APPLICATION OF NUCLEAR STEAM SUPPLY SYSTEM OF NIKA SERIES FOR SEAWATER DESALINATION

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Abstract

The nuclear steam supply system (NSSS) NIKA has been developed on the basis of experience available in Russia in designing, construction and operation of similar systems for ship propulsion reactors. Major systems and equipment of the NSSS are designed to take advantage of the proven engineering features and to meet Russian regulations, standards, practices and up-to-date safety philosophy. NSSS NIKA-75 has been designed for arrangement on barge. This permits to manufacture all NSSS equipment at the factory and to deliver it to the exploitation area ready for operation. NSSS NIKA-300 is designed for erection on land. It seems very interesting to use those NSSS types for seawater desalination.

The main technical solutions, concept statements, technical and economical evaluations of NIKA series nuclear steam supply systems for seawater desalination are described.

Reactor design

The NSSS of the NIKA series use the integral type reactor (see Fig. 1,2) that provides space-saving arrangement of equipment and media characterized of their own or induced radioactivity and enhances reliability of the plant as a whole due to minimization of pipes operated under primary coolant pressure. Materials, parameters and media characteristics chosen for NSSS are broadly used in Russian and worldwide practice of reactor designing. In combination with proven engineering features for major equipment (e.g., core, steam generator etc.) such an approach enables to make use of extensive research experience in thermal hydraulics, properties of structural materials, corrosion, water chemistry and so on, thus eliminating the need for any further research studies and only focusing on the minimum scope of R&D activities required for development of the pilot plant.

The core has a negative reactivity coefficient in the whole range of coolant parameters variation. This feature ensures core self-control capability and is beneficial in terms of safety.

To compensate for reactivity change, burnable poison rods and control rods assembled in groups are provided. Each group is equipped with an individual drive mechanism based on linear step motor for NIKA-300 and on rotary step motor for NIKA-75. Drive mechanisms of such design have shown high-reliability performance during long-term operation at the power and ship reactors.

Primary coolant circulation is provided by means of main circulation pumps (MCP) installed on the reactor cover and fitted with sealed electrical drive mechanisms (2 MCP for NIKA-75 and 4 MCP for NIKA-300). The pump prototypes underwent long-term operation under similar conditions and demonstrated a high reliability. Simplicity of the design of the primary coolant path ensures high flow rate of natural circulation sufficient for trouble-free core cooldown in case of loss of power to MCP.

In-vessel once-through helical steam generator made of titanium alloys is incorporated in NSSS. The steam generator consists of cassettes (16 for NIKA-75 and 12 for NIKA-300), each of them comprising 6 modules. From the secondary side, the steam generator is divided into 4 sections. In case of leaks in heat transfer surface, these sections can be isolated on power operation using special isolating valves. Steam generators of similar design have been in operation for many years and demonstrated a high reliability of their performance.

All primary equipment do not require on-load maintenance and therefore can be placed in the strong leaktight safeguard vessel which is non-attended while on power operation. Under the design basis accidents radioactivity release from the primary circuit will be mitigated in the safeguard vessel.

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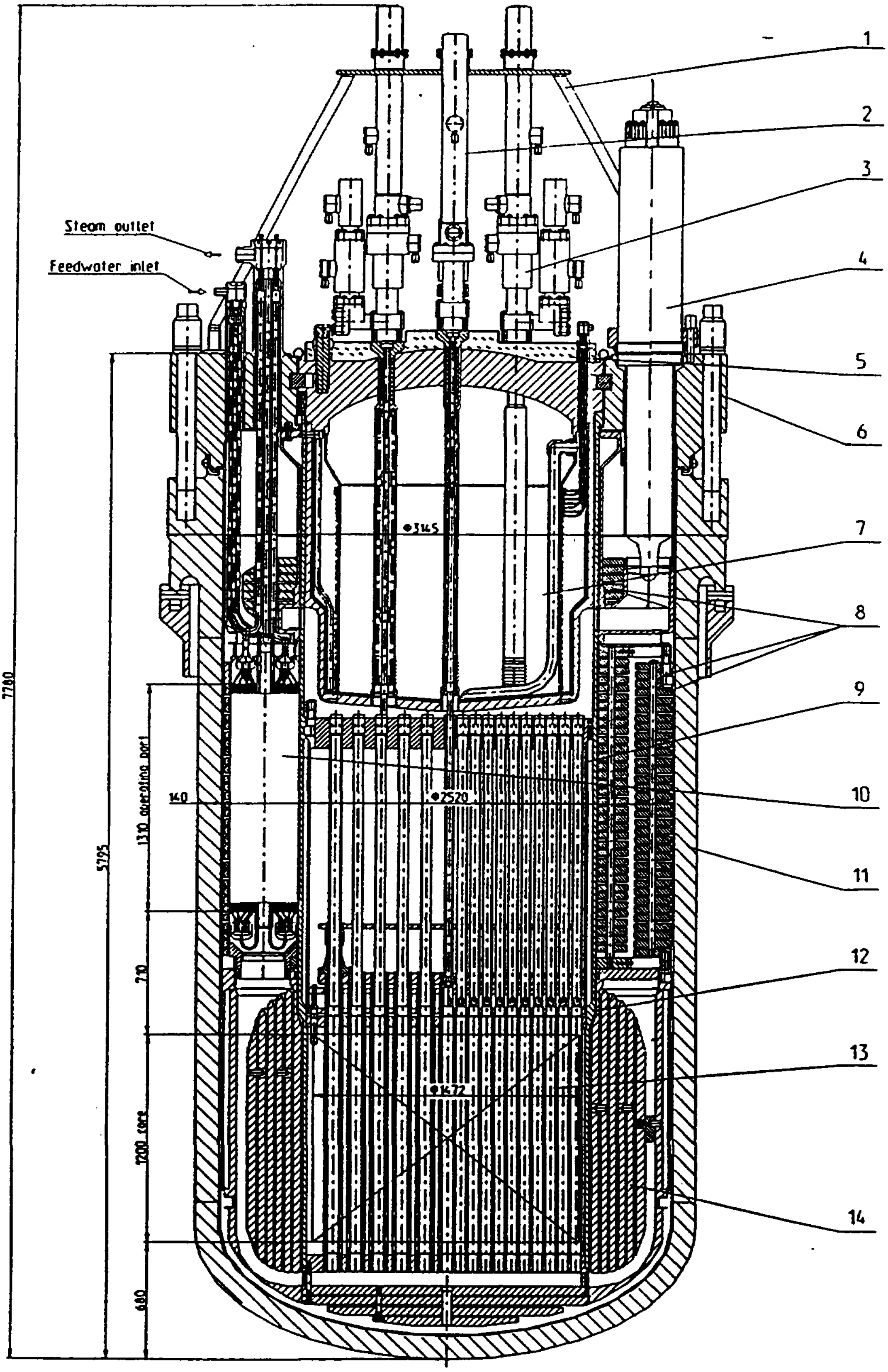

Fig. 1. General view of the reactor principle for NIKA-75.

1 - drive fastening frame; 2 - shim rod group (SG) drive (7 pieces); 3 - SG-EP drive (9 pieces); 4 - MCP (2 pieces); 5 - thermal insulation; 6 - annular cover; 7 - pressurizer; 8 - displacers; 9 - metalwork with control rod clusters; 10 - SG; 11 - vessel; 12 - core barrel; 13 - fuel assembly (379 pieces); 14 - side screen.

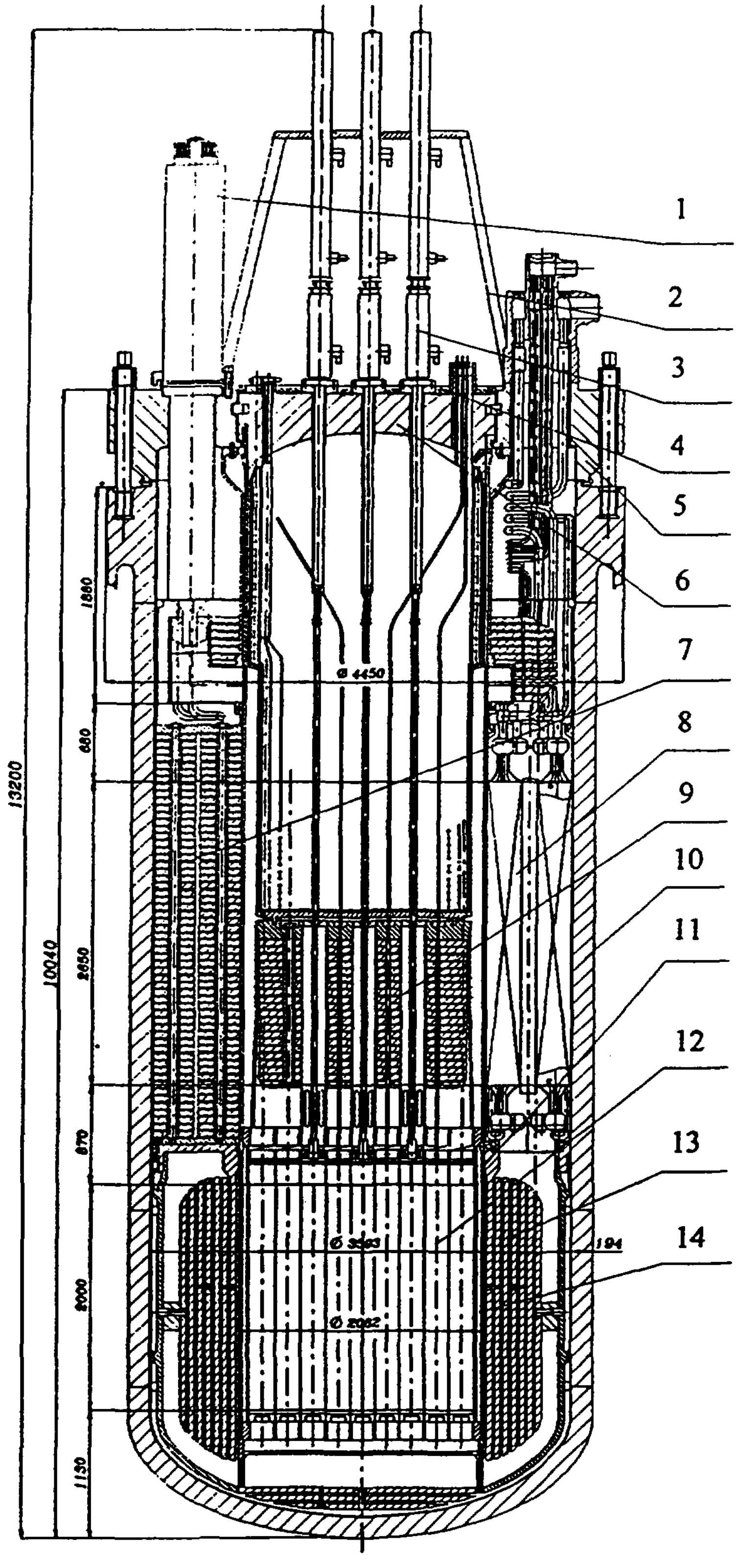

Fig. 2. General view of the reactor NIKA-300.

1 - MSP (4 pieces); 2 - drive fastening frame; 3 - shim rods drive (25 pieces); 4 - thermal insulation; 5 - annular cover; 6 - pressurizer; 7 - displacers; 8 - steam generator; 9 - protection tubes unit; 10 - vessel; 11 - core barrel; 12 - fuel assembly (57 pieces); 13 - side screen; 14 - partition.

To provide capabilities for retention of radioactive substances in case of beyond design basis events, NSSS is housed in the strong leaktight containment accessible for the purposes of equipment repair and maintenance.

NSSS will provide long-term and steady operation in the power range from 20 to 100% of full power irrespective of the number of power changes.

To prevent progression of the emergency situations into the accidents and to minimize their possible consequences, NSSS is fitted with a number of engineered safety features, namely: systems for emergency cooldown; emergency core cooling system (ECCS); reactor ,safeguard vessel and containment overpressure protection system; independent equipment cooling system and severe accident mitigation system. All the above systems are passive, i.e. they will come into action without the intervention of an operator and control systems.

In developing NSSS design concepts for medium size CNPP, primary consideration was given to ensuring operational reliability and safety of such a plant at all stages of its life cycle. It was assumed that the CNPP would meet safety requirements if its radiation effects on personnel, public and environment under normal operation and during design-basis accidents are significantly lower or at least are found within the specified limits of personnel and public exposure and standards for permissible releases and content of radioactive substances in the environment. In case of beyond design-basis accidents, such effects should be limited as much as possible.

The main design features adopted for the NSSS are aimed at ruling out any core damage beyond the specified limits of safe operation during all design-basis accidents without personnel's intervention or external assistance for no less than 72 hours. This problem should be also solved for the beyond design-basis accidents caused by any initiating events considered credited and accompanied by postulated failures of electrical control systems and active systems which rely on power supply for their operation.

Essential to a high safety level of NSSS is implementation of the following:

1. **Use of an integral water-cooled water-moderated reactor** with elaborated inherent self-protection and the following unique features:

- negative power and temperature coefficients of reactivity throughout the operating range of parameters;
- high flow rate of natural circulation of the coolant which affords effective cooling and heat removal from the core during design-basis and beyond design-basis accidents;
- high heat storage capacity of metal structures and a great mass of coolant in the reactor which result in a relatively slow progression of transients during accidents with upset heat removal from the core.

2. **Defense-in-depth provided as a system of barriers** to off-site release of ionizing radiation and radioactive uranium fission products, and implementation of a package of engineering and organizational measures to protect these barriers against internal and external impacts.

The system of safety barriers includes:

- fuel matrix;
- fuel cladding;
- leaktight primary circuit;
- safeguard vessel;
- isolating valves;
- containment.

3. **Use of passive systems and safety features** whose operation is based on natural processes with no need for external power supply.

Such systems include:

- CPS drives design which provides assured insertion of control rods into the core by gravity and drop springs;
- interlocks in CPS drives which prevent unauthorized withdrawal of control rods from the core during commissioning, maintenance and repair;
- passive systems for emergency residual heat removal;

- a safeguard vessel which ensures core coverage with coolant and heat removal under all severe accidents, and guarantees radioactivity confinement in case of a leak in the primary circuit;
- a containment which limits radioactive releases in case of the safeguard vessel opening and under beyond design-basis accidents;
- iron and water biological shielding which apart from its direct functions, serves as bubbler tanks to hold cooling water supply as well as to remove heat from the reactor vessel to avoid its melt through under a postulated beyond design-basis accident with core dryout.
- molten core catcher(only for NIKA-300).

4. Safety systems reliability

High reliability of the safety systems is provided owing to the following philosophy:

- the systems are passive, i.e. they need as few as possible special actuators to initiate them, if any at all:
- the safety systems and features are diverse which are based on the different principles of system operation (for example, electromechanical CPS drives and liquid poison injection system are used for emergency shutdown);
- the safety systems are redundant (for instance, the redundancy of the shutdown system is 2 × 100% , of ECCS - 4 × 50%, etc.)
- systems and equipment are subjected to periodic in-service inspection or continuous monitoring.

5. Protection against human errors

The design safety philosophy pays much attention to prevention, or mitigation of the consequences of human errors and deliberate actions meant to render the nuclear plant inoperative.

These measures include:

- minimum scope of on-load maintenance and repair of major systems and equipment;
- design solutions and organizational measures intended to prevent an unauthorized access to NSSS systems (all vital systems are housed in the safeguard vessel or containment);
- use of systems satisfying as far as possible the safe failure principle (the system component failures transfer the system to safety function performance or in a safe state);
- passive safety systems and features are used so that they do not have to be actuated with special means (a safeguard vessel, a containment) or they can be brought into action in a passive way (emergency cooldown systems, ECCS, system for reducing overpressure in the safeguard vessel and containment);
- reliable control systems are used, which minimize or disable erroneous operator's actions, with personnel given no access to interlocks and setpoints;
- operator support systems are provided, which rapidly assess the plant state and suggest optimum control actions;
- special hardware is used for training and maintaining the skills and knowledge of the operating and maintenance personnel, in particular, a simulator is used to drill operating personnel in various situations, including emergencies.

6. Protection against external impacts

Building structures of the power plant shall guarantee undamaged state of the NSSS containment and safeguard vessel under such external impacts as typhoon, hurricane, heavy snow and icing as well as in case of helicopter or airplane crash onto the CNPP.

Technical and economic estimation of seawater desalination

The technical and economic estimation has been carried out with the use of spreadsheets IAEA COGENERATION/DESALINATION COST MODEL [1], which, using the technical and economic indexes of nuclear plants, allows to calculate basic performances of nuclear water desalination plants. As initial data it was accepted specific cost of power plant construction 2000 $/kWe for NIKA-3000 and 3500 $/kWe for NIKA-75. The net electical power is 15 MW(e) for NIKA-75 and 100 MW(e) for

NIKA-300. The other initial data were taken from the spreadsheet [1], for example, specific water plant cost 1440 $\$/(\mathrm{m}^3/\mathrm{day})$ for multi-effect distillation, 1125 $\$/(\mathrm{m}^3/\mathrm{day})$ for reverse osmosis; interest rate 8 %. Some results of calculations are submitted in Table 2 and Fig.3-5.

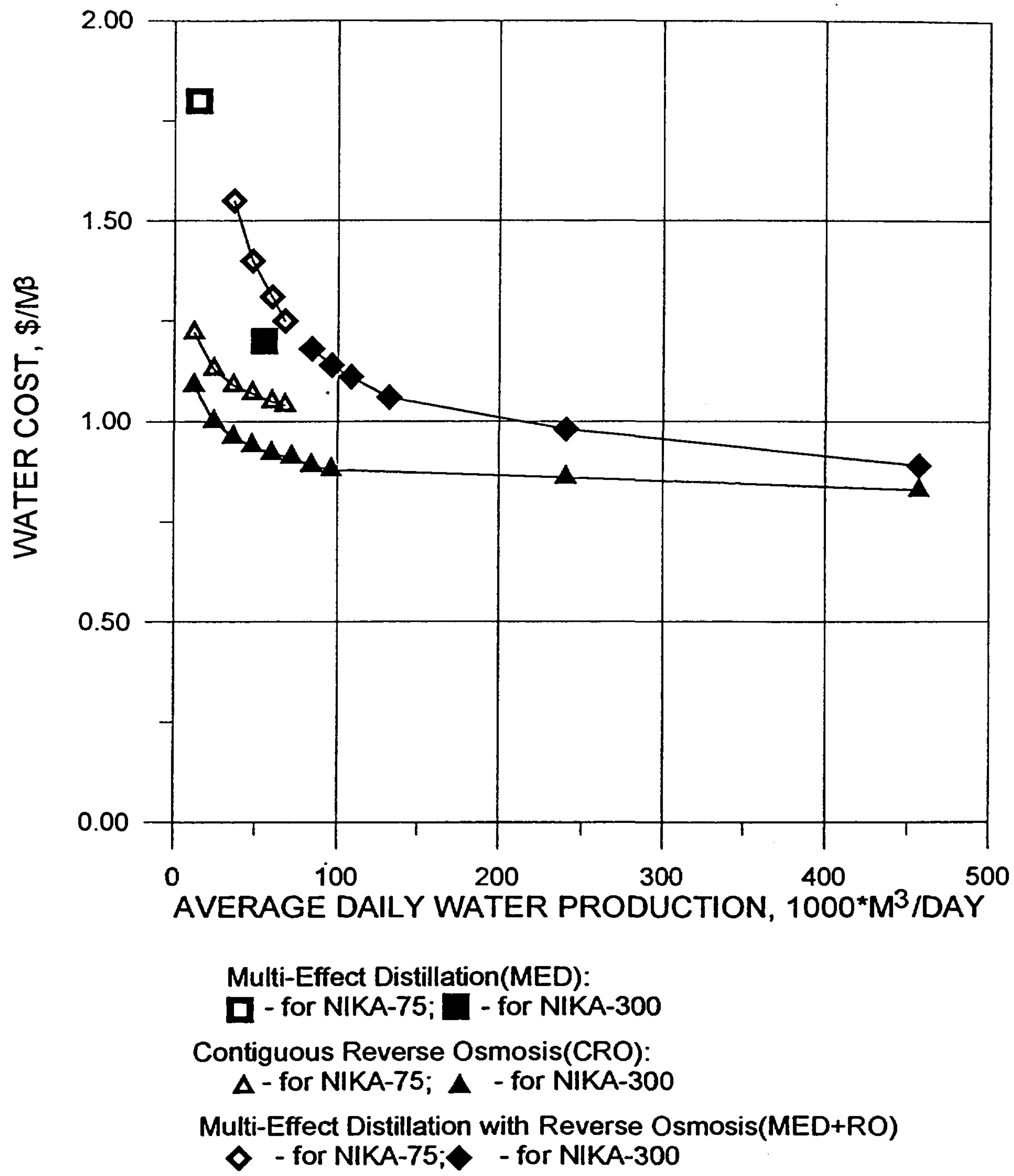

Fig. 3. Water cost versus water production.

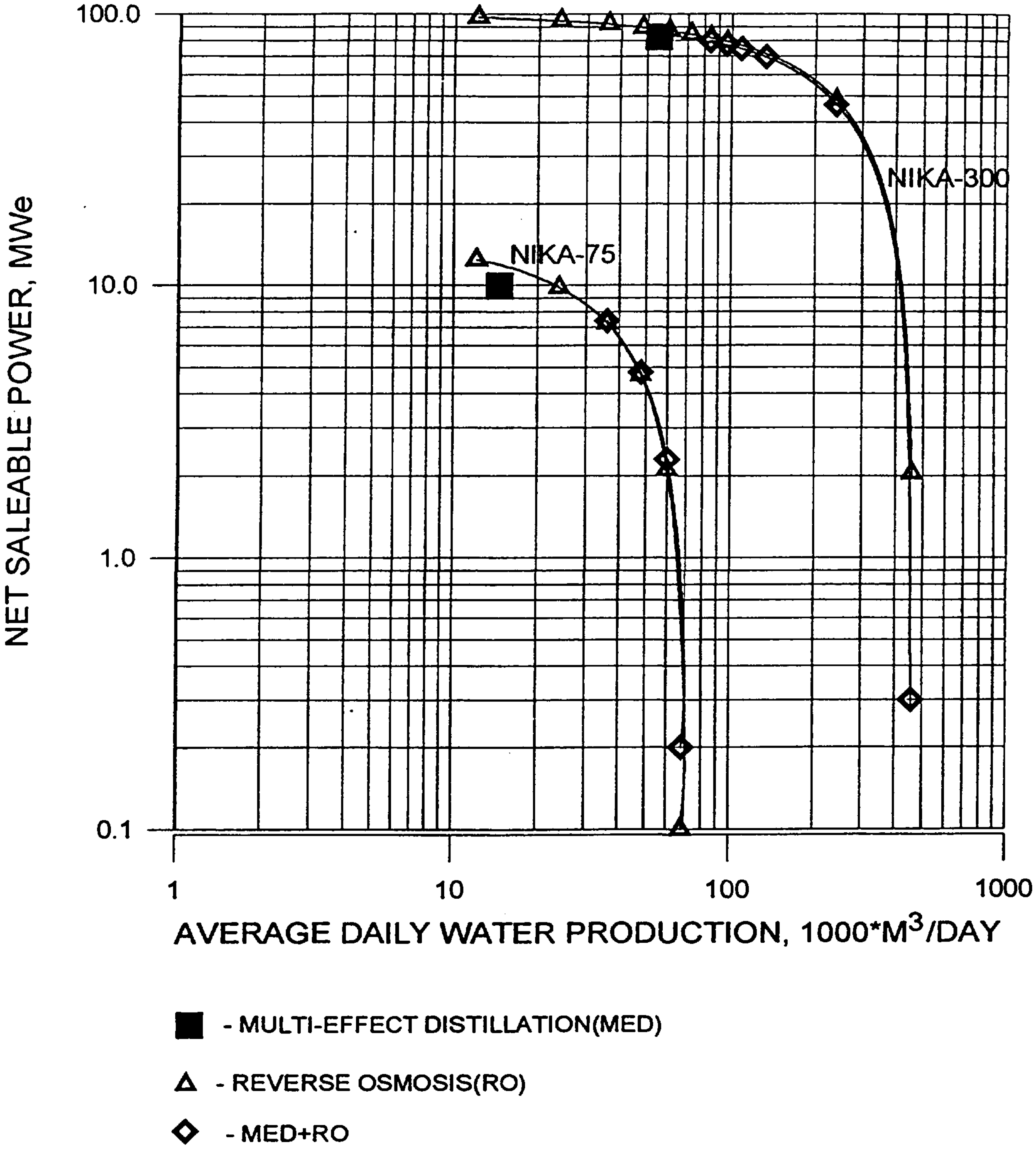

Fig. 4. Net saleable power versus water production

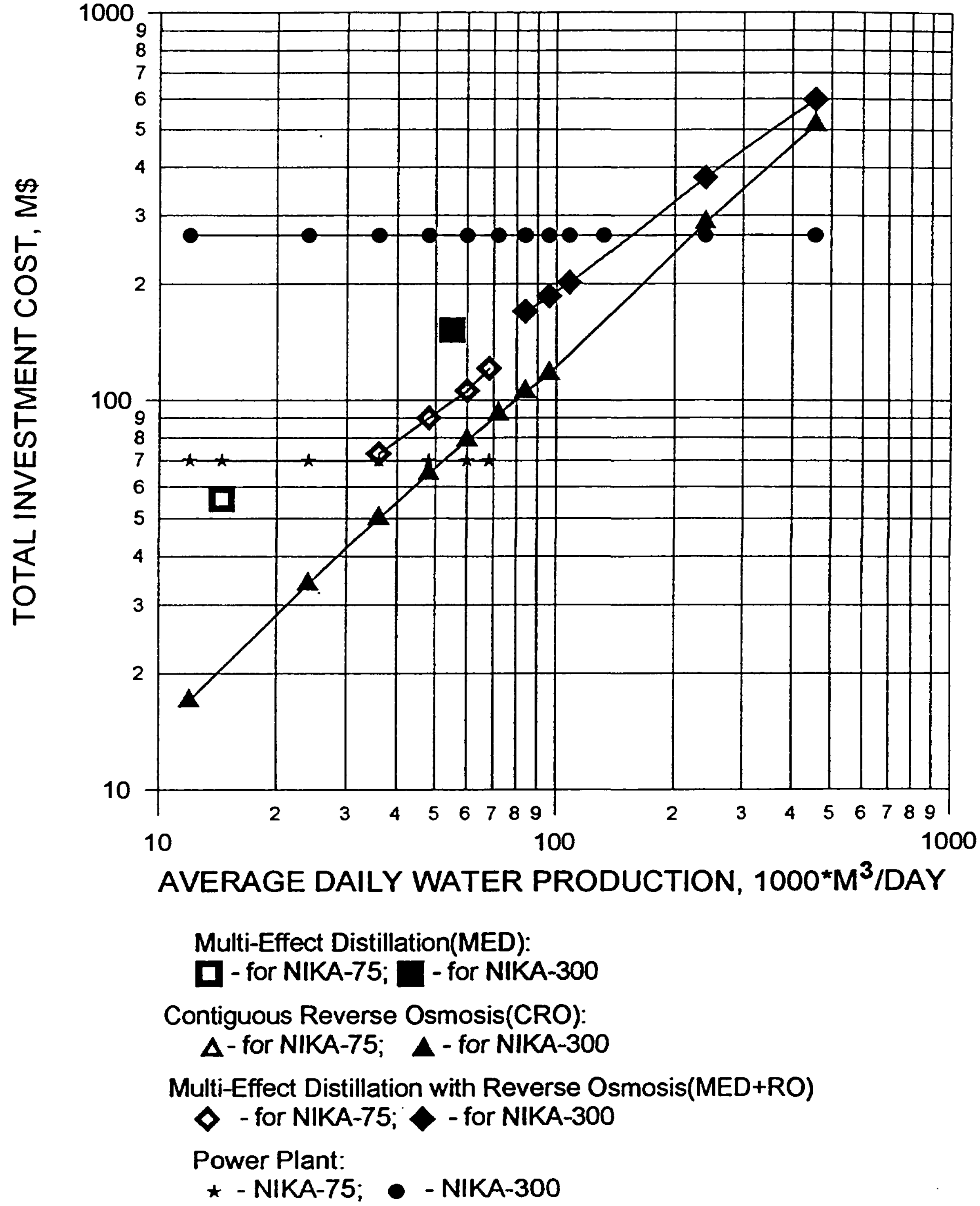

Fig. 5. Total investment cost versus water production.

TABLE 1. DESIGN CHARACTERISTICS OF NSSS

No.	Characteristic	Unit	NIKA-75	NIKA-300
1	Thermal power of the core	MWth	75	330
2	Net electrical power	MWe	15	100
3	Steam generating capacity	kg/s	27	152.7
4	Superheated steam pressure	MPa	3.0	3.0
5	Superheated steam temperature, at least	°C	274	274
6	Feed water temperature	°C	60	180
7	Nominal pressure in primary circuit	MPa	15	15
8	Primary coolant temperature while operating at nominal power:			
	at core inlet	°C	260	270
	at core outlet		300	310
9	Operating range of power change	% N_{nom}	20 ÷ 100	20 ÷ 100
10	Effective campaign of core	years	5	4
11	Core – water-water type:			
	equivalent diameter	mm	1500	1800
	height	mm	1200	2000
	Fuel:			
	U^{235} enrichment	%	19.7	5
	U^{235} load	kg	260	681
	specific power rating	kW/l	36.7	62.6
12	Service life	years	30	60

In Fig.3 dependence of fresh water cost on average daily water production is presented. The water cost decreases with increase of water production and can compete to cost of water produced by fossil cogeneration plants.

In Fig.4 dependence of net saleable electrical power on fresh water production is presented. It is visible, that electrical capacity of power plant is enough for water desalination over a wide range of fresh water flowrates. The net saleable electrical energy can be used for supply of other consumers.

In Fig.5 dependence of total investment cost on water production is presented. For water plants the size of cost increases with increase of water production.

TABLE 2

Characteristic and water plant type	**Unit**	**NIKA-75**	**NIKA-300**
Average daily fresh water production			
Multi-Effect Distillation(MED)	$1000*m^3$/day	14.5	54.95
Stand-Alone Reverse Osmoses(SARO)		12...60	12 ...456
Contiguous Reverse Osmoses(CRO)		12.09...60.42	12.09...459
Hybrid (MED + RO)		36.04...72	84...457
Fresh water cost			
MED	$\$/m^3$	1.8	1.2
SARO		1.12...1.38	0.86...1.25
CRO		1.05...1.22	0.83...1.09
MED+RO		1.25...1.55	0.89...1.18
Total investment cost			
Power Plant	M$	70	267
MED		54	152
SARO		24...93	24...553
CRO		17...79	17...514
MED+RO		73...121	170...598

Conclusion

New generation NSSS of NIKA series has been developed in accordance with modern safety requirements. One possible use of those NSSS is seawater desalination. Power plants based on NSSS of NIKA series can be coupled with water production plants of various types for potable water production from 12000 to 72000 m^3/day for NIKA-75 and from 12000 to 459000 m^3/day for NIKA-300. The water production costs could compete economically.

REFERENCE

[1] Technical and Economic Evaluation of Potable Water Production Through Desalination of Seawater by Using Nuclear Energy and Other Means, International Atomic Energy Agency, IAEA-TECDOC-666, Vienna, September 1992.

PART V

SIMULATION OF NUCLEAR REACTORS