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CAHORA BASSA NORTH BANK POWER PLANT DESIGN REVIEW AND ECONOMIC EVALUATION (*)

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1. INTRODUCTION

The Cahora Bassa Scheme was established as a result of the Master Plan for the whole of the Mozambican part of the Zambezi River Basin [1] and a final Design [2] was developed (1967-1969) for its first phase, consisting mainly in the double curvature 163.5 m high arch Dam, a South (right) Bank Power Plant equipped with 5 x 415 MW Power units (Francis Turbines), the Songo main Substation and a HVDC conversion and transmission equipment to the Apollo Substation in South Africa. For the flood control, eight sluices on the Dam served

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as spillways, able to discharge about 1700 m^3/s each, under a head of some 60 m.

Both the Design flood and the energy calculations were based on a time series with a period of record of 36 years (1931-1966). Although some data existed also for the period 1907-1930, it could not be validated due to the lack of regularity in the readings, made without proper checking. The above mentioned period of record (1931-1966) contained in general wet or dry-wet periods, with an average annual volume of 85 000 hm^3 at the site of the Dam.

On the basis of these data, a preliminary Design was advanced also for a North (left) Bank Power Plant [3] as a second phase to be launched later, equipped with 4 x 415 MW units (the same size as those on the South Bank Plant).

The works for the first phase went over through 1969-1975, the impounding of the Dam having begun on December 1974. During the construction works, a basin was also excavated to serve as an entrance to the intake structures for the North Power Plant, and a cofferdam was left in place to allow the execution of the future works for those intakes, assuming a reservoir draw-down to a level just a little above the minimum operation level.

The testing of the equipment went on for some time – mainly due to the HVDC conversion/transmission equipment, which was a novelty at the time – and the commercial operation of the Power Plant started on the year 1977.

A short while later, new lines were constructed, for the North and Center of Mozambique and later on to Zimbabwe. These new lines are AC, due to shorter distances, among other factors.

The hydrologic data for the Zambezi River were compiled and revised by the SADCC [4]. All the data from 1931 onwards were carefully examined and validated, leading to a comprehensive data base, considered generally as fully reliable. On the other hand, all inflows into the reservoir were registered daily at Cahora Bassa, thus forming another data base for the Dam itself, from 1975 up to present days.

Soon after the beginning of operation, the climate began to change to a drier pattern. This pattern would become worse after 1980, reflecting a severe drought that lasted for about 18 years, up to 1998. From there, the run-offs restarted to increase, up to the present day.

Recently the Owners, Hidroeléctrica de Cahora Bassa (HCB), considering that it was the right moment to develop the Scheme to its full potential, decided to launch a review of the preliminary design for the North Bank Power Plant taking into consideration the time series of the enlarged period of record (1931-2001), and commissioned the same Consultants that had developed the studies for the first phase of the Scheme, to carry on this new task.

2. HYDROLOGIC STUDIES

The hydrologic studies carried out on this phase comprise: first, the definition of a design flood and, consequently, the establishment of new security rule curves for different additional discharge capacities; and second, the establishment of data for energy simulations.

2.1. DESIGN SECURITY FLOOD

During the first phase of the studies, a limited time series was available, as mentioned, and design flood calculations followed one of the usual methods generally employed at the time, i.e., statistical treatment of three-month period run-offs (February-March-April) was used. These calculations led to the design of eight spillways, with a discharge capacity of about 1700 m^3/s each, plus a small surface spillway able to discharge some 600 m^3/s. To complement this discharge capacity, a security rule curve was drawn, that led to a draw-down of the reservoir just before the flood months.

As time passed, it was found that the draw-down imposed by the rule curve was too drastic, leading to appreciable losses in the energy generation: an additional spillway was, therefore, judged necessary. On the other hand, the design flood should be adapted to new International Standards, and the most recent methods as well as the modern computing facilities should be adopted.

Indeed, modern trends for design flood calculations for large River Basins is to abandon the classical statistical methods and the concept of the maximum inflow, that have no real sense for such large basins and large reservoirs. Instead, the total annual volume should be calculated, preferably by a stochastic generation method [5] and then use disaggregation to obtain monthly volumes following very precise methods [6].

To calculate the annual flood volume, the old statistical methods are replaced by a stochastic generation of run-offs, departing from the time series of the period of record, up to a period equal to the desired return period. The maximum annual run-off of the total period will be the run-off corresponding to a flood of the chosen return period. This volume is then disaggregated into monthly run-offs following the rules and expressions mentioned above, on the basis of observed floods.

This method was applied to all the four partial catchment areas that form the total basin at Cahora Bassa: The Kariba, the Kafue Gorge, the Luangwa catchment areas as well as the Cahora Bassa own catchment area (the area that drains directly into the reservoir). A period of return T = 5000 years has been fixed, based on International Standards for concrete Dams in a situation of high downstream risk. The same return period was applied separately to all four catchment areas – since the method is based on the concept of a general meteorological event – and then the disaggregated monthly run-offs were added on, month by month, to form the total flood wave at Cahora Bassa.

Three additional discharge capacities were then considered, along with the existing spillways, in the routing of the defined flood wave: 2200, 3600 and 4400 m^3/s. It was found that the conservation level could be raised to elevation 329 (normal conservation level was previously considered at elevation 326), and the draw-down levels were found to be elevation 311 with no additional discharge, 321 with 2200 m^3/s additional discharge, 325 and 327 for additional discharges of 3600 m^3/s and 4400 m^3/s, respectively.

2.2. RUN-OFF FOR ENERGY SIMULATIONS

As it was said before, the period of record 1931-2001 includes a long period (18 years) of severe drought that would represent a drastic reduction in energy production. This would not correspond to a true image of reality for investments to be made for a future scheme, since climatic events are cyclic by nature, and the four last years of the period show a trend to wetter times. So, to have a better perspective of the situation, the same method of stochastic generation that was used to predict floods with a given return period was used also to make a projection, with the basis on the 71 years of the period of record, to an equal period in the future. This has already been done, even for the Zambezi River, for Kariba Dam, by the ZRA [7], and the results show the same trends than those found for Cahora Bassa, presented in Fig. 1.

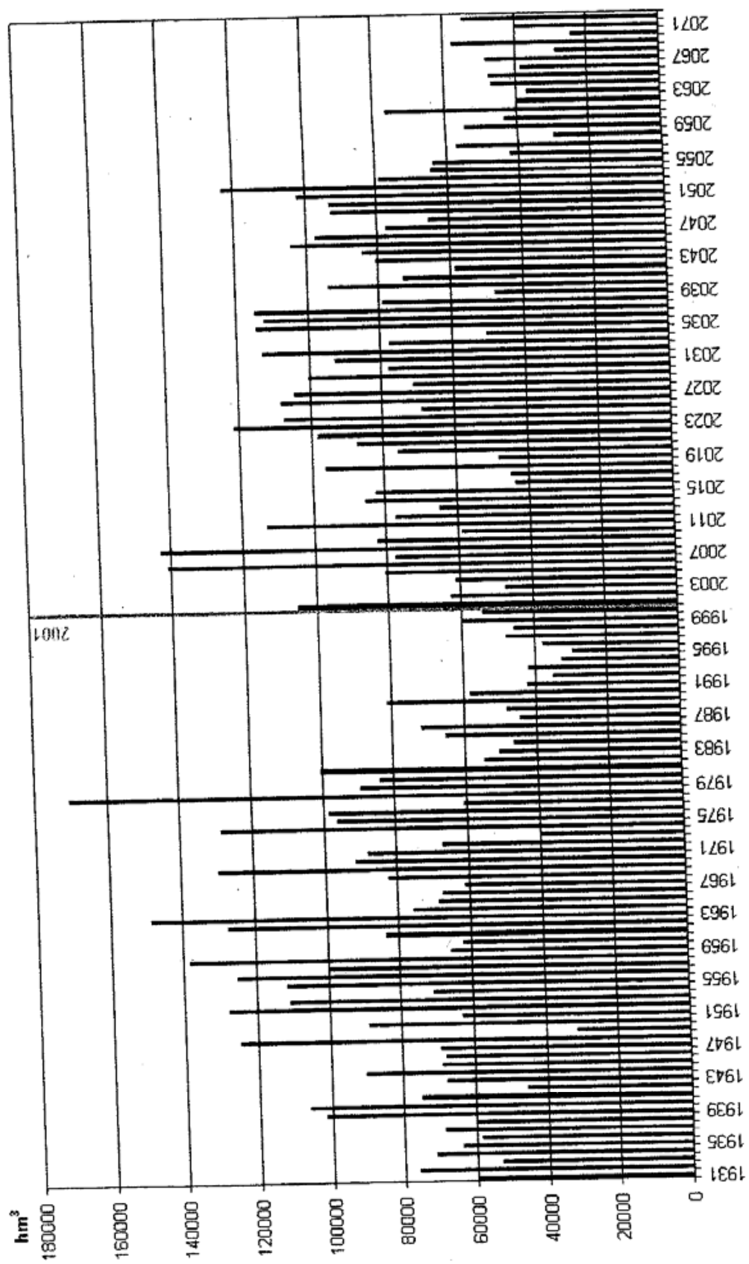

Fig. 1

Annual run-offs 1931 - 2050 (historic and generated time series)

Écoulements annuels 1931-2050 (historiques et projetés)

3. ENERGY STUDY

The energy simulations were made with the help of U.S. Corps of Engineers HEC-5 computer program. For the different rule curves derived from the four cases of additional discharge capacity, historic time series and projected time series were applied, leading to a total of eight different cases and this was done for five cases of installed capacity (existing Plant only, existing Plant plus new Plant with two and three 305 MW units, existing Plant plus new Plant with two and three 415 MW units).

Fig. 2 shows the energy distribution for the case of maximum additional discharge capacity (4400 m^3/s), both for historic and projected time series (just up to year 2050, for the sake of simplicity). In this Fig., the severe drought condition 1980-1998 can be clearly seen on the historic time series part of the graphic, as well as the recuperation of the last 4 years of the century. As for the projected period, the trend to wetter times up to the year 2050 can also be clearly observed.

This graph refers to annual total energy, and shows the present situation, i.e. 5 x 415 MW units with zero additional discharge capacity, as well as the gain with a 4400 m^3/s additional discharge capacity and, finally, the extra energy from the North Bank Power Plant with 3 x 415 MW units. In short, it can be observed that, if it is true that the North Power Plant would have been inactive during the past period of drought, the projected period looks quite promising for its operation. The increased discharge capacity, on the contrary, would be most effective during drier periods.

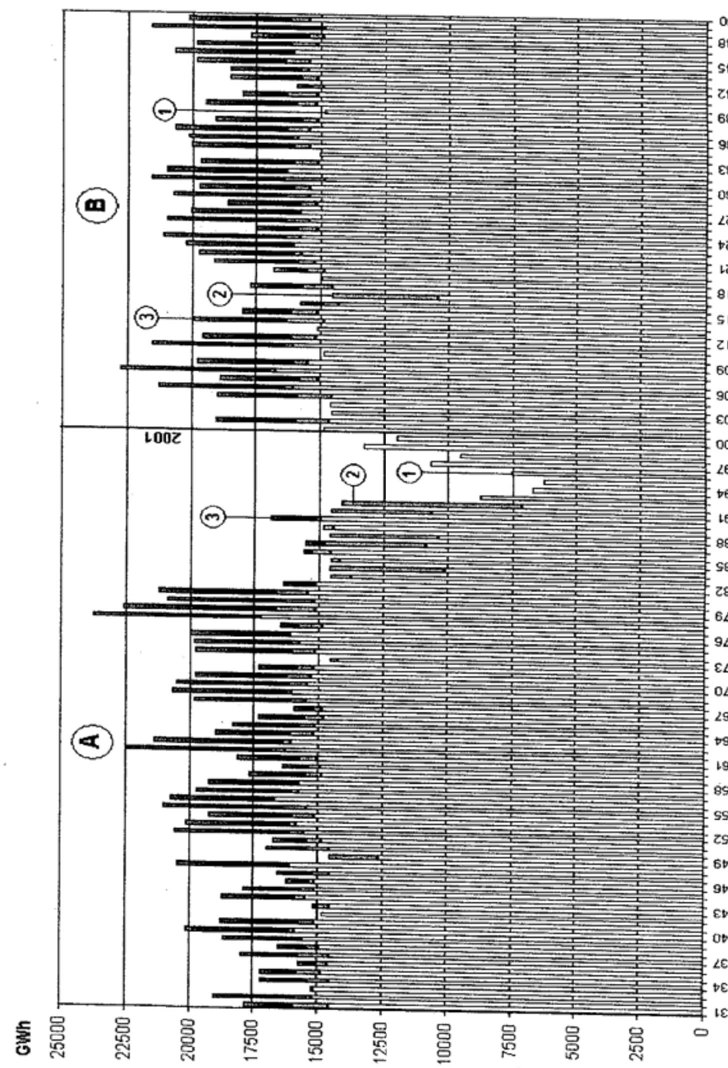

Fig. 2
Annual total energy (1931-2050)
Énergie totale annuelle (1931-2050)

A – Historic time series
B – Generated time series
1 – Existing Plant
2 – Additional spillway 4400 m^3/s
3 – North Plant (3 x 415 MW units)

A – Écoulements enregistrés
B – Écoulements projetés
1 – Usine existante
2 – Évacuateur additionnel 4 400 m^3/s
3 – Usine Nord (3 Groupes x 415 MW)

4. GENERAL LAY-OUT OF THE WORKS

The general lay-out of the North Power Plant works, presented in Fig. 3, was developed at the same time as the hydrologic, energetic and economic studies, and was thought independently of the conclusions of those studies, on the basis only on previous studies and expedite calculations. For this reason, the expected maximum was chosen, for the installed capacity, as well as for the discharge capacity, since it is easier to reduce than to enlarge the works, due to limitations in physical space.

Fig. 3

4.1. BRIDGE OVER THE ZAMBEZI RIVER DOWNSTREAM OF THE DAM

The use of the road over the Dam – presently the sole communication between the two banks – for the construction works was put aside from the beginning, for three main reasons: security, efficiency and economy.

Security: the road over the Dam was not designed for the large and repeated loadings due to construction, and even less for the transportation of heavy equipment.

Efficiency: as there will be several work fronts, an unique and rather narrow passage would have been a hindrance.

Economy: to attain the level of the works, and namely the main floor of the Power Station departing from the top of the Dam, a very long (about 1.5 km) tunnel would have to be constructed, to transpose 130 m of difference in level between the two, while just about 400 m will be sufficient from the North (left) abutment of the bridge.

All these reasons were already considered on the preliminary Design, where the bridge was included, although in a slightly different position.

In order to facilitate its construction, considering it to be impossible to have any intermediate support, the bridge will be formed by two symmetric cable-stayed 10 m deck bridges with inclined masts, launched from each bank and united by a joint at their extremities.

Fig. 3
General lay-out of the North Bank Plant
Disposition générale des ouvrages de l'usine Nord

1. Power house
2. Transformer hall
3. Intake structures
4. Pressure tunnels / Penstocks
5. Tailrace tunnels
6. Tailrace outlets
7. Access tunnel
8. Inclined masts cable-stayed bridge
9. Cable-line transition platform
10. Additional spillways

1. Usine
2. Galerie des transformateurs
3. Prises d'eau
4. Galeries d'amenée / conduites forcées
5. Galeries de fuite
6. Restitution
7. Tunnel d'accès
8. Pont à haubans, à mâts inclinés
9. Plateforme câbles-lignes aériennes
10. Évacuateurs de crue additionnels

4.2. INTAKE STRUCTURES, PRESSURE TUNNELS AND PENSTOCKS

The intake structures will be constructed differently from what was scheduled in the preliminary Design, that is, without the use of the cofferdam left in the first phase. Indeed, the use of the cofferdam would imply the lowering of the reservoir during an appreciable amount of time to a level that would lead to great losses in the production of the existing Power Plant, even to an extent that could affect unfavorably the feasibility of the new Plant. The construction method presented below is, therefore, a key item for the design of the new Plant.

The general principle of the construction of the works is that it will proceed from downstream to upstream. So, the construction of the intake structure will be made at the same time from the downstream tunnel and from a vertical shaft excavated from a platform at the level 331, leaving a rock barrier that will serve as a natural cofferdam to be demolished after the construction, within the shaft, of a tower where stop-logs as well as the flat gate of the waterway will be placed.

In order to facilitate this constructive method, the minimum operation level was raised, for the North Plant, some 12 m above that of the South Plant. This will reduce the volume of excavation and underwater removal of debris, since the major part will fall on the existing excavated platform which will rest 15 m below the sill of the intakes. Energy simulations show that this raising of the minimum level of operation will not affect the energy generation, since if such low levels are attained, only Primary energy would anyway be generated, for which the existing Plant is sufficient.

Following the gates of the intake structures there is a transition to a circular tunnel of 9.80 m diameter (same as for the existing Plant), that continues through a length of about 94 m slightly pending downstream, followed by a 98 m high vertical shaft, and again a 60 m long almost horizontal tunnel, ending in a penstock.

4.3. POWER STATION

The Power Station will be similar to that of the South Plant, with the reduction of 60 m in length, corresponding to having two units less in the new Plant (3 instead of 5). The main floor is placed at elevation 200, that is, 35 m below the elevation of the bridge abutment, which implies an access tunnel of just about 400 m of length.

The distribution of the different locations within the Power House is not yet defined, but it will be very similar to that of the existing Plant. The mantling/dismantling hall will be placed on the northern part, in continuation of the access tunnel. As in the South Plant, the control room will be placed in the other end, in this case the southern end, with an independent access by elevator to the left abutment of the Dam.

4.4. TAILRACE TUNNELS

The tailrace tunnels of the two southern units will be assembled into one, for the sake of saving available space at their respective outlets. These tunnels will be excavated under the protection of a downstream natural rock barrier at their outlets, and their construction will begin from the inside of the rock mass, through auxiliary galleries departing from the main access tunnel to the Power Station.

There seems to be no need for a surge chamber, due to the short length of the tailrace tunnels. This will, however, be further investigated on a second phase of these studies.

4.5. ADDITIONAL SPILLWAY

For a 2200 m^3/s additional spillway a tunnel was designed with a 15 m diameter horse-shoe cross-section, with an entrance structure and an outlet in the form of a ski-jump structure controlled by two segment gates, with two protection flat gates for maintenance works on the main gates. The division of the tunnel into two outlets, each controlled by a separate gate, means that, in practice, there will be two, instead of one spillway, which will favor outflow regulation.

For the case of a spillway with a discharge capacity of 4400 m^3/s, the tunnel will be doubled; finally, for the intermediate case of 3600 m^3/s two tunnels 13.6 m in diameter will be needed.

The construction of the entrance structure will be made in a similar way as the intake structure, with a rock barrier serving as cofferdam. In this case, however, it will not be possible to lower the entrance sill at such a low level as that of the intakes, due to necessary submersion problems. In the cases where two tunnels will be needed, there is also the drawback that it will not be possible to use the excavated basin for the entrance structure of the second tunnel, which will have to be prolonged some 80 m upstream.

5. ECONOMIC ANALYSIS

All the cases considered for energy calculations were thoroughly investigated also for the respective economic indicators: cost/benefit ratio, Pp (Payback period) and IRR (internal rate of return). The cost per kWh was also calculated. All this was done both for the period of record (1931-2001) and for a 25 years period (2010-2034) near the beginning of the period of the generated run-offs (2002-2072).

It is not possible to present in this paper all the results of the above mentioned calculations, nor is it the purpose or the right place to do so. In this way, although the expectable energy is shown for the different cases, referred to the generated period, the economic indicators are shown only for the case of one installed capacity, that is, 3 x 415 MW units.

5.1. ENERGY EVALUATION

For the projected period (2010-2034) the results are summarized as follows for different capacities of discharge and installed power on North Power Plant.

	Existing power plant	**Installed power in North Plant**			
Additional Discharge Capacity	**5 x 415 MW**	**2 x 415 MW**	**2 x 305 MW**	**3 x 415 MW**	**3 x 305 MW**
0 m^3/s	14 871 GWh ***reference***	16 099 GWh 8.3 %	15 805 GWh 6.3 %	16 658 GWh 12.0 %	16 216 GWh 9.0 %
2200 m^3/s	15 688 GWh 5.5%	17 546 GWh 18 %	17 099 GWh 15.0 %	18 306 GWh 23.1 %	17 714 GWh 19.1 %
3600 m^3/s	15 762 GWh 6.0 %	17 822 GWh 19.8 %	17 328 GWh 16.5 %	18 643 GWh 25.4 %	18 005 GWh 21.1 %
4400 m^3/s	15 827 GWh 6.4 %	17 806 GWh 19.7 %	17 315 GWh 16.4 %	18 658 GWh 25.5 %	17 994 GWh 21.0 %

The results show that the construction of the additional spillway for 2200 m^3/s has an impact of 5.5 % more on the energy generated. This percentage rises for the other two studied capacities, but at a slower rate.

As to the power to be installed in the Power Plant, the solution with 3 units rated at 415 MW each seems to be more favorable than the machines rated at 305 MW. In fact, the energy increments for 415 MW units is in the range of 4 % higher than for 305 MW units.

In respect to the number of units to be installed, it is important to note that the increment of the generated energy is in the range of 5 % more favorable for the 3 machines rated 415 MW.

5.2. COST ESTIMATES

As it is obvious, the basis for the economic calculations is: the investments to be made; and the benefits due to the sale of energy. Cost estimate calculations are, therefore, essential to the analysis.

The civil construction works were sufficiently detailed in the drawings and sketches as to arrive to a pretty close estimate of the costs, since even secondary access roads and tunnels were included.

On the contrary, the cost estimates for the equipment were approximated through the experience of other similar plants. On a second phase of these studies, it is intended to make a consultation to the manufacturers of the different parts of the equipment, in order to arrive to a more precise cost estimate.

This revised cost estimate will indicate, in the end, which will be the most favorable case on the economic point of view.

5.3. ECONOMIC INDICATORS

At this phase of the studies, the results of the economic evaluation are necessarily provisional, since they depend on a more credible cost estimate of the equipments. However, they indicate some trends that show the feasibility of the Plant, though not yet under which of the forms considered since the differences between the various possibilities are not clearly significant.

As an indication, the following Table shows the economic indicators for the 3 x 415 MW Power Plant for all discharge capacities:

Assumed energy price: 2.0 c€/kWh Actualization rate: 8 %			
Additional Discharge Capacity	**Cost/benefit ratio**	**Internal rate of return**	**Payback period**
0 m^3/s	0.85	6.67 %	-------
2200 m^3/s	1.51	12.04 %	15 years
3600 m^3/s	1.52	12.11 %	15 years
4400 m^3/s	1.47	11.74 %	16 years

6. MARKET EVALUATION

The main markets for the energy coming out from the North Power Plant are the big projects foreseen for Mozambique – located in Center and North regions – the increment of supplies to Eskom (South Africa) and ZESA (Zimbabwe), and throughout the SAPP Grid (Southern African Power Pool) to supply other countries such as BPC in Botswana.

The supply of energy to ESCOM in Malawi is also another opportunity that needs a new line (to be built) between Matambo and Blantyre.

The Short Term Energy Market (STEM) is another possibility for day-to-day selling of energy.

Taking into account the seasonality of the power produced by the North Power Plant, it is important to look at the possibilities to supply rather peak power and average energy as opposed to firm power as it was considered in the ancient contracts.

7. CONCLUSION

It becomes clear that the studies described here must be followed by a second phase, with consultations to the manufacturers, which will lead to more precise cost estimates, since the cost of the equipments cover the major part of the overall costs.

The effect of this actualization will be to provide sufficient data for the choices to be made by the Owner.

In general, however, the results of the studies presented here show that the construction of a North Bank Power Plant looks economically attractive.

Indeed, if 3 x 415 MW units are considered, along with an additional discharge capacity greater or equal to 2200 m^3/s, annual energy supply contracts can be agreed to provide an average energy of 18 300/18 650 GWh, against 14 870 GWh with the existing Plant.

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SUMMARY

For the existing Cahora Bassa Scheme, the first phase consisted in the construction of the Dam itself, and the whole South Bank Plant including accesses and other appurtenant works, along with the main substation and a conversion-transmission HVDC equipment to Apollo Substation in RAS. New transmission lines (AC) to Central and Northern Mozambique as well as to Zimbabwe were constructed some time later.

As for the North Bank, there was a preliminary Design (1968), based on simulations with the time series available at that time (1931-1966). This paper describes the studies made to adapt that Design to present conditions, with an enlarged period of record (1931-2001) and new concepts both for the determination of the design flood as well as for energy simulations using HEC-5. A projection was also made using more recent methods for stochastic generation of run-offs, for a future period equal to the period of record (71 years).

An additional spillway is proposed, to provide an almost constant level to the operation of the reservoir, with none or a very small draw-down to cope with a design flood situation. Three possible capacities were studied; each leading to a different security curve on the reservoir, for which values for firm and average energy were calculated using simulations with HEC-5.

Economic evaluations were made for different values of the installed capacity on the new Power House and for the different values of the additional discharge capacity.

RÉSUMÉ

Pour l'Aménagement de Cahora Bassa, la première phase a compris la construction du barrage-voûte, d'une usine dans la rive Sud (rive droite), incluant tous les ouvrages annexes et routes d'accès, ainsi que le poste principal à Songo et l'équipement de transformation-transmission HVDC pour le poste Apollo en Afrique du Sud. Un peu plus tard, des nouvelles lignes (AC) ont été construites pour le Centre et le Nord du Mozambique, et aussi pour le Zimbabwe.

En ce qui concerne la rive gauche (Nord), Hidrotécnica Portuguesa a élaboré un avant-projet sommaire (1968), en se basant sur des enregistrements des écoulements disponibles à l'époque (période 1931-1966). Le présent rapport décrit les études réalisées pour adapter ledit APS à la période élargie disponible (1931-2001), et aussi aux méthodes plus récentes de détermination de la crue de projet et de simulations énergétiques avec le logiciel HEC-5. Une projection a été faite aussi, avec des méthodes de génération stochastique des écoulements, pour une future période égale à celle des enregistrements (71 années).

Un évacuateur supplémentaire est proposé afin de maintenir un niveau presque constant pour l'exploitation de la retenue, avec aucun ou un très fabile abaissement du niveau de retenue pour encaisser la crue de projet. Trois capacités possibles ont été étudiées, conduisant chacune à une courbe de sécurité différente pour la retenue, l'énergie résultante (l'énergie garantie ainsi que la moyenne annuelle) ayant été calculée au moyen de simulations avec le logiciel HEC-5.

Des évaluations économiques ont été faites pour différentes puissances installées dans la nouvelle usine Nord, ainsi que pour les différentes capacités de l'évacuateur supplémentaire.