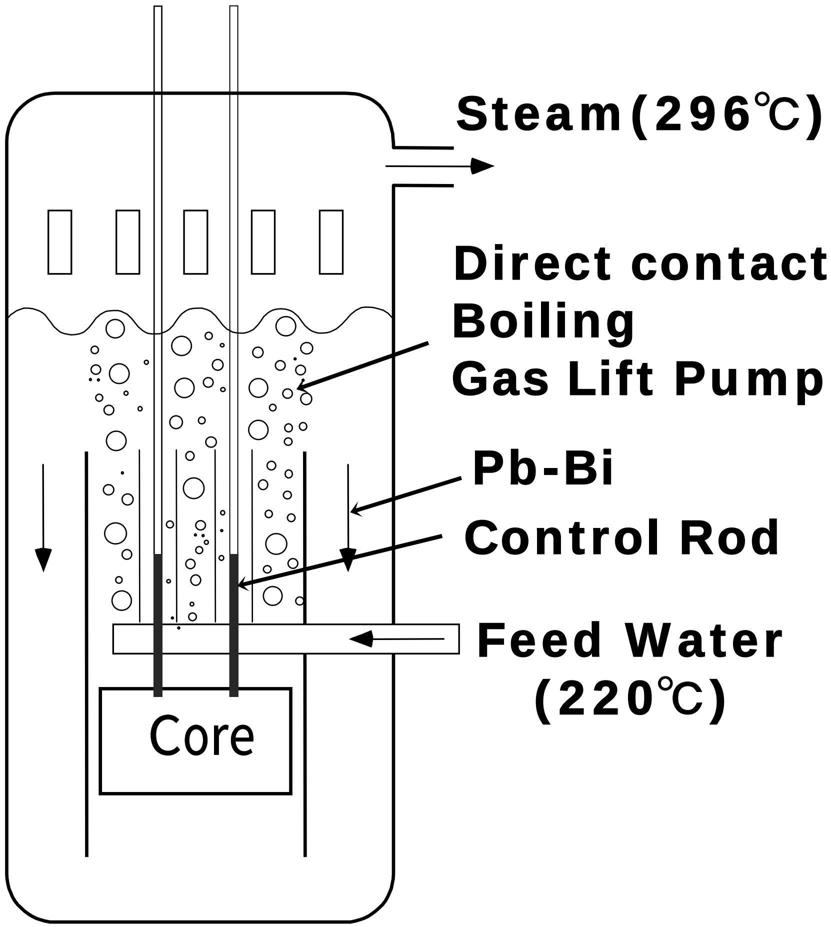
HTGR (CANDLE Burning)

CO_2 Gas Turbine Reactor(High Efficiency, LMFR)

Requirements of Innovative Small Reactors

Safe	Coolant: Inactive with air, water
	Void reactivity: Negative
Economic	Simple or Reduction of material
	e. g., Elimination of
	- Pumps
	- Steam generators
	- Intermediate loop
Efficient in uranium utilization	Breeding ratio > 1
Proliferation resistant	Long life core > 10-15 yrs

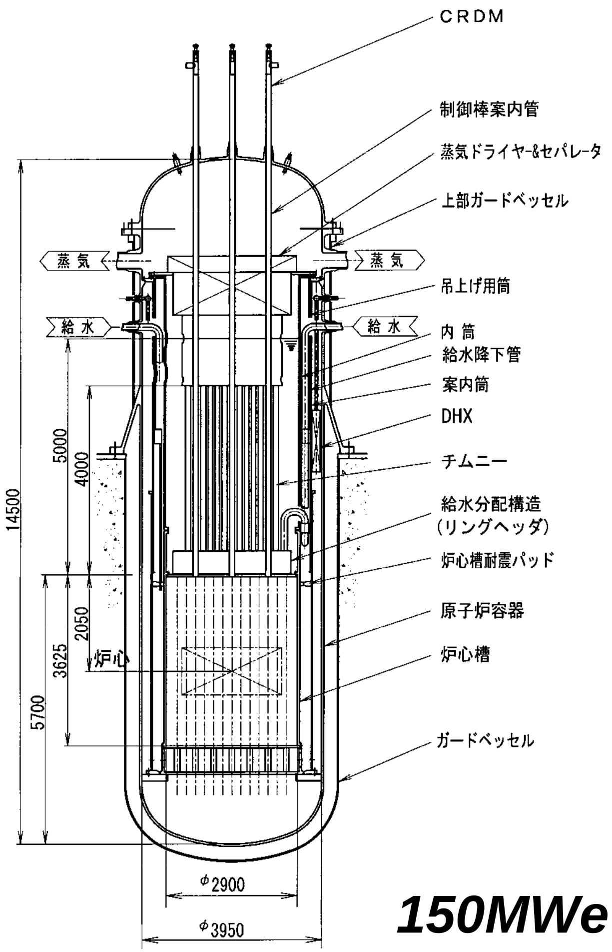
Direct Contact LFR (PBWR)



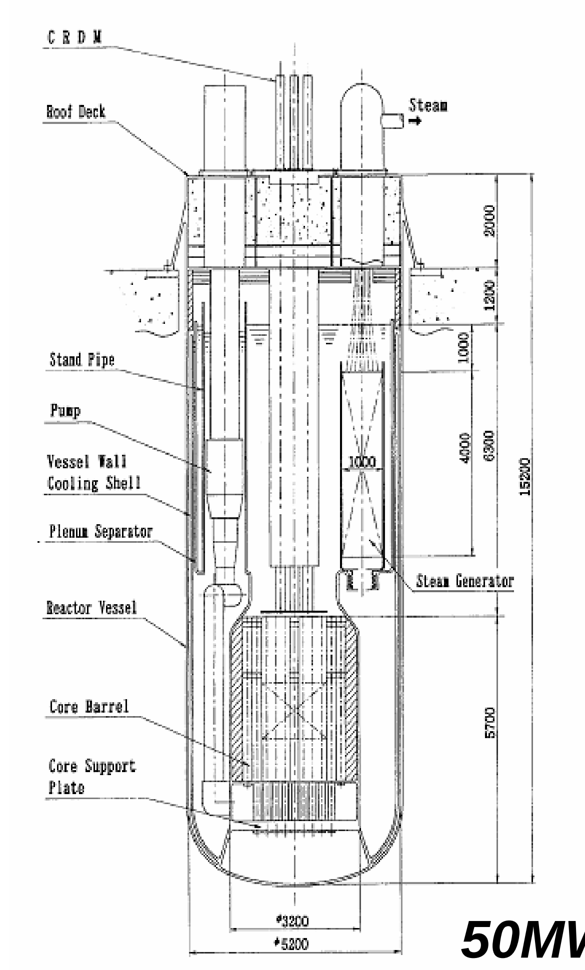
proposed by J. Buongiorno, N. E. Todreas, et al.,
at ANS Winter Meeting, Long Beach, USA, in 1999.

Economy

Reduction of component material



150MWe



50MWe

Steam Lift Pump (PBWFR)
Φ5.1mx14.5mH

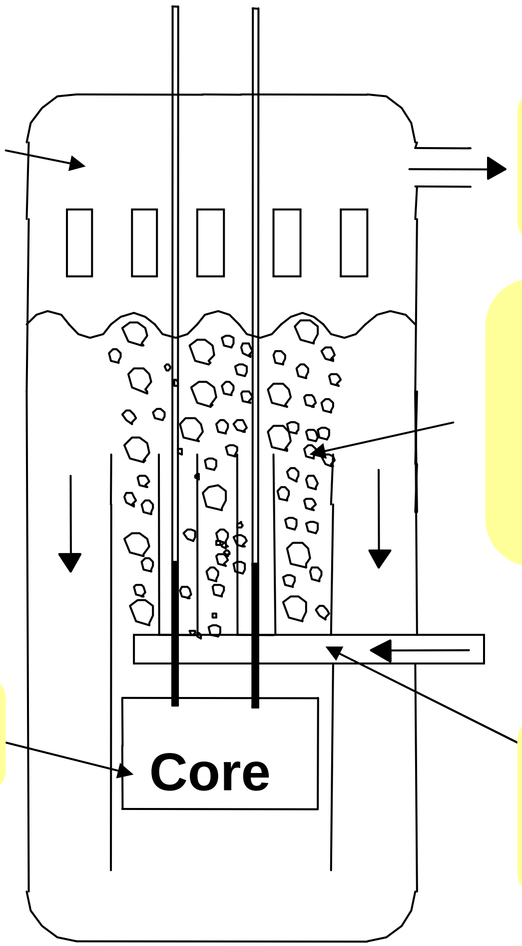
Forced Convection
Φ5.2mx15.2mH

Pb-Bi Cooled Direct Contact Boiling Water FR (PBWFR)

Research Projects for Development of Innovative Nuclear Technologies by MEXT (FY2002-2004)

Polonium measure

Corrosion



Steam with Pb-Bi mists

Direct contact boiling/
Steam lift pump performance

Water injection/
Oxygen control

Theme

1. Conceptual design
2. Pb-Bi-water direct boiling test
3. Test of steam injection into Pb-Bi/ O-control
4. Corrosion
5. Polonium measure

Challenges of PBWFR Technology

1) Conceptual design

- Long life core, void reactivity and specific structural design,
- Safety evaluation.

2) Material and chemistry

- Control of oxygen potential in Pb-Bi,
- Compatibility of core and structural materials with Pb-Bi,
- Measure of Po transport into steam system.

3) Hydraulics

- Lift pump performance,
- Suppression of carry-over of Pb-Bi mist/aerosol into steam system,
- Suppression of carry-under of steam bubbles into down-comer,
- Ultrasonic flow-meter.

4) Thermal effect

- Direct contact steam generation performance,
- Flow instability and vapor explosion.

Phenomena

Pb-Bi

Molecular

Metal solution
Diffusion
Penetration
Corrosion
Melting point

Chemical

Reaction with air, water
Oxidation
Oxygen control
Oxygen sensor
Aerosol

Nuclear

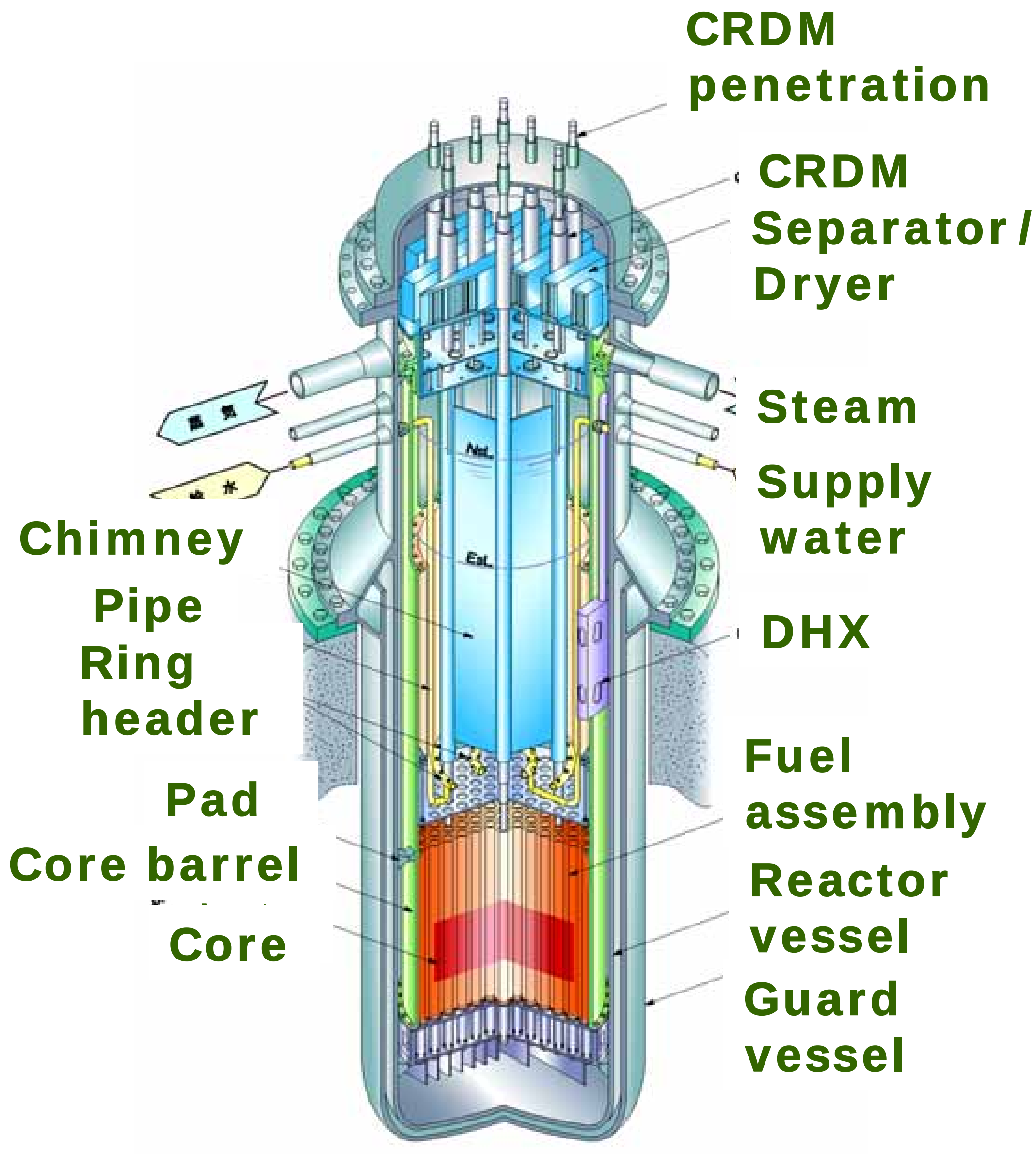
Core design
Void reactivity
Po production

Hydraulics Transport

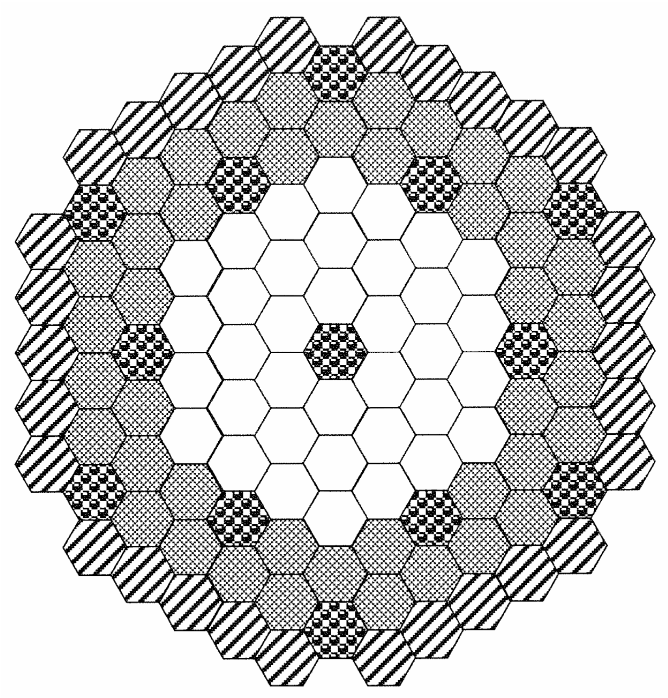
Mass transport
Two-phase void
Mist
Erosion

Conceptual Design of 150MWe PBWFR

Thermal power	450 MWt
Core inlet temp.	310 °C
Core outlet temp.	460 °C
Max. cladding temp.	620°C
Pb-Bi flow rate	73970 t/h
Steam pressure	7 MPa
Steam temperature	296 °C
Supply water temperature	220 °C
Steam flow rate	863 t/h
Burnup	110 GWd/t
Breeding Ratio	1.05
Refueling interval	15 yrs



Core Design



Inner Core Fuel Assembly 36

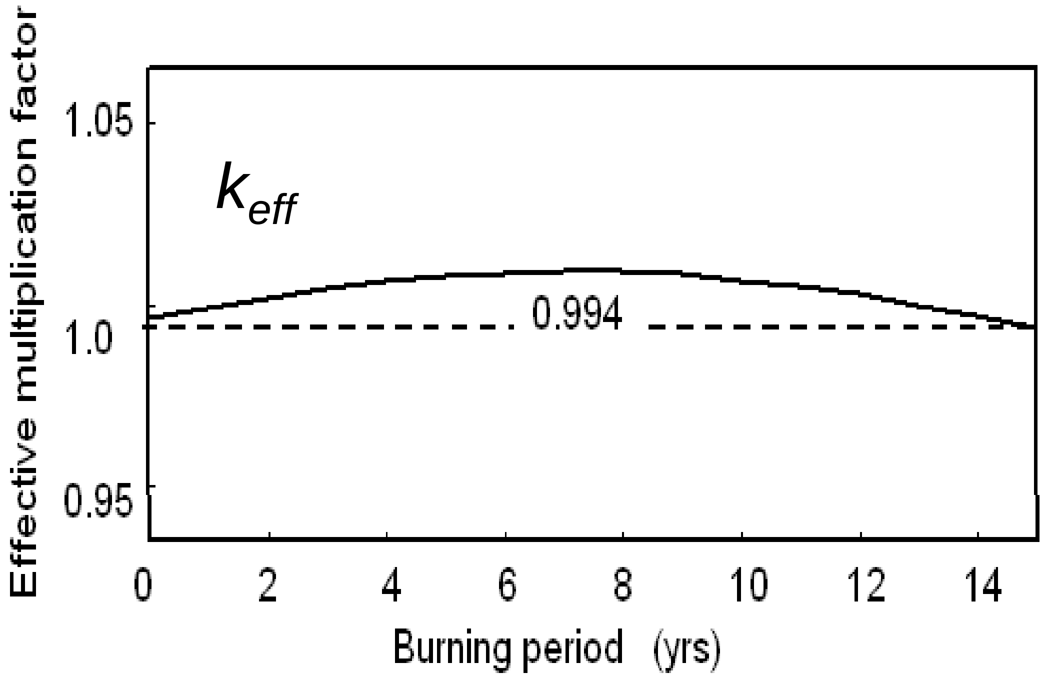
Outer Core Fuel Assembly 42

Pb-Bi Shielding 30

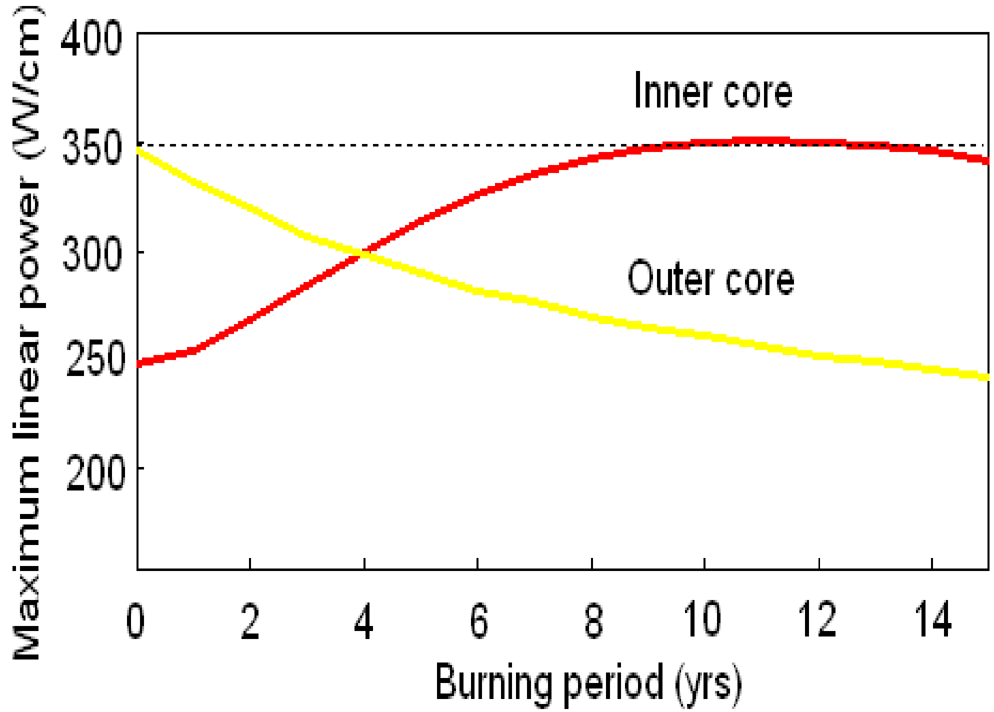
Control Rod 13

Total 121

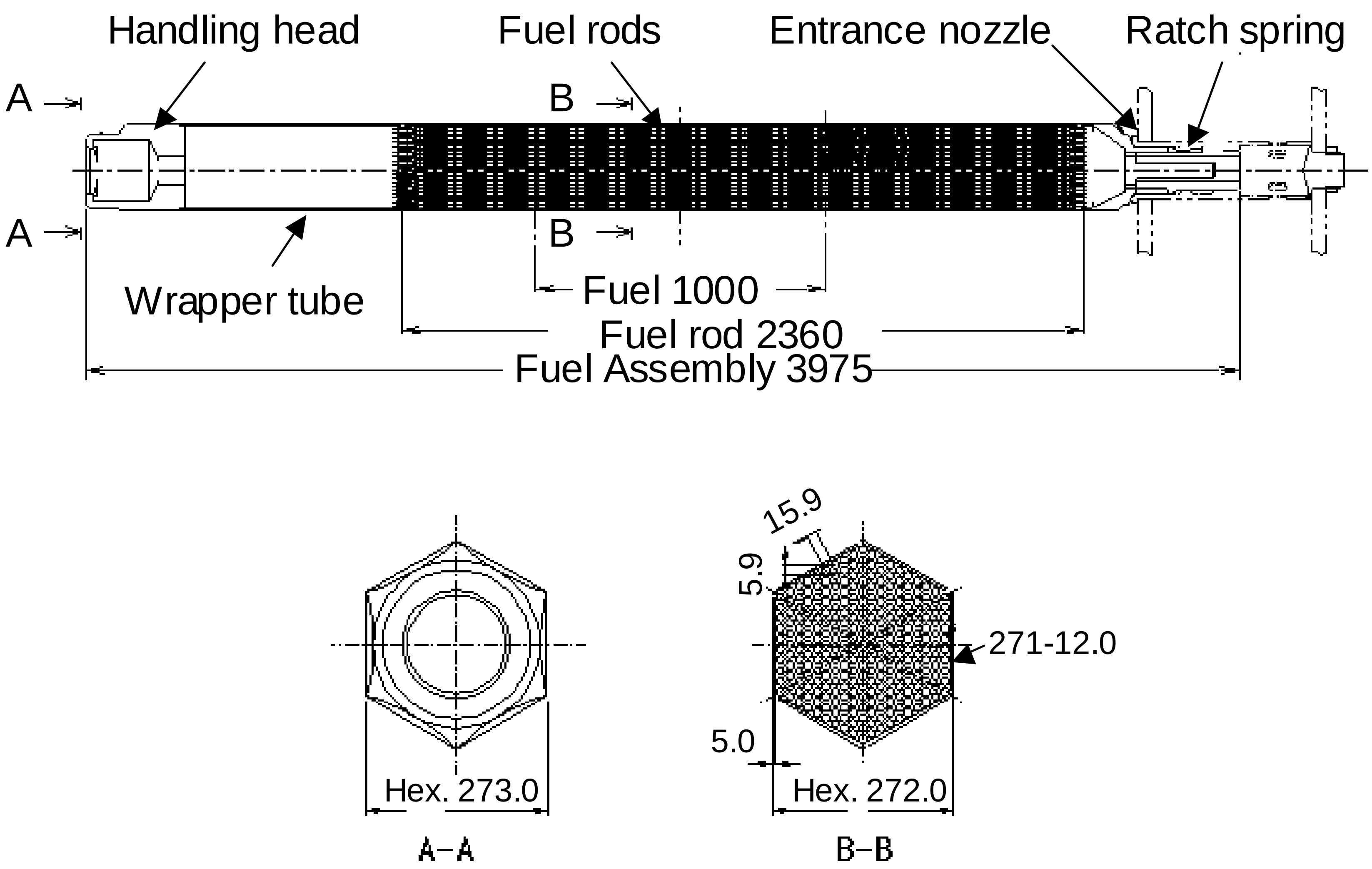
Core	Type	*Homogeneous core*
	Zones	*Two enriched zones.*
Fuel		*Pu-U nitride (N^{15} 100%)*
Core	Diameter	*267 cm*
	Height	*100 cm*
Blanket	Radial	*Non*
	Upper axial	*30 cm*
	Lower axial	*Non*
Pu enrichment	Inner zone	*11.5 w/o*
	Outer zone	*15.8 w/o*
Contents of U^{235} in core fuel		*0.3 w/o*



Maximum linear power

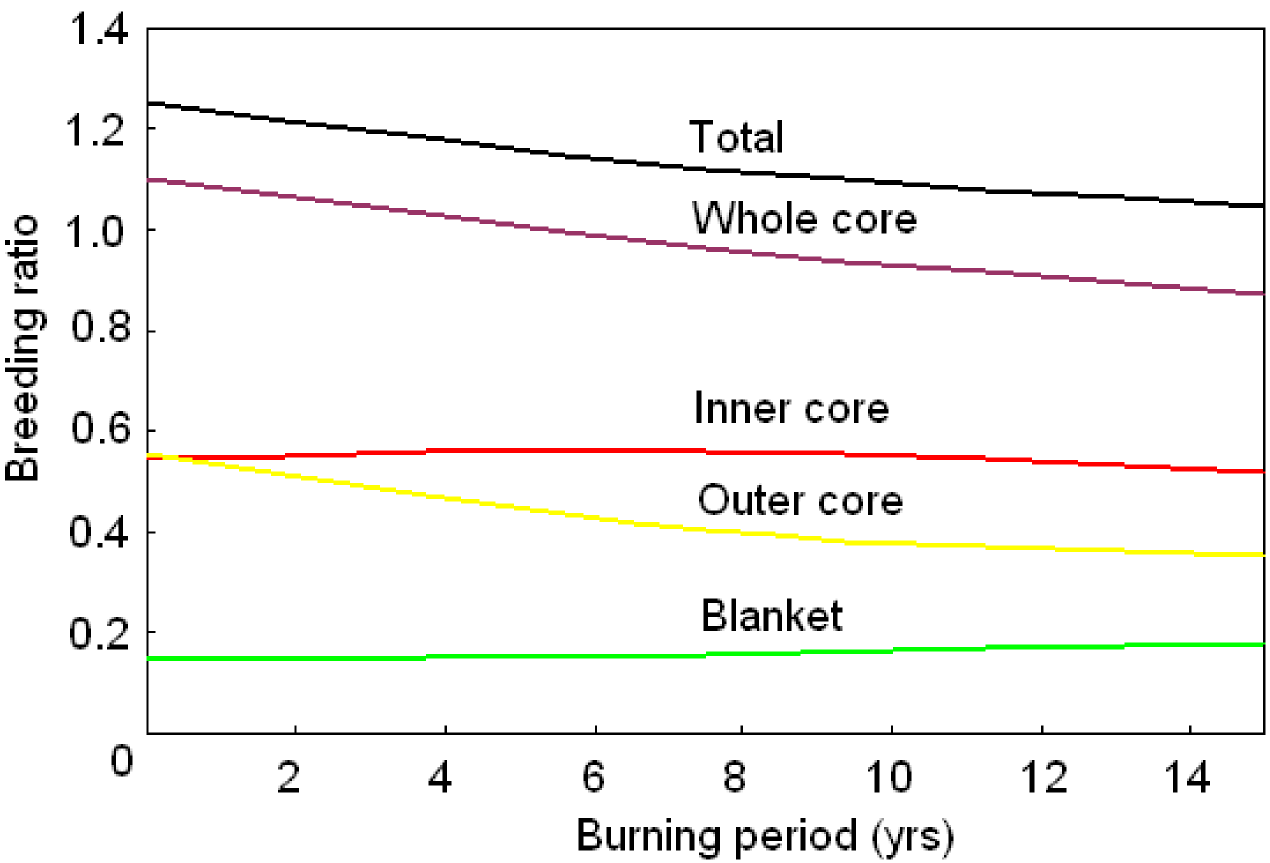


Fuel Assembly



Burn-up reactivity loss		**1.5 %dk/kk'/15 yrs**
Breeding ratio		**>1.05**
Void reactivity	**Core**	**$ 7.4 (EOL)**
	Core, axial blanket and plenum	**$ 3 (EOL)**

Breeding ratio



Fuel Assembly

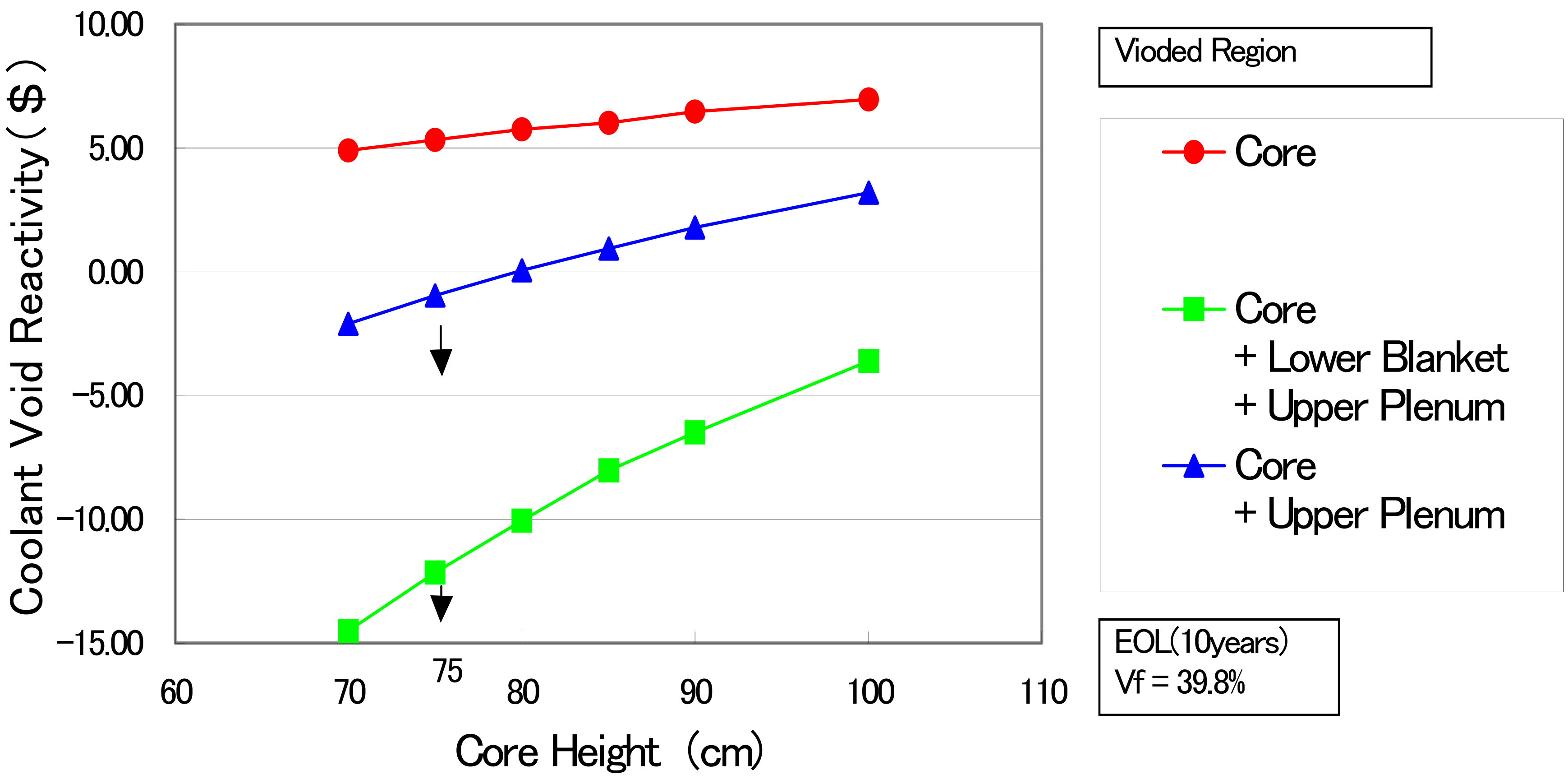
Type	*Duct type*
Spacer type	*Grid spacer*
Pellet smear density	*80 %*
Number of rods	*271*
Outer diameter of cladding	*12.0 mm*
Pitch of rod arrangement	*15.9 mm*
Face distance of wrapper tube	*272.0 mm*

Pitch of assembly arrangement		*275 mm*
Volumetric fraction	Fuel	*39.8 %*
	structure	*14.1 %*
	coolant	*46.1 %*
Friction pressure drop in fuel bundle		*0.04MPa*

Additional Consideration for Low Void Reactivity Core

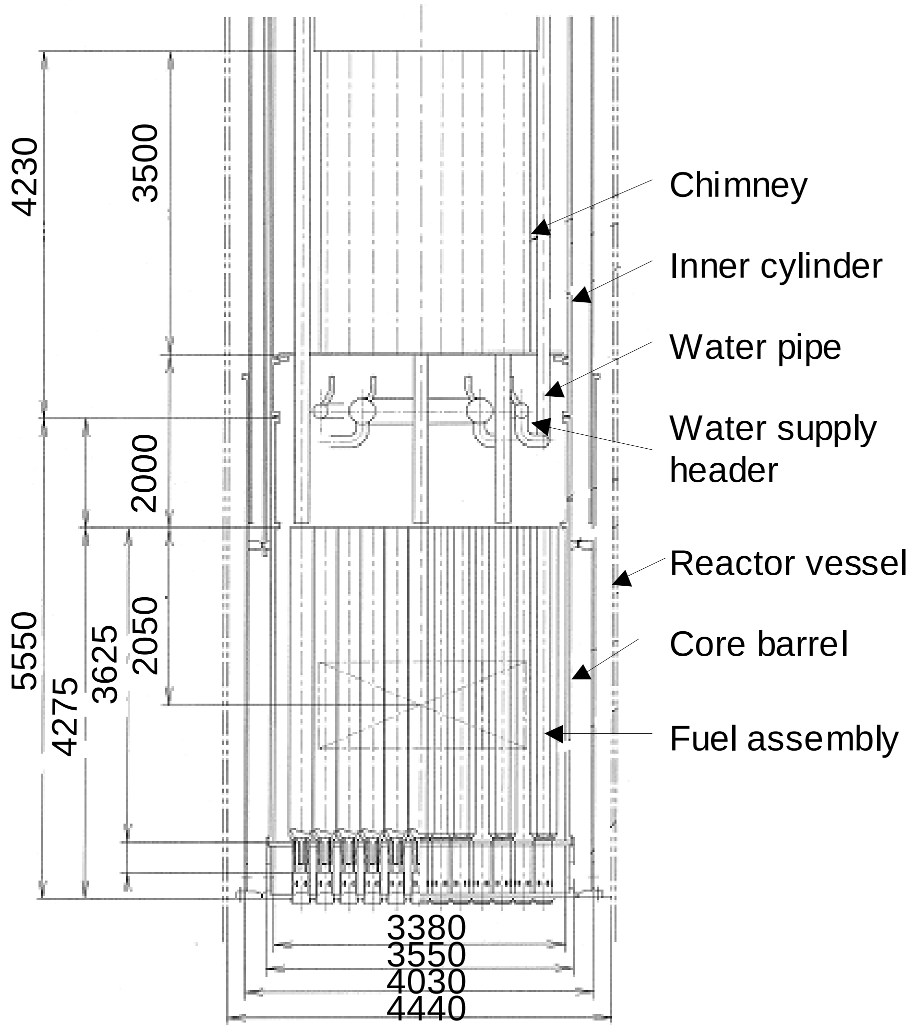
- Safety design demands negative void reactivity for the case of core and upper plenum region voided from considerations of core void pattern of PBWFR.
- Void reactivity (core +upper plenum) of core mentioned above is +3$.
- Considerations of core specification adequate for safety demands have been performed by core height adjustment with same core layout.

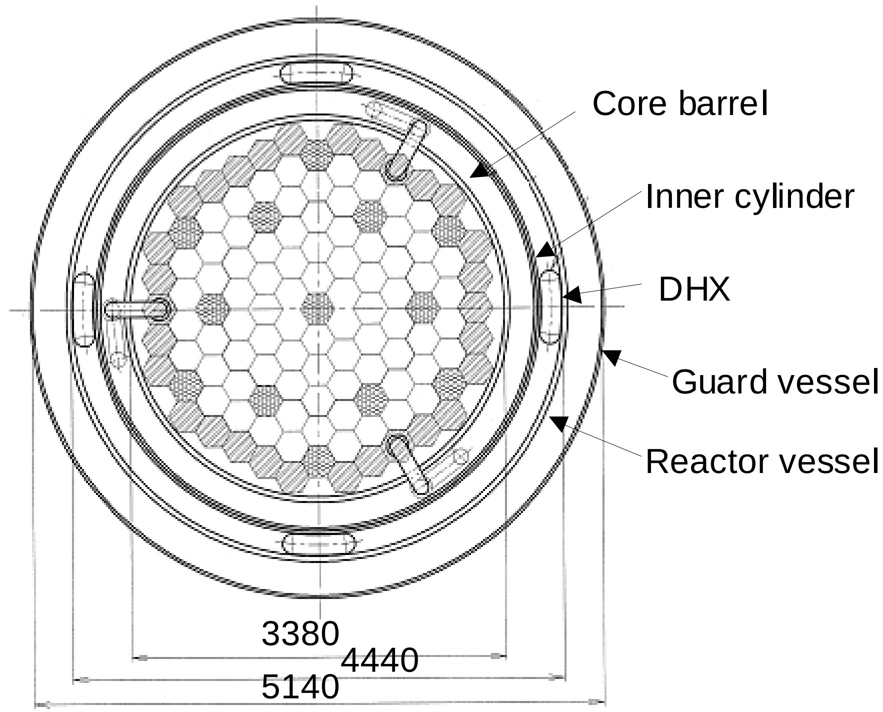
Relation of Core Height and Coolant Void Reactivity



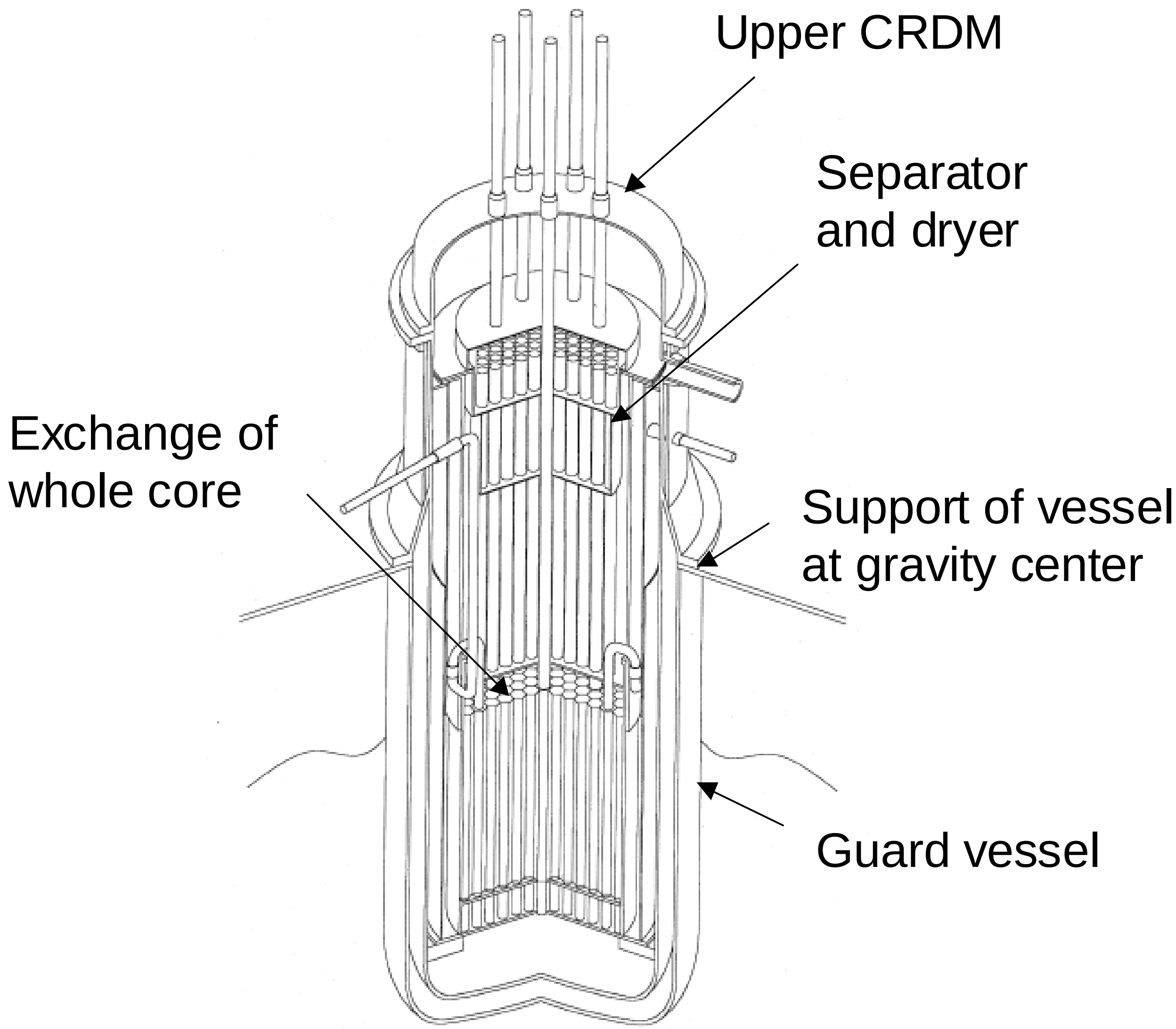
Specification of Low Void Core

Item	Reference Core	Low Void Reactivity Core
Core Residence Time (years)	15	10
Core Height (cm)	100	75
Core Equivalent Diameter (cm)	267	278
Fuel Pin Diameter (mm)	12	12
Fuel Pin Pitch (mm)	15.9	15.2
Pin Number per Assembly (-)	271	331
Assembly Length (mm)	3,625	3,205
Burn up Reactivity Loss (%ΔK/kk')	1.53	0.9
Breeding Ratio (-)	1.122	1.17
Void Reactivity(Core) ($)	7.4	5.6
Void Reactivity(Core+Upper Plenum) ($)	3.0	-5.3





Structure in Reactor Vessel



Reactor Structure

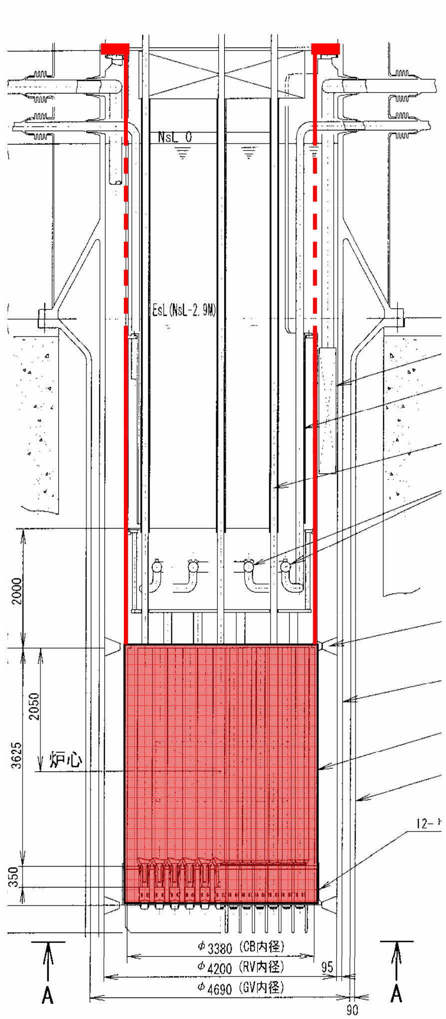
Core Support Structure

◆Core Support Structures and Core Barrel

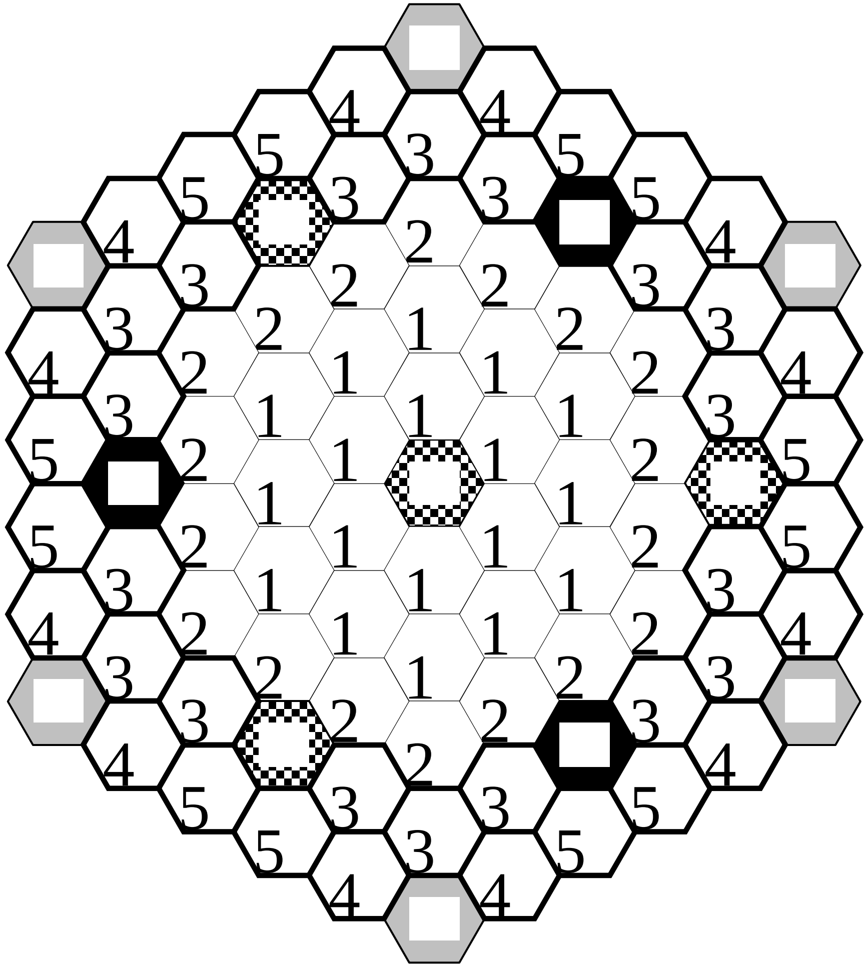
- Hung from upper flange
  in order to pull up when refueling
- Supported horizontally
  by earthquake-proof pads.

◆Control Rod Guide Tubes

- Guide Control Rods
  from Head Plate to Core
- Penetrate Upper Structures,
  such as Dryer, Separator and Chimney.
- Supported by penetrations
  (CRGTs maintain CR insertion anytime)



Flow Allocation



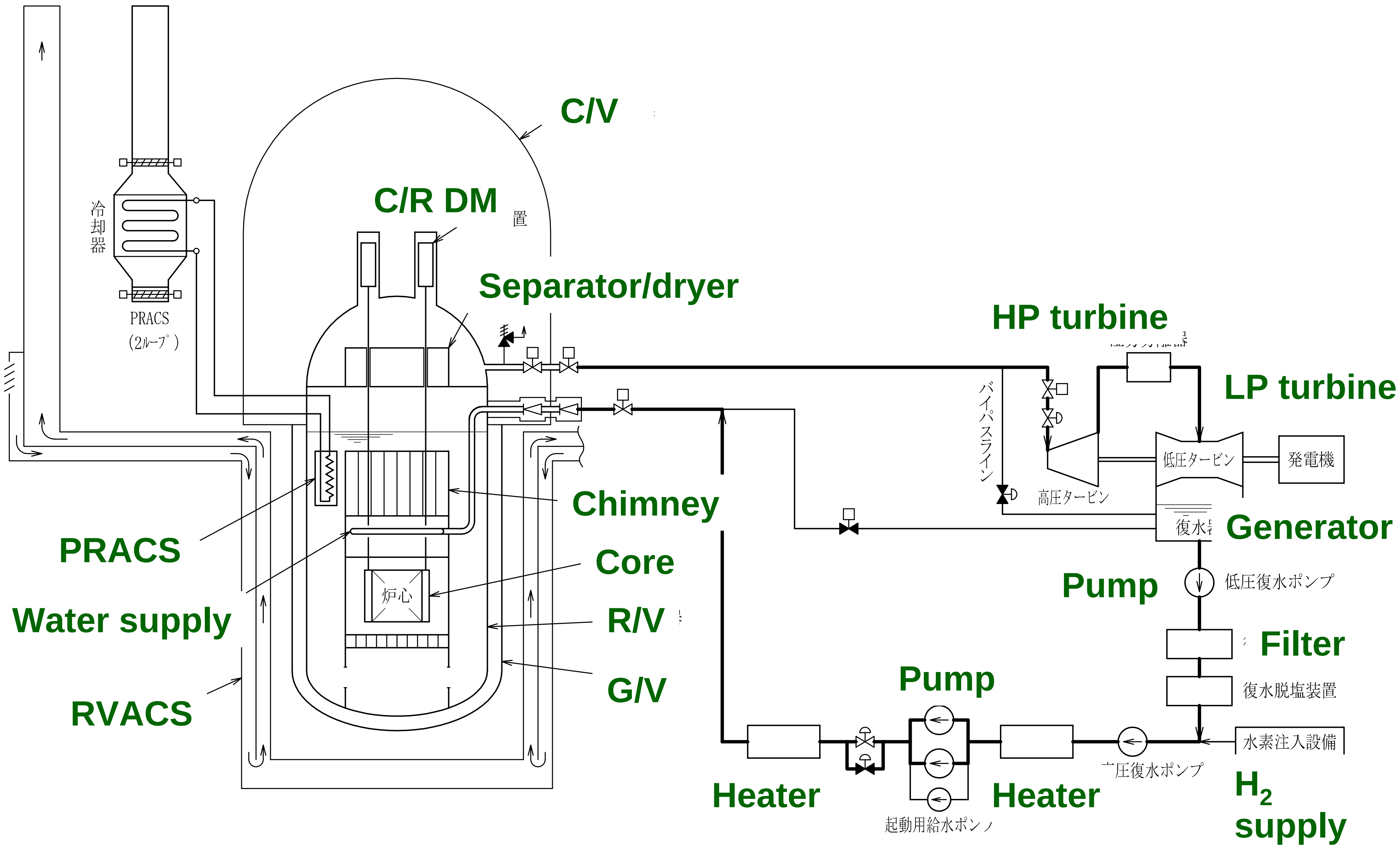
Inner Core: 1,2

Outer Core : 3,4,5

Power of Fuel Rod and Max. Cladding Temperature

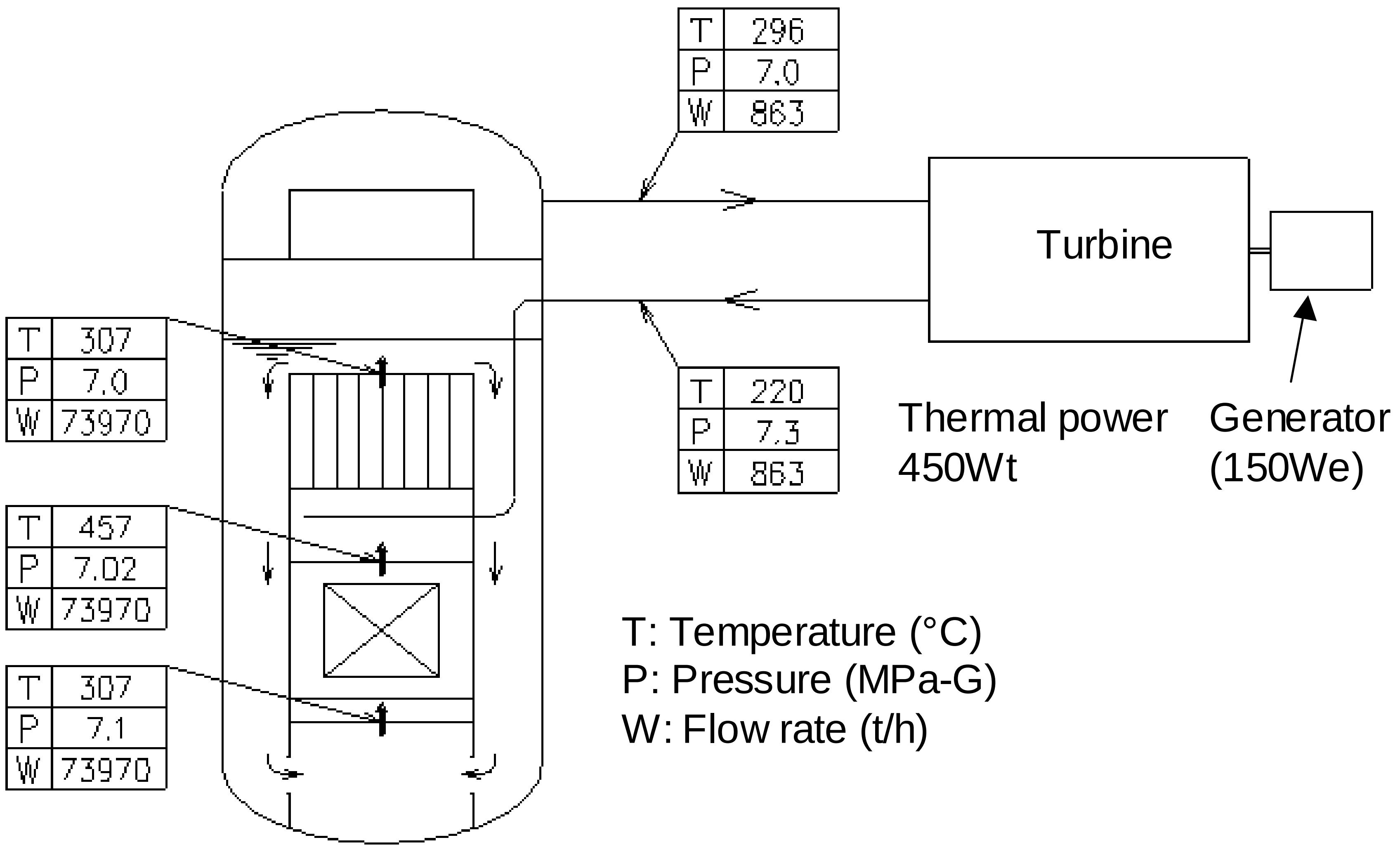
P: Power of fuel rod (kW), T: Cladding temperature (°C);
Initial: 0 days, Middle: 2737 days, Final: 5475 days

	Region	Assemblies	Flow rate (kg/s)		Initial	Middle	Final
Inner core	1	18	272	P	*18.4*	*26.2*	*31.1*
				T	*496*	*571*	*618*
	2	18	249	P	*20.6*	*24.9*	*28.7*
				T	*536*	*579*	*619*
Outer core	3	18	264	P	*30.3*	*29.2*	*24.9*
				T	*619*	*608*	*563*
	4	12	247	P	*28.4*	*23.5*	*18.5*
				T	*619*	*565*	*510*
	5	12	225	P	*26.1*	*23.2*	*18.4*
				T	*619*	*585*	*527*

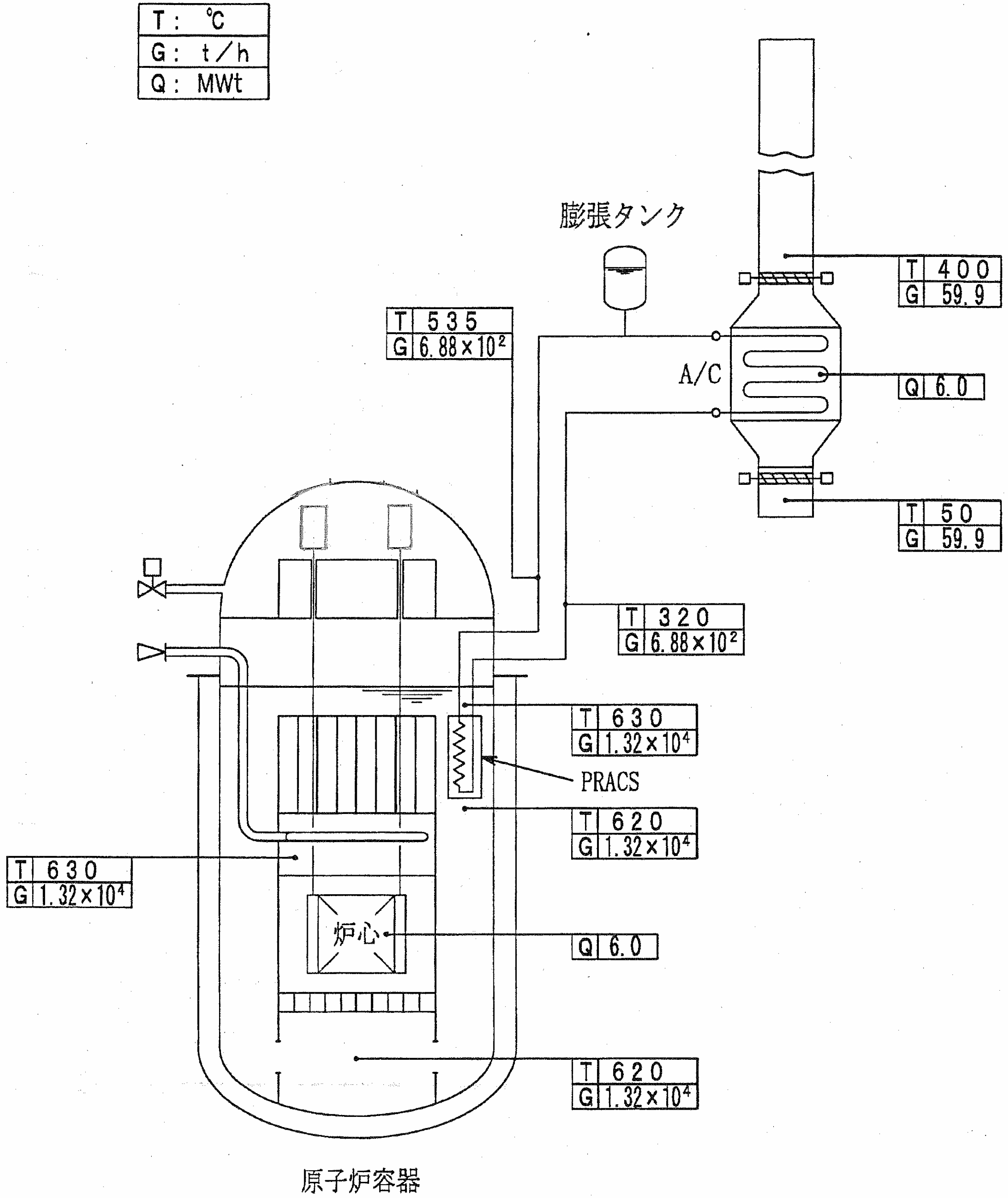


Plant System

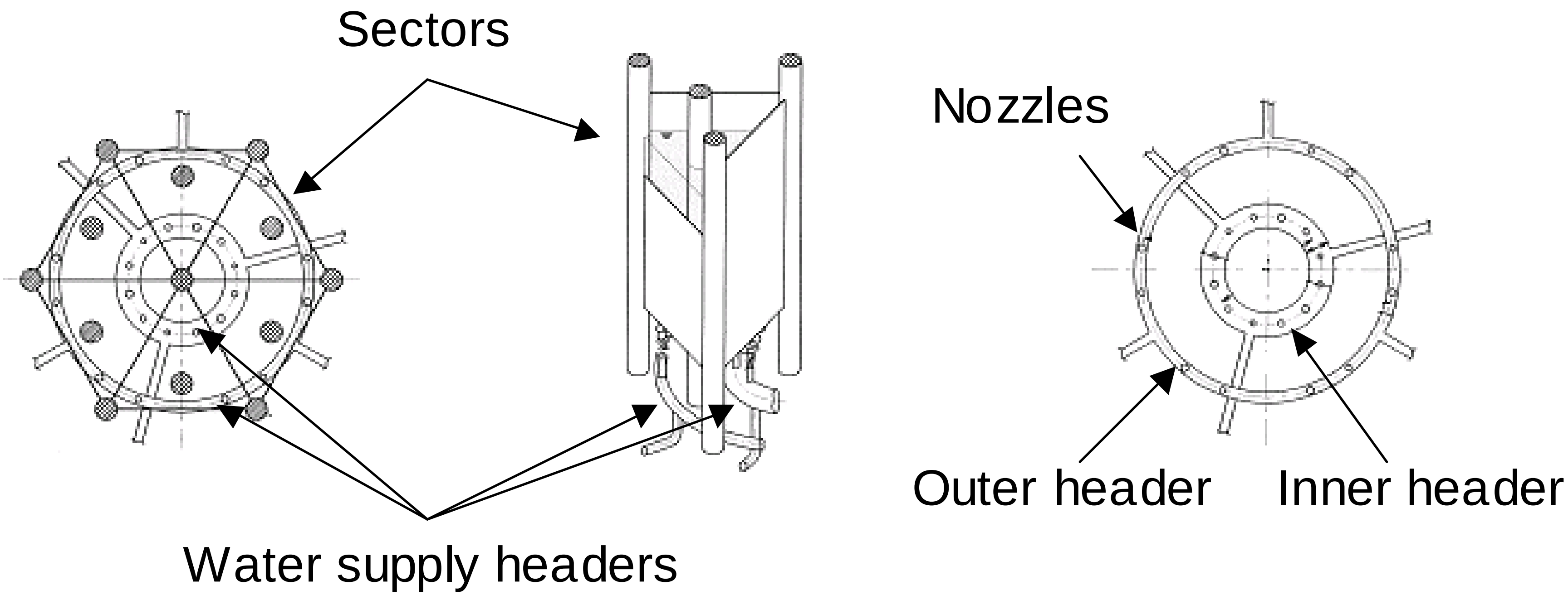
Heat balance



Decay Heat Removal



Performance of lift pump in chimney



Requirement in sector-type chimney

- Uniform distribution of void fraction
- High void fraction, i. e.
  Low slip ratio of steam velocity to Pb-Bi velocity

One-dimensional analysis of lift pump performance

Balance of head and pressure loss for Pb-Bi circuit

Total pressure loss	**0.156MPa**
Bundle	0.081MPa
Assembly	0.020MPa
HD plate	0.029MPa
Chimney	0.025MPa
Down-comer	0.00068MPa

$<$

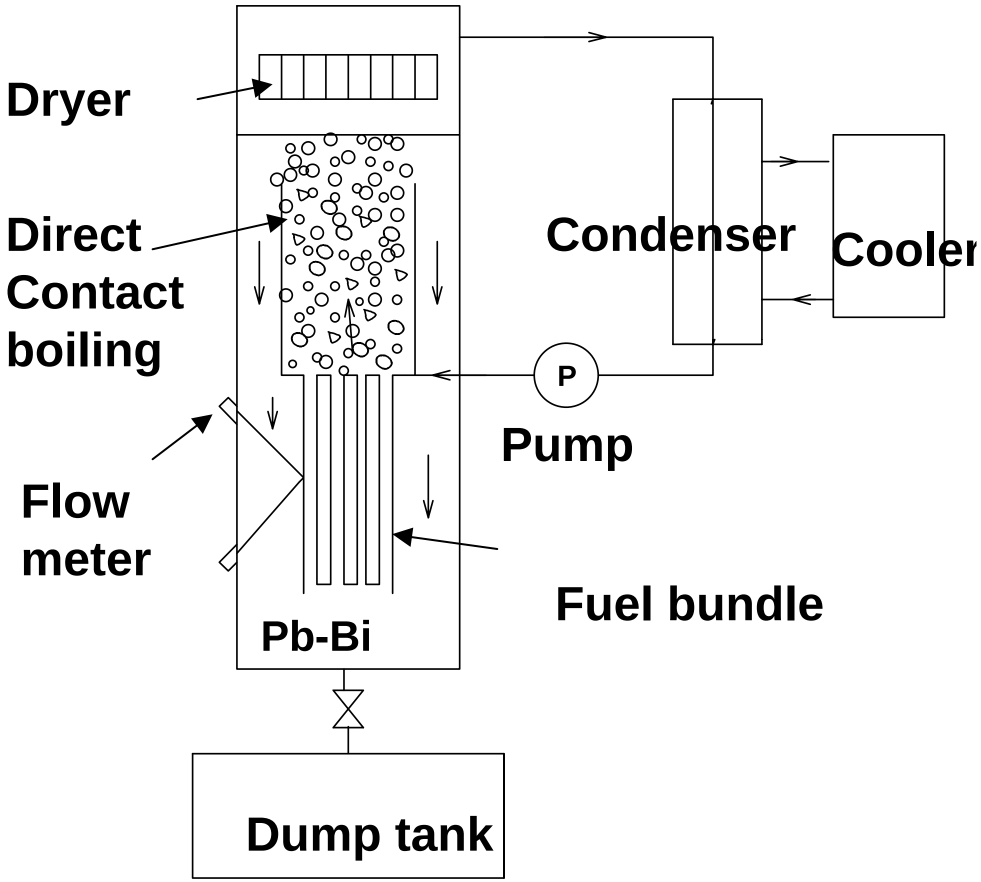
Total lift pump head 0.198MPa

Chimney height 3,000mm

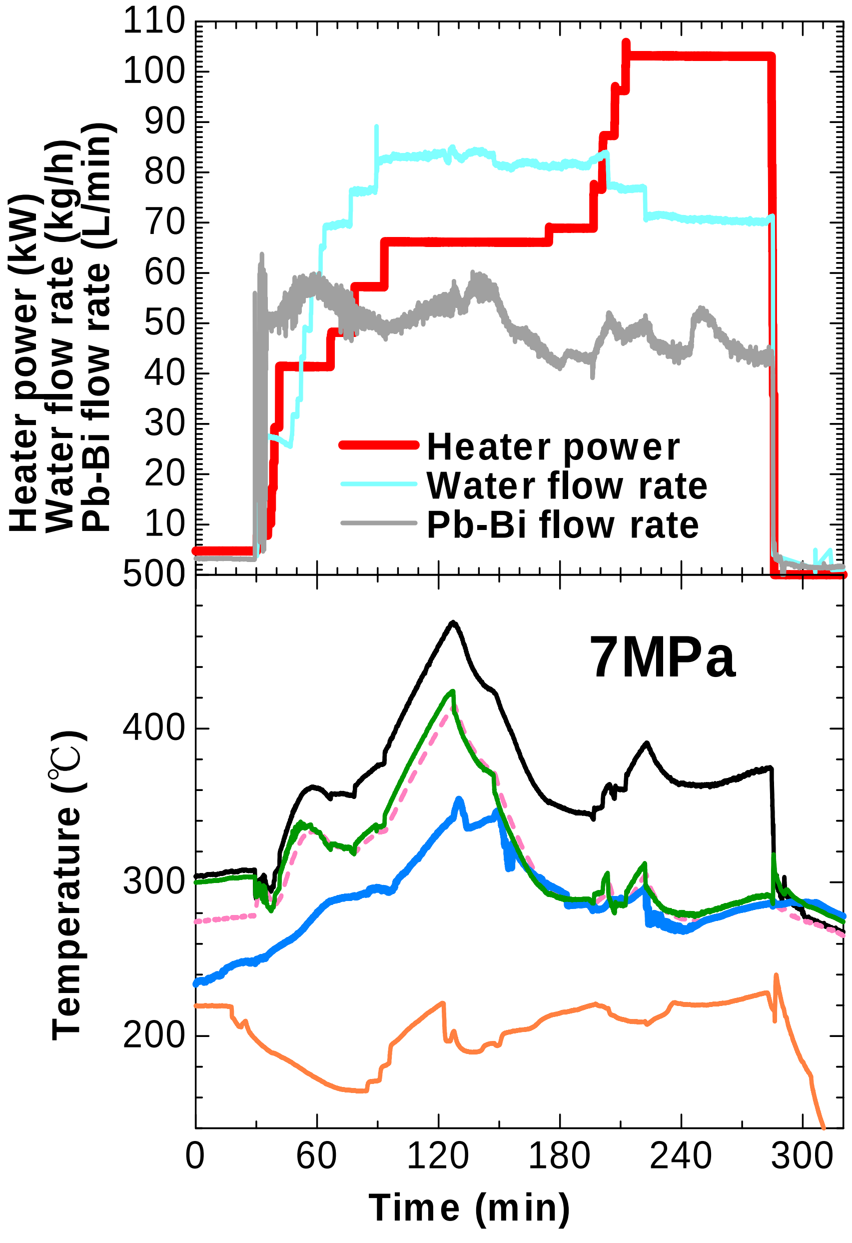
Average density 3,788kg/m^3

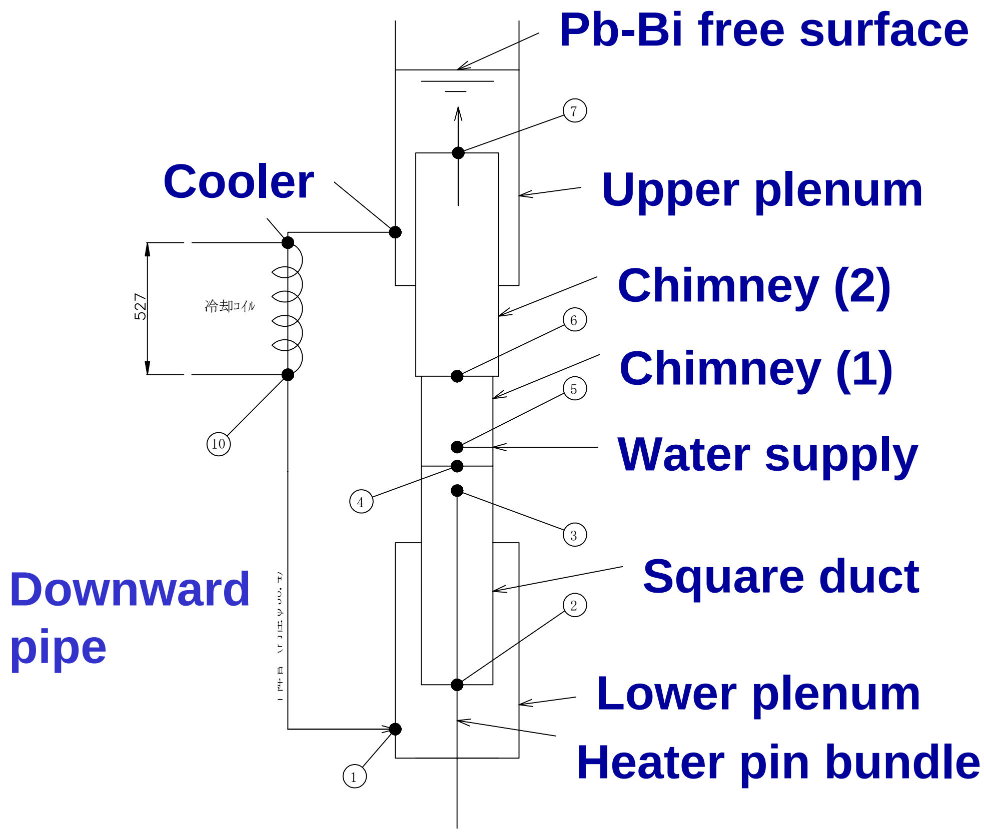
（Void fraction 0.645）

Experiment of Pb-Bi-Water Direct Contact Boiling Two-phase Flow



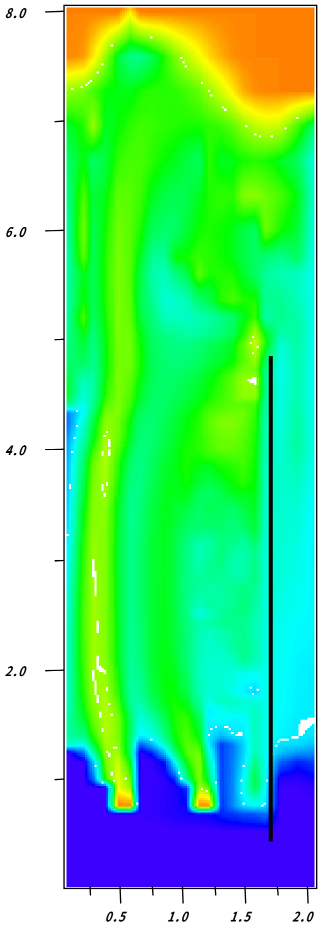
Pb-Bi-Water Direct Contact Boiling Two-phase Flow Test Apparatus


7MPa
Heater power (kW)
Water flow rate (kg/h)
Pb-Bi flow rate (L/min)
Temperature (℃)
Time (min)
Heater power
Water flow rate
Pb-Bi flow rate
Outlet of heater pins
Inlet of heater pins
Outlet steam
Chimney
Injected water

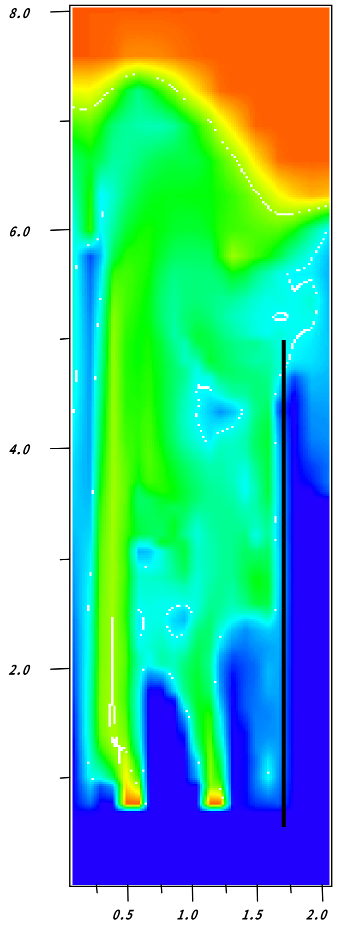

Pb-Bi free surface
Cooler
Upper plenum
Chimney (2)
Chimney (1)
Water supply
Downward pipe
Square duct
Lower plenum
Heater pin bundle

Flow model

Pb-Bi-steam 2-d two-phase flow in chimney

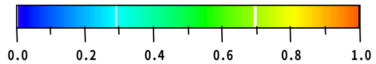


2mm



10mm

Void fraction

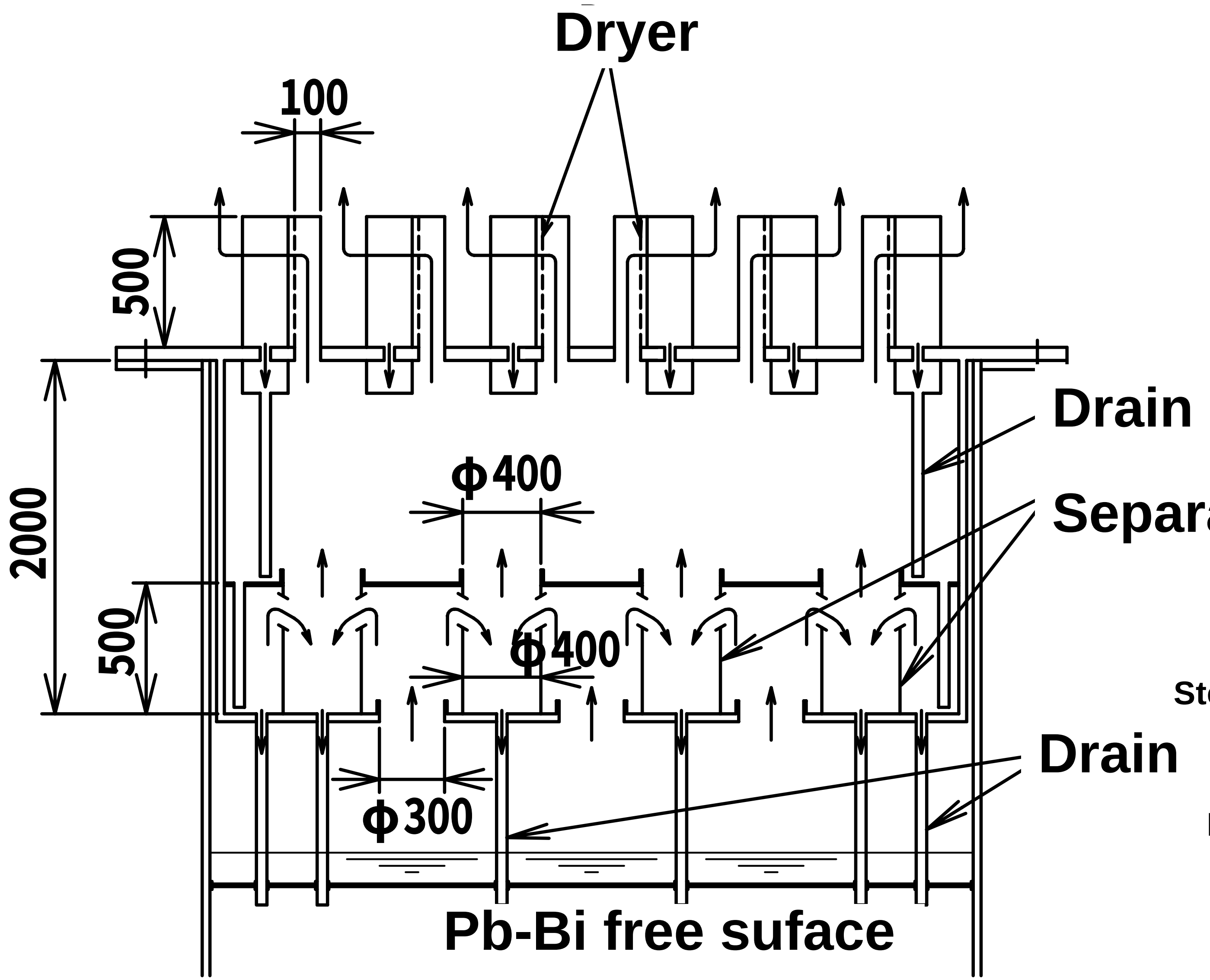


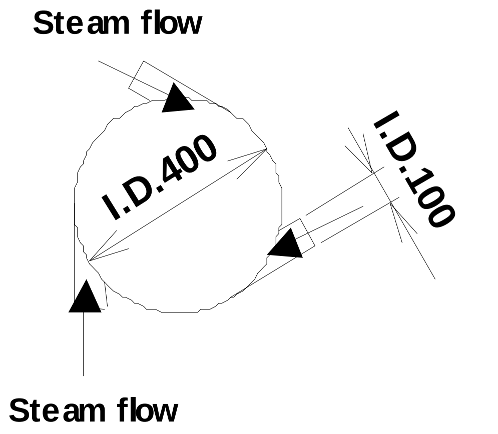
Key issues:
-Suppression of carry-under of bubbles
-Estimate of bubble diameter

Bubble diameter

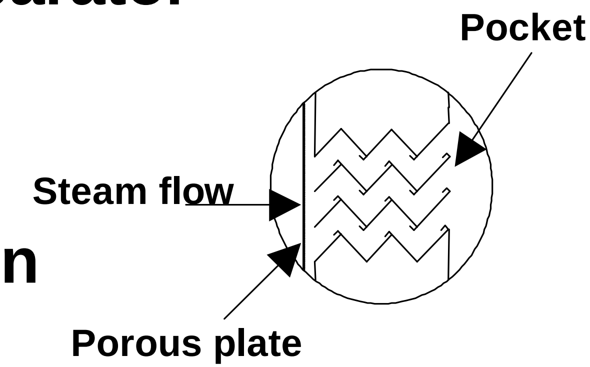
Analysis of Pb-Bi-steam flow

Removal of Pb-Bi mists





Cyclone separator



Chevron dryer

Estimate of Pb-Bi mists and Pollonium

Mist flow rate

Removal efficiency	*Separator 95.5%, Dryer 2.6%*
Flow rate	*$4.8x10^{-4}$ kg/s or 15.2 t/y*
Ratio of mist flowrate to steam flowrate	*$2.0x10^{-4}$% lower than 2.0%-5.0% in LWR*

Polonium

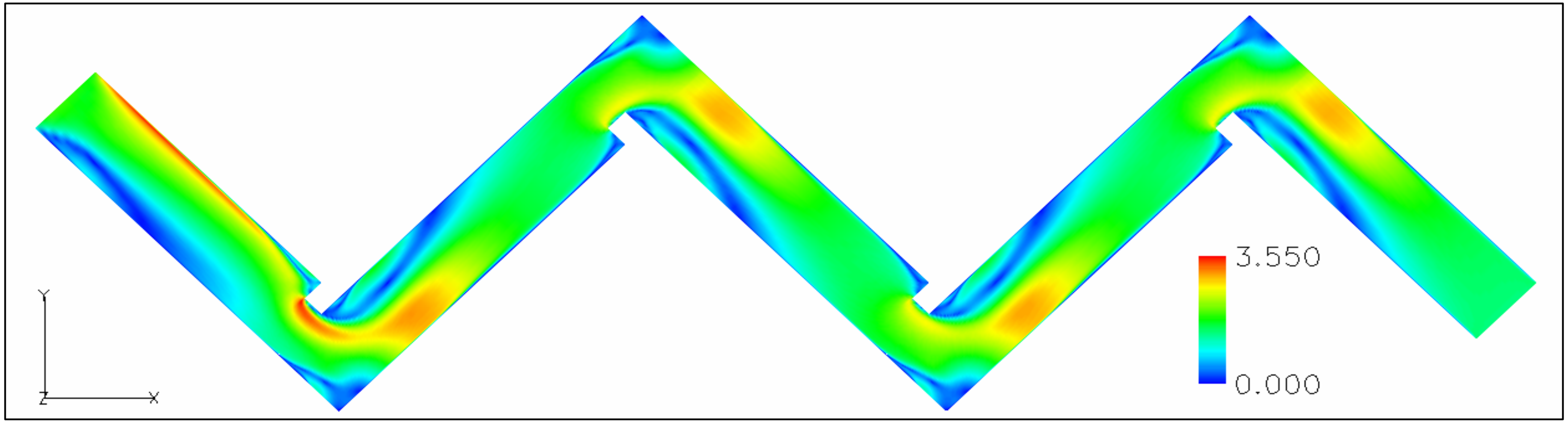
Production	*1.5×10^{17}Bq*
Concentration in Pb-Bi	*1.06×10^{11}Bq/kg*
Transport into steam system	*1.1×10^{8}Bq/s*

Requirement

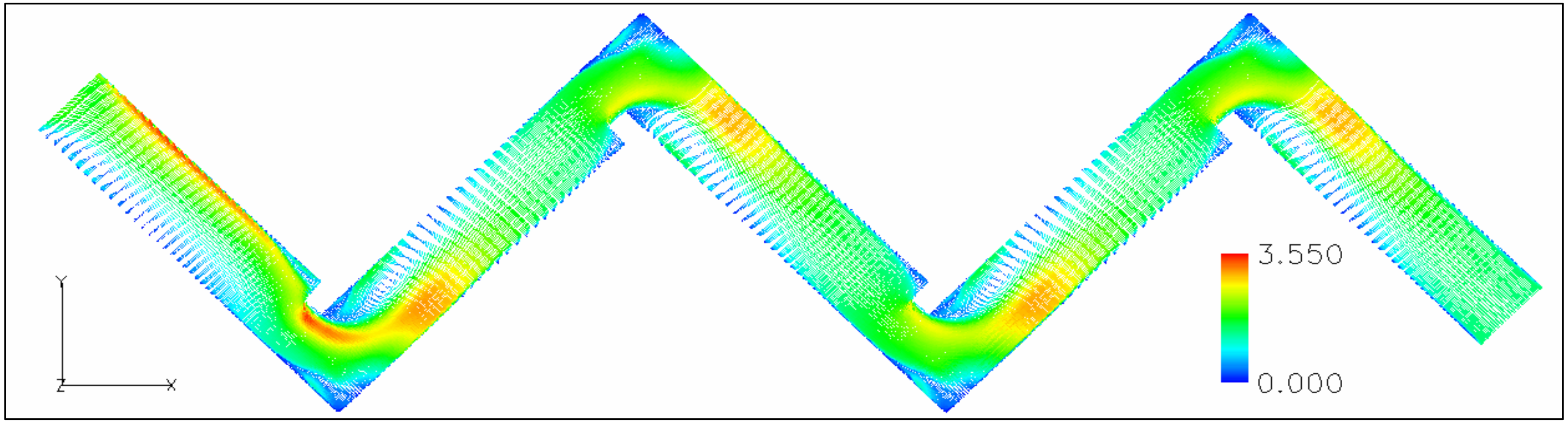
1) ***Additional precipitation device***
2) ***Ceramic coated turbine blades***

Steam flow in dryer

Flow velocity distribution [m/s]



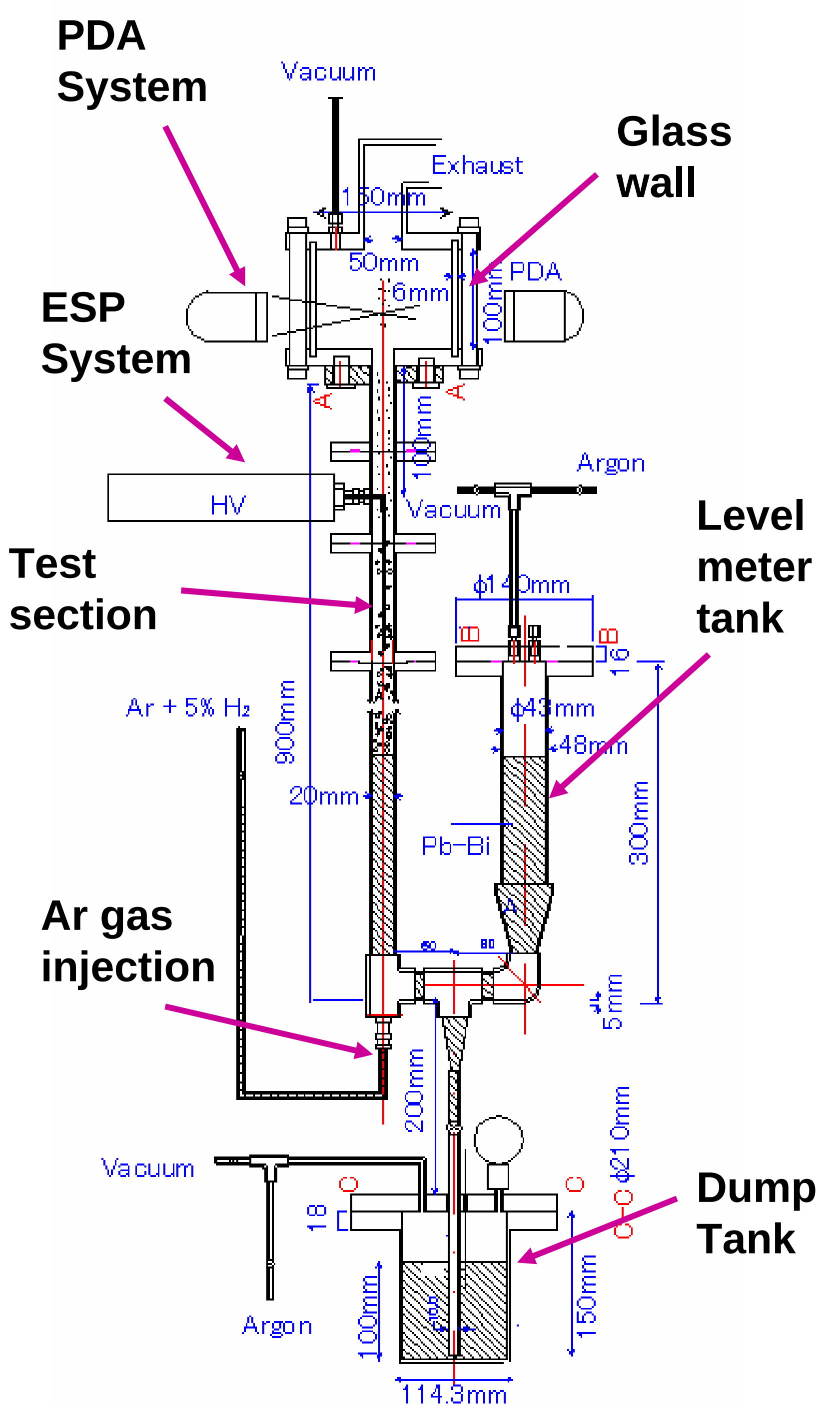
Flow velocity vector



Droplet measurement and Electro-static precipitation

Design consideration is for a representative PBWFR condition

Comparison	PBWFR	Experiment
Velocity	0.6 m/s	up to 0.1 m/s
Medium	Steam	Argon Gas
Pressure	7 Mpa	0.1 Mpa
Temperature	296 C	180 C
Flowrate	329400 L/mnt	0.5 – 2 L/mnt



Concluding remarks

A design concept of PBWFR has been formulated with design parameters identified, and will be modified by the results of the following studies:

- **Two-phase flow test in the chimney**
  for structure design of chimney with gas lift pump,
- **Pb-Bi droplet removal test**
  for the reduction of carry-over and Po transport rate into steam system,
- **Pb-Bi-water direct contact boiling test**
  for stable boiling and Pb-Bi circulation under practical conditions,
- **Corrosion/steam injection tests**
  for corrosion-resistant steels, oxygen control/measurement method and the other Pb-Bi technology.