OVERALL CONCLUSIONS

1. The validity of thermohydraulics in fast reactor core and heat exchanger is largely influences by the accuracy of the system of correlations written for the friction factors, heat transfer coefficients, mixing factors and so on. The development of the complete and accurate system is critical in nuclear power engineering. Method of thermohydraulic analysis, features of thermohydraulic phenomena, computer codes developed with the use of closing relations are based on the experimental results and numerical modeling of the processes in nuclear reactor units.
2. Two computation procedures form the basis for prediction of reactor core and heat exchanger thermal hydraulics: subchannel approach (subassembly) and a porous body model (intermediate heat exchanger). In working out the codes much attention has been given in the IPPE to the non-nominal reactor operation being caused by diabatic conditions at the wrapper, by the random departure of parameters from nominal values in campaign, by the transients associated with liquid metal boiling. In all instances the inter-channel exchange is of primary importance in the computations.
3. Analysis of the process and performance of experiments with the ensuing development of computer codes are based on the following principles:
    - thermal modeling of fuel pins (heat flux up to 1.2 MW/m^2) with the distributed power production;
    - modeling of reactor core and heat exchanger thermal hydraulics;
    - local measurement technique, including electromagnetic flow meters, miniature thermocouples, with the ensuing correlation between hydraulic and thermal data, that gives sufficient information on fast reactor subassembly performance;
    - high-power liquid metal facilities operating in a wide range of working temperatures with sodium or sodium-potassium alloy used as a coolant, which allow the large-scale out-of-pile experiments to be carried out.
4. Electromagnetic technique allows the local hydraulic characteristics of axial, transverse and combined (axial-transverse) flows through the models simulating subassembly and heat exchanger to be measured. The advantages and possibilities of the technique are as follows:
    - experiments may be performed with the same coolants as those in reactor;
    - small-sized sensors meet reactor technological standards;
    - local flow rate can be defined around and along the pins;
    - local hydrodynamic features in deformed systems (bending and shifting of pins, blockages, manufactoring tolerances and others) can be revealed;
    - Measurements remain precise due to sensors' sensitivity as well as due to the lack of any elements inserted into the flow which can distort the hydrodynamics.
    - The technique is easy to realize, low in cost, advantageous for reading information. It can be convenient means for studying physics of combined transverse-axial flow.
5. Features of thermohydraulics in reactor core and heat exchangers are as follows:
    - Among the main factors defining hydraulic behavior in fast reactor core subassembly are large velocity non-uniformities around the edge pins and intensive inter-channel exchange due to wire wrap;
    - Inter-channel exchange is one of the most important reasons for the hydraulic characteristics in pin bundle to differ from those in insulated channels;
    - Combined prediction and experiment researches have yielded information on the influence of various factors on liquid metal flow behavior;

- As distinct from the previous hypothesis on the possibility to predict hydrodynamics using the averaged, across the subassembly, coolant velocity or hypothesis of isobaric section, it has been shown that such a prediction does not provide the wanted accuracy. Feasibility of the hypothesis of isobaric section should be limited by the bundles of smooth pins being free from displacers;
- Hydraulic features in mutually relative channels are properly reflected by the subchannel analysis accompaning for inter-channel exchange, which allows predicting reliable velocity distributions over the pin bundles;
- Subassembly hydrodynamics, as a whole, depends, to a large measure, on the features of the edge areas of the pin bundle. Predictions and experimental data on local hydrodynamic characteristics in the edge channels allow the optimal geometrical variants to be chosen;
- Local hydrodynamic measurements, as applied to fast reactor heat exchangers, permit gaining the experimental data needed for predicting combined flow. Appropriate codes have been developed and verified on the experimental data available.

6. On the subject of inter-channel exchange in fast reactor subassembly the following remarks are in order:
    - Study of inter-channel exchange was performed by the use of the electromagnetic technique which permits probing deeper into the finer details of the process with the ensuing correlations derived for the local and integral mixing factors within a wide ranges of defining parameters;
    - Physical picture of the inter-channel exchange in the bundle of wire wrapped pins is as follows;
        - convective component of inter-channel exchange intensity distribution along the bundle follows sine law;
        - the exchange intensity depends on the relative pitch of the bundle, on the kind and pitch of wire wrap, on Reynolds number;
        - directed coolant flow is observed around the subassembly wrapper.
    - Modified thermal track technique allows investigation of the local and integrated mixing factors. Using this technique the data on the total thermal mixing factor have been obtained;
    - Joint application of electromagnetic and thermal track technique allow the total mixing factor to be divided into separate components, the non-equivalence factor between heat and mass transfer to be determined;
    - The main component of inter-channel exchange in fast reactor core subassembly is convective component due to the wire wrapped on the pins, whereas in reactors with high conductive pins an exchange due to pin heat conduction dominates;
    - The equivalence factor is found in liquid metal experiments to be equal to about 0.7;
    - To evaluate mixing factors due to turbulent, molecular diffusion and convective transport the empirical and analytical correlations have been derived within the pitch-to-diameter ratio range $0.1<s/d<2.0$;
    - Experimental data on inter-channel exchange are at the basis of procedures developed to predict velocity and temperature behavior in reactor core and heat exchangers. A knowledge of thermal mixing factors allows an influence of a number of the factors resulting in campaign to be estimated, such as: pin bundle deformation, non-uniform power production, blockages, thermal interaction of the subassemblies, low coolant velocity including natural convection and so on. The

subchannel approach and the porous body model are straightforward and reliable procedures;

- Theoretical analysis of liquid metal heat removal supplements experimental investigations. The notions of inter-channel exchange (mass, momentum, energy mixing factors, non-equivalence factor between heat and mass transport, "effective" mixing factor and so on) allow the numerical procedure to be developed and the system of thermal hydraulic governing equations to be reduced to single equation of convective heat transfer (using the concept of equivalent thermal conductivity of pin bundle).

7. Generalized relations derived from the experiments form the basis for most calculations of steady state heat removal in any axi-symmetric system cooled by liquid metal;
8. Analytical procedures and experimental techniques have been successfully combined in considering an irregular processes (variable power production, entrance section). The main physical features are as follows:
    - Relative length of entrance section reduces with the pitch-to-diameter ratio and equivalent thermal conductivity of pins. In laminar flow the entrance section length is in direct proportion to Peclet number (heat transfer due to molecular heat conduction), in turbulent flow it has a peak;
    - Universal formula describing variations in temperature and heat transfer at the entrance section has been proposed;
    - It is Duhamel's integral that allows the experimental data gained under hydraulically unstable conditions being converted into those under variable power production (at least in fast reactors).
9. Due attention should be given to the thermophysical validation of the edge (wall) pins as the most dangerous area of subassembly in terms of temperature non-uniformity. The main features of the edge pins performance are as follows;
    - Temperature non-uniformity at the edge pins far exceed those at the inner pins;
    - Heat transfer coefficients in the edge area of fast reactor subassembly are lesser than expected in the internal area by a factor of 1.5-2.0. The relations presented take into account the availability of displacers within the edge channels;
    - Maximum temperature non-uniformity at low Peclet numbers (transition region) can present a severe hazard to emergency cooling of reactor core provided that power is kept at sufficiently high level;
    - Heat removal in the edge channels is, as a rule, of unstable character, that depends on equivalent thermal conductivity, relative pitch, shape and size of displacers and other factors;
    - Pin bundle deformation causes the temperature non-uniformity to increase and the heat transfer coefficient to reduce at the edge pins;
    - As coolant passes through the gap between subassemblies, it reduces coolant temperature in the edge channels, so temperature non-uniformity increases by ~50% in the event of the ratio between flow through the inter-subassembly space and those through the subassembly is ~5-6%;
10. Transient reactor core and heat exchanger behavior is the key problem of fast reactor thermal hydraulics:
    - During operation subassembly is subject to the combined action of various factors, with the temperature non-uniformity being among the most important one.
    - The combined subchannel codes TEMP involving solution of macro-transport equations, having regard to inter-channel exchange, has been verified on the extensive experimental data that allows predicting to a high accuracy nominal and

non-nominal temperature behavior in fast reactor core. The code TEMP is of high-performance and has gained widespread acceptance.

- Thermal mechanical analysis performed having regard to subassembly deformation indicates the enhancement of maximum temperature of the pins, as well as maximum temperature non-uniformity.

11. Combined experimental & analytical investigations of intermediate heat exchanger thermal hydraulics have presented a basic information on velocity and temperature behavior. The main results are as follows:

in the field of hydrodynamics:

- The use of electromagnetic technique has allowed the physics of axial-transverse flow to be studied, as well as characteristics of triangular and square arrangement of the tubes in a wide range of Reynolds number;
- From the local measurements of transverse and axial components of velocity we can conclude whether the given design of heat exchanger is optimum;
- Equalization of coolant flow over the tube bundle reduces heat transfer surface area and, in doing so, its economic feasibility is enhanced;
- Experimental data have been used as a closing constants in the code development.

in the field of thermal behavior:

- Data on heat transfer coefficients and temperature behavior can be used in the validation of heat exchanger equipment and in the development of optimization methods;
- The local thermal modeling allows the processes going on in the multi-tube heat exchanger to be studied on the small-scale models (19 tubes);
- Computer codes verified on the experimental data are profitably employed in thermal hydraulic validation of fast reactor heat exchangers.

12. For the purpose of developing procedure of transient data generalization and to derive approximate criteria, the transient temperature behavior has been investigated in the bundle with various kinds of fuel. It has been shown that pin wall temperature dynamics can be expressed in the form of universal time-dependence;

13. The objectives of experimental and analytical validation of reactor core performance under accident conditions to be pursued by extensive researches into sodium boiling. Experiments have been concerned with the investigations:

- onset and development of the coolant boiling under various flow and power productions;
- critical heat flux;

possible destruction of pins and inherent phenomena.

Predictions have been concerned with the analysis of the following processes:

- molten fuel/coolant interaction;
- drastic increase in the fragment surfaces within the system under consideration;
- vapor explosion;
- aerodynamical effects;
- the process propagation.

Up to now the following researches have been performed:

- Experimental base has been built up (high temperature facility, equipment and measurement technique);
- Experiments have been carried out to study liquid metal boiling dynamics;
- The model two-phase flow has been stated;

- The system of macro-transport governing equations has been analyzed in the framework of subchannel approach;
- Inter-channel characteristics have been analyzed, as applied to two-phase flow.

14. The foregoing shows that the complete system of closing relations and constants required in thermal hydraulic analysis of fast reactor core and heat exchangers have beenderived for the following :

- prediction of coolant flow distribution over the channel having regard to inter-channel exchange;
- prediction of coolant temperature distribution over the channel;
- definition of temperature difference "wall-liquid" and maximum temperature non-uniformity;
- consideration of variable power production;
- inclusion of various factor defining temperature behaviour;
- definition of maximum pin temperatures.

The most advanced thermohydraulic codes are the codes GID, TEMP, MIF, MID developed for the LMFBR core, and those for intermediate heat exchanger are PROTVA, UGRA, TAKT and others.

Authors consider that the material presented fulfill the modern thermal hydraulic requirements.