STEAM GENERATOR DESIGN AND DEVELOPMENT FOR A HELIUM-COOLED MODULAR HTR

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Abstract

A modular helium cooled high temperature reactor system with a thermal output of 200 MW per reactor has been developed by the KWU group for cogeneration of electricity and process steam.

For this system a steam generator producing superheated steam of 190 bar, 530 °C is under development in cooperation with the component supplying industry. The steam generator is heated by helium of 60 bar pressure and 700 °C inlet temperature.

The design of the cross-counterflow helical tube bundle steam generator will be described. Thermal hydraulic aspects and helium flow distribution problems are considered. Special attention is paid to the interaction of the tube bundle with the steel pressure vessel which serves as the primary system boundary.

The presented design is to a large extend supported by operational experience from a 10 MW steam generator prototype which is in operation in the Interatom test facility KVK at helium temperatures even up to 900 °C. Some test results and their application to the 200 MW steam generator will be presented.

1. Introduction

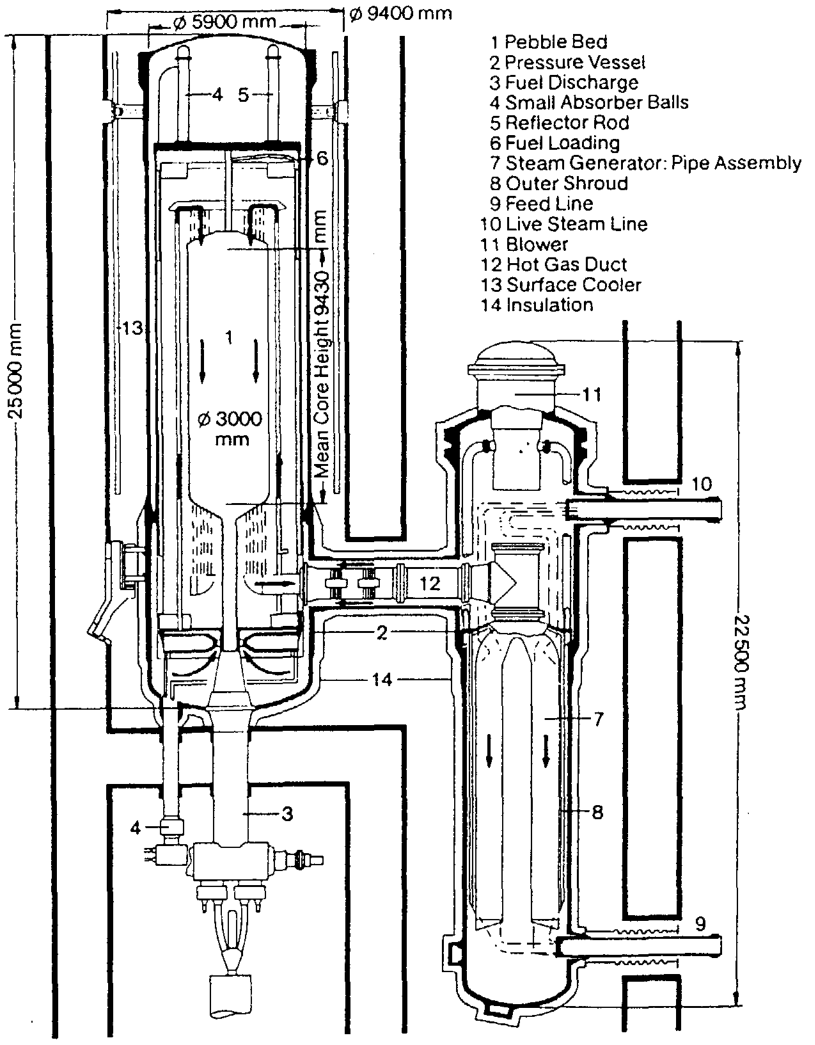
A modular helium-cooled high temperature reactor system especially for cogeneration of electricity and process heat has been developed by the KWU Group (Kraftwerks Union-Interatom). For inherent safety reasons the thermal output of each reactor module is limited to 200 MW_{th}. The typical arrangement is shown in fig. 1. Helium of 60 bar, 250 °C flows downwards through the pebble bed and is heated up to 700 °C; via a concentric hot gas duct the helium is fed to the steam generator bundle, flows downwards through the bundle, in which steam of 190 bar, 530 °C is produced, flows upwards in an annular space, screening the bundle, to an one-stage radial circulator. From the circulator the helium is fed via the cold gas annulus to the graphite reflector structure surrounding the pebble bed core, flows upwards through flow channels in the reflector and enters again the core inlet plenum. The helium mass flow is 85,4 kg/s. The side by side arrangement offers some strong advantages:

1. Minimizing the effects of graphite-steam interactions in case of steam generator leaks,
2. Suppression of convective flow during hot stand by conditions,
3. Improvement of accessability to the components for maintenance and repair.

Based on KWU experience in LWR application the primary system is contained in ferritic steel vessels of 20 MnMoNi 55 which is in Germany the well proven material for LWR pressure vessels.

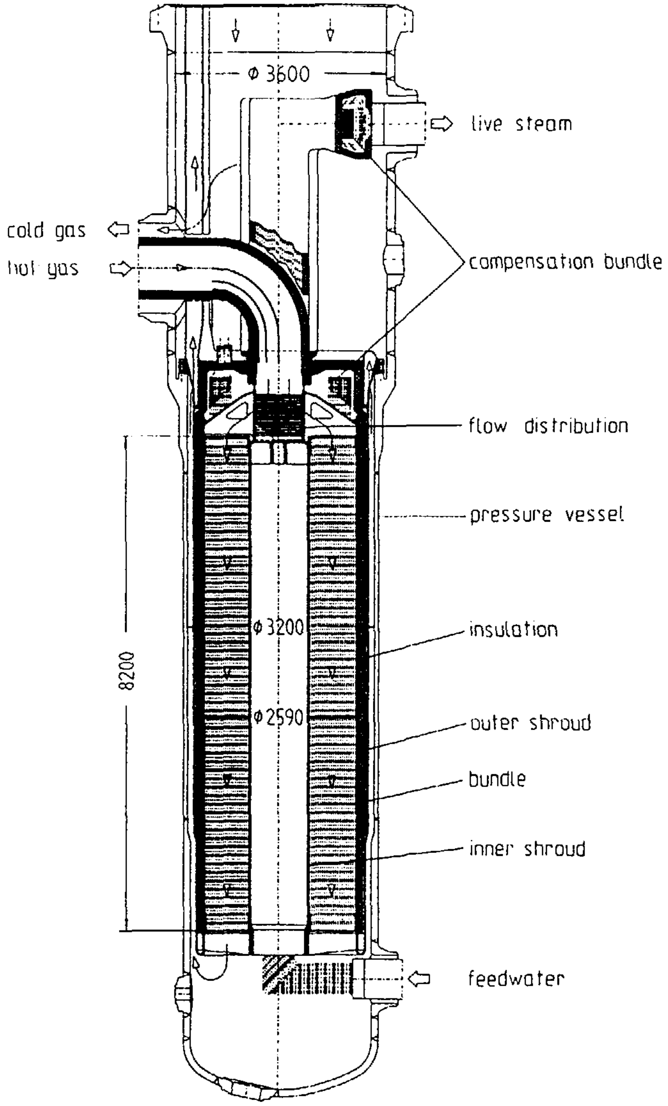
2. Steam generator design

The general design of the SG was performed in close cooperation with qualified manufacturers. Fig. 2 shows the solution - presented in this paper - which has been achieved in cooperation of KWU/Interatom and L+C Steinmüller.



Cross Section of a Modular Unit with Steam Generator (Primary Circuit)

FIG. 1.



200 MW Steam Generator

FIG. 2.

The heat transfer tube bundle is of a helical counterwound design in which 220 Incoloy 800 tubes in 22 concentric layers are arranged. The outer diameter of the tubes is 23 mm; the active length of each tube is 133 m. Additional data are given in table 1. On the feedwater side the bundle is connected via expansion bends to an Inc. 800 tube plate. On the superheater side the active bundle is followed by two separate compensation bundles which are necessary for sufficient compensation of differential thermal expansions in the high temperature region. The upper compensation bundle is designed in a toroidal shape in order to have free access to the hot gas bend. An Inc. 800 tube plate finally collects the individual tubes, leading to the live steam penetration. In order to achieve a proper quality control and inservice inspection the tube-tube plate connections are made by machined pintles on the tube plate and inbore welding. The tube penetrations through the cold/hot separation wall are sealed by a hydraulic expansion process. In case of leak paths through the outer insulated flow shroud, the contact of a hot gas stream with the pressure vessel wall is avoided by an additional surrounding pressure skirt which is connected to the cold high pressure side. It was a main design request to have a self supporting arrangement of the internals which allow a pressure vessel independent fabrication. The only points of interaction with the pressure vessel in this design are the two tube plates and the upper support flange inside the vessel.

Some special design studies should be mentioned in more detail:

2.1 Tube bundle optimisation (table 2)

In comparison with the reference Inc. 800 plain tube bundle some alternatives were studied. A real cost reduction would be achievable in case of an Incoloy 800 - 2 1/4 Croloy combination; independent from the question of low finned or plain tubes. However there are two reasons to keep the plain Incoloy 800 bundle as the reference; first the avoidance of transition welds in order to minimize the risks for leakages and second the comparably high Tritium permeation to the water/steam side in case of a ferritic preheater and evaporator. In the latter case the permeation rate is appr. 25 times higher. This is a very important value in case of direct process steam production without use of a steam converter.

Table 1 Main operating and design data

1. Operating data		
Thermal power	202	MW
Helium flow	85,4	kg/s
Helium pressure	60	bar
Helium inlet temperature	700	°C
Helium outlet temperature	245	°C
Live steam flow	77,2	kg/s
Live steam pressure	190	bar
Live steam temperature	530	°C
Feedwater temperature	170	°C
2. Main design data		
Heating bundle		
Tube dimension PRH/EVAP	23 x 2,5	mm
Tube dimension SPHR	23 x 4,2	mm
Pitch transversal/longitudinal	36/35	mm
Heating surface	2110	m^2
Tube length	133	m
Number of tubes	220	
Number of tube cylinders	22	
Height of tube bundle	8,2	m
Compensation bundle		
Tube dimensions	21,2x3,3	mm
Tube length	10	m
Total tube length	146	m

Table 2. Tube bundle optimisation

			Plain tubes		Finned tubes	
			In 800	2 1/4 Croloy/ In 800	In 800	2 1/4 Croloy/ In 800
Variantes			1	2	3	4
Tube dimensions	PHR/EVAP	mm	23x2,5	23x2,5	23/20x2,7	23/20x2,7
	SPHR	mm	23x4,2	23x4,2	23x4,2	23x4,2
Material	PHR/EVAP	-	In 800	2 1/4 Croloy	In 800	2 1/4 Croloy
	SPHR	-	In 800	In 800	In 800	In 800
Tube length	PHR/EVAP	m	109,4	95,2	95,9	69,2
	SPHR	m	23,6	23,6	23,6	23,6
Total active tube length		m	133	119	120	93
Tube bundle height		m	8,2	7,3	7,4	5,7
Relative costs		%	100	92	100	90
Tritium permeation rate		Ci/a	10	250	10	250

2.2 Stability calculations

For the reference bundle first stability calculations were performed. The water mass flow in a single tube was varied, while the helium side temperature profile was assumed to remain constant. The results show (fig. 3) that in the whole operational load range the bundle behaves stable without any ferrules at the feed water tube plate. Nevertheless to overcome fabricational tolerances ferrules with ca. 10 bars nominal pressure loss will be used.

2.3 Live steam nozzle (fig. 4)

The design of the live steam penetration through the pressure vessel wall asks for a carefull consideration. While the design temperature for the primary pressure vessel is limited to 350 °C, the live steam temperature will be 530 °C.

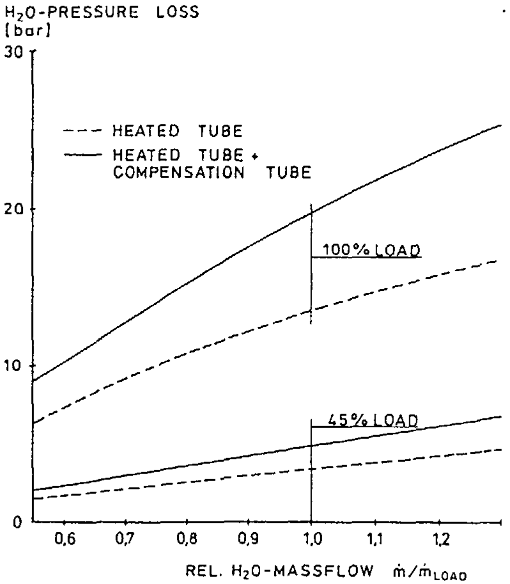
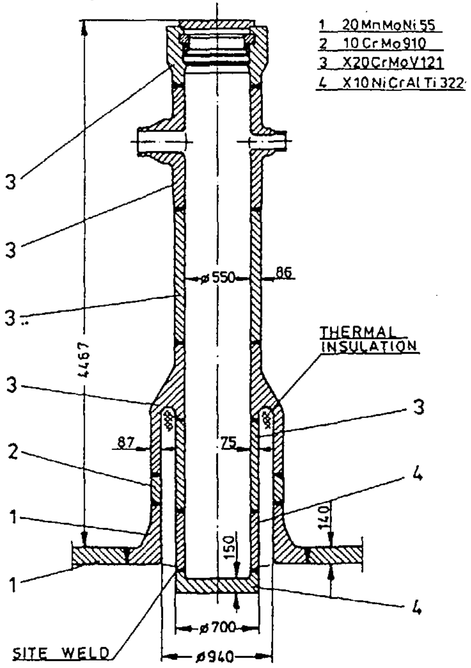


FIG. 3. CALCULATED STATIC STABILITY, SINGLE TUBE



LIVE STEAM NOZZLE

FIG. 4.

The transition from the pressure vessel material 20 MnMoNi 55 to the live steam line material X 20 CrMo V 121 is made by an intermediate piece of 10 CrMo 9 10. On the steam side the tube plate made of X 10 NiCrAlTi 32 20 (Inc. 800) is connected to the live steam line via an additional Inc. 800 transition piece. This allows the final mounting of the tube bundle at site without having any transition welds there. To allow a still smoother transition special buttering between several material combinations is recommended. To minimize thermal loading the annulus between inner and outer part of the thermal sleeve will be insulated. The shown removable special flange design allows an easy access to the tube plates for inservice inspection purposes.

2.4 Helium flow distribution (fig. 5)

Special attention is necessary to guarantee an uniform flow distribution of the helium to the bundle.
Under nominal conditions the helium velocity in the hot gas duct is about 60 m/s. Within a very short distance the flow has some extreme changes in direction. To avoid a flow separation in the hot gas bend special guide baffles have to be inserted. There is still some development work to do. In order to achieve a uniform flow distribution an already existing Steinmüller patent which is well experienced for water/steam separators is applied. To confirm the concept some preliminary tests at the KfA Jülich were already performed. Fig. 6 shows the used model which is a simplified sector of the bundle inlet region. The results gained so far (fig. 7) are very encouraging. Already after the fourth row in the simulated bundle the tolerances are in the range of ± 20 %. But further investigations and improvements are necessary.

2.5 Tube support and clamping concept

The individual tubes of the main tube bundle are positioned by 3 radial tube support plates which are fixed at the inner flow shroud. Inner and outer shroud are connected by 6 radially arranged support beams. The outer flow shroud itself serves therefore as the main carrier of the bundle and is supported by the reinforced inner flange of the pressure vessel (see fig. 2). For reasons of limiting flow induced vibration loads the outer 16 rows of the bundle are positioned with 3 x 2 additional so called "floating" spacer plates (fig. 8). When assembling the bundle the already coiled individual tubes have to be screwed through the prepositioned support plates. Inside the support plate bores the tubes are fixed by a special, already

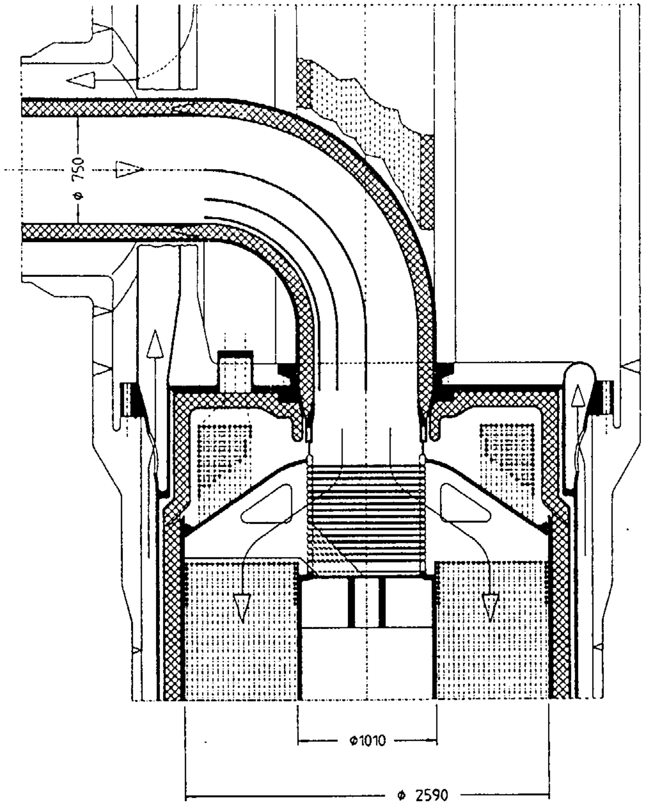
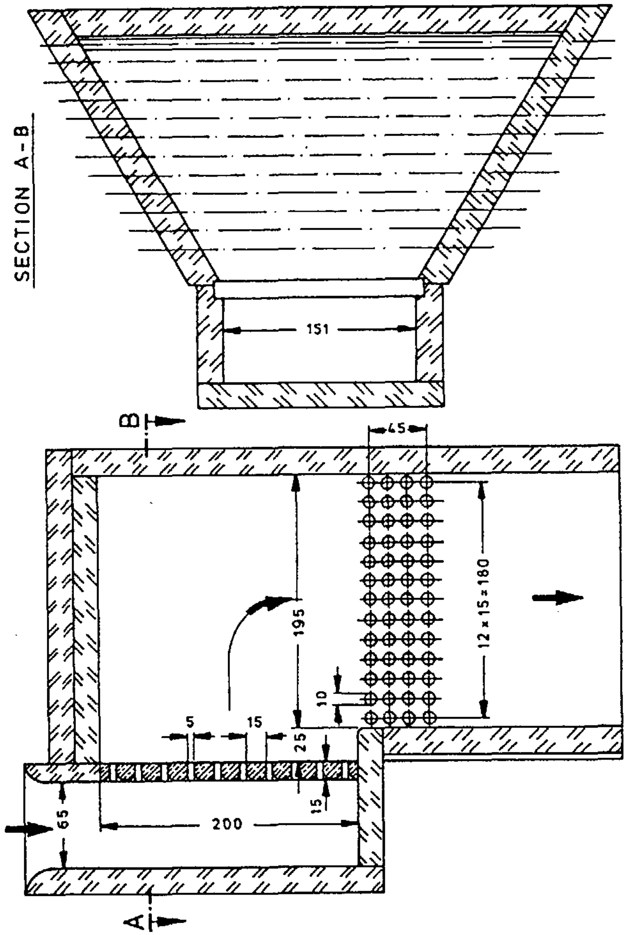
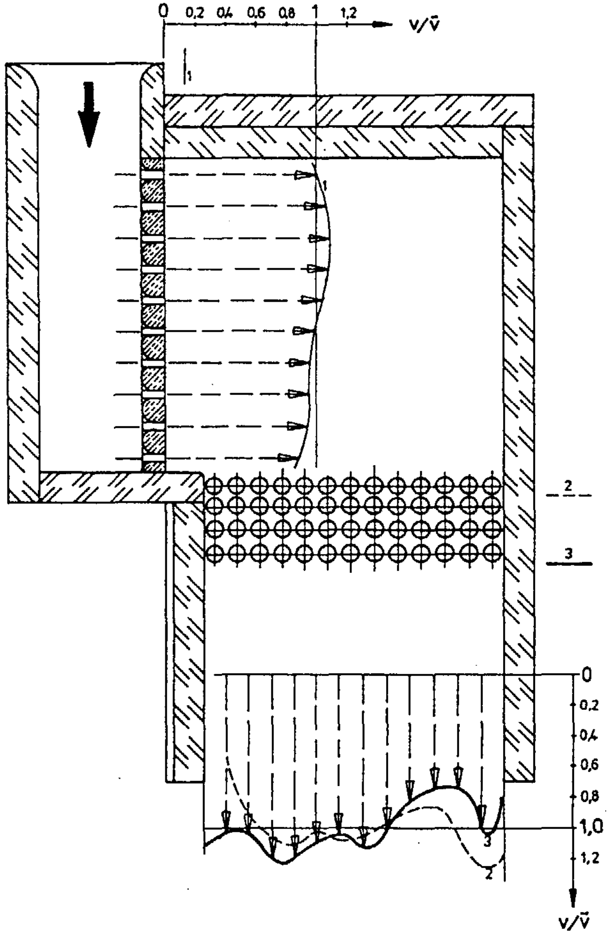


FIG. 5. Flow distribution design



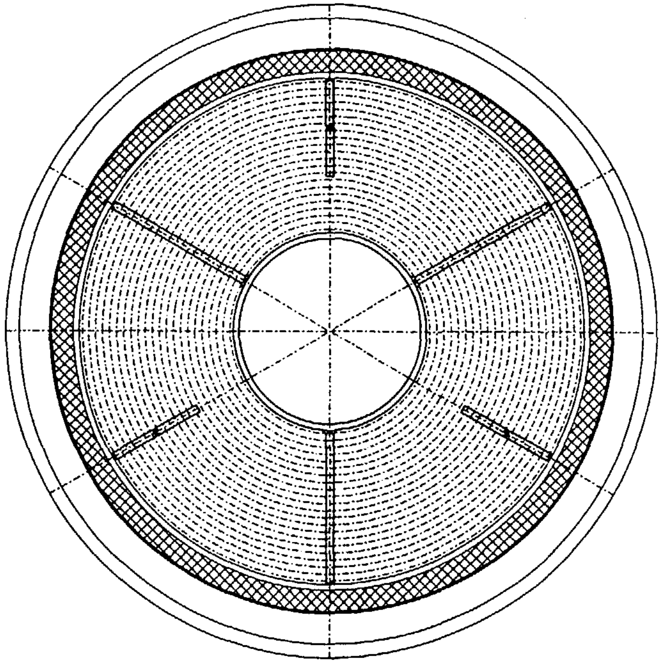
FLOW DISTRIBUTION MODEL

FIG. 6.



FLOW DISTRIBUTION MODEL:
TEST RESULTS OF VELOCITY MEASUREMENTS

FIG. 7.



Cross section through the bundle

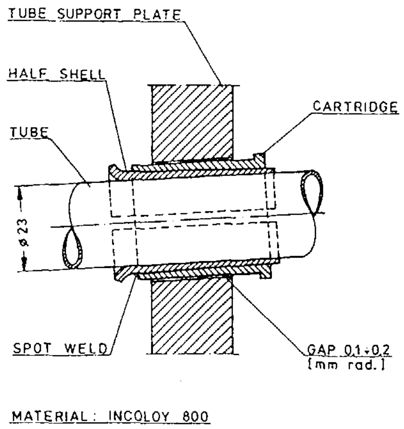
FIG. 8.

proven clamping device (fig. 9). The tube is surrounded by 2 conical half shells and is finally positioned by an additional cartridge. Half shells and cartridge are clamped elastically together. An additional fixation by welding points is possible. The assembling procedure sounds very complicated and time consuming. But it is a quite proven solution of Sulzer Brothers, a solution to which Steinmüller has complete access because of consortional contracts.

3. Experimental background

It is self-evident that the known features of the operating steam generators of AVR and THTR-300 have been taken into consideration. In addition a large amount of the presented design is supported by an own already existing experimental background. Interatom is operating for already several years a large test facility KVK for the performance of component tests for the project nuclear process-heat (PNP). This plant operates with helium up to 40 bars and 950 °C. Part of the plant is a 10 MW_{th} steam generator, originally designed to serve as a heat sink for special heat exchanger tests.

Fig. 10 shows schematically this steam generator made by Steinmüller. Tube material, tube support and clamping design are equivalent to the reactor component; from the operational point of view it should be mentioned that the unit was in operation at helium temperatures up to 900 °C. Fig. 11 shows roughly the calculated average temperatures of water/steam and helium respectively in comparison with measured helium-side wall temperatures. Due to the fact, that the bundle consists only of 3 radial tube rows the boundary effects at the inner and outer tube row are comparably large. But wall temperature measurements were only possible in the outer row.



TUBE CLAMPING DEVICE

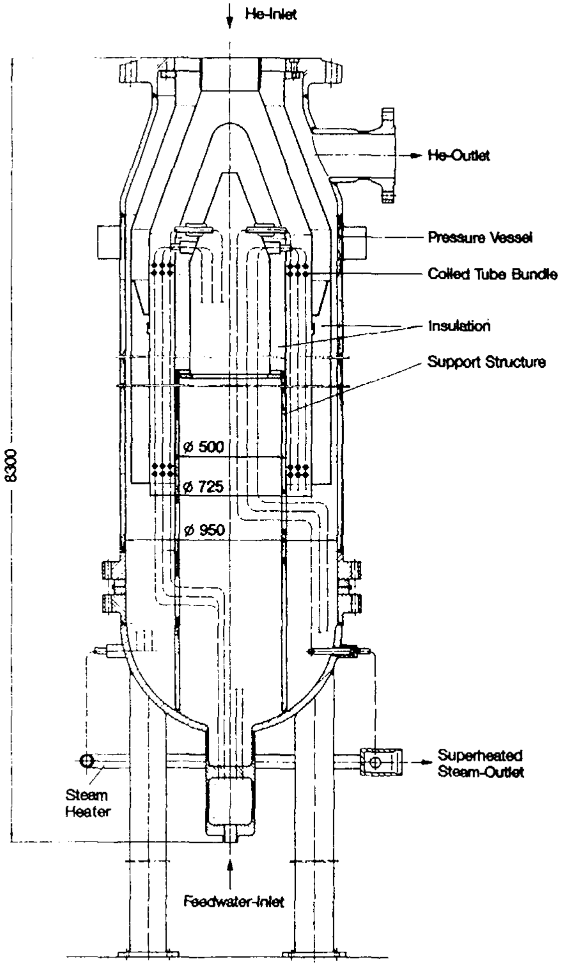
FIG. 9.

Operating Data

	He	Steam
Flow rate	2,9 kg/s	3,7 kg/s/4,0 kg/s
Inlet Temperature	900 °C / 950 °C	150 °C
Outlet Temperature	210 °C	540 °C
Inlet Pressure	41,0 bar	125 bar
Outlet Pressure	40,5 bar	125 bar
Power	10,5 MW	

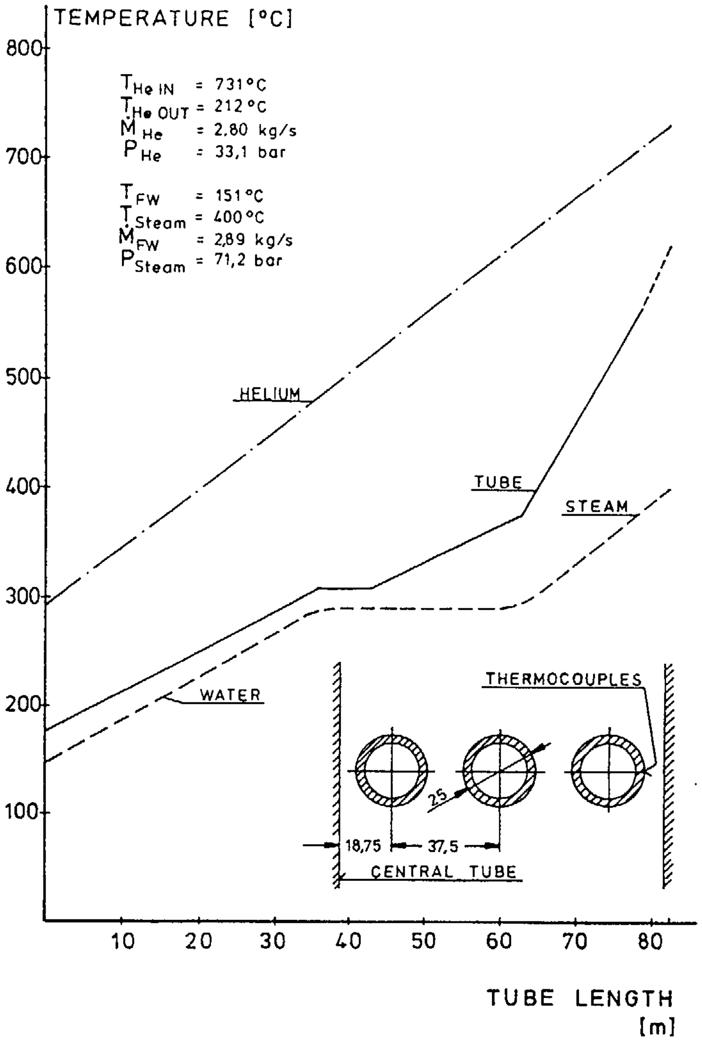
Dimensions and Materials

Number of Tubes	12
Tube Length	71 m
Heating Surface	66,5 m²
Tube Dimensions	ø 25 x 4 / ø 25 x 2,6
Tube Material	Incoloy 800 H / 15 Mo 3
Vessel Material	W St E 36



10 MW Steam Generator

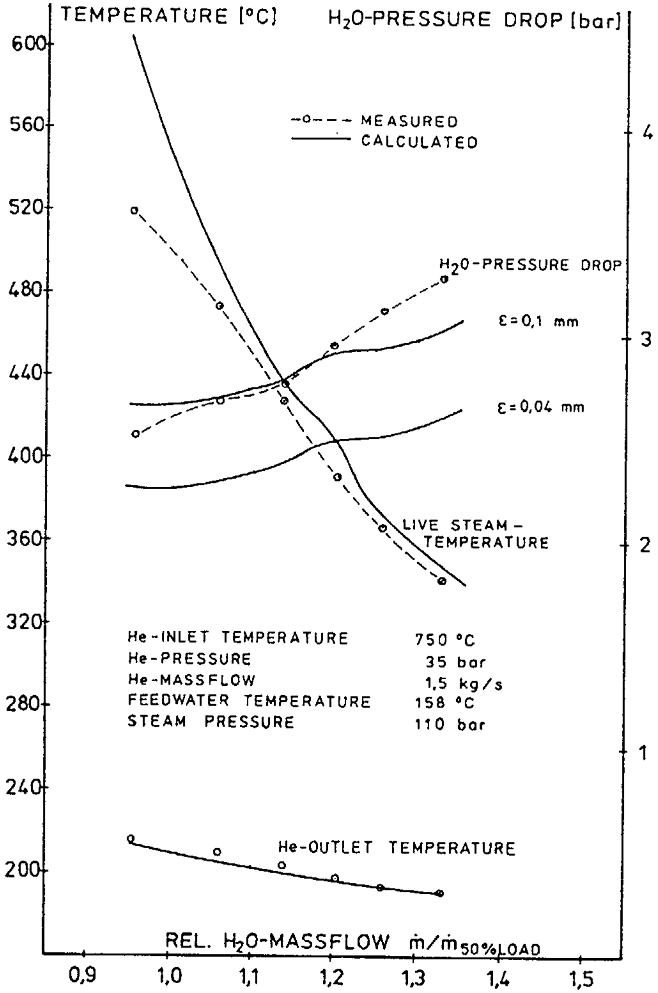
FIG. 10.



10 MW STEAM GENERATOR KVK

TUBE TEMPERATURE VERSUS TUBE LENGTH

FIG. 11.



KVK STEAM GENERATOR

RESULTS OF STABILITY CALCULATION AND MEASUREMENT

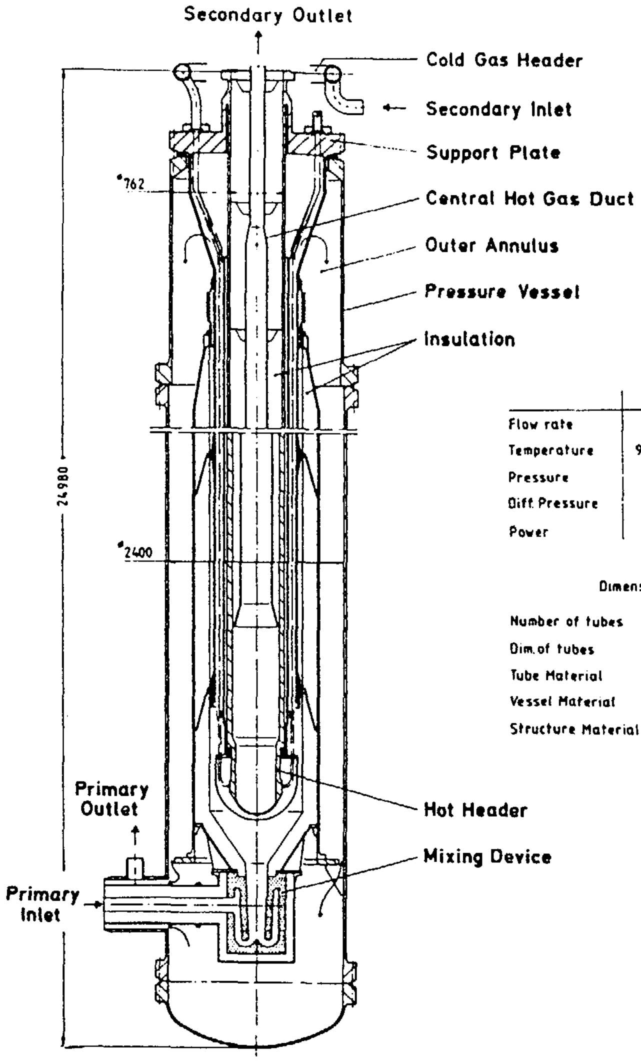
FIG. 12.

Stability measurements (fig. 12) confirmed so far our calculations for the big unit. After an operation time of 10600 hours (7000 hours > 750 °C) the test component was dismantled and inspected. Except some loosened tube clamping devices in the upper temperature region above 750 °C the inspection showed no additional failures. For the future it is foreseen to apply throttling valves to each individual tube in order to study furtheron effects of dynamic stability.

There is a last point of development where experience will be gained from.
In the frame work of the project nuclear process-heat (PNP) a helium/helium intermediate heat exchanger of 170 MW_{th} is under design by the consortium Sulzer Brothers/Steinmüller.
To qualify this design a 10 MW prototype (fig. 13) has been built and is now under test in Interatoms KVK test facility. Such design features as helical bundle, tube support plates, tube clamping devices and thermal insulation are similar to those of the 200 MW steam generator, but the intermediate heat exchanger operates at maximum temperatures of 950 °C.

4. Conclusion

The design of the steam generator for the KWU/Interatom modular HTR system seems to be sound. It is already broadly supported by experimental results, the experience of capable manufactures, also received from other projects and as far as the pressure vessel is concerned by successfull operation of LWR systems. However, some points ask for additional R+D considerations.



Operational Data

	Primary	Secondary
Flow rate	2,95 kg/s	2,85 kg/s
Temperature	950/293°C	900/220°C
Pressure	39,9 bar	41,9 bar
Diff. Pressure	0,55 bar	1,65 bar
Power	10 MW	

Dimensions and Material

Number of tubes	117
Dim. of tubes	⌀22 × 2,0
Tube Material	2.4663 (Nicrofer 5520)
Vessel Material	1.6368 (WB 36)
Structure Material	1.7380 (10 CrMo 910) 1.4876 (Incoloy 800H)

10MW He/He Heat Exchanger in Helical Tube Design

FIG. 13.