ONE MW BINARY CYCLE TURBOGENERATOR MODULE MADE IN EUROPE

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ABSTRACT

An Organic Rankine Cycle Turbogenerator producing 1.3 MW gross electric power has been designed, built and installed by two Italian Companies. The machine is the first One Megawatt size geothermal ORC completely realised in Europe.

The unit operation started in July 1992 and the measured performance, compared to calculated values, is reported. Though the efficacy of the condenser is somewhat hindered by the incondensable gases, the overall efficiency is quite high, with a turbine efficiency in excess of 80 percent.

The characteristics of some eligible, non combustible working fluids, as well as the advantages of multiple unit cascading, are discussed.

In conclusion ORC operating with non flammable fluids are an efficient and environmentally safe way to exploit low temperature geothermal sources.

1. INTRODUCTION

The development of geothermal power generation is nowadays based on the exploitation of water-dominated fields, by far more common than steam-dominated ones.

An increasing share of generating capacity recently installed in reservoirs of the former type is made up of binary units, particularly suited for low and medium temperature resources.

The incremental installed power of binary units totalled around 300 MW at the end of 1993, most of which in the U.S. (Table 1), with an approximate two-fold increase in the five years period 1988-1993.

This means an average 15% yearly increase of capacity, compared with an almost stagnant situation for geothermal capacity worldwide.

Binary power plants feature many advantages.

- They are environmentally more acceptable than any other kind of

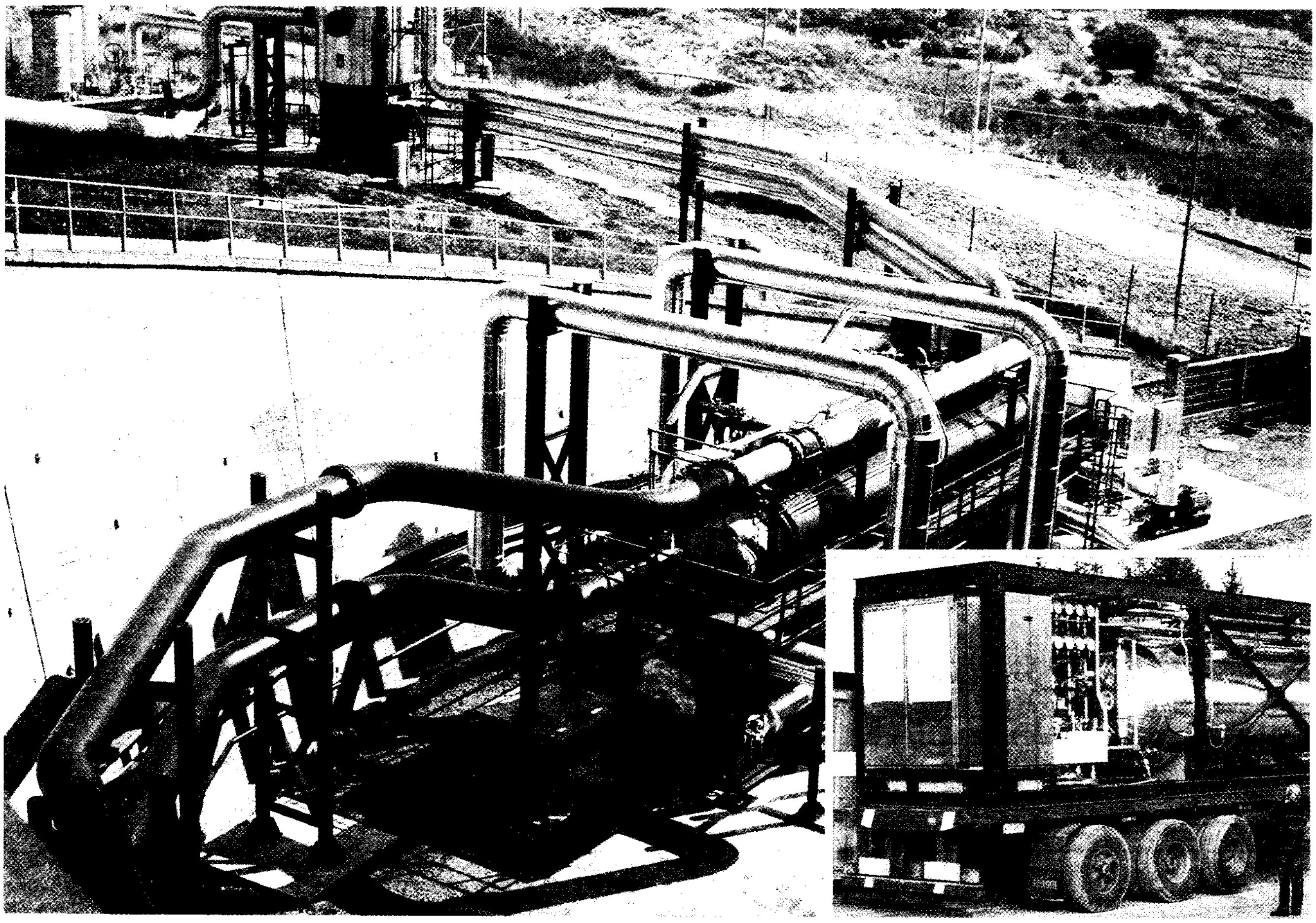

Fig. 1 -The 1.3 MWel Organic Rankine Cycle Turbogenerator installed at Castelnuovo V.C., and lower skid ready for transport

geothermal power plant: the segregation of the geothermal fluid throughout the whole process prevents any release of gases or other substances to the environment, thus eliminating the pollution problems.

- They have a definite thermodynamic advantage, in terms of power production, compared to the conventional flashed steam cycles, for resources at moderate temperatures (up to 150-180 °C).
- They can be used for electricity generation with low-temperature resources (close to 90-100 °C).
- They reduce the problems associated with scaling fluids: carbonate scale is prevented by installing downwell pumps, while silica scale is minimised avoiding the concentration caused by flashing.
- They may be the best technical and economical choice, despite the generally higher unit cost of the installed capacity, thanks to the higher power output and to the reduction of the on-site construction time.

2. THE CASTELNUOVO 1.3 MW UNIT.

In the frame of the EEC THERMIE program, a 1.3 MW unit was designed and built by two Italian Companies: Sowit and Turboden. The basic ORC technology was handed by Turboden.

The unit was tested at Castelnuovo V.C., near Larderello, in the vicinity of an Enel geothermal power station.

The site being in a steam-dominated field, there was no geothermal water source in the area.

Enel thus decided to design and build a water loop with direct-contact condenser and circulation pumps in order to pr[illegible]ce hot water from low-pressure steam.

In this situation, with the aim of obtaining the maximum power output from the binary unit, the choice was made to have a large circulating flow rate (140-280 kg/s) with a small temperature difference (11.5 °C) across the pre-heater/vaporiser of the binary unit.

The machine (Fig. 1) was completed and connected to the grid in July 1992. It was then operated often but not continuously, as the installation was intended as a test bed: in fact the ORC operation reduces significantly the steam available for to the power station.

The ORC unit will be finally transferred to a water dominated field, Torre Alfina, near Rome.

At the time of transfer the working fluid will be substituted to meet the requirements of Montreal Convention concerning ozone-depleting fluids (see chapter 3).

The Italian 1.3 MW ORC Turbogenerator was designed for ease of transport and final site erection; hence it is composed of three

Table 1 - Commercial Binary Units in Operation as of 31.12.1993

Plant name	Field (Country)	Start Year	Power (MW)	Units	Cooling Medium	Notes	References
U.S.A.							
B.C. Mc Cabe (GEM 1)	East Mesa (CA)	1979	13.4	1	Water		McLarty and Reed (1992)
Ormesa 1	East Mesa (CA)	1986	30	26	Water		McLarty and Reed (1992), Ram and Krieger (1989), [s]
Ormesa 2	East Mesa (CA)	1987	20	20	Water		McLarty and Reed (1992), Ram and Krieger (1989), [s]
Ormesa 1E	East Mesa (CA)	1988	12.8	10	Water		McLarty and Reed (1992), [s]
Ormesa 1H	East Mesa (CA)	1989	13.2	12	Water		[s]
Heber	*Heber (CA)*	*1985*	*70*	*1*	*Water*	[a]	EPRI AP-4612-SR (1986)
Second Imperial (Heber II)	Heber (CA)	1993	40	12	Water		Anon (1993), [s]
Mammoth-Pacific 1	Casa Diablo (CA)	1985	12	2	Air		McLarty and Reed (1992)
Mammoth-Pacific 2	Casa Diablo (CA)	1990	15	3	Air		McLarty and Reed (1992)
PLES 1	Casa Diablo (CA)	1990	15	3	Air		McLarty and Reed (1992)
Amedeee 1	Amedee (CA)	1988	3.2	2	N/A		McLarty and Reed (1992)
Wineagle	Wendel H.S. (CA)	1985	0.8	2	Air/Water		McLarty and Reed (1992)
Far West (Steamboat 1-1A)	Steamboat (NV)	1986	9.4	9	Air		McLarty and Reed (1992), Ram and Krieger (1989), [s]
Steamboat	Steamboat (NV)	1993	32	2	Air		Anon (1993)
Tad's Enterprises	Wabuska (NV)	1984	1.8	2	Water		McLarty and Reed (1992), [s]
Soda Lake 1	Soda Lake (NV)	1987	3.6	3	Water		McLarty and Reed (1992), Ram and Krieger (1989), [s]
Soda Lake 2	Soda Lake (NV)	1991	12	6	Air		[s]
Stillwater	Stillwater (NV)	1989	15.3	14	Air		McLarty and Reed (1992), [s]
Empire	San Emidio (NV)	1987	4.8	4	Water		McLarty and Reed (1992)
Sulphurdale 1 (Cove Fort)	Cove Fort (UT)	1985	2.6	4	Water		McLarty and Reed (1992), [s]
Hammersly Canyon	*Lakeview (OR)*	*1983*	*2.1*	*6*	*Water*	[a]	Wood (1983)
Puna (PGV)	Puna (HI)	1992	30	10	Air	[b]	Ram and Krieger (1989), [s]
TOTAL (U.S.A.)			286.9	147			
OTHER COUNTRIES							
Copahue	Argentina	1988	0.6	1	Water		Gropper and Yarimi (1994), [s]
Nagqu (Tibet)	China	1993	1	1	Air		Cuellar et al. (1991), [s]
Svartsengi	Iceland	1989	3.9	3	Water		Elovic and Gilon (1992), [s]
Svartsengi	Iceland	1992	5.2	4	Air		Elovic and Gilon (1992), [s]
Travale 21	Italy	1991	0.7	1	Water		Elovic and Gilon (1992), [s]
Castelnuovo V.C.	Italy	1992	1.3	1	Water		Bini et al. (1994), [t]
Los Azufres	Mexico	1993	3	2	Air		Gropper and Yarimi (1994), [s]
Tarawera (TOI)	New Zeland	1989	2.6	2	Air		Elovic and Gilon (1992), [s]
Kawerau (TG2)	New Zeland	1993	3.5	1	Air		[s]
Tu Chang	Taiwan	1987	0.3	1	Water		[s]
Egat (Fang)	Thailand	1989	0.3	1	Water		[s]
Kapysya	Zambia	1988	0.2	2	Water		[t]
TOTAL (other countries)			22.6	20			
TOTAL			**309.5**	**167**			

[a] - Dismantled
[b] - Integrated generating modules (backpressure steam turbine+binary cycle turbine)
[s] - Ormat Power Plant Data Sheet
[t] - Turboden Power Plant Data Sheet

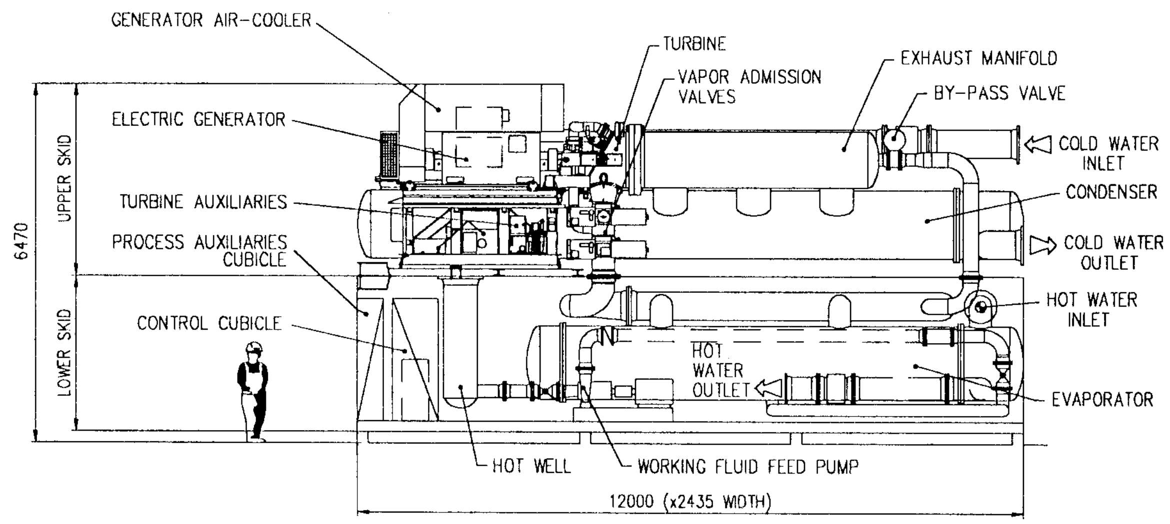

Fig. 2 - Castelnuovo ORC Turbogenerator lay-out and overall dimensions.

preassembled modules, each one of them completely wired and blank tested by the suppliers.
The ORC cycle is implemented in the first two modules which are mounted one on top of the other.
The upper one contains the turbine, the fluid control valves, the electric generator and the condenser, while the lower one contains the evaporator, the feed pump, most controls and power systems for the auxiliaries (Fig. 2).
The third module includes the electric cubicles for the main breaker and the power lines, the uninterruptible power supply, the console for the operator in an air-conditioned cabinet.
The evaporator and the condenser are shell and tubes heat exchangers. They both feature low aspect ratio fins, obtained by cold rolling of the tubes.
The cold section tubes are stainless steel (AISI 316), while the hot section tubes are made of titanium, the tube sheet being titanium lined.
Though the selection of these expensive materials was not mandatory for the Castelnuovo heat source, they were adopted since future utilisation of the machine on a not yet identified geothermal water flow was expected.
The adoption of high corrosion resistance materials is preferable in modular machines, to allow the use of a standard system on most sources, and to allow re-location of used machines.
The hot side single shell contains, besides the evaporator tubes, a pre-heating section and a superheating section.
The latter is modest and was added mainly as a vapour drying section, nearly negligible from the thermal power point of view.
The expander is a single stage, full admission axial turbine.
The asynchronous electric generator is connected to the turbine shaft through a flexible coupling.
The supporting frame for the electric generator is connected to the turbine casing so as to maintain the shafts centred, compensating for the thermal displacement of the turbine casing and for the overall structure deflection.
A medium voltage (6 kV) electric generator was selected, in order to allow for further power increase in future machines, and to reduce the cable and switch gear size.
The main design data are given in Tab. 2.

Tab. 2 : Data sheet of the 1.3 MWel ORC Turbogenerator of Castelnuovo V.C. (near Larderello, Italy).

Hot source: hot water of geothermal origin.

Hot water inlet temperature	: 114	°C
Hot water flow	: 1000	t/h

(heated by condensing the geothermal steam in a closed loop circuit).

Cold source: cooling tower water of geothermal origin.

Cooling water inlet temperature	: 25	°C
Cooling water flow	: 1760	m^3/h
Gross electric power	: 1210	kW
Generator rated power	: 1300	kW
Maximum generator power	: 1430	kW
Electric power to the auxiliaries (•)	: 40	kW
Generated electric voltage	: 6	kV
Power factor (at rated power)	: 0.90	

Dimensions during transport:

a) Turbogenerator (2 modules) (◆)	: 2.5x12x5.6 m
b) Auxiliary box (◆)	: 2.5x9x2.5 m

Weight:

Over-all weight of the machine .... : about 80 t

(•) Internal auxiliaries only, the cooling system auxiliarie are not included.
(◆) Width x length x height.

3. WORKING FLUID SELECTION: PRESENT AND FUTURE OPTIONS.

In the case of binary cycles, the working fluid selection represents the most important single choice in the full system design.
Even neglecting heat transfer characteristics and related heat exchangers costs, at least two independent optimisation procedures can be carried out leading in one case to a fluid assuring the highest

conversion efficiency and in the second case to another fluid allowing the best turbine design for a given plant capacity.
With reference to an isothermal or almost-isothermal heat source the rule for the thermodynamic optimisation is fairly simple, conversion efficiency being invariably favoured by the use of a fluid with a high critical temperature and with a simple molecular structure.
On the contrary, for a variable temperature heat source the largest energy output is obtained for the best combined ability of the conversion system to extract heat from the source and to use efficiently each unit heat extracted. Under the somewhat simplifying assumption that the source can be cooled down to the condensation temperature of the conversion cycle it could be shown (Energy Department of Politecnico di Milano, 1990) that each fluid yields the best energy performance when associated to a heat source at a temperature somewhat above the fluid critical temperature.
This trend is illustrated in Fig. 3, giving the source temperature as a function of the fluid critical temperature at the optimum conversion efficiency.
Only saturated cycles at a maximum vaporisation temperature of 0.9 T_{cr} were considered.

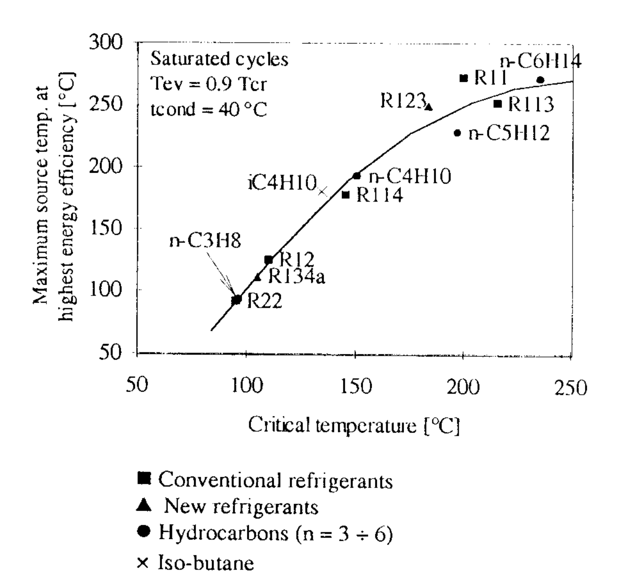

Fig. 3 -Maximun source temperature at highest energy efficiency as a function of the selected organic working fluid.

According to the suggestion of Fig. 3, R134a with a condensation pressure of 10.1 bar should be used with a source at 110 °C while R123 with a condensation pressure of 1.5 bar should be used with a source at 250 °C.
This alternative deeply affects the turbine design leading, for a 3000 rpm solution, to a much larger unit power in the first than in the second case.
A modular construction, making the turbine capacity independent of the overall plant output allows the combined thermodynamic and fluid-dynamic optimisation.
A similar conclusion holds also for an isothermal source which favours low pressure (high T_{cr}) fluids, thus limiting the turbine unit power and consequently requiring the use of a number of modules to saturate the source potential.
For different reasons, as just quoted, the fluid critical temperature represents the key parameter in binary cycle optimisation for both isothermal and variable temperature sources.
Before the discovery of the negative effects of standard refrigerants on stratospheric ozone two classes of fluids offered a variety of options with closely spaced T_{cr} within a very wide range: the hydrocarbons, with their safety problems, and the chlorofluorocarbons CFC (or, in some cases, the hydro-chlorofluorocarbons HCFC).
The international agreement to phase out gradually both CFC and HCFC starting with the most harmful compounds and the parallel development of new fluids led to a quickly evolving picture which can be outlined as follows.

In the low T_{cr} range several new fluids are commercially available which can be considered as definitive substitutes for the old refrigerants being fully non flammable, non-toxic with a z o ODP (ozone depletion potential) and an acceptable GWP (g. nhouse warming potential) (Montreal Protocol Assessment, 1991).
R23 (CHF_3, T_{cr}=25.6 °C), R125 (C_2HF_5, T_{cr}=66.3 °C) and R134a ($C_2H_2F_4$, T_{cr}=101.1 °C) are the most important compounds in this class.
Fluids with similar chemical structures, but containing enough hydrogen to be flammable such as R32 (CH_2F_2, T_{cr}=78.2 °C), R143a ($C_2H_3F_3$, T_{cr}=73.6 °C) or R152a ($C_2H_4F_2$, Tcr=113.3 °C), all with a zero ODP are also available and currently used to formulate non-flammable mixtures of great interests for the cold generation industry.
In the higher T_{cr} range the situation is much less satisfactory, no definitive substitute for the old refrigerants being yet available.
Presently the main challenge is to develop a low pressure fluid for the needs of the some 100 000 centrifugal chillers existing worldwide, 80% of which use R11 (CCl_3F, T_{cr}=198.0 °C).
A number of fluids are now available which, although representing an improvement with respect to the old refrigerants, are still questionable owing to a non zero ODP and in some cases to a residual flammability or to a marginal toxicity.
In principle this class of fluids is of great interest for geothermal use since their low vapour pressure guarantees the large volume flow that is needed for a good turbine design.
R123 ($CHCl_2CF_3$, T_{cr}=183.7 °C) is the best known compound of this class, being a strict alternative to R11; other fluids are R141b (CH_3CCl_2F, T_{cr}=204.4 °C; R142b (CH_3CClF_2, T_{cr}=137.2 °C, R124 ($CHClFCF_3$, T_{cr}=122.5 °C).
The active worldwide search for definitive, safe low pressure working fluids will probably yield in a 5-8 years' period several non flammable, non toxic, non ozone-depleting substances probably found in the fluorinated propanes or in the fluorinated ethers classes (Doerr et al., 1992; Adcock et al., 1991).
Among the 30 possible fluoro-substituted propanes the ones having the largest number of hydrogen atoms without becoming flammable offer the best environmental and thermodynamic performance.
These are the five R245 isomers, among which R245ca (CHF_2-CF_2-CH_2F, T_{cr}=178.4 °C) has the highest probability of success as the final substitute for R123 and R11.
Preliminary thermal stability tests and thermodynamic tests produced encouraging results.
Similarly R236ea ($CHF_2CHCFCF_3$ T_{cr}=141.2 °C) seems to have a good probability to become a substitute for R114 (Kazachki and Gage, 1993; Kazachki and Hendriks, 1993).
When available these or similar fluids will moreover offer a greatly improved thermal stability in comparison with the old chlorine-containing refrigerants and will lead to a conservative turbine design in comparison with hydrocarbons, owing to their large molecular mass.
When the conversion system illustrated in this paper was designed, prior to CFC phase-out, the only non-flammable low-pressure fluid available was R11 which was selected as the engine working medium.

4. CONTROL AND DATA ACQUISITION SYSTEM

The control system consists of a Programmable Logic Control, a number of local control loops and a host computer.
The following general criteria were adopted:

- the control system can keep the machine operating, independent of the host computer;
- the host computer is used as a monitor for the operator, duplicating and enhancing the operator console, and as a supervisor allowing to modify some operation parameters;
- all the local control loops are interfaced to the main control in order to keep track of operation and to modify the settings;
- critical items like the turbine speed feature multiple protection circuits and are polled at a higher rate.

A large number of analogic and digital signals enters the control and are transferred to the host PC for data acquisition and monitoring.
The operation historical trend is accumulated in the hard disk, with the criterium of intensifying the rate of acquisition for the signals

with high rate of change.
The operator can select on the monitor a number of screens with mimic diagrams of the machine process.

5. THE UNIT PERFORMANCE: EXPERIMENTAL DATA AND THEORETICAL PREDICTIONS.

The unit performance was thoroughly tested in a wide range of operating conditions: hot water temperatures and flow rates were varied between 90-115 °C and 500-1000 m^3/h respectively, while cold water flow rate was varied between 900 and 1800 m^3/h.
The resulting electric output ranged from a maximum value slightly above 1300 kW_{el} down to less than 600 kW_{el}, with gross electrical efficiency (electric output power/thermal input) ranging from 6.6% (at low power output) to 9.2% (at full load).
These measured efficiencies are quite satisfactory, since they exceed 70% of the efficiency of a Carnot cycle operating between the measured evaporating and condensing temperatures.
The test results are summarised in Fig. 4 and in Fig. 5, where theoretical predictions for the off design operation of the machine are also given.
The gross electric power produced by the Castelnuovo ORC Turbogenerator is reported for the indicated hot and cooling water flows and for two different cooling water temperatures.
Thanks to the adoption of a variable speed drive (inverter) for the working fluid feed pump, the initial auxiliary consumption is minimised and varies according to the generated electric power (up to a maximum of about 45 kW).

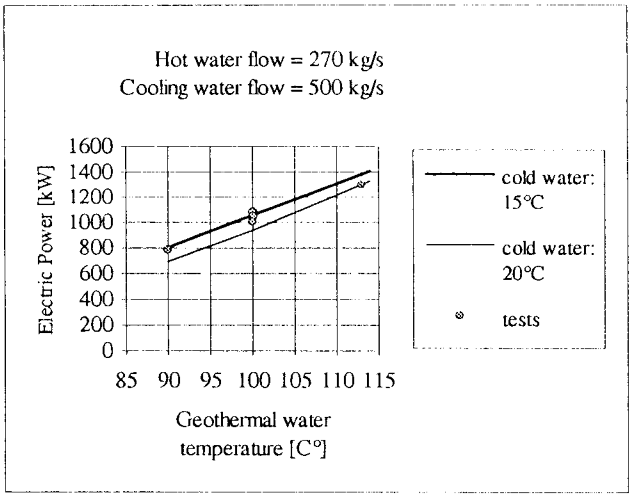

Fig. 4 - Castelnuovo ORC plant performance - full geothermal flow.

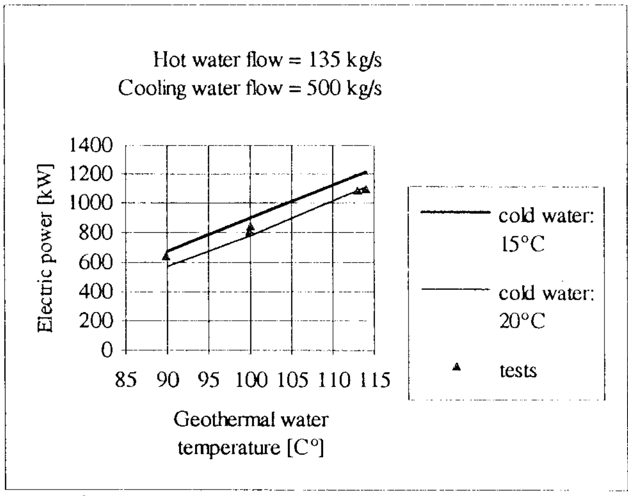

Fig. 5 - Castelnuovo ORC plant performance - half geothermal flow.

The test results are dispersed between the upper and lower curve as the actual cold fluid temperature during the test varied between 15°C and 20°C, but the intermediate curves were not drawn.

The machine performance is influenced by the presence of a significant amount of incondensable gases in the loop, which caused an increase of condensing pressure corresponding in some tests to about 7-10°C.
The elimination of this inconvenience would improve the engine performance (both power output and efficiency) of about 15-20%, raising to over 11% the unit efficiency at design hot water conditions (1000 t/h and 114 °C).
During tests, the temperature and pressure of the working fluid at each component inlet/outlet section were recorded, so that the actual performances of heat exchangers - heat transfer coefficients and friction factors - as well as turbine efficiency could be derived.
This closer inspection of the experimental data pointed out that, as expected, the single stage, axial-flow transonic reaction turbine maintained an efficiency well above 80% in most of the investigated range (expansion ratios ranged between 2.7 and 3.7).
Near design conditions, a turbine efficiency as high as 83.1% was measured.

6. ORC CASCADING

In order to better exploit a relatively high temperature geothermal source, it is often convenient to utilise a series of ORC units connected in cascade, in such a way that the water discharged by a unit (still hot) is utilised by a downstream unit (cascading scheme).
In this way the source can be cooled down to a lower temperature with respect to a single unit scheme and the electric power output can be maximised.
For example, in Fig. 6 the hot water cooling diagram and the related organic fluid heating diagram are reported, in the case of one single evaporation level scheme.
Hot water temperature and flow are respectively 180 °C and 56 kg/s, with a condensing temperature of 40 °C.
Optimised hot water discharge temperature is 75.6 °C which yields 3215 kWel production.

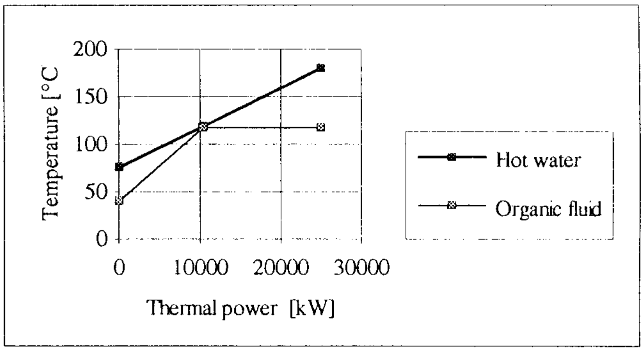

Fig. 6 -Hot water cooling and organic fluid heating diagrams for the One evaporation level scheme.

In Fig. 7, under the same assumptions of the previous figure, a scheme based on three evaporation levels (three units in cascade) is reported.
Optimised hot water discharge temperature is 65.8 °C which yields 3216 kWel production.

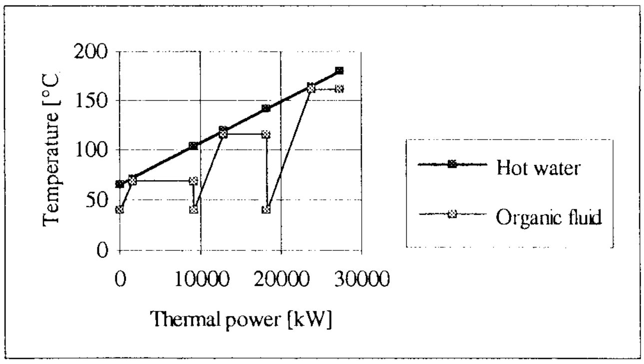

Fig. 7 -Hot water cooling and organic fluid heating diagrams for the three evaporation levels scheme. Pre-heaters not optimised.

In order to maximise source exploitation it is possible to arrange the pre-heaters of the three units in such a way as to obtain the heating curve of Fig. 8, with an optimised hot water discharge temperature of 62.8 °C and a total electric power output of 3714 kWel.

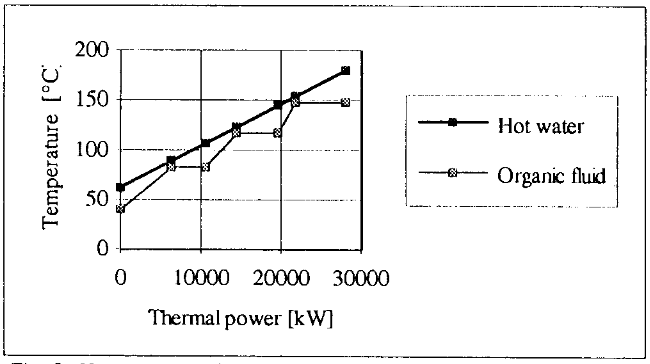

Fig. 8 - Hot water cooling and organic fluid heating diagrams for the three evaporation levels scheme. Pre-heaters optimised.

The minimum pinch point Δt for the 3 cases examined has been changed in order to keep the overall dimensions of the heat exchangers (pre-heaters + evaporators) constant: the electric power produced in the optimised solution is some 15.5% higher than in the single evaporating level scheme.
Furthermore it has to be noted that by utilising the 3 evaporation level scheme of Fig. 7, the electric output does not increase.
This fact is a consequence of the assumption of keeping the overall heat exchangers surface constant, the more efficient high temperature sub-cycle being balanced by the less efficient low temperature sub-cycle.

7. CONCLUSIONS

The performance of the first 1 MW size Organic Rankine Cycle Turbogenerator realised in Europe was up to the expectations, and the technical solutions adopted were efficient and reliable.
These good results confirm the viability of ORC units for the exploitation of low temperature geothermal sources.
The adoption of a non flammable fluid, though not mandatory, seems sensible, in the perspective that new, zero ODP fluids will be available in the next future.

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