	FSV	THTR	MODULAR HTGR
OVERALL HEIGHT M(FT)	16.8 (55.2)	18.6 (61)	26.5 (86.8)
OVERALL DIAMETER, M(FT)	1.7 (5.6)	2 (6.6)	4.2 (13.7)
NUMBER PER REACTOR	12	6	1
APPROX. WEIGHT METRIC TONS (US TONS)	22.7 (25)	65 (71.6)	466.3 (514)
THERMAL RATING / UNIT, MW	28.5	128	350
HELIUM INLET TEMP, °C(F)	775 (1427)	750 (1382)	685.6 (1266)
STEAM OUTLET TEMP, °C(F)	540.6(1005)	550 (1022)	540.6 (1005)
STEAM PRESSURE, bar (PSIA)	173.2 (2512)	186.2(2700)	173.4 (2515)
NUMBER OF TUBE CIRCUITS	18/54	40/80	350

COMPARISON OF HTGR STEAM GENERATORS

FIG. 7.

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MAIN CHARACTERISTICS AND DESIGN FEATURES OF STEAM GENERATORS FOR VG-400 PLANT

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Abstract

The description of a steam generator for the VG-400 plant performed in two variants depending on a heat-exchange surface arrangement: one-bundle coil and module-cassette construction is given.

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1. Main Requirements for Steam Generator

In developing a detail design of a steam generator for a pilot-commercial installation with VG-400 reactor the analysis and generalization of both home and available foreign experience of designing and operation of steam generators for NPI with HTGR was accomplished. In NPP with HTGR operating now in the world use of steam generators which apply as a heat surface tube bundles from multiple helical concentrically located cylindrical coils with a large arrangement diameter. A manufacture of similar tube bundles requires a special complicated equipment and long production cycle [1]. For the installation with VG-400 reactor steam generators are developed with an other scheme of heat-exchange surface which is to be described below. Main requirements for the VG-400 installation steam generator design are formulated as follows:

- The design reliability ensuring a long operation of steam generator (up to 100.000 hours) in all operating conditions of the VG-400 installation including accident ones and the installation safety as a whole.

- Technological effectiveness of the steam generator design, making it possible to master its manufacture without development and creation of unique instrumentation and equipment.
- Transportability of steam generator making it possible to transport it to a mounting site by a railway, water or automobile transport.
- The high air-tightness and compactness of configuration.
- The acceptable cost price.

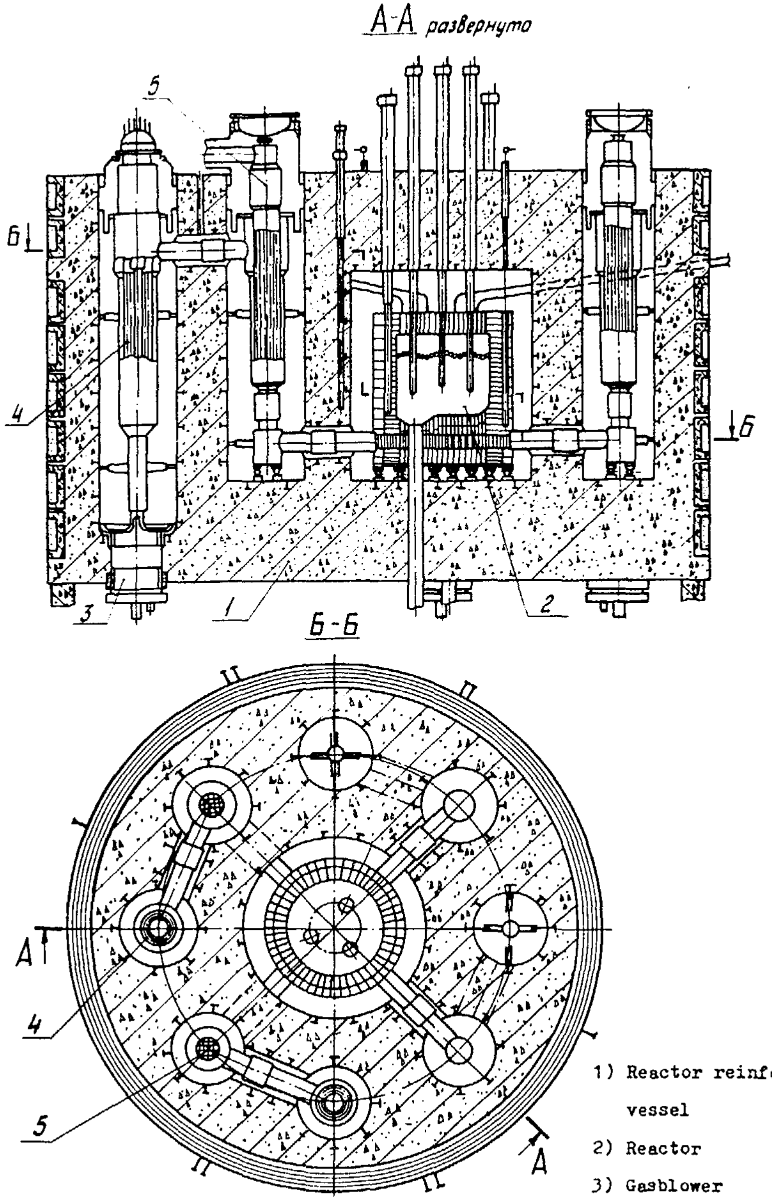
2. Steam generator main characteristics

In the VG-400 installation are provided 4 parallel operating cooling circuits every of which includes a high-temperature intermediate heat exchanger "He-He" located behind it, a steam generator and a gas blower (see Fig.1). Depending on NPI VG-400 operating conditions the steam generator should provide the following technical data:

Characteristics of steam generator (SG) for NPI VG-400

	Denomination of parameters (characteristics)	Nominal values
1	2	3
1.	Thermal power, MW	180.5
2.	Helium temperature at the input into SG, °C	750
3.	Helium temperature at the output from SG, °C	342
4.	Helium flow rate, kg/sec	85
5.	Helium pressure, working, MPa (bar)	4,9 (50)
6.	Hydraulic losses over primary circuit, MPa (bar) not over	0,029(0.3)
7.	Steam-generating capacity, t/h (kg/sec)	248(68,9)
8.	Over-heated steam temperature, °C	540
9.	Overheated steam pressure, MPa (bar)	17,2(175)
10.	Feed water temperature, °C	180
11.	Hydraulic losses over II circuit including external steam and water headers, MPa (bar), not over	4,12(42)
12.	Minimum permissible load over steady operation conditions	10%
13.	Overall dimensions:	
	- external diameter over heat-exchanged surface, mm	2245
	- steam generator total length, m	18,35
14.	Steam generator mass	
	- in dry state	88(76,8)*
	- in the state filled according to II category	90,4 (80,2)*

*) The data are given for the coil variant of steam generators.



1) Reactor reinforced concrete vessel
2) Reactor
3) Gasblower
4) Steam generator
5) Heat-exchanger

FIG. 1.

3. Steam generator design

3.1. The steam generator design scheme.

In developing the steam generator design a number of various schemes was considered. The scheme of direct-current steam generator without an intermediate overheating of steam, with a counter-flow scheme of coolant motion, was admitted optimal. The motion of the heating coolant (helium) - from the top - to the bottom in an intertube space, the heated coolant (water-steam) - from the bottom to the top in an intra-tube space.

Dropping of the steam intermediate overheating reduces slightly the installation thermal efficiency as a whole, but simplifies the SG construction, decreases an amount of steam penetration pipes through its force cover, increasing the steam generator cover reliability as a whole.

The chosen steam-generator type - is the vertically-housing - tube heat-exchanger placed in the box of the installation's concrete vessel.

3.2. The substantiation of taken design solutions and the description of a steam generator construction.

For the pilot VG-400 plant it was decided to carry on development and experimental mastering of steam generators for two variants of a heat-exchange surface manufacture - one-bundle coil and the module one from fine - coils with a small winding radius ($R_{wind} \geq 1.75$ dt.) [2]. In this case the condition of complete interchangeability of the both steam generator variants over the rest construction characteristics and specifications was laid down.

From the results of experimental mastering one can come to a decision on manufacture of either variant of a steam generator for the VG-400 plant, not eliminating the possibility to produce the both variants.

The steam generator (Fig.2) comprises the sectional heat-exchange surface of heating-up, coil thermal expansion compensator pipes of feeding water and steam sections placed over the surface, the external cowling covering the heat-exchange surface and the compensators, and the force elliptical cover connected to the external cowling.

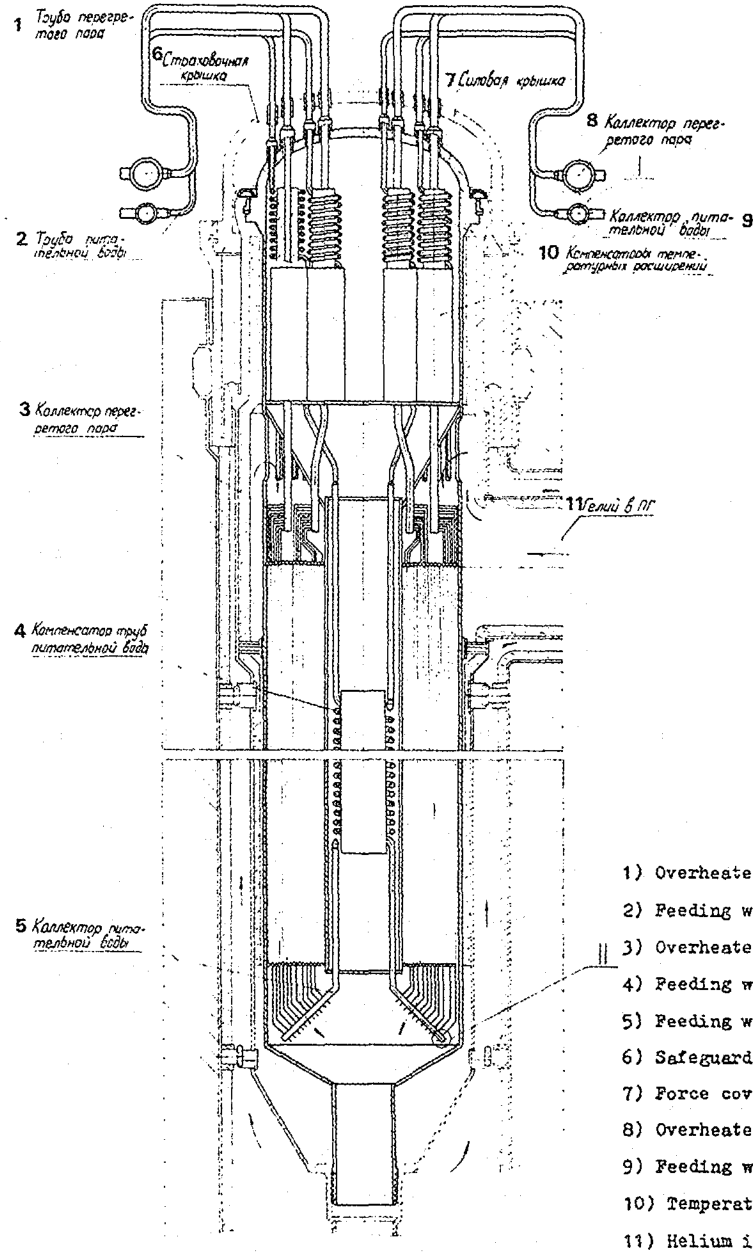
In the lower part of SG there is an outlet connection which, when mounted the steam generator, enters over a slide fit into the gas blower accepting duct.

The steam generator force cover is attached to the body flange by means of a key joint (similarly to buoyant) and is sealed off by welding a torus compensator.

Above the steam generator force cap there is located a safeguard cover secured in its flange by the key joint too but without sealing off by the torus. Above the safeguard cover there are placed feed and discharge pipes with overheated steam of the steam generator sections, connected to corresponding external feed and steam headers.

Such a design manufacture provides seeking and damping of a leaky SG section, as well as, if necessary, dismantling and replacement of a steam generator spent service life from the reactor vessel pit.

The steam generator operates as follows. A heating coolant (helium) from HTGR with temperature of 750°C is delivered through a central connection to the steam generator and arrives at the interpipe space through inlet windows in the outside SG cowling,



1) Overheated steam pipe
2) Feeding water pipe
3) Overheated steam header
4) Feeding water tube compensator
5) Feeding water header
6) Safeguard cover
7) Force cover
8) Overheated steam header
9) Feeding water header
10) Temperature expansion compensator
11) Helium in SG

FIG. 2.

passes from the top to the bottom and giving off its warmth to the II circuit medium with temperature of 342°C enters into the blower accepting pipe.

The feed water with temperature of 180°C from external headers over feed pipes through penetrations in the force cover, feed compensators and discharge pipes, arrives at the bottom part of the heat-exchange surface. Throttling insertions are placed at the inlet of each heat-exchange pipe to provide the necessary hydrodynamic stability of SG at small loads. The overheated steam through internal outlet pipes, steam compensators and penetrations in the SG force cover is discharged to external steam headers and then to consumers.

3.3. The heat-exchange surface design for the SG coil variant.

The heat-exchange surface design is made as a tube coil consisting of 19 multi-entry cylindrical coiled pipes placed in rows around the steam generator central cowling (Fig.2).

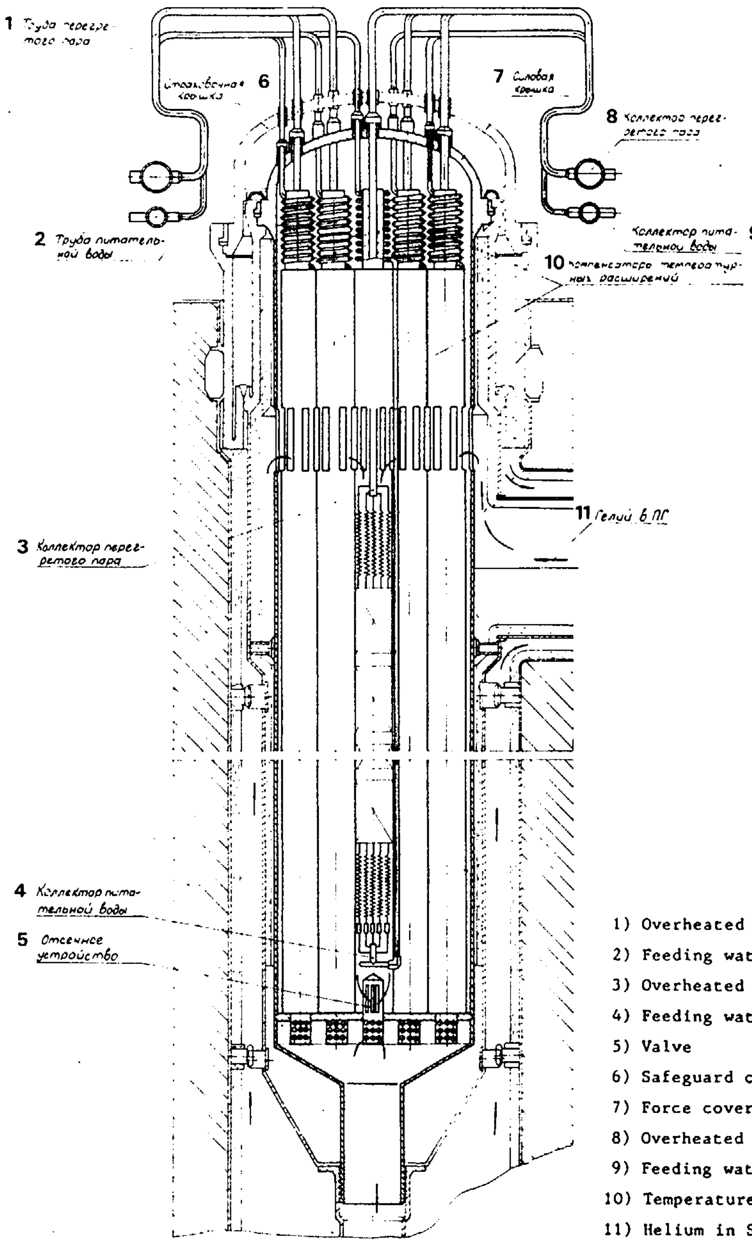
The coiled pipes are kept by the system of remote-controlled plates which are anchored to radial ribs closed on the SG external cowling. The coiled pipes are made of 20x3 mm tubes, connected in operation in parallel between themselves and joined into 18 headers both over steam and a feed water. Pipes from headers are led out through penetrations and welded to the SG force cover. The tube coil is assumed to be manufactured by the method of by turn assembly of prefabricated rows of coiled pipes with tube binding elements installed on them. In this case, lugs of remote-controlled elements of one row enter into elements of the other row, etc., ensuring fixation of coiled pipe rows with respect to each other. The erected coiled pipe rows by means of a cross-headpipe are secured between SG internal and external cowlings.

3.4. The heat-exchange surface design of the SG module variant.

The heat-exchange surface design consists of 19 identical hexahedral in cross-section cassette-modules every of which has an individual feed water supply and steam pipe discharge and is the steam generator section which can be cut off outside the SG cover over steam and fold water if in it an intercircuit leakiness will be found (Fig.3).

The cossette heat-exchange surface is made of 16 x 2.5 tubes as coiled pipes with a small winding-on radius $(\frac{d_{wind}}{d_{tube}} = 3.5\text{-}5)$, where d_{wind} is the coiled pipe diameter along its axis, d_{tube} is the external diameter of the coiled pipe tube. Seven coiled pipes welded in series in joint on their folded linear sections form a heat-exchange element. In the lower part of every heat-exchange element there is a throttling device. One-type heat-exchange elements in the cassette in amount of 19 pieces are groupied over a three-angle grid into a hexahedral cassette and joined into steam and feed headers in the upper and lower parts, respectively. The steam and feed headers are tightly secured on the cassette body. Within the cassette in its upper part there are placed compensators of linear expansion of inlet and outlet section pipes made as coiled-pipes.

To exclude a slip of hot uncooled gas from the top to the bottom at a SG plugged leaky section, a cutting device is installed in the lower part of cassette, which responds when it is heated up to the gas inlet temperature (750°C) and reduces the gas flow rate through the plugged cassette up to 10-15% as compared



1) Overheated steam pipe
2) Feeding water pipe
3) Overheated steam header
4) Feeding water tube compensator
5) Valve
6) Safeguard cover
7) Force cover
8) Overheated steam header
9) Feeding water header
10) Temperature expansion compensator
11) Helium in SG

FIG. 3.

with operating. This decreases significantly the gas heating-up in the gas blower inlet duct.

The module arrangement of heat-exchange surface, in our opinion, has a number of advantages as compared to the coil variant.

- The cassette-module being, in principle, the complete element of steam generator, can be made without appreciable expenditures in the development and manufacture of a complicated equipment.

- Times of manufacture and assembling of the heat-exchange surface are reduced in comparison with steam generators of other types.

- The experimental mastering of such cassette-modules does not involve significant difficulties and much cheaper than the SG coil variant.

One of the distinguishing features of the cassette-module are its unique arrangement possibilities - the ability on its basis to create a steam generator of practically any power and arrangement, the basic possibility of replacement of the failured module without replacement of SG as a whole, etc. This is of special interest in developing the module-integrated installations with HTGR.

The heating capacity of such modules can be within the limits of 10-15 MW.

4. Materials in use

As construction materials for steam generators use was mainly made of heat-resistant high-nickel chrome-containing materials alloyed with additives, stabilizing necessary service properties of materials and impaing their technological effectiveness.

4.1. The heat-exchange surface including internal collectors, compensators of steam and feed water - high nickel steel.

4.2. The external and internal shells of SG and remote-controlling elements - steel 03 X 16H9M2.

4.3. The force cover of SG - steel 03 X 16H9M2.

4.4. External steam and water pipes of sections and corresponding collectors - steel 12 X 18H12T.

4.5. The SG safe-guard cover - the alloyed carbon steel.

In order to reduce the net cost of steam generators, the possibility of application of other less high-temperature on economizer and evaporation sections and, as a result, with less cost of materials will be considered on the basis of results of their experimental mastering and operation.

5. Experimental mastering of steam generators [2,3]

To confirm technical solutions laid in the steam generators' design, the following complex of works is provided:

- Aerodynamic tests of tube bundles of heat-exchange surfaces, inlet and outlet sections of steam generators. In order to specify aerodynamic characteristics the following tests are performed over the gas path on full-scale and scale models (M 1:2 - M 1: 4) on aerodynamic benches of our country.

- Vibration tests of full scale fragments of the heat-exchange surface of the steam generators **of both variants** to optimize the chosen elements of remote-control.

- Heat engineering tests in order to confirm main technical data of steam generators and to determine temperature states of heat-exchange surface elements. The tests are carried out on both the elementary models of SG (thermal capacity of 300 - 500 kW) and larger models (thermal capacity of 10-12 MW).

- Mastering of reliability of steam generator elements are carried out on full-scale or large-scale models of SG units determining its operability as components of the VG-400 installation. Among these are the keyed joint of the cover with the body, the cut device of SG cassettes over gas, termination of tubes in the collector, remote-control elements, etc.

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