CERNAVODA NPP's PERFORMANCE
and
ITS AVAILABILITY TO SUPPLY STEAM FOR DISTRICT HEATING

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Abstract

The paper presents the results of the warranty/ performance tests carried-out at Unit 1 of Cernavoda NPP (Romania), during 1997, and the availability of the unit, confirmed at the tests, to supply steam for the district heating , without reducing the electrical output.

Among the tests' results , extremely good seems the Gross Heat Rate which allowed the turbogenerator - 706,5 MWe design capacity - to actually generate 718,4 MWe, while the reactor was loaded at 99,1 percent. Based on this result, an assessment was initiated of the possibility to increase the rated electrical output of the Unit; the analysis being now in progress.

The tests demonstrated the availability of an additional steam flow, in comparison with the flow required for the rated electrical output., Based on this result, a decision was taken, in order to provide heat for district heating: to extract the steam directly from the Unit's steam header, fed by the Steam Generators, maintaining the design rated electrical output. Thus, the modifications required for the operation of the turbine in co- generation were postponed.

A comparative analysis is presented in the paper for two alternatives : # I - steam taken directly from the Unit's steam header , and # II - turbogenerator operated in co-generation , with the extraction of the steam from the exit of the High Pressure (HP) cylinder of the turbine. The basic assumption in this analysis - acceptable for a limited heat demand - is that the electrical power and the thermal power for heating are equal in both alternatives.

The calculation proves that the higher thermal efficiency of the operation in co-generation (alternative # II) leads to insignificant savings in the consumption of nuclear fuel.

The operation of the turbine in co-generation (alternative # II) becomes really efficient, from economical point of view, only when the heat load will be so large that the additional steam flow, mentioned above, will be not sufficient to cover all the heat demand; hence, for getting more steam will be necessary to reduce the electrical output. Such threshold of heat demand for Cernavoda NPP Unit 1 is at 30 - 33 Gcal/h. The drop in electrical output will be smaller in alternative # II than in alternative # I; from this difference , will rise the main advantage of co-generation at Cernavoda NPP Unit 1.

After long expectations, the year 1996 brought about a great "premiere" in Romania : the Unit 1 of Cernavoda NPP went into service. The day of April 16, 1996, 5:32 p.m. became the memorable time of "the first criticality" of Cernavoda nuclear reactor; on July 11, 1996, the first connection of the electrical generator to the National Grid took place, and on October 2, 1996, the unit reached the design rated power. Between October 9-23, 1996, "the 10 days acceptance test" was carried-out, with the turbogenerator operated continuously at 100% power level. After one month outage, for inspection and repairs, on December 2, 1996, the Cernavoda NPP Unit 1 started its commercial operation.

As it is well-known, the nuclear reactor of Cernavoda NPP Unit 1 is a CANDU 6 reactor type, designed by the Atomic Energy of Canada Limited (AECL). The conventional part of the plant is based on a 706 MWe turbogenerator, manufactured by General Electric - USA, including also a participation of the Romanian industry. The design of the conventional part of Unit 1 and a significant volume of the equipment in the Balance Of Plant were supplied by ANSALDO - Italy.

In 1997, the share of Cernavoda NPP Unit 1 in Romania's overall electricity production was 9,7%. The load factor achieved by the unit for 1997 calendar year was 87,27 %. Cernavoda NPP Unit 1 was ranked on the 85-th position among more than 370 power reactors with capacity above 150 MWe all over the world,, in the classification based on the 1997 load factors ("Nuclear

Engineering International"-May 1998), This is a remarkable accomplishment, if compared with the world performances and taking into account Cernavoda is the first nuclear power unit in Romania and it is still in its "childhood".

<u>Cernavoda Unit 1 performance features, reflected in the results of the warranty tests</u>

The list of the warranty/performance tests and the level of the warranted indicators have been specified in the contracts Romania signed with AECL in 1978 (for NSP) and with ANSALDO Italy - General Electric USA in 1981 (for BOP and turbogenerator). Even if some of the contractual warranties were not valid any more, the tests were nevertheless performed in the first months of the commercial operation.

The NSP steam output test was carried-out on February 19, 1996, with the reactor's load at 99,66 % FP (Full Power), in order to ensure the licensing limit for reactor's thermal power is not exceeded.

The tests for the determination of Gross Heat Rate (GHR) and electrical output were carried-out on February 20-21,1996. As required by the contract, all the steam produced in the steam generators went to turbine (the others steam consumers were fed with steam from auxiliary boilers) and the governor valves were wide open; in these conditions, the reactor's load was 99,1% FP. The generator's power factor at the test was 0,97, as permitted by the national grid,, instead of 0,9 required by the contract.

The corrected values, determined at the tests, were obtained from the measured values using corrections, which took into account the difference between the reference conditions defined in the contract and the conditions actually encountered during the tests. The corrections considered the deviation of flow and enthalpy for feed-water, reheater drain, blowdown and sampling, the deviation of steam pressure, the deviation of the steam quality, the deviation of the exhaust pressure.

The indicated value, determined only for the NSP steam output test,, took into account either the corrections mentioned above and the instrumentation error, as required by the contractual provisions.

The tests' results are presented in the following table.

Test indicators	Warranted; nominal value (as per contract)	Value determined at the test		
		measured	corrected	indicated
NSP Steam Output, t/h	3769	3782	3762	3783
Gross Heat Rate, kJ/kWh	10507	10243	10253	
Generator Electrical Output, MWe	706.496	718.420	725.090	

The tests' results were very good and the related contractual warranties were deemed fulfilled. Among the results, extremely good seems Gross Heat Rate which allowed the turbogenerator to actually generate 718,4 MWe, while the reactor was loaded at 99,1 percent. Based on this result, an assessment was initiated of the possibility to increase the rated electrical output of the Unit; the analysis being now in progress.

N.B.: the corrected generator output was obtained by extrapolation, considering reactor load increased from 99,1 % FP to 100% FP, assuming that turbogenerator can produce 0.9% more power. It is not obvious that this can be really achieved.

The increase in generator power and the improved GHR , compared to the nominal reference, can be attributed to two inter-related factors:

1. Pressure drop across the main steam lines and across governor valves is lower than designed. This leads to higher pressure in front of and across the HP cylinder (about 1 bar) and therefore better heating conditions for feed-water (final actual feedwater temperature 191,6 °C, versus 187,7°C in design). Also, there is a higher available pressure drop across LP cylinders which results in a higher enthalpy drop per kg of steam available for conversion to electrical output.
2. Boiler steam output is slightly higher for the same reactor power due to higher feedwater temperature at the boilers' entry, which would also contribute to a higher output.

Two other warranty tests, requiring a longer duration, are: the test for the specific consumption of nuclear fuel and the test for heavy water loss . Both tests started in 1997, but their final results are not yet available.

The test for specific fuel consumption was carried-out between July 28, 1997 and January 21, 1998 (about 150 FPD - Full Power Days). The indicated fuel consumption, determined at the test, was 1.792 gU per 1000 MJ of energy transferred to the steam generators. This value is lower than the warranted contractual value of 1.81 gU/ 1000 MJ. The contractual value should be corrected for the differences encountered during the test between the actual conditions and conditions applicable for the warranty; these corrections are still under review, but the preliminary assessment indicates the test's result is acceptable and the warranty test was successful. It is worth mentioning that, at the beginning of the test , more than 60% of the fuel bundles in the reactor were Romanian made, at the company's facility in Pitesti, which was upgraded with the technical assistance of AECL and ZIP-Canada ; by the end of the test, practically all the core was filled with Romanian fuel. The fuel exhibited excellent features and the reactor's test for the specific fuel consumption was performed in normal conditions, without any problem induced by the quality of the fuel.

The test for the heavy water losses started on March 1, 1997, and will last 2 years. The warranted value for D_2O losses is 14.3 kg/ day. The average value of this indicator , achieved in the period December 2, 1996 (unit in service) - June 30, 1998 is 11.74 kg/ day. The largest D_2O losses were related with the outages.

Availability of reactor's steam for district heating

Historical background

Due to the specific social and economical conditions in Romania, the problem of district heating was - and still is - an important concern. It was reflected in the contract signed by General Electric with the Romanian companies for Cernavoda Unit 1 turbine. At the request of the customer, the supplier confirmed the capability of the turbine to be operated in co-generation, providing up to 200 Gcal/h, with the corresponding reduction in the generated electrical power.

For this operation mode , the suggested solution was to extract the steam at the exit of HP stage - from the lines connecting HP cylinder with Moisture Steam Reheater (MSR) - and to direct it to some large Heat Exchangers (HX) providing the hot water for district heating. But this special system was not erected by the time when Unit 1 of Cernavoda NPP was commissioned (end of 1996).

From the other side, because of the changes which occurred in Romania after 1989, the demand of heat in the town and on the construction site (for Units 2-5) was about 17 Gcal/h only and its expected pace of increase was very small. Therefore, it was decided to install two small HX (2x 20 Gcal/h) in the area of Unit 3 and to feed them with steam from the auxiliary oil-fired boilers existing on the site; this was thought as a temporary solution for the district heating, till the system for steam extraction will be ready and the turbine will be able to operate in co-generation.

Fortunately, the operating experience and the results of the warranty tests pointed-out an interesting circumstance: the availability of the additional steam flow from NSP, apart from that required to generate the rated electrical power. The turbine requires only 3699 t/h of steam for an electrical output of 706,5 MWe, instead of 3755 t/h, as specified in the contract; this additional steam supplied by NSSS can produce about 25-30 Gcal/h. Under these conditions , AECL- ANSALDO Consortium who was managing the unit, in agreement with the Romanian partners, decided to use for district heating the steam taken directly from the steam header - fed by nuclear unit's steam generators ; thus, the auxiliary oil-fired boilers remained only a back-up source and , for the moment, the plans to achieve the steam extraction from turbine and to operate the turbine in co-generation were postponed.

With the actual and forcast heat consumption (from 12000 to 25 000 Gcal per month) , the existing solution allows to supply the required steam for heating and , on the same time, to keep the turbogenerator at the design rated electrical output.

Further on, the paper evaluates the gain , in terms of fuel consumption, risen from the use of the steam produced in co-generation, instead of the steam taken from the steam header.

Technical indicators for different modes of steam use

The following modes of steam use are evaluated :

Mode 0 - Steam flow through turbine, operating in condensation; in this mode, the considered steam flow is used only for electricity generation. Flow is measured on the main steam lines.

Mode 1 - Steam flow taken from steam header ; in this mode, the considered steam flow is used only for heating production . Flow is measured at the point of exit from the steam header.

Mode 2 - Steam flow through turbine , operating in co-generation ; in this mode, the considered steam flow enters the turbine and is extracted after the HP cylinder . This steam flow is used firstly for electricity generation and then for heating production. Flow is measured at the point of extraction from turbine (exit of HP cylinder)

For each mode , we calculated the following indicators:

- p_{ej} : the specific electrical power (i.e. electrical power generated by a steam flow of 1 t/h, used according to the mode "j") ;
- p_{tj} : the specific heating power (i.e.heating power produced by a steam flow of 1 t/h, used according to the mode "j") ;
- c_j : the specific consumption of nuclear fuel (i.e. the amount of fuel burnt for the generation of a steam flow of 1 t/h, used according to the mode "j") ;
- η_j : the thermal efficiency of steam use, in mode "j";
- C_j : the consumption of nuclear fuel for 1000 MJ of useable energy (electrical or/and thermal)

In the calculation, we used the results measured or obtained at the performance tests, as well as some design figures and empirical values (for heat or other losses).

The calculated indicators for different modes are presented in the following table:

	- p_e - MWe per 1 t/h	- p_t - Gcal/h per 1 t/h	- c - gU/h per 1 t/h	- η -	- C - gU/1000MJ
Mode 0	0,191	-	3,57	0,35	5,17
Mode 1	-	0,528	4,94	0,81	2,23
Mode 2	0,061	0,485	4,92	0,83	2,18

The value c_2 = 4,92 gU/h can be shared, by calculation, in :

c_2^e=0,40 gU/h (i.e. the specific consumption of nuclear fuel, required for the energy production converted into electricity, generated by a steam flow of 1t/h extracted from the turbine - mode 2);

c_2^t=4,52 gU/h (i.e. the specific consumption of nuclear fuel, required for the energy production converted into heat,, generated by a steam flow of 1t/h extracted from the turbine - mode 2).

In the calculation, we introduced two coefficients which will be used further :

$K_I = F_{ent}^{HP} / F_{ex}^{HP}$ = 1,094 - the coefficient indicating the value of the steam flow required to enter the HP cylinder, in order to extract a steam flow of 1 t/h at the HP cylinder exit, in mode 2 (the difference between flows represents the steam extracted for feed-water regenerative heating) ;

$K_2 = p_{t1} / p_{t2}$ = 1,089 - the coefficient indicating the value of the steam flow extracted from the turbine (HP exit) , able to to produce the same heat amount as the steam flow of 1t/h taken from the steam header.

Comparison of two alternatives for steam supply for heating

The Alternative # I is the existing today system: the turbine is operated in condensation and the steam for heating is taken from the steam header.

The Alternative #II is the designed system (in draft, at the present time) : the turbine operated in co-generation, the steam for heating extracted from the turbine , at the HP exit.

The evaluation is performed by the method of superposition of 2 parallel steam flows, each of them used in its own mode. Thus ,we define:

Q- the steam flow used for electricity production only - Mode 0 (fully to condenser);

I - the steam flow used for heating , either in Mode 1 (steam taken from steam header) ,or in Mode 2 (steam extracted from turbine , after having generated a certain amount of electricity).

For further analysis, we note:

F^{SG} - steam flow from steam generators

F^T - steam flow to the turbine (including MSR)

F^{CU} - steam flow for the Unit's consumers (like ejectors, etc.)

For Alternative # I : $F_I^{SG} = F_I^T + I_I + F^{CU}$

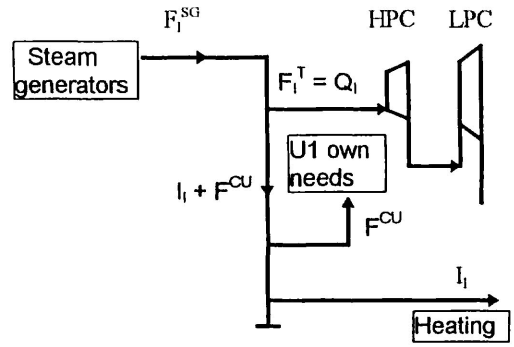
$F_I^T = Q_I$

For Alternative # II : $F_{II}^{SG} = F_{II}^T + F^{CU}$

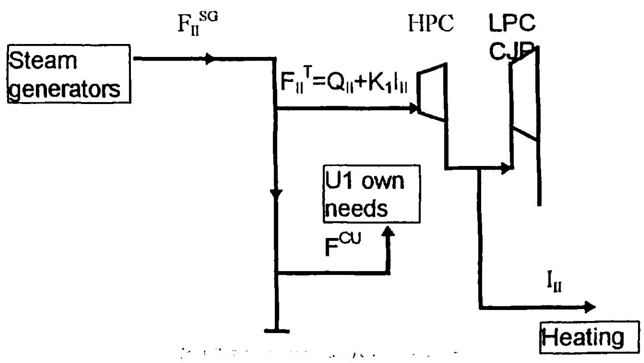
$F_{II}^T = Q_{II} + K_1 I_{II}$

The above relations are clearly reflected in the following drawings.

Alternative # I



Alternative # II



The difference in efficiency between the two alternatives will be assessed comparing the fuel consumption - S, in gU/h - for both alternatives.

Alternative # I : $S_I = Q_I c_0 + I_I c_1 + F^{CU} c_1$ (1)

Alternative #2 : $S_{II} = Q_{II} c_0 + I_{II} c_2 + F^{CU} c_1$ (2)

The following conditions must be observed simultaneously, in order to have comparable alternatives:

* the heat for district heating must be the same for both cases , which means:

$I_{II} = K_2 I_I$ (3)

* the electrical output must be the same (equal to design rated) for both cases, which means :

$Q_I p_{e0} = Q_{II} p_{e0} + I_{II} p_{e2}$ (4)

Such a situation is achievable at Cernavoda NPP Unit 1, when the heat demand is limited, due to the availability of additional steam flow -for Alt. # I - and to the possibility to increase slightly the flow through HP cylinder - in Alt. # II - for compensation of the steam extracted before the LP cylinders.

From the above relations (1) - (4) ,we calculate the gain in the fuel consumption of Alternative # 2, opposite to Alternative #1 :

$$\Delta S = S_I - S_{II} = I_I[c_1 + K_2(c_0 \frac{p_{e2}}{p_{e0}} - c_2)] = 0{,}823 I_I$$

The relationship shows that, in case of a steam flow for heating I_I =1 t/h (i.e. heat load 0,528 Gcal/h) , the gain in fuel consumption risen from co-generation (Alternative #2) is 0,823 gU/h. For the present heat demand in Cernavoda - 12 000 Gcal/month - the gain would be only 18,70 KgU/month , less than one fuel bundle.

This surprisingly small gain achievable through co-generation in the case of Cernavoda NPP Unit 1 has two explanations ,which can be found in the relationship for ΔS :

(1) The flow required for district heating, I_I , is small ; it represents less than 1% from the total flow to turbine demonstrated at the performance test (about 30 t/h against 3761 t/h) ;

(2) The ratio p_{e2} / p_{e0} =0,32 and the coefficient K_2 have small values in comparison with the corresponding values of the turbines designed for co-generation. This happens because the extraction point of the steam (exit from HP) is relatively close to the steam admission into turbine; the position of the extraction point was chosen there, taking into account the low parameters of the steam produced in Steam Generators, as well as the potential construction difficulties involved by any other location of the extraction point.

The following tables summarize the comparison between the Alternatives #1 and #2 for two scenarios.

(1) **Increase of heat demand twice (24 000 Gcal/month ,or 3,7 Gcal/h)** ; the total steam flow from Steam Generators will be still able to produce the turbo-generator 's rated electrical output and the required heat load, in both alternatives.

Parameters	Alt. #I	Alt. #II
Heat load /demand ; H, [Gcal/h]	32,7	32,7
Electrical load; P, [MW]	706,5	706,5
Steam flow for heating ; I, [t/h] $I_I = H / p_t$; $I_{II} = K_2 I_I$	 62 	 67
Steam flow through turbine , used in Mode 0; Q, [t/h] $Q_I = P/p_{e0}$; $Q_{II} = Q_I - K_2 I_I(p_{e2}/p_{e0})$	 3699 	 3677
Total steam flow through turbine; F^T, [t/h] $F_I^T = Q_I$;	 3699	

$F_{II}^{T} = Q_{II} + K_1 I_{II}$		3751
Steam flow for Unit's consumers; F^{CU}, [t/h]	25	25
Total steam flow from Steam Generators ; F^{SG}, [t/h] $F_I^{SG} = F_I^T + I_I + F^{CU}$; $F_{II}^{SG} = F_{II}^T + F^{CU}$	3786	3776
Fuel consumption, C, [gU/h] $C_I = Q_I c_0 + I_I c_1$; $C_{II} = Q_{II} c_0 + I_{II} c_2$	13512	13459
from the above value C, fuel consumption for heating ; C_T [gU/h] $C_{IT} = I_I c_1^{\,i}$ $C_{IIT} = I_{II} c_2^{\,i}$; the same C_T in [bundles/ month]	306,3 11,63	305,2 11,58
Gain in fuel Alt.#1 opposite to Alt. #2, [bundles/month] $(C_I - C_{II})$ x (720 h/month)/ (18970 gU/bundle)	-	2,01

In this scenario, the efficiency of co-generation - expressed in nuclear fuel savings - is small (about 2 bundles , or 4000$ per month), and can not justify the additional investment (about 1 million $) required for the modification of the turbine and auxiliary systems in order to make possible the turbine operation in co-generation mode.

(2) **Increase of heat demand up to 110 Gcal/h** (as per previous, optimistic forecast). Now, we must observe the limitation in flows : max. F^{SG}=3795 t/h and max. F^T=3761t/h, according to the results of the performance tests. The electrical load will be different in Alt. # I and Alt. # II.

Parameters	Alt. #I	Alt. #II
Heat load /demand ; H, [Gcal/h]	110	110
Steam flow for heating ; I, [t/h] $I_I = H / p_I$; $I_{II} = K_2 I_I$	208	227
Total steam flow from Steam Generators ; F^{SG}, [t/h] F_I^{SG} (given, as initial condition); $F_{II}^{SG} = F_{II}^T + F^{CU}$ (for F_{II}^T and F^{CU}, see next rows)	3795	3786
Steam flow for Unit's consumers; F^{CU}, [t/h]	25	25
Total steam flow through turbine; F^T, [t/h] $F_I^T = Q_I$ (for Q_I, see next row); F_{II}^T (given , as initial condition)	3562	3761
Steam flow through turbine , used in Mode 0; Q, [t/h] $Q_I = F_I^{SG} - I_I - F^{CU}$; $Q_{II} = Q_I - K_2 I_I (p_{e2}/p_{e0})$	3562	3513
Electrical load; P, [MW] $P_I = Q_I p_{e0}$; $P_{II} = Q_{II} p_{e0} + I_{II} p_{e2}$	680	685
Fuel consumption; C, [gU/h] $C_I = Q_I c_0 + I_I c_1$; $C_{II} = Q_{II} c_0 + I_{II} c_2$	13744	13658
from the above value C, fuel consumption for heating ; C_T [gU/h] $C_{IT} = I_I c_1^{\,i}$ $C_{IIT} = I_{II} c_2^{\,i}$; the same C_T in [bundles/ month]	1028 39,0	1026 38,9
Gain in fuel Alt.#1 opposite to Alt. #2, [bundles/month] $(C_I - C_{II})$ x (720 h/month)/ (18970 gU/bundle)	-	3,26

In this scenario, the efficiency of co-generation rises from :

- nuclear fuel savings (which are still small : 3,26 bundles , or 6 500 $ per month);

- additional electrical energy production, due to the higher electrical load achievable in co-generation , when the decrease of turbogenerator's electrical output against the rated output becomes necessary, because of the high heat demand (about 3600 MWe , or 115 000 $ per month).

Conclusions

1. For the present heat demand in Cernavoda , as well as for a realistic predicted demand (up to 24 000 Gcal/month) for the next period, Unit 1 of Cernavoda NPP is able to supply the required steam flow, maintaining the design rated electrical output of the turbogenerator - 706,5MWe - and using the existing systems (steam taken directly from the Unit's steam header) , without modifications for turbine's conversion to co-generation.

2. The above mentioned possibility is due to the Unit's performance indicators, which are better than the design indicators, as it was demonstrated at the warranty tests (Gross Heat Rate about 2,5% better) .Therefore, the turbogenerator is able to produce the rated electrical output with a steam flow smaller than the design flow.

3. The evaluation of the advantages of the turbine's operation in co-generation, opposite to the operation of two separate sources for elctricity and heating, shows:

- the gain from the drop in fuel consumption is not significant , because of the parameters of the extracted steam, which are close to the parameters of the "live" steam, supplied by Steam Generators; this is a specific feature of nuclear turbine, designed for operation in condensation mode.

- when the supply of steam for heating will increase and will require a drop in the Unit's electrical output, the turbogenerator will be is able to produce in co-generation a higher amount of electrical energy, in comparison with the existing system at Cernavoda (where there are two separate sources for electricity and heating, the turbine being not involved in the supply of steam for district heating) ; only in such circumstances , the co-generation will be an economically justified mode for turbine's operation.