Proceedings of ICONE10
10th International Conference on Nuclear Engineering
Arlington, VA, April 14-18, 2002

ICONE10-22570

STEAM GENERATOR OF THE INTERNATIONAL REACTOR INNOVATIVE AND SECURE

L. Cinotti*, M. Bruzzone, N. Meda, G. Corsini
Ansaldo Nucleare,
Corso Perrone, 25
16161 Genova, Italy
*cinotti@ansaldo.it

C. V. Lombardi,* M. Ricotti
Polytechnic of Milan
Dept. Nuclear Engineering
Via Ponzio 34/3, 20133 Milano, Italy
*carlo.lombardi@polimi.it

L. E. Conway
Westinghouse Electric Co.
1344 Beulah Road
Pittsburgh, PA 15235, USA
conwayle@westinghouse.com

ABSTRACT

IRIS (International Reactor Innovative and Secure) is a light water cooled, 335 MWe power reactor which is being designed by an international consortium as part of the US DOE NERI Program. IRIS features an integral reactor vessel that contains all the main reactor coolant system components including the reactor core, the coolant pumps, the steam generators and the pressurizer. This integral design approach eliminates the large coolant loop piping, and thus eliminates large loss-of-coolant accidents (LOCAs) as well as the individual component pressure vessels and supports. In addition, IRIS is being designed with a long-life core and enhanced safety to address the requirements defined by the US DOE for Generation IV reactors. The design of the steam generators, which are internally contained within the reactor vessel, is a major design effort in the development of the integral IRIS concept. The ongoing design activity about the steam generator is the subject of this paper.

INTRODUCTION

Several configurations have been examined for the IRIS steam generator (SG): straight-tube, U-tube, helical tube, C-tube, bayonet tube. Based on overall lifecycle costs, design and manufacturing experience, and high reliability, a helical-coil tube bundle steam generator (SG) was selected. The helical-coil tube bundle is a proven design that has operated in various reactors, including the French LMFBR Superphénix. There is also the ten years (1968-1979) operating experience of the PWR powered German nuclear ship Otto Hahn with its 38 MW SG. The good experience of this nuclear ship did encourage the designer to carry out studies for larger-capability SGs of the same type up to a rated power of 190 MW.

The helical-coil tube bundle design is capable of accommodating thermal expansion without excessive mechanical stress, has high resistance to flow-induced vibrations, and is designed to have thermal performance second only to a straight-tube design (which was discarded because of the high loads due to thermal expansion caused by temperature transients, mainly compressive forces developed between the feed and steam headers).

In the early 90's Ansaldo designed the integral PWR 650 MWt ISIS (Inherently Safe Immersed System) reactor, which in many respects is similar to IRIS. In particular, the ISIS SG is also helical-tube and could be considered a reasonable reference design for IRIS. The innovative aspects of the ISIS SG were successfully tested in an extensive test campaign conducted on a 20 MWt full diameter, reduced height, test article. The test SG consisted of 50 tubes arranged in 5 rows of 10 tubes, each row forming – alternately – 5 clockwise and 5 counterclockwise coils. Performance characteristics (thermal, vibration, pressure losses) were investigated along with the determination of the operating characteristics domain for stable operation.

Keywords: IRIS, Steam generator, Helical coil, Generation IV, In service inspection

STEAM GENERATOR DESIGN

In the early preliminary IRIS design, the steam generator tube bundle was conveniently accommodated in an annular space co-axial with the core to allow easy absorber rod insertion and fuel handling from the top. Several possible conceptual schemes were examined for the modular helical coil steam generator solution from the feasibility standpoint of mechanical and hydraulic separation and other mechanical/thermal-hydraulic features (e.g. tube diameter, fluid temperature, header scheme, safety, power upgrading, etc.).

After an assessment of the different configurations, it was decided to adopt the solution which uses eight identical helical coil steam generators modules (see Figure 1), completely separated, located in the annular space between the core barrel (outside diam. 2.74 m) and the reactor vessel wall (inside diam. 6.10 m).

This selection was based on the following considerations:

- failure of one steam generator does not involve other units;
- at least four mechanically and functionally independent components are required.

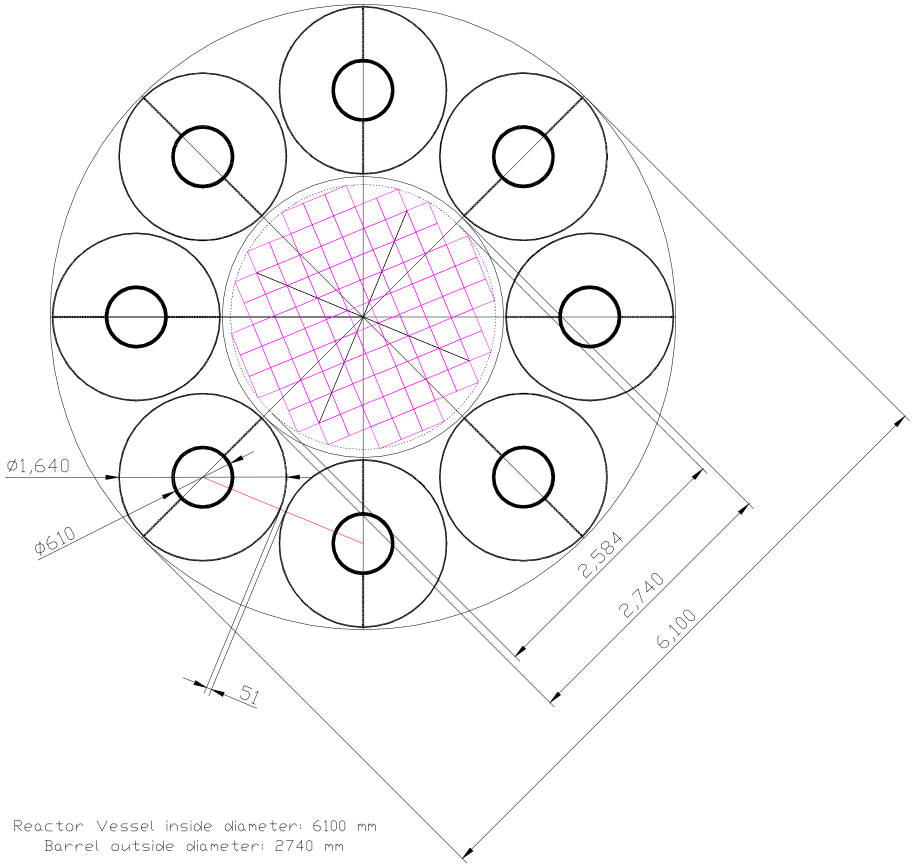
The adoption of the eight steam generators allows a modular construction of reduced-size components and limits the length difference between the various rows, so that it is possible to adopt tubes of commercial length with no intermediate welding.

The SGs are once-through type and have the feedwater/steam inside the tubes and the primary side reactor coolant on the outside of the tubes.

Each IRIS SG module consists of a central inner column which supports the tubes, with the lower feed water header and the upper steam header connected to the vessel. The tube coils are 1.64 m in diameter and the helical tubes are arranged in annular rows. The tubes are connected to the vertical sides of the lower feedwater header and the upper steam header. The SG module headers are bolted to the vessel from the inside of the feed inlet and steam outlet pipe.

The steam, generated in the tubes, flows upward and exits through the upper header; feedwater enters the steam generator at the bottom header (at an elevation above the top of the core) through a feedwater nozzle.

The tubes are fabricated of nickel-chromium-iron Alloy TT-690. Flow restriction orifices are provided at the tube inlet, to promote an even flow distribution through the tubes in the tube bundle and to avoid parallel channel instability. The required pressure drops for these orifices are of the same order as the tube pressure drops.



Reactor Vessel inside diameter: 6100 mm
Barrel outside diameter: 2740 mm

Figure 1 Layout of Steam Generator Modules

A preliminary sizing resulted in the following characteristics:

SG's modules number	8
Rated power	125 MW
Tube outside diameter	19.05 mm
Tube thickness	2.26 mm
Tube inside diameter	14.53 mm
External shell inside diameter	1620 mm
Internal shell outside diameter	610 mm
Number of helical rows	20
Tubes number	856
Tube bundle average length	32000 mm
SG height (headers centerline)	10000 mm
Primary side inlet temperature	328.4°C
Primary side outlet temperature	292°C
Feedwater temperature	212°C
Steam temperature	317°C
Primary side pressure	15.5 MPa
Steam outlet pressure	7 MPa
Primary flow rate	589 kg/s
Secondary flow rate	62.5 kg/s
Primary side pressure loss	136 kPa
Secondary side pressure loss	101 kPa

A subsequent thermal cycle optimization with reduced steam pressure and increased superheating has indicated that a significant reduction of the tubes number is possible as shown in Table 1.

Table 1 Effects of reduced steam pressure and increased superheating

Steam Pressure [bar]	Tubes number	ΔT pinch point	Saturation temperature [°C]	Superheating [°C]
70	856	12.6	285.8	31.2
69	828	13.4	284.8	32.2
68	800	14.2	283.8	33.2
67	775	15.0	282.8	34.2
66	752	15.8	281.8	35.2
65	730	16.6	280.8	36.2
64	708	17.4	279.8	37.2
63	685	18.2	278.8	38.3
62	668	19.0	277.7	39.3
61	651	19.8	276.6	40.4
60	636	20.7	275.6	41.5

Figures 2a and 2b present the temperature through the tube bundle for the steam pressure of 70 bar and 60 bar, respectively. The temperature difference between the primary water and the secondary coolant increases from 12.6°C to 20.7°C at the pinch point, when reducing the steam pressure from 70 bar to 60 bar. As shown in Table 1 the required tube number strongly depends on the steam pressure.

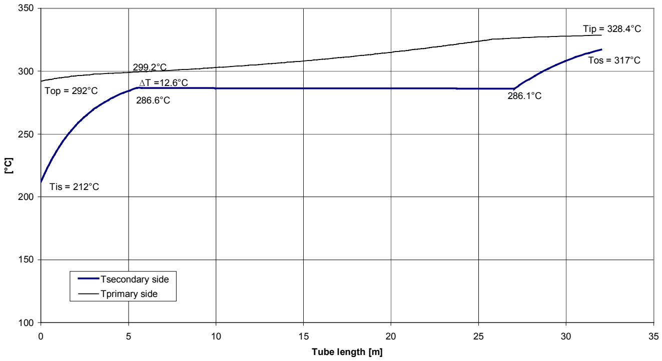


Figure 2a Temperature through the tube bundle for 70 bar steam outlet pressure

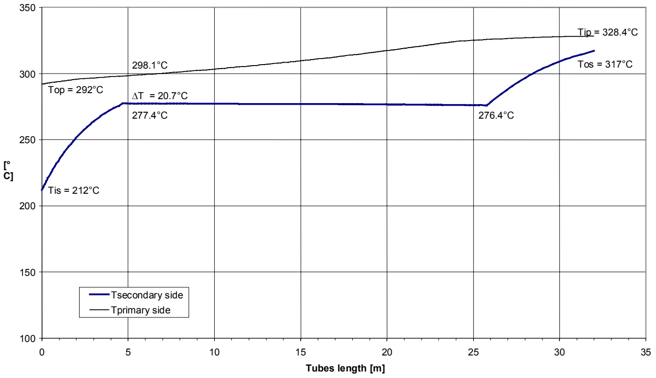


Figure 2b Temperature through the tube bundle for 60 bar steam outlet pressure

Starting from a case of: steam pressure = 65 bar; feedwater temperature = 212°C; steam temperature = 317°C, the effects of variations in steam pressure, superheating and feedwater temperature have been evaluated as reported in Table 2.

The results are visualized in Figure 3, which shows the costs (in term of tubes number) of efficiency increase resulting from different strategies in varying the operating characteristics.

Table 2 Sensitivity effects of steam pressure, steam temperature and feedwater temperature

Steam pressure [bar]	Feedwater temperature [°C]	Steam temperature [°C]	Tubes number	Efficiency
65	212	317	730	34.026
70	212	317	856	34.273
60	212	317	636	33.887
65	212	310	681	33.922
65	212	300	648	33.769
65	236	317	784	34.255
65	190	317	683	33.704

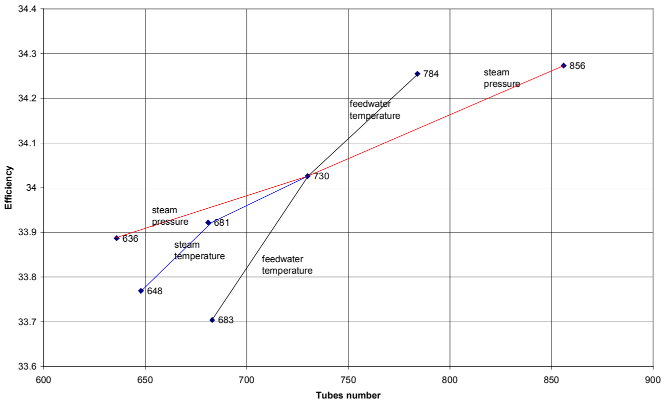


Figure 3 Relationship between Efficiency and Number of Tubes

The impact of the increase of the number of tubes can be quantified as follows:

- to increase the steam pressure: an increase from 60 to 70 bar involves an additional power of 2.2 kW_e for each additional tube;
- to increase the steam temperature: an increase from 300°C to 317°C involves an additional power of 3.9 kW_e for each additional tube;
- to increase the feedwater temperature: an increase from 212°C to 236°C involves an additional power of 5.3 kW_e for each additional tube.

The impacts of the main parameters for selection of a new steam generator configuration could be summarized as follows:

- *A lower steam pressure:*
  - reduces the required tubes number;
  - reduces the cycle efficiency;
  - allows a greater superheating.
- *A higher steam superheating:*
  - increases the required tubes number;
  - increases the cycle efficiency;
  - guarantees a better uniformity between steam temperatures at tubes outlet;
  - stabilizes the secondary flow;
  - improves the steam quality.
- *A lower feedwater temperature:*
  - reduces the required tubes number;
  - reduces the cycle efficiency;
  - reduces the water preheating stages.

These preliminary optimization studies indicate that in order to increase the efficiency without penalizing the steam generator size, the superheating should stay at 317°C and the steam pressure decrease toward 60 bar, while the feedwater temperature would be reasonably fixed in the range from 212°C to 236°C.

The optimization has been pursued further considering a smaller tube diameter, in order to further reduce the steam generator height.

Currently the IRIS steam generator sizing (one module of eight) is as follows:

Rated power	125 MW
Tube outside diameter	17.46 mm
Tube thickness	2.11 mm
Tube inside diameter	13.24 mm
External shell inside diameter	1620 mm
Internal shell outside diameter	610 mm
Number of helical rows	21
Tubes number	655
Tube bundle average length	32000 mm
SG height (headers centerline)	7900 mm
SG overall height	8500 mm
Primary side inlet temperature	328.4°C
Primary side outlet temperature	292°C
Feedwater temperature	223.9°C
Steam temperature	317°C
Primary side pressure	15.5 MPa
Steam outlet pressure	5.8 MPa
Primary flow rate	589 kg/s
Secondary flow rate	62.5 kg/s
Primary side pressure loss	72 kPa
Secondary side pressure loss	296 kPa

EXPERIMENTAL DESIGN BASIS

The steam generator proposed for IRIS will profit from design experience and test results of the ISIS (Inherently Safe Immersed System), a modular light water reactor with innovative, full-passive safety characteristics developed by Ansaldo in the past ten years. A mock-up of the ISIS steam generator was constructed and tested by Ansaldo.

The reduced-scale mock-up of the tube bundle of the integrated SG of ISIS can also be considered as the mock-up of one of the eight identical SG modules of IRIS. This because the tube bundle geometries of ISIS and IRIS are similar, so that the results of the test campaign carried out on the SG mock-up of ISIS are applicable to the SG of IRIS. The test campaign, to confirm the thermalhydraulic and mechanical performances of the SG, was successfully carried out, including tests aimed at identifying instability thresholds.

The ISIS System. The primary system of ISIS is, like IRIS, of the integral type with the steam generator unit inside the reactor vessel. Within the reactor vessel, a cylindrical inner vessel provided with wet metallic insulation separates the circulating low-boron primary water from the surrounding high-boron cold water. Hot and cold plena are hydraulically connected at the bottom and at the top of the inner vessel by means of open-ended tube bundles, referred to as the lower and the upper density locks. The inner vessel houses the core, the steam generator unit and the primary pumps, that are located at the top of the inner vessel.

Characteristic features of ISIS are, *inter alia,* the full immersion of the pressure boundary in a large, borated reactor pool and the innovative helical-tube SG.[1,2]

The ISIS SG. The steam generator of ISIS was not only designed to fit into the integrated reactor but also it is a key component for ensuring its intrinsic safety. The passively safe behaviour of ISIS during accident conditions is illustrated by its predicted behavior following the steam line break design basis accident. In integral SGs, steam is generated inside the tubes, and the water inventory inside the tubes is kept by design far less than the primary water outside them. This, coupled with substantial steam throttling, owing to the long runs of the small-bore tubing, allows to limit both rate and amount of cooldown of the primary water, which, in turn, limits both rate and amount of fed-back reactivity insertion. This behavior of ISIS can also be engineered into IRIS.

The ISIS SG mock-up and the IRIS SG module. The innovative design of the ISIS SG required the construction of a mock-up to confirm its thermalhydraulical and mechanical performances. A 20 MW mock-up of the helical-tube SG of ISIS was constructed in 1997, to test the overall thermal-hydraulical performance in regime of secondary-side flow stability, i.e. at operating conditions characterized by stable feed water flowrate within each tube and stable flowrate distribution among the several rows of tubes. The concern was that steam generation takes place inside the tubes, a condition with potential parallel-channel flow instability. Furthermore the tube bundle support system had to be tested in order to ensure minimal flow-induced vibrations. The construction of the mock-up demonstrated the feasibility of building this compact SG.

A comparison of the geometry of the ISIS SG mock-up and the IRIS SG module, i.e. tube diameter and length (number of tubes, number of rows and tube bundle height are not essential parameters for the simulation of thermal-hydraulic performance and mechanical behavior) as well as of the primary and secondary-side temperatures and flow rates indicate that the results of the test campaign of the ISIS SG mock-up are also useful for assessing the IRIS SG module.

The results of the test campaign. The test campaign was carried out at the SIET test facility near Piacenza (Italy). The main test results[3], were as follows:

- Absence of tube vibration.
- Confirmation of the thermal performances.
- Identification of about 25% margin on the calculated primary side pressure losses.
- Identification of the domain of stable operation as a function of:
    - Primary coolant inlet temperature;
    - secondary coolant flow rate;
    - secondary coolant inlet temperature; and
    - secondary coolant pressure.

IRIS SG's IN-SERVICE INSPECTION: PRELIMINARY STUDIES

ISI experience for helical coil tube bundle steam generators. Framatome and Ansaldo jointly developed and fabricated a system for the Ultrasonic (US) and Visual (VI) inspection of the SuperPhenix (SPX) Steam Generator tubing. Following a convincing demonstration of performance (1993) and the final acceptance by the client EDF (1996), an inspection campaign was carried out (1997/98) for several SG tubes.

Ultrasonic and Visual Inspection of the SPX SG tubing is a complex operation, owing to the severe technical specifications about flaw detection/sizing, the high inspection speed, and the unfavorable characteristics of the tubes, such as their length (~100 m), tortuous geometry (helical tubes with orthogonal bends) and associated friction.

The main characteristics of the probe are as follows:

- 80 multiple adjacent piezo-elements;
- high speed inspection with 360° electronic scanning;
- high inspection flexibility with electronic focusing and beam steering;
- inspection of bent tubes with small radius of curvature;
- center frequency from 8 MHz to 15 MHz.

Main performances of the US phased-array probes are the following:

- Inspection feasibility thanks to space-saving circular array;
- High resolution thanks to the frequency of 10 MHz.

The SG Inspection System, including its Signal Acquisition System, the tube Cleaning and Gauging System, and the Hydraulic Probe Driving System, is shown schematically in Figure 4.

The US probe is shown in Figure 5. A Eddy Current Module (not shown in the Figure) detects tube supports, for the prelocation of flaws. An Umbilical Cord, provides the electrical and mechanical links between probe and the Data Acquisition System.

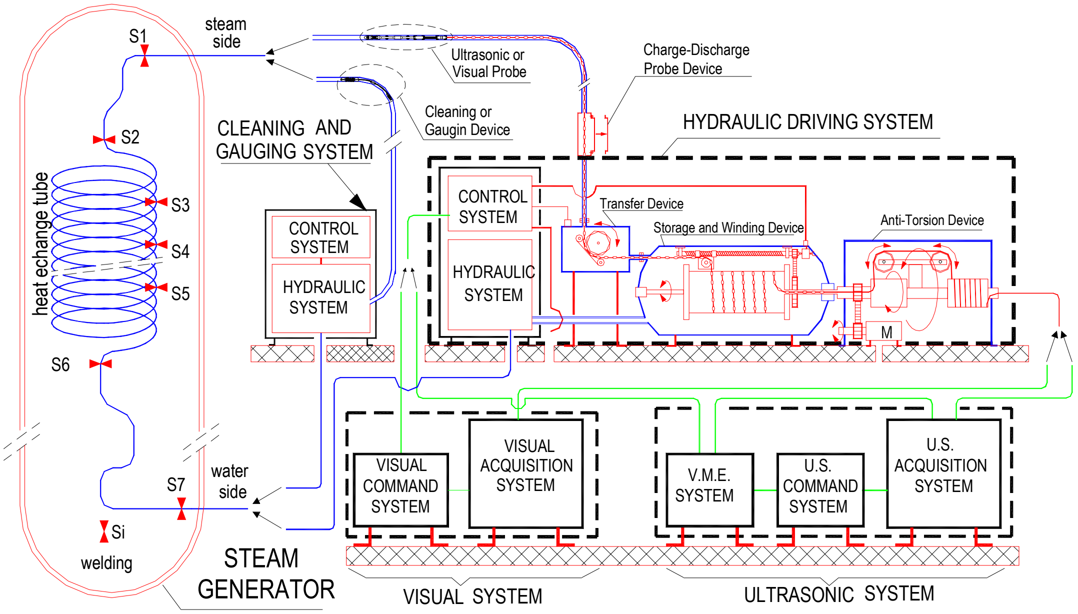


Figure 4 Steam Generator inspection system

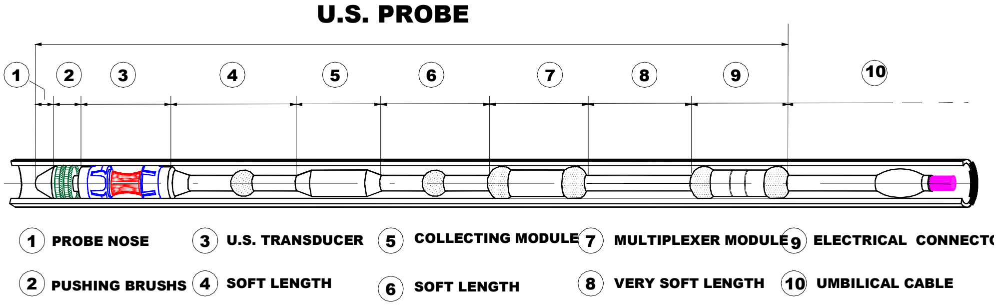


Figure 5 Scheme of the ultrasonic probe

The *Visual System* is equipped with an axial and a radial microcamera.

The *Hydraulic Driving System*, shown in Figures 4 and 5, uses a reversible water stream to push the probe with attached umbilical cord inside the tube.

The *Cleaning/Gauging System* has been designed to remove pulverable deposits from the internal surface of the SG tube and to verify the absence of inner geometric deformations of the SG tube . A *Hydraulic System* feeds a water stream into the SG tube, to push the Brushing or the Gauging Devices .

The *Brushing Device*, shown in Figure 6, is a component of the *Cleaning and Gauging System* In the *Gauging Module Configuration*, the Brushing Device is replaced by a calibrated ball.

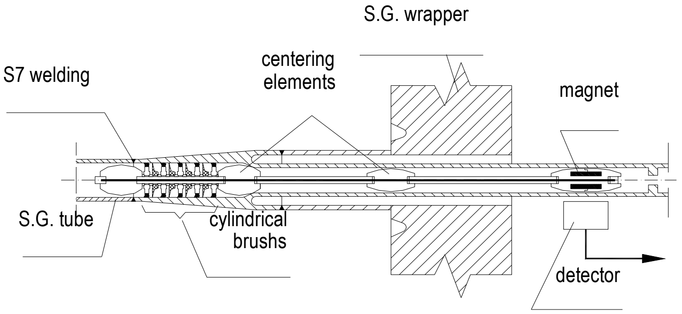


Figure 6 Brushing Device

In 1997, 36 SPX SG tubes were successfully inspected with this US system: three flaws due to manufacturing were detected and no defects were due to the SG operation.

Proposed In-Service Inspection of the IRIS SG tube bundles. The IRIS SG modules have helicoidal-tube bundles, akin to the SPX SG. The average tube length, the tube ID and the smallest bend radius of the helical rows are different from SPX:

- IRIS tube length is about 32 m, no welds, vs ~100 m length and 7 welds of the SPX tubes;
- IRIS tube ID is 14.5 mm vs 19,8 mm ID of SPX (reduced, however, to 17.8 mm at the welds and bends);
- IRIS smallest bend diameter of the rows is about 640 mm vs 1170 mm of SPX;
- IRIS has a smaller number of bends in the tubing connecting tube bundle and tubesheets (4 to 5 bends vs 10 bends of SPX);
- higher radii of curvature for the IRIS bends: 6 to 8D vs 5D of SPX.

A US probe can be used also in IRIS, because the greater difficulty in pushing the probe inside a smaller tube (US probes are available for testing tubes with ID as small as 12 mm) is compensated by the shorter tube length and the lesser bends. Thus, the SPX SG In-Service Inspection System could also be used for testing the IRIS SG tubes, with only the modifications to the US probe assembly required by the different steam header, which features two vertical tube sheets.

The scheme of a possible mechanism for introducing probes into the tubes is shown in Figure 7 and details A and B.

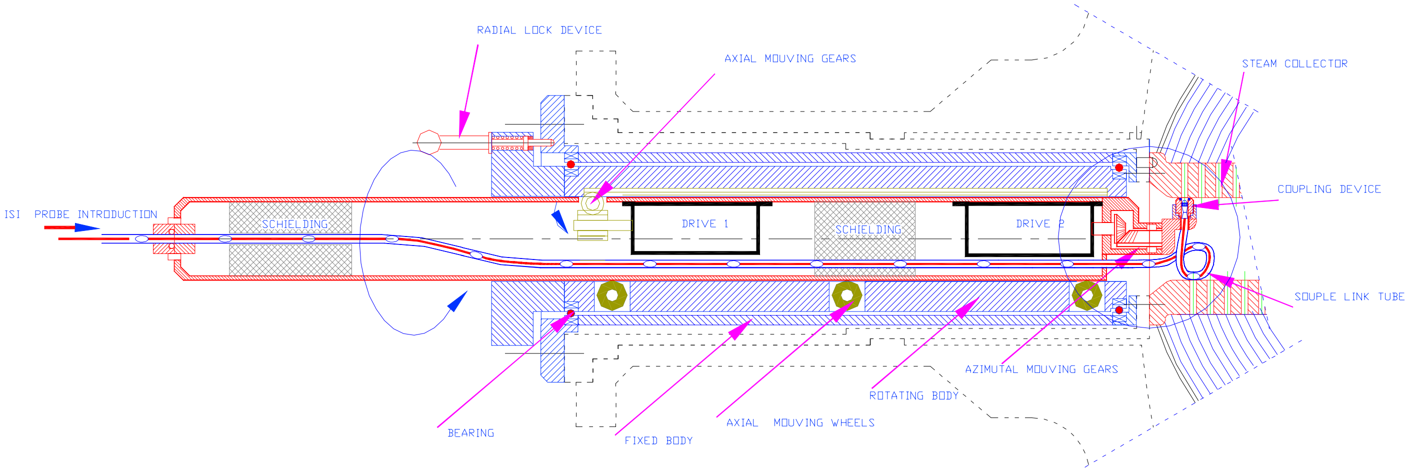


Figure 7: Scheme of the ISI probe assembly bolted on the steam nozzle

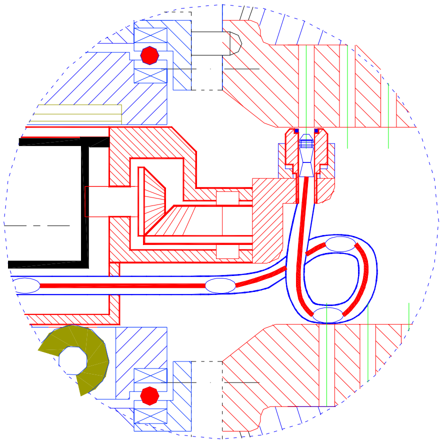


Figure 7: Detail "A"

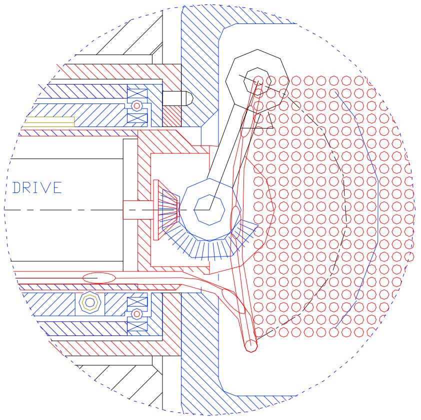


Figure 7: Detail "B"

The US probe assembly consists of three concentric cylinders, complete of stepping motors and gears, the function of which is to place the probe-carrying tube end/tube sheet coupling device exactly on the generic tube hole as shown in Fig 7 and detail drawing A. The outer cylinder is bolted on the steam nozzle, whereas the intermediate cylinder is rotated and locked on position manually. The inner cylinder, driven by a motor, carries the coupling device one tube hole further, while a second motor coupled to a pinion gear allows the coupling device to reach each row, as shown in detail drawing B. The probe and attached umbilical cord, provided with uniformly spaced beads, which fill out the cross sectional area of the tube, can thus travel along the SG tube, pushed by water. Location of flaws is determined by probe travel measurements.

It will be noted that, with the proposed mechanism, it is possible to carry out ISI by simply removing the blind flange bolted on the steam nozzle, without removing the steam lines or having to operate from inside the reactor vessel.

ACKNOWLEDGEMENTS

The financial support of the IRIS program (NERI Grant DE-FG03-99SF21901) by the US DOE is gratefully acknowledged. Contributions by the IRIS consortium members were invaluable to the progress of the project.

REFERENCES

[1] Cinotti L. et al., 1993 - *The Inherently Safe Immersed System (ISIS) reactor* - Nucl. Eng. Des. Vol. 143; pp. 295-300.

[2] IAEA-TECDOC-881, May 1996, Design and Development Status of small and medium reactor systems.

[3] SIET 00530RP96, Rev.0, “ISIS: Sezione di Prova del Generatore di Vapore, Rapporto Finale di Prova” (Final Test Report), issued April 20th, 1998 (Proprietary).