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HIGH TEMPERATURE TECHNOLOGICAL HEAT EXCHANGERS AND STEAM GENERATORS WITH HELICAL COIL ASSEMBLY TUBE BUNDLE

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INTRODUCTION

Analysis of thermal hydraulis characteristics of nuclear steam generators with different tube bundle arrangements and waste heat boilers for ammonia production units was performed on the base of operating experience results and research and development data.

The present report involves the obtained information. The estimations of steam generator performances and repair-ability are given. The significant temperature profile of the primary and secondary coolant flows are attributed to all steam generator designs. The intermediate mixing is found to be an effective means of temperature profile overcoming. At present the only means to provide an effective mixing in heat exchangers of the followng types: straight tubes, Field tubes, platen tubes and multibank helical coil tubes (with complicated bend distribution along their length) are section arrangements in series in conjuction with forced and natural mixing in connecting lines.

The heat exchangers with tube bundles in a from of helical coils (with small radius of coiling) are characterized by the unique possibility to from several effective mixing zones inside tube bundle along the primary coolant flow.

The tube bundle consists of undressed assemblies manufactured as one-to-three bank multipass helical coils with several strongly twisted crossbars placed between the helical coil sections along assembly length. The crossbars act as mixing intensifier and separating device simultaneously.

The experimental and theoretical computations are carried out to justify the steam generator design feasibility.

The base advantages achieved by an effective intermediate mixing coupled with the design feature (tube bundle assembly arrangement) allow to consider the proposed steam generator and heat exchanger designs for NEPPHG and NEP* as competitive ones with other designs.

I. Main features of processing heat exchangers for ammonia production units

The pilot-commercial nuclear energy technological plant for combined ammonia and electric power generation is one of variants of usage of high temperature gas cooled reactors designing in the USSR. High potential thermal energy, carried by helium coolant of intermediate circuit from nuclear reactor to ammonia production unit, is used in hydrocarbon vapour conversion and steam generation processes for hydrogen containing gas producing. The generated steam is needed for nitrogen-hydrogen mixture compressor driving (1, 2).

The layout of the steam generation system in the ammonia production unit is shown in Fig. 1.

Thee feed-water flow of 350 t/h is delivered by pump 1 through low pressure heaters 2 (heated by gas, steam condensate or nitrogen-hydrogen mixture) to deacrator 3. Then the water

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* NEPPHG - nuclear energe plant for power and heat generation.
NEP - nuclear energy plant.

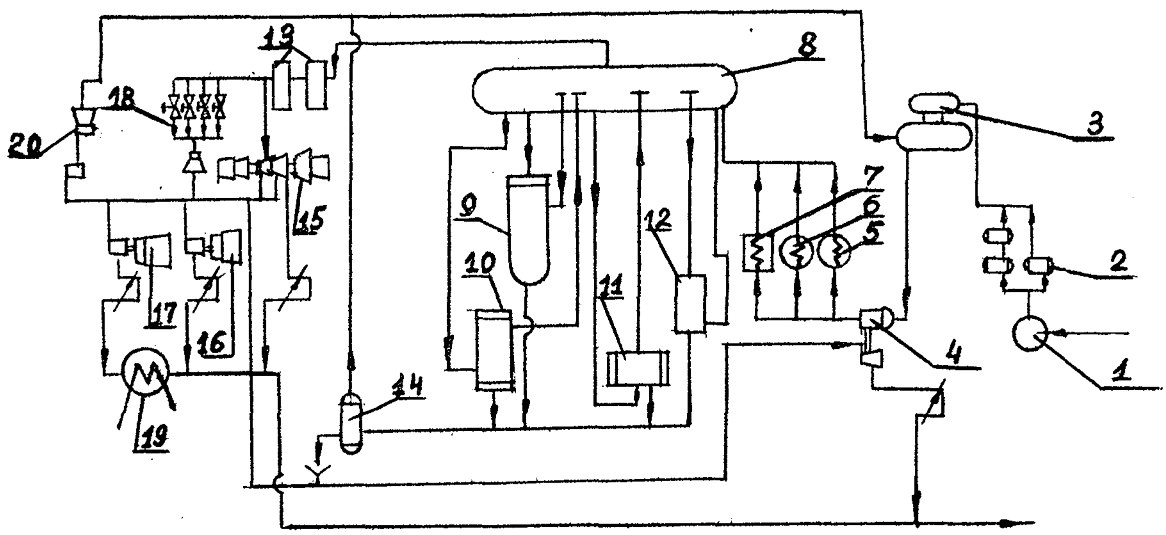

Fig 1

The steam generating schematic diagram

1 - pump; 2,5-7, - heaters; 3 - deaerator head; 4 - feed pump; 8 - steam header; 9-11 - waste-boilers (1 stage after mine methan conversion, 11 stage after carbon oxide conversion); 12-13 - helium evaporator and superheaters; 14 - secondary boiling tank; 15 - turbine for driving of gas synthesis compressor; 16-17 - condensing turbines for air, natural gas and ammonia compressor driving; 18 - the thrott ling facility; 19 - Condeser; 20 - Condensate injector.

heated to 102°C is pumped by high pressure pump 4 to high pressure heaters 5-7 (heated by converted gas, nitrogen-hydrogen and nitrogen-hydrogen-ammonia mixture). After that water heated to 250°C flows to steam header 8, from it the water, at the saturation temperature 317°C, is distributed to waste boilers 9-11. Evaporators 9-10 are located along the primary coolant flow behind the methane and carbon oxide conversion units where conversion process is followed by heat release. Evaporator 12 is heated by helium intermediate circuit. The saturated steam from steam header is supplied to superheaters 13 with helium heating. Then, the steam, superheated to 500°C, at pressure 11 MPa is delivered to turbines and is also used for technological needs.

Thus, the steam generation system in ammonia production units is equipped by the water heaters and evaporators, heated by converted gas, and evaporator and superheaters, heated by helium.

The selection of the above described equipment may be based on the available designs, used in steam generating system with fire heating or on the alternative designs, developed for electric power needs for example. Moreover it is considered at present the scope of the steam generating system modification by using once-through helium steam generators and waste heat boilers in ammonia production unit.

The operating experience of the existing ammonia production units revealed the waste boilers to be the least reliable component of steam generating system. The waste heat boiler tube bundle consists of Field tubes, heated by the converted gas with inlet/outlet temperatures 1000/600°C at pressure 3,2 MPa,Fig.2.

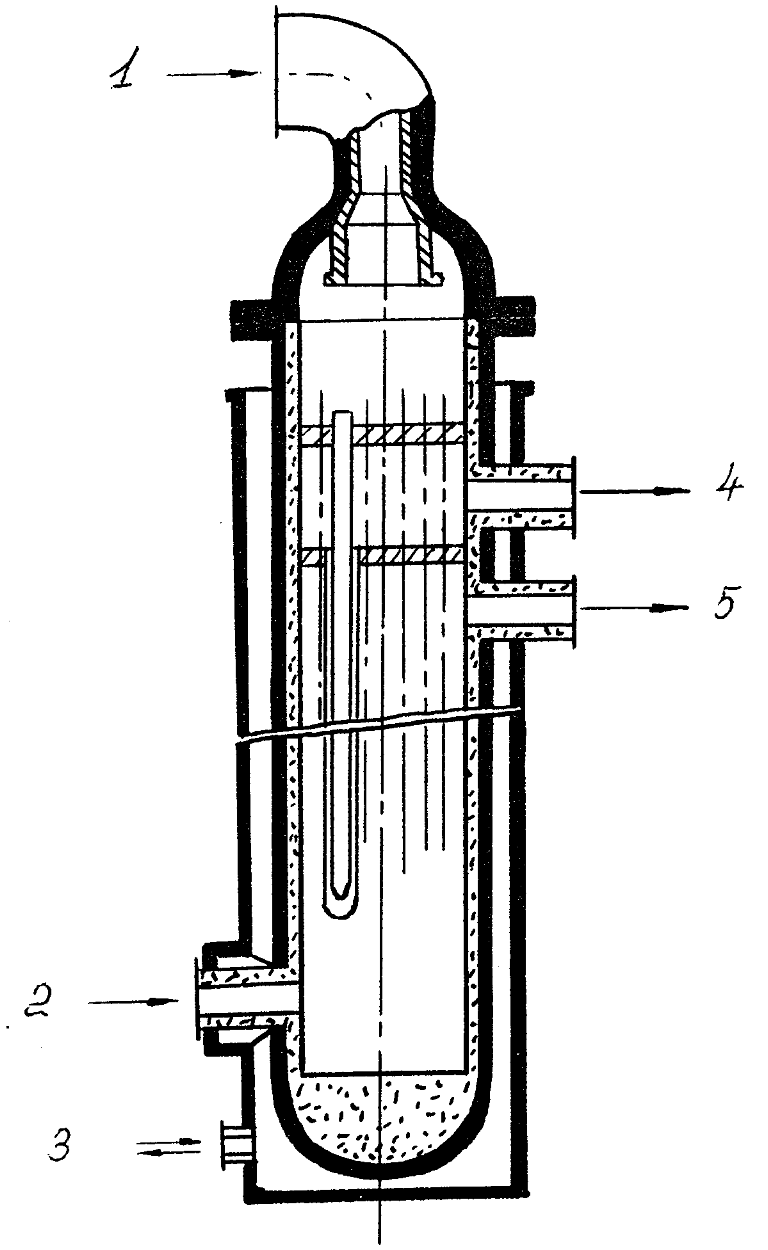

Fig 2.
Waste-boiler layout

1 - Feed water; 2 - Gas; 3 - Cooling water; 4 - Steam-water emulsion; 5 - Gas.

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Swelling and disrupture of the outer Field tubes under the tube wall overheating action was observed during the operation. It may be attributed to the nonuniform distribution of water flow through tubes and gas flow through intertube space, resulted in the separate tube overheating at high heating gas temperature.

Taking into account the shown and other disadvantages of available heat exchanger types for steam generating system, a problem is arised to develop an alternative design of heat exchangers, including the development of the new equipment with helium heating for nitrogen industry.

2. Large temperature differences through tube bundles

In foreign steam generator engineering for nuclear energy plants with sodium and gas coolants it is used preferable helical coil tube bundle (in a form of multibank multipass helical coil) instead of platen and straight ones on the base of engineering-economic considerations.

By contrast with it the tube bundles with small radius of coiling are used in the USSR. It is a forced decision and the above mentioned design is inferior in multibank helical coil one.

In this connection the necessity is arised to evaluate the promising concepts of these two steam generators designed for electric power generation and technological needs on the base of designing and research experience.

The most significant operational data and information on structural materials published in scientific works on AGR Heysham I and Hartlpool I steam generators with multibank helical coil heat exchangers (3, 4).

These steam generator heated by CO_2 (650°C and 5 MPa) are characterized by high unit power - 250 Mwt (th) and standard steam-water parameters - 157/543°C and 16,9 MPa.

The tube bundle consists of 285 helical tubes forming 19 ring banks around the central displacer. To compensate the hydraulic irregularity effect on heat exchange rate along the ring banks, a hydraulic control of feedwater flow distribution by an orifice was carried out. Steam generating tubes of economizer section are manufactured from carbon steel, the tolerable tube wall temperature is 350°C.

The evaporator section is manufactured from ferritic steel 9Cr - 1 Mo, the tolerable wall temperature is 500°C, the superheater section - from austenitic steel, the tolerable wall temperature is 650°C. An additional restriction is imposed on steam temperature of the last section. Its temperature should be more by 30°C of the saturation one for preventing water drop carry - through superheater and austenitic steel corrosive cracking.

The steam generator operating experience revealed the following: The significant temperature differences along the ring banks were observed, that was not predicted at the design stage, Fig. 3.

The temperature differences followed by the available tolerances on structural steels allow to bring the plant to output not more than 64% from rated one (Fig. 3, compare curves 1 and 2), when using the initial flow diagram of feed water dis-

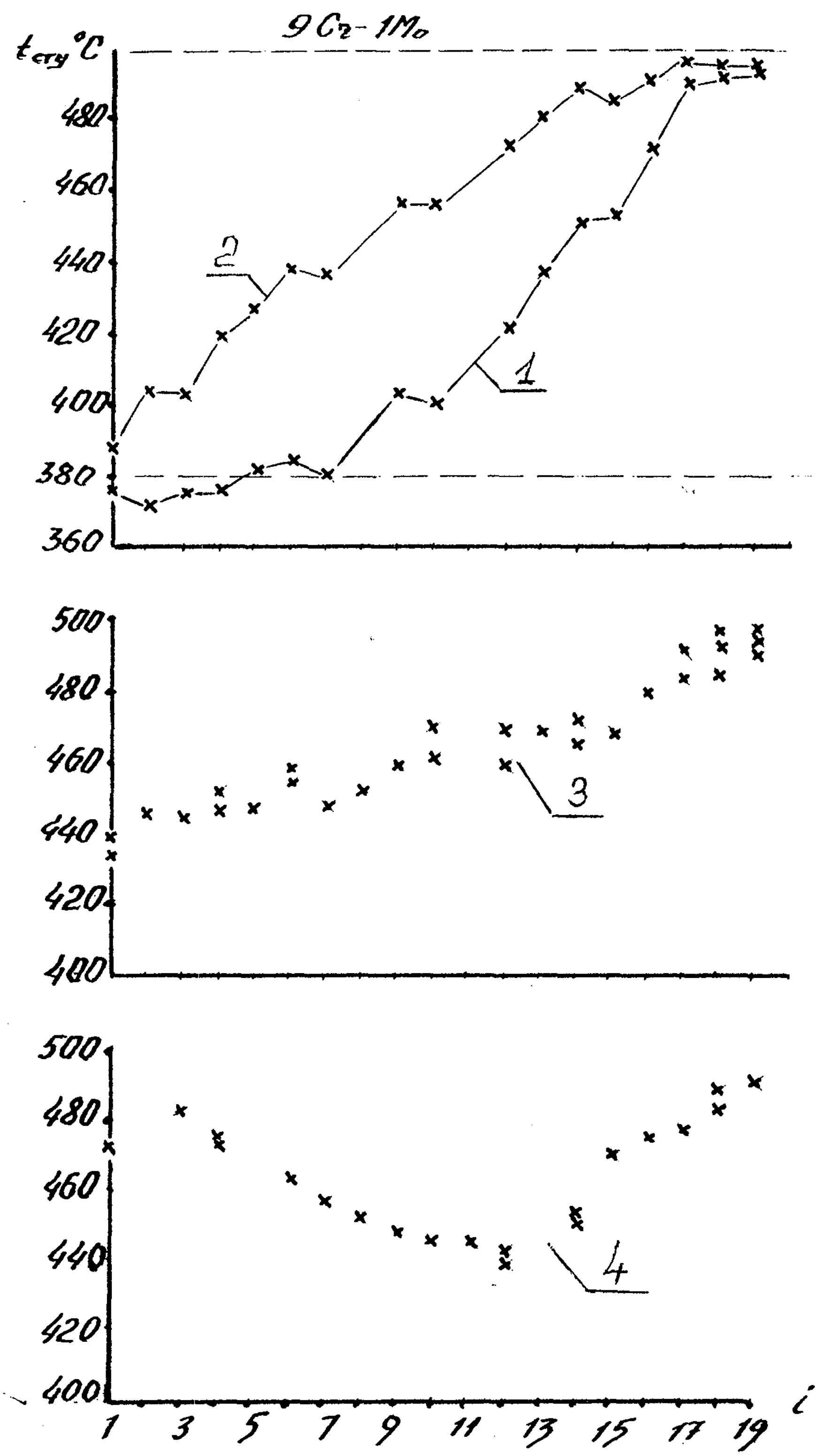

Fig.3

Tube temperature distribution along the ring banks
1 - 70% load; 2-64% s.w., 100% gas ; 3 - 78,5% load, new profiles Heysham 1; 4 - 73% load, Hartlepool 1.

tribution, and to output not more than 78,5% from rated one, when using new throttle devices.

Temperature differencies for any of 16 steam generators were appeared to have an own nature and value (compare curves 1 and 4).

The results of suitable excecuted computations showed these temperature differencies not to be connected with deviations of tolerances during tube bundle manufacturing process.

Thus, it should be noted, that there are random geometry deviations of multibank helical coil tube bundles from designed one owing to the specified manufacture tolerances and quite possible development of residual deformations during this tube bundle to be under service. The tube bundle deformation results in such intertube space flow distribution through the ring banks, that being relatively stable for each steam generator, the flow distribution is changed randomly from one steam generator to another. The above described phenomena may be the main reason of unsatisfactory prediction of the new throttle devices on the deterministic mathematical model approach to heat mass transfer in tube bundle. The mathematical model described in the reference (3) was not verified by the experimental data of the work (4).

Moreover the steam temperature decrease caused by nonunifrom heat load on tubes may be turn out an important factor even in view of a promising use of more resistant structural materials. The mechanism of steam temperature difference development and mean temperature decrease at the steam generator outlet are given in Fig. 4. The tube bundle geometry deviation from design one causes a disturbance of ratio of coolant

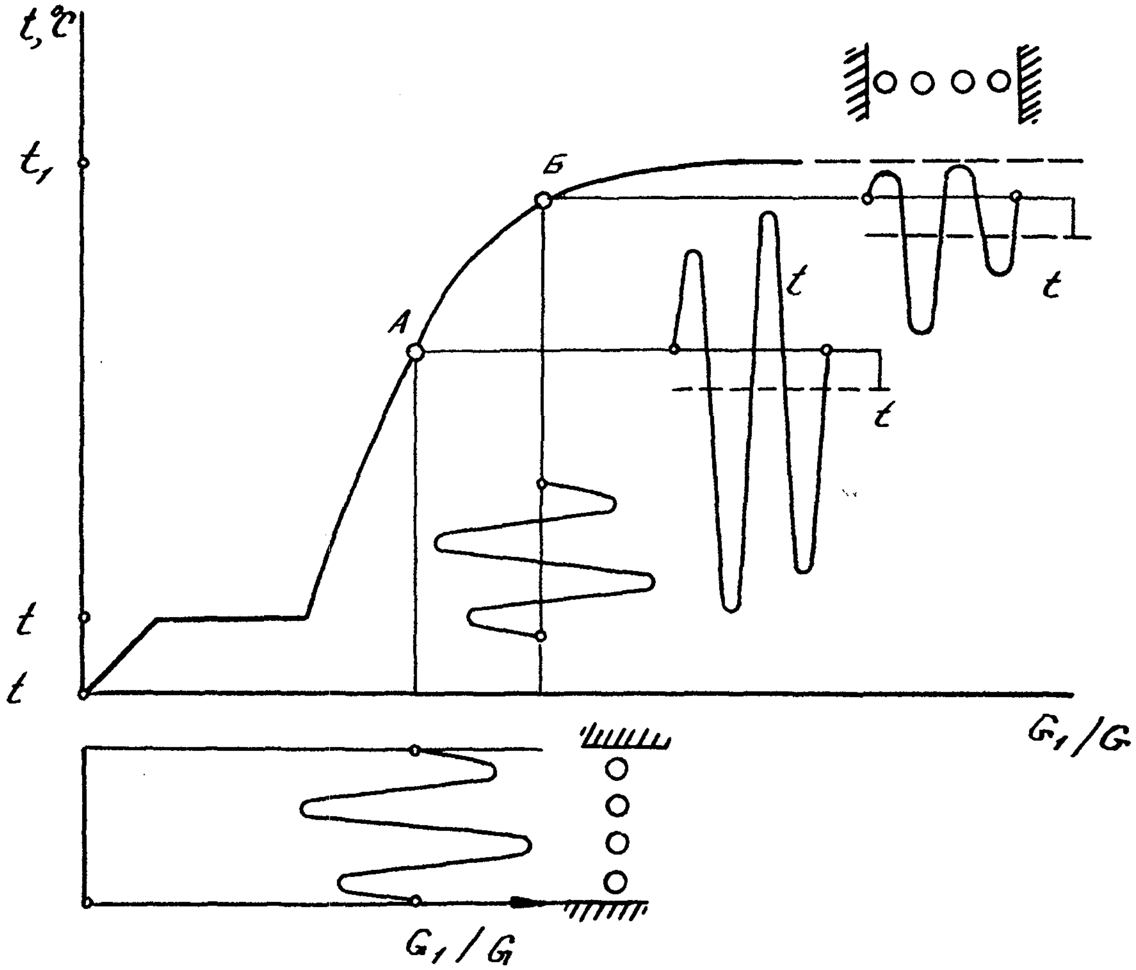

Fig.4

Mechanism of large temperature difference development and steam mean temperature decrease due to the hydraulic irregularities.

flow on side of intertube space, falling at one tube, to coolant flow inside the tube.

Spatial response of a multitube steam generator on this input disturbance may be plotted analogous with diode detecting by using monotube steam generator characteristic, that is the steam outlet temperature dependence of isolated steam generating circuit on the coolant flow ratio.

The selected work point A corresponds to the power steam generators of gas-cooled nuclear power plants, and point B, approaching to the primary maximum coolant temperature corresponds to the nuclear energy plant for power and heat generation and steam generators for nuclear energy plant with fast reactor.

In the first case the significant outlet temperature difference is arised at some decreasing of mean steam temperature.

In the second case steam temperature decreasing may be large enough owing to the strong nonlinearity of steam generating circuit characteristics in point B.

Shutting off the damaged tubes and deposit development inside tubes may give rise to negative effects. The only method to equalize heat load on tubes of the multibank helical coil steam generators is practically the hydraulic control of feed water flow distribution. It should be realized on the base of direct temperature measurements separately for each steam generator.

The operating experience of the AGR reactor steam generators with platen heat exchangers (5) showed that the tube bundle temperature measurements for revealing the temperature processes involved are quite complex and expensive ones.

It seems to be even more undesirable to replace periodically the throttling devices on the existing AGR steam generators or to equip the steam generators by a control system of feed water flow distribution in the tube bundles as in the case of THTR-300 reactor plant.

If the above mentioned problem will be neglected, the rated service life and safety operation of steam generator, and design outlet parameters also can not be assured. The above mentioned factors should not be considered as arguments against the multibank helical concept in favour of platen and once-through designs.

The real approach to this problem allows to consider thermal hydraulic irregularities of random or deterministic natures (Fig. 5) as inherent features of shell-tube heat exchangers (including the steam generators) of any known tube bundle arrangement. It is confirmed by the world wide development

of deterministic circuits or homogenious models for two- and three-dimensional thermal hydraulic analysis of heat exchangers with different coolants, various tube bundle arrangements and mutual coolant flow circuits. The first attempts of heat exchanger probabilistic modeling are given in references (6, 7). They were aimed to evaluate such a static tube bundle characteristic as an equivalent tube deflection on the base of experimental date for straight tube sodium - sodium heat exchangers. In the intermediate sodium - sodium heat exchangers of Phenix nuclear power plant, the sodium temperature difference at the tube outlet of the second circuit sometimes reached 32°C, at the design value of 15°C (8).

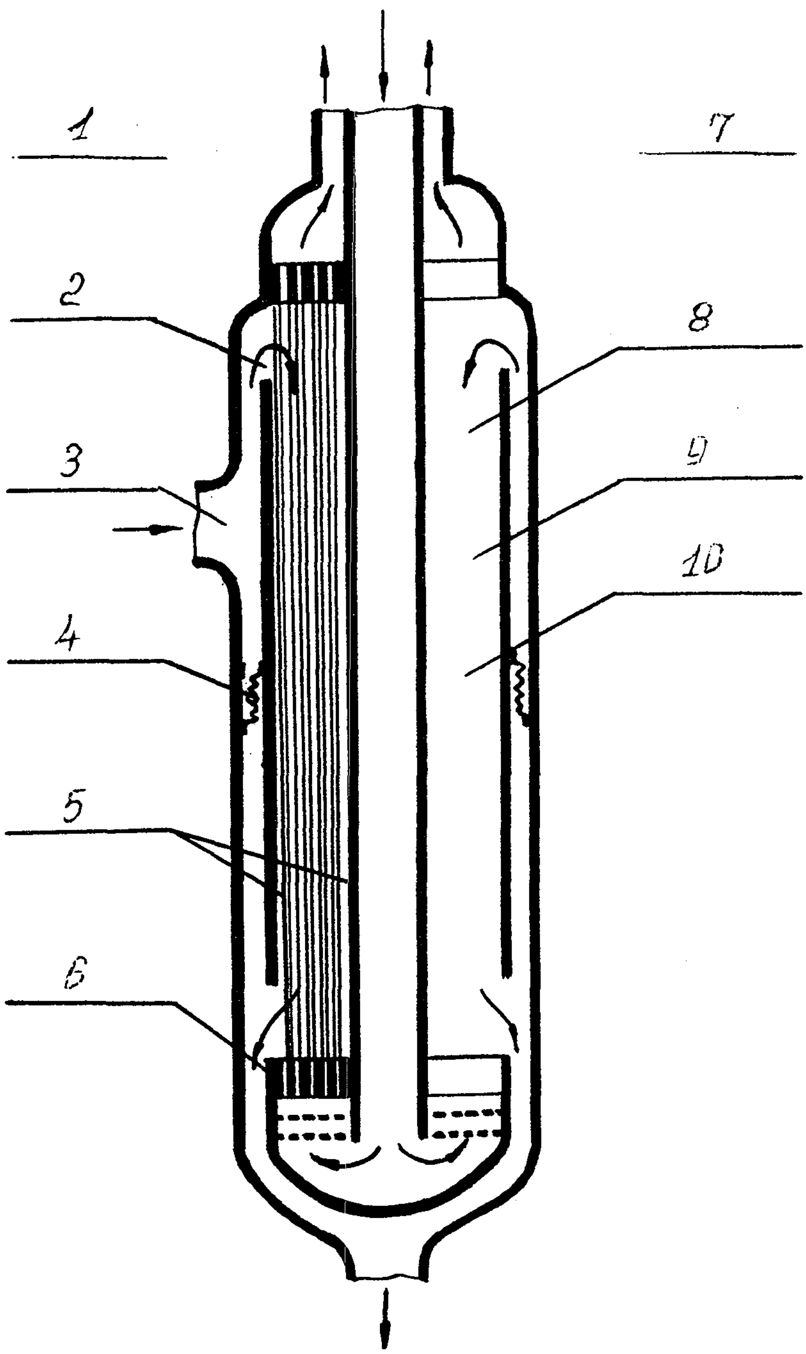

Fig. 5. Hydraulic irregularity development

1.- Determinated irregularities; 2 - The side inlet and outlet; 3 - Single side supply; 4 - Sealing leakage; 5 - Leakage along the shell; 6 - The distributing header; 7 - Random irregularities; 8 - tube bundle manufacturing inaccurasies; 9 - tube dimension tolerances; 9 - tube deflection.

This temperature difference was computed on the results of tube bundle hydrodynamic experimental investigations on full-scale model.

The intertube space temperature differences, insufficient rate of heat exchange and tube deflections in straight tube bundle of high temperature intermediate helium - helium heat exchangers are noted in references (8).

The large temperature differences between the tubes of 45 MW experimental straight tube steam generator with sodium heating are discovered in the 162 tube economizer-evaporator, sections (10).

The tube bundle geometry deviation from design one is found in a platen heat exchanger steam generators (5) and in a helical coil (with small radius of coiling) steam generator (11, 12).

Experimental data analysis showed the mean steam temperature decrease by 15-20°C at helium parameters: 700°C and 4 MPa (work point A, Fig. 4) to be attributed to the tube bundle geometry deviation from design one.

3. The stabilizing effect of coolant mixing

The coolant flow mixing along the tube is an effective means for decreasing the sensibility of heat exchanger and steam generator outlet characteristics to the thermal hydraulic irregularities.

However, the natural mixing efficiency appeared to be insufficient to equalize the tube thermal load at the quite large tube number (platen tube bank, ring banks in package).

The sections arranged in series coupled with the forced and natural mixing in connecting circuits is an effective coolant mixing means for all known tube bundle arrangements (straight tube Field's tube, platen and multibank helical coil).

The tube bundle, consisting of helical coils (with small radius of coiling) is the exclusion from this rule. Until recently, of such tube arrangement was inferior to the multibank helical coil one and was considered as a forced decision.

The received limited experimental data may be as it seemed to enhance this estimations (11, 12). Indeed, the experimental data static processing executed according to ZMEI PG programme on three-dimensional thermal hydraulic analysis of these steam generators (13), showed the significant equivalent deflection of 3mm value for helical coil modules of experimental section of steam generator. The characteristics of this experimental section are given in references (11, 12).

The temperature differencies of experimental section, predicted by programms (with deflection modules being included) do not exceed the temperature differencies of multibank helical coil AGR steam generators (taking into account deflection modules too). But if deflection modules are shut off, the received results would became unsuitable (Fig. 6, the left part).

On the other side, this arrangement is a unique means for providing primary coolant forced mixing in the existing or specially formed zones between the helical parts of coil module.

To provide an effective intermediate mixing, the strong twisted crossbars were installed in the technological gaps. Thus, the heat transfer assembly (module) arranged in helical

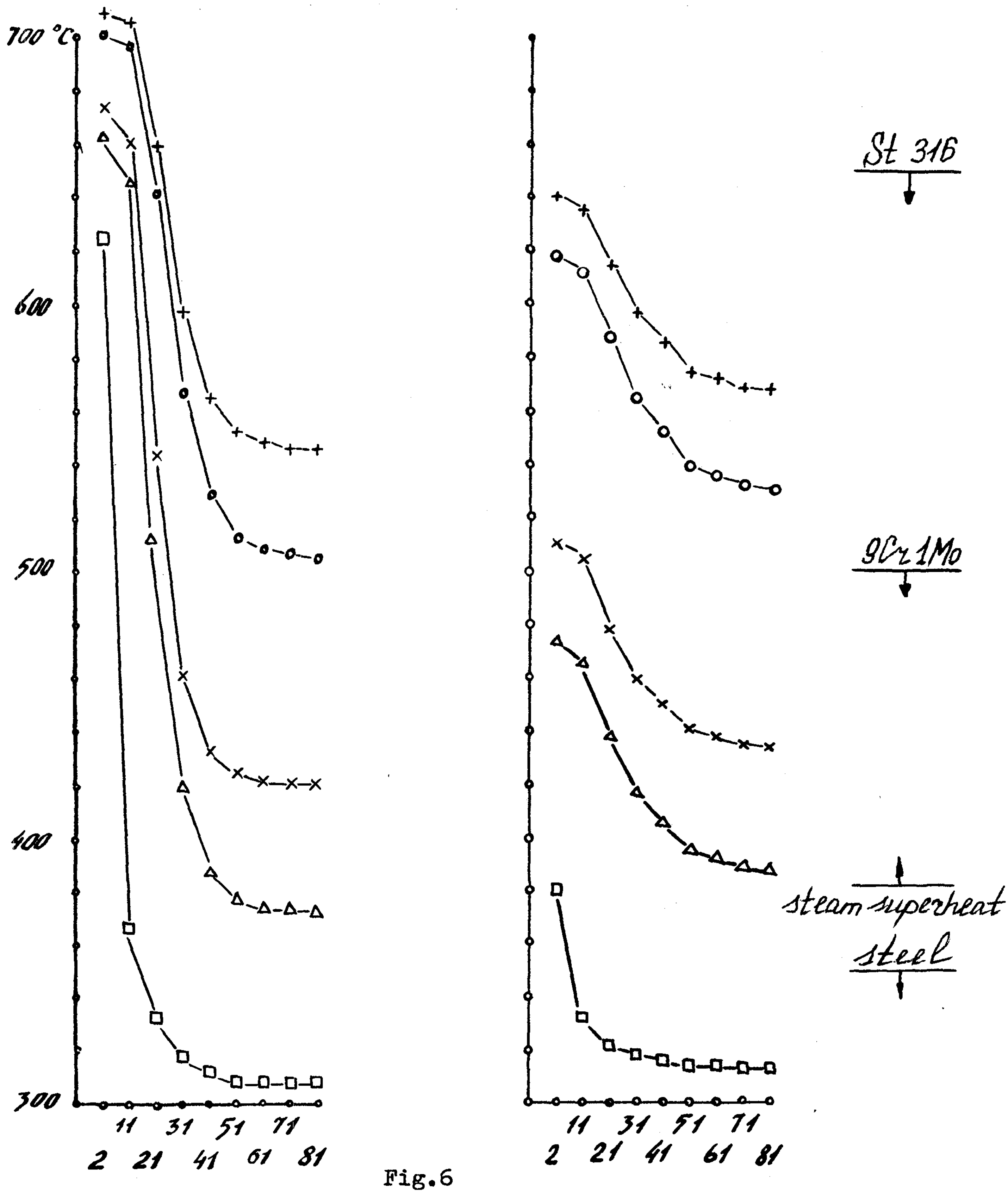

Fig.6

Cell temperature distribution at coil module shut off
X - metall; O - outlet steam; Δ - steam; □ - outlet helium

coil tube section of interchanging length ensures the heat transfer between the primary and secondary coolants and twisted crossbar sections (Fig. 7).

At the hexagonal packing geometries of heat transfer assemblies in tube bundle(Fig. 8) the twisted crossbars form several chambers of the effective intermediate mixing of primary coolant along the tube bundle and can act simultaneously as a separating device with fin-to-fin contact. The mixing efficiency in these chambers is 10-20 times more than the natural one in the intertube space of helical coils (14).

The mean mixing efficiency increases by 5-10 times at twisted crossbar overall length, equal to 25-50% of the tube bundle one.

The crossbars installed at the tube bundle inlet and outlet smoothes the inlet irregularities and the primary coolant temperature field at the tube bundle outlet, when the damaged assemblies are shut off.

Inspite of the worse initial parameters (without forced mixing) the helical coil (with small radius of coiling) steam generators with several chambers (5-7) of intermediate forced mixing along coolant flow appear to have basic advantages over the multibank helical coil tube bundle steam generators for example.

Three dimensional thermal hydraulic analysis executed according to ZMEI PG programme showed intermediate mixing to be effective enough to reduce to acceptable level such negative disturbance effects as deviation of tube geometry from design one and shutting off coil modules.

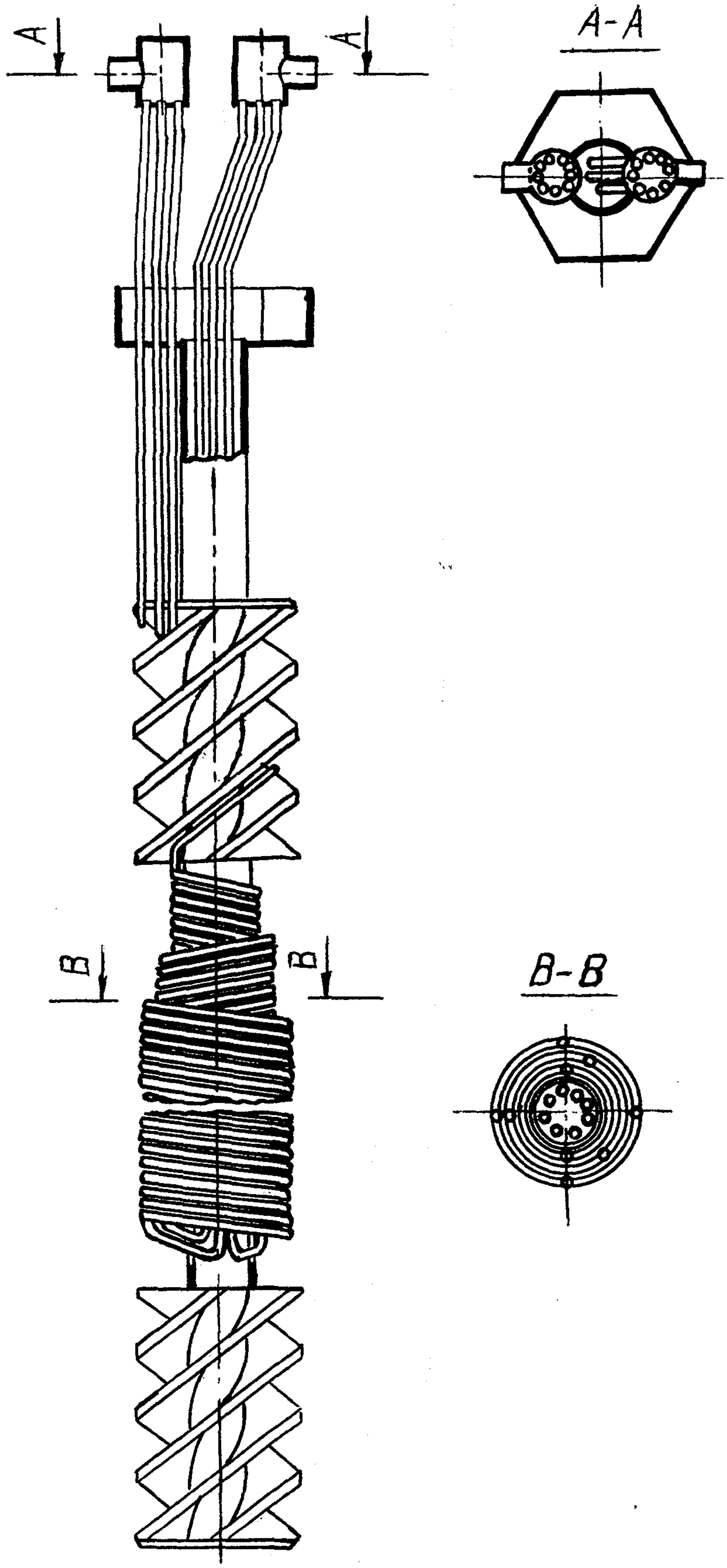

Fig. 7

Arrangement of undressed mini helical coil heat transfer assembly.

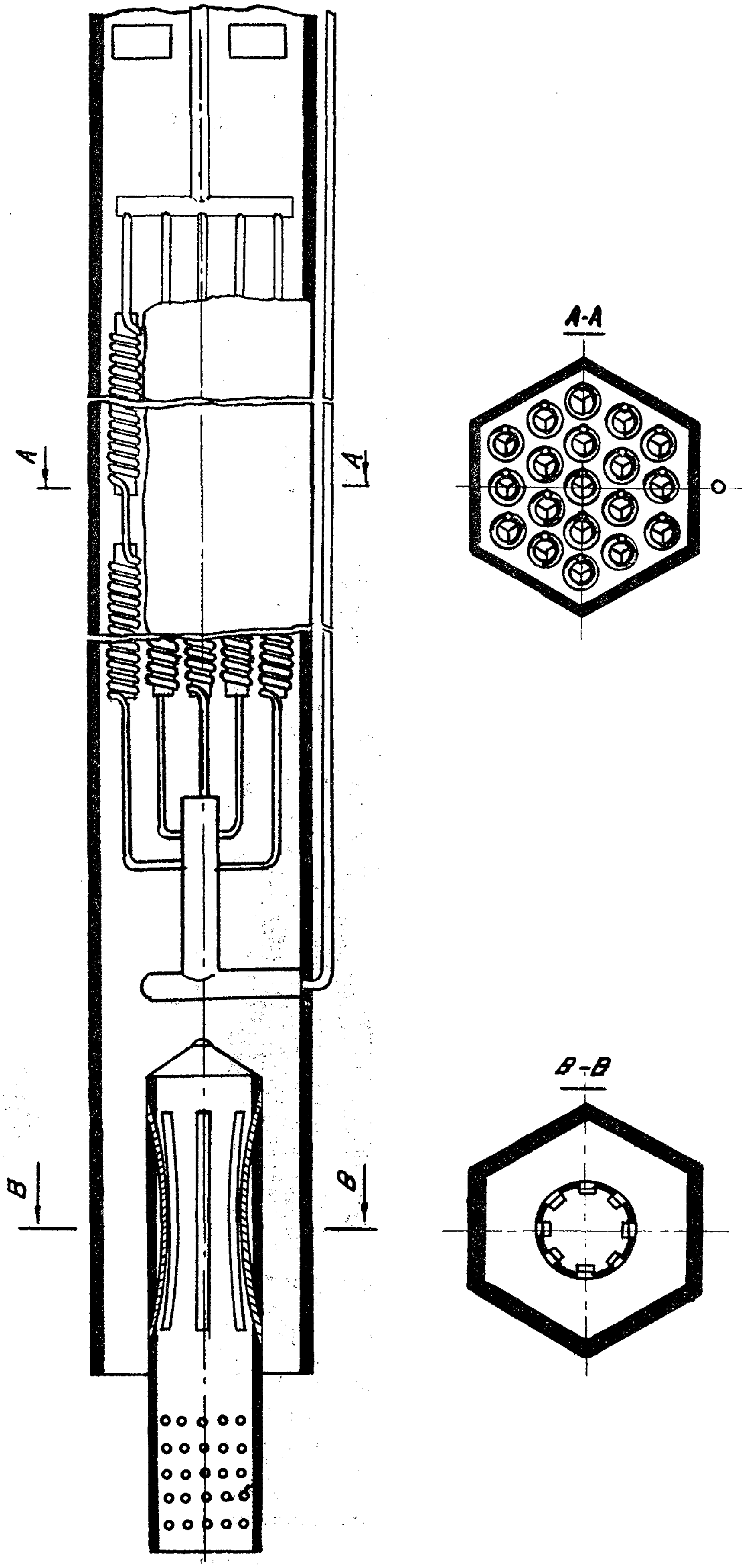

Fig. 8

Tube bundle assembly arrangement.

To illustrate the above phenomena it is given in Fig. 6. The profiles of steam temperature (tubes and helium in cells along the main diagonal of hexahedral shell when the angular feed water assembly (61 assemblies in total) is shut off.

In the left part of the figure it is given the corresponding temperature profiles of natural mixing in the tube bundle. The profiles of the forced mixing for the six high levels are given in the right part of the figure.

As it is seen from the present example of computation, the development of intermediate mixing allows to assure the constraints imposed on the AGR steam generator structural material, even in the case of such strong disturbance, as an angular chamber shutting off in the multimodular tube bundle.

Moreover, the effective mixing has a stabilizing effect on steam generating tube static stability (taking into account deposits) (15) and on reliability of prediction by mathematical modeling (taking into account the uncertainty of reference data and the static deviation of tube bundle geometry from the design one).

The reliable prediction (and reproducibility) of the steam generator parameters in operating long life conditions allows to refuse in principle from a detailed temperature control and a control of feed water flow distribution in tubes.

4. Arrangement of multibank helical coil tube bundle or assembly

Helical coils (with small radius of coiling) are often considered as singlebank (one or multipass) helical coils, which are opposed to the multibank (about 20 banks) multipass helical coils formed multibank helical coil tube bundle.

One- , mini- and multibank helical coil arrangements may be examined from the common positions.

The requirement of identical heat loads on tubes of any, i-th ring bank may be easily complied with the following conditions:

1) The tube length should be uniform

$$L_i = l_i \sqrt{(\pi D_i)^2 + (n_i S_z)^2} = \text{idem}, \qquad (1)$$

where

l_i - the number of coiling in one tube;

D_i - mean diameter of coiling

n_i - the number of tubes in bank;

S_z - axial pitch of tube spacing.

- The number of cross stream-lined tube banks along z axis should be identical

$$Z_i = l_i \cdot n_i = \text{idem} \qquad (2)$$

- ratio of intertube space coolant flow falling at i-th ring bank) to coolant flow in tubes of this bank should be identical (or the corresponding pitch to tube diameter ratio).

$$\frac{\pi D_i \cdot S_R}{\pi d_{in}^2 \cdot n_i} = \text{idem}, \qquad (3)$$

where

$S_R = \frac{1}{2} (D_{i+1} - D_i)$ - radial pitch

d_{in} - inner diameter of tube.

These conditions are complied with the following arrangement formulae:

- for mean diameter of coiling

$$D_i = 2S_R \cdot i; \quad i = M_{in.}, M_{in} \cdot 1 \ldots, M_{out.} 3, \tag{4}$$

where

$M_{in} \geqslant 1$ - first (inner) ring bank number;

$M_{out} \geqslant M_{in}$ - last (outer) bank number;

- for the number of tube in bank

$$n_i = A \cdot i \tag{5}$$

where for the whole numbers A = 1, 2, 3 ... ratio of symmetry is satisfied exactly and for the fractional numbers - approximately.

Then, the other geometric characteristics can be defined by the formulae:

- each tube length

$$L = z \cdot \sqrt{\frac{4 \; ^2 S_R^{\;2}}{A^2} + S_z^{\;2}} \tag{6}$$

- the number of ring banks

$$N_{bank} = M_{out} - M_{in} + 1 \tag{7}$$

- the number of tubes in multibank helical

$$N_{tube} = \frac{1}{2} A \; (M_{in} + M_{out}) \cdot N_{bank} \tag{8}$$

- multibank helical coil length

$$H = Z \cdot S_z \tag{9}$$

- central displacer diameter

$$D_{displ.} = (2M_{in} - 1) \cdot S_R \qquad (10)$$

- outer shell diameter

$$D_{sh} = (2\ M_{out} + 1) \cdot S_R \qquad (11)$$

Table 1 shows the formula validity on the example of multibank helical coil steam generator with different coolants.

The fractional coefficient A corresponds to the tube elongation owing to their number reduction and it is used for steam generators with downward steam-water mixture in tubes.

Rounding of the tube number ring bank to the whole one forms some asymmetry that may be compensated by the hydraulic control of feed water flow distribution.

The given arrangement formulae are true both for single-pass helical coils with small radius of coiling (A = I; M_{in} = M_{out} = I), and for several- and multibank helical coils, that makes their comparison easier.

5. Heat transfer assemblies in a form of helical coils

An attempt was made to realize the constructive advantages of multibank helical coil tube bundle assembly and module assemblies in design, consisting of several minibank helical coils (with small radius of coiling).

It is appeared, as it will be shown later, that 2-3 bank helical coils from 5 or 9 tubes are the optimal steam generating assemblies with central displacer. Inside of this displacer, the downcomer throttling pipes are placed as in the case of multibank helical coils.

Such module is essentially a minihelical coil, in which there are no obstacles for strong twisted crossbars to be installed between the helical tube sections.

Mini helical coil steam generators compares favourable with the multibank helical coils in heat transfer surface compactness. As to repairability, production engineering, flow detection and installation, the possibilities to develop a wide range of the minihelical coil heat exchangers on the base of standartization within the system may gain even an advantage over the multibank helical coil owing to tube bundle assembly arrangement concept.

Tube bundle assembly arrangement allow to realize in principle the flexible three-staged fail-safe concept in the case of the steam generator tube leakages.

1. Shut off the wholly faulted assemblies quickly without steam generator operating state loss.

2. Inspection and plugging of separate damaged tubes during the preventive repair, remotely or at the direct access with the first loop to be covered (medium steam generator repair).

3. Dismounting and replacement of separate nonrepairable assemblies with the first loop to be uncovered (capital repair of steam generator).

There are three alternative tube assembly arrangements in a form of helical coil.

A. Several (for instance, 19) singlebank coils (with small radius of coiling) are placed in parallel in the assembly shell, Fig. 9. If even one coil in such assembly is shut off, it would result in nonadmissable temperature shifts.

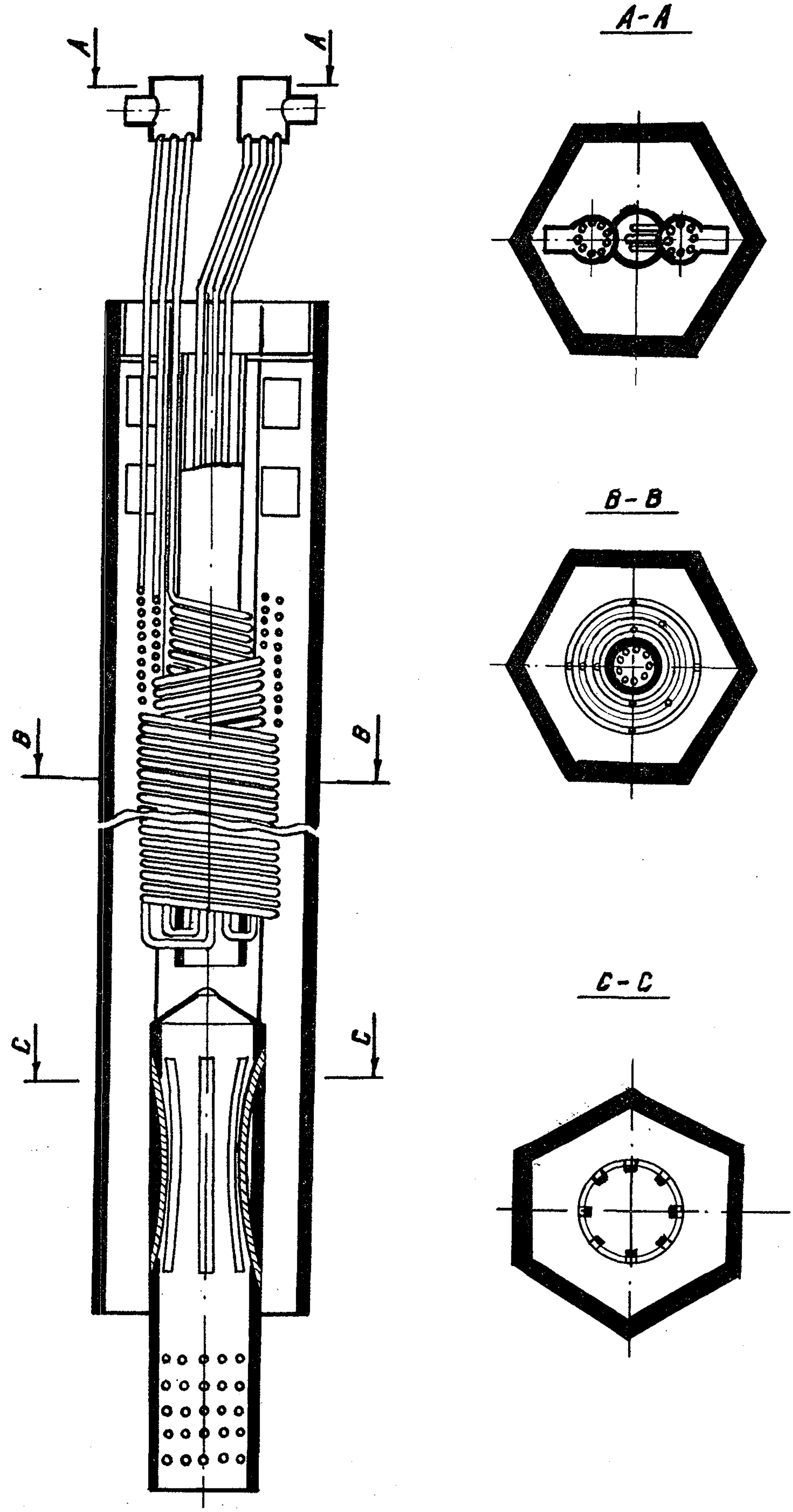

Fig.9

Arrangement of heat transfer assembly from coil modulus

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Therefore the assembly with damaged tube should be shut off quickly on steam-water and primary coolant sides only followed by replacement during repair.

B. In the assembly shell it is placed one severalbank mini helical coil (from 19 tubes for example) allowing plug a tube without assembly operating state loss. In such a case it is advisable to connect each tube with upper part of distributing and collecting headers of each assembly with downcomer tubes to be placed inside of the central displacer, Fig. 10. The assembly should be shut off on the water-steam and primary coolant sides, but the faulted assembly with the limited number of damaged tubes may be repaired without replacement.

C. The undressed mini helical coil (Fig. 7) with a forced mixing of primary coolant should not be shut off on the primary coolant side and faulted assemblies may be repaired without their replacement independent of the number of damaged tubes. Unlike the above mentioned dressed assemblies, the steam generator operating state loss at assemblies, being shut off quickly on water-steam side, is attributed to their mutual lay-out.

Namely, according to the temperature shift conditions, it is allowed to shut off not more than 3 inner adjacent assemblies.

If the mini helical coils are placed in a tube bundle of hexagonal geometry in addition to the inner ring cells inside mini helical coil, the triangular cells between the ajacent mini helical coils are formed. The circumferencial and angular cells are formed near the shell. Let us consider the conditions, when the triangular cells will be equivalent to ring ones without application of any symmetry providing units (for instance,

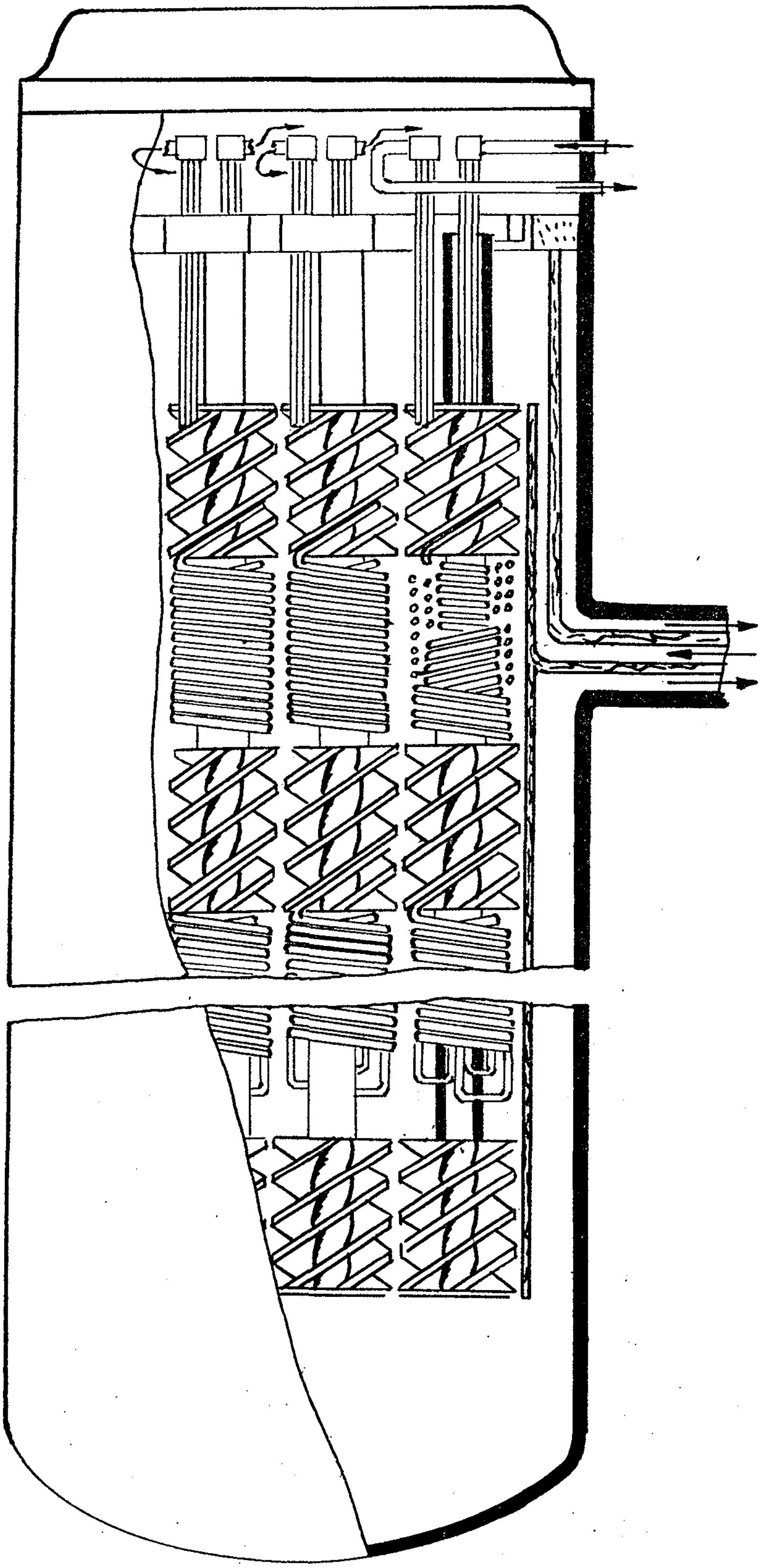

Fig. 10

Arrangement of dressed mini helical coil assembly.

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displacers in triangular cells). Then, the arrangement concept shall be expressed as follows:

$$d_{ri} = \frac{4F_i}{\Pi_i} = 2S_R \qquad (12)$$

for any form of cell, provided that the hydraulic resistance coefficient does not depend on the cell form.

In the case of the hydraulic diameter estimations, the perimeter Π_i can be regarded as a circle, corresponding to the mean diameter of coiling and cross-- section F_i - as pitch to tube diameter ratio along the free-stream flow, that is, between such circles.

If the gap between the outer coilings of tubes of the adjacent assemblies should be equal to Δ, the radial pitch of coiling provides condition of equivalence of triangular and

$$S_R \approx 10.74 \frac{d + \Delta}{9.74 - M_{out}} \qquad (13)$$

ring cells. Proceeding from the relative radial pitch for multibank helical coil tube bundle taken to be $S_R/d = 1.5 \div 2.0$, the increasing of the number of coil banks over 4 is considered as unadvisable, the value of $M_{outer} = 1 \div 4$ is preferred, but for the mini helical coil with a displacer the value of M should be equal $2 \div 3$. The displacer may be installed instead of the first coil bank ($M_{outer} = 1$), then its diameter is equal:

$$D_{displ.} = 3S_R \qquad (14)$$

It worth of note, that changes of coil steepness from bank to bank results in variation of heat transfer ratio and hydraulic resistance coefficient inside the tubes. For threebank mini helical coil with a central displacer heat transfer ratio is

1,2 - 1,4 times more (with variation of ± 7-8%), and hydraulic resistance coefficient is 1,23 - 1,36 times more (with variation of ± 4-6%) then for straight tubes.

The central displacer part in two-three-bank mini helical coil is equal to 10-20% of the whole tube bundle cross-section.

The table 2 illustrates three possible assembly arrangements. These arrangements provide approximately uniform tube bundle dimensions and helium steam - generator (reactor VG-400) output. For A-arrangement, the assemblies correspond to the design, described in reference (19).

The comparative metal requirement for three assembly arrangements is related to the helical tube section weight, which is identical for all cases with allowance for surface.

Table 3 shows the comparative initial metal requirement with aiiowance for the damaged tubes shutting off.

The table also gives the summary comparative characteristics of the different assembly arrangement steam generator with the account of the repairability during the service life. These characteristic analyses based on the assumptions, that 10% of tubes would be out of service during 30 year operation, and the preventive repair to plug some tubes and replacement of faulted assemblies should be performed once in a year.

It should be noted that the equipment to shut off quickly the faulted assembly on the steam-water side provides the significant decrease of the unscheduled outages induced by the steam generator damage. It concerns all variants of assembly arrangements. Only for the undressed mini helical coil assemblies (variant V), the assembly replacement would not required, plug of some damaged tube is performed during the preventive repair.

In the rest cases (variant B and especially A) one assembly set is not enough for overall service life; that increases the summary metal requirement and results in the periodical tube bundle capital repair.

Conclusion

Thus, the proposed high temperature heat exchangers and steam generators of new designed may be used in chemical and petroleum chemical industries and for high temperature gas cooled nuclear energy-technological plants, where technological processes of heat transfer and steam generating are proceeding at 900^{o} coolant temperature.

The heat exchange surface of mini assemblies from helical coils allo to clean the waste heat boiler heating surface by vibration without tube bundle strength decrease. The commercial vibrating cleaners can be used for the inducing periodic tube oscillatory motion, by electromechanical vibrator (20). It seems reasonable to consider feasibility of continuous vibratory cleaning with the help of tube vibration induced by a coolant flow.

The twisted crossbars, located between the helical tube sections,can intensify the tube vibration induced by coolant flow in an intertube space.

In this case this phenomena may be considered as a positive factor but it requires, however, the development of special distance facilities to prevent the tube damage due to the vibration effect.

The high repairability of heat exchangers and steam generators with heat transfer surfaces in the form of mini helical coil assemblies allows to decrease outage duration to minimum when some tubes have been failed and to reduce the repair expenses.

The advantages of such tube bundle arrangement in comparison with multibank helical coil, straight tube, platen ones and so on, assure their thermal engineering safety during long life operation already at the development stage. That is mean the indentification assurance to the specified tolerance deviations of real operational characteristics arising due to the tube bundle geometry deformation, deposit development and damaged tube shutting off.

These advantages are realized by the unique possibility to provide the stabilization of coolant mixing, that is achieved by simple design features of the mini helical coil tube bundle, namely.

In this case, the detailed temperature and hydrolic control of flow distribution during the operation may be excluded, in principle, what is necessary for the other designs, as a rule.

Assembly arrangement concept of the tube bundle for heat exchangers, designed for the different purposes, allows to standardize and unificate heat transfer assemblies in a form of the limited bank of optimal geometries of undressed mini helical coil assemblies.

It creates the base for different heat transfer equipment development on the base of unification and commercial standartization within the system.

In turn this approach provides the base for automatization of production engineering, flaw detection, reliable reproducibility and prediction of main characteristics of standard components, the modification of installating and dismantling processes and repairability of tube bundles.

Development of the unificated system from mini helical coil assemblies allows to design and manufacture heat exchangers and steam generators within the wide range of operating conditions without additional expenses on the research and development work.

Table 1

Multibank helical coil steam generator parameters

	THTR 300	KWU	AGR	Super Phenix
Unit power, MW	125	200	250	750
Primary coolant:	He	He	CO_2	Na
pressure/resist., atm	39.5/0.39	60/1.5		
temperature, °C	250/750	245/700		
H_2O: pressure/ resist, atm.	186/54	190/20		
temperature, °C	180/550	200/530		
Tubes: number	80	314	285	357
diameter, mm	25	22x2.8	31.5	25x2.6
length, m	196	106	96	91.5
full surface, m^2	1230	2200	2710	2570
Multibank helical coil A	1/3	1/2	1	1
Coil bank	9.11...23	17.18...39	6.7...24	13.14...29
number of ring bank	15	23	19	17
Pinch: S_R, mm	38.33	31	60.8	45
S_Z, mm	30.8	35	40	34
relative pitch $\frac{S_R}{d} \times \frac{S_Z}{d}$	1.53x1.23	1.41x1.59	1.93x1.27	1.80x1.36
mean relative pitch	1.37	1.50	1.57	1.56
Diameter: displacer, m	0.65	1.04	0.67	1.125
shell, m	1.80	2.45	2.98 t	2.65
displacer part,%	13	17.4	4.9	18
helical coils	8.28	9.4	10.0	10.9
Number of bank along axis	268	270	250	321
Compactness, m^2/m^3	57.5	50	38.7	42.7
	16,17	18	3,4	19

<u>Note</u>. The present data were obtained for the design, modified on the base of limited information and given formulae, therefore they can be differ a little from the rated one.

Table 2

Helical coil assembly arrangements

Comparative configurations of heat transfer assemblies	A PG 94BO	B mini helical coil (dressed)	V mini helical coil (undressed)
Number of: assemblies	19	37	37
tubes in assemblies	19	9	9
tubes in steam generator in whole	361	333	333
Tube dimensions: length, rated, m	40	43.4	43.4
Diameter, mm	16x2.5	16x2.5	16x2.5
Assembly pitch: axial S_z, mm	20	20	20
radial S_R, mm	32.7	36	36
Between coils, mm	92	-	308
Diameter: displacer, mm	-	108x4	108x4
coil/pass	65.4/1	144/2 216/3 288/4	144/2 216/3 288/4
(wrapper) dress, mm	500x4	316/4	-
Bank number along axis Z	194	191	191
Cross section of helium circuit for free-stream flow	2.64	2.70	2.70
Length: inlet section, m	0.70	0.70	0.4
coils, m	3.88	3.82	3.82
technol. clearance	0.3x6=1.8	1.8	-
twisted crossbars, m	-	-	2.82
outlet section, m	1.1	1.1	0.4
the whole tube bundle, m	7.48	7.42	7.44
Hydraulic resistance, kg/sm^2			
coils	0.262	0.210	0.210
twisted crossbar	-	-	0.048
the whole bundle	0.262	0.210	2.258
Metal requirement, %			
coils	100%	100%	100%
dress (wrapper)	58%	71%	-
displacer	-	23.6%	23.6%
twisted crossbars	-	-	17.1%
the whole bundle	158%	195%	141%

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Table 3

Helical coil tube bundle assembly characteristics with allowance for repairability

Comparative configuration of heat transfer assemblies	A PG 90BO	B mini helical coil (dressed)	V mini helical coil (undressed)
Surface margin for faulted tubes shut off	1.21	1.1	1.1
Tabulated value of metal requirement at the steam generator start up conditions	1.23	1.38	1.0
Unscheduled repair possibility	0.4%	0.45%	0.4 - 0.5%
Necessary set of assembly with allowance for replacement of damaged one during 30 years	2.68	1.22	1.0
Tabulated value of metal requirement for 30 years	3.3	1.7	1.0

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