TORREVALDALIGA NORTH
ULTRA SUPERCRITICAL
CLEAN COAL FIRED BOILERS:
AN EXPERIENCE OVERVIEW

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Introduction

The Torrevaldaliga North 3x660 MW USC pulverised coal fired boilers project (see fig.1) has been completed and all the three units are now in commercial operation following the successful performance tests. The Enel Power Plant of Torrevaldaliga North (Civitavecchia-Italy) is one of the most advanced clean coal fired power plant in the world, adopting the best available technologies in terms of boiler material selection and boiler emission abatement.

Based on the experience gained, this paper gives an overview of the most significant design data and provides an update on the operational behaviour of the boiler. It focuses on the results of the functional tests and presents the data related to the various load variation conditions. Finally this paper reports the experience gained with the welding processes of P92, advanced alloy steels and austenitic steels and describes peculiar design features of boiler components.

Fig. 1 - Torrevaldaliga North Boilers view

Project Description and Updating

The Torrevaldaliga North project execution started in December 2004 and the three units were completed in June 2009 (first unit), January 2010 (second unit) and August 2010 (third unit); the steam generators have been in commercial operation for several months following the successful performance tests.

The details of the final commissioning time schedule before commercial operation are reported in the table below; Ansaldo Caldaie performed such commissioning activities leading the boiler commissioning team.

	First Unit GR. 4	**Second Unit GR. 3**	**Third Unit GR. 2**
First coal firing	Dec. 08	Aug. 09	March 10
First full load coal firing	05 March 09	24 Sept. 09	28 Apr. 10
Start of boiler commercial operation	22 June 09	31 Jan. 10	05 Aug. 10

Successful performance tests were carried out, respectively, on

◊ 26-27 May and 3 June 2009 for Unit 4

◊ 12-13-14 January 2010 for Unit 3

◊ 3-4-5 August 2010 for Unit 2

just before the beginning of the commercial operation of each unit.

The three boilers have operated regularly and smoothly during the commercial operation period and have cumulated, as at March 30, 2011, about 15,000 hours of operation, full load equivalent, and a power production of 10 TWh [4].

The steam generators have been supplied by a consortium (Temporary Association of companies “ATI” according to the Italian law) formed by Ansaldo Caldaie S.p.A. and Babcock Hitachi Kure (BHK) with Ansaldo Caldaie acting as Leader of the Consortium and Leader Manufacturer.

According to the regulations in force in the European Union, Ansaldo Caldaie was legally the Boiler Manufacturer who has the sole and ultimate responsibility for designing, manufacturing and installing the boiler, guaranteeing the conformity of the product with the applicable European Directives.

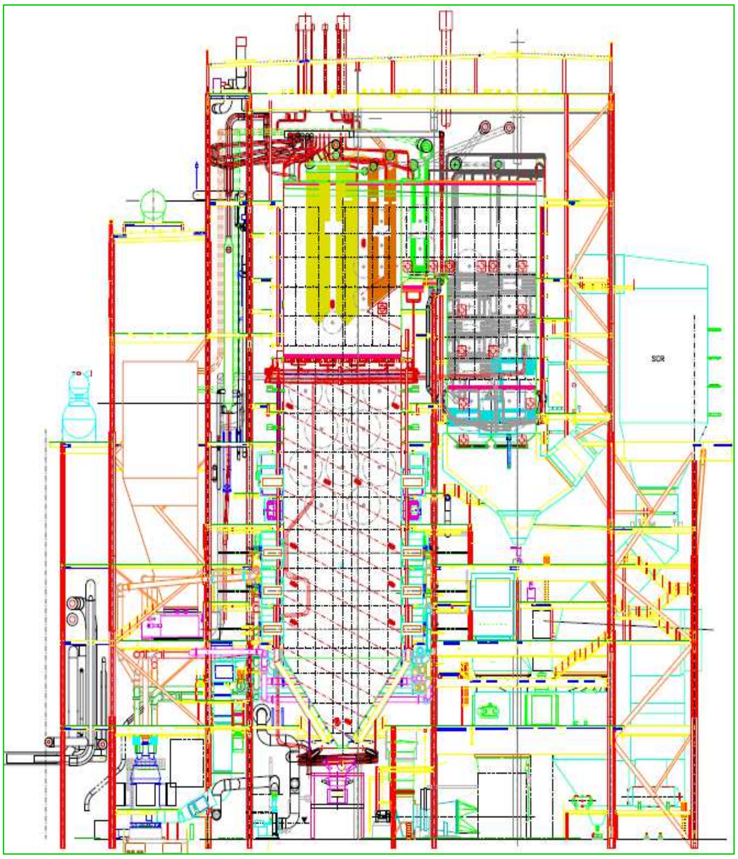
The steam generators are Benson type with spiral wound furnace wall tubes suitable for variable pressure operation, according to the Benson technology licensed by Siemens to most of the utility boiler makers in the world as Ansaldo Caldaie, BHK and other primary steam generator suppliers.

Each steam generator is rated 660 MWe at the Boiler maximum continuous rating (MCR), with steam conditions of 253 bar/604 °C at superheater outlet and 55.7 bar/612 °C at reheater outlet with a feedwater temperature of 313 °C [1].

The steam generators (see fig. 2) are designed to fire an extended range of worldwide sourced bituminous coals: 16 types of coals from South Africa, Indonesia, China, Columbia, Venezuela, Poland, USA, Australia, Russia, Ukraine, with the following range of coal properties on as received basis:

Moisture	%	6.5 ÷ 15.5
Ash	%	3.5 ÷ 15.0
Volatile matter	%	22.0 ÷40.0
Sulphur	%	0.3 ÷ 1.0
HHV	KJ/kg	25960 ÷ 30150

Fig. 2 - Torrevaldaliga North Power Plant view including coal handling systems and Storage domes



The steam generators (see fig. 3) are of the two-pass type with opposite front-rear firing system and divided back pass with gas biasing dampers to control reheater steam temperature by modulating the flue gas flow through primary reheater and primary superheater surfaces located in the two parallel gas passes; the system is designed for zero spray water attemperation for RH steam temperature control in the whole control range.

Fig. 3 – Torrevaldaliga North Boiler – Longitudinal section view

The pulverised coal system and the air and gas system include: six pulverised coal mills of the vertical spindle type feeding twenty-four register low-NOx burners located on four rows on front and rear walls for opposite firing; two trisector regenerative air heaters of the Ljungstrom type; two forced draft fans of the axial type and two primary air fans of the centrifugal type.

The boiler unit is equipped with a SCR system, located upstream the regenerative air heaters, designed to reduce NOx emission to values below 85 mg/NM3 (6% O_2 dry, by vol.).

The plant is also equipped with a bag filter for dust emission control and with a FGD system, both not included in the boiler contractual scope, in order to achieve minimum emission levels below 50% of the regulation limits [2].

The steam parameters and the very low emissions are such that the plant can be considered among the most advanced “Clean coal” fired plants in the world and represents a benchmark for the European power generation technology [3].

This has been fully demonstrated by the positive results of the performance tests.

The steam generators demonstrated continue and regular operation during the initial months of commercial operation and are now completing the warranty period of two years from beginning of commercial operation.

The development of Supercritical coal fired boilers in the Italian Power Plants

Ansaldo Caldaie includes in its reference list all the supercritical boilers operating in Enel Power Plants in Italy; among such units, the Torrevaldaliga Nord steam generators represent the key milestone in the development of Italian coal fired supercritical plants from old "UP" type supercritical to the state of art Benson ultra-supercritical (see fig. 4).

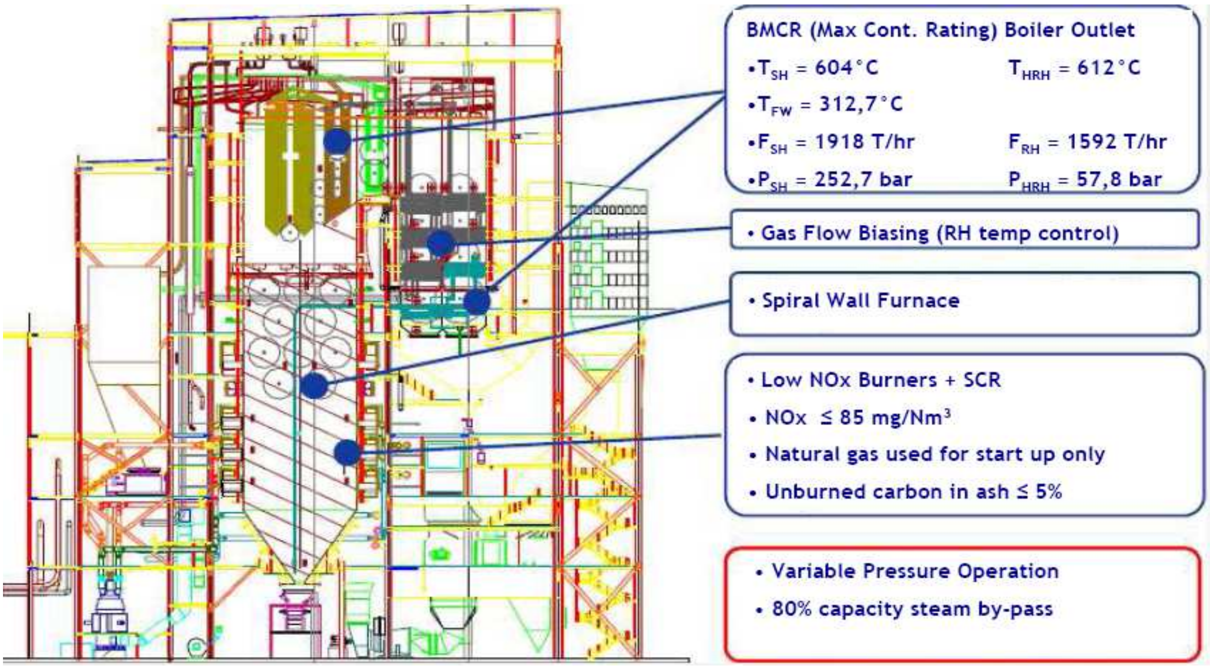


Fig. 4 – Torrevaldaliga North Boilers – Main Design Data

The tables below highlight a comparison between the main design data of Torrevaldaliga Nord (Benson USC) and Brindisi Sud (UP supercritical) the latest previous coal fired supercritical plant entered into commercial operation in Italy in the years 1998-1999.

The development of supercritical coal fired boilers in the Italian Power Plants – Main Features

	TORREVALDALIGA NORD	BRINDISI SUD
Boiler type	Benson	UP
Boiler arrangement	Two-pass	Two-pass
Applicable pressure	Supercritical	Supercritical
Operating pressure	Sliding	Constant
Furnace walls tube arrangement	Spiral	Vertical multi-pass
Furnace tube outside diameter	38 mm	28.6 mm.
Material	16 Mo 3	A 213 T2
Start up system	Separator & circulating pump	Flash tank
Minimum load for once through operation	30-35%	30%
Load change rate	Higher	Base
Start-up time	Faster **(*)**	Longer **(*)**
SH and RH temperature control range	50-100%	55-100%
SH temperature control method	Spray water (2 stages)	Spray water (one stage)
RH temperature control method	Biasing dampers	Gas recirculation
SH and RH outlet temperature	604 / 612 °C	540 / 540 °C
SH and RH outlet headers material	P92	P22
Final SH and RH tubes material	Super TP 304 H	TP 304 H

(*) for cold start-up: "steam to turbine" time 220 min. (Torrevaldaliga Nord) vs. 300-540 min. (Brindisi Sud)

The development of supercritical coal fired boiler in the Italian Power Plants - Furnace Design Data

		TORREVALDALIGA NORD	BRINDISI SUD
Rated power	MWe	660	660
SH steam flow at MCR	t/h	1918	2160
SH/RH steam temp.	°C	604/612	540/540
SH steam pressure	Bar abs	252.7	256
Design fuel	-	Bituminous coal	Bituminous coal/heavy oil
Coal HHV	Kcal/kg	6313	5926
Furnace width	m	22.5	20.1
Furnace depth	m	14.2	15.5
Numbers of mills	n	6	7
Number of burners	n	24	56
Volumetric heat release on HHV (1)	KW/m^3	91	117
Furnace heat release on EPRS (1)	KW/m^2	181	245
Heat input / plan area (1)	KW/m^2	4819	5591
Flue gas velocity (maximum)	m/s	17	15
Residence time (2)	sec	3	2.3

Notes: (1) Heat input calculated as HHV x Flue flow @ BMCR load

(2) Residence time calculated from the centreline of main burners zone to the horizontal plane at boiler arch tip

From the above data, the steam generator design development towards the highest steam temperatures appears associated to conservative criteria for the furnace heat release rates and, in particular, to longer residence times in the furnace to support the requirements of the modern in-furnace NOx reduction techniques while maximizing the combustion efficiency. In addition to the well known advantages of a Benson Boiler in terms of high performance due to the sliding pressure operation and high operating flexibility with fast starting times and higher load change rates, the conservative sizing of the furnace and of the convective passes allows high operating reliability in relation to the use of a wide range of coals.

Steam Generator Functional Test Results

The steam generators functional parameters have been tested in relation to the overall "Unit Performance Test" carried out in order to verify the maximum continuous capability of the power plant meeting or exceeding the specified 660 MW.

For each unit, tests have been performed at maximum continuous rating (MCR) and at the steam temperature control rating (STCR) corresponding to 50% of nominal continuous rating of the steam turbine (NCR) according to the contract specifications.

Each test had a duration of 4 hours and all the parameters have been measured with a frequency of 30 seconds.

The functional tests have been carried out in accordance with the latest edition of ASME PTC 4.1 "Test Code for Steam Generating Units" (Heat loss Method) and the boiler efficiency has been calculated as "fuel efficiency" with the formula

Boiler efficiency = 1 + B – L

where B (heat credits) and L (heat losses) are according to the definitions of ASME PTC 4.1, par. 7.3.

In the test results evaluation, no tolerances coming from measurements uncertainties have been taken into account.

The main reference conditions for the tests were:

- flue gas temperature (corrected for AH leakage) not less than 120°C at boiler MCR with 30°C ambient temperature
- oxygen at economizer outlet not greater than 3.5% by vol.
- five (out of six) pulverisers in operation
- steam air heaters excluded

- unit control mode “turbine follows”, turbine under load limitation, participation to the secondary frequency control excluded

Significant functional test results are summarized in the following tables:

		MCR FUNCTIONAL TESTS RESULTS (AVERAGE)		
Functional Parameter	**Design Value**	**FIRST UNIT (GR. 4)**	**SECOND UNIT (GR. 3)**	**THIRD UNIT (GR. 2)**
Boiler heat output (actual vs.design)		+ 3.2%	+ 3.45%	+ 3.7%
SH steam flow (kg/s)	≥ 532.8	533.3	538.7	535.2
SH steam temperature (°C)	604 + 4/-0	604.4	604.5	604.5
RH steam temperature (°C)	612 + 4/-0	615.3	612.9	612.4
FEGT (°C)	≤ 1160 ± 20	1162.5	1118	1124
Boiler efficiency on LHV (%)	94.6	94.9	94.82	94.74
Pressure drop from ECO inlet to SH outlet (bar)	≤ 35	29.1	34.85	34.8
Pressure drop through RH (bar)	≤ 1.96	1.40	1.49	1.66
Flue gas draft loss from furnace to AH exit (mbar)	≤ 34.2	24.7	28.8	24.3
NOx at AH exit (mg/Nm^3)	≤ 85	40.9	75.6	47.2

		STCR FUNCTIONAL TESTS RESULTS		
Functional Parameter	**Design Value**	**FIRST UNIT (GR. 4)**	**SECOND UNIT (GR. 3)**	**THIRD UNIT (GR. 2)**
SH steam temperature (°C)	604 + 4/- 0	605.5	604.3	604.5
RH steam temperature (°C)	612 + 4/- 0	615.8	612.3	613.5
Boiler efficiency (%)	94.36	94.98	94.91	94.6

During the tests, coal composition was close to the guarantee reference fuel (i.e. South African coal) for all the three Units.

The following table reports coal composition during tests versus the guarantee reference.

		Ref. Coal	Unit 4 / Test	Unit 3 / Test	Unit 2 / Test
Moisture	%	7.4	9.3	9.0	7.8
Volatile matter	%	24.6	22.7	31.8	24.4
Ash (dry basis)	%	13.6 (*)	21.2	16.6	13.6 (*)
HHV	KJ/kg	26426	25966	25410	26124
LHV	KJ/kg	25460	25217	24411	25112
Ash I.D.T.	°C	> 1340	> 1300	1250	> 1400

(*) as received basis

We highlight the following considerations from the successful results of the performance tests:

- the proper design margins of the steam generator and its auxiliaries are confirmed by the achievement of a significant overcapacity over 3% greater than the design heat output for each unit and by the pressure drops of both water and steam circuits and flue gas circuit less than guaranteed;
- the superheater and reheater outlet steam temperature are easily controlled at the nominal values over all the load control range by means of the biasing dampers located in the rear pass, thus confirming the effectiveness of such system for a USC boiler as already verified on several drum type coal fired boilers installed by Ansaldo Caldaie in the past years;
- the very low emissions achievable by the combination of in-furnace emission reduction techniques with a selective catalytic reduction system properly sized.

<u>Operational behaviour of the boiler</u>

Testing activities highlighted the operational behaviour and the flexibility of Torrevaldaliga North steam generators during steady-state condition and during load change variations requested by the grid in order to satisfy load-frequency control requirements. It has to be noted that during the first two years of commercial operation most of the continuous operation hours have been performed from 60% MCR to MCR and the daily load variations from day to night time occurred within such load range.

a) <u>Steady-state condition</u>

The operational behaviour of Torrevaldaliga North steam generators during steady-state condition at maximum continuous rating (MCR) has been evaluated by comparing the performance data collected during test activities with the expected calculated performance data.

A good compliance between measurements and predictions has been demonstrated; referring to the boiler performance tests of Group 4 steam generator, the following significant performance data have been compared:

- Water and steam temperature of the high pressure circuit (Fig. 5).
- Water and steam pressure of the high pressure circuit (Fig. 6).
- Water and steam pressure of the reheater circuit (Fig. 7).

The following diagrams show the comparison between calculation and boiler performance test data at various sections of the boiler heating surfaces.

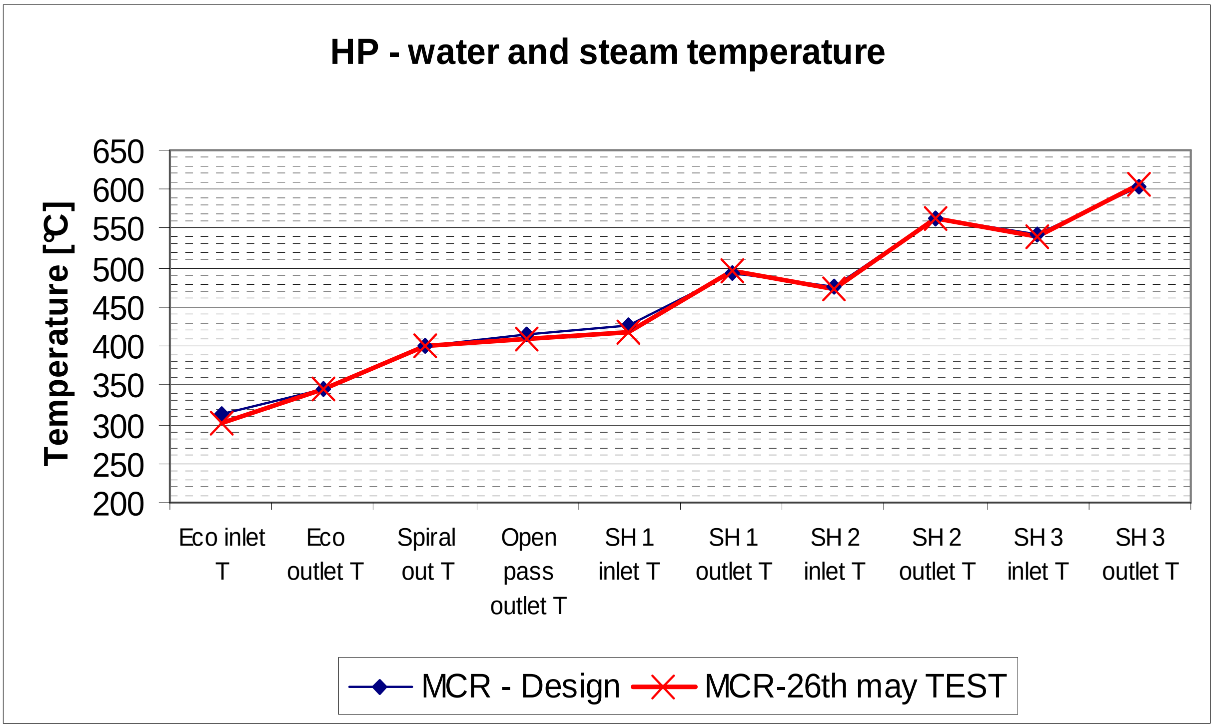


Fig. 5 - As shown in the diagram above, the predicted data are very close to the Test data

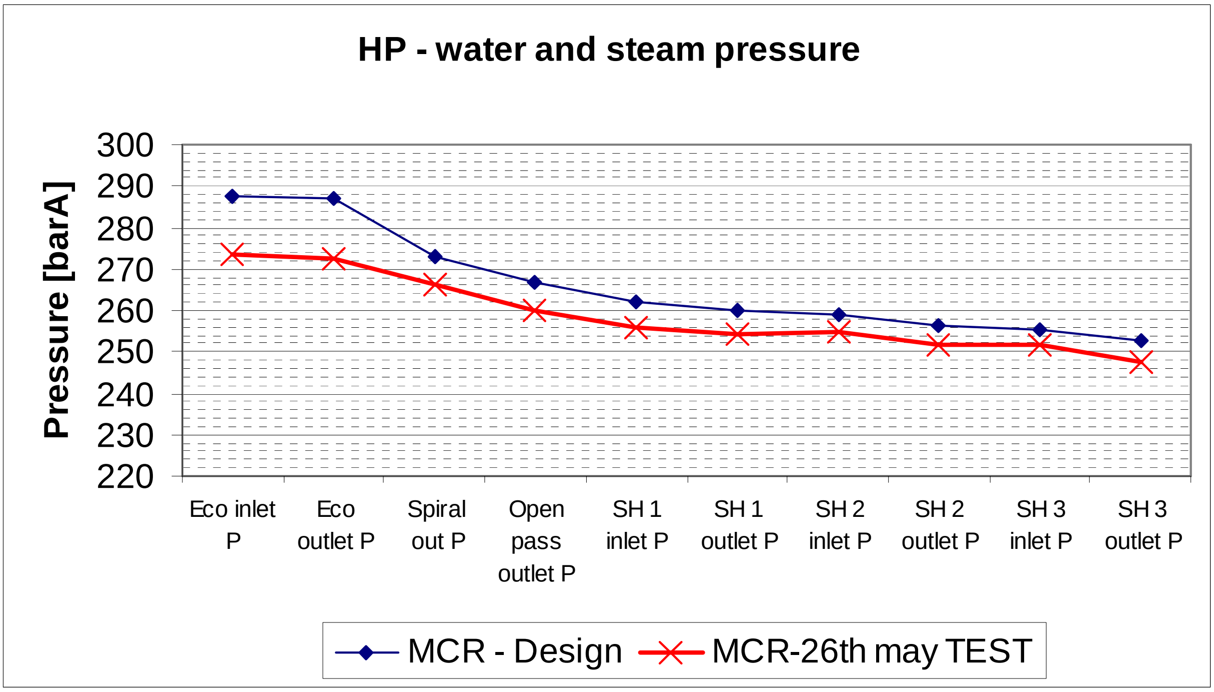


Fig. 6 - Water and steam pressure drops of the high pressure circuit from the Test are lower than the ones calculated during design phase.

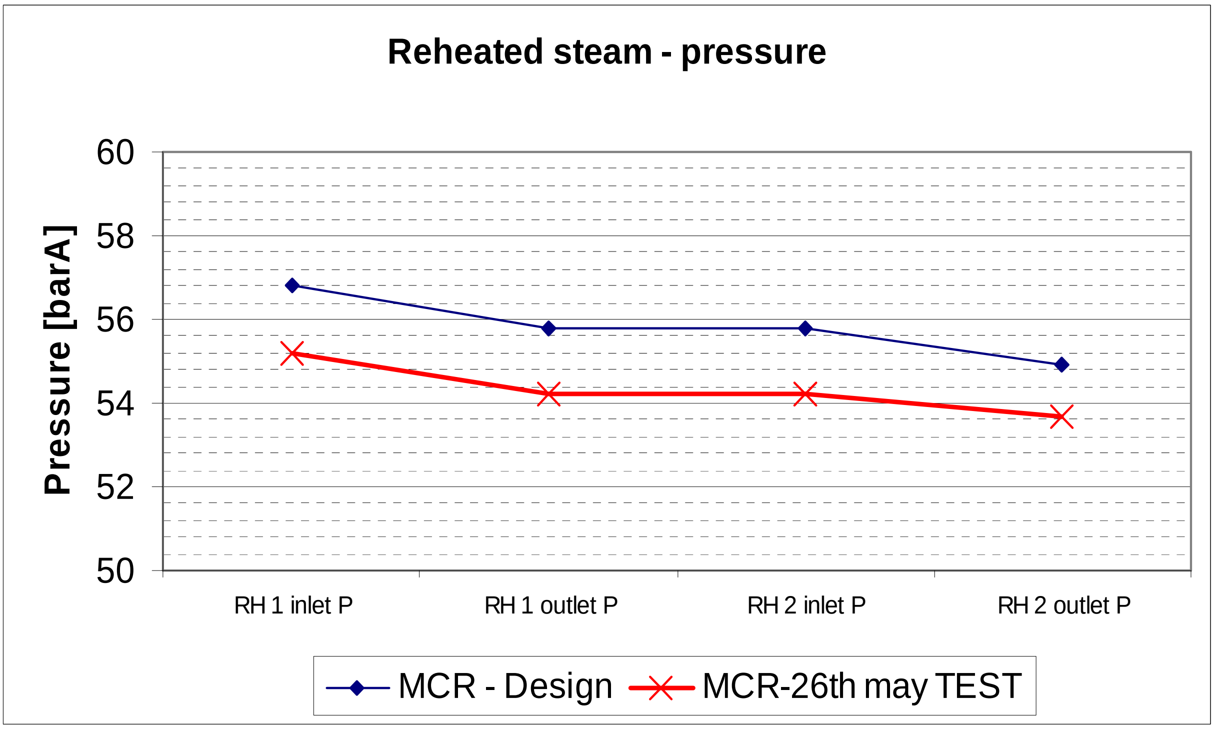


Fig. 7 - The actual Reheater pressure drop is slightly lower than the predicted value, thus satisfying the guarantees.

b) Primary Frequency Control

The Torrevaldaliga North steam generators demonstrated their capability of operating in compliance with the requirements of the grid code regarding primary frequency control according to the specified design requirements.

In general, the objective of primary control is to maintain a balance between power generation and power demand. In case of frequency variation each Power Generating Unit shall provide the foreseen primary reserve in order to stabilise the grid condition.

Each Power Generating Unit shall be capable of guaranteeing primary reserve according to frequency error as per formula reported below:

$$\Delta P_e = -\frac{\Delta f}{50} \cdot \frac{P_{eff}}{\sigma_p} \cdot 100$$

ΔPe = Net Power Variation

Δf = Frequency Variation

σp = “Statism”

Peff = Net Power

Based on this formula, for frequency error Δf ≤ 100 mHz during normal operation a net power variation Δpe = 4% Peff should be released in 30 seconds.

Test activities have been carried out successfully, the capability of the plant to achieve primary reserve of the Net Power has been confirmed.

Referring to a frequency error of about 100 mHz, the required primary band of Net Power has been provided by turbine valve throttling.

Considering the turbine inlet pressure behaviour, the Boiler response time has been calculated to be around 90 seconds, this time allows to recover the primary reserve provided by the turbine system and to maintain the power reserve for 15 minutes as required by the grid code.

Considering the Turbine throttling valve operation, the power reserve is immediately available and rapid boiler response allows to maintain this power.

<u>Experience gained with the manufacturing processes of advanced alloy steels under PED and EN regulations.</u>

Through the activities performed during the different phases of the Torrevaldaliga North project, Ansaldo Caldaie gained a large experience on material design criteria, purchasing specifications, manufacturing and construction procedures for boiler pressure parts components realized with some of the most significant new advanced high performance materials, such as:

- EN 10216-2 – 7CrMoVTiB10 – grade T24
- EN 10216-2 - X10CrMoVNb5 – grade 92
- Vd TUV WB 550 - SUPER 304 H.

Moreover, a large quantity (about 400 tons for each boiler) of “traditional” high alloy high creep strength steel, i.e.:

- EN 10216-2 - X10CrMoVNb9-1 – grade 91

has been used for boiler and external piping systems.

An overview of boiler pressure parts material is given in figures 8 and 9.

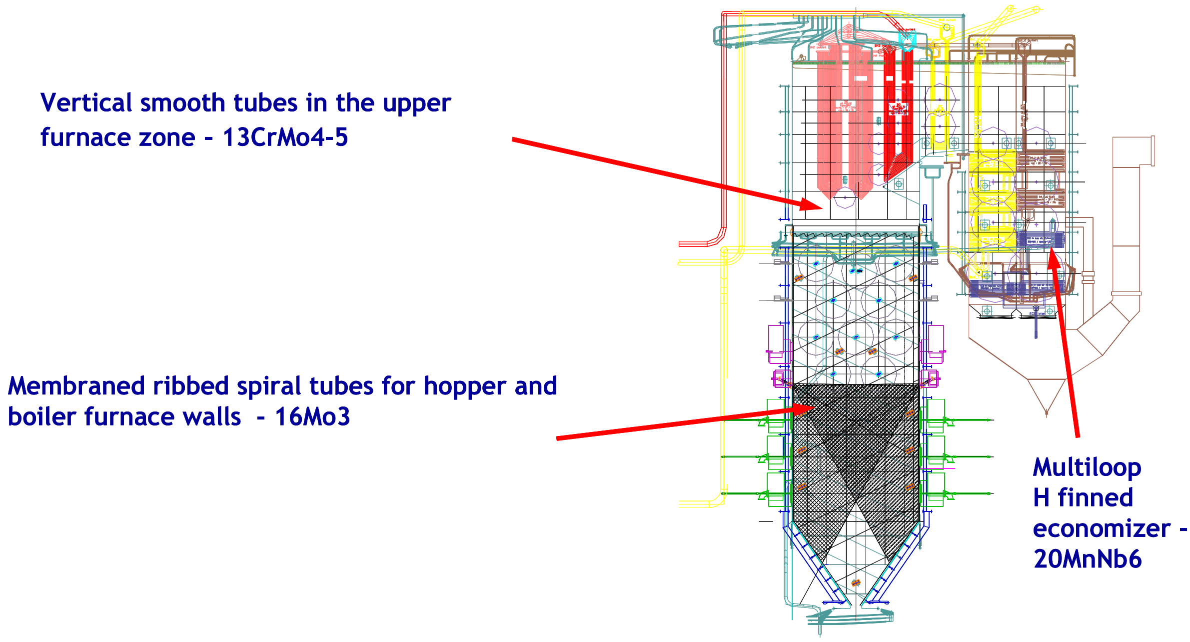


Fig. 8 - Pressure Parts Materials – Furnace and rear pass walls, economizer

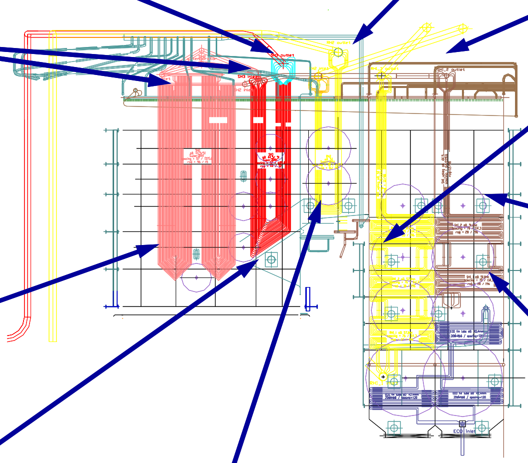


Fig. 9 - Pressure Parts Materials – Superheater and reheater

For material procurement, dedicated Purchasing Technical Specifications have been prepared, containing technical and certification requirements, in order to assure that the raw materials for pressure components (tubes, pipes, forgings) would be manufactured and tested according to PED and EN standards and, in particular, would have the required design mechanical and metallurgical characteristics and properties.

During workshop manufacturing, Ansaldo Caldaie has qualified the procedures for the required processes, such as automatic and manual welding, cold bending and hot forming, as per design requirements.

Of course, welding activities involved not only homogeneous or heterogeneous tubes and pipes welding, but also welding of high alloy supports and accessories.

Superheaters and reheaters coils in grade T24 material have been manufactured, for a total quantity of about 600 tons (for each of the three boilers); more than 6,000 shop welds (for each of the three boilers) have been performed and more than 3,000 welds (for each of the three boilers) have been carried out on site, partly in the pre-assembly area and partly during boiler erection.

All these components have been effectively heat treated, implementing a manufacturing cycle with Post Weld Heat Treatment, including also bending activities, where required. Site welds also have been subjected to P.W.H.T., assuring the required characteristics of toughness.

During erection activities (see fig. 10) Ansaldo Caldaie has also qualified the procedures for the required site welding processes.

High temperature Superheater and Reheater headers and pipes in grade P92 material have been erected, assembled and welded on site, for a total amount of 150 tons (for each of the three boilers); about 100 heavy thickness welds (up to 115 mm) have been performed, post weld heat treated and positively tested.

High temperature Superheater and Reheater coils in grade SUPER 304 H material have been assembled and erected on site, for a total amount of 700 tons (for each of three boilers); more than 3,000 welds have been performed and tested.

The above extensive experience in fabrication and welding of "advanced" alloys has been transferred into several updated or new welding procedures prepared, adjusted and qualified according to EN by Ansaldo Caldaie during the project execution.

Such know-how is added to the wide past experience of Ansaldo Caldaie with the standard alloy and austenitic steels for utility boilers and completes the various development activities on welding processes performed in the last years by Ansaldo Caldaie through the participation in European R&D projects (such as COST and AD 700 Phase 2).

At present the steam generators have cumulated several months of successful full load operation without any problem related to the welds including the welded joints between all kind of high alloy steels.

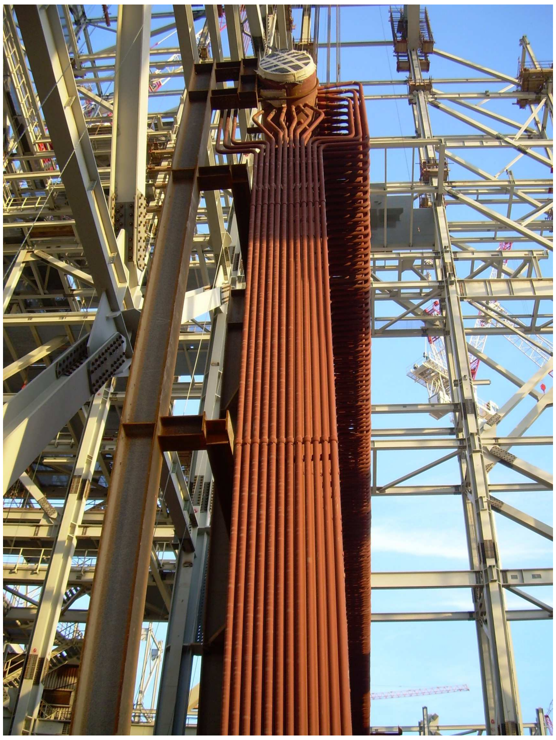


Fig. 10 – Torrevaldaliga North – Pressure parts erection phases

Pulveriser design

According to Enel’s decision taken in the bid phase, 18 existing pulverisers and feeders (6 for each boiler) owned by Enel were refurbished by Ansaldo Caldaie and installed on the new boilers. They derived from a past 4x660 MW coal fired project interrupted in the 90s before starting the site activities, at that time the components were completely manufactured and delivered to Enel and then left stored for more than ten years.

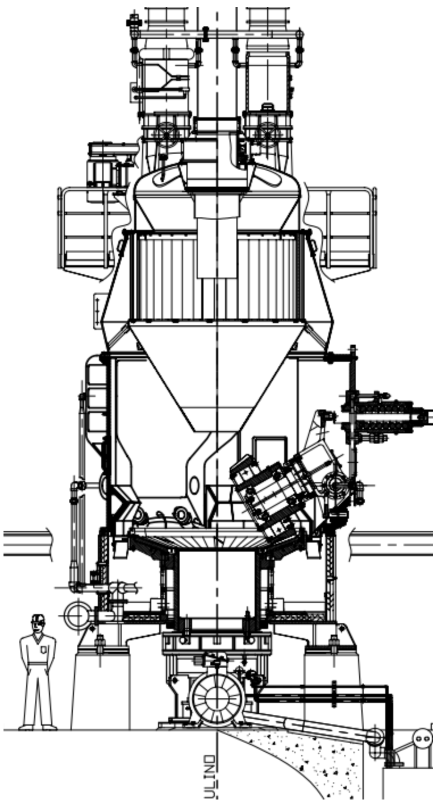


Fig. 11 - HP 1003 Mill

In particular, the pulverisers were of the type HP 1003 from CE-Raymond design (see fig. 11), manufactured by Franco Tosi, one of the predecessor companies of Ansaldo Caldaie.

In order to be installed in the new plant of Torrevaldaliga, the pulverisers had to undergo a complete refurbishment (including gearbox, lube oil system, roller bearings, motor-gearbox coupling), and have been upgraded replacing the original static classifier with a rotary classifier in order to achieve the fineness requirements of modern low NOx firing systems. New mill motors have been also procured and the complete mill has been revamped as needed in order to be certified according to ATEX and CE marking rules.

The rotary classifiers have been supplied, on the basis of Ansaldo Caldaie specifications, by Loesche, one of the primary pulveriser suppliers in the market.

In addition, some modifications of the throat gap have been implemented in order to suit the mill internals to the new operating conditions deriving from the rotary classifier.

The pulveriser expected original performance versus the anticipated performance due to the above modifications were:

	Existing original pulveriser	Modified pulveriser
Hardgrove Index	45	45
Moisture content (%)	10	12
Raw coal feed (max. capacity) (t/h)	54	46
Primary air flow (kg/h)	101.000	86.900
Mill outlet temperature (°C)	80	85-90
PC fineness through 200 mesh (%)	75	80
through 50 mesh (%)	< 98	99.5
Motor rating (KW)	450	500
Pressure loss (mm w.g.)	406	481

According to the above data, the modified pulveriser maximum capacity has been selected for the worst coal conditions (minimum HGI and maximum moisture, corresponding to one type of South African coal) with a margin of more than 10% on the coal flow at MCR with 5 mills in operation; the maximum capacity increases up to 48.5 t/h with other coals of the contractual range due to a different combination of coal parameters (lower moisture, higher HGI and heating value) keeping a margin of up to 15% on the MCR coal flow.

The field measurements demonstrated a good accordance of the anticipated performances with the actual performances.

Minor operating problems, related to mill outlet shut-off valves or pyrite discharge devices, have been analyzed in detail and successfully solved with specific engineering efforts.

The same refurbishment activity has been developed by Ansaldo Caldaie for the volumetric coal feeders, Metallic plate conveyor type, “ERKO”, Besta design (see fig. 12), again originally manufactured by Franco Tosi.

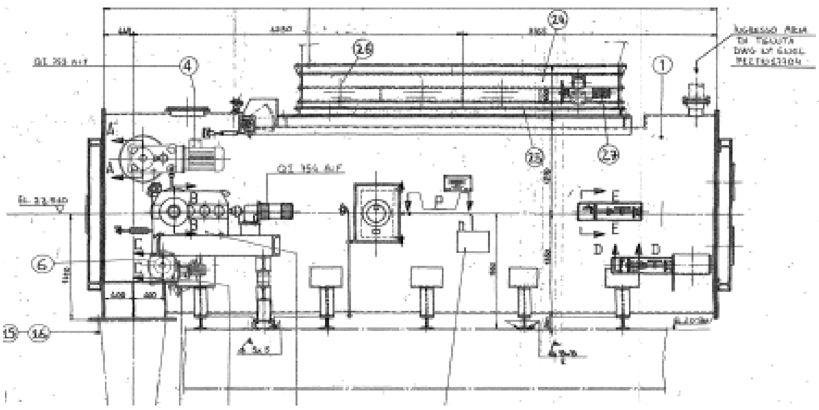


Fig. 12 - Erko Feeder

Specific revamping actions, such as replacement of electric motors and selected instrumentation, have been implemented also in this case in order to certify these machines according to ATEX and CE marking rules.

Conclusions

The experience gained by Ansaldo Caldaie in Torrevaldaliga North project execution can be considered as a significant milestone in the Company's own development of the USC Benson Boiler product for pulverised coal firing.

The design and construction experience with advanced pressure parts materials industrially available and the operational experience with advanced steam parameters firing a wide range of coals represent a proven reference for the next projects of supercritical and ultra-supercritical Benson Boilers suitable to satisfy the up-to-date requirements of high performance, high operating flexibility and high reliability for the world wide state of art power plants.

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