Phenomenon of Local Natural Circulation in a Circuit of Nuclear Power Plant

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Purposes of tests carried out at the BN-350

A series of four tests has been performed in 1996 at the BN-350 for substantiation of its safety in modes related to loss of grid and reliable power supply and water supply:

- ***In the first two tests confirmation of heat-dissipating and heat-storage characteristics of heat removal loops of the primary and secondary circuits was planned;***
- ***In the second pair of tests study of coolant NC in loops of the BN-350 primary and secondary circuits with drained steam generators (SG) was envisaged.***

The basic idea of tests 3, 4 related to study of NC consisted in that heating up sodium of the primary circuit will promote occurrence of coolant NC in loops of the primary circuit and in corresponding loops of the secondary circuit.

Experimental data were also assumed to be applied for verification of DINRUN code which was used for substantiation of permissible power levels of BN-350 RF.

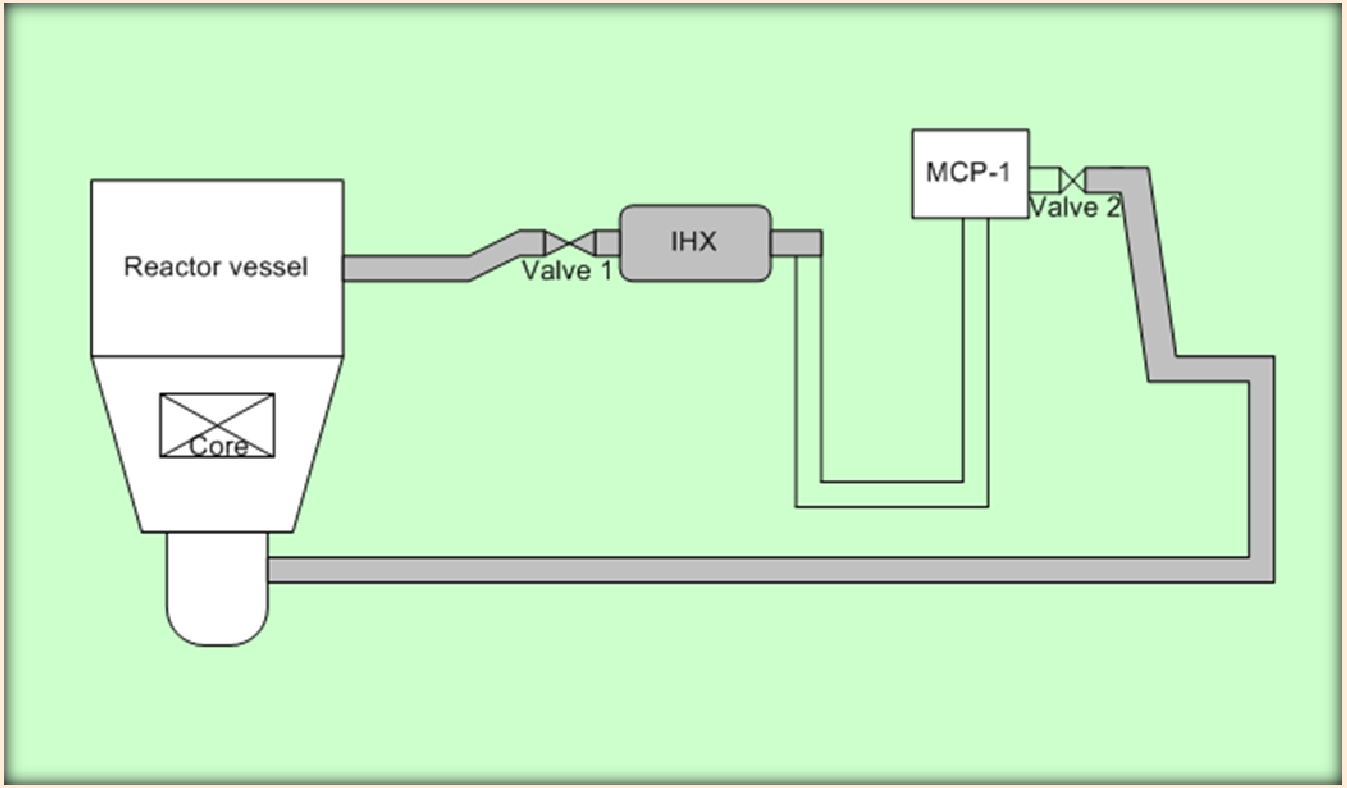
Test conditions

The BN-350 loop configuration in tests and their duration

No	Test target	Duration, h	Configuration of operating loops	Operating MCP
1.	Determination of characteristics of RF loops	90	Circuit 1 - loops 1,2,4; Circuit 2 - loop 12 (SGF)	MCP-1 (loops 1,2,4); MCP-2 (loop 12)
2.	Determination of characteristics of RF loops	50	Circuit 1 - loops 1,2,4,6; Circuit 2 - loops 10 (SGN), 12 (SGF)	MCP-1 (loops 1,2,4,6); MCP-2 (loops 10,12)
3.	Study of NC in loops of circuits 1 and 2 with drained SG	24	Circuit 1 - loops 1,2,4,6; Circuit 2 - loops 7,8,12 (SGF), 10 (SGN)	MCP-1 (loops 1,2,4,6)
4.	Study of NC in loops of circuits 1 and 2 with drained SG	32	Circuit 1 - loops 1,2,4,6; Circuit 2 - loops 7,8,12 (SGF), 10 (SGN)	MCP-1 (loops 1,2,4,6)

BN-350 loop configuration

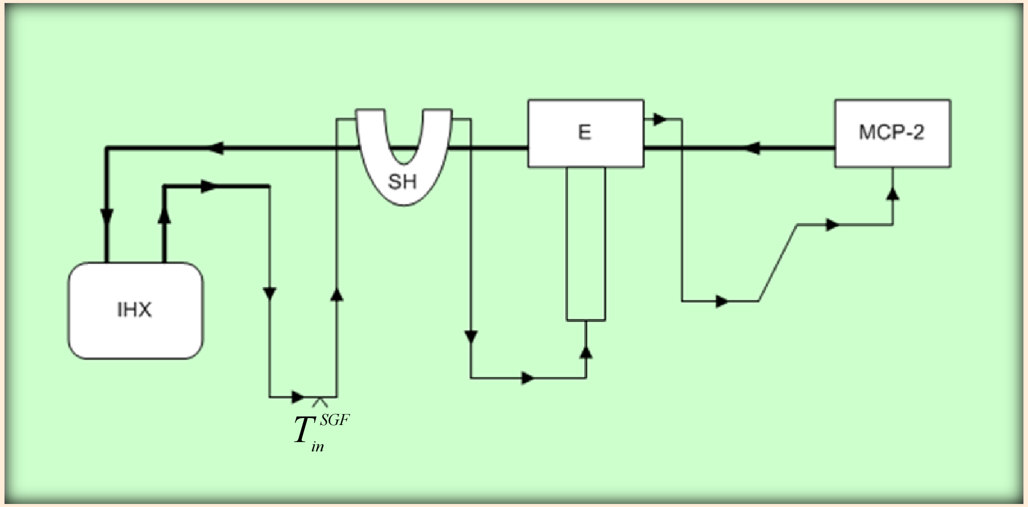
Scheme of the BN-350 primary circuit loop



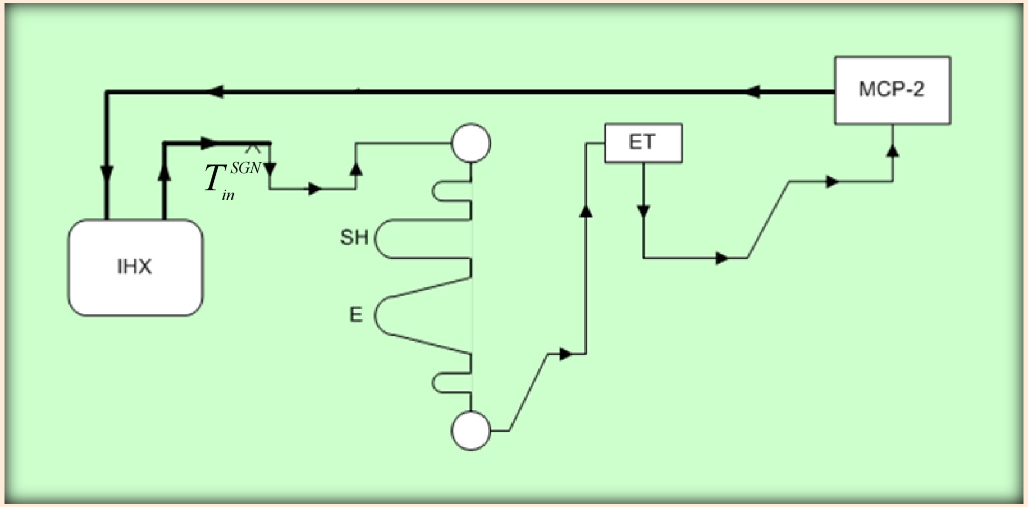
Sections of the BN-350 primary circuit loop, where LNC can arise, are marked

BN-350 loop configuration

Scheme of the BN-350 secondary circuit loop with SGF



Scheme of the BN-350 secondary circuit loop with SGN



Sections of the BN-350 secondary circuit loops, where LNC can arise, are marked

Test conditions

Special measures have been provided for excluding heat leakage from operating loops into non-operating ones:

- ***Valves No. 2 in non-operating loops of the primary circuit have been closed;***
- ***Coolant circulation in non-operating loops of the secondary circuit has been interrupted owing to decrease of coolant level in them (in superheaters for loops with SGF and in expansion tank for loops with SGN).***

Such measures were based on the assumption that appreciable heat leaks from operating loops can occur only due to conventional total-circuit natural circulation (TNC) in non-operating loops and they did not consider possibility of local natural circulation (LNC) occurrence.

These measures have been inefficient owing to existence of local natural convection flows in loops.

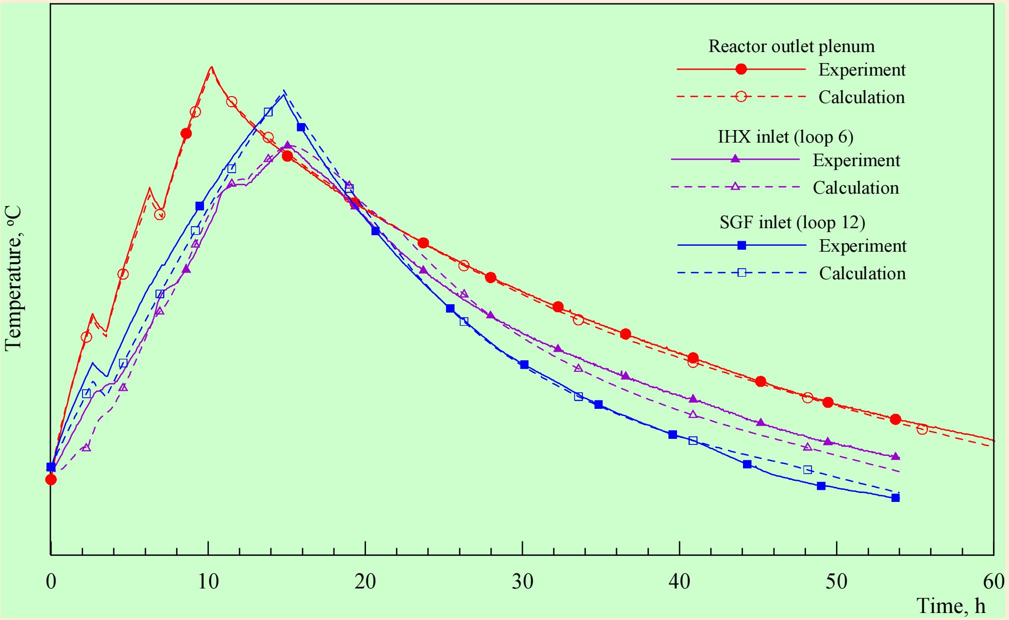
Experimental results and their comparison with calculations

Experimental results testified to existence of LNC in BN-350 loops in modes under investigation that is comparable with TNC.

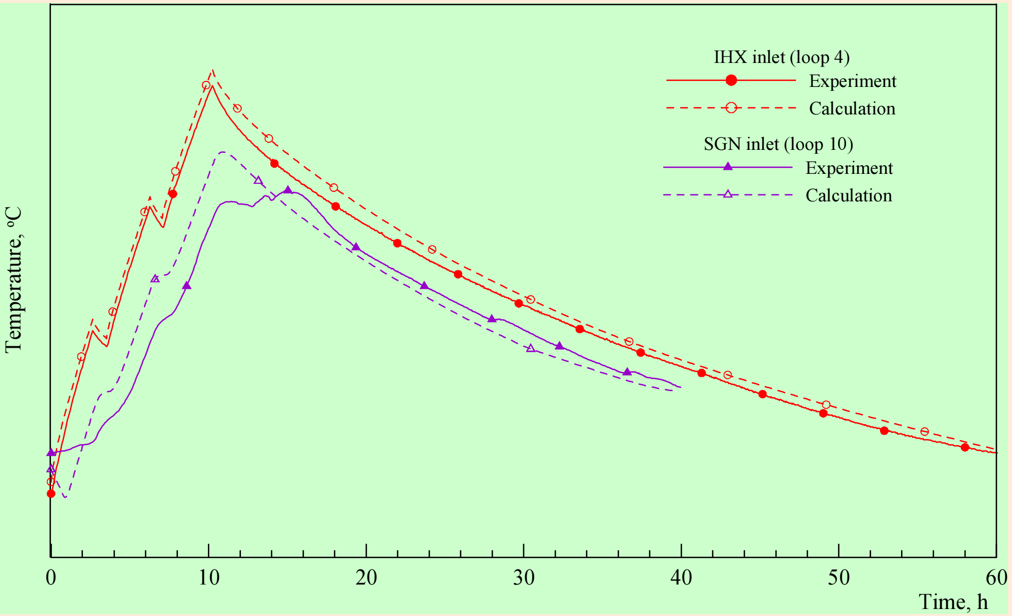
- Despite the fact that valve No. 2 in loop No. 6 (test 1) was closed, thermocouple indications at the inlet into IHX of this loop on the primary circuit side practically correlate with change of sodium temperature in reactor vessel and in loop No. 12.
- During test 1, upsurge of sodium level has been observed in non-operating loops No. 8 and 10 of the secondary circuit.
- This is also confirmed by growth of sodium temperature at SGN inlet in loop No. 10.
- Indications of surface thermocouples of IHX of loop No. 6 in tests 3, 4 confirm existence of intensive LNC. Coincidence of indications of thermocouples located at IHX inlet and outlet testifies to simultaneous heat propagation owing to LNC in two opposite directions – to SG and to MCP-2.

Experimental results and their comparison with calculations

Sodium temperature in reactor vessel and in loop 6 and 12 (test 1)

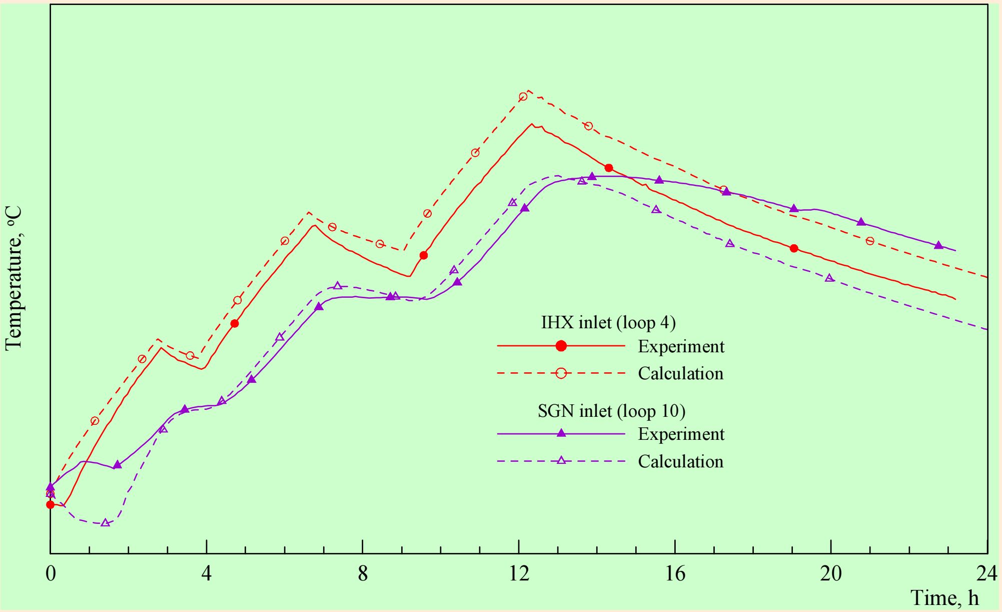


Sodium temperature in loop 4 and 10 (test 1)

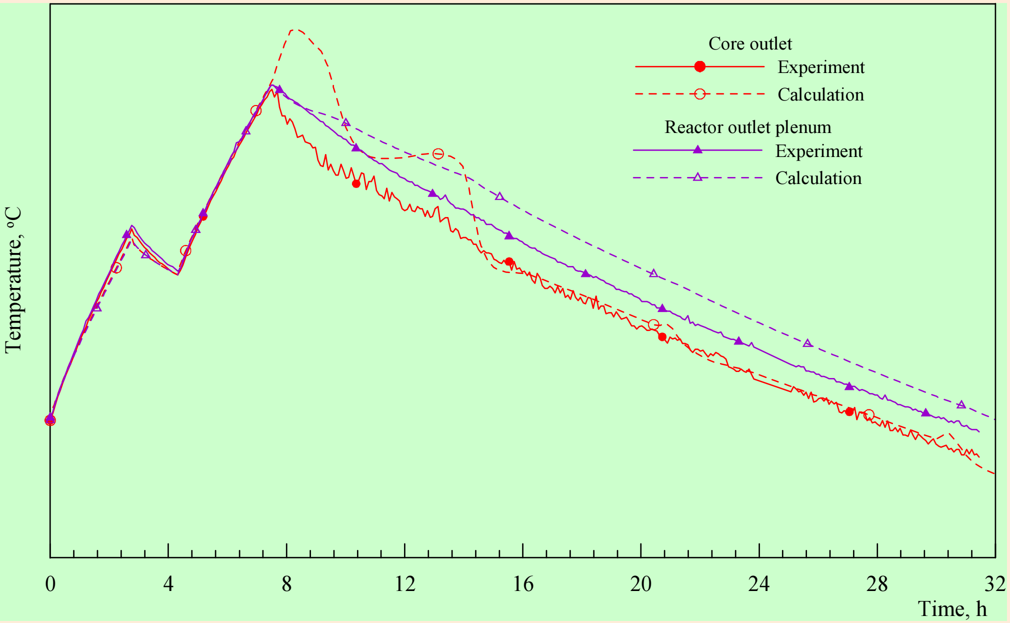


Experimental results and their comparison with calculations

Sodium temperature in loop 4 and 10 (test 3)

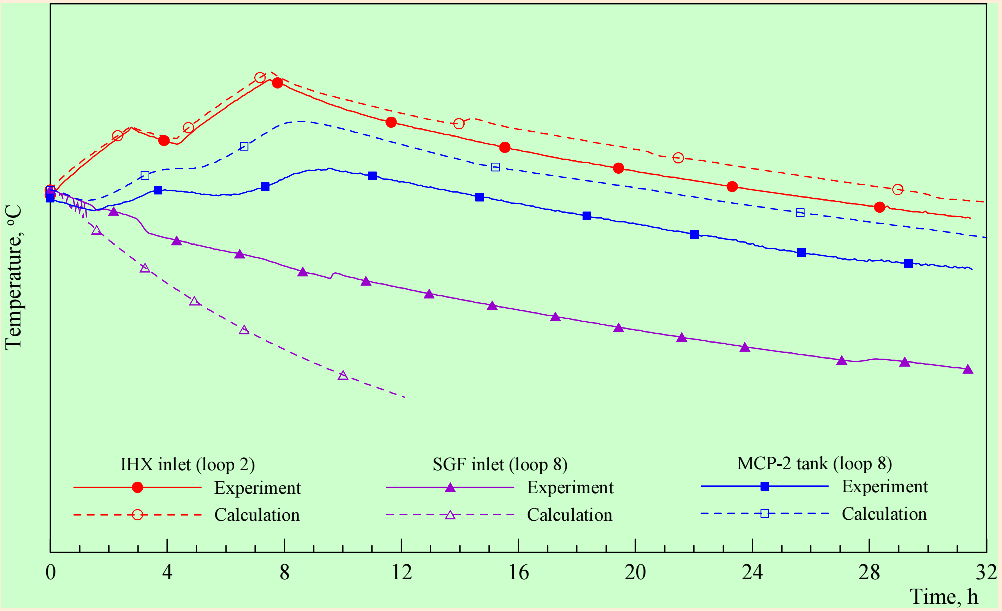


Sodium temperature in the primary circuit (test 4)

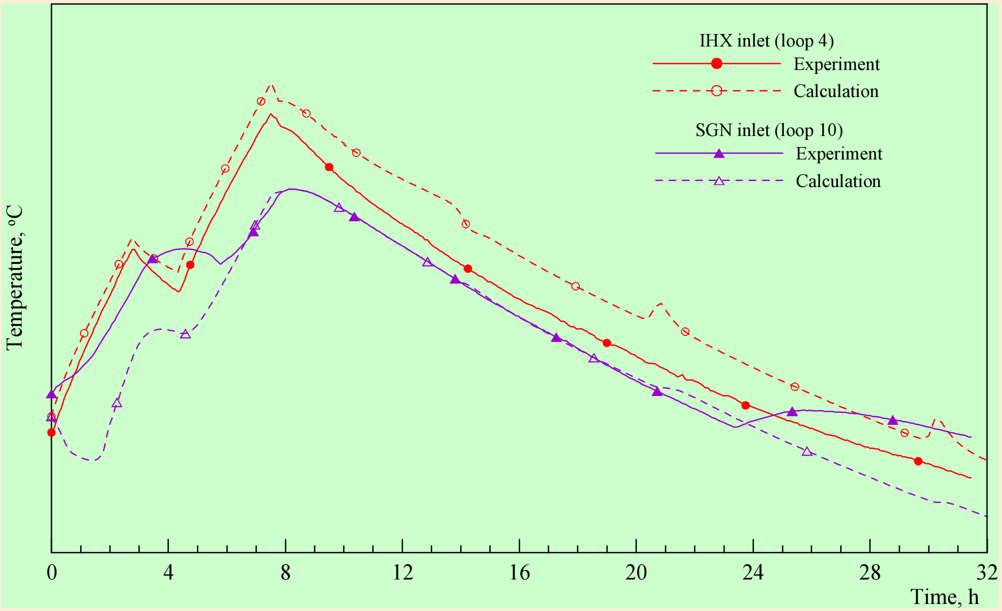


Experimental results and their comparison with calculations

Sodium temperature in loop 2 and 8 (test 4)

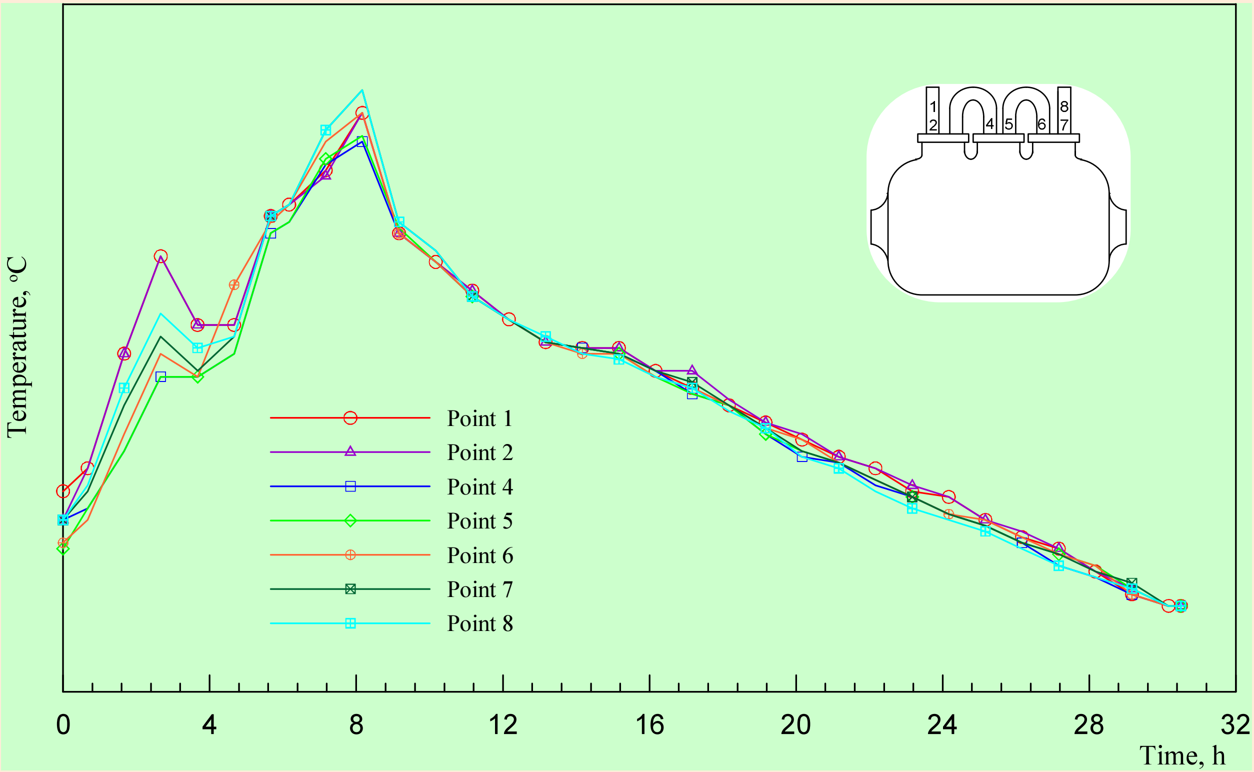


Sodium temperature in loop 4 and 10 (test 4)



Experimental results

Temperature of the IHX inlet and outlet connections in loop 12 (test 4)



Experimental results and their comparison with calculations

One-dimensional model of heat propagation along loop due to LNC has been developed on the basis of theoretical explanation of LNC mechanism presented below, and incorporated in DINRUN code.

Verification of DINRUN code performed on the basis of experimental data has shown a satisfactory coincidence between calculational and experimental results (without LNC model discrepancy between calculational and experimental data reached several dozens degrees).

Thus, results obtained confirm necessity of taking into account LNC phenomen when analyzing modes with natural circulation.

TNC and LNC features

Conventional total-circuit natural circulation (TNC) arises in the closed circuit.

Basic specific features of TNC are as follows:

- ***existence of directed movement of coolant mass along the loop (in general, not equal to zero), accompanied by heat transfer along the loop (every time direction of TNC is the same in each place of the loop);***
- ***the same value of TNC coolant flowrate through any cross-section of the loop.***

Natural circulation flow arising within local section of the circuit we name local natural circulation (LNC).

Main specific features of LNC are the following:

- ***existence, within the local closed circuit of circulation, of direct and reverse coolant flowrate in any cross-section of the pipeline section which are equal on value and are opposite in direction, i.e. unlike TNC it means absence of directed coolant mass transpot along the loop as total coolant flowrate through any cross-section of the pipeline section is equal to zero;***
- ***presence of certain heat transfer along the section – from side with higher temperature to side with lower temperature owing to difference of temperature of direct and reverse LNC flows.***

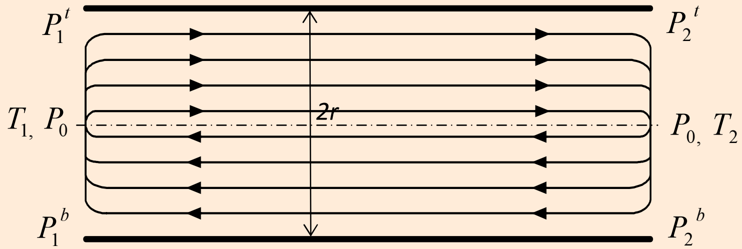
It is necessary to note two more distinctions between LNC and TNC:

- ***TNC can exist only in heat removal loops with closed coolant circulation circuit while LNC can arise in loops with interrupted coolant circulation circuit too;***
- ***in the loop of simple configuration (without branchings) only one TNC circuit arises, at the same time some LNC circuits can be formed within one loop.***

P_1^t

Schemes of LNC in various pipeline sections without TNC

LNC circuits in various sections of the loop



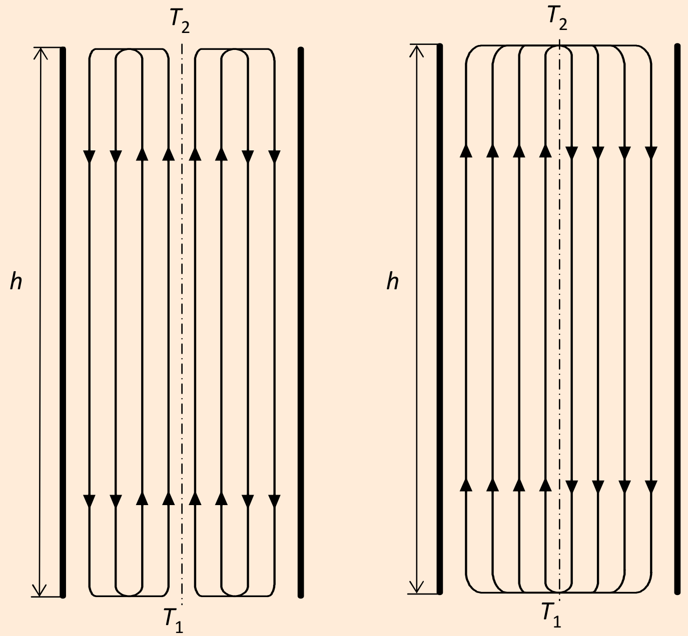
a) Horizontal section ($T_1 > T_2$)

$$P_1^t = P_0 - \rho_{c1} \cdot g \cdot r$$

$$P_1^b = P_0 + \rho_{c1} \cdot g \cdot r$$

$$P_2^t = P_0 - \rho_{c2} \cdot g \cdot r$$

$$P_2^b = P_0 + \rho_{c2} \cdot g \cdot r$$



Variant 1 Variant 2

b) Vertical section ($T_1 > T_2$)

LNC conditions in the interupted circuit

Unlike the horizontal section where presence of temperature difference at the section ends is a single necessary and sufficient condition for LNC occurrence, in the vertical section LNC arises only when coolant temperature at the upper section end is less than coolant temperature at the lower end ($T_1 > T_2$).

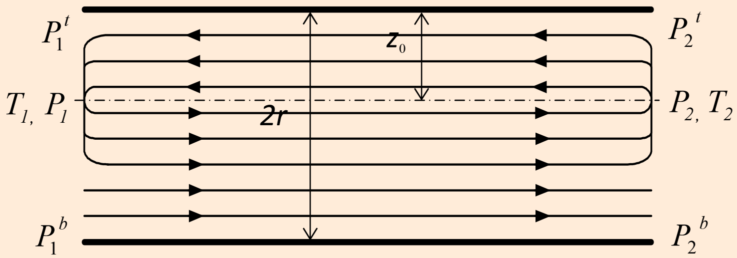
Conditions of LNC occurrence in the inclined sections are the same, as well as for the vertical sections with variant 2 of closing LNC circuit.

Thus, in the horizontal sections heat transfer by LNC can occur in any direction, but in the vertical and inclined sections heat transfer by LNC can exist upwards only.

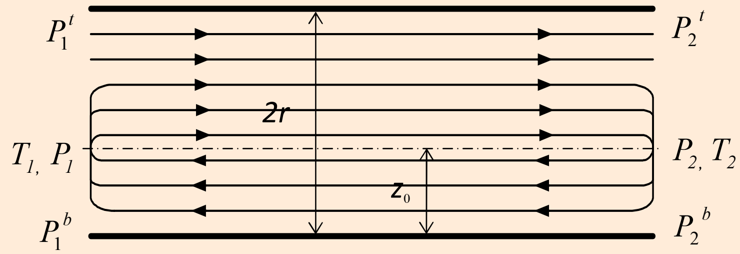
P_1^t

Schemes of superposition of LNC and TNC in the horizontal pipeline section

TNC and LNC superposition in horizontal section of the loop



a) (T_1<T_2)



b) (T_1>T_2)

$$P_1^t = P_1 - \rho_{c1} \cdot g \cdot r$$

$$P_1^b = P_1 + \rho_{c1} \cdot g \cdot r$$

$$P_2^t = P_2 - \rho_{c2} \cdot g \cdot r = P_1 - \Delta P - \rho_{c2} \cdot g \cdot r$$

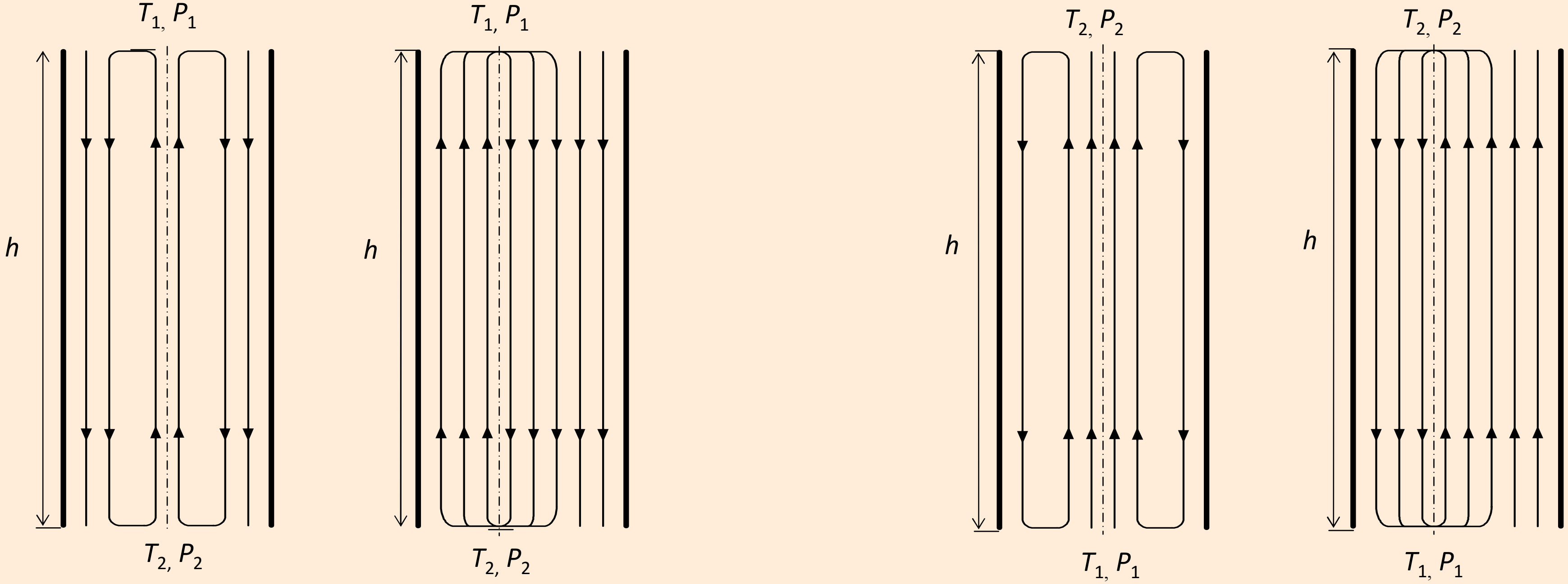
$$P_2^b = P_2 + \rho_{c2} \cdot g \cdot r = P_1 - \Delta P + \rho_{c2} \cdot g \cdot r$$

$$z_0 = r - \frac{\Delta P}{(\rho_{c1} - \rho_{c2}) \cdot g}$$

$$z_0 = r - \frac{\Delta P}{(\rho_{c2} - \rho_{c1}) \cdot g}$$

Schemes of superposition of LNC and TNC in the vertical pipeline section

TNC and LNC superposition in vertical section of the loop



a) b) c) d)

Downward TNC flow

Upward TNC flow

Observance of the inequality $P_1 + \rho_{c2} \cdot g \cdot h < P_2$ is the condition for existence of upward coolant flow within the section and occurrence of LNC circuit accordingly.

Observation of the inequality $P_1 < P_2 + \rho_{c2} \cdot g \cdot h$ is the condition for existence of downward coolant flow within the section and creation of LNC circuit in it accordingly.

Influence of LNC on operational modes

LNC circuits will influence TNC parameters.

Firstly, heat exchange between LNC and TNC flows influences distribution of coolant temperature along length of the heat removal loop and, therefore, value of TNC flowrate, as tests performed at the BN-350 have shown. (For example, small value of reverse TNC flowrate in loop No. 8 in test 4, is explained, first of all, by unfavourable influence of appreciable LNC flows.)

Secondly, occurrence of closed LNC circuits in certain parts of the heat removal loop, leads to narrowing cross-section for TNC flow in these parts of the loop and, as a result, increases hydraulic resistance of TNC path on the whole.

Heat propagation in the loop owing to LNC can lead to an unfavourable thermal mode of pipelines and equipment of the loop (pumps, valves, etc.) and, hence, possible influence of LNC should be taken into account when estimating their operating capability and lifetime.

CONCLUSIONS

- **The results of tests on substantiation of NC modes performed at the RF BN-350 in 1996 have shown complex spatial behaviour of coolant NCF arising in various sections of the heat removal loops. The LNC phenomenon that can arise in certain sections of the loop along with TNC owing to non-uniformity of coolant temperature distribution along the loop's length, has been revealed by results of these tests.**
- **Universal behaviour of the LNC phenomenon and specific features of its superposition with TNC confirm necessity to take into consideration this phenomenon both when modeling NC modes in the RF loops, and when substantiating temperature modes of the loop's equipment and pipelines.**
- **Problems of interaction of neighbour LNC circuits, including determination of factors influencing amount of LNC circuits and their extension in various sections of closed circuit of RF heat removal loop, require further investigation.**

Thank you for your attention !