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DANUBE HYDROPOWER AND SOME RELATED PROBLEMS

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Rezumat: *Dunărea are lungimea de 2912 km, debitul la vărsare de 6500 m³/s şi un potenţial energetic amenajabil de 42 TWh pentru exploatarea căruia ar trebui amenajate în jur de 50 centrale hidroelectrice. Aproximativ 30% din potenţialul total se află pe sectorul ce formează frontiera româno-sârbă. Aici au fost ridicate două mari sisteme energetice şi de navigaţie: „Porţile de Fier I" (1964-1971) şi „Porţile de Fier II" (1977-1986). Contribuţia prezentă, analizează Dunărea din punct de vedere energetic, compară CHE Porţile de Fier I cu realizări similare şi examinează comportarea în exploatare a echipamentelor hidromecanice.*

Abstract: *Danube has a length of 2912 km, a 6500 m³/s final discharge and a hydroelectric potential of 42 TWh, the recovery of which necessitate to build approximately 50 power plants. About 30% of this potential is found at the river sector making the Romanian-Serbian border. Two important hydroelectric and navigation systems "Iron Gates I" (1964-1971) and "Iron Gates II" (1977-1986) were built here. Paper analyzes the Danube from the point of view of the hydroelectric potential, compares the Iron Gates power plants with other similar achievements and examines the running behavior of this huge hydraulic equipment.*

Keywords: Danube, hydraulic power plants, Kaplan turbines, Bulb turbines, cavitation

1. Introduction

Danube with a length of 2912 km, a basin of 817,000 km^2 and 6047 m^3/s discharge is the Europe second largest river (after Volga 3692 / 1,380,000 / 8060). In an average year, the hydroelectric potential of Danube is about 42 TWh. Economically this potential can be utilized by around 50 power stations, with a total installed power of 8000 MW.

Approximately 30% from this potential is found on the Danube sector which is the Romanian-Serbian border (total length 229.5 km), with 8050 KW/km, but in some restricted zones even 82,000 kW/km, which represents for Europe the biggest specific power. In June, 1956 a common "Romanian - Yugoslavian Declaration was made in which was stated the decision to begin studies for the use of this huge hydroelectric potential.

After approximate two years of researches result the conclusion that two complex systems can be put into operation.

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The first one, **Iron Gates I** (realized between 1964 and 1971) consists of two identical hydroelectric power plants, each with six Kaplan units, and two identical navigation systems each with two double locks. In every lock chamber can enter two self-propelled barges of 5,000 tones capacity. When the hydroelectric power plant was put into operation its Kaplan turbines were the biggest units both as dimensions (runner diameter 9.5 m) and nominal output (178 MW) [1].

The principal part of **Iron Gates II** systems was constructed between 1977 and 1986 and consists also in two power plants each with 10 tubular Kaplan turbines with 7.5 m runner diameter and a nominal power of 32.5 MW.

2. Danube River

2.1 Danube Name

The Danube upper part was named by Thracian *"Tanais/Donaris"* and the lower one *"Istros"*. Probably the first name came from the Indo-European term for river "danu" and for the river Goddess "Danu". In the seventh century BC the Greek sailors reached the Black Sea and the Danube Delta, taking over the name "Istros". In the Greek mythology is used also the name ”*Okeanos Potamos"(Okeanos River)* or *"Keras Okeanos" (Gulf of Okeanos)*. The legend tell us that near the end of this river is the holy Pelasgian island of "*Leuke"* (at present Isle of Snakes) were the hero Achilles was buried. It is interesting to note that until now one Danube branch is called Chilia, perhaps after the hero Achilles. The Romans, making the river as the empire north frontier, baptize it "Danubius". This name, with minor changes, is found in most actual European languages [2].

2.2 Danube Genesis

Before Pleistocene epoch, it was an old "*Upper Danube*" (in German "*Urdonau"*), greater than the contemporary upper section of the river. In time, most of this upper watershed was cached by Rhine (till now mostly in the Immendingen zone). The remnants of the old huge river are some great canyons of the Swabian Alb. The diminishing process (watershed capture) continues and in a far future the upper Danube will suffer important decreases. There are fears that finally, even the important Inn tributary will be cached by Rhine.

On the other hand, the contemporary Danube was created just in Pleistocene. In this time in Central Europe were at least four great lakes or even inland seas: Vienna, Little Panonic, Great Panonic and the Dacic. All this lakes were remnants of the Neogene Parathetys Sea [3].

The present river connects all the mentioned basins. How and when were penetrated various ridges to form the nowadays gorges remain to be established by future researches. Geological fault, tectonics and glaciations are some keys for deciphering the Danube polygenesis.

Finally the river found his way from “Black Forest” mountains to the sandbank and village “Caraorman” (a Turkish name which means also black forest) and curiously ended in the Black Sea. In this long way, Danube caches the water from about 120 tributaries, 30 of which are navigable. The catchment area is approximate symmetric 56% lying on the left bank (with 20 important tributaries) and 44% on the right one (with 15 important tributaries). The right bank tributaries supply two thirds of the Danube water.

The total water discharge into the Black Sea in a normal year is about 6047 m^3/s (with a 15,540 m^3/s recorded maximum in 1970 and a minimum of 1610 m^3/s registered in 1954).

2.3 Danube Springs

Danube is certainly born in Baden-Würtenberg Germany, near Donaueschingen town. Regarding the river sources there are at least three theories [4].

1. The first states that Danube begin only after the junction of two rivulets, Brigach (with the length of 43 km and the catchment basin of 195 km^2) and Breg (length 49 km and a basin of 1029 km^2).
2. The second states that the Danube spring is identical with those of Breg, being placed near Martinskapelle, 6 km north-west from Furtwangen. Here was mounted a table with the following content *“Here is the principal spring of Danube, the Breg, at the altitude of 1078 m, at 2,888 km from the discharge in Black Sea and at 100 m from the watershed border between Danube and Rhine, between Black Sea and North Sea”.* Effectively, at a distance of only 900 m there is the spring of the rivulet Elz, a tributary of Rhine. The name Breg is perhaps of Celtic origin (in Celtic mythology there existed a triple Goddess with the same name).
3. The third considered that the Danube spring is placed in a yard near the Donaueschingen Palace. This rivulet has a flow capacity of 0.05…0.15 m^3/s and discharges in Brigach approximately 150 m south from the Palace. A round basin and a statue increase the tourist attraction [3].

The junction Danube-Inn at Passau also raises a problem. Here the flow capacity of the Inn is greater than that of Danube even if the latter has a greater length. For other junctions, in this situation, the river name is given after the bigger one.

Symmetrically with the three sources, the discharge in the Black Sea is done also by three principal branches: Chilia (63% of the discharge), Sulina (16%) and St. George. Since 1984 there are two navigable ways from the river to the Sea: the old one on the Sulina branch and the new one on the Danube-Black Sea canal, shortening with 250 km the ships ways. The canal begins in Cernavoda ends in Agigea and has the important advantage of negligible silting up.

2.4 Danube Sectioning

From the power potential point of view, Danube can be divided into three main sections:

- **The upper course** extends from Donaueschingen till Bratislava (Devin Gate Gorge). Here, Danube is a characteristic mountain river, initially with an average bottom gradient of 1.2‰ but from Passau to Bratislava the gradient becomes only 0.6‰. Depths vary from 1 to 8 meters and the velocity is about 2.5 m/s. Upstream Linz the river never freezes entirely The northernmost point is reached in Regensburg. In Austria, Danube narrows and its bottom abounds with reefs. The maximum flow discharge occurs in June when the snow melts in the Alps, and the minimum occurs in winter. In this section there is possible to realize approximately 38 power stations. Till now, in Germany there were accomplished 14 power stations. In Austria, were buildings of dams is also a navigation necessity, there were realized 10 power stations from 12 possible.
- **The Middle Section** is extended From Bratislava till Prahovo (this section ends normally at Iron Gates Gorge but in this paper we want to include both Iron Gates power plants in the same section). Here, the average bottom gradient becomes only 0.06‰. After Devin Gate, the river stream slows abruptly and loses the capacity to transport slurries. As a result two huge Islands were formed, one in the Slovak side and the other in the Hungarian side supporting more than 100 settlements with more than 190,000 inhabitants. The maximum flow discharge has two peaks, in April (as a result of local tributaries) and June (as a result of the peak flow in the upper part). On this section occurs a huge increasing of the flow capacity, from 2400 m^3/s at Budapest to 5420 m^3/s at Iron Gates. Here can be realized approximately 8 power stations. Till now, here were built the Danube greatest power stations: Iron Gates I (Romania/Serbia), Gabcikovo (Slovakia), and Iron Gates II (Romania/Serbia).
- **Lower Section**: From Prahovo to Sulina. The average bottom gradient decreases to 0.03‰. The Danube becomes slower and broader. The possibilities to realize a concentrated waterfall is very expensive. There are studies to realize approximately 3…5 power plants. Perhaps "*Turnu Magurele"* is the most important objective. In the near future, in this section, no power plants building are foreseen.

3. Danube Hydroelectric Power Stations

Nowadays, approximately 70% from the Danube hydroelectric potential is taken-off in 27 power stations. The first installed was the Kachlet German power plant (building period 1924-1927, situated at km. 2234). In the initial project (1920/21) there were provided 10 Francis type turbines running under 7.65 m head and 700 m^3/s total discharges [5].

In the final design there were provided 8 Kaplan units (this turbine type was invented in 1912, patented in 1913, and the firma Voight realized in 1922 a few turbines with 0.8 MW power). The second one was Ybbs-Persenbeug realized in two stages 1938-44 and 1954-59. The second stage built plant contains 3 Kaplan and one Bulb unit.

The running behavior of such mixture is important for our country, because we can also build Bulb turbines at Iron Gate I, for great discharges. The third is Jochenstein (building period 1952-56) situated on the Austria/Germany state border. In 1956, Jochenstein was the largest run-of-river power station in Central Europe.

In Table 1 are presented the most powerful stations on Danube. We can see that Iron Gates has the greatest level difference (27.17 m) in comparison with Gabčikovo (16), Altenwörth (15) and Greifenstein-Wien (12.6) and in the same time, the flow capacity of Iron Gates I (8700 m^3/s) overcome the other great stations Gabčikovo (5100) and Greifenstein-Wien (3150).

As a result, the mean power obtained at Iron Gates I overcome approximately 3 times that obtained in Gabčikovo, 3.6 times that of Iron Gates II and 6.5 times that of Altenwörth which is the fourth greatest power plant.

Table 1 Greatest Danube Power Plants

Power Station					*Turbine*				
Name	*Power*	*Year*	*Pos.*	*Head*	*No.*	*Type*	*Power*	*D*	*Q*
-	MW	-	km	m	-	-	MW	m	m^3/s
Iron Gates I	**2136**	**1965/71**	**943**	**27.2**	**6+6**	**K**	**178/195**	**9.5**	**732**
Gabčikovo	720	1978/92	-	16.0	8	K	90	9.3	636
Iron Gates II	**591**	**1977/86**	**853**	**7.8**	**10+10**	**B**	**32/27**	**7.5**	**475**
Altenwörth	328	1973/76	1980	15.0	9	B	22.3	6.3	300
Ottensheim	324	1970/74	2147	10.5	9	B	20	5.6	238
Greifenstein	293	1981/85	1949	12.6	9	B	35	6.5	350
Ybss	236.5	1954	2060	10.9	6+1	K+B	33.8/48	7.6	

4. Iron Gates I Power and Navigation System

4.1 The original system

After the Second World War there were been voices (for example Prof. dr. Aurel Barglazan m.c. of the Romanian Academy) who claimed the building of a power station at the Iron Gate location.

Until 1953, such a construction was inconceivable because the extremely bad relations between the Yugoslavian leader Josip Broz Tito and the Soviet leader Joseph Stalin. The death, in April 1953 of the USSR leader Joseph Stalin alleviates the pressure upon Romania and Yugoslavia, allowing normal political relations between these neighboring countries.

Consequently, in June the 26th, 1956, a Common Declaration was communicated, which announce the decision to begin studies for the utilization of this huge hydroelectric potential. As the result of many year studies, was agreed a plan to realize this important water work. For the mechanical and electrical equipment it was asked the assistance of Soviet Union.

Romania imported three complete units from LMZ (turbine factory) and Electrosila (electric generators factory) and manufactured the other three in Resita. Yugoslavia imported all the six turbines form LMZ and manufactured at home all the six electric generators. The Romanian specialists participated in Leningrad to the design of the turbines and the generators as well as to the laboratory tests. This agreement was extremely important for increasing their professional competence.

The main structure of the system has a total length of 1278 m and is composed by the following parts:

- Spillway dam (441 m) formed of 14 sections each with a 25 m span and 13 piers 7 m wide. The dam is provided with hooked twin gates 14.86 m high. The 15,400 m^3/s maximum overflow capacity can pass over the dam.
- Left bank power house (214 m). The dam power station type is 74.40 m height and is divided into three blocks (two power generating units in each block). A 26 m wide assembling block is supplementary provided. The hydraulic turbines are of the Kaplan type. The runner with a maximum diameter of 9.5 m has 6 adjustable blades. The hub has 3.6 m diameter and a length of 4.275 m. The wicket gates have 32 blades and the stator 12 stay vanes. The volute is in concrete construction. The vertical synchronous three phase electric generator has the outer diameter of 16.90 m and the rated voltage of 15.75 kV. The rotor diameter is 14.19 m. The revolving part of the unit weights 3,500 t and is supported by a thrust bearing. Each generator is coupled to a 190 MVA/15.75/231 kV transformer.

- Right bank power house (214 m) is identical with the left one with the exception of transformers.
- Left bank navigation lock (53 m) is foreseen for a maximum level difference of 35 m and is of double chamber type. The inner part of lock chambers is 310 m long and 34 m wide.
- Right bank navigation lock. Identical.
- Earth fill left bank dam (117 m), closes the space between the lock and the left bank
- Earth fill right bank dam (186 m).

The Romanian Government decree to buy from Soviet Union three hydroelectric groups as well as the manufacturing license for the other three was not only an intelligent political decision but certainly lead to the increase of our country technical capacity.

We give a few arguments to sustain this statement.

- In that time, the soviet specialists have the greatest experience in realizing Kaplan turbines with uncommon great power and dimensions (only for the Volga GES they realized 22 Kaplan turbines with a diameter of 9.2 m.).
- The decision to employ suppliers from the “capitalist camp” would raise insurmountable political objections, especially for Romania.
- For realizing in Romania three hydroelectric groups, the national technical capacity was substantially increased. The UCMR factory was outfitted with modern equipments, purchased especially from the industrialized countries. The endowment was realized between 1960-1965, some equipments surpassing through complexity and performances those of LMZ – the principal supplier.
- As a result of the agreement with the Soviet Union, a great number of Romanians, experts in various fields (designers of hydraulic turbines and electric generators, executives in the field of machinery manufacturing or in the field of hydroelectric power plant management) were accepted for training or even for working together with the soviet partners (inclusive for designing and laboratory testing of the turbines).
- The national capacity of manufacturing huge and complex details of the hydroelectric aggregates determined the independence from the supplier. This important favorable circumstance was not sufficiently used in the revitalization period.

Then again, the decision of manufacturing in Romania three hydroelectric aggregates raises numerous technical, economical and managerial problems. Between the most difficult ones were the casting and transport of the turbine and generator hub.

The constructive solution chosen by LMZ was to cast both the turbine hub and the runner servomotor cylinder as a single piece. The final piece resulted with a weight of 80 to, but together with the dead-head and the pouring gate the weight rises to over 120 to.

No Romanian steel foundry has the capacity to realize simultaneous such a quantity of liquid steel. The greatest Romanian steel foundry was in Bucharest and had three furnaces. The added up mass was under 120 to.

There existed two possible solutions:

- Two-stage casting, with the danger that the subsequent poured metal would not made a perfect junction with the cooled metal formerly poured and finally the piece to be wastage.
- The 150% overload of all three furnaces, with their possible deterioration.

The foreign experts consulted did not agree with those solutions and recommended to import these pieces. It was decided to apply the second solution (overloading) and the results were excellent.

Another difficult problem was to transport those heavy details from Bucharest to Resita (here was the single engineering shop able for mechanical working of such huge and heavy details).

It was taken the decision for railway transportation. For this purpose there were taken two complementary measures, to design and realize in Arad a freight truck able to support such pieces (the truck was provided with 24 axles) and the reinforcement of the railway Bucharest-Resita in order to transport such a weight.

Evidently, the beginning of these operations was made with approximately two years before to carry out the first transport.

4.2 Maintenance problems

The six Romanian turbines worked in good conditions over 30 years. The most difficult maintenance problems were: cracks of stay vane ring, runner blades crack, runner casing crakes (especially near the visiting door), and runner blade tip cavitation. In a single case occurs the detachment of the runner hydrodynamic bonnet.

The stay vane ring cracks were determined by the improper hydrodynamic shape of the vanes trailing edge, which generates Karman vortexes determining alternative stresses of the joints stay vane-rings.

This phenomenon occurs at all turbine dimensions but become a problem for turbines with runner external diameter over 5…6 m.

At Iron Gate turbines the cracks were observed after approximately 80,000…90,000 running hours at more than half of the stay vanes. The phenomenon is extremely dangerous because it difficult to be seen with the naked eyes at current inspections.

The runner blade crakes occurred especially at the trailing edge, in the vicinity of the runner periphery. The causes are also of hydrodynamic nature and the cracks are amplified by the fatigue in corrosion conditions.

The cracks appeared at the beginning after approximately after 50,000 running hours but repeats after each 10,000…12,000 running hours.

Fortunately, no crack appears at the hub end of the blade in the joining zone with the supporting pin (a very dangerous zone because the blade can be detached from the hub).

The runner casing cracks are determined by the inadequate concrete filling of the gap between the metallic casing and the substructure wall. The phenomena are unpleasant because it extends the length of the repair work.

Cavitation erosion affected the runner hub, the blades and the runner metallic casing. The hub and the casing were affected by gap cavitation. The blades were affected both by gap (especially at the blade tip) and by hydrofoil cavitation erosion in the vicinity of the leading edge.

The hydrofoil cavitation is shallow but affects greater areas, the gap cavitation has a smaller extension but is very profound (sometime goes over half of blade thickness).

The repair works, in the initial running phase must be done after 10,000…12,000 working hours.

After realizing Iron Gates II dam, the downstream level increased and the cavitation erosion was substantially reduced,

The examination of the maintenance problems shows that both the design and the manufacturing of turbines were of good quality.

This motivates numerous specialists to have the opinion that the revitalization work must be done by Russian and Romanian specialists.

This opinion prevailed in Serbia were the revitalization is done, just now, in common with the LMZ specialists.

Economic reasons conducted Romania to make the revitalization operations with the specialists of the Swiss company Sulzer which take over the Escher-Wyss (a company with excellent reputation in manufacturing hydraulic machineries).

4.3 Revitalizing and Upgrading Iron Gates I Turbines

As the result of the Romanian Government Decision 470/20.08.97 at the end of 1997 was finalized the Contract16636 between Romanian firm RENEL and SULZER Hydro ABB (both firma suffered name modification, the Romanian one becoming HYDROELECTRICA and the foreign partner become at first VATECH Hydro Ltd and finally ANDRITZ Hydro Ltd.). The main objectives of the upgrading the Romania part of power plant were:

- replacement of worn-out components/equipments,
- repairing other components/equipments in order to be subjected to a new running cycle of 30…50 years,
- increasing the power of each unit until 190…200 MW.

Finally, the complete replaced components were: the massive turbine shaft, the runner blades, runner blades bushings and seals, the guide ring for wicket gate adjusting ring, all the bushings for the wicket gate vanes (the new ones are made from polytetrafluoroethylene).

Table 2 Computing parameters for Original/Revitalized turbine

Parameter	*H*		*Q*		*P*		*n*	
MU	m	m	m^3/s	m^3/s	MW	MW	rpm	rpm
O/R	*Orig.*	*Revit.*	*Orig.*	*Revit.*	*Orig.*	*Revit.*	*Orig.*	*Revit.*
design	27,17	26,25	725	840	178	194	71.5	71.43
max.	34,50	31,40	-	-	-	200	-	-
min.	17,50	15,40	-	-	-	-	-	-

For the design of the new runner blades were used the latest achievements of hydrodynamics. The greatest concern was to obtain an important power increase (from 178 to 200 MW) regardless of the level differences reduction caused by the Iron Gates II system which raised the downstream level.

Table 2 presents a comparison between the hydraulic parameters taken into consideration for the original and the revitalized design of the turbine runner.

The revitalized turbine model was at first tested in Sulzer Hydro Laboratory (Zürich) and after that verified in Astro Laboratory (Graz). Comparing the efficiencies curves results that those obtained in Astro laboratory are a little greater (with approximately 0.5 %) then those in Sulzer Hydro but are in the tolerated error limits [6].The model performances were transposed for the prototype using IEC (International Electrotechnical Commission) Standards.

Analyzing the turbine universal diagram, results the following conclusions: the maximum efficiency 94.74 % is obtained for H=28 m, Q=570 m^3/s and P=151 MW. For a head close to the design one (26 m), the efficiency remain over 94.5% for discharges between 475 m^3/s (P=115 MW) and 680 m^3/s (P=163 MW).

The maximum power of 200 MW is obtained at Q=840 m^3/s with the efficiency of 93%. These results represent important improvements with regard to the original turbine. In the universal diagram the best efficiency lines are shifted towards higher heads and smaller discharges, situation favorable for draught periods.

The newly obtained blades with completely different shape are thinner than the original ones. The blade tips were provided with cavitation lips (this are volumes similar to the winglets used for airplanes).

Most running parameters of the revitalized turbines are between the guarantied limits. Unfortunately, some deficiencies occurred from the beginning of the running period.

On a few blades appeared dangerous fatigue cracks in the inner part (near the hub and the blade axle, towards the leading edge). After minute, complex and expensive researches the situation was remediated for all blades by realizing stress relieve grooves.

Other deficiencies occurred on the cavitation lips as a result of the cavitation erosion produced by tip vortexes.

The guaranteed depth of the cavitation erosion is of about 6 mm for 8000 running hours but the actual one in most cases is over 10 mm, reaching sometimes 40 mm. The first repair solution was by welding the eroded areas.

The welding repair work must be done after each 8000-10000 running hours and is dangerous because every time introduce new internal stresses.

The final proposed solution was the use in the middle of the cavitation lips (zone with maximum erosions) a sector manufactured from a metallic material called satellite (with the best cavitation erosion resistance), mounted with the help of bolts.

CONCLUSIONS

1. Danube presents some odd coincidences: it begin in a place named “Schwartz Wald” (Black Forest) and ends in Black Sea in the close vicinity of a place named “Caraorman” (meaning also Black Forest); the nowadays river Danube was formed in Pleistocene Epoch and in the same time begin the capture of its superior sector by the river Rhine (we can say the death of superior sector).

2. From the total 42 MWh hydroelectric potential only 70% is used, in 27 realized power stations.
3. The biggest power station is Iron Gates I. It was put into operation between 1964 and 1971 and revitalized between 2000 and 2005. Both design solutions for the mechanical parts were of high quality.
4. For the old machines the unpleasant events were: intense cavitation erosion near the blades tip (produced by vortex cavitation); dangerous fatigue cracks on the stay vanes, moderate fatigue cracks on the runner blades and on the metallic runner casing.
5. For the revitalized hydraulic machines the unpleasant events were: after a short running time, dangerous fatigue cracks appeared on the runner blades (design error corrected by modifying the shape of the blade) and extremely intense cavitation erosion on the blade cavitation lips (produced by vortex cavitation).

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