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Worldwide Report

NUCLEAR DEVELOPMENT AND PROLIFERATION

(FOUO 4/82)

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UDC 621.039.001

DEVELOPMENT OF CEMA NUCLEAR POWER SYSTEM VIEWED

Prague JADERNA ENERGIE in Russian No 12, 1981 pp 439-443

[Article by Yevgeniy P. Vlasov, International Scientific Research Institute of Control Problems, Moscow; Milos Dragny, Czechoslovak Atomic Energy Commission, Prague; and Yuriy A. Tyurin, Department of Scientific and Technical Cooperation of the CEMA Secretariat, Moscow: "A Study of Methodological Problems in the Forecasting and Optimal Development of a Nuclear Power System for CEMA Member-Nations"]

[Text] One of the important directions in solving the fuel-and-power problem of CEMA member nations is the accelerated development of the nuclear power industry. The present stage of the cooperation among these countries in this area is characterized by the large-scale and comprehensive implementation of measures, the considerable influence of scientific and technical progress on production efficiency and the great contribution of these countries to the overall issue of realizing the nuclear power-production portion of the long-term specific program of cooperation (DTsPS) to provide for the economically founded requirements of the CEMA member-nations for the basic types of power, fuel and raw materials to the year 2000. The indicated conditions for the development of the nuclear power industry are dictated by the necessity of improving methods of controlling and planning the development of the entire nuclear power complex (YaEK) of the socialist countries [1,2].

Figure 1 presents the interindustry structure of the nuclear power-production complex. It includes the fuel-cycle industries (extraction, processing and enrichment of fuels, the manufacture of fuel elements, chemical processing of spent nuclear fuel and processing and storage of radioactive wastes), nuclear stations and installations for the generation of electric and thermal power (nuclear electric-power stations, nuclear heat-and-power stations and nuclear power-production installations) and all capital-generating sectors of the nuclear power complex (metallurgy, heavy, chemical and power-engineering industries, the electrical equipment industry, instrument engineering, power industry construction and the construction industries).

Of course, the nuclear power complex of a given country can and must be considered a subsystem of the integrated nuclear power complex of the CEMA member-nations. It is possible to rationally solve problems which within the framework of a single country cannot be solved at all or, at least, cannot be solved efficiently. This can be accomplished through international cooperation, division of labor, specialization of production and construction through combined effort or cooperation within the scope of capital investment in construction.

The industries in the nuclear power complex are embraced by complex interrelationships, including reciprocal relationships (for example, the chemical processing of spent fuel). The formation of this aggregate of industries into a unified nuclear power complex is dictated by the degree of specialization, the influence they exert on one another as well as by the overall production cycle.

The characteristic integrity of the nuclear power complex which we have pointed out determines the necessity for applying a systematic approach to examining the prospects for its development and the introduction of methods for multisector planning and control.

The overall organizational structure for planning the long-term development of the nuclear power complex can be presented in the following manner (fig. 2). This diagram displays the operational makeup and the interrelationships of these operations in the forecasting and formation of nuclear power programs and a comprehensive long-range plan of development for those industries included in the nuclear power complex. The close interrelationship between the planning of scientific research and industry is shown by a block for the determination of the needs of industry in the development of equipment and technology and effective directions for the utilization of the new results from scientific research and experimental design work. A positive feature of this long-term planning program is the combination of the processes for forecasting and forming programs and plans for the development of the nuclear power complex into a unified cycle of interrelated operations. The results from forecasting programs and the coordinating of these programs with specialized plans should insure the best continuity.

At the present time, we have good reason to believe that the CEMA member-nations will insure the realization of a comprehensive and specific approach to managing the development of the nuclear power industry up to the year 1990. Within the scope of the previously mentioned long-term specific program of cooperation, we have concluded the Agreement on Multilateral International Specialization and Cooperation in the Production and Mutual Supply of AES Equipment for the Period 1981-1990. We are creating the necessary organizational prerequisites and are solving three of the most important problems in scientific and technical cooperation within the nuclear power industry: the mastery of water-cooled water-modulated reactors with outputs on the order of 1,000 MW; the development of high-output fast reactors; and the development of nuclear heat and power stations and nuclear heat plants.

However, features of the process for the integrated development of a nuclear power complex--a considerable rate of growth, a broad spectrum of scientific research and feasible structural transformations, the time lag and the capital-intensive nature of the problem--dictate that technical and economic studies of the prospects for a CEMA member-nation nuclear power complex be conducted for the years beyond 1990 and that corresponding long-term cycles for managing its development and progress be organized.

Control over the development and progress of the nuclear power complex and the realization of the corresponding industrial-economic and scientific-technical activities are contained in the field of activity of a number of agencies and organizations, primary among which are:

a) at the national level:

- the highest organs (government and joint agencies for planning, finance, technical development, foreign trade, etc.)

- special ministries (ministries of power, metallurgy, machine construction, instrument engineering, construction and the construction industry, etc.)

- the organization of a scientific-research and experimental-design base;

b) at the CEMA level:

- supreme organs (Supreme Soviet, Executive Committee),

-committees for cooperation in the area of planned activity and for scientific and technical cooperation, as well as their working agencies (namely, the Working Group for the Fuel and Power Balance and the Council for Scientific and Technical Cooperation in the Area of Fuel and Power Problems--the TEP Council),

- special Permanent Committees (namely, those for the utilization of nuclear power for peaceful purposes, for electric power, for machine building and for construction) and their working agencies,

- international economic organizations (namely, international economic organizations of Interatomenergo and Interatominstrument),

- international organizations of the scientific research base (namely, MNIIPU--the International Scientific Research Institute for Control Problems).

Within the organizational plan, integrated programmatic-specific planning and management of the CEMA member-nation nuclear power complex according to diagram 2 should be constructed on one interrelated plan of harmonious work coordinated by the above-mentioned agencies and organizations at the national and international levels.

Let us now dwell upon the status of the work being done in the area of forecasting the long-range development of the nuclear power industry in socialist countries. We refer here to the work being carried out within the scope of activity of the Committee of the Scientific and Technical Council which, on behalf of the 24th meeting of the CEMA Session, organizes the development of a scientific and technical forecast for the solution to fuel and power problems in the period to the year 2000 and for the long term. This work, being carried out from 1980 to 1984, is based upon data from interested CEMA member-nations regarding the planned development of national fuel and power complexes.

The first meeting of the Provisional Collective of Scientists and Specialists (VKUS), created by the TEP Council to develop a forecast for the development of the nuclear power industry, took place from 27 to 30 January 1981 in the city of Ostrava in the Czechoslovak Socialist Republic. The meeting examined materials prepared jointly by the Czechoslovak and Soviet sides with the participation of a department of the Secretariat's Scientific and Technical Council and MNIIPU. Two major documents were submitted for approval:

1. a program of development and
2. organizational and methodological statutes regarding the development of a forecast for the growth of the nuclear power industry in CEMA member-nations in the period to the year 2000 and for the long term.

The sixth session of the TEP Council which took place in Berlin, East Germany from 16 through 19 June 1981 approved both documents and noted that the Soviet Union had assumed the duties of the coordinating nation.

This program of development and the organizational-methodological statutes determine the makeup and the interdependence of work being done at the national and CEMA levels. Work at the CEMA level is oriented toward correlating and systematically combining national forecasts and forming the best strategy for the intensive development of the nuclear power complex of CEMA member-nations together with the drawing-up of recommendations for the individual countries. Forecast studies at the national level are oriented toward the formation of an optimum long-term strategy for the country which is based on its specific situation and which insures the participation of national organizations in international cooperation for the realization of integrating measures in the area of nuclear power generation and related areas of the nuclear power complex. Studies carried out at the national level are the chief and initial basis for forecasting. Two major stages have been proposed: the development of a forecast plan and, naturally, the forecast itself. During the first stage, alternative strategies for the development of the power industry itself are examined and evaluated. During the second stage, these strategies are refined and adjusted. In addition, suggestions are developed regarding integrating measures and the contribution of each country toward their realization.

At first, the countries develop a structure for the development of the national nuclear power industry and carry out an initial evaluation of the long-term requirements for external deliveries of the basic types of equipment and scarce resources and the feasibility of making their own deliveries to the other countries. On the basis of these data presented in CEMA, the Provisional Collective of Scientists and Specialists work out alternatives for an interindustry structure and scenarios for the development of the nuclear power complex so as to satisfy the countries' requirements for the development of the national nuclear power industries to the maximum degree possible. As a result, the basic directions for the development of the nuclear power complex are determined. They expand and deepen the sphere of scientific-technical and industrial-economic cooperation among the countries and contribute to the achievement of their national goals.

At the next stage, the structure for the development of the country's nuclear power industry is refined, with consideration being given to the basic directions for the development of the CEMA member-nations' nuclear power complex on the whole. Specific alternatives are being developed for the realization of long-term goals for the growth of the national nuclear power base.

At the same time, on the international level, alternatives are worked out for the realization of integrating measures for CEMA member-nations as well as mutually advantageous alternatives for scientific-technical and industrial-economic cooperation.

At the concluding stage of forecast development, the specific structure is submitted for approval and a plan of the decisions is prepared for examination by the corresponding CEMA agencies with regard to integrating measures which insure the long-term growth of the CEMA member-nation nuclear power complex.

Let us dwell in more detail upon the development of a forecast plan for the growth of the national nuclear power industry. The development of a forecast begins with the determination of the scope of the national nuclear power industry for the years 1990-2000-2010 and the selection of types, unit outputs and the stages of utilization of nuclear reactors. Then studies are developed for determining the basic tasks of scientific research, alternatives for the development of an industrial and construction base and the demand for scarce materials and the basic types of equipment. Simultaneously, as a result of the determination of the structure of AES's, ATETs's and AST's planned for construction in the period to 2010 and the evaluation of the prospects for the utilization of nuclear power installations in metallurgy, chemistry, agriculture, transportation and in other sectors of the economy, we are conducting:

- an analysis of ecological factors and the identification of the corresponding limitations on and requirements for the construction of nuclear power installations;

- the development of alternative methods for maintaining, storing and transporting spent fuel and for processing and burying radioactive wastes;

- the development of alternative methods for decommissioning nuclear power installations.

Naturally, these problems in the development of the nuclear power industry give rise to their own scientific-technical and industrial-economic questions. A study of the alternative methods for developing production and scientific research in individual sectors of the nuclear power complex concludes with a system for evaluating alternative methods for the development of the power industry. If it becomes necessary, the previously selected structure and alternative methods for the utilization of nuclear reactors can be adjusted according to the results of this evaluation in order to improve the effectiveness of the solutions obtained. After satisfactory results are obtained, a selection is made of the major directions for the scientific and industrial work being done to insure the development of the national nuclear power industry. The country then draws up proposals for international cooperation in the given area.

It must be noted that the initial selection of the structure and alternative methods of utilization of nuclear reactors is a most critical stage in the development of a national forecast. This selection essentially determines future scientific and industrial activity both within the scope of the national nuclear power program as well as international programs for the integrated development of the nuclear power complex. Thus, we must develop this stage with particular care, enlisting the aid of leading scientists from various sectors of the nuclear power industry.

In order to carry out systematic research and optimize strategies for the long-term development of the CEMA member-nations' nuclear power complex, MNIIPU together with the interested national organizations is formulating a system of mathematical economic models. This system includes models for the development of fuel-cycle sectors, a model for the development of the power-production base, a model for the development of the machine-construction base and the related nuclear-power production industries as well as a model of the interrelations among sectors of the nuclear power industry. This system of models reflects the multistage process of production (for example, the extraction, enrichment, processing, etc. of ores) and considers the basic production parameters which determine its technological feasibility and its technical and economic efficiency. Moreover, the models directly reflect the results of the development of new equipment and techniques and their introduction into industry.

The realization of tasks regarding research and the optimization of long-term strategies for the development of a nuclear power complex utilizing the indicated models is accomplished on the basis of the SOPOT [expansion not provided] man-machine system developed at the International Scientific Research Institute for Control Problems. This system is problem-oriented toward the solution of tasks involving simulation and the optimization of intersector industrial complexes [3]. The SOPOT system consists of: a data bank; a generator of model programs; a numerical-method library; a model-research and problem-solving block; and an interactive-procedure block.

The features of the SOPOT system provide:

- the capacity for system correlation and problem decomposition in multilevel organizational systems;

- facility in adjusting mathematical economic models and problem conditions;

- the solution to complex data problems, including the answers to nonoperational queries.

At the present time, MNIIPU is organizing the exchange of SOPOT system software with interested national organizations. The planned exchange will enable the countries to reduce considerably the time and resources spent on creating a system for simulating the growth of national fuel-and-power complexes, as well as to prepare a basis for combining national systems of power-industry models in order to conduct joint investigations of alternative strategies for integrated development of fuel-and-power complexes.

In conclusion, we must emphasize:

1. the importance of data formulated at the national level and, thus, the complexity of the makeup of national working groups. It is desirable that all interested agencies and organizations in the scientific-technical and economic spheres of each country participate within the scope of these working groups. The participation of administrative and economic agencies (the State Planning Committee, the ministries, etc.) is necessary in view of the fact that these agencies are the ones which will subsequently utilize the results of the forecast and can from the very outset intro-

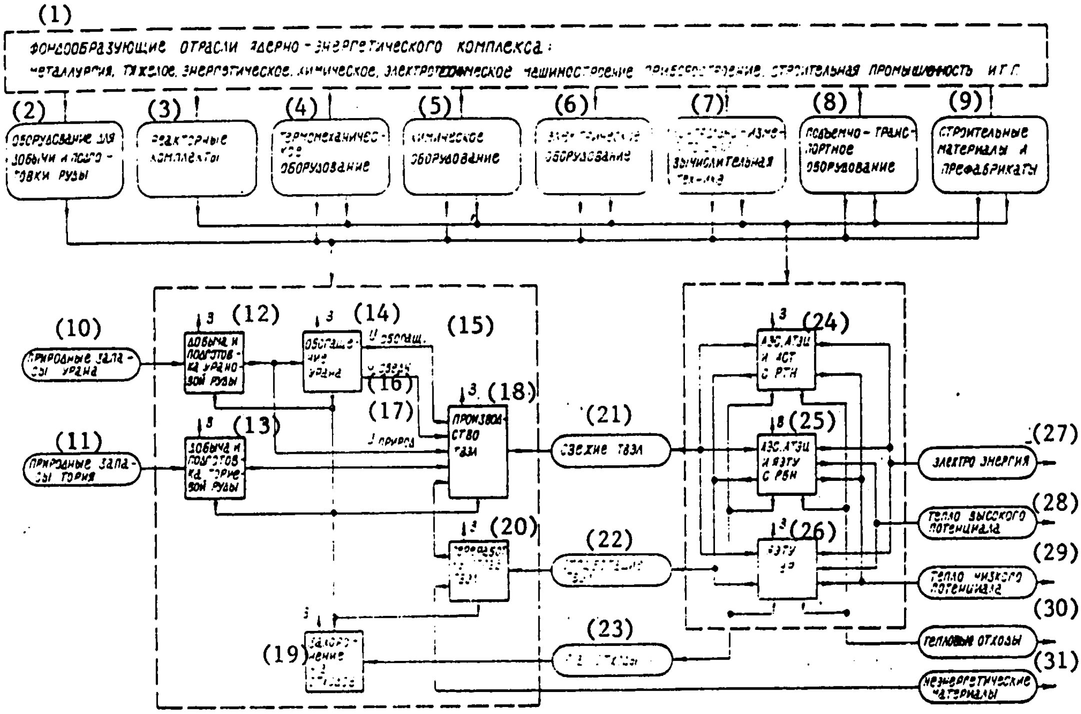

Figure 1. Diagram of Interindustry Structure of the Nuclear Power Complex

Key:

B. Radioactive discharges and waste
1. Revenue-generating sectors of the nuclear power complex: metallurgy, heavy, power, chemical and electrical machine construction, instrument engineering, the construction industry, etc.
2. Equipment for extracting and preparing ore
3. Reactor units
4. Thermonuclear equipment
5. Chemical equipment
6. Electrical equipment
7. Instrumentation and computers
8. Hoisting and transporting equipment
9. Construction and prefabricated materials
10. Natural reserves of uranium
11. Natural reserves of thorium
12. Extraction and preparation of uranium ore
13. Extraction and preparation of thorium ore
14. Uranium enrichment
15. Enriched uranium
16. Depleted uranium

Figure 1. Key (con'd.)

17. Natural uranium
18. Production of fuel elements
19. Burial of radioactive wastes
20. Processing of spent fuel elements
21. Fresh fuel elements
22. Spent fuel elements
23. Radioactive wastes
24. AES's, ATETs's and AST's with thermal reactors
25. AES's, ATETs's and nuclear power installations with fast reactors
26. Nuclear power installations with high-temperature reactors
27. Electric power
28. High-potential heat
29. Low-potential heat
30. Thermal wastes
31. Non-power materials

duce the necessary corrections in the studies being conducted and orient these studies in accordance with their own requirements. The immediate users will be the organizations in the scientific-technical sphere which will introduce the desired scientific approach and methodological apparatus into forecast studies;

2. the important role of meetings of the Provisional Collective of Scientists and Specialists which will observe and evaluate the progress of the work, insure the exchange of information and experience as well as consolidate individual points of view and discuss all data presented by the member-nations and the coordinator;

3. the extraordinarily vital and complex role of the coordinator. In contrast to the Provisional Collective of Scientists and Specialists, which can operate only periodically during the course of its meetings and will be limited to the discussion of the materials presented, the coordinator will continuously carry out the following activities on an international scale:

- prepare proposals for refining methodological instructions and working programs,

- develop a conceptual plan for an integrated nuclear power complex (at the first stage of development),

- evaluate materials presented by the countries regarding national nuclear power complexes and develop plans of the corresponding recommendations,

- evaluate the countries' considerations regarding an integrated nuclear power complex, summarize them and, finally,

- complete editing of the forecast plan and the final forecast for the integrated nuclear power complex.

Naturally, in order to successfully implement such broad and multilateral activity, the coordinator must make extensive use of its own scientific-technical potential and accumulated expertise in the area of organization of forecast work.

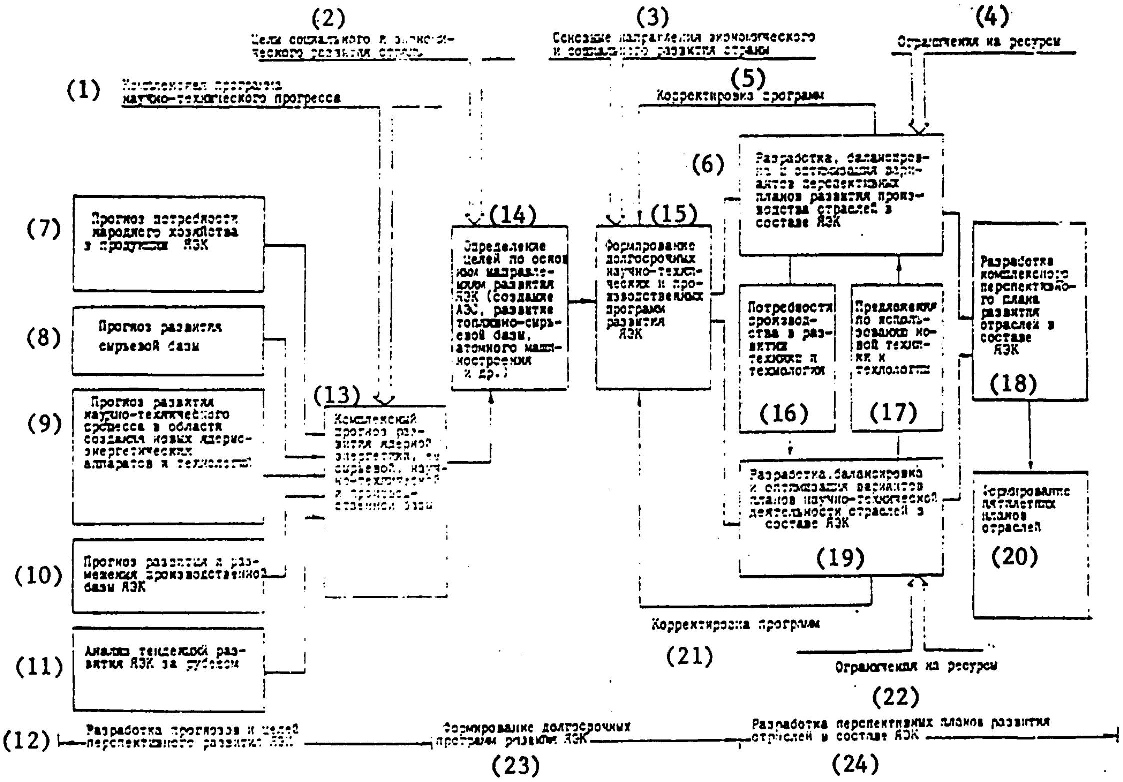

Figure 2. Overall Structure of a System for the Long-Range Developmental Planning of a Nuclear Power Complex

Key:
1. Joint program of scientific and technical progress
2. Goals of the country's social and economic development
3. Basic directions for the country's economic and social development
4. Limitations on resources
5. Program adjustment
6. Formulation, balancing and optimization of alternative long-range plans for the development of industrial production within the nuclear power complex
7. Forecast of economic requirements for the output of the nuclear power complex
8. Forecast for the development of the raw materials base
9. Forecast for the development of scientific and technical progress in the creation of new nuclear power equipment and technology
10. Forecast for the development and situation of the nuclear power complex's production base
11. Analysis of foreign trends in the development of the nuclear power complex
12. Formulation of forecasts and goals in the long-range development of the nuclear power complex

Figure 2. Key (con'd.)

13. Integrated forecast for the development of the nuclear power industry and its raw-material, scientific-technical and industrial base
14. Determination of goals according to the basic directions for the development of the nuclear power complex (the creation of AES's, development of the fuel and raw-material base, nuclear equipment construction, etc.)
15. Formation of long-term scientific-technical and industrial programs for the development of the nuclear power complex
16. Industry requirements for the development of equipment and technology
17. Proposals for the utilization of new equipment and technology
18. Formulation of an integrated long-range plan for development of industries within the nuclear power complex
19. Formulation, balancing and optimization of alternative plans for scientific-technical activity in industries within the nuclear power complex
20. Formulation of five-year plans for industry
21. Program adjustment
22. Limitations on resources
23. Formulation of long-term programs for the development of the nuclear power complex
24. Formulation of long-range plans for the development of industries within the nuclear power complex

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3. Vlasov, Ye. P., Tyurin, Yu. A., "The Study of Methodological Questions and the SOPOT Man-Machine System for the Forecasting and Optimal Planning of the Development of the CEMA Member-Nation Fuel and Power Complex (Based on the Example of the Nuclear Power Complex)," International Scientific Coordinating Conference on the Problem of Improving the Control System for the Development of the CEMA Member-Nation Fuel and Power Complex, Moscow, 1-3 December 1980.

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CZECHOSLOVAKIA

REACTOR SIMULATION PROGRAM RESULTS SUMMARIZED

Prague JADERNA ENERGIE in Slovak No 12, 1981 pp 428-433

[Article by Ivan Kinka, Energoprojekt, Prague; Rostislav Pernica, Institute of Nuclear Research, Rez; Jozef Misak, Research Institute of Nuclear Power Stations, Jaslovske Bohunice; and Bedrich Hermansky, Faculty of Nuclear Science and Physical Engineering, Prague: "Evaluation of Results of Test Runs of the REPA1D, VVER-D, SICHTA and DYN79 Programs: Part II. Summary of Results"]

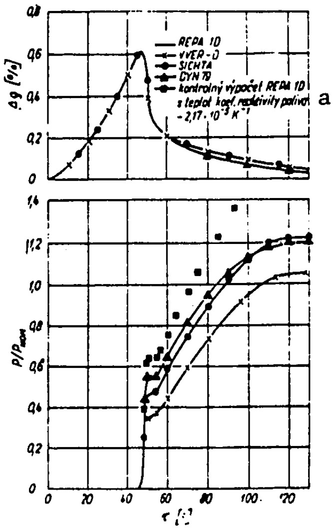
[Text] The first part of this article gave a concise description of the programs tested (REPA1D, VVER-D, SICHTA and DYN79) and discussed the formulation of the simulation problems and the input data. This second part is devoted to the computation results and evaluation of the individual programs. The most important parameters that were monitored are presented in figures and tables.

5. Results of Individual Simulation Runs

In addition to the results presented in this article, a considerably greater amount of information can be obtained from references 5-11, which report the capabilities of the individual programs on the basis of practical results. The relative deviations given in the tables are always calculated relative to the lowest value obtained.

5.1. Uncontrolled Removal of Control Rod Groups at Zero Reactor Power

The course of the process as determined by the individual programs is summarized by the selected parameters given in Figs. 1a-1c. Because the results were obtained taking the programs in pairs, i.e., REPA1D with VVER-D and SICHTA with DYN79, it was quite apparent that the reason for the considerable differences in the results for these two pairs was the fuel-reactivity coefficients, which were temperature-dependent in the first pair and constant in the second. In spite of this evident fact, we conducted an extra control computation with the REPA1D program using a constant fuel-reactivity coefficient of $-2.17 \cdot 10^{-5}$ deg^{-1}, which in absolute terms is somewhat lower than that used in the SICHTA and DYN79 programs. The curve of power as a function of time for this case, shown in Fig. 1, also indicates the effect of reactivity coefficients on the process.



Key: a. Control computation with REPA1D with temperature coefficient of reactivity equal to $-2.17 \cdot 10^{-5}$ deg^{-1}

Fig. 1a. Uncontrolled removal of control rod group, zero reactor power: reactivity and relative power as functions of time (P_{NOM}--nominal power).

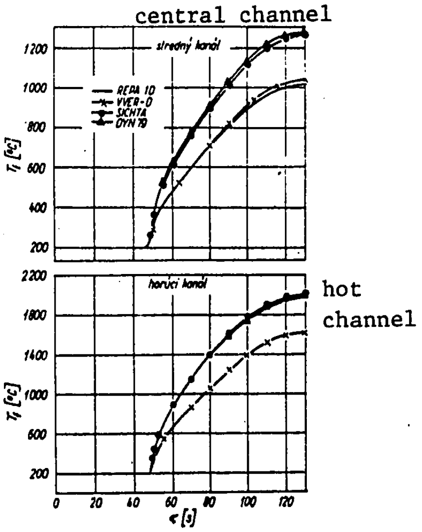


Fig. 1b. Uncontrolled removal of control rod group, zero reactor power: maximum fuel temperature in central and hot channels as function of time.

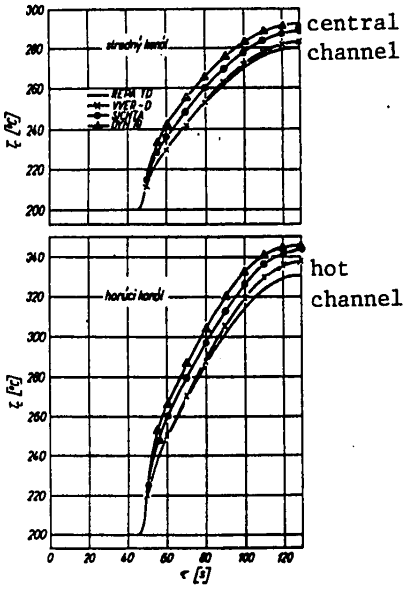


Fig. 1c. Uncontrolled removal of control rod group, zero reactor power: maximum temperature of inner surface of cladding for hot and central channels as a function of time.

It is worth noting again that the interpretation of "power" is slightly different in the SICHTA program than in the others: in the SICHTA program the "thermal power" figure takes account of the quantity of heat liberated by fission products, while the neutron-flux density obtained from this program is approximately in agreement with the interpretation of "power" in the other programs.

Table 1 surveys the extreme parameters obtained with all four programs. For completeness we also give the largest absolute differences obtained in our results, including the case in which the reactivity coefficient was altered [REPA1D program]:

--relative power, 0.185;
--maximum total reactivity, 0.004%;
--maximum fuel temperature, 396°C;
--maximum temperature of inner surface of cladding, 14.7°C;
--outlet temperature of coolant, 12°C.

Table 1. Comparison of extreme values obtained for uncontrolled removal of control rod group at zero initial reactor power. ST--central channel; HOR--hot channel. Meaning of numerical values: parameter value, time at which attained (sec), relative deviation (%).

Parameter a	kanál b	REPAID	VVER-D	SICHTA	DYN79
výkon reaktora, P/P_{NOM} (vztiahnutý k nominálnemu) c	—	1,05 133 0	1,05 140 0	1,235 150 17,6	1,20 120 14,3
max. hodnota celkovej reaktivity $\Delta\varrho$ [%] d	—	0,617 46,6 0,65	0,613 46,7 0	0,615 46,6 0,33	0,615 46,7 0,33
maximálna teplota paliva [°C] T_f e	ST	1020 133 0	1041 140 2,06	1281 150 25,6	1275 130 25,0
	HOR	1609 133 0	1636 140 1,7	2005 150 24,6	1980 130 23,0
maximálna teplota vnútorného povrchu pokrytia T_c [°C] f	ST	280,7 133 0	284,2 140 1,2	290 150 3,3	282 130 0,5
	HOR	331,3 133 0	339 140 2,3	346 150 4,4	346 130 4,4
maximum výstupnej teploty chladiva [°C] g	ST	239 133 1,3	239,1 140 1,3	246 150 4,2	236 130 0
	HOR	263,5 133 0,96	263,8 140 1,07	273 150 4,6	261 130 0

Key:

a. Parameter
b. Channel
c. Reactor power P/P_{NOM} (relative to nominal power)
d. Maximum total reactivity $\Delta\rho$ (%)
e. Maximum fuel temperature T_f (°C)
f. Maximum temperature T_c of inner surface of cladding (°C)
g. Maximum exit temperature of coolant (°C)

5.2. Ejection of Control Rod at Nominal Reactor Power

The graph of the parameters in question over time is presented in Figs. 2a-2d, and the extreme values obtained are given in Table 2. At the power peak, which in this case is produced almost exclusively by the kinetic equations, there are only extremely small discrepancies: the lower value from the SICHTA program results from the interpretation of "thermal power" already described. If we take the neutron-flux density in the SICHTA program as the power, we obtain a peak value of 2.07. The greatest discrepancies are in temperature, particularly on the inner surface of the cladding, where the heat-transfer equations and the thermophysical parameters of the cladding which were used may have been responsible.

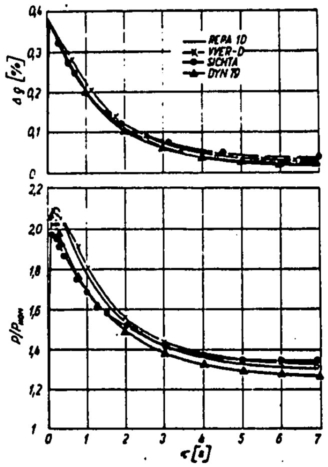


Fig. 2a. Ejection of control rod at nominal reactor power: reactivity and relative power as functions of time.

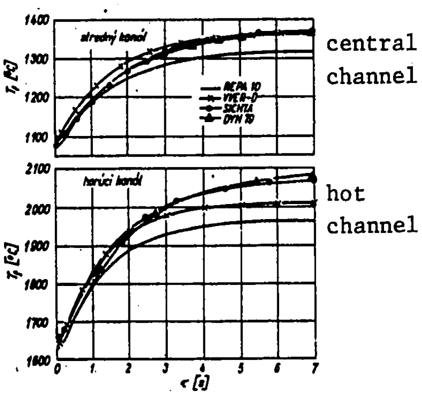


Fig. 2b. Ejection of control rod at nominal reactor power: maximum fuel temperature in central and hot channels as function of time.

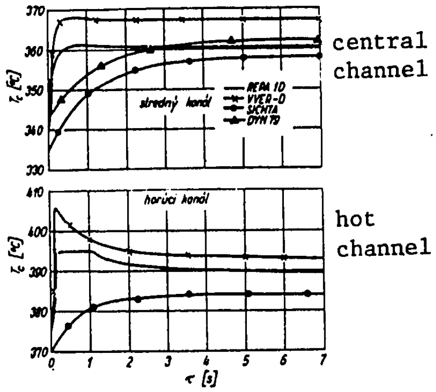


Fig. 2c. Ejection of control rod at nominal reactor power: maximum temperature on inner surface of cladding of central and hot channels as a function of time.

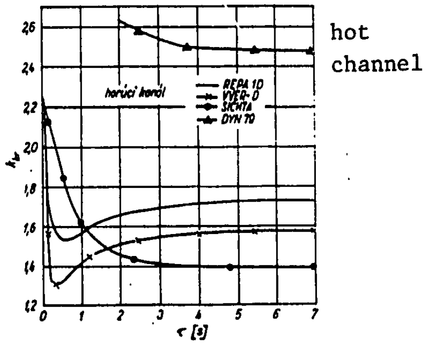


Fig. 2d. Ejection of control rod at nominal reactor power: critical temperature ratio in hot channel as function of time.

Table 2. Comparison of extreme values achieved in ejection of control rod at rated initial reactor power. ST--central channel; HOR--hot channel. Meaning of numerical values: parameter value, time at which attained (sec), relative deviation (%).

Parameter a	kanál b	REPAID	VVER-D	SICHTA	DYN79
výkon reaktora, P/P_{NOM} (vztiahnutý k nominálnemu) c	—	2.102 0,2 6.6	2,092 0,13 6.1	1.971 0.13 0	2,07 0,13 5.0
maximálna hodnota celkovej reaktivity $\Delta\varrho$ [%] d	—	0,37 0,1 1,4	0,37 0,1 1,4	0,365 0,1 0	0,37 0,1 1,4
maximálna teplota paliva T_f [°C] e	ST	1320 7 0	1370 7 3,8	1384 25 4,8	1365 7 3,4
	HOR	1970 7 0	2010 7 2,0	2078 11,2 5,5	2090 7 6,1
maximálna teplota vnútorného povrchu pokrytia T_c [°C] f	ST	361 0.75 0,5	368 0.64 2.4	359.2 25 0	362 7 0,8
	HOR	395 0,75 2,7	406 0,16 5.6	384,5 7 0	—
maximum výstupnej teploty chladiva [°C] g	ST	310 3,9 0,3	311 4,45 0,6	311 9 0.6	309 7 0
	HOR	326,3 0,43 0	326,3 0,22 0	326.3 0,9 0	326,3 1 0
minimálna hodnota kritického tepelného pomeru k_{kr} h	HOR	1.54 0,43 17,6	1,31 0,28 0	1,378 10,5 5.2	2.48 5 89,3

Key:

a. Parameter
b. Channel
c. Reactor power P/P_{NOM} (relative to nominal power)
d. Maximum total reactivity $\Delta\rho$ (%)
e. Maximum fuel temperature T_f (°C)
f. Maximum temperature T_c of inner surface of cladding (°C)
g. Maximum exit temperature of coolant (°C)
h. Minimum critical temperature ratio k_{kr}

In the case of the critical temperature ratio no benefit is gained from comparing DYN79 with the other programs, because the equations used differ considerably (Bezrukov equations vs Osmachkin equations). In addition, in this situation the VVER-D program's more precise description of the hydrodynamic ratios in the channels has a pronounced effect on the results.

In this case, we obtained the following largest absolute differences in the values of the parameters monitored:

--relative power, 0.131 (owing to interpretation of power in SICHTA program);
--maximum total reactivity, 0.005%;
--maximum fuel temperature, 120°C;
--maximum temperature of inner surface of cladding, 21.5°C;
--exit temperature of coolant, 2°C (apparently as a result of boiling in the hot channel);
--critical temperature ratio, 0.23 (Osmachkin equations only).

5.3. Leakage of Cold Water Into Core

The qualitative difference between this process and those described above is that the output temperature of the coolant and the mass flow change over time and the change in reactivity is produced by the reactivity coefficient of the coolant.

The dispersion of the results obtained, particularly between SICHTA and the REPA1D and VVER-D pair, is partly explained by the fuel-reactivity coefficients and partly by the heat-transfer coefficient of the crack. The most notable differences between the DYN79 program and the others--since they show up even at time τ = 0--are apparently produced by the heat-transfer coefficient of the crack. The power peak in the SICHTA program, with a neutron-flux density of 1.375, is considerably lower than that obtained from the VVER-D and REPA1D programs.

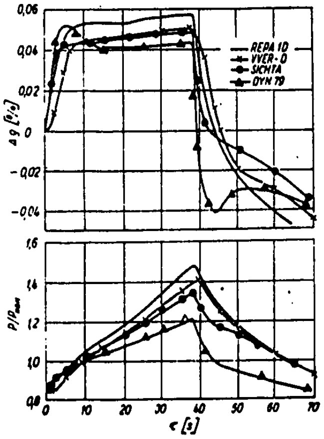


Fig. 3a. Leakage of cold water into core: reactivity and relative power as functions of time.

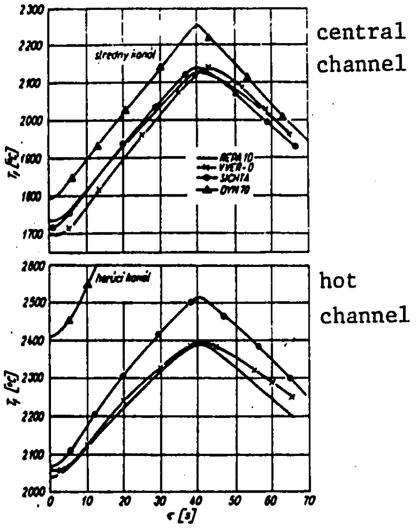
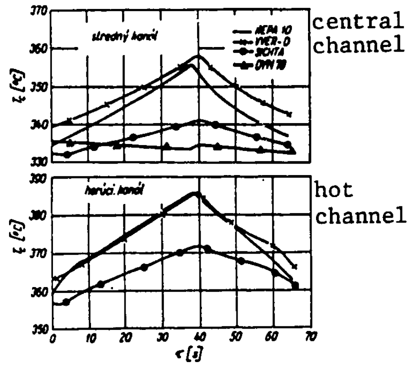


Fig. 3b. Leakage of cold water into core: maximum fuel temperature in central and hot channels as function of time.



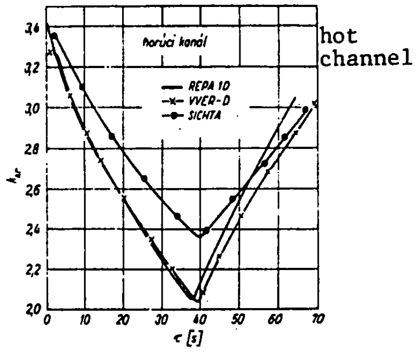


Fig. 3c. Leakage of cold water into core: maximum temperature on inner surface of cladding of central and hot channels as function of time.

Fig. 3d. Leakage of cold water into core: critical temperature ratio in hot channel as function of time.

Table 3. Comparisons of extreme values obtained for leakage of cold water into core at 5/6 of nominal power at beginning of process: ST--central channel; HOR--hot channel. Meaning of numerical values: parameter value, time at which attained (sec), relative deviation (%)

Parameter a	kanál b	REPAID	VVER-D	SICHTA	DYN79
výkon reaktora P/P_{NOM} (vztiahnuté k nominálnemu) c	—	1,48 38,2 22,3	1,405 38,9 16,1	1,335 37,9 10,3	1,21 38 0
maximálna hodnota celkovej reaktivity $\Delta\varrho$ [%] d	—	0,057 30,7 32,6	0,051 37,4 18,6	0,049 35,4 14,0	0,043 37,5 0
maximálna teplota paliva T_f [°C] e	ST	2129 40,7 0	2141 43,4 0,56	2145 39,6 0,75	2255 40 5,9
	HOR	2390 40,2 0	2398 41,9 0,33	2512 39,7 5,1	2750 26 15,1
maximálna teplota vnútorného povrchu pokrytia T_c [°C] f	ST	356 38,2 6,1	358 38,9 6,7	341,3 39,9 1,7	335,5 0 0
	HOR	386 38,2 3,5	386 38,9 3,5	372,8 39,2 0	—
maximum výstupnej teploty chladiva [°C] g	ST	301 0 —	301 0 —	302 0 —	299 0 —
	HOR	317 38,2 1,93	318 38,9 2,3	313 0 0,6	311 0 0
minimálna hodnota kritického tepolného pomoru k_{kr} h	HOR	2,05 38,2 0,49	2,04 38,9 0	2,36 39,9 15,7	5,25 42,5 157,4

Key:

- a. Parameter
- b. Channel
- c. Reactor power P/P_{NOM} (relative to nominal power)
- d. Maximum total reactivity $\Delta\rho$ (%)
- e. Maximum fuel temperature T_f (°C)
- f. Maximum temperature T_c of inner surface of cladding (°C)
- g. Maximum exit temperature of coolant (°C)
- h. Minimum critical temperature ratio k_{kr}

The change of parameters over time is shown in Figs. 3a-3d, and the extreme values obtained are presented in Table 3. On the basis of the results obtained, in this type of situation we may expect the following dispersion of the extreme values of the parameters monitored for the different programs (including the effect of the input data, namely the coefficient of reactivity and heat-transfer coefficient of the crack):

--relative power, 0.27;
--maximum total reactivity, 0.014%;
--maximum fuel temperature, 360°C;
--maximum temperature of inner surface of cladding, 22.5°C;
--exit temperature of coolant, 7°C.

5.4. Uncontrolled Removal of Group of Control Rods at Nominal Reactor Power

The last of the test runs is the classical emergency situation, in which limiting values may be approached (or exceeded), even in the central channel. Accordingly, it is in this case that physical models of the individual programs have the most evident effect. This case is, moreover, the most suitable one for comparing the REPA1D, VVER-D and SICHTA programs, because a temperature-dependent fuel-reactivity coefficient was also used here for the SICHTA program. The results are most readily apparent from the power curves of Fig. 4, which are virtually identical for almost the entire simulation period of the programs. The constant fuel-reactivity coefficient value again had an evident effect in the DYN79 program. The abrupt increase in the temperature of the inner surface of the cladding of the hot channel given by the REPA1D program results from the transition to film boiling, while the VVER-D program uses equations for nucleate boiling even after the critical neutron-flux density is exceeded. The temperature discrepancies are small on the whole and mostly reflect differences in the thermophysical parameters and heat transfer modes used. It is noteworthy that the SICHTA program gives a relative power figure (represented by the neutron-flux density) of 2.38 at time $\tau = 60$ seconds.

The variation of the values monitored over time is given in Figs. 4a-4d; the extremes at time $\tau = 60$ are given in Table 4. The time $\tau = 60$ sec is merely an arbitrary reference point, since some of the programs followed the process farther.

On the basis of our results, in this type of situation we may expect about the following dispersion in extreme values (including inconsistency of input parameters):

--relative power, 0.49;
--maximum total reactivity, 0.034%;
--maximum fuel temperature, 184°C;
--maximum temperature of inner surface of cladding, 146°C;
--exit dryness of coolant (hot channel), 30.7%;
--minimum critical temperature ratio, 0.27 (excluding DYN79 and hot channel).

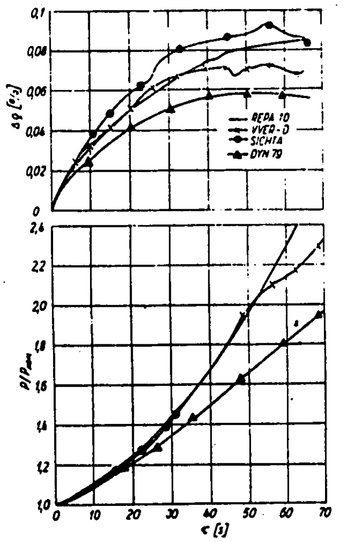


Fig. 4a. Uncontrolled removal of control rod group at nominal reactor power: reactivity and relative power as functions of time.

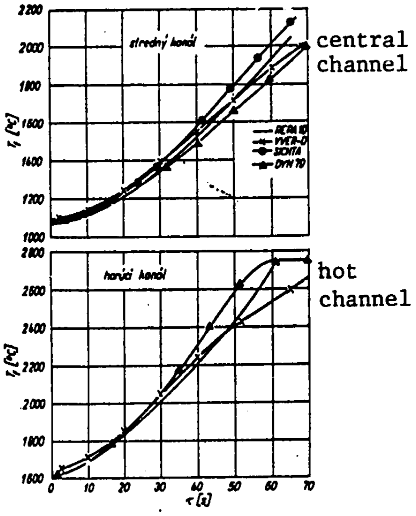


Fig. 4b. Uncontrolled removal of control rod group at nominal reactor power: maximum fuel temperature in central and hot channels as function of time.

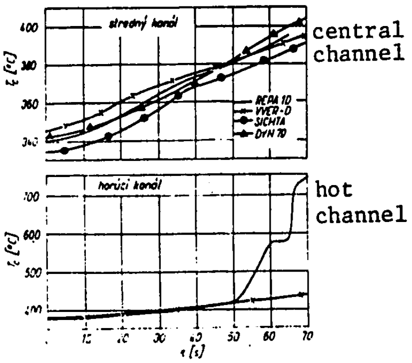


Fig. 4c. Uncontrolled removal of control rod group at nominal reactor power: maximum temperature on inner surface of cladding for central and hot channels as function of time.

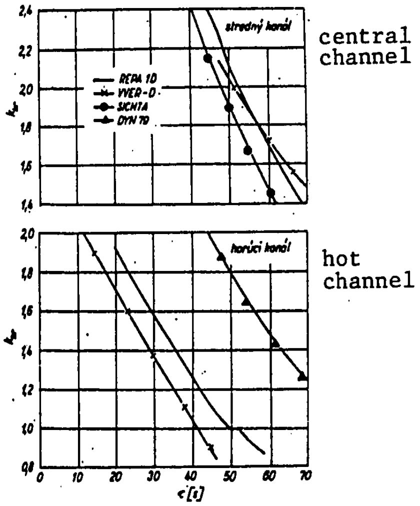


Fig. 4d. Uncontrolled removal of control rod group at nominal reactor power: critical temperature ratio for central and hot channels as function of time.

Table 4. Comparison of extreme values achieved for uncontrolled removal of control rod group at nominal initial reactor power. ST--central channel; HOR--hot channel. Meaning of numerical values: parameter value, relative deviation (%). Reference time is τ = 60 sec for all cases except for reactivity and exit temperature of coolant, where the time of attainment is shown in parentheses.

Parameter a	kanál b	REPAID	VVER-D	SICHTA	DYN79
výkon reaktora P/P_{NOM} (vztiahnuté k nominálnemu) c	—	2,30 27,1	2,14 18,2	2,29 26,5	1,81 0
maximálna hodnota celkovej reaktivity $\Delta\varrho$ [%] d	—	0,085 (65) 44,1	0,073 (55) 23,7	0,093 (55) 3,4	0,059 (52) 0
maximálna teplota paliva T_f [°C] e	ST	1938 5,6	1890 2,9	2020 10,0	1836 0
	HOR	2705 4,8	2580 0	—	2750 6,6
maximálna teplota vnútorného povrchu pokrytia T_c [°C] f	ST	390 1,8	380 1,6	383 0	393 2,6
	HOR	575 34,0	429 0	—	—
maximum výstupnej teploty chladiva [°C] g	ST	326,3 (52)	326,3 (49)	326,3 (53)	326,3 (73)
	HOR	326,3 (20)	326,3 (7)	—	326,3 (20,8)
výstupná suchosť chladiva [%] h	HOR	23,2 105	42,0 272	—	11,3 0
minimálna hodnota kritického tepelného pomeru k_{kr} i	ST	1,69 16,6	1,72 18,6	1,45 0	3,714 156
	HOR	0,85 70,0	0,5 0	—	3,71 642,0

Key:
- a. Parameter
- b. Channel
- c. Reactor P/P_{NOM} (relative to nominal power)
- d. Maximum total reactivity $\Delta\rho$ (%)
- e. Maximum fuel temperature T_f (°C)
- f. Maximum temperature T_c of inner surface of cladding (°C)
- g. Maximum exit temperature of coolant (°C)
- h. Exit dryness of coolant (%)
- i. Minimum critical temperature ratio k_{kr}

6. Conclusions

On the basis of the results from our test runs, we may state that all of the programs produce equivalent results in the solution of the basic sets of equations, and that the discrepancies result by and large from the capabilities of the programs (selectability of input parameters) and from physical characteristics built into them. Other than the reactivity values used, the decisive figures affecting the process over time are the fuel-reactivity coefficients, for which the temperature dependency of the Doppler effect generally cannot be ignored. The maximum fuel temperatures are affected not only by the development of power over time, but also to a substantial degree by the heat-transfer coefficient of the crack. The equations for heat transfer to the coolant have a quite prominent effect in the region of heat transfer to cooled liquid, while certain discrepancies appear in the equations after the beginning of boiling. The critical heat-flux density is highly dependent on the equations used, with the Osmachkin equations giving considerably lower values. The results for crisis heat-transfer conditions are greatly affected by the precision with which the pressure and flow ratios in the core are described. In spite of these differences, which increase in such a way that they could be eliminated (or reduced) without great difficulty, each of the programs tested may be considered capable of performing computations for safety documentation, since we are dealing with a point model of the reactor and since the redistribution of coolant flow between channels under different temperature loads can be ignored.

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