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WATER AND HYDROGEN IN HEAVY LIQUID METAL COOLANT TECHNOLOGY

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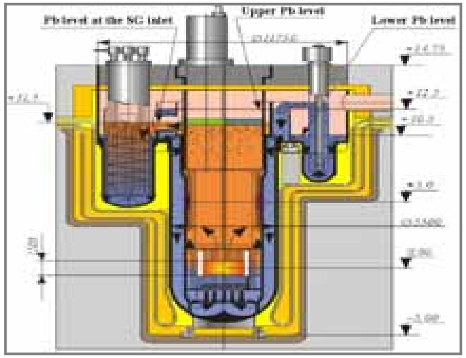
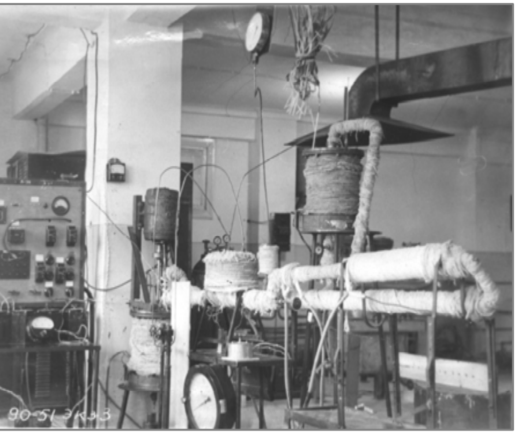
The Technology of Heavy Liquid Metal Coolants



Stage # 1
(1951 – 1968)

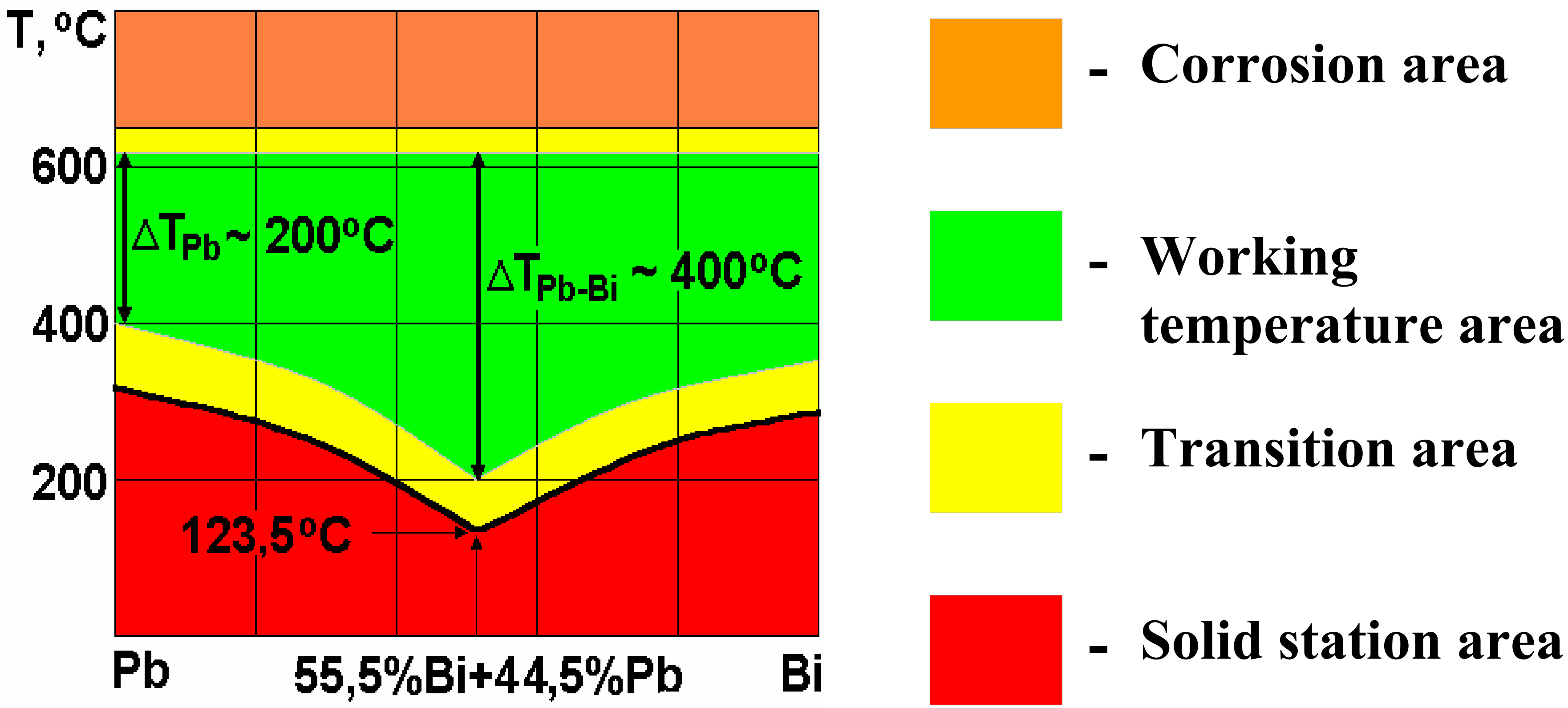


Stage # 2
(1968 – 1995)

Stage # 3
(1995 – 2020)

- hydrogen power engineering
- direct contact methods
- automatic intellectual system of coolant control
- creation of the new control systems
- production of new materials (nanotechnologies)

Diagram of state and working temperatures of liquid Pb and Pb-Bi as coolants



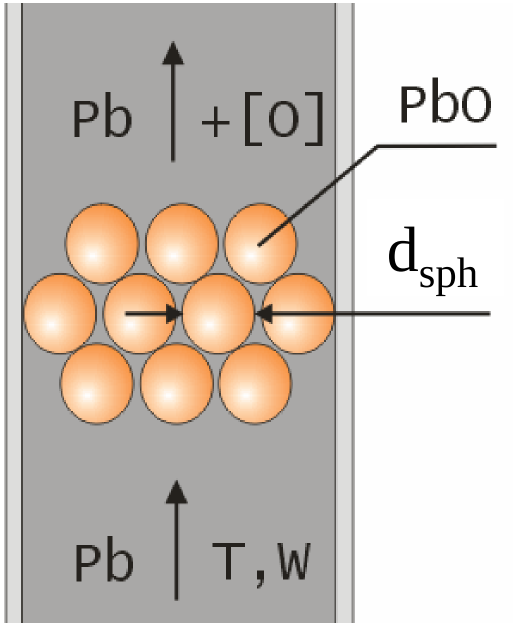
Melting point	- 123.5 °C
Density	- 10150 kg/m^3
Thermal conductivity	- 14.2 W/m K
Heat capacity	- 0.146 kJ/kg K
Viscosity	- 1.4 10^{-7} m^2/s

Base problems of heavy Liquid metal (Pb, Pb-Bi) coolant technology

1. Assurance of purity of coolant and circuit surface

2. Prevention of corrosion and erosion of structural materials

Constant of PbO spheroid dissolving rate vs temperature and lead coolant velocity



$$Sh = 8{,}7 \cdot 10^{-4} \cdot Re^{1{,}42} \cdot Sc^{0{,}83}$$

for Re=1000÷5000, Sc=30÷200

$K_d = Sh \cdot D/l \cdot C_s \cdot \rho \cdot 360$, $[K_d] = g_{[O]}/(cm^2_{<PbO>} \cdot hour)$

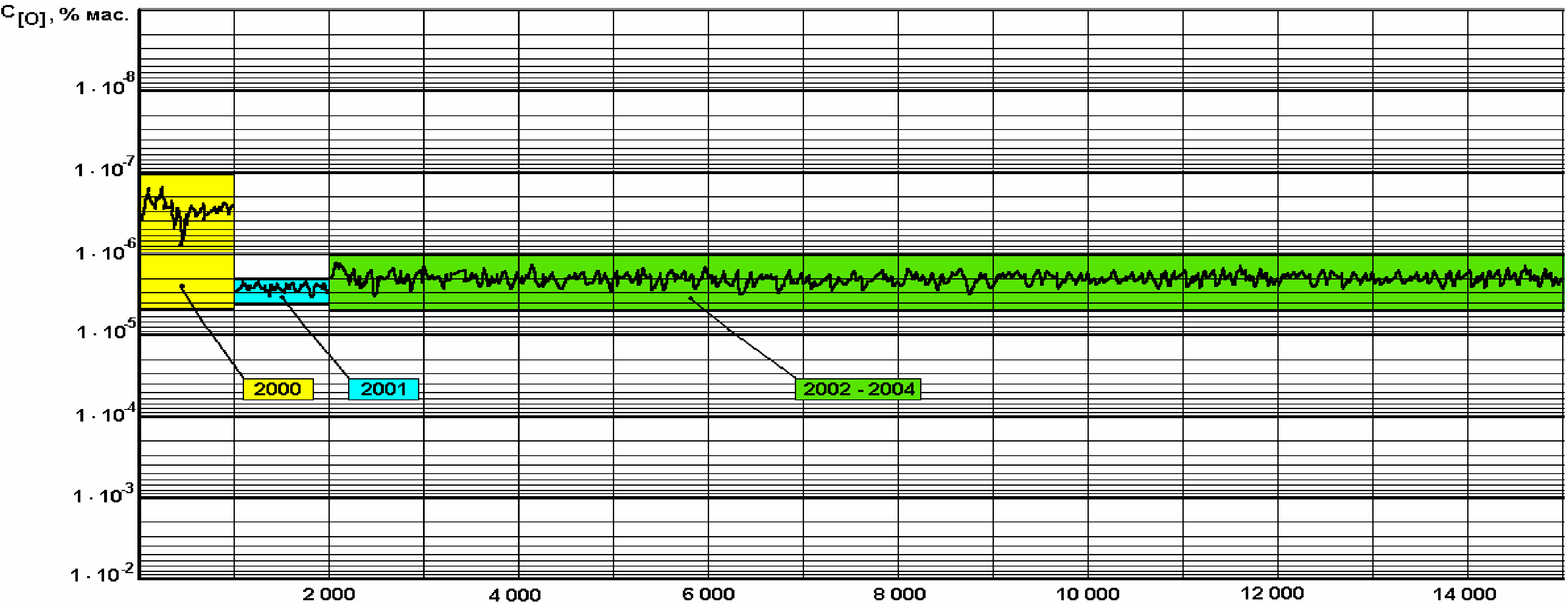
$Q = K_d \cdot (1 - \overline{a_{[O]}}) \cdot S_d$, $[Q] = g_{[O]}/hour$, $(\overline{a_{[O]}} << 1)$

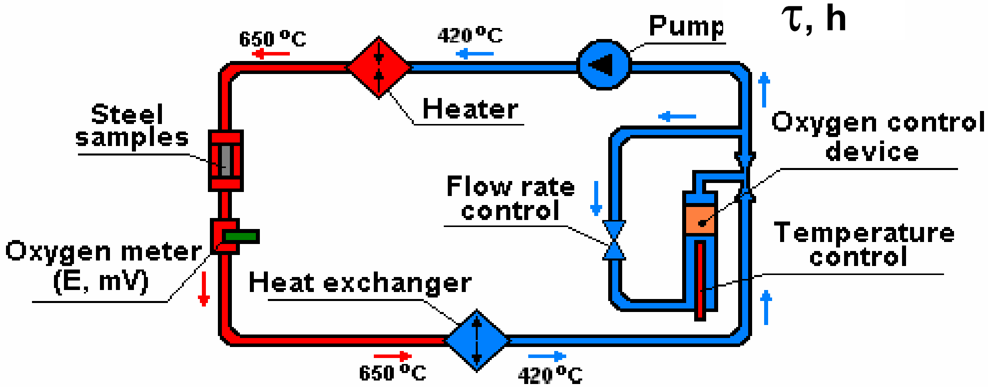
$Sh = \frac{\beta \cdot l}{D}$ - *Sherwood number;* $Re = \frac{w \cdot l}{\nu}$ – *Reynolds number;*

$Sc = \frac{\nu}{D}$ - *Schmidt number;* $l = \frac{2}{3} \cdot \frac{\varepsilon \cdot d_{sph}}{1 - \varepsilon}$ – *characteristic dimension, m*

***β** – mass transfer coefficient, m/s;*
***$a_{[O]}$** – oxygen thermodynamic activity;*
***ρ** - lead density, kg/m³;*
***C_s** – oxygen saturation content in lead, mass fractions of 1;*
***ν** - kinematic viscosity, m²/s;*
***D** - molecular diffusion coefficient of oxygen in lead, m²/s;*
***ε** – porosity of PbO spheroids layer (assumed 0.4 for layer of spherical particles);*
***d_{sph}** - spheroid diameter, m;*
***S_d** – dissolution surface of PbO, cm².*

It was the first time in the practice of heavy liquid metal coolant technology under "BREST - OD – 300" program that continuous regulation of oxygen content in Pb has been performed for a long period in required small concentration range during normal and abnormal operation of circuit facilities (SSC RF IPPE, 2000 - 2004 г.г.)





Test parameters

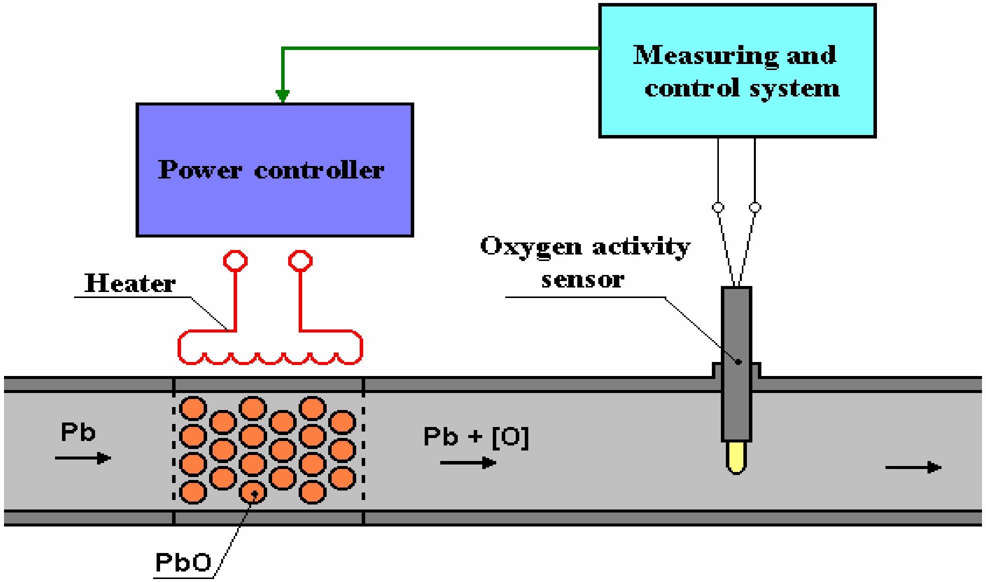
T_{max} = 650 °C

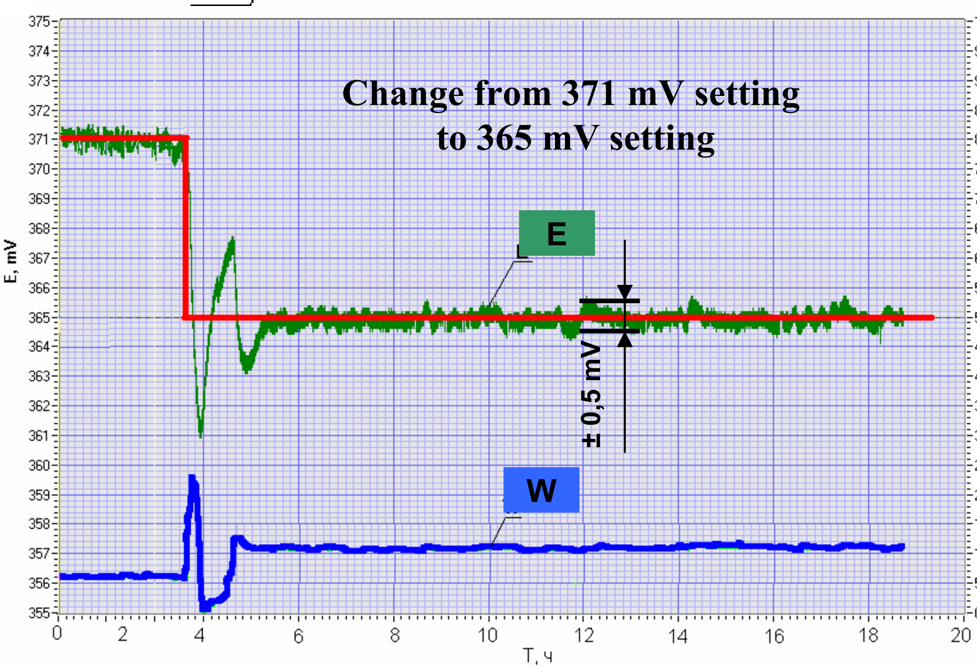
T_{min} = 400 °C

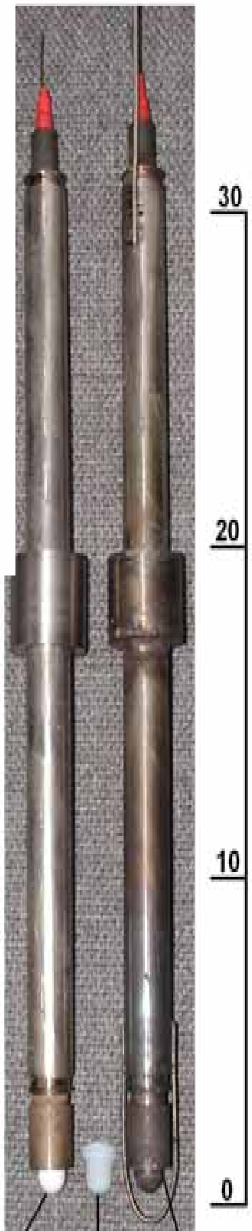
v_{Pb} ~ 1.7 m/c

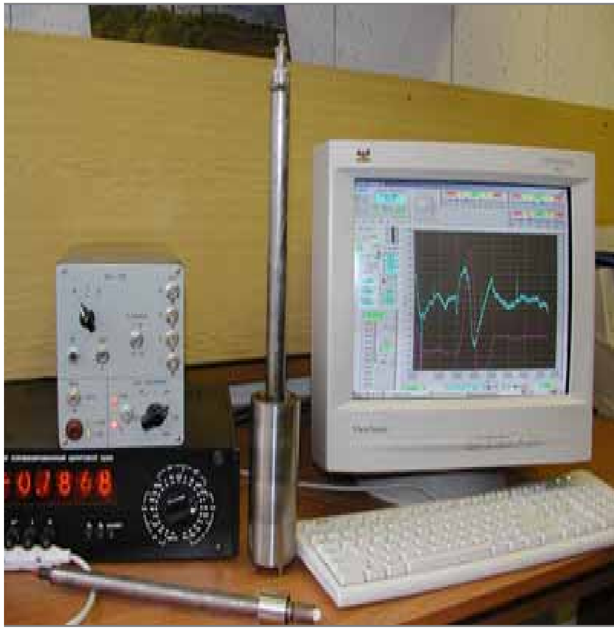
M_{Pb} ~ 700 kg

System of automatic control of oxygen thermodynamic activity (SAC TDA) was created and successfully tested in heavy liquid metal coolant as applied to "BREST-OD-300" Program









"SACURA"

- oxygen automatic control system

SSC RF-IPPE, 2002

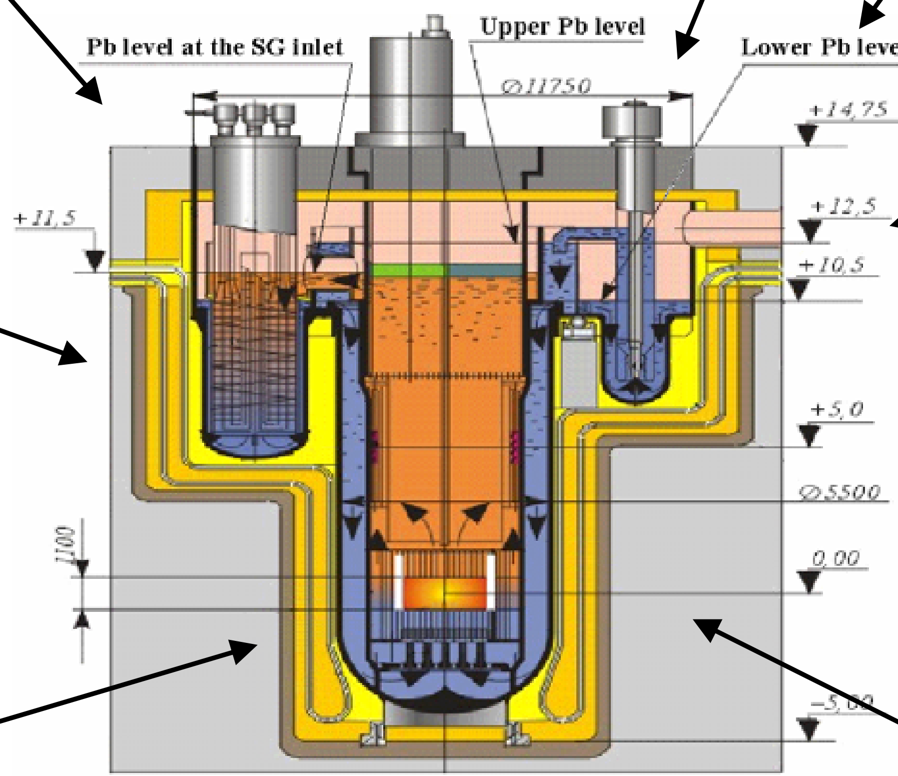
Test facility models of devices used in heavy liquid metal coolant technology

High efficiency double-section aerosol filter FAS-3500-D

Detector of gas phase in the coolant

Oxygen mass exchanger

Filter for removal of impurities from the coolant



Sensors of oxygen activity and film electric resistance

Device for gas reactant supply to the coolant flow

Coolant flow meter

BREST-OD-300

Critical conditions of Pb-Bi circuit caused by accumulation of solid impurities (slag)

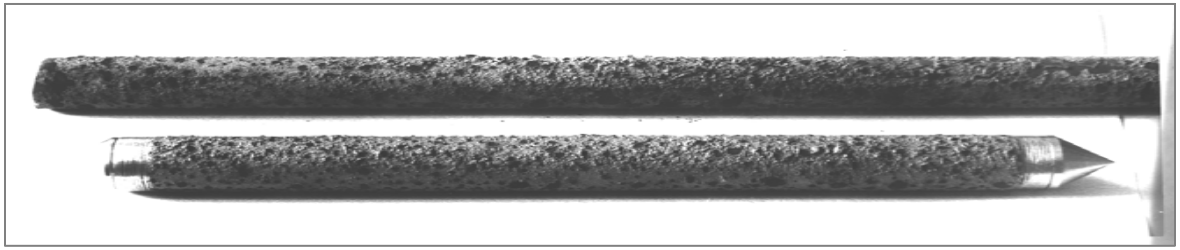
K-27 – first submarine with Pb-Bi cooled reactor

1963 – Commissioning
1968 – Accident

Slag deposits in
The vessel

Slag deposits in
heat exchanger

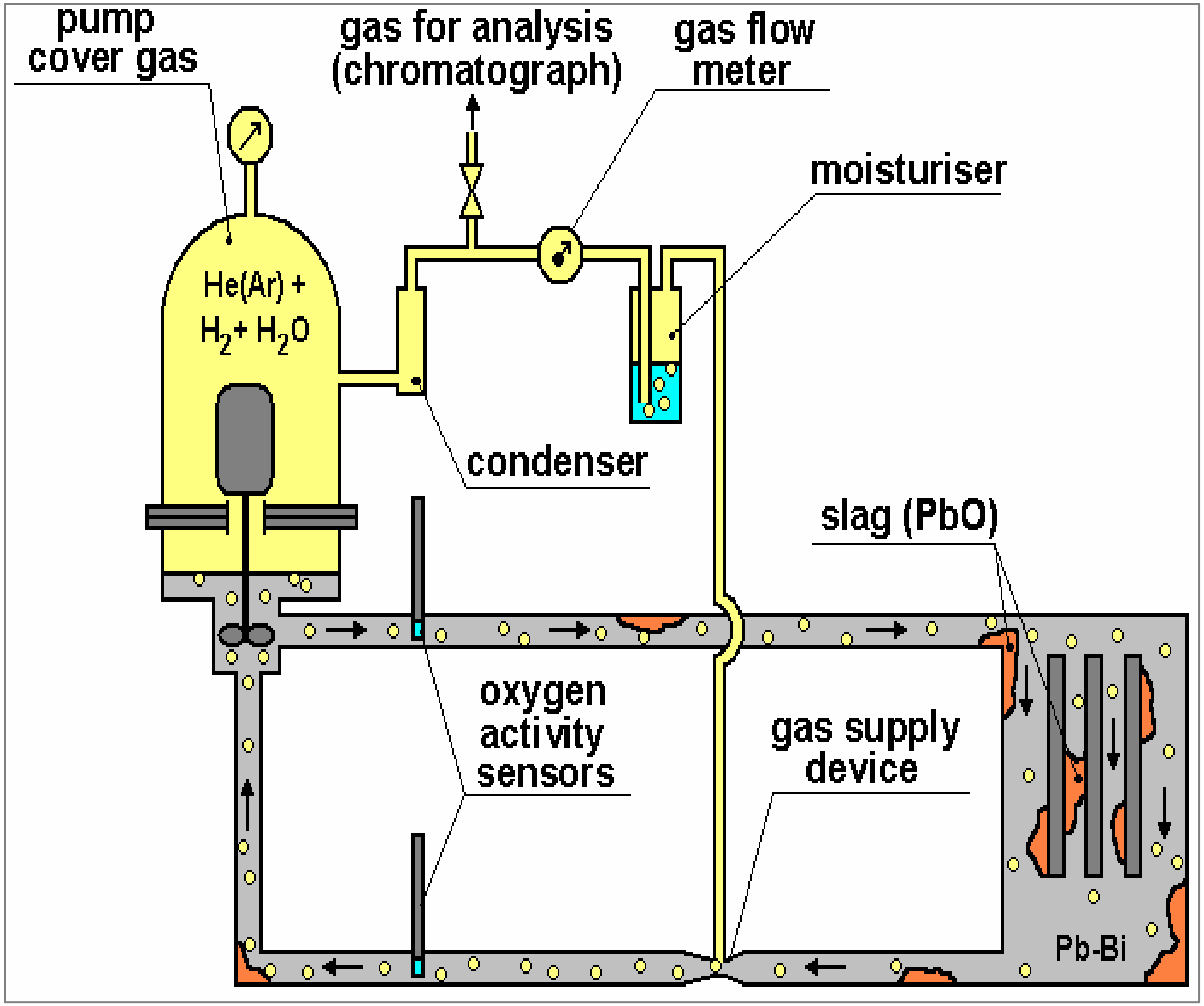
Slag on pipeline



Slag deposits on recuperator tubes

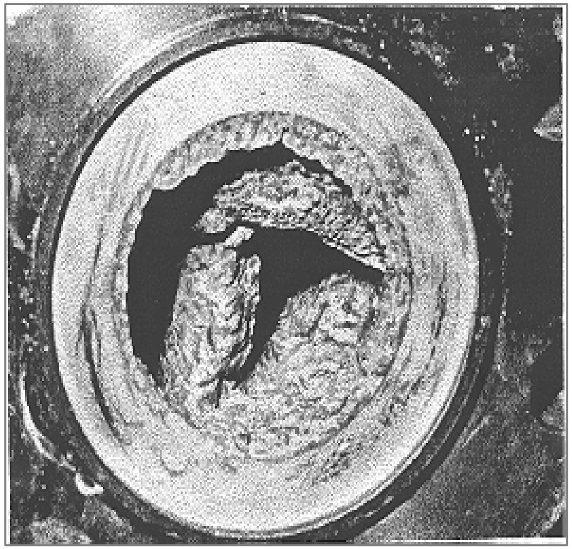
Pb+Bi	PbO	Bi_2O_3	O	Fe	C	Mg
60÷42	48÷30	≤2	~3.5	4.5÷0.4	~ 3.3	~1.8

Initial coolant purification and deposits removal from the circuit surface by hydrogen containing gas mixtures

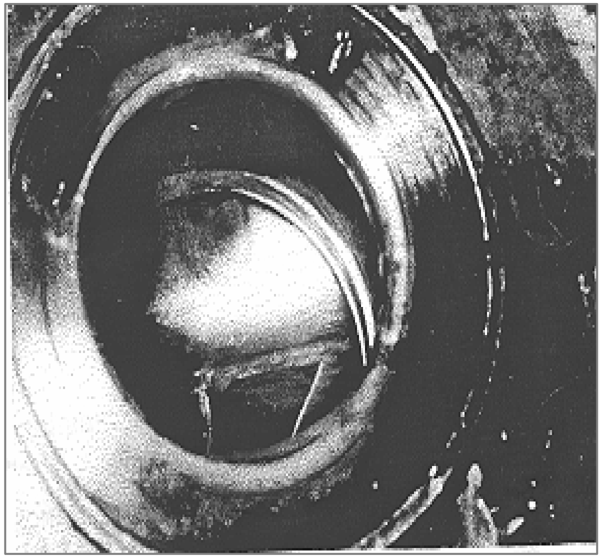


$$(H_2) + \langle PbO \rangle \rightarrow (H_2O) + [Pb]$$

$$(H_2)+[O] \rightarrow (H_2O)$$

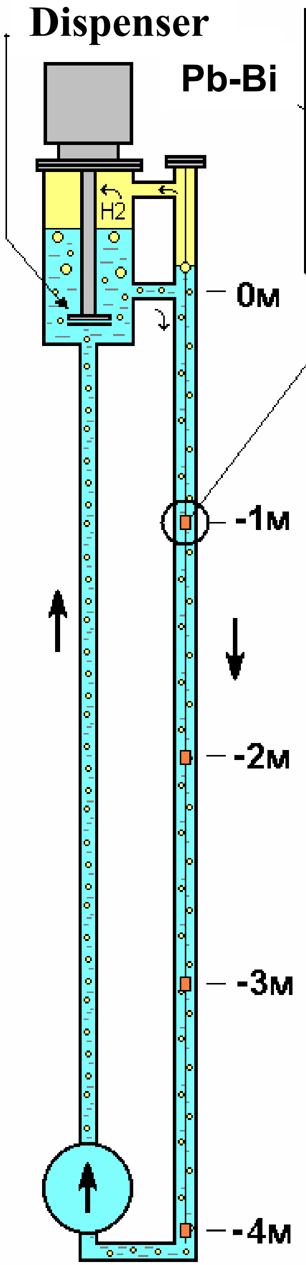


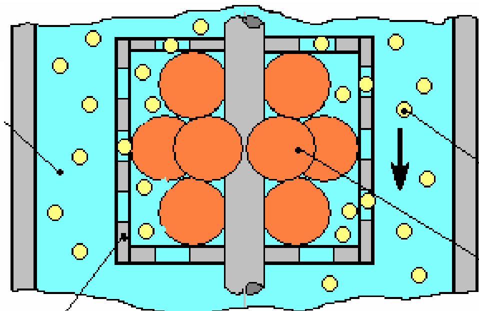
Circuit section before purification

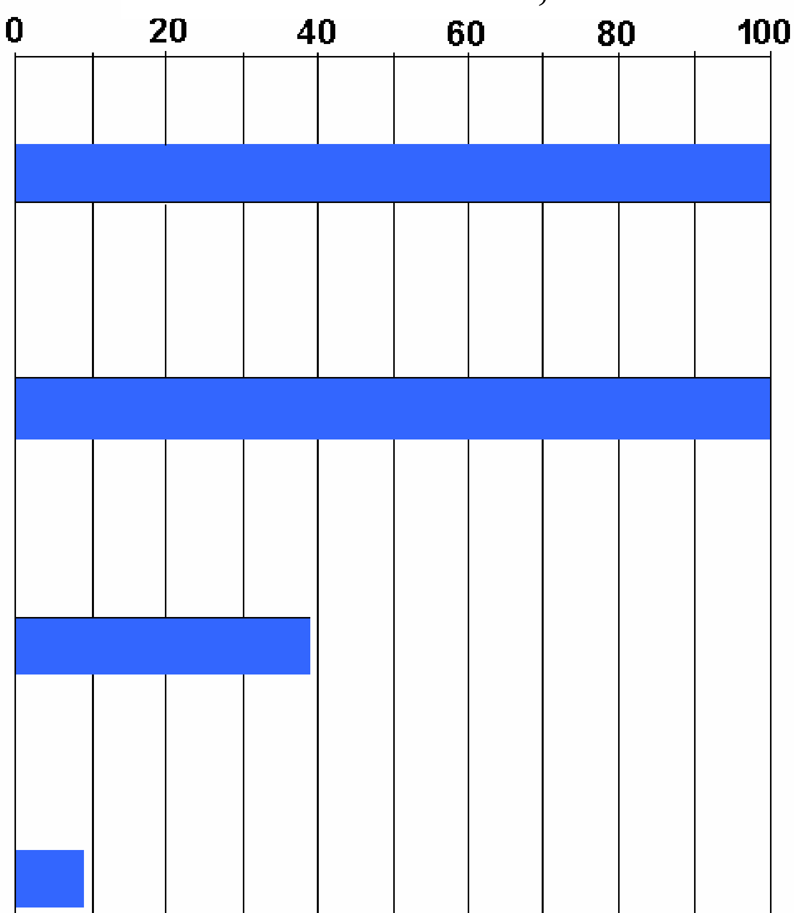


Circuit section after purification

Hydrogen regeneration using gas dispenser

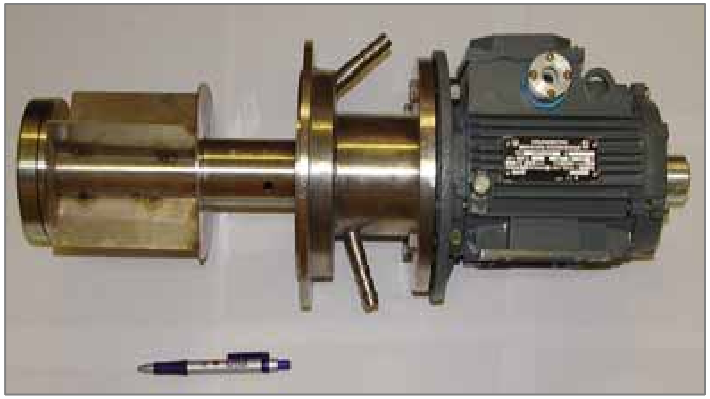






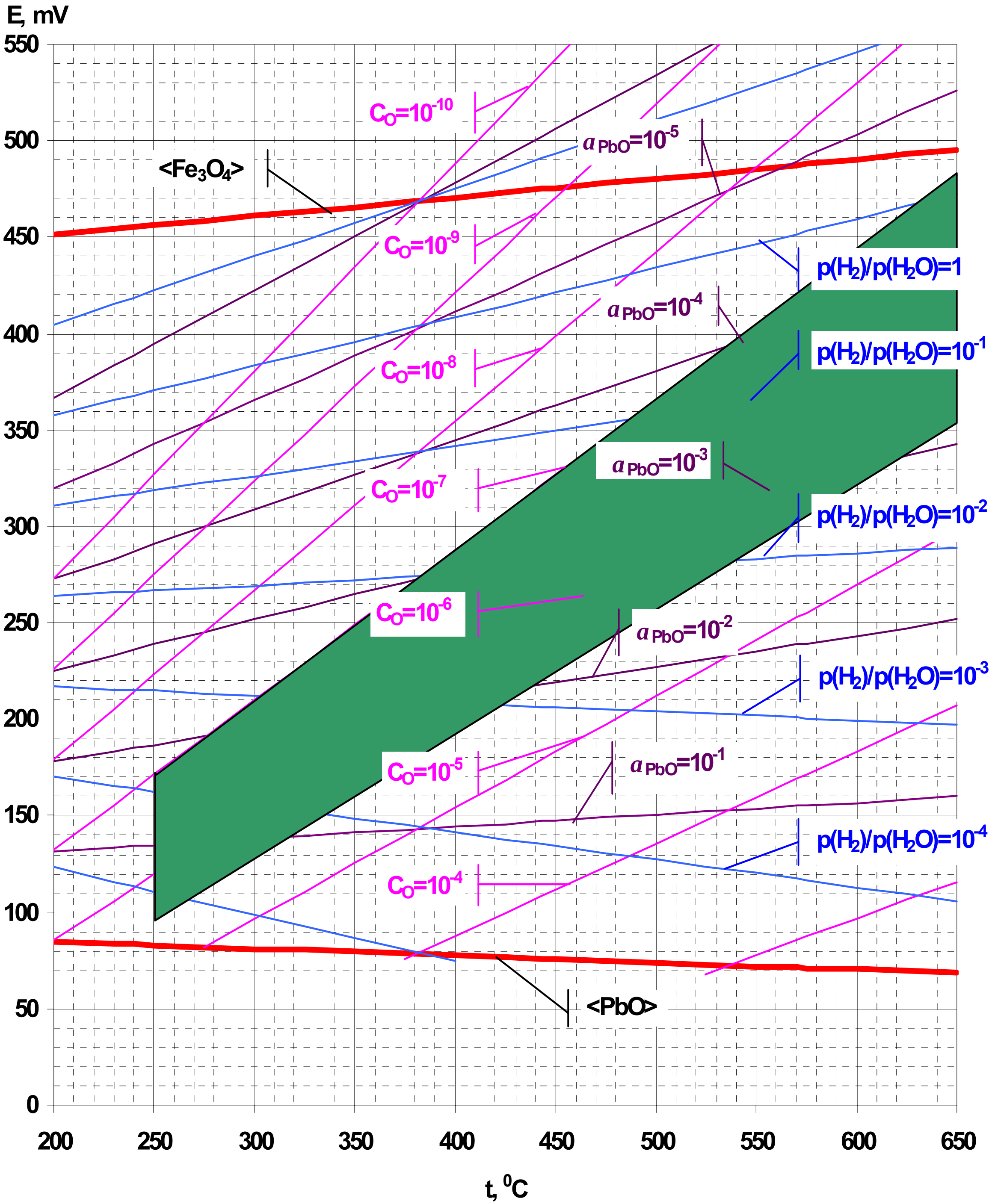
Test parameters

$\tau \sim$ 14 hours
t ~ 400 °C
v_{Pb} = 0,1 – 0,2 m/c
M_{PbO} ~ 30 g (in one section)
$\varnothing_{bubbles} \geq 10$ μm
Gas mixture: $H_2 – H_2O – Ar$ in Pb – coolant, where
C_{H2} ~ 20 vol. %



$$(H_2) + \langle PbO \rangle \rightarrow (H_2O) + [Pb]$$
$$(H_2)+[O] \rightarrow (H_2O)$$

E-t diagram of state of Pb-Bi alloy in term ofoxygen impurity relative to the reference electrode {Bi} - <Bi_2O_3>



$$E, mV = \frac{(-\lg a_O - 0{,}18)\cdot T}{100{,}94} - 88$$

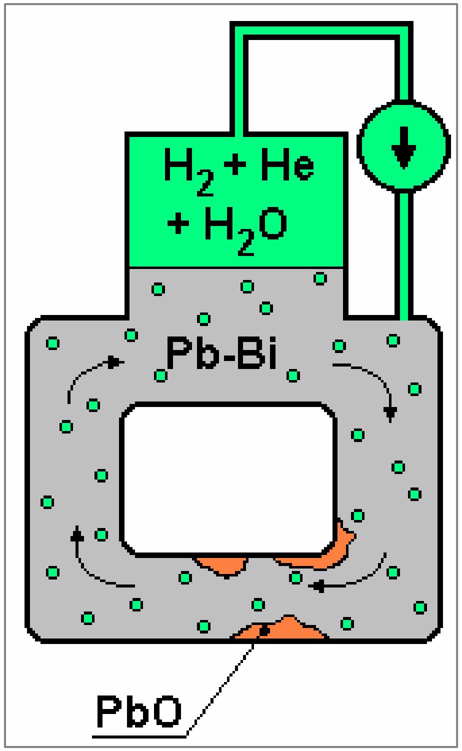
$$a_O = \frac{C_O}{C_O^S}$$

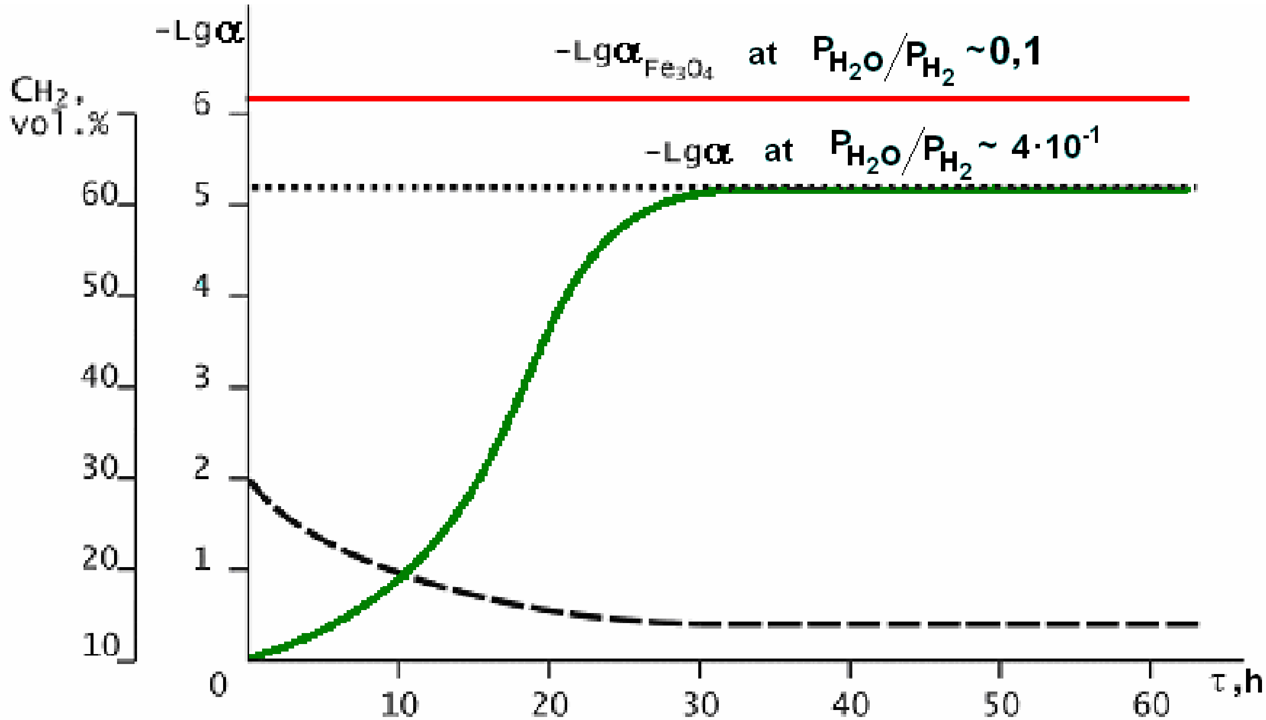
$$\lg(C_O^S, \%mas) = -\frac{3400}{T} + 1{,}2$$

$$\lg a = \lg\frac{P_{H_2O}}{P_{H_2}} - \frac{2065.25}{T} - 2.13$$

Behavior of oxygen activity (*a*) and hydrogen content in the process of hydrogen regeneration of isothermal Pb-Bi circuit

$$(H_2)+[O]+\{Pb\text{-}Bi\} \rightarrow (H_2O)+\{Pb\text{-}Bi\}$$





— — C_{H_2}, Hydrogen concentration (experiment)

—— α, Oxygen thermodynamic activity, α=C/Cs (experiment)

······ α, In equilibrium with mixture H_2-H_2O (theory)

—— α, In equilibrium with $\alpha_{Fe_3O_4}$ (theory)

C - Oxygen concentration in the coolant, %mas.

Cs - Concentration of coolant saturated with oxygen, %mas.

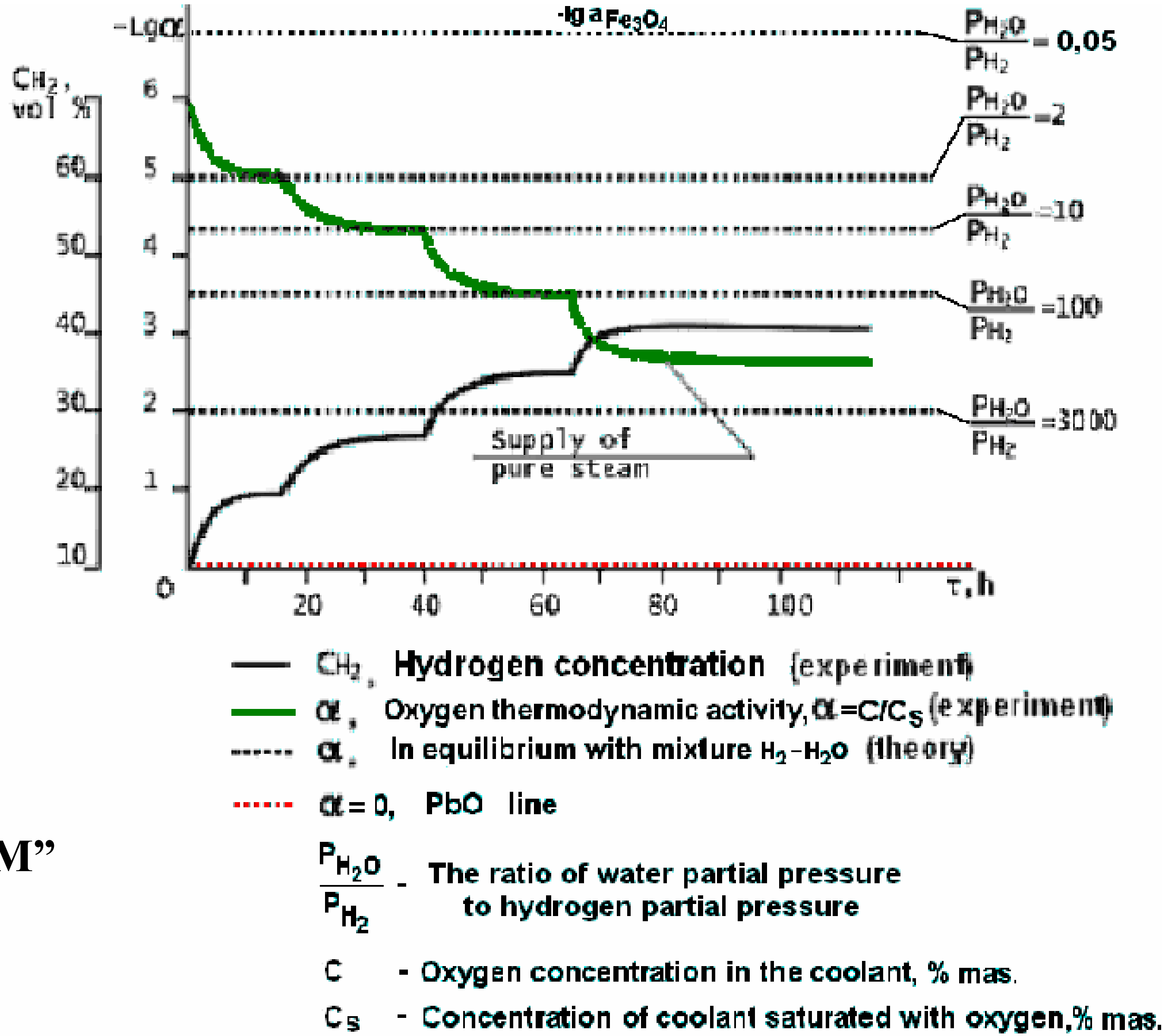
P_{H_2O}/P_{H_2} - The ratio of water partial pressure to hydrogen partial pressure

<u>Test parameters (2001):</u>

liquid metal loop “TT-2M”
Pb-Bi
T = 400 °C

Behavior of oxygen activity (*a*) and hydrogen content in case of oxidation of Pb-Bi coolant in isothermal circuit

$$(H_2O)+\{Pb\text{-}Bi\} \rightarrow (H_2)+[O]+\{Pb\text{-}Bi\}$$

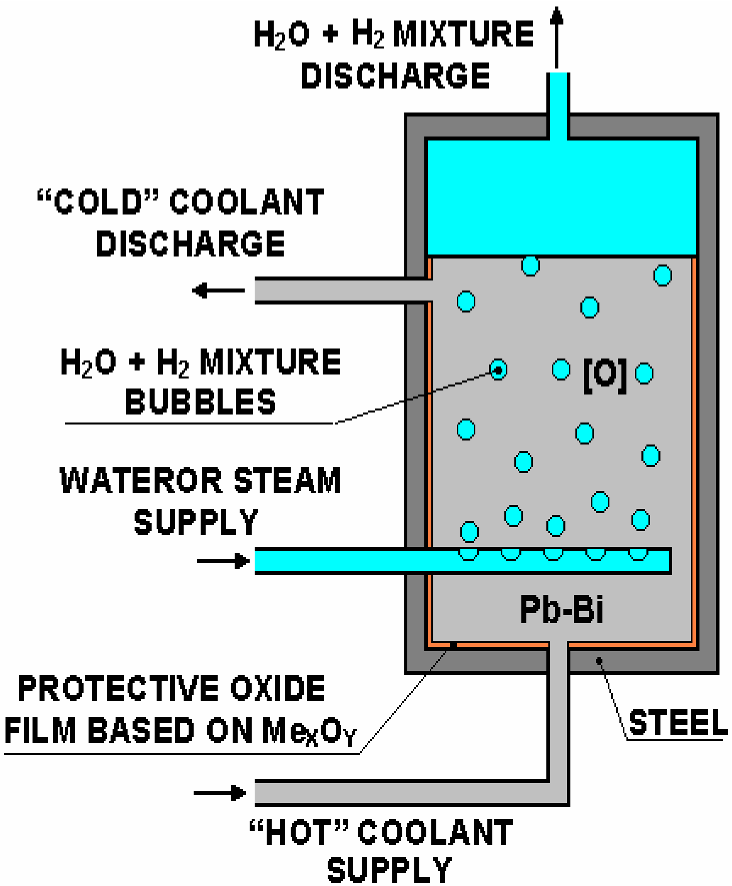


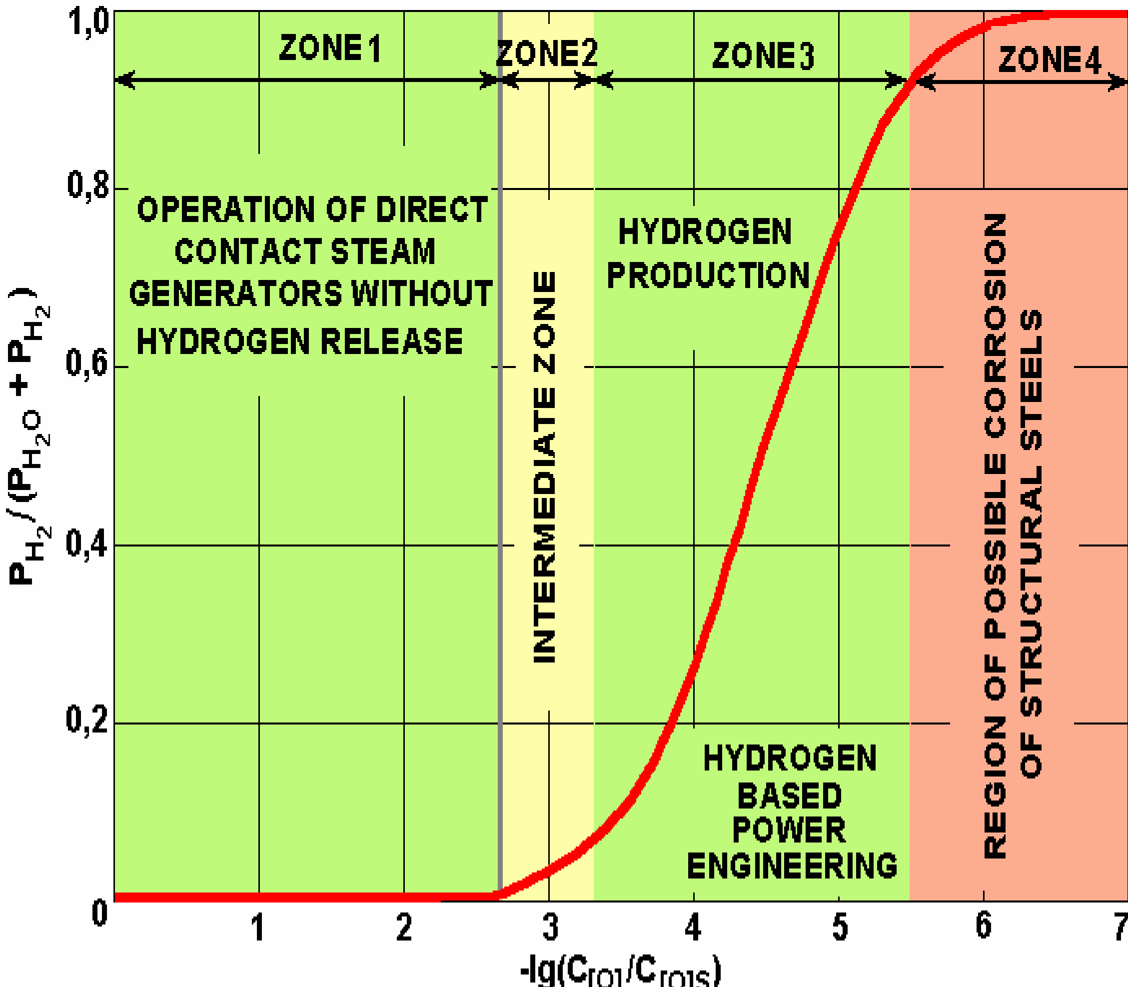
<u>Test parameters (2001):</u>

liquid metal loop "TT-2M"
Pb-Bi
T = 350 ^{o}C

Various options of steam interaction with the coolant

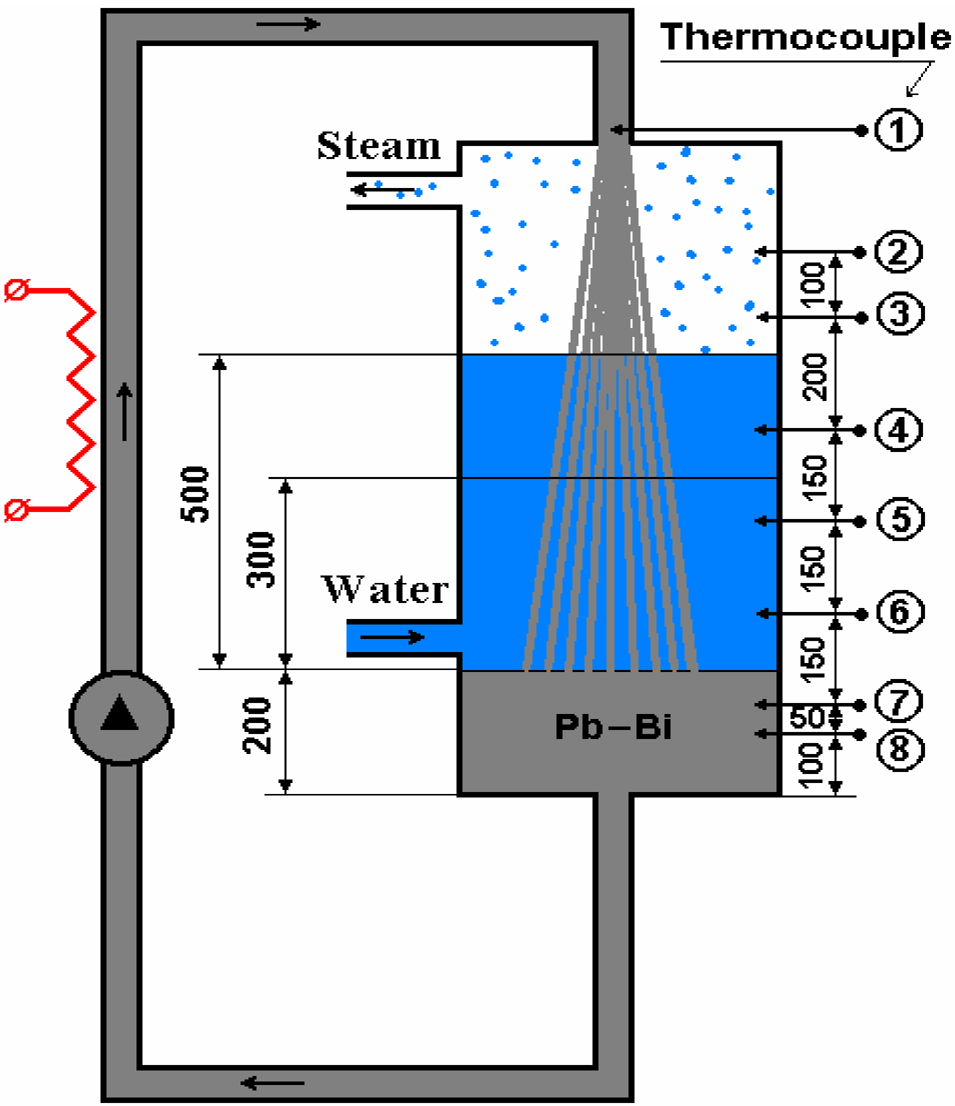
$$(H_2O) + \{Pb\text{-}Bi\} \rightarrow (H_2) + [O] + \{Pb\text{-}Bi\} \quad T = 600^oC$$





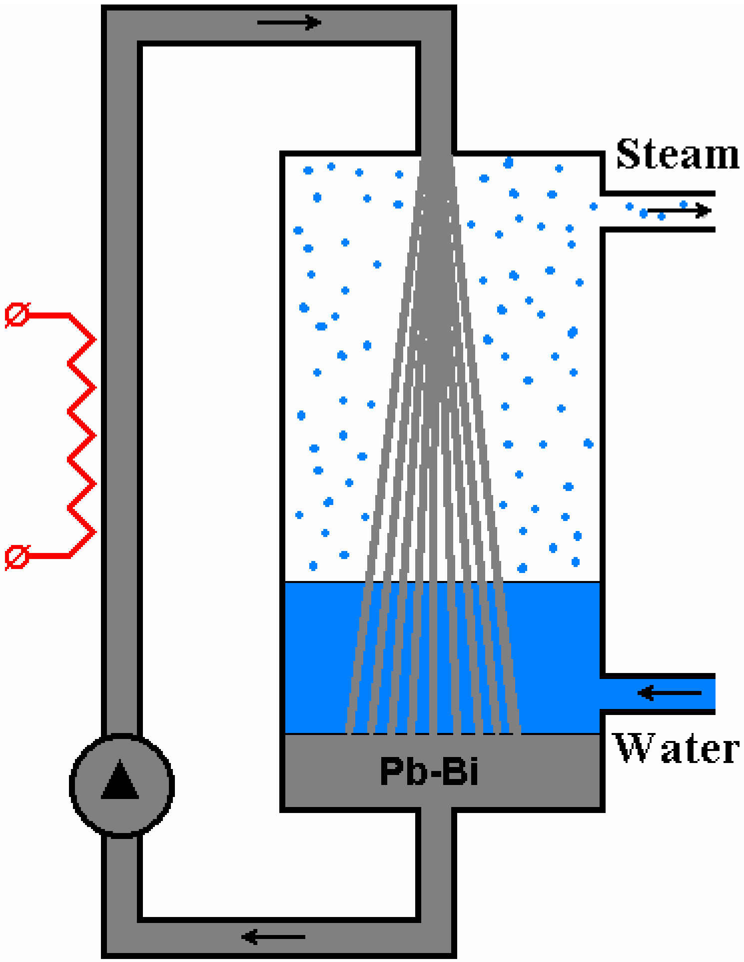
P – partial pressure ; C – content in the solution

Arrangement of thermocouples and temperature distribution over the height of steam generator model, N = 14 kW, T = 750 hr, SSC RF - IPPE, 1990



Thermocouple	Test No. 1	2	3	4	5	6	
							T, K
①	682	740	755	673	733	743	
②	507	529	548	536	539	551	
③	506	527	573	567	567	572	
④	507	527	541	544	546	553	
⑤	506	527	542	535	536	549	
⑥	506	527	541	535	536	549	
⑦	507	527	542	536	537	550	
⑧	507	527	542	536	537	550	
	2,80	4,10	5,39	5,07	5,23	5,98	P_S, MPa
	504	524	542	538	540	548	T_S, K
	178	216	213	135	193	195	ΔT, K
	0,5			0,3			h_{water}, м

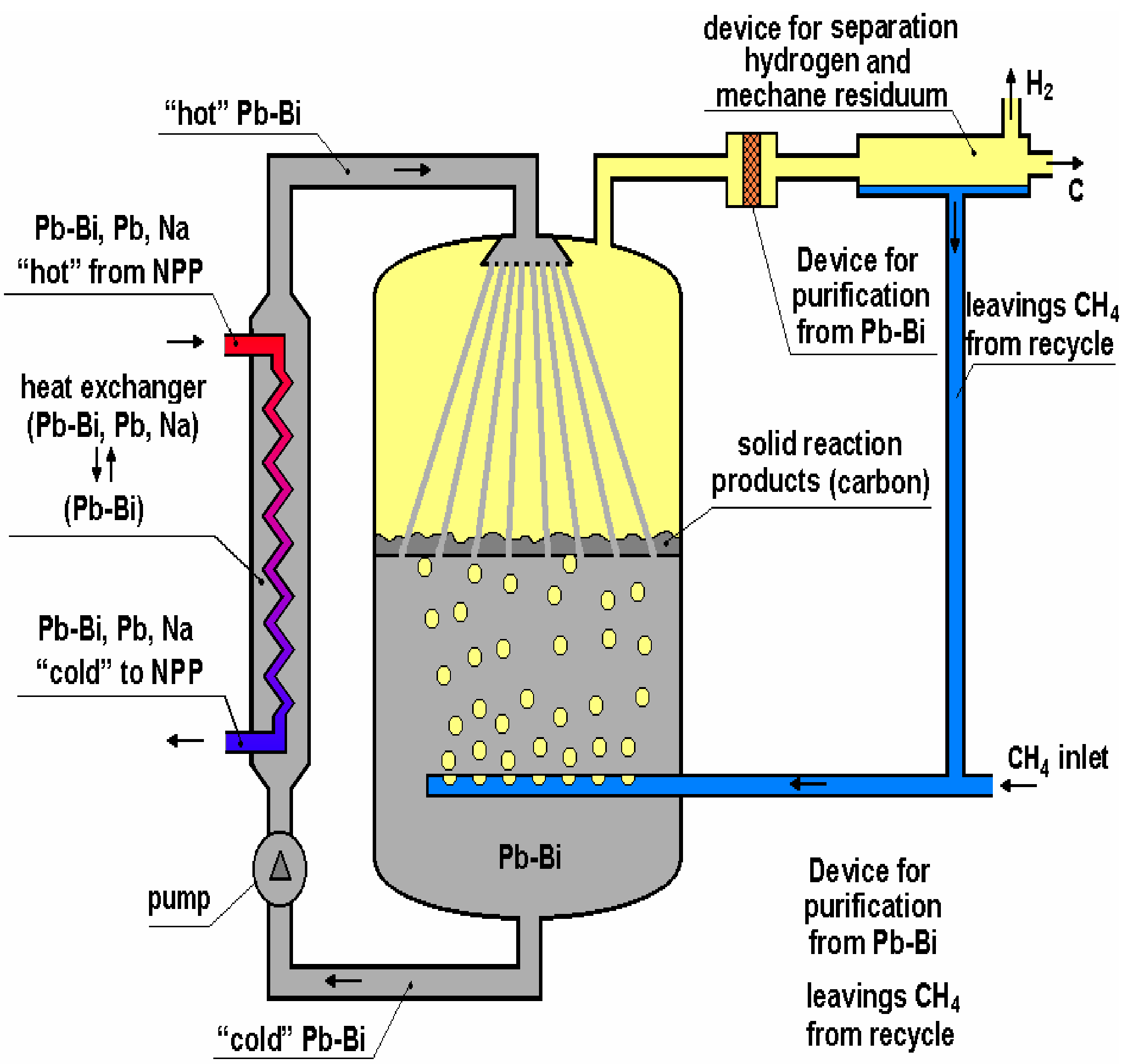
Model of steam generator, N = 500 kW. SSC RF - IPPE, 1992



PARAMETERS OF EXPERIMENT:

- velocity of Pb-Bi outflow through the nozzle – 1 ÷ 6 m/s;
- Pb-Bi temperature – 300 ÷ 500°C;
- coolant pressure – 2 ÷ 6 MPa;
- water flow rate 0.026 ÷ 0.084 kg/s;
- superheated steam temperature – up to 137°C;
- operation time ~ 1200 hours;

Hydrogen production by methane thermal disintegration in the coolant (pyrolysis)



$$(CH_4) \rightarrow \langle C \rangle + (2H_2)$$

Calculated yield of hydrogen

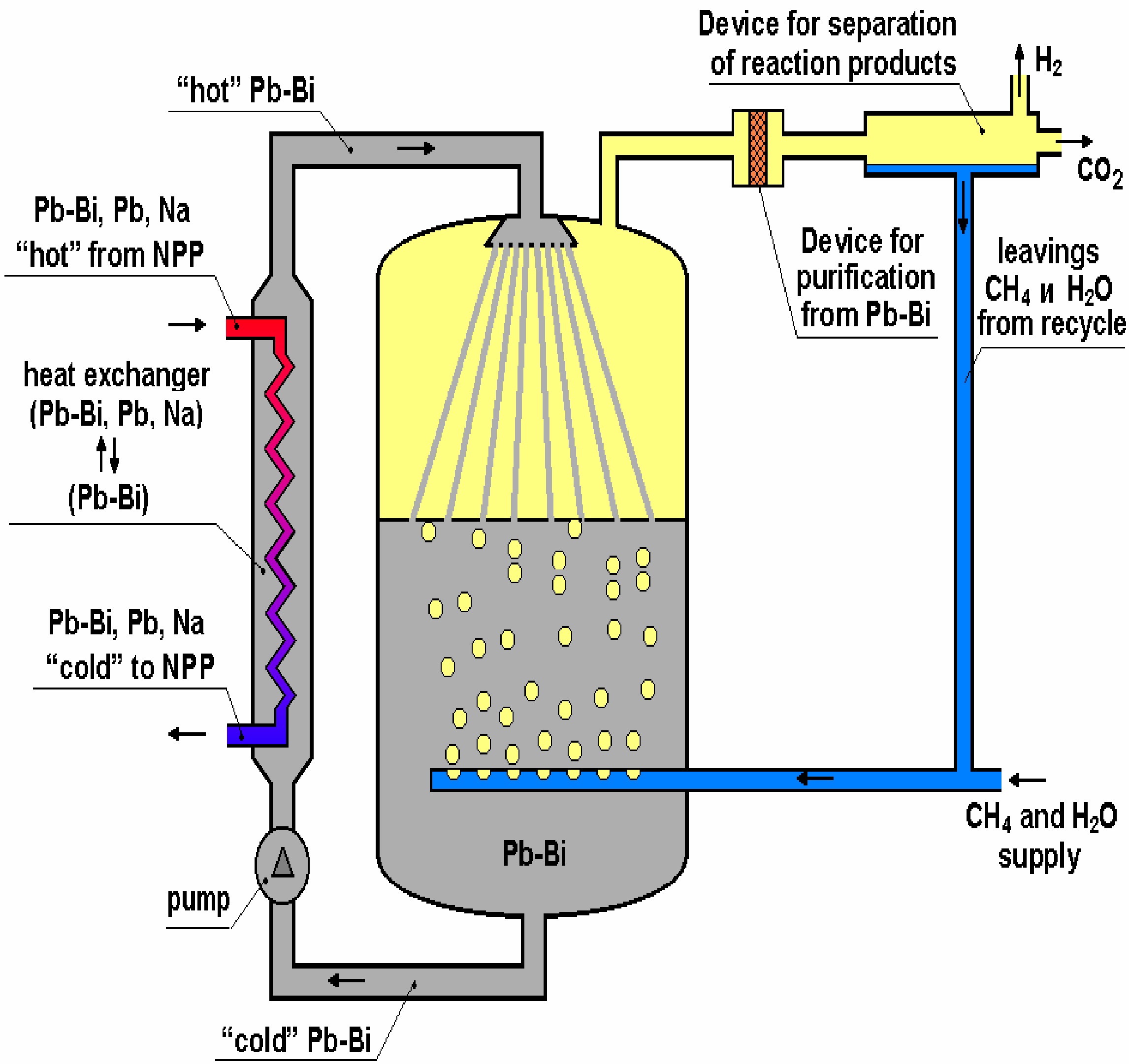
up to 95%

(T=973 K, P_{CH4}=0.1 MPa)

Advantages in engineering:

1. The use of high-temperature heat from NPP for electricity generation and hydrogen production.
2. No slagging on heat exchanging surfaces.
3. Minimum dimensions.
4. High intensity of the process.
5. Preparatory scientific and engineering works have been fulfilled.

Hydrogen production by methane interaction with water vapor in the coolant (conversion)



$$(CH_4) + (2H_2O) \rightarrow (CO_2) + (4H_2)$$

Calculated yield of hydrogen

up to 55%

T=973 K, $(P_{CH4}/P_{H2O})_{init}$ =1/2

Advantages in engineering:

1. The use of high-temperature heat from NPP for electricity generation and hydrogen production.
2. No slagging on heat exchanging surfaces.
3. Minimum dimensions.
4. High intensity of the process.
5. Preparatory scientific and engineering works have been fulfilled.

CONCLUSION

1. Physical and chemical fundamentals of lead-bismuth and lead coolant technologies have been developed by the SSC RF-IPPE; several methods and devices for the purification of coolants and corrosion protection of steels in the coolant have been used at the institute.
2. Water and hydrogen can be used effectively for the purification of the coolant and circuit surfaces from the solid-phase impurities and for the control of levels of oxygen dissolved in the coolant.
3. The heavy liquid metal coolant technology can be applied for ensuring a high-effectiveness direct contact heat transfer in steam generation and hydrogen production.
4. It is expedient to proceed with the research on heavy coolant technology for a more complete realization of their potentials in new projects and designs of power facilities for steam and electricity generation, production of hydrogen, and other technological issues.