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Inverted Steam Generators for Sodium Cooled Fast Reactors

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STEAM GENERATORS OF THE CZECH PROVENIENCE

Steam generator types and design parameters

Four types of steam generators for plants with sodium cooled fast reactors were developed in cooperation of Russian (Soviet Union) organizations and Czech (Czechoslovak) organizations and manufactured in the Czech organizations and delivered to BOR 60 in the RIAR Dimitrovgrad (Micro Modular Steam Generator - MMSG, Micro Modular Inverted Steam Generator - MMISG and Modular Inverted Steam Generator - MISG) and to BN 350 (MMSG NADA I and NADA II) in the period of 1966 to 1992.

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STEAM GENERATORS OF THE CZECH PROVENIENCE

Table 1. Some design parameters of steam generators of the Czech provenience and reactor inlet/outlet sodium temperatures

Design parameters	MMSG (BOR 60)	MMISG (BOR 60)	MISG (BOR 60)	MMSG NADA I NADA II (BN350)
Thermal power, MW	30	28	26,3	200
Sodium temperature reactor outlet, °C	550	550	550	500
Sodium temperature reactor inlet, °C	**340**	**340**	**340**	**300**
Sodium temperature SG inlet, °C	565 (max)	500	505	453
Sodium temperature SG outlet, °C	320	302	309	273
Superheated steam temperature, °C	540 (max)	475	490	435
Superheated steam pressure, MPa	10	11,6	11	5
Feed water temperature, °C	215	210	210	158
Water/steam system	forced	forced	forced	natural circulation
Sodium side	shell side	in tubes (inverted)	in tubes (inverted)	shell side

STEAM GENERATORS OF THE CZECH PROVENIENCE

Micro Modular Steam Generator (MMSG)

The MMSG operated at one of two loops of the BOR 60 experimental reactor in Dimitrovgrad, Russia, from 1973 to 1980. MMSG design features [1]:

- 8 branches parallel connected to the inlet and outlet sodium chambers,
- each branch consisting of 3 modules (economiser, evaporator and superheater modules),
- each module – U shaped shell tube of 159 mm O.D. with inserted tube bundle and sodium at the shell side,
- once-through design at the water/steam side,
- thermal power of 30 MW (for BOR 60 application).

STEAM GENERATORS OF THE CZECH PROVENIENCE

Micro Modular Steam Generator (MMSG)

MMSG safety tests were performed by artificial water/steam into sodium leaks (series of leak rates of 0,05 to 1 g/s and one steam into sodium injection of 0,17 kg/s of duration of 60 seconds) at one branch of the operating MMSG in October and November 1979 and responses of sensors and diagnostic systems based on chemical as well physical principles of actions were recorded at the same time [2][3].

STEAM GENERATORS OF THE CZECH PROVENIENCE

Micro Modular Steam Generator (MMSG)

After them the MMSG was shut down, cooled and the leaked branch was cut out and corresponding pipes plugged by covers at the MMSG side. In the time period of only two months (sodium purification, inspections etc.) the MMSG was taken into the operation at BOR 60 in 1980 again to demonstrate the SG repairability and ability to operate after the large steam into sodium accident.

STEAM GENERATORS OF THE CZECH PROVENIENCE

Micro Modular Steam Generator NADA I and NADA II

Two steam generators of the type NADA were developed and manufactured by companies in Czechoslovakia and operated at two of the five loops of the nuclear power plant BN 350 NADA I was taken in operation in May 1980 and NADA II in June 1982 [4].

The BN 350 was configurated into loops and operated to provide electricity and to desalinate the seawater.

STEAM GENERATORS OF THE CZECH PROVENIENCE

Micro Modular Steam Generator NADA I and NADA II

SG NADA design features:

- each SG consisted of branches and the steam drum,
- each branch consisted of two modules (one was evaporator and one was superheater module),
- each module – U shaped shell tube with inserted tube bundle and sodium at the shell side,
- natural circulation of the water/steam in the system steam drum and evaporator modules,
- SG unit thermal power of 200 MW (for BN 350 application).

STEAM GENERATORS OF THE CZECH PROVENIENCE

Micro Modular Inverted Steam Generator (MMISG)

Developed in cooperation of Czech and Russian organizations and manufactured by companies from the Czech Republic [5][6][7][8].

MMISG has been still in operation at one of the two loops of the BOR 60 reactor facility since September 1981 with no water into sodium leak.

STEAM GENERATORS OF THE CZECH PROVENIENCE

Micro Modular Inverted Steam Generator (MMISG)

MMISG design features:

- 8 branches parallel connected to the inlet and outlet sodium chambers,
- SIGMA shaped branch,
- each branch consists of 3 modules (economiser, evaporator and superheater modules),
- module - shell tube O.D. of 194 mm and tube bundle of 19 tubes,
- once - through design at the water/steam side,
- sodium in tubes concept – a basis of the inherent steam generator safety if a water/steam leak into sodium should occur,
- thermal power of 28 MW (for BOR 60 application).

STEAM GENERATORS OF THE CZECH PROVENIENCE

Modular Inverted Steam Generator (MISG)

MISG was technologically developed and manufactured by companies from the Czech Republic [8]. MISG has been still in operation at one of the two loops of the BOR 60 reactor facility since March 1991 with no water into sodium leak.

STEAM GENERATORS OF THE CZECH PROVENIENCE

Modular Inverted Steam Generator (MISG)

MISG design features:

- one module SG design,
- banana shaped vertical oriented module,
- module - shell tube O.D. of 521 mm and tube bundle of 246 tubes,
- once - through design at the water/steam side,
- sodium in tubes concept – a basis of the SG inherent safety,
- thermal power of 26,3 MW (for BOR 60 application).

INVERTED STEAM GENERATOR SAFETY BENEFITS

There are some specific design feature of an inverted steam generator that positively contribute to its inherent safety, namely:

Overpressure at the outer surface of tubes in the ISG mitigates or eliminates potential crack growth in the tube walls.

INVERTED STEAM GENERATOR SAFETY BENEFITS

There are some specific design feature of an inverted steam generator that positively contribute to its inherent safety, namely:

Cross section of the one tube at the sodium side in the ISG is considerably smaller that the cross section at the shell side with sodium of the traditional steam generator. Consequently, in case of even small water into sodium leak flow regime of displacement can start, it means that the liquid sodium does not flow in the leaked tube and this tube is filled by the gas and no wastage of the target tube wall to the leak location can occur.

INVERTED STEAM GENERATOR SAFETY BENEFITS

There are some specific design feature of an inverted steam generator that positively contribute to its inherent safety, namely:

Crystallization of products of the water - sodium reaction, namely of NaOH, on the tube wall at the temperatures below 350 °C is a phenomenon that can lead to a self blockade of the sodium flow into the tube with leaked wall [9].

INVERTED STEAM GENERATOR SAFETY BENEFITS

There are some specific design feature of an inverted steam generator that positively contribute to its inherent safety, namely:

Many parallel channels (parallel tubes in the tube bundle) to the leaked tube at the sodium side in the ISG module are available and only a redistribution of sodium flow inside the tubes of module bundle is a consequence of many of water into sodium situations.

INVERTED STEAM GENERATOR SAFETY BENEFITS

All these above mentioned items that have an inherent safety character are reasons, why there are substantial positive safety differences in an ISG in comparison to a traditional SG design in water into sodium leak situations.

STUDIES ON ISG MODULE SELECTION FOR ESFR

Module design selection criteria

In the framework of the European Sodium Fast Reactor project [10] studies on heat transfer and optimization in inverted steam generator (ISG) modules were performed. To evaluate results selected criteria were used, namely predesign criteria, like tube bundle length, inner diameter (I.D.) of the module shell tube, mean heat flux at the tube bundle, tube bundle mass to module thermal power ratio, and safety criteria like resistance to water/steam into sodium leaks and ISG response to water sodium reaction etc.

STUDIES ON ISG MODULE SELECTION FOR ESFR

A brief summary of study results

Tube bundle length limits

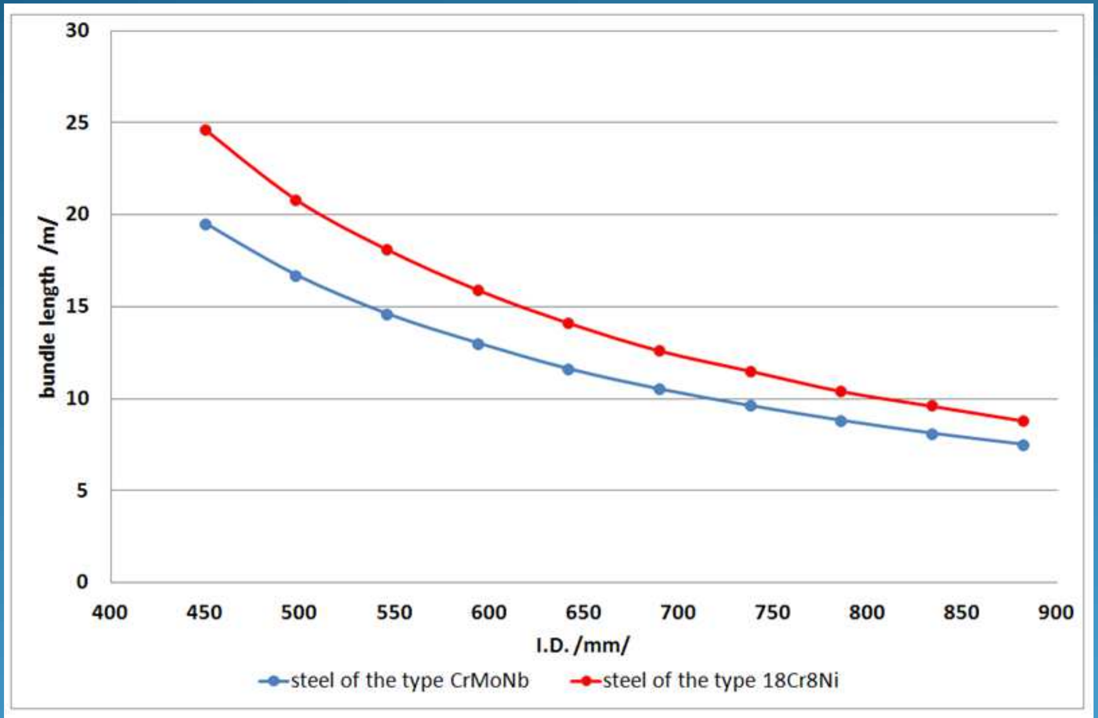
Tube bundle length is limited by tube manufacturer´s technological limits, steam generator box dimensions and the goal to avoid tube to tube welds at the heat transfer area.

Module shell tube I.D. or O.D.

Module shell tube I.D. or/and O.D. is strongly influenced by manufacturer´s technological limits and steam generator box dimensions. Module shell tube I.D. decreases with the bundle length increase.

STUDIES ON ISG MODULE SELECTION FOR ESFR

A brief summary of study results



Tube bundle length is increasing with decreasing diameter of the module shell tube. Long and slim ISG modules promise an acceptable mass to thermal power ratio.

ISG MODULE CANDIDATES FOR ESFR

Based on preliminary ESFR design data [10] with reactor heat output of 3600 MW and six secondary sodium loops each of the thermal power of 600 MW following IHX and ISG design parameters were considered.

ISG MODULE CANDIDATES FOR ESFR

Keeping in mind the successful design concept of the MISG being still in operation at BOR 60 since 1991 and „cost most interesting as well as safety most interesting feasible design“ preliminary two ISG module candidates for ESFR has been considered, Table 3.

Table 3. 100 MW ISG module candidates for the ESFR application

Item	Dimension	ISG module	
		Option 1	Option 2
ISG module thermal power	MW	100	100
Module O.D.	mm	850	720
Number of tubes in bundle	1	593	520
Length of the tube bundle	m	11,2	12,5
Mean heat flux	kW/m^2	285	325
Estimated pressure drop at the sodium side	MPa	0,21	0,52
Expected module mass to thermal power ratio, approximately	kg/MW	250	210
Module shape and orientation	1	banana shaped, vertical orientation	banana shaped, vertical orientation

ISG MODULE CANDIDATES FOR ESFR

A comparison of needed space and ground plan area for ISGs of 100 MW thermal power that would use micro-modules of the O.D. 194 mm (same as used at the micro modular inverse steam generator – MMISG), modules of the O.D. 521 mm (same as used at the modular inverse steam generator – MISG) and one module concept with the shell tube of O.D. 850 mm is in the Table 4.

Table 4. Comparison of estimated space and ground plan area needed for a SG of 100 MW thermal power in the three variants of inverse steam generators (ISG)

ISG type	Module O.D. [mm]	Number of needed modules	Space (approx.) [m^3]	Ground plan area (approx)[m^2]
MMISG	194	28	140	26
MISG	521	4	115	12
ISG one module	850	1	55	5

INDUSTRIAL DEVELOPMENT OF MATERIAL AND TECHNOLOGY FOR STEAM GENERATOR COMPONENTS IN THE CZECH REPUBLIC

Development of material and technology for SFR steam generator components was performed in the framework of research and development project of the same name initiated by ENERGOVYZKUM and supported by the Ministry of Industry and Trade [11][12]. The production of the steel of the type CrMoNb with very high purity (B factor smaller then 8) and forging, heat treatment, welding and machining technologies were verified in the Czech Republic industrial conditions in years 2003 and 2004. Manufacturing of tubes of 10mm, 20 mm and 22 mm O.D. (heat exchanging tubes for liquid sodium heated steam generators) was verified in industrial conditions too.

INDUSTRIAL DEVELOPMENT OF MATERIAL AND TECHNOLOGY FOR STEAM GENERATOR COMPONENTS IN THE CZECH REPUBLIC

Realization of an industrial steel melt

The realization of a steel melt of the CrMoNb type steel in the industrial conditions was performed in four steps:

- metal charge and direct reduced iron process
- hot melt processed in an electric arc furnace
- vacuum processed steel
- pot furnace and ingot mould

Realization of forged ISG components

This was proven in three steps:

- ingot long term homogenization in preheating furnace
- forming process
- component semi-products

Fabrication of heat exchanging tubes

Fabrication of heat exchanging tubes for ISG applications was carried out also in industrial conditions in four steps:

- tube rolling and piercing process
- tube drawing process
- tube inspections and testing
- verification of tube material and mechanical properties (R_m, $R_{p0,2}$, A5, …)

CONCLUSIONS

Two inverted steam generators of the Czech industry provenience have still been in successful operation with no water into sodium leaks at BOR 60 (RIAR Dimitrovgrad, Russian Federation). Micromodular inverted steam generator (MMISG) since 1981 and modular inverted steam generator (MISG) since 1991.

CONCLUSIONS

In the framework of the CP ESFR project predesign studies of 100 MW (thermal) ISG modules were performed with the consideration of MMISG and MISG design, operational and safety benefits and experience.

CONCLUSIONS

Development of material and technology for sodium heated steam generators components reflecting contemporary domestic industrial conditions in the Czech Republic was restarted in the years 2003 to 2004 and supported in the years 2008 to 2011 by the European CP ESFR project and by the Ministry of Industry and Trade of the Czech Republic.

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