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Increasing fish survival prospects at hydro plants

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Projet d'aménagement hydroélectrique de la Toulnustouc par Hydro-Québec

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Some of the activities and innovative technologies which are currently being used to improve compatibility of hydropower with the environment and to increase its energy generation potential are reviewed here. The rehabilitation of existing hydro plants incorporating new fish-friendly runner designs, aerating turbines, and advanced control systems for environmental optimization are all providing improved environmental compatibility as well as increasing revenue and reducing maintenance costs.

Environmental concerns broadly affecting the electric power generation industry include: the potential for global climatic change as a result of the emission of greenhouse gases produced by combustion; the depletion and disruption of fossil fuel supplies, air and water quality; aquatic life impacts; and, uncertainties about long-term nuclear waste management. As a result of these concerns (in many instances stimulated by environmental groups and regulatory agencies), the US electric power industry is focusing attention on technologies for renewable, non-polluting energy generation. Among these, hydropower has the potential to play a significant role.

Hydropower supplies about 10 per cent of the electricity output in the USA and approximately 20 per cent of all electricity generated worldwide [SERI, 1990[1]]. In the near term, further development of hydro potential, through the upgrading of existing plants and the installation of new facilities, could increase clean energy production and make a near-term contribution to the reduction of greenhouse gas emissions [Sale and Neuman, 1998[2]].

Impoundments and releases from hydro plants can, in certain conditions, adversely impact the water quality of impounded and discharged flows as well as the aquatic life upstream, downstream, and migrating through the sites. These impacts have been severe enough to cause political and environmental activists to demand improvements. Today, in the USA, environmental demands include the release of higher spills from impoundments to increase fish passage survival and even demands for the removal of large dams in some areas of the country, in both cases reducing hydro energy generation.

To address these adverse effects of hydro plants, new technologies are emerging which can remove many of the negative environmental effects of hydropower generation and enhance the recognition of hydro as a source of renewable energy. Some of these new developments address the improvement of fish passage survival and the reduction of hydro's impact on both water quality and aquatic habitat. This paper discusses work currently underway in the USA related to these issues.

Developing better environmental alternatives for hydro

Beginning in the mid-1950s, some utilities in the USA began to respond to environmental concerns and initiated steps to improve the environmental compatibility of their hydro plants. Two areas of the country were particularly active. In the Pacific Northwest, biologists, governmental agencies, and utilities on the Columbia river were experimenting with ways to increase the survival of fish as they passed downstream through hydro plants (fish passage is now also emerging as an important issue in the eastern USA). In the southeast, the Tennessee Valley Authority (TVA) was a pioneer in using an integrated system approach, finding improved ways to balance the multiple uses of water resource projects among hydropower generation, flood control, municipal and industrial water supply, water quality, and recreation. TVA, adopting a pro-active approach to environmental stewardship, has invested significantly in R&D and hardware to develop and implement improvements to system operation that optimize benefits among all stakeholders in their water resource projects [TVA, 1990[3]].

As part of its strategy to respond to the needs of its customers, Voith has had a long-term commitment to developing hydro equipment designs with technologies for environmental enhancement. In the 1950s, Voith played a leading role in Europe with R&D to develop turbine designs capable of boosting dissolved oxygen (DO) levels in water passing through low head turbines [Wagner, 1958[4]]. In the 1970s, their engineers began investigations into the use of greaseless components in turbine power control elements. In the 1980s, Voith continued the development of oil-free Kaplan turbine hub designs with the installation of several oil-free Kaplan turbines and began R&D to improve the understanding of issues leading to the mortality of fish passing through hydro turbines [Breymaier, 1994[5], Eicher Associates, 1987[6]]. Voith Hydro, Inc., also invested significant funds, with TVA, in a joint R&D partnership to develop improved hydro turbine designs to enhance DO concentrations in releases from Francis turbines.

During the 1990s, these efforts were further intensified [Fisher and Roth, 1995[7]]. In 1995, under the stimulus of a cost-shared Department of Energy contract, Voith Hydro, Inc. began the development of an 'advanced environmentally friendly' family of turbine designs, in collaboration with the Georgia Institute of Technology, Harza Engineering Co., Normandeau Associates, and the Tennessee Valley Authority. The environmental improvements for the advanced designs addressed the goals of:

- improving fish passage survival;
- increasing the levels of dissolved oxygen in hydro plant discharges;
- developing special turbine designs for efficiently

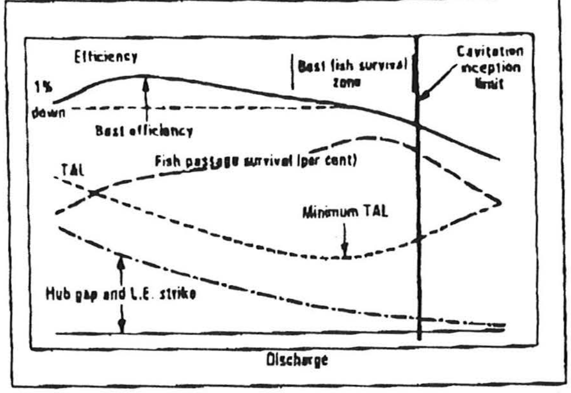

Fig. 1. At Wanapum dam, measured fish passage survival maximized at flows where efficiency was more than 1 per cent below peak efficiency, where blade tilts were large, internal turbulence levels (TALs) were minimal, and blade-to-hub gaps were small.

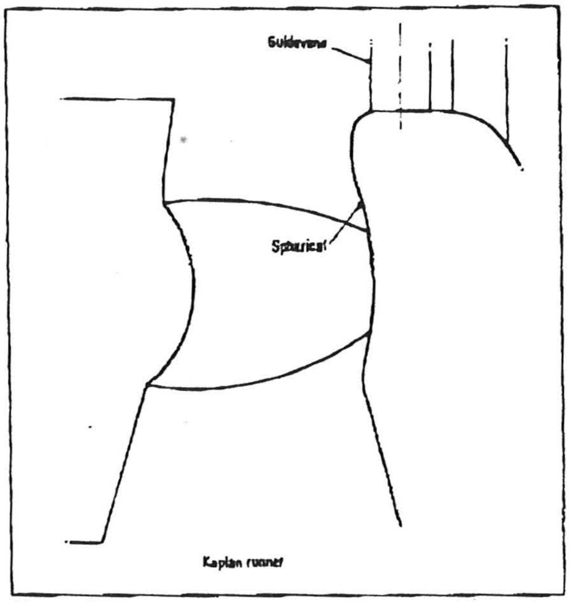

Fig. 2. Minimum gap Kaplan runner with spherical hub and discharge ring profiles, and no guidevane overhang at high gate openings.

providing minimum stream flows to protect downstream aquatic habitats; and,

• developing designs to provide reduced oil and grease pollution.

These concepts primarily addressed the enhancement of hydropower's environmental compatibility through upgrades of turbines at existing hydro stations. However, the environmentally improved design concepts provide additional benefits, including improved plant energy generation and reduced operating and maintenance costs. The concepts are applicable to new turbine installations as well. An independent investigation by the joint venture of Alden Research Laboratory, Inc., and Northern Research and Engineering Corporation, under a second DOE contract, also supported the achievability of 'fish friendly' turbines with a unique design that is primarily applicable to fish bypass flow schemes and new turbine installations.

Today, a number of utilities in the USA are upgrading turbines to environmentally friendly designs as part of their programme for relicensing and energy generation improvement. Utilities and water resource agencies are also developing strategies and implementing control systems to improve how they operate their turbines to enhance water quality and fish survival when fish and/or low levels of DO are present. The direct fish mortality of turbine bypass systems, including spillways (which may also add detrimental dissolved nitrogen) and fish collecting structures, are under investigation to provide an understanding of how all of the components of a hydro project can be used to improve its environmental compatibility. In many cases, passing fish through environmentally enhanced turbine designs can result in higher overall survival than bypassing fish through the dam's spillways [Ledgerwood, et al, 1990[8], Normandeau Assocs, 1997[9]].

Increasing fish passage survival

By 1990, more than 40 years of investigating fish survival by catching fish downstream of turbines had not provided comprehensive insights into actual mechanisms affecting fish survival. The turbine had been treated as a 'black box' by many researchers, and only vague rules-of-thumb had been developed to characterize turbines biologically. Beginning in 1990, a more precise method for measuring fish passage survival was introduced. This technique uses carefully designed and controlled testing with fish which can be recovered with 'balloon tags' [Heisey, et al, 1992[10]]. Based on the results of those experiments, statistical characterizations demonstrating much higher fish survival began to emerge [Mathur and Heisey, 1992[11]]. Survival rates measured for fish passing directly through large turbines ranged from 88 to 94 per cent.

In the past five years, important research aimed at further understanding the mechanisms leading to fish mortality has been completed. Numerous workshops bringing biologists, operators, regulators, and designers together have improved insight into factors which may influence survival. The US Department of Energy's Advanced Hydro Turbine (AHT) programme further stimulated a detailed investigation into mechanisms for fish passage mortality through the use of detailed numerical simulation of fluid flows in turbines with 3D viscous computational fluid dynamics (CFD) methods and careful balloon tag testing. As a result of the studies, turbine design improvements which can be implemented in new machines or through the rehabilitation of existing machines have been developed [Franke, et al, 1997[12]]. Limited field testing to date has verified many of the conclusions reached [Normandeau Assocs and Skalski, 1996[13] and 1998[14]].

An especially enlightening test of the existing turbines at Wanapum dam, using balloon tagged fish, verified many of the fish mortality mechanism models [Normandeau Assocs and Skalski, 1996[15]; Fisher, et al, 1997[16]] and showed that best efficiency operation of Kaplan turbines is not necessarily the most favourable operating condition for fish survival, as had previously been believed. Instead, operation at higher flows was found to be safer for passing fish (Fig. 1).

The research developed insights into mortality mechanisms for Kaplan turbines, with mortality being related to:

• turbulent flows resulting from low efficiency designs or plant operating strategies;

• turbulent flows and the trapping and cutting of fish in the zone of flow passing near the turbine hub when large gaps between blade and hub exist (characterizing the lower output operation of Kaplan turbines);

• strike of fish by turbine blades or impact of fish on other turbine structures:
• cavitation in turbine water passages;
• abrasion of fish driven into rough turbine surfaces by flow turbulence; and,
• turbulence-induced or impact-induced dizziness enhancing the chance for predation losses as disoriented migrating fish are eaten by birds or other fish when they emerge from the draft tube.

The number of turbine runner blades and stayvanes, the length of the fish compared with the size of the turbine, and the quality of the flow at the point of operation are key elements that characterize survival [Franke, et al. 1997[12] and Fisher, et al. 1997[16]]. Also, the location of the fish in the water column and the zones of flow through which the fish pass have been found to be important.

As a result of insights gained, a comprehensive environmentally enhanced Kaplan turbine concept was developed. The required features depend on site-specific goals and include designs having:

• high efficiency over a wide operating range with reduced cavitation potential (results from today's advanced technology design verification tools);
• a gapless design for hub, discharge ring, and blades (Fig. 2) that enhances fish passage survival;
• a non-overhanging design for guidevanes;
• environmentally compatible hydraulic fluid and lubricants;
• greaseless guidevane bushings; and,
• smooth surface finishes in conjunction with upgrades for stayvanes, guidevanes and draft tube cone.

To address the changes in mortality associated with how the turbines are operated, new technology in measurement transducers and control systems have been used to improve control system designs to:

• sense fish presence at each turbine and limit turbine operation to 'fish friendly' modes when fish are present;
• automatically update Kaplan turbine 'digital cam surfaces' to most efficient operation at each head and flow to ensure proper optimization of operations and minimization of fish injuring flow turbulence;
• sense active cavitation and limit turbine operation to non-cavitating conditions; and,
• optimize plant output when fish are present to achieve targeted fish passage survival based on fish presence, location, turbine passage mortality, spillway fish mortality, fish bypass characteristics, and total dissolved gas generated during spilling (Fig. 3).

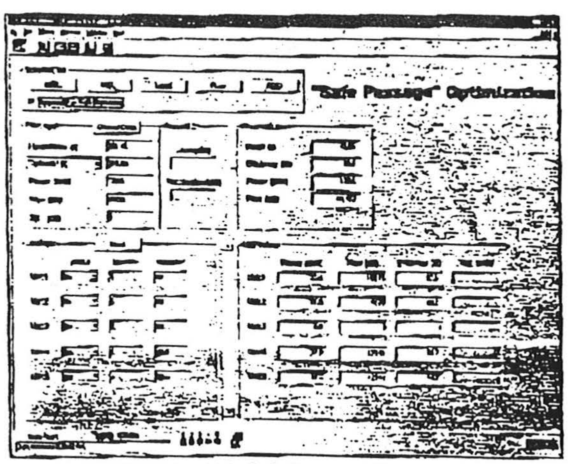

Fig. 3. The WaterViewTM 'Safe Passage' Plant Optimized Operation Module (patent pending) responds to the presence of fish by forcing operation of the turbines with sensed fish presence to the discharge providing the highest fish survival.

Furthermore, new technology for generator designs can be implemented for plants with large changes in head. Particularly important for Francis units is that turbine operations can be adjusted for optimum fish survival conditions, independent of the operating head, by using adjustable speed generators and advanced control systems.

Elements of the e-'fish'-cut™ Kaplan have been implemented in the rehabilitated designs installed at the Rocky Reach powerplant in Washington State, USA, [McKee and Ross, 1995[17]] and at the Bonneville project of the US Corps of Engineers [Moentenich, 1997[18]]. An even more advanced design has been developed and model tested for the Grant County P.U.D.'s Wanapum dam [Hron, et al. 1997[19]]. These turbines feature partly or fully 'gapless' designs, as well as some of the other features discussed above. Fish survival testing using balloon tags at Rocky Reach showed that elimination of the gaps downstream of the blade centre of rotation resulted in a 4 per cent improvement in fish passage survival at lower operating powers where gap size was large [Franke, et al, 1997[20]]. Testing of the fish passage survival of the new minimum gap design at Bonneville is planned for the spring of 1999.

An environmentally enhanced Francis turbine concept was also developed. Features include: a low turbulence, high efficiency design with reduced cavitation and a reduced number of blades compared with traditional designs; a non-overhanging design for guidevanes; use of environmentally compatible hydraulic fluids for governors; greaseless guidevane bushings; upgraded surface finishes for stayvanes, guidevanes, and draft tube cone; adjustable speed generator for wide head range plants; and, an advanced control system for speed adjustment and/or for optimized energy generation while operating units and the plant at flows maximizing fish passage survival when fish are present in the flow. The Table below shows the strike related effect of turbine size and number of blades on fish survival.

Further research is under way. Advanced zonal matrix models to estimate fish passage survival as a consequence of turbine geometry and operational characteristics are being developed and evaluated. Fig. 4 shows the results of such a model where lines of constant fish passage survival are shown superimposed on the turbine efficiency performance characteristics. Field tests of eel survival for a propeller turbine design correlated well with predicted survival [Normandeau Associates and Skalski, 1998[14]] using the zonal matrix model.

Strike related effect of turbine size and number of blades on fish survival

	Number of blades	Using D = 1.0 m Survival probability (per cent)	Using D = 5.41 m Survival probability (per cent)
New	25	89.7	98.1
Original	18	92.6	98.6
New	15	93.8	98.9
New	13	94.6	99.0
New	11	95.5	99.2

Considering only strike induced mortality for Francis turbines of two different sizes (D) and various numbers of runner blades, large turbines with a smaller number of blades provide better conditions for survival.

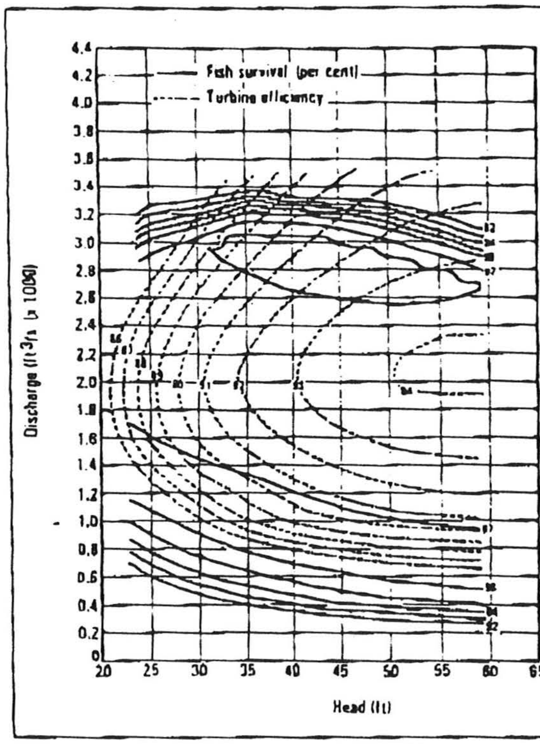

Fig. 4. Calculated fish survival for a bulb turbine superimposed on the turbine performance characteristic curve. Note that best survival occurs at flows higher than best efficiency flow. The calculated survival is a function of the specific turbine geometry (including the number of blades and stay-vanes), the hydraulic condition of the the turbine and the size and location of the fish entering the turbine.

In another application of new technology, an advanced computational method for estimating trajectories of fish-like bodies passing through hydropower plants is now under development. The method is based on the assumption that a fish swimming through the complex, three-dimensional flow field of a hydro turbine (obtained by a separate 3D viscous calculation) can be approximated as a body of simplified, yet fish-like geometry moving through the precomputed flow field. The motion of such a 'virtual fish' is governed by a set of differential equations which account for the fish mass and various flow-induced forces.

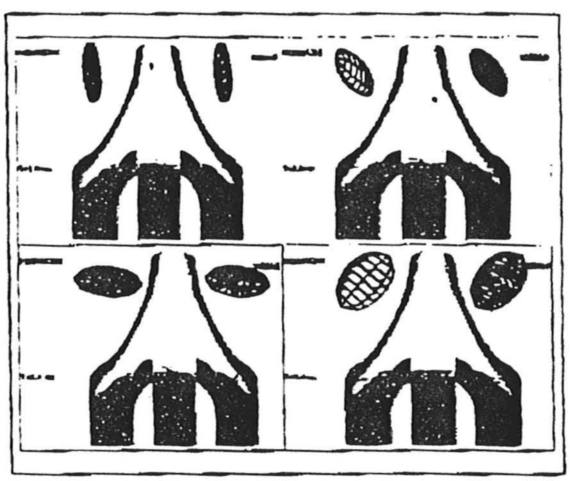

Fig. 5. The small ellipsoids characterize the position of the 'virtual fish' passing through a turbine draft tube flow field. Forces acting on the virtual fish are calculated from velocity and pressure loading acting on the fish body surface and are displayed external to the draft tube above.

This model can not only be used to estimate the trajectory of a virtual fish from the forebay to the tailrace, but can also provide very specific information about a variety of flow-induced loads to fish passing through various zones of turbine flow, see Fig. 5 [Sotiropoulous, Ventikos and Fisher, 1997[21]].

Use of these advanced tools, in conjunction with well planned and executed physical tests to validate the injury mechanisms, will help turbine designers and biologists to improve fish passage survival and enhance the image of hydropower as 'green power' and a renewable resource.

Increasing dissolved oxygen in turbine discharges

Development of methods for increasing dissolved oxygen in turbine discharges has been underway for nearly 50 years, and in the last ten years, significant progress has been made. TVA has been a consistent driver of these developments. Through its Norris Engineering Laboratory, TVA has developed reliable line diffuser technologies for low-cost aeration of reservoirs upstream of hydro plants [Mobley and Brock, 1996[22]] and effective labyrinth weirs and infuser weirs for aerating flows downstream from hydro plants [Hauser and Brock, 1994[23]]. The most cost-effective technology for Francis turbines, where site conditions permit, has been found to be the use of the low pressures induced by the water flowing through the turbine to aerate the flow.

For upgrades and new construction, an on-going joint development project by TVA and Voith Hydro, Inc. has made substantial improvements in the design of the 'auto-venting' turbine (AVT) [Hauser and Brock, 1994[23]; US DOE, 1991[24]; March, et al, 1992[25]]. Extensive development with scale models and field tests was used to validate aerating concepts and determine key parameters affecting aeration performance.

The new auto-venting turbine for Norris dam Unit 2.

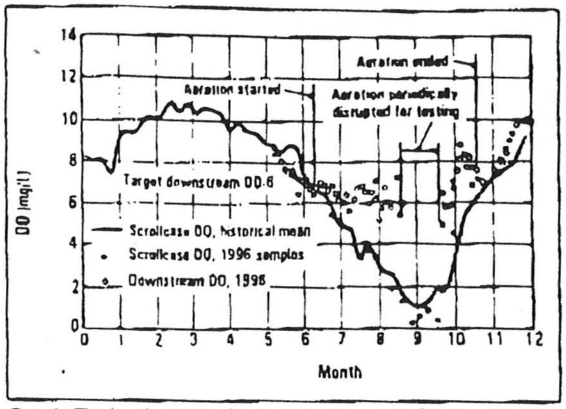

Fig. 6. The levels of dissolved oxygen in water discharging from the turbine was increased as a result of the turbine aeration at Norris dam (1996).

Specially shaped turbine component geometries were developed for enhancing low pressures at locations for aeration outlets in the turbine water passage, for drawing air into an efficiently absorbed bubble cloud as a natural consequence of the design, and for minimizing the power lost as a consequence of aeration. New methods were also developed to manufacture turbine components for effective aeration.

TVA's Norris dam was selected as the first site to demonstrate this technology. The two Norris AVT units contain options to aerate the flow through central, distributed, and peripheral outlets at the exit of the turbines.

In testing the new auto-venting turbines, measurements are required to maximize the environmental and hydraulic performance of the aeration options. The environmental performance is evaluated primarily by the amount of DO uptake, while the hydraulic performance is based on the amount of aeration-induced efficiency loss. At Norris, each aeration option has been tested [Ruane and Hauser, 1993[26]; Hopping, et al, 1997[27]] in single and combined operation over a wide range of turbine flow conditions. For environmental performance, results show that up to 5.5 mg/L of additional DO uptake can be obtained for single unit operation with all aeration options operating. In this case, the amount of air aspirated by the turbine is more than twice that obtained in the original turbines with hub baffles. To meet the 6.0 mg/L target that has been established for the project, an additional 0.5 mg/L of DO improvement is obtained by the flow over a reregulation weir downstream of the powerhouse. For hydraulic performance, efficiency losses ranging from 0 to 4 per cent are obtained, depending on the operating condition and the aeration options. Compared with the original turbines at the plant, these replacement units provide overall efficiency and capacity improvements of 3.5 and 10 per cent, respectively [Hopping, March and Fisher, 1997[28]]. The new runners have also shown significant reductions in both cavitation and vibrations.

In general, the environmental and hydraulic performance of a given option varies with the site head and site power output. In these conditions, the options used to meet a target DO can be strategically chosen to minimize the aeration-induced efficiency loss.

As an example, consider the 1996 DO data for the new units at Norris, shown in Fig. 6. Turbine aeration was initiated in July, when the scroll case DO began to drop. Throughout the low DO season, based on the head, power and required DO uptake, a mix of aeration options was used. Aeration ended in November after reservoir turnover. On average, the DO downstream of the project was maintained near the 6 mg/L target (except for a period when aeration was disrupted for an extreme series of performance tests of the new units). During the same period the average aeration-induced turbine efficiency loss was about 1.9 per cent.

As is the case with improvements to fish passage survival, additional research is under way to improve designs for aerating turbines further. In one project, computer flow simulations using advanced numerical methods have been developed to model the processes involved in increasing the effectiveness of aeration. 'Virtual bubbles' injected into turbine flows are being used to calculate bubble size and oxygen transfer efficiency. By the use of the advanced numerical simulation, oxygen uptake efficiency as a function of changing design and operating parameters can be refined further. Improved software to calculate the influence of aspirated air on turbine performance and on the pressure at the air admission point is being studied, and the design of improved mechanical systems for transporting air to critical locations is underway. Field tests to verify design assumptions continue to play an important role in improving the methodology.

Conclusion

Significant progress is being made in removing the 'tarnish' from hydro's image and supporting hydro's legitimate role as a clean, environmentally sound, renewable, and affordable resource. Testing of prototype solutions has indicated that effective improvements are being achieved, improving water quality at hydro sites and reducing hydro's impact on aquatic life. Progressive utilities are working hard to implement these new developments and to operate their hydro systems to balance environmental responsibility and economical power generation.

Additional research is needed to refine fish damage models and additional testing must be conducted to enhance the understanding developed to date and to verify the applicability of the new designs to a wider range of projects. ○

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