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FURTHER DEVELOPMENT OF THE PNEUMATIC METHOD TO HARNESS HYDROPOWER AND ITS EXPERIMENTAL IMPLEMENTATION IN THE STATE OF MAINE

FINAL REPORT

(Contract DE-FG02-91ER12113)

By

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DOE Science Contract Monitor:
DR. Walter M. Polansky, Director
Division of Advanced Energy Projects

Boston, March, 1994

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1. ABSTRACT

This report contains conclusive results of the research project entitled "Further Development of the Pneumatic Method to Harness Hydropower and its Experimental Implementation in the State of Maine" sponsored by the US Department of Energy (Contract DE-FG02-91ER12113). The results obtained by this research are considerably beyond the original goals anticipated by the contract which were a theoretical study of the method only and its possible applications.

In fact, the success of the analytical research program has allowed us to move on to development, construction and testing of a physical model of the hydro-air power converter and, subsequently, to development of a well equipped hydro-pneumatic power laboratory at Northeastern University. Photographs 1a and 2a show both the laboratory and the model.

Good perforance of the model proves that the hydro-pneumatic concept holds much promise for development of an ecologically save and commercially attractive novel approach to harnessing ultra low-head hydropower. As a result, private companies have started to support this new technology, and to invest money in its further development and construction of demonstration power plants (Appendix 1). Visitors at the Northeastern University laboratory often praise this new technique, as it attested by the articles in the Wall Street Journal (Appendix 2) and the Technology Review (Appendix 3).

2. SUMMARY

The objective of this research is further analytical and experimental study and development of the pneumatic approach to harnessing ultra low-head hydropower with minimized effect on the riverine or marine ecology.

Masses of water carried by most rivers have very low natural density of power because the water is distributed over large areas. To make hydro energy commercially feasible it must be concentrated by means of high dams, lifting the natural water heads. However, artificial high dams and water heads cause adverse effects on riverine ecology, destroying it. The best way to preserve the environment during harnessing hydropower is to first convert the natural energy of water movement to the air and then to manipulate the air, concentrating and improving the quality of its power. This leaves the water environment practically intact, allowing at the same time for the generation of electricity by hydro power. This method, which is called the hydro-pneumatic concept, is described in this document.

The concept has been developed and tested at Northeastern University under contracts with the U.S. Department of Energy and Central Maine Power Company. The principal idea of the method is to convert energy of flowing water to energy of compressed air and then to generate electricity by means of high speed air turbines. This eliminates hydro turbines in the water and allows for power plants to operate with water heads less than 12 feet. Ultra low-heads and absence of high speed turbines in the water are the major factors for ensuring the ecological safety of the pneumatic power installations.

The hydro-pneumatic concept is one of very few novel and prospective approaches to hydropower, which has been dominated by hydroturbine technology for about two centuries. This approach is the least environmentally damaging of all other conventional methods in the hydropower industry, and can utilize the power of numerous plain rivers, canals, and tidal estuaries around the world. It has already triggered research activity in many laboratories outside of the United States after originally having been developed and patented in this country. In addition to ecological advantages the pneumatic technology should be less expensive than conventional hydro mainly because air turbines are simpler, substantially less expensive and easier to maintain than hydro turbines.

The DOE grant helped to develop a hydro-pneumatic power laboratory at Northeastern University that is the only one of this kind in the USA (Fig. 1a). This laboratory has been used for experimental study of broad aspects of hydro/air energy conversion and for further development of this novel approach to harness ultra low-head hydro power without damaging the environment. One of the next major tasks of the project is to optimize and test in the laboratory all mechanical and electrical elements of the hydro-pneumatic mechanism including gates, air turbines, generators, with emphasis on ecological safety and a subsequent feasibility study of some demonstration hydro-power installations.

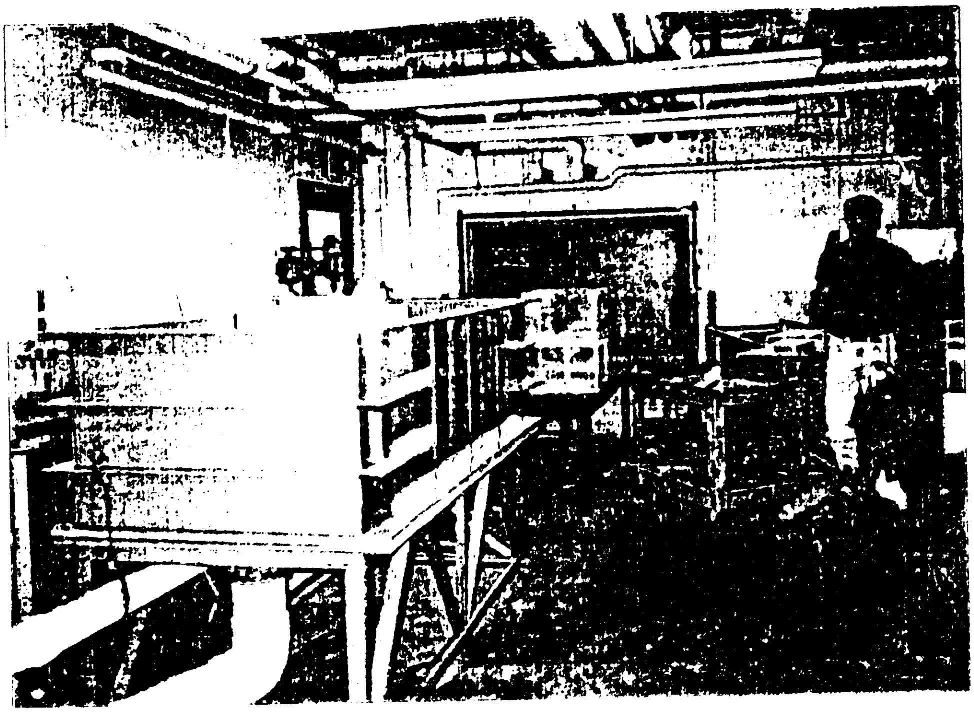

Fig. 1a
Hydro-Pneumatic Power Laboratory

CONCEPTUAL DESCRIPTION OF THE METHOD

(Proceedings of the NESC conference, Japan, 1993)

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A SYNCHRONIZED HYDRO/AIR ENERGY CONVERTER FOR ULTRA LOW-HEAD HYDROPOWER PLANTS

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Abstract: Masses of water carried by most rivers and ocean tides have very low natural density of power because it is distributed over large areas. To make hydro energy commercially feasible it must be concentrated by means of high dams, lifting the natural water heads. However, artificial high dams and water heads on rivers cause an adverse effect on riverine ecology, destroying it. The best way to preserve the environment during harnessing ultra low-head hydropower is to convert first the natural energy of water movement to the air and then to manipulate the air, concentrating and improving the quality of its power. This method, which is called the hydro-pneumatic concept has been originally developed by author in 1978, and then tested at Northeastern University in Boston. The principal idea of the method is to convert energy of flowing water to energy of compressed air by means of a hydro/air energy converter and then to generate electricity by high speed air turbines.

1. INTRODUCTION.

Initially, this method has been offered and developed to some degree for tidal power exploitation (see [1], [2], [3]), and later it was expanded for applications to riverine sites [4]. Its main idea is to harness hydroenergy by means of air turbine machinery instead of hydroturbines. This can be done if an intermediate technological link is introduced, namely a hydro/air converter for converting the energy of flowing water into the energy of compressed air by forcing the water to oscillate inside the chamber. Main advantages of air turbines are their high sensitivity to the air pressure, maintenance simplicity and low cost. Indeed, the pressure of 0.05 atm. which corresponds to half of the meter of the water head is enough for air turbine stable operation [6].

The approach, although to some extent more complicated than the conventional hydroturbine for a large scale plant, has a number of major advantages for small, low-head hydropower which could make it quite attractive both for tidal and riverine applications. A detailed description of the pneumatic method and its application for pneumatic power plants is given in [2,3]. A conceptualized view of such a plant is shown in Fig. 1.

A hydropneumatic power plant which operates according to the proposed method contains three main elements: 1. An air chamber, which converts the energy of water flow into the energy of compressed air. 2. A barrier (dam), which creates a low-head upper water pool, forcing the river water to flow through chamber 1, where it oscillates and compresses the air. The amplitude of the water column oscillation depends on the head created by the dam. 3. A powerhouse above the high waters, which contains a number of air turbo-generator units.

Chamber 1 is a waterproof, reinforced-concrete or steel structure installed on the river floor. A system of flap sluice-gates is located along two opposite sides of the chamber, with the upper edge of the gates lower than the minimum water level of the tail water.

There are two phases of chamber operation, namely the filling cycle (Fig. 2) and the emptying cycle (Fig. 3). During the filling cycle the upstream gates are open, and the downstream gates are closed. The water filling the chamber compresses air in the upper part of the enclosure. The compressed air, flowing from the chamber through the pipe on the chamber roof, drives the air turbo-generator unit until the water level in the chamber reaches the upstream level. After that, a second cycle starts, (Fig. 3); the upper gates close, while the lower gates open, and water flowing out of the chamber into the river creates a partial vacuum in the upper part of the enclosure. Now the air turbo-generator unit is driven by the air jet from the atmosphere into the chamber due to the vacuum in the chamber (suction).

This is a simple, automatic system in which, by alternately locking and unlocking the opposite gates, the chamber is either filled (compression cycle) or emptied (vacuum cycle). Chamber sluice gates are designed as flap systems which are supposed to be able to close under the action of a counter balance, which will be described later.

2. CYCLE TIME AND AIR VELOCITY.

The air chamber is a substantial functional element of the plant and its size is important for overall power plant design. To find the chamber dimensions we have to know the duration of each filling/emptying cycle. Detailed hydrodynamical analysis of the problem is given in [3].

The duration of a filling cycle can be obtained from the equation of water-air energy balance inside the chamber (Fig. 4)

$$F dz = p dV + dW + dK \tag{1}$$

where F is the resultant force applied to the water at the reference level, p is the chamber air pressure, V is the water volume, W is the potential energy and K kinetic energy of the water mass inside the chamber.

$$\begin{aligned} F &= A(p_1 + \rho_0 g H_0) \\ dV &= A dz \\ W &= (1/2) g \rho_0 A z^2 \\ dW &= g \rho_0 A z dz \\ K &= (1/2) m v^2 = (1/2) \rho_0 A z (\dot{z})^2 \\ dK &= \rho_0 A [(1/2) \dot{z}^2 + z \ddot{z})] dz \end{aligned} \tag{2}$$

After substitution in (1)

$$\ddot{z}z + 1/2(\dot{z})^2 + gz + \left(\frac{p_1 - p_0}{\rho_0} - gH_0\right) = 0 \tag{3}$$

The solution of Equation (3) in terms of the water velocity $\dot{z}$ is

$$\dot{z} = \left[\frac{gz_0 - \varepsilon}{\alpha^2}\left(\frac{z_0}{z}\right)^{2\alpha^2} + \frac{\varepsilon - gz}{\alpha^2}\right]^{1/2} \tag{4}$$

and the duration of a filling cycle is

$$T = \frac{2}{g}\alpha(\varepsilon - gz_0)^{1/2}$$

$$\text{where} \quad \varepsilon = \frac{p_0 - p_1}{\rho_0} + gH_0; \; \alpha^2 = 1/2 + \frac{\rho}{2r^2\rho_0}; \; \alpha^2 >> 1; \; r = \frac{A}{A_{aw}} \tag{5}$$

Table I contains some numerical results obtained for different water heads.

3. CHAMBER-TO-CHAMBER OPERATION ("Double box system," in the terminology of [7]).

The single-chamber system suffers a disadvantage caused by interruptions of the water flow. Indeed, the downstream flow is interrupted during the filling cycle, and the upstream flow is interrupted in turn during the emptying cycle. Besides, the single-chamber method assumes that the air is discharged from the turbine directly to the atmosphere, which causes a very high noise from the rapidly rotating turbine.

These disadvantages can be eliminated by constructing two air chambers connected by an air pipe on the top, allowing chamber-to-chamber operation.

The working cycles of the chambers are shifted in time in such a way that when one chamber is being emptied (vacuum cycle), the other chamber is being filled (compression). Thus the air flows from one chamber into the other instead of to the atmosphere. Moreover, the air turbine works in this case under simultaneous action of air pressure on the ingress side, and a draught on the egress side. In other words, the air pressure on the turbine blades is doubled because of a supplementary draught from the adjoining chamber.

The author's most recent research on the hydropneumatic technique led to the development of double chamber system shown in Figures 5 and 6 [10].

The system, which provides a water gate array for harnessing power from current flow or tidal movement in the water, comprises first and second hydropneumatic chambers (12 and 14 of Fig. 5) each having ingress (32 and 33) and egress (31 and 34) ports below the water surface near the river or ocean floor and water gates that open and close the ports to the passage of water. Each pair of gates is mounted upon a common shaft. Because of such a design the gates are synchronized during their operation, so that the ingress ports of each chamber are connected to the egress ports of the other chamber. Thus, one set of gates is closed while the other is open, thereby allowing water to flow into one chamber and build air pressure therein and allowing water to flow out of the adjoining chamber and create a partial vacuum therein. A pipe (46) connects the chambers, and an air turbine (48) harnesses the air movement within the pipe. When water levels are equilibrated, the open set of gates is closed by a counterweight (43), and the other set is allowed to open by pressure buildup of the water differential. Different phases of filling/emptying of the chambers follow each other. In case of a large water flow rate, the water gates may be comprised of a plurality of louvers which are gauged for simultaneous opening and closing.

The gate closing mechanism is simple and accessible for maintenance. No motor is designated for rotating the gates, and no energy source is supplied other than that from the natural water flow. The gates close automatically by the gravitational lock (43 and 44 on Fig. 5) when the water pressures becomes about the same from both sides of the gates.

Filling/emptying cycles in two adjoining chambers are perfectly synchronized because their phases differ by 180°. This means that while one chamber fills, the other simultaneously drains, following the same sinusoidal operation. As has been said, synchronization is achieved by means of mounting each pair of gates on a common shaft.

The duration of each opening/closing cycle of the gate operation is as short as 4-6 seconds, thereby reducing dimensions of the chambers. Indeed, the size of the chambers depends on how fast they can be filled or drained. For high speed of gate operation, the chambers would be small and inexpensive.

An operational model of the water gate array was designed, constructed and successfully tested in the mechanical laboratory of Northeastern University. Laboratory experiments proved the reliability and capability of the original theoretical concepts. The model can be seen in Figure 7.

A Wells air turbine, developed in England, [7] or a McCormick turbine, developed in the USA, [5,6], can be used for hydro-pneumatic installations. These high-speed turbines produce a unidirectional torque on the shaft under reversible air flow. They are substantially less expensive than low-head hydro turbines of the same power.

In conclusion one can point out that the slow flowing water in plane rivers and tidal estuaries is a form of solar energy conversion. The pneumatic hydro converter described could become a new efficient mechanism for exploiting this energy.

Acknowledgement: The research is sponsored by the U.S. Department of Energy and Central Maine Power Company.

4. REFERENCES

[1] AM. Gorlov, Some New Conceptions in the Approach to Harnessing Tidal Energy. Proc. of the 2nd Miami International Conference on Alternative Energy Sources, 1979.

[2] AM. Gorlov, "A Novel Approach to Exploitation of Tidal Power", Progress report to the US DOE, 1980, (Vol. 1 and 2).

[3] AM. Gorlov, Same Title,,Final Report, 1981, (Vol. 3 and 4).

[4] A.M. Gorlov, Hydropneumatic Concept for Small Riverine Applications. Proc., 2nd International Conference on Small Hydro, Hangzhou, China, 1986. (Int'l Water Power & Dam Construction).

[5] Richards and Weiskopf, "Studies of the McCormick Pneumatic Turbine" Proc., Utilization of Ocean Waves Symposium, La Jolla, Calf. 1986.

[6] M.E. McCormick and S.W. Surko, "An Experimental Study of the Performance of Counter-Rotating Wave" Energy Conversion Turbine", Journal of Energy Resources Technology, Sept. 1989.

[7] N.W. Bellamy, "Low-Head Hydroelectric Power Using Pneumatic Conversion", Power Engineering Journal, May, 1989.

[8] Small Hydro 1990. Water Power & Dam Construction, June 1991.

[9] "Prospects for Hydropower in the Northwest", US Army

Corps of Engineers, New England Division, 1980.

[10] A.M. Gorlov, A New Opportunity for Hydro: Using Air Turbines for Generating Electricity. Hydro Review, Sept. 1992, Vol. 11, N5.

Table 1

Water Head, H m	Cycle Time, T sec	Max. Air Jet Velocity (m/sec)
1.0	6.3	141
2.0	8.9	200
3.0	11	245
4.0	13	280

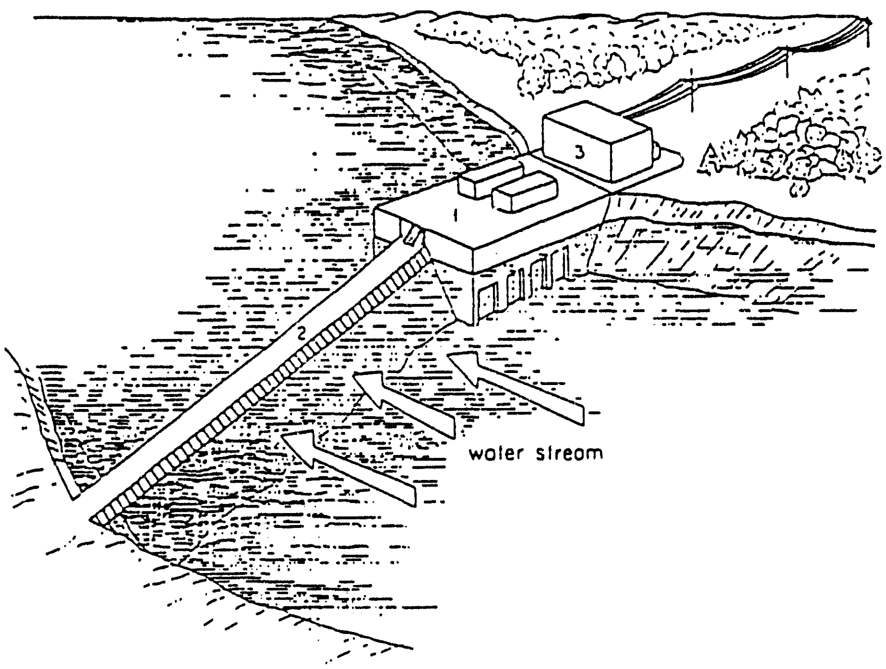


Fig. 1 Conceptualized View of Pneumatic Power Plant

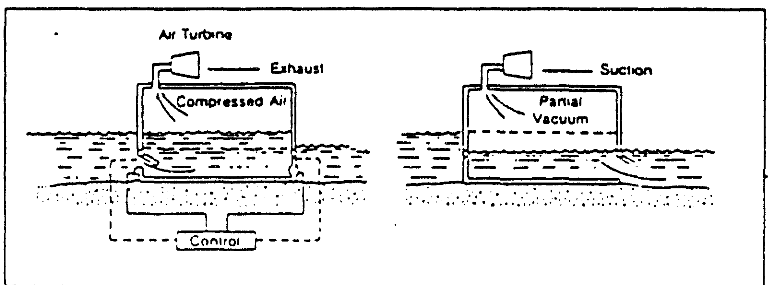


Fig. 2 Filling Cycle

Fig. 3 Emptying Cycle

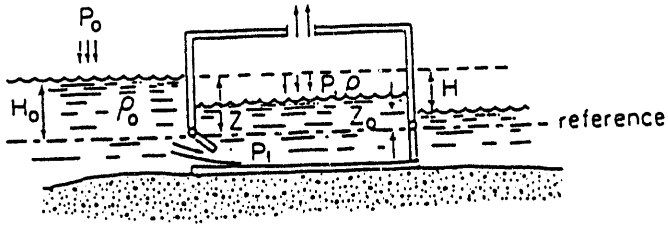


Fig. 4 Reference Diagram

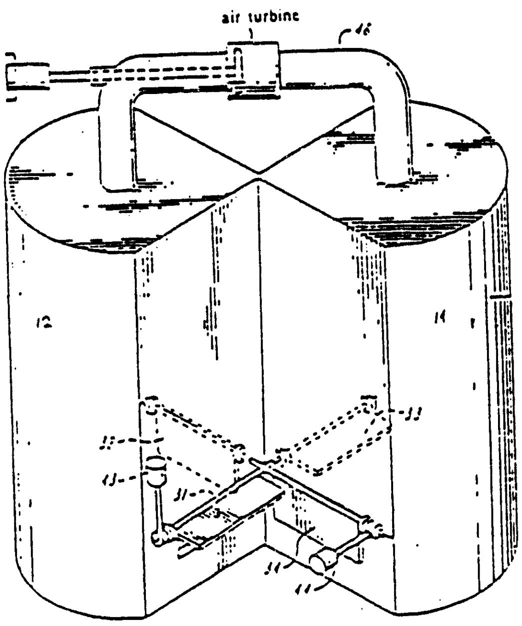


Fig. 5 Double Chamber System

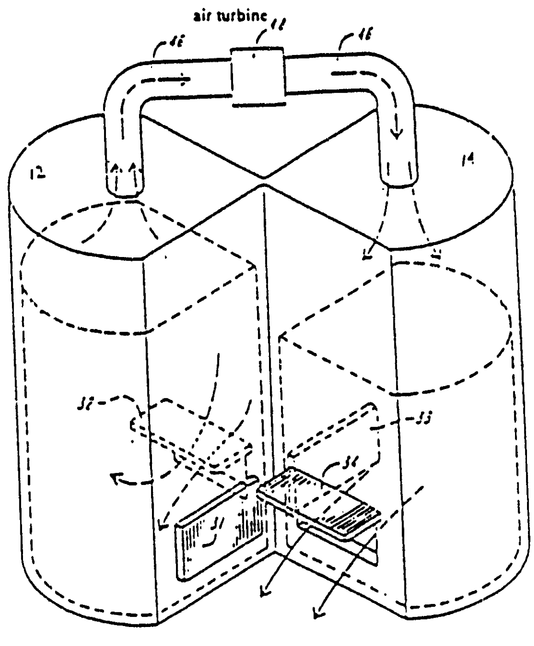
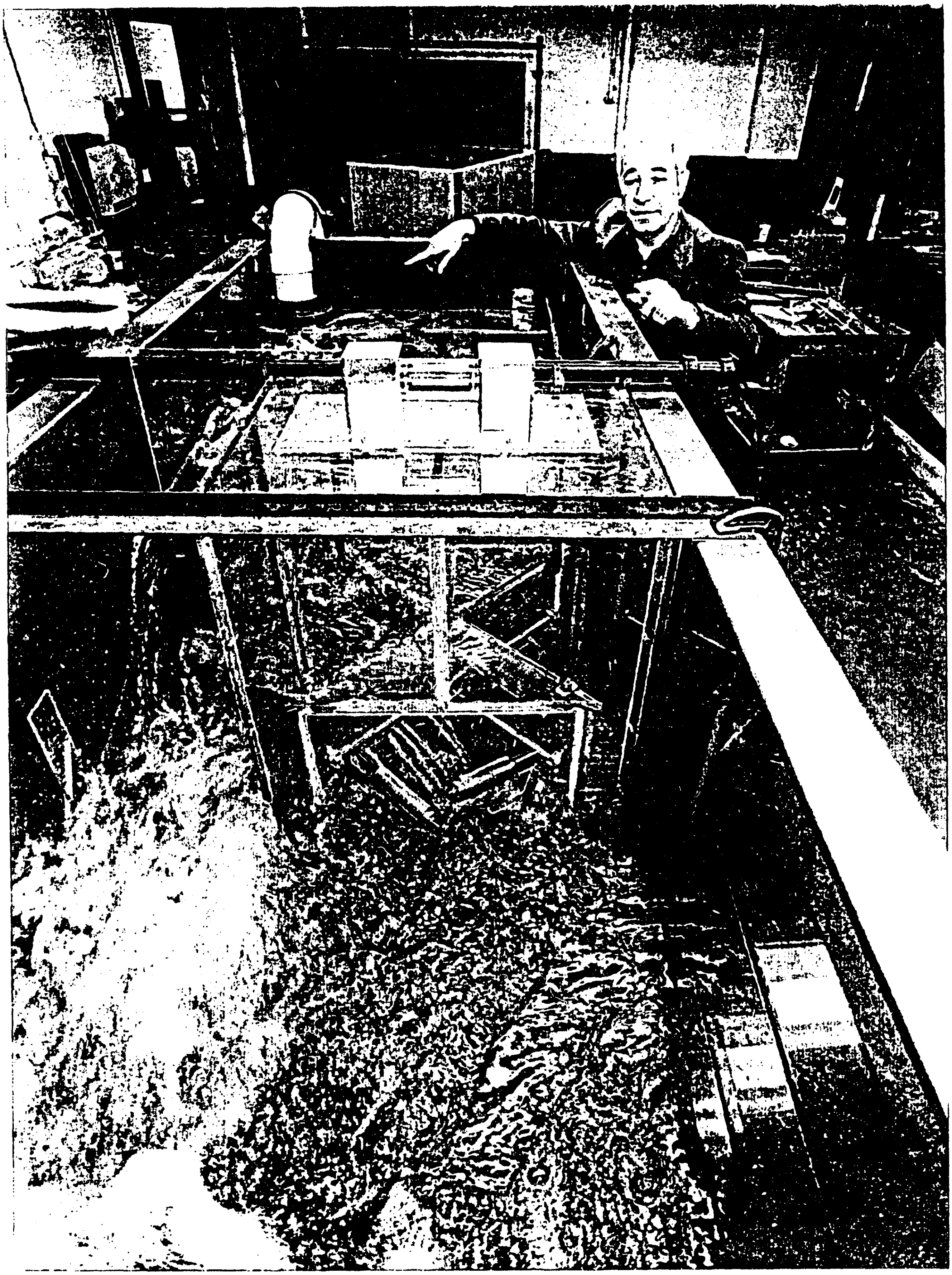


Fig. 6 Oscilating of Water Columns
(Left Chamber-Filling, Right Chamber-Emtying)



2a Hydro/air energy converter in the laboratory at Northeastern University

3. ENVIRONMENTAL ASPECTS. ADVANTAGES OF ULTRA LOW-HEAD HYDRO POWER PLANTS

Hydroelectric power is the best developed non-air pollutant renewable source of power, which contributes about 13% of the United States' total electric energy capacity. Almost all of this hydroelectricity is being produced by hydropower plants located in mountain or elevated regions where high water heads can easily be developed. The higher the water head, the better are the attainable technical and economic characteristics of the hydro turbines. For this reason many modern tall water dams have heights measured in hundreds of feet.

The most promising mountain hydro sites have already been developed in industrial countries in Europe and America as a result of intensive construction of hydro power plants during this century. Some other prospective projects, such as the Hydro Quebec, are very expensive in exploitation due to their remote locations from potential consumers and to terrain difficulties. This is one of the main reasons why only 5% of the existing dams in the United States are used for power production.

Therefore, any further substantial development of the hydro energy industry cannot rely on construction of new high-head stations. It becomes more and more difficult to find appropriate sites for such projects or to justify them.

In addition, there are environmental factors which would further constrain and eventually prevent development of high-head hydro projects. The most malignant of these factors are:

a. Artificial upstream water pools, which can flood agricultural land and swamp adjacent territories;

b. High dams, which can destroy natural wild life in rivers by obstructing its migration;

c. High speed and pressure hydroturbines, which can kill a fish population trapped by the water jet flowing through the turbines.

d. Low concentration of dissolved oxygen (DO) in the tail waters after high dams which can suppress life in the rivers. The phenomenon of "dead tail waters" is well known. It is caused by releasing through turbines purely oxygenated deep waters from the upstream reservoir, and eventually by breaking up micro organisms and air bubbles by the fast rotating turbine blades.

The nature of conventional hydroturbine technology is such that any improvement can hardly eliminate these harmful effects. Land flooding is one of the most damaging adverse effects on the environment of a low graded riverside. Let us consider this aspect in more detail.

As one can see from the diagrams of Figures 2 and 3, the riverside land flooded is

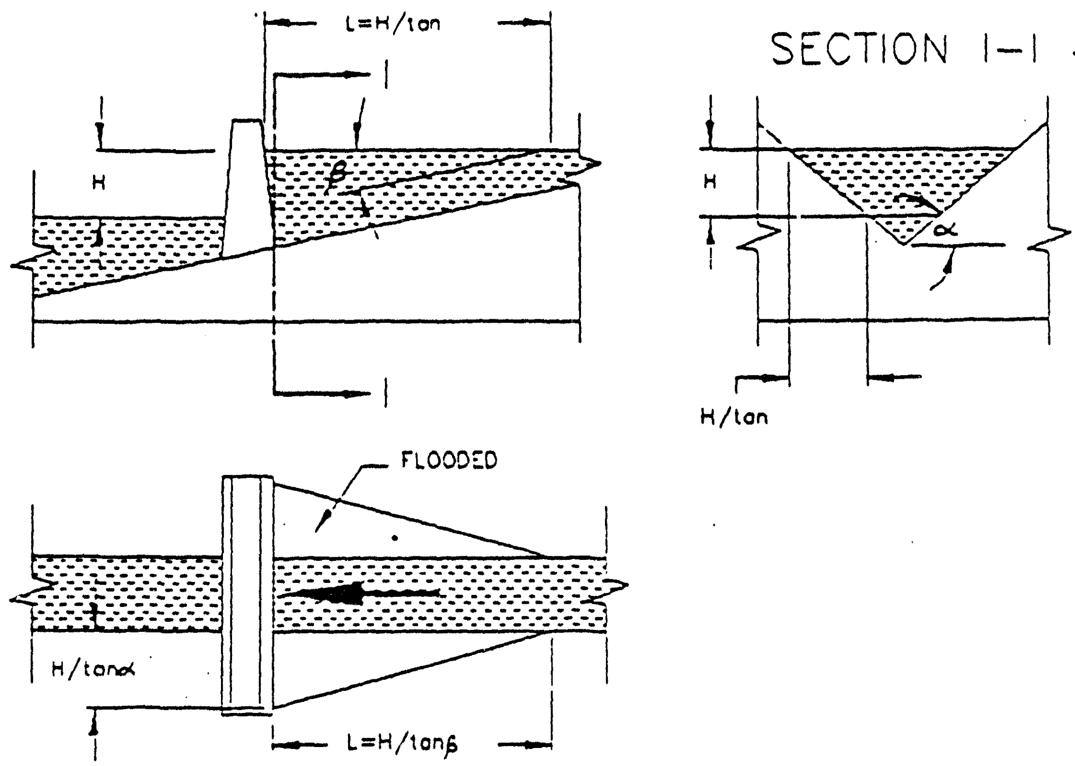


FIG. 2

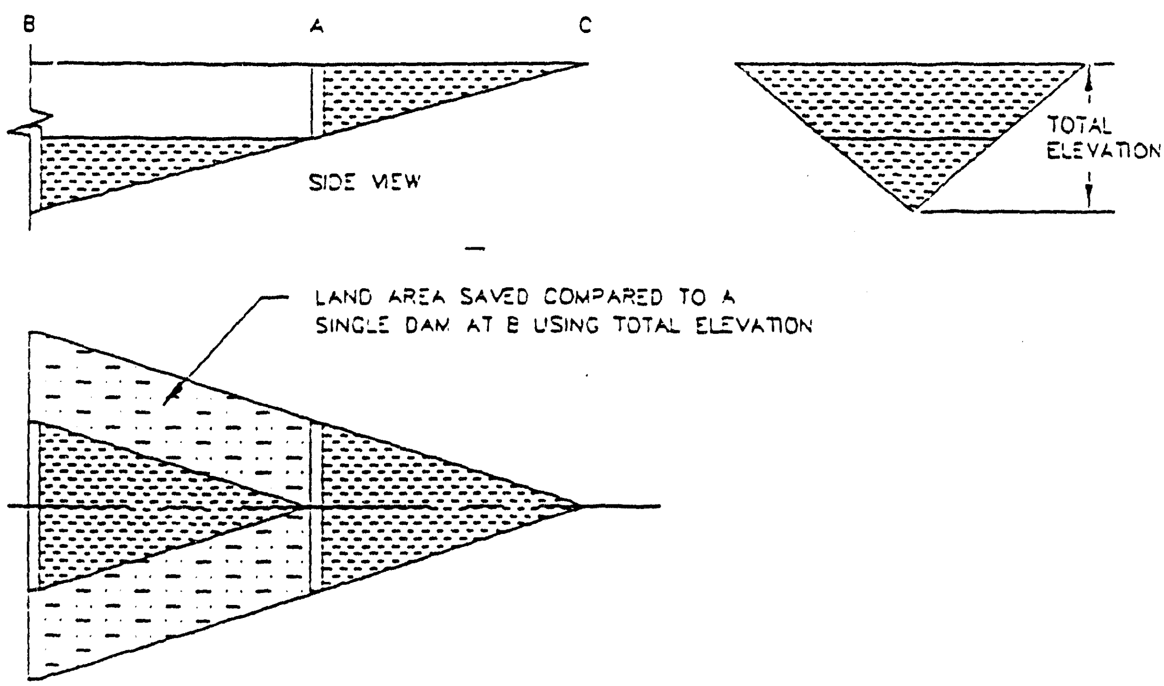


FIG. 3 SIMPLIFIED V-SHAPED VALLEY DIAGRAM

proportional to $H^2/(\tan \alpha \tan \beta)$, where H is the water head, and α and β are lateral and longitudinal slopes of the river basin. Thus, the land takings dramatically depend on the bank relief i.e., on α and β as well as on the water head H. Therefore, big H and small α and β can result in losses of large agricultural fields. It should be noted that these losses result not only from direct land flooding, but also from swamping of marginal areas by rising underground waters.

Thus, f.om the viewpoint of environment preservation it would be better, in the case of small α and β to construct two plants with a waterhead H, than to obtain the same power from one plant of a twice the waterhead. Unfortunately in spite of less land flooding, such an approach can not be justified economically for conventional plants due to unproportional cost increasing for two hydroturbine power houses.

At the same time, the energy potential of plane rivers could be greater than accessible mountain water streams. Indeed, plane rivers accumulate the water flowing down from multiple sources, including mountain streams. Moreover, planes with small and big rivers occupy a greater part of the land. In the USA for example, they make up about 60 - 70% of the territory, and in Europe and Russia plane land is up to 80% of the territories. If we add to this tidal basins and estuaries, it becomes clear that ultra low-head hydro power stations can be one of the most promising sources of renewable energy in the future.

A breakthrough in the hydroelectric industry can be reached by developing an efficient approach to harnessing ultra low-head (12 feet or less) power on plane rivers, canals and tidal basins.

The present project discusses such approach where conventional hydroturbines are replaced by air turbines. High sensitivity of advanced air turbines along with their simplicity and low maintenance costs open good prospectives for hydro-pneumatic power industry.

A paper by Dr. Andrey Ryazanov discusses some other environmental aspects of conventional and hydro-pneumatic methods to harness low-head hydro energy (Appendix 3).

4. AIR TURBINE OPTIONS

Turbines designed to be powered by reversible air movement are a relatively recent development, with only two types known to have reached operational stages, i.e. the Wells turbine and the McCormick turbine. These turbines have been mostly tested on ocean wave energy systems in Europe and Japan. The turbines have been described in the progress reports.

Researchers at Coventry Polytechnic Institute in England built a 150-kW prototype Wells air turbine. In extensive tests, researchers found that their turbine demonstrated good performance. One disadvantage of Wells turbines is their high level of noise during fast rotation.

The double Wells turbine was built and installed on the hydro/air power converter in the hydro-pneumatic laboratory at Northeastern University (Fig 4). During testing, it developed 1200 rpm speed corresponding to one foot of water head.

The other operational air turbine that can be used with hydro/air power converter is the 150-kW McCormick turbine, developed in the early 1980s at the U.S. Naval Academy in Annapolis, Maryland. Researchers at the Naval Academy were studying approaches for capturing the energy available in ocean waves. As part of the study, they built this turbine. In 1991 this turbine was delivered to CMP in Maine as an available option for the first planning demonstrational power plant on Androscoggin River (Fig. 5).

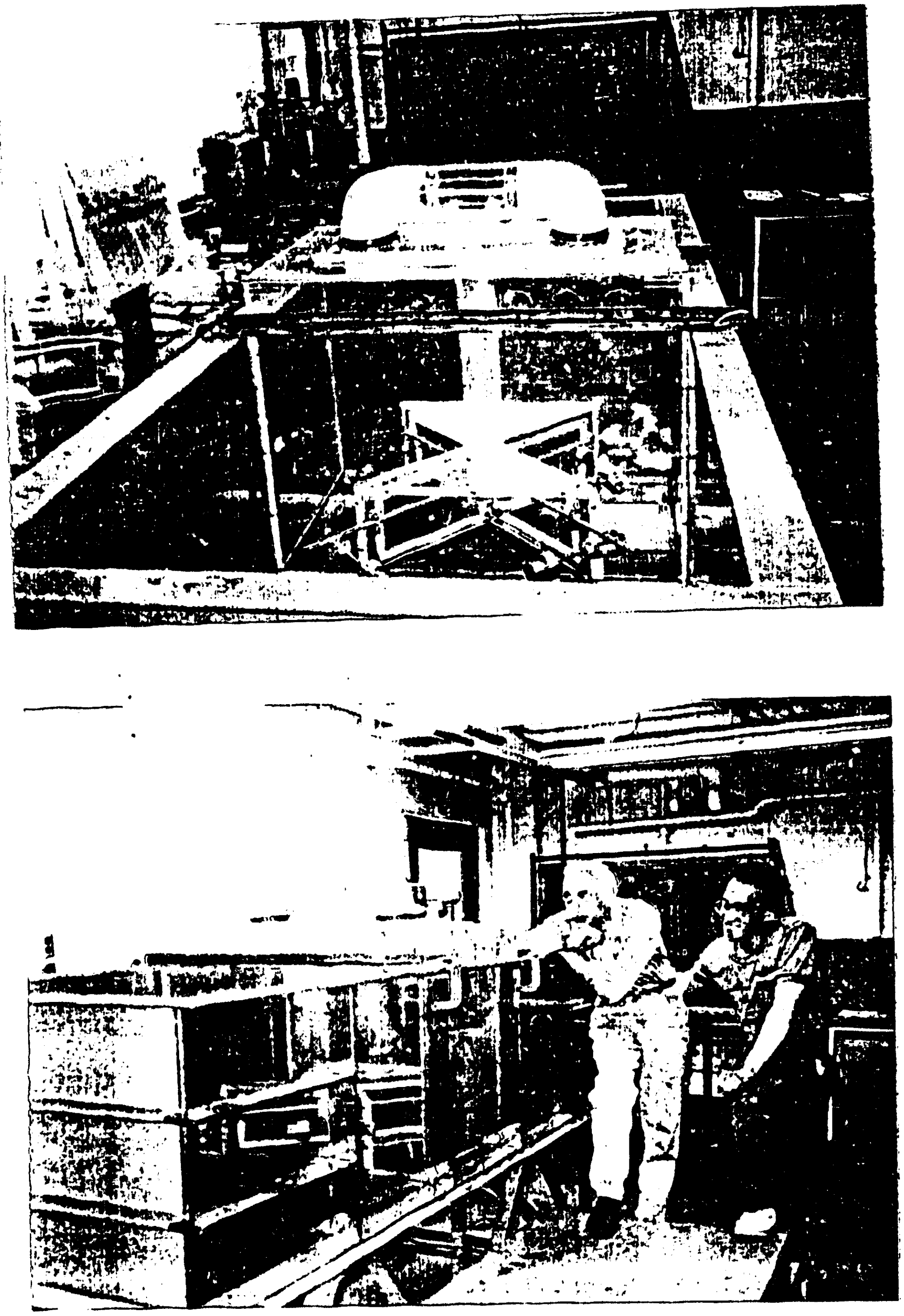


Fig. 4 Double Wells turbine on the hydro/air power converter.

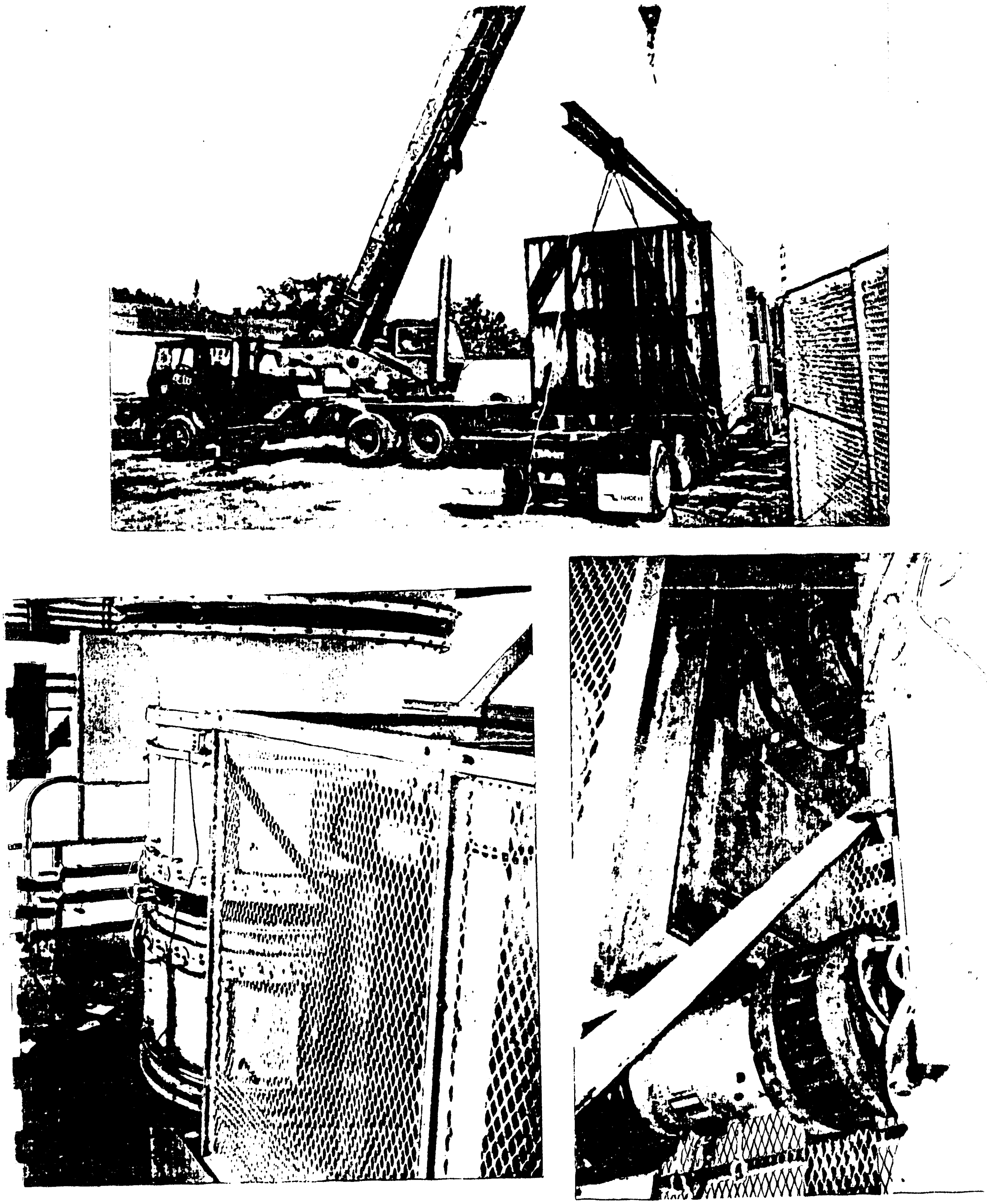


Fig. 5 Transporting of McCormick turbine.

The first version of the McCormick turbine contained two counter-rotating blade sets mounted on the same shaft. This version has been described in a progress report, in 1992. The more recent design uses a single set (Fig. 6). Even with a single set of blades, the McCormick turbine is more complicated and more expensive than the Wells turbine. However, the new McCormick turbine is quieter and might be more efficient than the Wells air machine.

And, finally, Russian researchers from Moscow Institute "Hydroproject" developed a radial air turbine that can potentially demonstrate better characteristics than other machines of this class. During the Summer 1993 Drs. Istorik and Spolyansky, from the Institute, visited the hydro-pneumatic power laboratory at Northeastern University. They brought a prototype of their turbine which has been installed and tested in assembly with our hydro/air power converter. The turbine easily developed speed up to 4000 rpm corresponding to one foot water head. The assembly with the radial turbine and power converter is seen in Figure 7.

Accurate comparative measurements of efficiency and other characteristics of all the air turbines mentioned will be the subject of subsequent study.

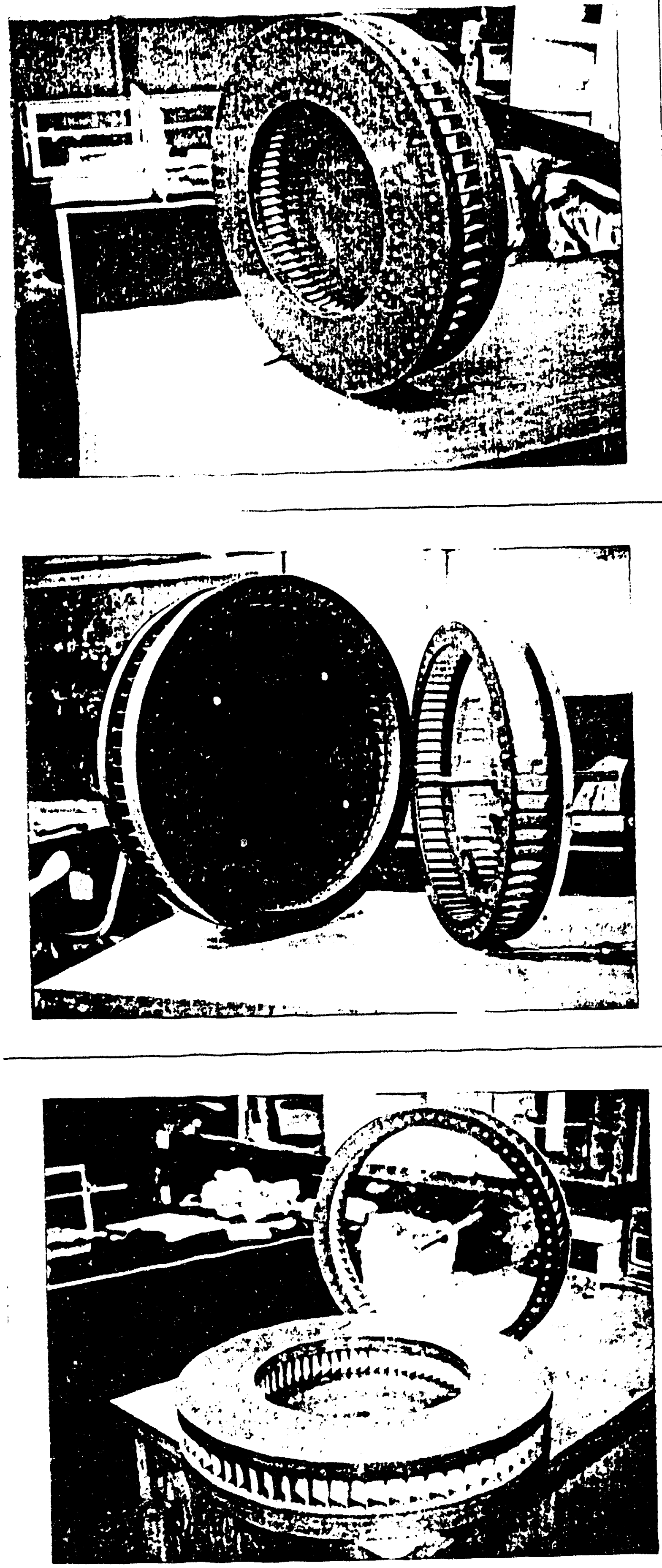


Fig. 6 New McCormick turbine.

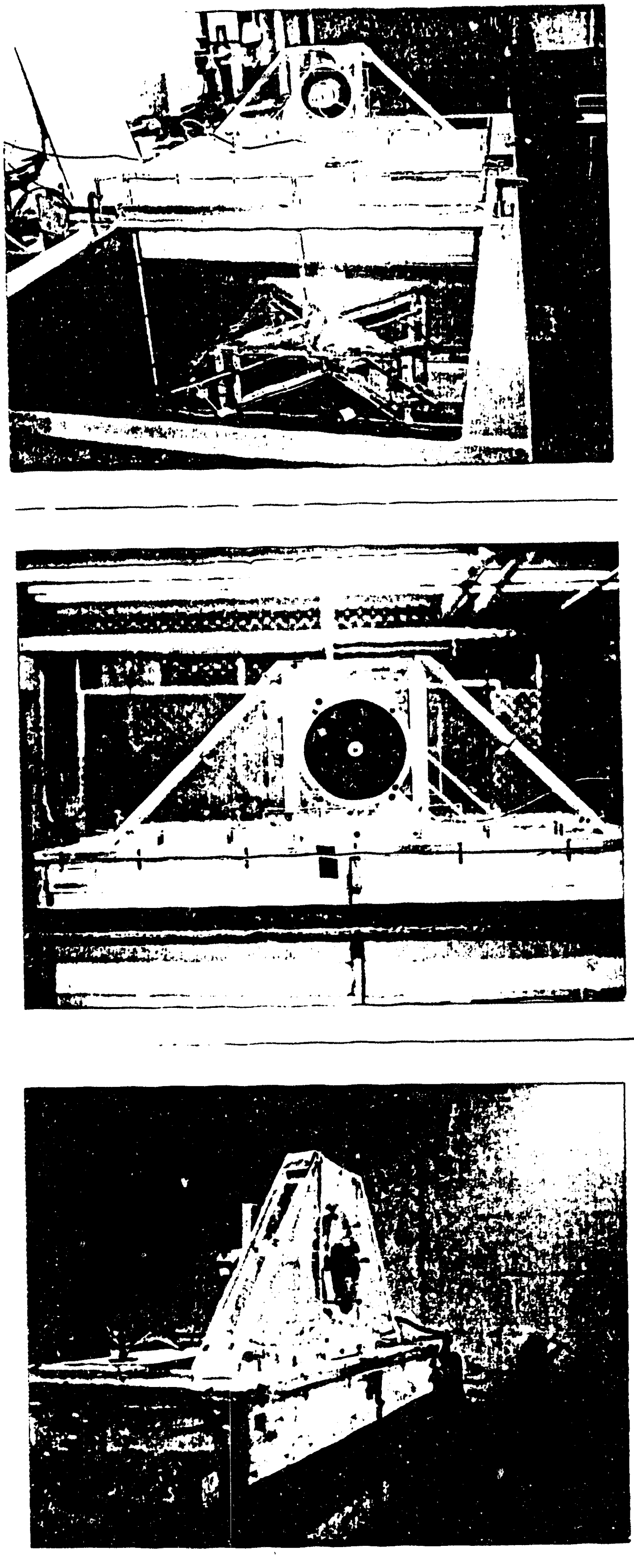


Fig. 7 Radial turbine combined with power converter.

5. WORKS ON IMPROVING THE GATE MECHANISM.

One of the principal tasks of this research is to optimize shape and exploitation characteristics of the gate mechanism. In particular, the following elements were added to gates and tested with the converter

a) Ailerons - to stabilize openings of the gates during filling of the chambers (Fig. 8).

b) Magnet locks - to reduce weight of counterbalances (Fig. 9).

c) Shaft of gates moved from top of port toward its center to reduce counterbalances (can be seen in Figures 8 and 9).

Testing of these improvements and analysis of measurements will be continued.

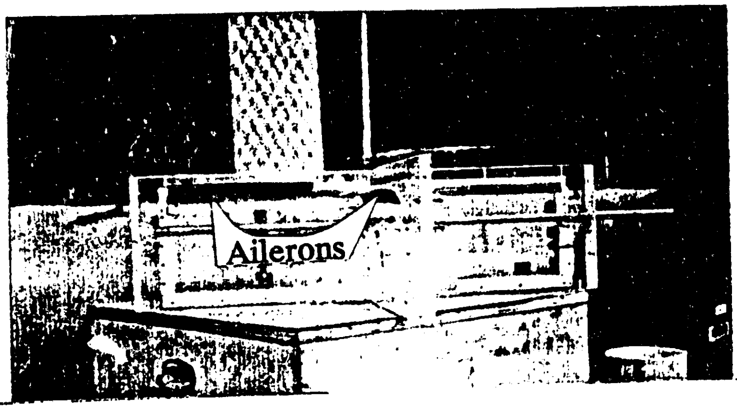


Fig. 8 Ailerons on top edges of gates.

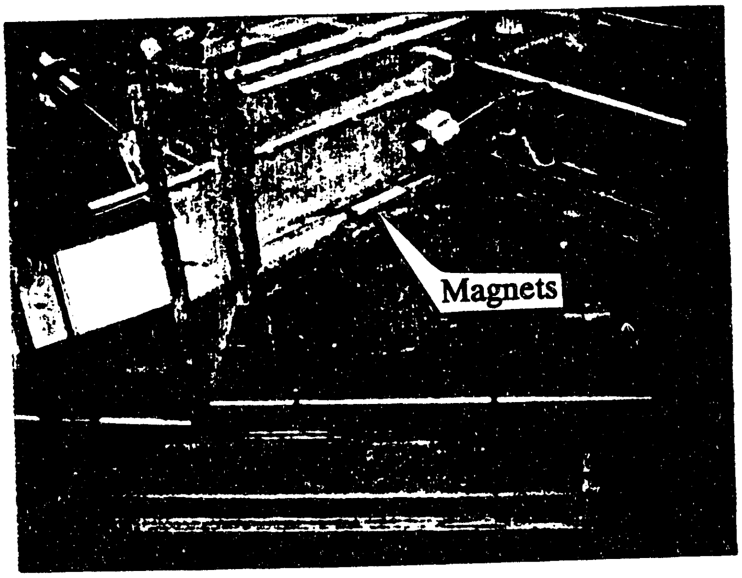


Fig. 9 Magnet locks.

6. CONTINUING AND FUTURE RESEARCH TASKS

1. Optimization of the converter shape.

    1.1 Analysis and experimenting with various configurations of walls.

    1.2 Operation with various dimensions of ports.

    1.3 Operation with various positions of gates.

2. Optimization of the gate mechanism.

    2.1 Operation with various relative positions of the inflow and outflow gates.

    2.3 Assessment of various design options to increase water flow through the converter.

    2.4 Analytical and experimental study of various options for reducing counterbalance.

    2.5 Design and experimenting with various shafts, bearings, sealings.

3. Assessment of air turbine options including construction and experimenting with models.

    3.1 Wells turbine.

    3.2 McCormick turbine.

    3.3 Orthogonal blades turbine.

    3.4 Other designs.

4. Assessment of generator options.

5. Analytical and experimental research of various approaches to the power output control.

    5.1 Design and testing of array of three converter in the line with 120° shifted phase of operation.

5.2 Flywheel option.

5.3 Other energy storage options.

5.4 Other relevant control problems.

6. Construction of optimal large model including water/air converter, air turbine, generator, control system.

7. Development tests plan including

   7.1 Operation with various air flow restrictions,

   7.2 Operation with various headwater elevations,

   7.3 Operation with various tailwater elevations,

8. Procure test equipment and finalize tests' set up.

9. Conduct the tests.

10. Estimation of losses and overall efficiency.

11. Publish tests results in the progress report.

12. Assess tests results and scale-up feasibility.

13. Assess sites for demonstrational project.

14. Preliminary estimate of demonstration costs.

15. Analytical and experimental study other options for ultra low-head hydro-pneumatic power harnessing system.

   15.1 Hydraulic air compressor.

   15.2 Syphon systems.

   15.3 Electrogasdynamic generators.

16. Publications

17. Annual progress reports.

18. Final report.

7. APPENDICES

1) Central Maine Power Company Request for Project Summaries.

2) The Wall Street Journal Article.

3) Article from the Technology Review.

4) Relevant publications.

   4.1 A.M. Gorlov - Hydro Review

   4.2 A.I. Ryazanov - Water Resources

   4.3 A.I. Ryazanov - Mathematical Modeling

Routing: RGL
GCP
File: 736(C)-6.4

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February 23, 1994

United States Department of Energy
1617 Cole Blvd
Golden, CO 80401

Attention Mr. John Meeker, Contract Specialist

RE: REQUEST FOR PROJECT SUMMARIES AND NOTICE OF SOLICITATION FOR FINANCIAL ASSISTANCE APPLICATIONS NUMBER DE-PS02-94CH10595

Gentlemen:

This letter requests a copy of the solicitation, referenced above, planned to be issued on or about 1 March 1994, as described in the Federal Register Vol. 59, No. 18 (27 January 1994).

Described below is a project to develop an innovative hydroelectric technology suitable for low-head applications, utilizing a hydropneumatic converter and an air turbine. The research and development expended by the participants has brought the technology to the point where it is ready to move from the laboratory to a demonstration; it is for this demonstration and subsequent commercialization that the participants plan to solicit DOE funds.

Early work on this technology by Northeastern University received funding from DOE's Office of Energy Research, under contract DE-FG02-91ER12113. A final report was issued by Prof. Alexander M. Gorlov in October 1993.

<u>Primary Contact Person</u>

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<u>Project Participants and Roles</u>

Northeastern University
Prof. Alexander M. Gorlov, Professor
Department of Mechanical Engineering

Central Maine Power Co. (CMP)
Chad P. Clark, Manager of Civil & Mechanical Support
Raymond J. Giglio, Principal Mechanical Engineer

Prof. Gorlov is the inventor of the concept and holds several patents, which have been assigned to Northeastern University. Central Maine Power Company has supported the research, initially in conjunction with DOE, and has purchased certain world-wide license rights. CMP will take the lead role in designing a demonstration of the technology at a site in Maine and in marketing the technology in the U.S. and elsewhere.

Summary of the Technology

A hydropneumatic power plant converts potential energy contained in a water source into electricity, by means of an air chamber and gate mechanism and an air-powered turbine-generator. The air chamber and gate mechanism converts the water flow into an oscillating water column, which compresses air in the upper part of the chambers.

The enclosed papers describe the technology more fully. They were contained in the final report to DOE under the contract referenced above.

"A New Opportunity for Hydro: Using Air Turbines for Generating Electricity", by Alexander M. Gorlov, in Hydro Review, September 1992.

"A Synchronized Hydro/Air Energy Converter for Ultra Low-Head Hydropower Plants", by Alexander M. Gorlov, in New Energy Systems and Conversions, June 27-30, 1993, Yokohama, Japan, Universal Academy Press.

Description of the Demonstration Project

Central Maine Power Company plans to demonstrate the technology with a demonstration project at Androscoggin Lower Hydro Station, in Lewiston, Maine. This generating station on the Lewiston canal system formerly had two units, but currently has one empty turbine location. The head is 10-12 feet and the flow is a constant 150 cubic feet per second (cfs). A hydro-pneumatic converter will be installed along with an air-powered turbine-generator. Output will be under 100 kW.

Potential Market

The technology is suited for heads of 3-12 feet and has the potential to be low cost. The potential locations are, therefore, quite large. Quantifying the market potential is one of the steps in the commercialization plan.

Potential Benefits of the Technology

The primary benefit of this new technology is its application to very low head sites - in the range of 3-15 feet. Such sites have smaller impoundments (if any) and require minimal dams. The technology utilizes a less costly powerhouse and simpler equipment and has the potential to make otherwise uneconomic sites cost-effective. Effects on aquatic organisms are also reduced.

Estimated Cost of the Project

The following is a preliminary estimate, in thousands of dollars, of the cost to demonstrate and commercialize the technology.

	1994	1995	1996	1997
R&D, license fees, and patent expenses	115	110	120	105
Demonstration Unit	100	400		
Marketing/Business Plan	20	50	100	100

Schedule

The above cost estimate allows for a demonstration project to be completed in 1995, with marketing studies and follow-up laboratory R&D work continuing into 1997. The first commercial sale is targeted for 1997.

Yours truly,

Raymond J. Giglio

Raymond J. Giglio, P.E.
Principal Mechanical Engineer

RJG:rjg:lhr
Attachments (3)
cc: Prof. A.M.Gorlov (NU)
Richard J. McNeil, Jr. (NU)
C.P.Clark
C.Irland

ATTACHMENT 1 - Questions

Please provide answers to the following questions when you send the solicitation.

1) What is the planned funding period?

2) Will the solicitation require a specific objective (e.g. a demonstration project) or will it allow funding of R&D and marketing work required to bring the demonstrated technology to market? In what detail do we have to define the R&D and marketing work?

3) Will the solicitation permit funding associated with verifying the performance of a first commercial unit? (An example of something similar to this is the Turbine Verification Program for new wind-turbines, which is being funded by DOE and EPRI.)

4) Please provide references to DOE documents which quantify low head hydro potential in the U.S., and abroad, if available.

②

THE WALL STREET JOURNAL.

MARKETPLACE

SCIENCE

Gorlov's Dam Pulls Its Oomph Out of Thin Air

By DAVID STIPP
Staff Reporter of THE WALL STREET JOURNAL

One day in 1971 Alexander Solzhenitsyn's car broke down. Thus began a chain of events leading to the birth of a new electric power technology in a Boston laboratory.

Mr. Solzhenitsyn was ill, so he asked a friend, an engineer named Alexander Gorlov, to retrieve a spare car part at the dissident novelist's summer cottage near Moscow. When Dr. Gorlov arrived, he found strangers rummaging inside. They beat him bloody, grilled him for hours and sent him home.

Mr. Solzhenitsyn, without consulting Dr. Gorlov, publicized the incident in the Western press as probable KGB thuggery. Comrade Gorlov—a quiet, well-respected research manager who helped design Egypt's Aswan High Dam — was branded an anti-Soviet activist. "Statistical analysis," he says, soon revealed that approximately half his acquaintances were avoiding him. Eventually he was fired from his job at a Moscow research institute.

Scraping by on odd jobs, he daydreamed not of fiery tracts but of watery ones: A novel hydropower concept took shape in his mind. After refusing a KGB demand that he spy on Mr. Solzhenitsyn, he was deported. Hired by Boston's Northeastern University in 1976, he arrived with two suitcases of books and his new idea.

Today, in a basement lab at Northeastern, Dr. Gorlov gestures like a maestro over a trough filled with flowing water propelled by a big pump. Inside it, a proof-of-concept model of his idea is proving away. A stationary, submerged box with clear plastic sides is taking energy from the water and turning it into electricity.

Its heart consists of adjoining chambers with louver-like doors that slowly open and close like big fish gills. The interconnected doors move in a synchronized way from the force of water and gravity, causing water to cyclically fill and empty the chambers. The rising and falling water inside a chamber acts as a piston, pushing out and then sucking in air through openings in the chamber roof. The rushing air is piped to a fan-like turbine, which spins an electric generator.

"It's a pretty radically new approach to hydropower," yet "very simple," says Chad Clark, a research manager at Central Maine Power Co., which plans to build a 100-kilowatt pilot plant based on Dr. Gorlov's idea near Lewiston, Maine, in a year or so.

In theory, it represents a small-is-beautiful answer to hydropower critics, who say big dams inundate precious ecosystems, kill fish and spoil the look of wild rivers. Dr. Gorlov says his system could generate power as an add-on to small "low-head" dams already implanted in rivers and canals for irrigation, flood control and other purposes. New England alone has more than 10,000 such dams, enough to generate as much power as several large nuclear plants with the help of his technology, he adds.

Low-head dams often create a water drop of only a few feet — not enough to generate electricity economically with conventional water-driven turbines. By converting water to air power, Dr. Gorlov's system can employ recently developed air turbines that are smaller, cheaper and easier to install and maintain than water-spun ones, he says. That promises to boost small-scale hydropower over the cost-effectiveness hurdle.

"With this machine, I believe hydropower installations would be feasible even for individual houses," says Dr. Gorlov, a white-haired man who daily pedals two miles to work through Boston traffic on a bicycle with a loud horn.

He envisions companies using his systems to power riverside plants. Utilities might install larger versions to add nonpolluting generating capacity. Developing countries might piggyback them to irrigation dams. The technology doesn't necessarily require a dam, says Dr. Gorlov, who proposes harnessing tidal flows in estuaries to generate electricity on islands.

Like many alternative energy proponents, Dr. Gorlov found himself paddling against political currents in the 1980s. Unable to win funding, he switched to research on ways to foil suicide car bombers after one in 1983 killed 241 U.S. marines in Beirut. Eventually he patented a device that snares a terrorist's vehicle with cables on a pivot and swings it around to slam into barriers well away from targeted structures.

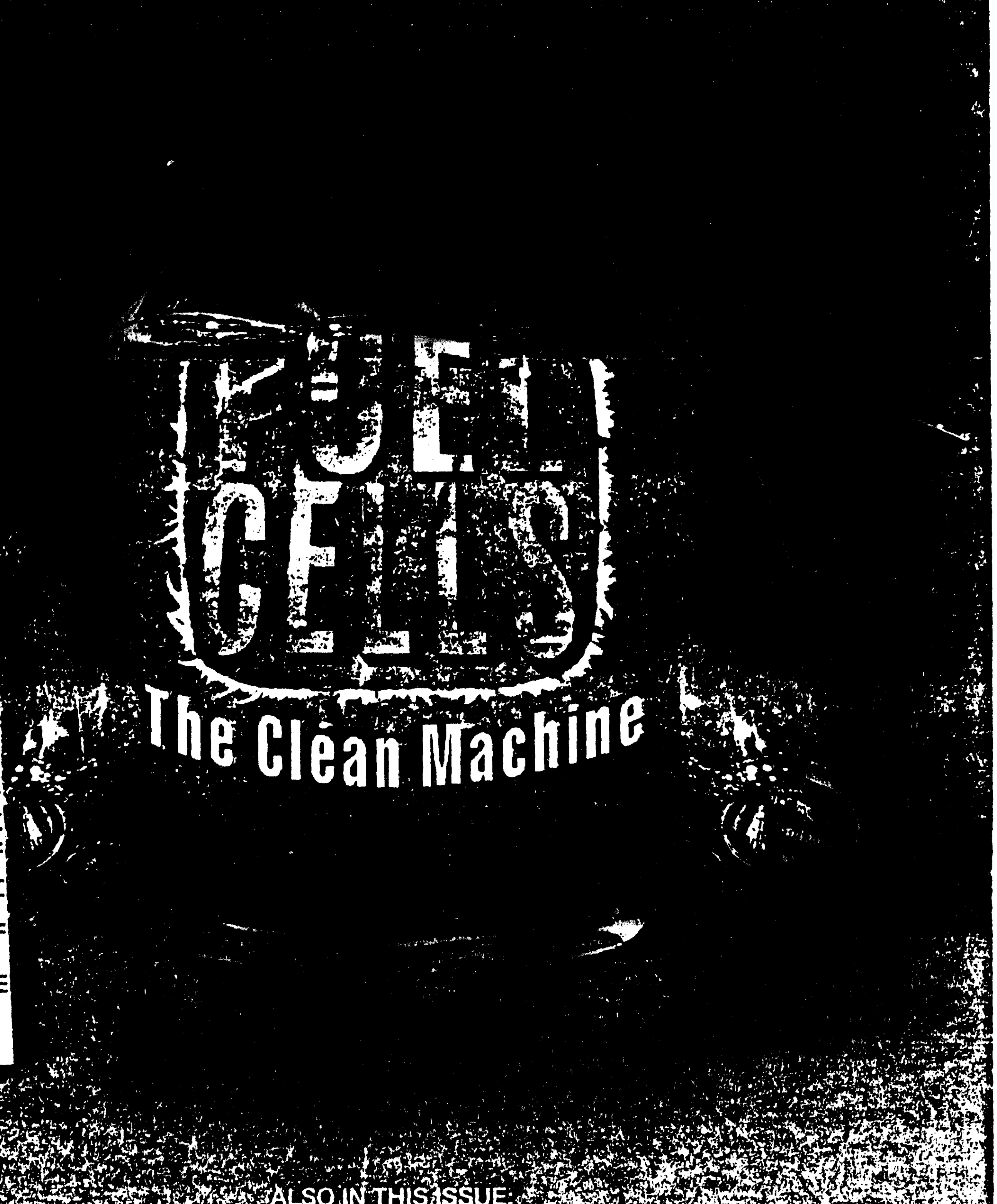
But Dr. Gorlov, whose stubbornness exasperated the KGB, never stopped pestering U.S. Department of Energy officials about his power idea. "For a number of years I insisted they support my research" on it, he says with a strong Russian accent. And for years, they were staunch refuseniks.

In 1990 he was finally rehabilitated as an energy researcher when the DOE awarded him a two-year grant. With additional funding from Central Maine Power, he built the lab prototype.

Hydropower experts agree Dr. Gorlov's idea has an intriguing design, appears technically feasible and probably would offer environmental pluses. But they say it won't necessarily generate electricity cheaply enough to warrant wide use—doubts Dr. Gorlov says can only be resolved by real-world tests like the one planned in Maine.

Dr. Gorlov's image also has been rehabilitated in Russia, where he is renowned as the man who became a Cold War hero trying to fix a friend's clutch. He traveled there twice recently as a visiting lecturer. "The last time I was there," he says proudly, "I got a thousand rubles a day." That's more than three times his monthly salary before being blacklisted—and equal to about $1 today.

Technology Review



FUEL CELLS
The Clean Machine

ALSO IN THIS ISSUE:

◆ GENES TO THE RESCUE ◆ TEAM INNOVATION ◆ SMART KIDS, DUMB SCHOOLS ◆

◆ SPRECHEN MIT DEUTCH: AN INTERVIEW AT THE PENTAGON ◆

Hydropower That's Clean and Green

Hydropower usually gets rave reviews as a means of generating electricity without producing the sulfur and nitrogen oxides responsible for acid rain or the carbon dioxide that contributes to global warming. But because the huge dams needed for cost-competitive hydroelectricity may flood thousands of acres of valuable land, block fish migration, alter the delicate ecological balance of rivers, and even displace whole communities, this clean technology is not always as green as many environmentalists would like.

A radical new approach to this energy technology, invented by Alexander Gorlov, a former Soviet hydropower expert who helped design Egypt's Aswan Dam, may help ease these concerns. Gorlov, now a professor of mechanical engineering at Northeastern University, says that instead of dropping dammed water onto turbines that spin and generate electricity, his patented hydropneumatic system is designed so that water never touches the turbine. Instead relatively slow-moving water is used to blast air past its blades.

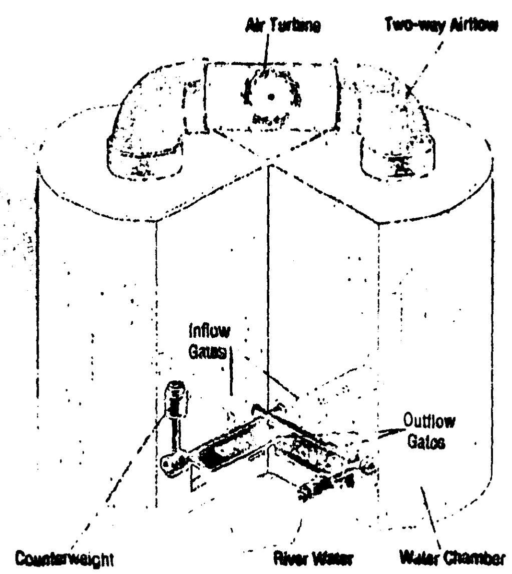
According to Gorlov's calculations and tests with a prototype, his system can efficiently generate electricity with water flowing from a dam that's only 10 feet high. Or, if a river flows fast enough, the device requires no dam at all.

"Contemporary hydropower is such a contradiction," says Gorlov. Rivers rarely flow fast enough to turn turbines at the high speed needed to generate utility-scale electricity. That's where dams come in, creating an abrupt, vertical drop that increases water speed and thus turbine speed. The higher the dam, the faster a turbine turns, but the more pronounced the structure's negative side-effects. What's more, most of the best sites have already been developed.

Gorlov thinks he has found a way to harness slow-moving plains rivers without damming them up. His technique could also use some of the 80,000 abandoned dams—originally built in the 1800s and early 1900s for grinding grain and powering looms or other machinery—that are too small to generate electricity with conventional hydropower technology.

In fact, it's quite easy to create a mini-version of Gorlov's hydropneumatic system at home. Take a plastic cup and poke a hole in the bottom. Hold it upside down in a stationary position near the bottom of an empty, stoppered sink, and turn on the tap. Water rising in the

Controlled by simple gates and counterweights, the two water chambers of this hydropneumatic device alternately fill and empty like a beating heart, whooshing air back and forth through a connecting tube. Air coming from the right chamber lifts the turbine's wing-shaped blades upward, while air from the left pulls the blades (now inverted) downward, spinning the turbine in one direction to generate a constant flow of electricity.



cup forces the air trapped inside out through the hole. Unplug the sink, and water draining out of the cup creates a vacuum that sucks air in through the hole. The larger the ratio between the cup diameter and the hole diameter, the faster air flows in and out.

A refrigerator-sized plexiglass prototype unit in Northeastern's Hydropneumatic Power Laboratory is a bit more complicated. It consists of a pair of meter-tall chambers connected at the top by a tube containing an air turbine the diameter of a dinner plate. A quick tug on a lever starts a 600-gallon-per-minute flow of water through the system. One chamber fills, pushing air past one side of the turbine; the other empties, sucking air from the tube.

Whereas a standard turbine uses a conventional fan blade that spins according to the direction of the water that pushes aside its broad angled face, the so-called counter-rotating turbine in Gorlov's system uses a blade shaped like an airplane wing that creates lift to spin the turbine when the airflow rushes over its front edge.

The blades are placed around the turbine in paddlewheel fashion. So as the first water chamber fills, air whooshes through the tube and hits the front of the paddlewheel, lifting each blade upward as it spins past the airflow. As the first chamber empties and the other fills, air races in the opposite direction through the tube and over the blades at the rear of the paddlewheel. The blades, having spun halfway around the wheel, are now upside down, so the "lift" pulls them downward. Thus, even though the airflow reverses with each cycle, the turbine rotates in the same direction, generating a constant flow of electricity.

Simple gates and counterbalances coordinate the operation of the unit as the chambers alternately fill and empty. At the top of the cycle, water pressure inside the filled chamber exceeds the pressure exerted by a one-pound counterweight on the outflow door at the bottom of the chamber, popping it open. The same motion closes the outflow gate in the opposite chamber, thanks to a single shaft that controls the two gates. As water flows from the full tank and heads "downstream," its empty neighbor begins to fill. This pattern repeats with the regularity of a beating heart.

"Anyone who sees Gorlov's system at work is greatly impressed," says Michael McCormick, professor of civil engineering at Johns Hopkins University. To construct an experimental hydropneumatic generator in Maine, McCormick gave Gorlov an industrial-sized counter-rotating turbine he designed for a wave-energy project in Japan.

For this crucial test, Central Maine Power plans to build a commercial-sized hydropneumatic generator at an existing low-head hydropower station on the Androscoggin River in Lewiston. The 100-kilowatt system will operate side by side with a conventional turbine generator, giving the company an opportunity to compare the newcomer against the proven technology.

Central Maine Power's preliminary analyses suggest it will be cheaper to build hydropneumatic systems than their conventional cousins at low-head sites. The smaller, lighter equipment requires less construction and fortification at the powerhouse, and there's no need to excavate deep into the riverbed to make room for spinning turbines.

If the tests are successful, the company says it could build small utility generating stations at a number of existing low-head dams in its territory; and it could build generators for riverside businesses that want to make their own electricity. "We're also intrigued with the idea of using hydropneumatic systems for isolated homes or villages near a small flowing river but far from the existing power grid," says Chad Clark, Central Maine Power's supervising research engineer.

Gorlov has bigger ideas. A sketch on the wall of his office shows a hydropneumatic powerhouse generating electricity from rising and falling tides in a rocky Maine bay. He also recently submitted a plan to the U.S. Army Corps of Engineers to generate electricity in Massachusetts's Cape Cod Canal. He even envisions fleets of his generators sitting atop floating platforms in the Gulf Stream or other ocean currents, generating electricity for remote island communities.

But before such plans take shape, engineers at Central Maine Power first want to find out not only whether the hydropneumatic systems will be cheaper to build than conventional hydropower systems, but whether they will be as efficient. They also want to test whether the devices will work in the winter on frozen rivers and whether they will allow fish to migrate more easily and safely than through rapidly spinning turbines.

"Gorlov's idea is intriguing, and his machine is unique," says John Smith, chief of coastal development for the Army Corps of Engineers. "But you have to build and operate one out of steel and concrete before concluding that it works."—*P.J. Skerrett*

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4. RELEVANT PUBLICATIONS

(4.1)

A New Opportunity for Hydro: Using Air Turbines for Generating Electricity

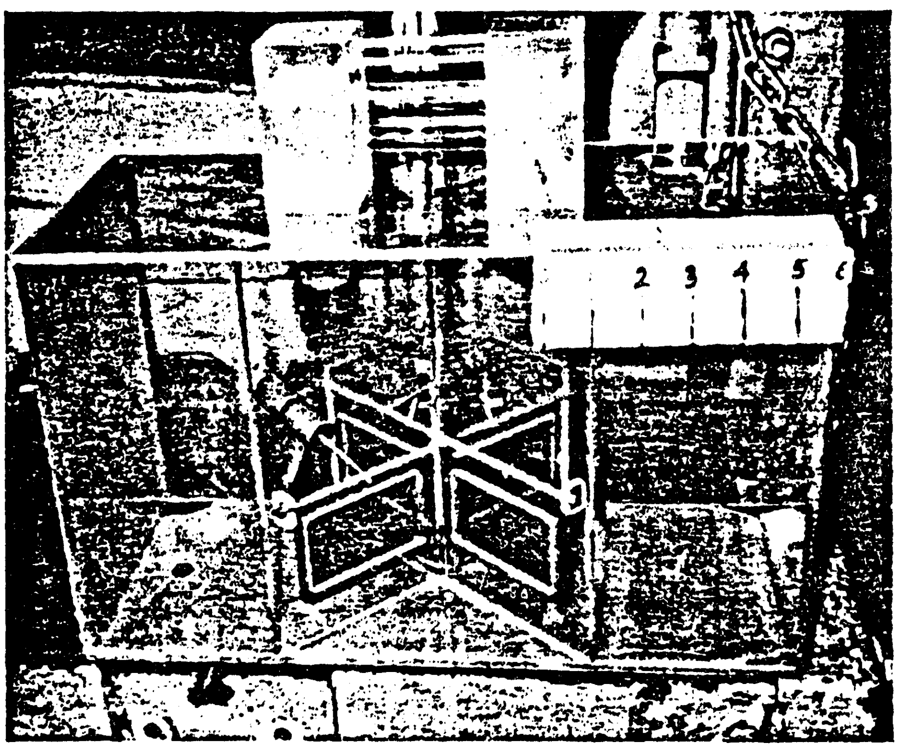
A concept that uses hydropower to compress air could increase the number of locations where hydro is economically and environmentally feasible. The idea is being tested in a demonstration project in the northeastern U.S.

By Alexander M. Gorlov

The hydroelectric industry could experience substantial growth in low-head hydro facilities if a concept now being developed proves successful. This concept aims to enable power developers to generate electricity economically at sites currently not feasible for hydropower because water heads are too low.

Many areas of North America are studded with low-head dams that could provide considerable hydro capacity if low-head generation were economically feasible. The six New England states in the U.S., for example, contain approximately 15,000 dams that have never been used to generate electric power because they impound water with heads ranging from 3 to 13 feet. Conventional facilities are not economically practical for generating electricity at these low heads. However, a promising alternative approach is to use water at these low-head dams to compress air, and then to use the air to power an air turbine-generator that produces electricity.

Alexander Gorlov, P.E., Ph.D., is professor of mechanical engineering and director of the hydropneumatic laboratory at Northeastern University, Boston, Massachusetts. He originated the concept of hydropneumatic generation for low-head hydro 15 years ago. Dr. Gorlov is continuing this research under a grant from the U.S. Department of Energy and Central Maine Power Company, which includes working on a full-scale hydropneumatic demonstration project in Maine.



This photograph shows the model of the hydro-to-air converter, including the water-gate array, built and tested in Northeastern University's hydropneumatic laboratory. The 0 to 6 scale in the upper right indicates inches; the model is about 1½ feet wide.

The concept, called "hydropneumatic" generation, can be visualized by imagining a container, such as a large teacup, inverted and submerged in tidal waters. As the tide rises, the water compresses the air trapped inside the container. When the tide ebbs, the pressure decreases, putting the air into a partial vacuum. If a vent pipe were installed from the container to the atmosphere, air would flow out of the container as the water depth increased, and flow back in as the water depth decreased.

Hydropneumatic energy is gen-

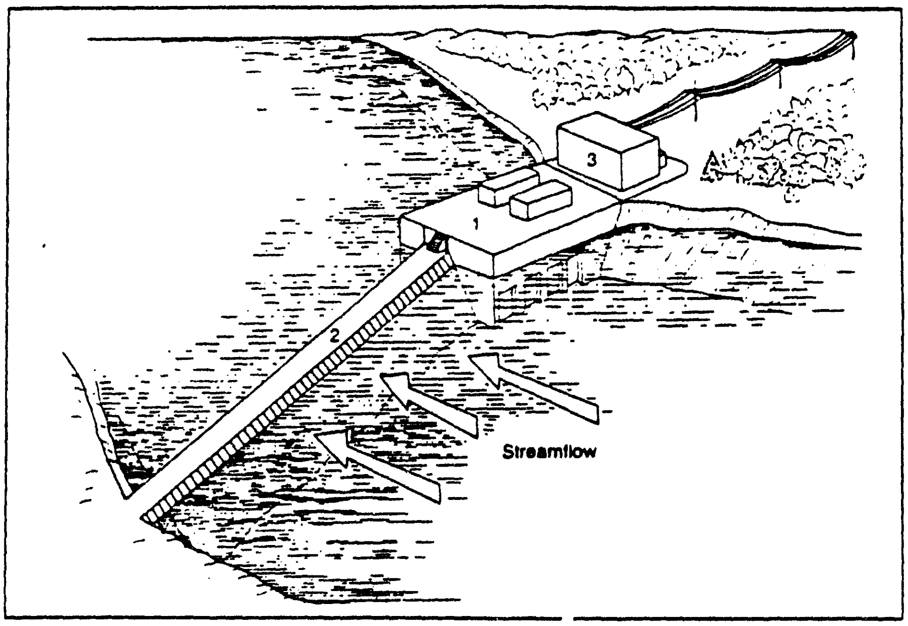


Figure 1: This drawing is a conceptual view of a hydropneumatic power plant. The dam (2) serves to restrict the water flow, requiring it to pass through the water/air chamber (1). In the chamber, the energy of the water flow is converted into pneumatic (compressed-air) energy. The powerhouse (3) contains the air turbine-generator units.

erated by installing an air-powered turbine to harness the energy of this airflow through the vent pipe. The turbine can be installed to rotate in the same direction at all times, even though the airflow reverses direction.

In the late 1970s, I was working under a grant from the U.S. Department of Energy. The objective was to study the feasibility of generating tidal power at Half Moon Cove in Passamaquoddy Bay northeast of Maine. During this work, I conceived the idea of hydropneumatic generation, which seemed to offer advantages over a conventional hydroturbine for harnessing tidal energy. Through further studies, I discovered that the concept was even more promising for use on rivers—a river provides a continual flow and thus results in more predictable energy output than tidal flow. Also, the unidirectional flow of the river simplifies the hydro-to-air converter's gate mechanism.[1,2,3,4]

By installing the hydropneumatic concept at existing dams in New England and developing selected tidal estuaries, I estimate that the region could generate up to an additional 5,000 MW of renewable power. This extra electrical supply would eliminate the need for new fossil-fueled power plants and boost the six-state region economically by allowing it to become self-sufficient in meeting its electricity needs.

Many areas in other regions of the country also have low-head dams built for flood control, irrigation, or other water-regulation needs.[5] A large percentage of these dams conceivably could be sites for hydropneumatic generating plants.

The environmental effects of harnessing power from these dams are expected to be minor. Because the dams already exist, no additional land would need to be taken or submerged.

Comparing Pneumatic Power And Conventional Hydropower

Hydropneumatic power differs from conventional hydropower primarily in the sensitivity of air turbines to small pressure differentials. Air turbines operate starting at pressure differentials as low as 0.05 atmosphere, which corresponds to a water head of about 2 feet. They operate with efficiencies of up to 80 percent at heads as low as 3 feet.[6] Once the head exceeds 13 feet, conventional hydroturbines are probably more cost-effective than hydropneumatic generators.

Figure 1, which depicts a conceptual hydropneumatic power plant installation, illustrates that such a plant would be visually similar to a conventional hydropower plant. It has three elements:

—An air chamber, which converts the energy of water flow into the energy of compressed air;

—A barrier (dam), which creates an ultra low-head upper water pool. This pool forces the river water to flow through the air chamber, where it oscillates (goes through a filling cycle) and compresses the air. The amplitude of the water column oscillation depends on the head created by the dam; and

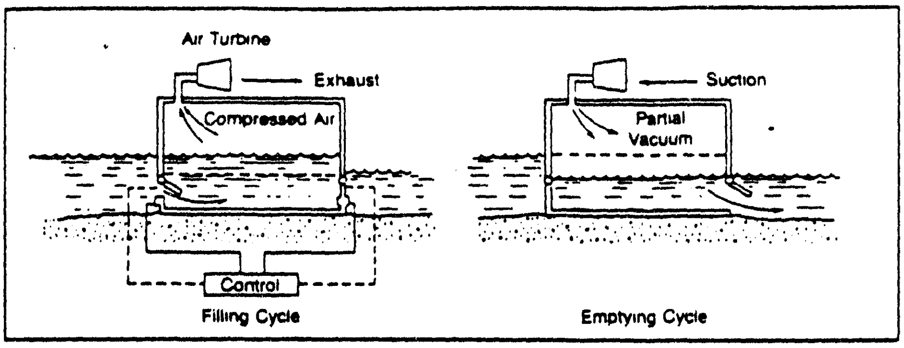
—A powerhouse that houses the air turbine-generator unit(s). Unlike a conventional hydro plant, the powerhouse is sited above the high-water line. By moving the units out of the water flow, the turbines are lighter and thus less expensive and easier to maintain. This arrangement also reduces or eliminates the risk of flooding the powerhouse.

Although air turbines are not widely available at present, their lower cost has been documented. Researchers at Coventry Polytechnic Institute in England, where hydropneumatic studies are underway, found that a 150-kW air turbine costs only one-fifth as much as a hydroturbine of the same capacity. In addition, construction costs, depending on site characteristics, often are reduced because the hydropneumatic system eliminates the need to construct the heavy foundations required for hydroturbines. Costs of the electrical-side components of the unit would be the same as for a conventional hydropower installation.[7,8]

During my U.S. Department of Energy project in the late 1970s, Anderson-Nichols, a Boston-based engineering firm, calculated the cost of installing an air-chamber converter (without the turbine-generator unit) to be \$880 per kilowatt for a tidal installation.[2] These calculations have not been updated. I believe that the cost of a river installation may be lower than the cost of a tidal installation, mainly because water flow is unidirectional and thus requires a simpler gate mechanism for the hydro-to-air converter.

Converting Hydropower To Air Movement

The hydro-to-air "converter" is the heart of the hydropneumatic concept. This converter is waterproof and airtight, constructed of concrete, and rests on the riverbed. The upper edges of flap-type sluice gates on the upstream and downstream chamber faces are below the minimum level of the tailwater, as shown in Figure 2.



Hydropneumatic Generation: How It Works
Figure 2: Hydropneumatic generators convert energy in water into flowing air, which is harnessed by an air turbine. The water action in the air chamber is similar to the water flowing into and out of a lock in a river or canal. At the beginning of the filling cycle (diagram on left), the upstream gate is open and the downstream is closed. The water rises in the chamber, compressing the air in the upper part of the chamber. This air flows out through a pipe, rotating an air turbine. When the water in the chamber reaches the level of the upstream pool, the upstream gate closes, the downstream gate opens, and the water flows out of the chamber (see diagram on right). Because this action creates a partial vacuum in the chamber, air flows back in. The turbine rotates in the same direction, even though the air flow reverses direction.

The converter must be designed and constructed to prevent air leakage, which would reduce the system's efficiency.

Figure 2 shows a simple, single-chamber system. A double-chamber installation eliminates disadvantages inherent in this single-chamber system. For example, while the single-chamber system is filling, the downstream flow is shut off; while it is emptying, upstream flow is halted. Moreover, the air exhausted from the single chamber vents to the atmosphere, typically producing a high noise level.

Both Figures 3 and 4 show a double-chamber system, sometimes described as a "double-box" system. It incorporates a pair of identical chambers connected by an air duct that houses the air turbine. The inlet gate of one chamber is mounted on a common shaft with the outlet gate of the other chamber—as one chamber is filling, the other is emptying, and vice versa. When the water level in the chamber that is filling rises to the upstream level, a counterweight (shown in Figure 3) closes the inlet gate and opens the discharge gate; as water begins to flow out of this chamber, the filling process begins in the second chamber.

As one chamber fills, the air flows from it through the duct into the chamber that is emptying. The air is propelled not only by the pressurizing effect of the filling chamber, but also by the partial vacuum simultaneously created in the emptying chamber. This effectively doubles the air pressure on the turbine blades. If, for example, the installation's net water head is 6.5 feet, pressure and vacuum effects combine to create a maximum gage pressure that is equivalent to a 13-foot head (neglecting natural mechanical losses). This means that a double-chamber installation will be more compact and more efficient than a single-chamber system. In addition, it is quieter, because the air flows within a contained system, rather than being exhausted to the atmosphere.

Experiments at Northeastern University in Boston, Massachusetts, have proven the viability of the concept of the double-chamber system, and have verified several important operational considerations:

—The gate-closing mechanism is simple and accessible for maintenance. No motor is required to rotate the gates. Energy from flowing water opens the gate. When the water pressure becomes approximately equal on both sides of the open gate, the counterweight closes the gate by gravitational force;

—Because the filling gate of one chamber is mounted on the same shaft as the emptying gate of the second, one chamber fills while the other empties in a perfectly synchronized relationship;

—Chamber dimensions can be reduced, thereby reducing their cost, by increasing gate size so that the filling/emptying cycle is very short (4 to 6 seconds); and

—Compared to the pressure produced by a single-chamber system, a double-chamber system doubles the measured air pressure at the turbine.

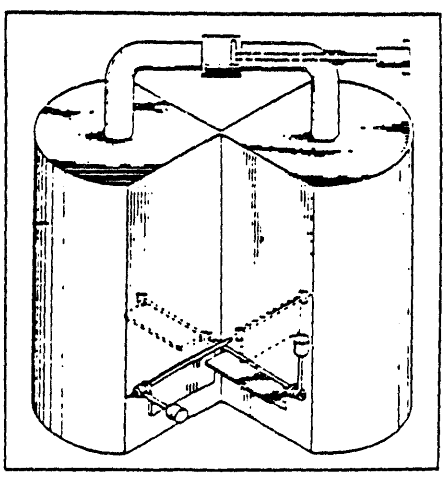
I received a patent, U.S. Patent No. 5,074,710, for the water gate array of the double-chamber system in December 1991.

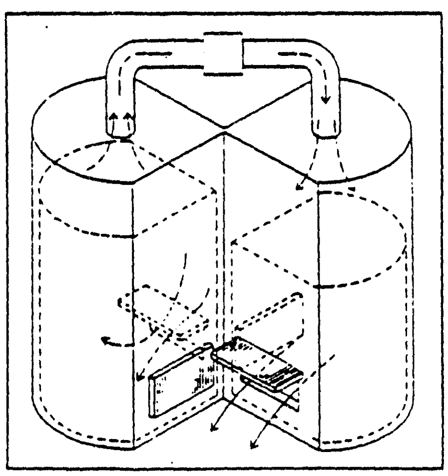
A Review of Operating Air Turbines

Turbines designed to be powered by air movement are a relatively recent development, with only two types known to have reached operational stages.

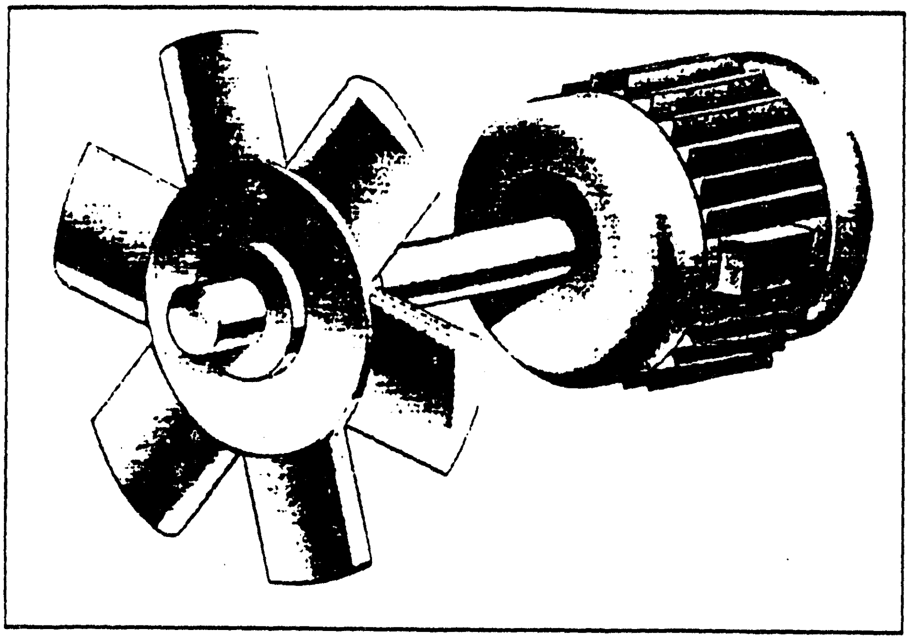
Researchers at Coventry Polytechnic Institute in England built a 150-kW prototype air turbine in 1989. In extensive tests, researchers found that their Wells turbine demonstrated good performance.

The other operational air turbine is the 150-kW McCormick turbine, developed in the early 1980s at the U.S.





Figures 3 and 4: A double-chamber hydropneumatic air converter system improves efficiency and eliminates adverse environmental effects compared to a single-chamber system. Because one chamber empties as the other is filled, constant streamflow is maintained. Figure 3, on the left, shows the converter system featuring mechanical shafts that connect the gates. Figure 4, on the right, shows water and air flow inside the converter.



The 150-kW Wells air turbine is a simple, self-rectifying that has symmetrical blades arranged in a single plane perpendicular to the shaft. The turbine, designed in England and tested extensively at Coventry Polytechnic Institute, is low cost and reliable.

Naval Academy in Annapolis, Maryland. Researchers at the Naval Academy were studying approaches for capturing the energy available in ocean waves. As part of the study, they built a small demonstration air turbine.[6,9]

The first version of the McCormick turbine contained two counter-rotating blade sets mounted on the same shaft. But, the more recent version uses a single set. Even with a single set of blades, the McCormick turbine is more complicated and more expensive than the Wells turbine. However, the McCormick turbine appears to be more efficient in extracting power from the moving air than is the Wells turbine. The McCormick turbine is also quieter.

Plans for the Future

The advantages of the hydropneumatic concept have attracted attention worldwide. Coventry Polytechnic Institute continues to study hydropneumatic power generation. Northeastern University recently established a hydropneumatic power laboratory, where researchers are evaluating different types of hydro-to-air converters. Moscow Institute "Hydroproject" in the Confederated Independent States (formerly the USSR) is studying a low-head hydropneumatic project for a 10,000 MW tidal power plant. In Japan and Scotland, two hydropneumatic power installations of 100 kW to 150 kW using the Wells turbine have been constructed to harness ocean wave energy. They use airflow energy caused by the fluctuation of waves captured inside the chambers. No gate mechanism is needed; however, the unit cost of power is very high because of unpredictable time, direction, and heights of waves.

In addition, the U.S. Department of Energy and Central Maine Power Company are co-funding a Northeastern University hydropneumatic research project. As part of the research, the university will study a demonstration hydropneumatic project that Central Maine Power is planning to build in Lewiston, Maine. The utility is considering installing an air turbine at the existing Androscoggin Lower Station in Lewiston. The two-unit hydro plant was built in the 1950s on an existing canal system connected to the Androscoggin River. One of the conventional vertical turbines in the plant still operates; the other unit is vacant. Central Maine Power previously studied installing a new conventional hydroturbine at the plant, but found the option to be uneconomical. An air turbine may provide an inexpensive alternative that would make use of unused water flow in the canal. The U.S. Naval Academy has offered its McCormick turbine for this project. Based on current plans, operation of the demonstration prototype tentatively could begin as early as 1994.

If the Androscoggin River demonstration project proceeds as hoped, it will prove that the hydropneumatic concept is an economical and environmentally sound procedure for generating electricity at low-head hydro sites. □

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Notes:

1 Gorlov, A.M., "Some New Conceptions in the Approach to Harnessing Tidal Energy," Proceedings of the 2nd Miami International Conference on Alternative Energy Sources, 1979.

2 Gorlov, A.M., *A Novel Approach to Exploitation of Tidal Power: Volumes 1 and 2*, Progress Report to the U.S. Department of Energy, 1980.

3 Gorlov, A.M., *A Novel Approach to Exploitation of Tidal Power: Volumes 3 and 4*, Final Report to the U.S. Department of Energy, 1981.

4 Gorlov, A.M., "Hydropneumatic Concept for Small Riverine Applications," Proceedings of the 2nd International Conference on Small Hydro, Hangzhou, China, 1986.

5 "Prospects for Hydropower in the Northeast," U.S. Army Corps of Engineers, New England Division, 1980.

6 McCormick, M.E., and S.W. Surko, "An Experimental Study of the Performance of Counter-Rotating Wave Energy Conversion Turbine," *Journal of Energy Resources Technology*, September 1989.

7 Bellamy, N.W., "Low-Head Hydroelectric Power Using Pneumatic Conversion," *Power Engineering Journal*, May 1989.

8 "Small Hydro 1990, Part 4: Oscillating Water Column Devices," *Water Power & Dam Construction*, Volume 43, No. 6, June 1991, pages 92-93.

9 Richards, and Weiskopf, "Studies of the McCormick Pneumatic Turbine," Proceedings of the Utilization of Ocean Waves Symposium, La Jolla, California, 1986.

4.2

WATER RESOURCES
No. 6, 1992
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Editorial: Although we do not fully share the author's belief that Gorlov's hydropneumatic stations can replace conventional hydrotechnology, we decided to publish this paper because it underlines the importance of ecological safety in developing hydro energy. We hope that the paper can trigger an interesting discussion.

Ryazanov A.I.*

COMPARATIVE ANALYSIS OF ECOLOGICAL SAFETY AND ECONOMICAL EFFICIENCY OF HYDRO-PNEUMATIC POWER PLANTS (GORLOV'S CONCEPT) AND CONVENTIONAL LOW-HEAD HYDROPOWER STATIONS

Conventional hydro turbine energy technology is always harmful to the water environment. For many years hydro power plants have been considered as the least ecologically dangerous compared with all other electrical technologies. However the most recent studies [8, 9, 13-15] substantially challenged this view and in many cases lead to the revision of further development of traditional hydro technology. The paper suggests a new mathematical model which is based on criteria of ecological safety widely used around the world for analysis of existing hydro power plants. The model can also be used for the development of the new generation of hydro power plants, namely for Gorlov's pneumatic stations [13-17].

The hydro-pneumatic power plant has no turbines in the water and operates under ultra low-heads (up to 3 m). It can be described in the following terms. A chamber has two gates: upstream (A) and downstream (B). The air turbine is positioned on the top of the chamber and is connected with the air inside the chamber. While water fills the chamber, the air inside is compressed, translating its pressure to the turbine. While the chamber drains, the inside vacuum causes air inflow from outside. In both cases an air turbine on the top of the chamber rotates generating electricity. The air velocity can reach a magnitude of 100 m/sec or higher with water heads starting from 1m. Experiments in the laboratory at Northeastern University (Boston) with the physical model have proved operation stability of such hydro pneumatic systems.

A joint study of the ecological effects of hydropneumatic stations has been done by the author and Northeastern University scholars. The results are presented in

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Table 1. The data was collected from [1-4, 6,7, 10-12] and has analyzed by means of multifactorial statistical methods [5].

Table 1

Comparative ecological safety of pneumatic and conventional hydro power plants

Pneumatic stations	Conventional power plants
Fishing environment	
Minimal flooding and minimal restriction to the fish migration. In contrast to the hydro turbines, the air turbines do not affect the water fauna. Slow moving water gates can hardly affect the wild life in the water. In general, there is no deterioration of water ecology.	Loss of the young fish population while passing through the turbines. Interruption of the natural ways of migration. Raising of upstream waters causes disappearance of spawning sites. Fishways and fish protecting structures are inefficient. Overall deterioration of fishing environment.
Dynamics of planktonic community	
There is no distortion in plankton passing through pneumatic chambers. A balance between reproduction of the organic mass (phytoplancton) and water purification from organic suspension (zooplankton) stays intact. There is no substantial flooding upstream; therefore existing flora and fauna stay preserved. Absence of hydro turbines protects plankton from traumatic affects. Its regeneration ability is not affected either. The dispersion of plankton individuals by size remains undisturbed both upstream and downstream.	The transit through the system "reservoir - hydro turbine - river" is fatal for the zooplankton. The river wild life does not survive in a lake and vice versa. Even slow streams can kill the lake plankton species. Downstream water becomes dead with plankton, its overall biomass reduced by an order of magnitude [in 8-15 times]. Plankton's natural ability for serf-purification and regeneration is ruined. All of these factors undermine the fish nutritional sources down stream.

(Table 1 cont.)

Pneumatic stations	Conventional power plants
Land flooding	
Land flooding is minimal. Thermal and stream conditions of the river remain intact. There are no factors causing proliferation of blue-green seaweeds.	Substantial flooding of land, forests and natural resources. A massive proliferation of blue-green seaweeds. The water becomes partially contaminated.
Climate conditions	
There are no changes in the climate.	There are substantial changes in the climate in the areas of high dams due to increasing air humidity, fog, and reduction in water temperature.
Erosion of the river banks	
There is no erosion of river banks because there is no substantial rising of the water and consequently, no flooding. The pneumatic power plant becomes a part of landscape.	Substantial erosion of the river banks and development of stagnant water have been widely observed. The most intensive erosion of banks occurs in the river downstream due to water level fluctuation. Gradual sedimentation in the upstream reservoir reduces its capacity. Displacements of peat islands are observed due to intensive decomposing of underwater vegetation. Peat moss has been saturated with methane and becomes buoyant, traveling across the reservoir.

(Table 1 cont.)

Pneumatic stations	Conventional power plants
Water pollution with oil	
Oil pollution of the water is practically non-existent because there are no hydro turbines.	Oil pollution of the water due to ejection of lubricants from turbines is quite common in the downstream. For example, the oil mass ejected from the turbines of Nizhnekamskaya Hydro Power Plant (Russia) reached an amount of tens of tons.

As can be seen from the table, the hydro-pneumatic stations are ecologically almost harmless. In contrast the conventional hydro-turbine power plants are inevitably malignant to surrounding flora and fauna, especially in the sites of high dams and stations' cascades.

Comparative economical analysis of pneumatic and conventional power plants has been performed by means of our mathematic model [9, 16]. This model makes it possible to find an optimal solution for the hydro system by making the most of water resource potentials while simultaneously minimizing the harmful ecological effects. This solution provides optimal costs for harnessed energy based on both economical and ecological factors. Neglecting ecological safety in developing the hydro-power industry would in future require billions of dollars for restoration of Mother Nature.

In conclusion, we have to point out that the ecological safety of modern hydro-power technology is becoming a primary goal in the industrial countries. The new regulations for water resources are aimed at maximally preserving the world ecological systems. Gorlov's hydro-pneumatic power plants are in line with those regulations and should be considered as a means for preservation of the environment.

References

1. Avakian A.B., Kocharian A.G. Influence of water reservoirs on the quality of the river waters, The Water Resources, 1988, No. 3, pp. 14-18.
2. Vasiliev U.S., Khrisanov N.I. Ecology of renewable energy sources. Nauka, 1991, pp. 21-40.
3. Vasiliev U.S., Khrisanov N.I., Kudryasheva U.G. Ecological Consequences from operation of hydro power plants, Hydrotechnical Construction, 1991, No. 8, pp. 10-12.
4. Kozhova O.M. Phytoplankton of the Bikal Lake and its influence on the flora of the Irkutsk Reservoir. Proc. of Academy of Science of the USSR, 1969, No. 12, pp. 114-117.
5. Korn G, Korn T. Mathematical Handbook for scholars and engineers, Nauka, 1973, pp. 615-618.
6. Lashkov A.S., Postroev V.S. Why are the river perishing? The Nature and The Man. 1988, No. 4.
7. Maslikov V.I., Ryabova V.N. Transformation of plankton during transit from upstream to downstream on the Ust-Ilimsky power plant. Hydrotechnical Construction, 1991, No. 9, pp. 30-31.
8. Ryazanov A.I. About a mathematical problem of dynamics of a gas bubble in incompressible fluid. Proc. of Ukrain Academy of Science, 1990, V. 32 pp. 95-98.
9. Ryazanov A.I. A problem of hydrodynamical analysis for pneumatic power installations. Problems of Machine Industry and Theory of Reliability, 1992, No. 6.
10. Sorokin U.I. Mortality of Plankton in High-Head Hydroturbines. Journal of General Biology, 1990. V. 51, pp. 1151-1153.
11. Fyodorov M.P. Ecological safety of new generation of hydrotechnical installations. Hydrotechnical Construction, 1990, No. 10, pp. 27-30.
12. Khrisanov N.I., Kerro H.I., Kolnik G.A., Estimation of ecological subsequences from hydrotechnical objects. Hydrotechnical Construction, 1190, No. 3, pp. 49-51.
13. Gorlov A.M. Some New Conceptions in approach to Harnessing Tidal Energy. Proc. 2nd Int'l. Conf. on Alternative Energy. 1979, Miami.
14. Gorlov A.M. A Novel Approach to Exploitation of Tidal Power. Report to the US DOE, 1981, V. 3, pp. 11-15.
15. Gorlov A.M. Hydro-Pneumatic Concept for Small Riverine Applications. Proc. 2nd Int'l. Conf. on Small Hydro. Hang zhou, 1986.
16. Gorlov A.M. A New Opportunity for Hydro: Using Air Turbines for Generating Electricity. Hydro Review, V. XI, No. 5, 1992.
17. Grabscheid M. An Environmentally Safe Solution, Northeast Sun, Spring - 1992.

4.3

4. MATHEMATICAL MODELING OF A SINGLE-CHAMBER POWER SYSTEM.

The following paper by Dr. A. Ryazanov develops an efficient and accurate mathematical method to study fluid and gas processes in the single-chamber hydro\air power converter. This method will be extended to analysis of processes in the double-chamber power system under the program described in this proposal.

MATHEMATICAL MODELING OF A SINGLE-CHAMBER POWER SYSTEM

by

A. Ryazanov*

This paper describes aerohydrodynamics of processes in single chambers of a hydro-pneumatic power system. The developed mathematical model enables one to determine the main parameters of the processes: water and air velocities, air pressure in the chamber, the periods of time for filling and emptying of the chambers, and the output of energy during the cycle. This is a basic problem in the aerohydrodynamic analysis of the processes taking place in the chambers of hydro-pneumatic power systems which are designed to improve nonconventional energy technology.

Notations

E_1 energy of a cycle (KJ)

g gravity acceleration (m/s)

H_0 upstream water level relative to the top of the gate (m)

P_0 atmospheric pressure (ATM = 101 KPa)

P chambers pressure (ATM)

P_i downstream pressure (ATM)

t time (s)

T_1 period of a cycle (s)

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S_1	cross-sectional area of air duct (m^2)
S_2	cross-sectional area of the chamber (m^2)
Z_0	initial water level in the chamber (m)
Z	relative water level in the chamber (m)
$\dot{Z}$	velocity of water rising in the chamber (m/s)
W	air jet velocity
γ	ratio of specific heats
ΔH_0	water head (m)
ΔP	amplitude of air pressure in the chamber (ATM)
ρ_0	water density (Kg/m^3)
ρ_1	density of undisturbed gas (Kg/m^3)
ρ	gas density in the chamber (Kg/m^3)

1. INTRODUCTION

The main concept of Gorlov's pneumatic chamber arrangement is to convert water stream energy into energy of compressible air. Initially, the pneumatic system was developed for harnessing tidal energy [1-5] and later was extended to small river applications [6, 7]. The detailed description of this system and its application is presented in [8, 9].

The hydro-pneumatic power plant has no turbines in the water and operates under ultra low-heads (up to 3 m). It can be described in the following terms. A chamber has two gates: upstream (A) and downstream (B). The air turbine is positioned on the top of the chamber and is connected with the air inside the chamber. While water fills the chamber, the air inside is compressed, translating its pressure to the turbine. While the chamber drains, the inside vacuum causes air inflow from outside. In both cases an air turbine on the top of the chamber rotates generating electricity. The air velocity can reach a magnitude of 100 m/sec or higher with water heads starting from 1m. Experiments in the laboratory at Northeastern University (Boston) with the physical model have prcved operation stability of such hydro pneumatic systems.

The straightforward mechanics of this process can facilitate the reliable and easily maintained hydro-pneumatic system. According to [6], this installation can operate under a relatively low water head; the minimal head is of order of one foot. Experiments with pneumatic hydroelectric systems with various arrangements conducted by the US Naval Academy in Annapolis, MD demonstrated a stable regime under a two foot water head. It was established that air stream velocity up to 100m/s is possible at a water head of 1m. This fact directly corresponds with the results of mathematic modelling of the process described in [14]. The chamber fills and empties intermittently at a fast and steady pace. Gorlov's model was tested at various scales of the installation.

Unlike conventional hydro-turbine installations which cause considerable ecological damage, pneumtic systems with low head are harmless to the environment. This fact is warranted by the very design concept which includes the systems of elements enabling one to implement a wasteless technological process [16]. Conventional power plants, in their design and landscaping of the site, can not help destroying the flora and fauna in the vicinity of the station, especially in the area of their cascades. It is more prudent to design and build an ecologically safe system from the beginning than to reconstruct already existing hydro power plants in accordance with safe environment requirements.

2. BASIC EQUATIONS

We introduce the equations of motion according to [14].

The equation of motion for a change in a relative water level inside the chamber can be given as

$$P_0 + \rho_0 g H_0 = P + \rho_0 g Z + \rho_0 \left[Z\ddot{Z} + \frac{\dot{Z}^2}{2} \right] \tag{1}$$

Conservation of mass for air is

$$\rho \dot{z} = r \rho_1 w, \quad r = S_1 / S_2 \tag{2}$$

The Bernoulli equation for gas has the form

$$\frac{P}{\rho} = \frac{\gamma - 1}{2\gamma} W^2 + \frac{P_1}{\rho_2}, \quad \gamma > 1 \tag{3}$$

An adiabatic process of air motion inside the chamber can be written as follows

$$P = P_1 \left(\frac{\rho}{\rho_1} \right)^{\gamma}, \quad \gamma > 1 \tag{4}$$

It is assumed that the liquid is ideal (dissipation is neglected) and incompressible. To apply equation [4] it is also assumed that the characteristic time of pressure relaxation for air in the chamber $\Delta H_0/C$ is much smaller than the period of a cycle and characteristic times of mechanical motion. Here C is the speed of sound in gas, $\Delta H_0 = H_0 - Z_0$. For the system of orginal equations of air and water motion inside the chamber the following initial conditions are posed:

$$z(0) = z_0, \quad \dot{z}(0) = 0, \quad P(0) = P_1, \quad \rho(0) = \rho_1 \quad z(T_1) = H_0 \tag{5}$$

The sequence of stages (phases) for filling the chamber with water are presented in Fig. 2.

A more simple problem for incompressible gas was considered in our earlier publication [14]. A solution to the above formulated problem is obtained by a generalization of methods presented in [14]. In the case of compressible air an exact analytical, as well as numerical, solution to the system of equations is obtained. Existence of an analytical solution is valuable as a foundation for developing an approach for analysis of the quite complicated motion of a two phase gas-liquid composite in the hydro-pneumatic chambers. As will be shown below, both numerical and analytical solutions are in good agreement with the results of model tests. Thus, the simple mathematical model developed is an authentic and reliable method for estimation the parameters of motion in Gorlov's chamber.

3. METHOD OF SOLUTION

The system of equations (1-5) has an exact solution to the problem of motion for air and water components. To obtain this solution we introduce the following functions

$$\xi = (P/P_1)^{1/\gamma}, \quad u = (z\dot{z})^2 \tag{6}$$

Then the original system of equations with the unknowns z, w, ρ, P reduces to the system of two equations with respect to u[z) and ξ (z)

$$z\frac{du}{dz} - u + 2gz^3 - 2\eta_3 z^2 + 2\eta_2 \xi^\gamma z^2 = 0 \tag{7}$$

$$\xi^{\gamma-1} = 1 + \eta_1^{-1} z^{-2} u \xi^2 \tag{8}$$

where $\eta_1 = (2\gamma P_0 r^2)/(\rho_1(\gamma - 1))$; $\eta_2 = P_0/\rho_0$; $\eta_3 = \eta_2 + gH_0$; $P_1 = P_0$

with the initial conditions

$$u(z_0) = 0; \quad \xi(Z_0) = 1 \tag{9}$$

These equations are equivalent to the sole ordinary nonlinear differential equation of the first order with respect to ξ(z).

$$\eta_1 z[(\gamma - 3)\xi^{\gamma - 1} + 2]\frac{d\xi}{dz} + 2\eta_2 \xi^{\gamma + 3}$$
$$+ \eta_1 \xi^{\gamma} + 2(gz - \eta_3)\xi^3 - \eta_1 \xi = 0 \tag{10}$$

with the initial condition

$$\xi(z_0) = 1 \tag{11}$$

The velocity of a rising water level $\dot{z}$ can now be determined as

$$\dot{z} = \xi^{-1}[\eta_1(\xi^{\gamma-1} - 1)]^{1/2}, \quad \gamma > 1 \tag{12}$$

and the air stream velocity is

$$w = r^{-1}\xi\dot{z} \tag{13}$$

The relative amplitude of air pressure inside the chamber is

$$\Delta P = \xi^{\gamma} - 1 \tag{14}$$

The energy conserved during the chamber's filling cycle, T_1, per unit area of a cross section S_2 is also found

$$\frac{E_1}{S_2} = \frac{\rho_1}{2r^2}\int_{z_0}^{H_0}[\xi^2\dot{z}]^2 dz \tag{15}$$

where the period of the chamber's filling cycle is determined as the integral

$$T_1 = \int_{z_0}^{H_0} (\dot{z})^{-1} dz \tag{16}$$

A solution of [10] is found by equivalent transformation to the nonlinear differential equation of the first order with respect to the function sought Z(ξ):

$$F(\xi, z)\frac{dz}{d\xi} + f(\xi)z = 0 \tag{17}$$

$$F(\xi, z) = 2\eta_2 \xi^{\gamma+3} + \eta\,\xi^{\gamma} + 2(gz - \eta_3)\xi^3 - \eta_1\xi;$$

$$f(\xi) = \eta_1((\gamma - 3)\xi^{\gamma-1} + 2)$$

with the initial condition

$$z = z_0, \quad \xi = 1 \tag{18}$$

A solution Z(ξ) can be found in the form of a series in (ξ-1) powers

$$Z(\xi) = \sum_{n=0}^{\infty} a_n(\xi - 1)^n, \; 1 \le \xi \le \xi(H_0) \tag{19}$$

where the coefficient a_n is determined by recurrent relationships. They are quite cumbersome and therefore are not presented here.

From the last equation we obtain the integral law of motion:

$$t = \int_1^{\xi} G(\xi)\, d\xi; \quad 1 < \xi \le \xi(H_0); \tag{20}$$

$$G(\xi) = \xi[\eta_1(\xi^{\gamma-1} - 1)]^{-1/2} \times$$
$$\times \sum_{n=0}^{\infty} (n+1) a_{n+1} (\xi - 1)^n$$

4. MODEL TEST RESULTS

The numerical experiment results based on the above formulae are presented in Figures 3 and 4. The obtained sets of trajectories, formed by marked lines, simulate the conditions of water filling the chamber. The presented segments of trajectories cover the entire range of parameters for ΔH_0 and r.

The numerical results show that the typical velocities can be in the range of a few meters up to tens of meters per second for water and from tens to hundreds of meters per second for air. Amplitudes of gas pressure in the chamber vary up to 0.3 of the atmospheric pressure. The periods of cycles are of the order of several seconds. The chamber is intermittently filing and emptying in a fast and steady rhythm. In this range of parameters the values of energy per cycle reach from 10 up to 70 KJ/m^2. The latter is in reasonable agreement with the experimental data obtained in the Northeastern University, USA experiment [15]. It is shown that the compressibility of a gas is extremely important in the vicinity of the air inlet for a very small r ($r << 1$), when the air stream velocity is of the order of one or two hundred meters per second. In the rest of the chamber the gas compressibility can be neglected since the gradient of $\dot{z}$ compared to the gradient of the stream velocity W is negligible. Here amplitudes of the pressure ΔP are also insignificant. As a result, main dissipative losses occur only in the vicinity of the air inlet.

5. CONCLUSIONS

1. The mathematical model for aerohydrodynimic analysis of Gorlov's pneumatic system quite accurately describes the phenomena. The exact analytical solution, as well as numerical results which are in good agreement with experimental data, are obtained.

2. The analysis of basic characteristics of the process shows that the pneumatic system is very sensitive to the relatively low water heads (up to two meters). In this case it is appropriate to choose a nondimensional cross-sectional area of an air duct r not greater than 1/10 for conservation of kinetic energy of the stream. However, the smaller the r, the larger the air stream velocity which inevitably induces dissipative losses. This effect should be considered more thoroughly.

3. It is found that the power of Gorlov's system can reach hundreds of kilowatts within a range of given parameters. The period of cycles is of the order of several seconds and the chamber can operate in a fast and stable regime. The pneumatic system also demonstrates reliability and simplicity in maintenance.

REFERENCES

1. Gorlov, A.M. Apparatus for Harnessing Tidal Power, U.S. Patent No. 4,095,423, June 1978.

2. Gorlov, A.M. Apparatus for Harnessing Tidal Power, U.S. Patent No. 4,103,490, August 1978.

3. Gorlov, A.M. Some New Conceptions in the Approach to Harnessing Tidal Energy, Proceedings of the 2nd Miami International Confernece on Alternative Energy Source, 1979.

4. Gorlov, A.M. High Volume Tidal or Current Flow Harnessing System. U.S. Patent No. 4,464,080, 1984.

5. Gorlov, A.M. and Zuo Ran, Pneumatic and MHD Concepts for Tidal Energy Conversion Projects, Proc., Int'l Conference on Ocean Energy Recovery, ICOER-89, Honolulu, Hawaii, 1989.

6. Gorlov, A.M. Hydropneumatic Concept for Small Riverine Applications. Proc., 2nd International Confernece on Small Hdyro, Hangzhou, China, 1986.

7. Richards and Weiskopf, Studies of the McCormick Pneumatic Trubine, Proc., Utilization of Ocean Waves Symposium, La Jolla, Calf. 1986.

8. Goriov, A.M. A Novel Approach to Exploitation of Tidal Power: Volumes 1 and 2, Progress Report to the U.S. Department of Energy, 1980.

9. Gorlov, A.M. A Novel Approach to Exploitation of Tidal Power: Volumes 3 and 4, Progress Report to the U.S. Department of Energy, 1981.

10. McCormick, M.E. and Surko S.W. An Experimental Study of the Performjance of Counter-Rotating Wave Energy Conversion Turbine, Journal of Energy Resources Technology, September 1989.

11. Bellamy, N.W. Low-Head Hydroelectric Power Using Pneumatic Conversion, Power Engineering Journal, May 1989.

12. Gorlov A.M. Water Gate Array for Current Flow or Tidal Movement Pneumatic Harnessing System, U.S. Patent No. 5,074,710, Dec. 24, 1991.

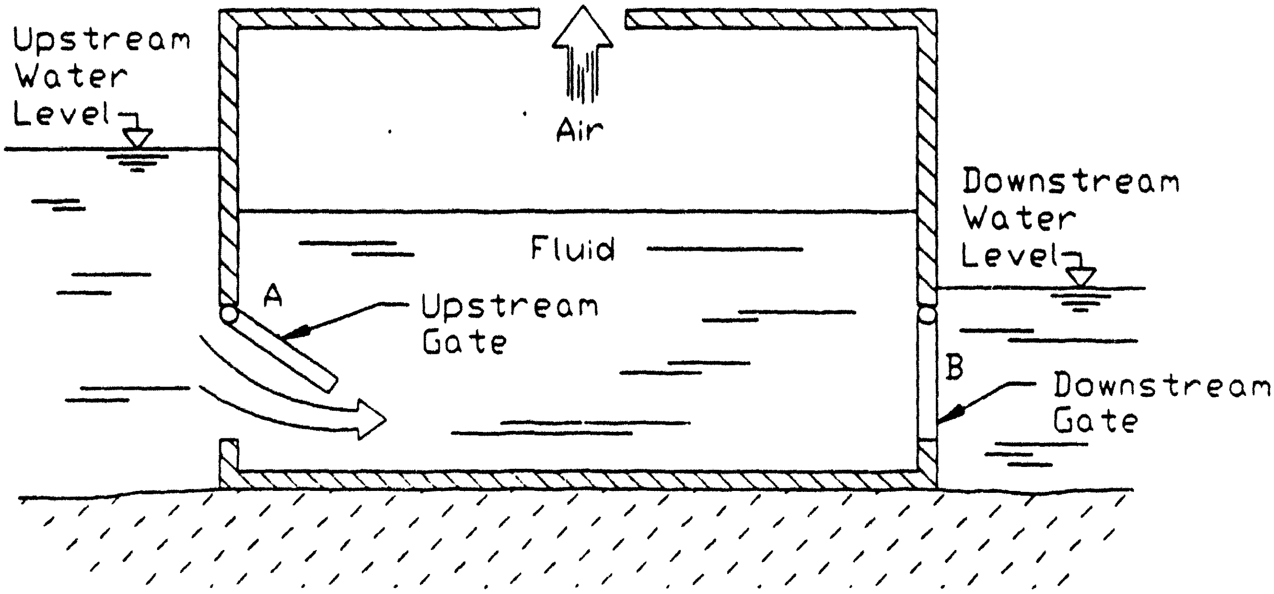
13. Prospects for Hydropower in the Northeast, U.S. Army Corps of Engineers, New England Division, 1980.

14. Ryazanov, A.I. On hydrodynamics of pneumatic chamber installations. Problemy Mashinostroenia and Nadezhnosti Mashin, 1992, N. 5, 22-26.

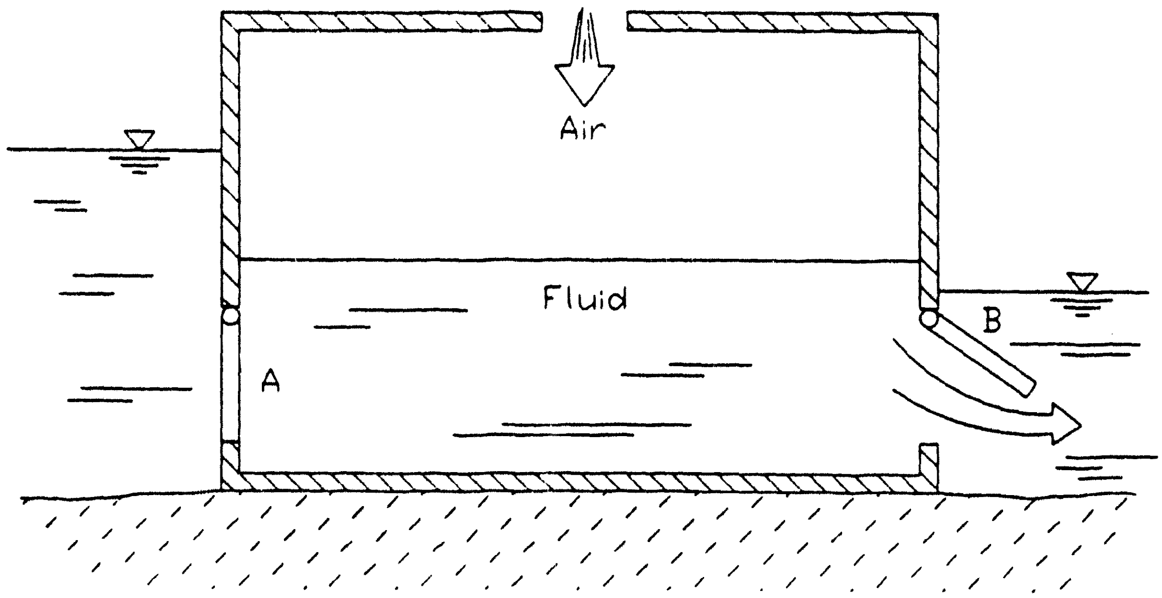
15. Gorlov, A.M. A New Opportunity for Hydro: Using Air Turbines. Hydro-Review, V. II, N 5, September 1992.

16. Ryazanov, A.I. Comparative analysis of ecological safety and efficiency of Gorlov's hydro-pneumatic power plant vs. conventional hydro-power plants with a low head. Vodnye Resursy, 1992, N. 6, 163-166.

17. Small Hydro 1990, Part 4: Oscillating Water Column Devices, Water Power & Dam Construction, Volume 43, No. 6, June 1991, pp. 92-93.



Filling



Draining

Fig. 1 Phases of operation of the water/air power converter.

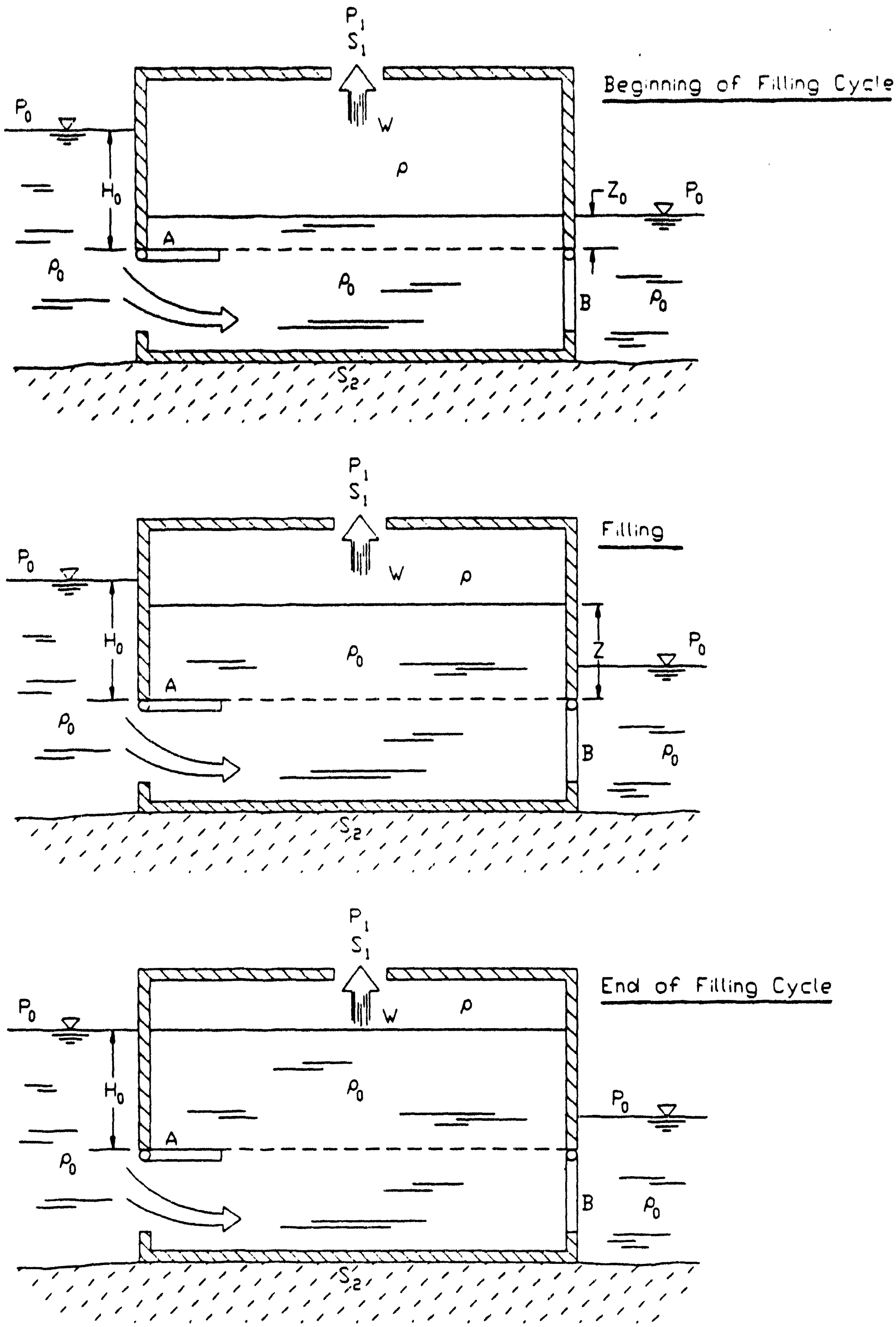


Fig. 2 Phases of filling of the chamber.

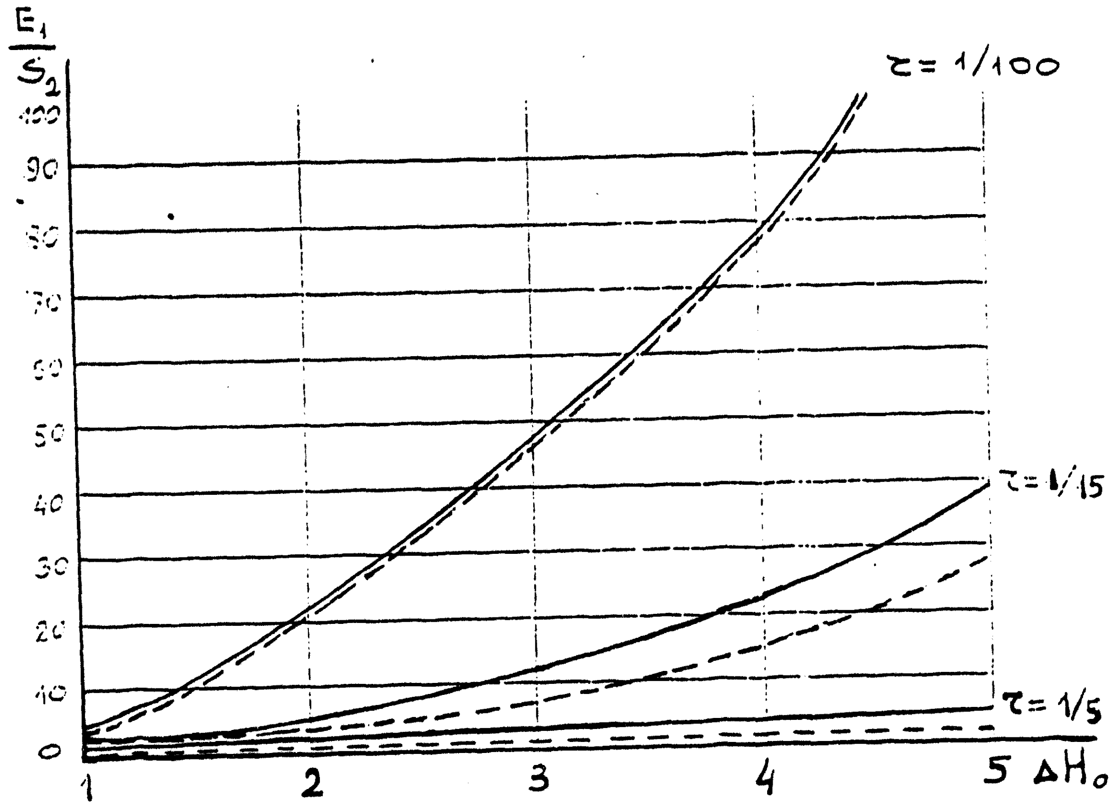


Fig. 3 Energy versus water heads

Notes: ——— for z_0 = 0.01

- - - - for z_0 = 1.0

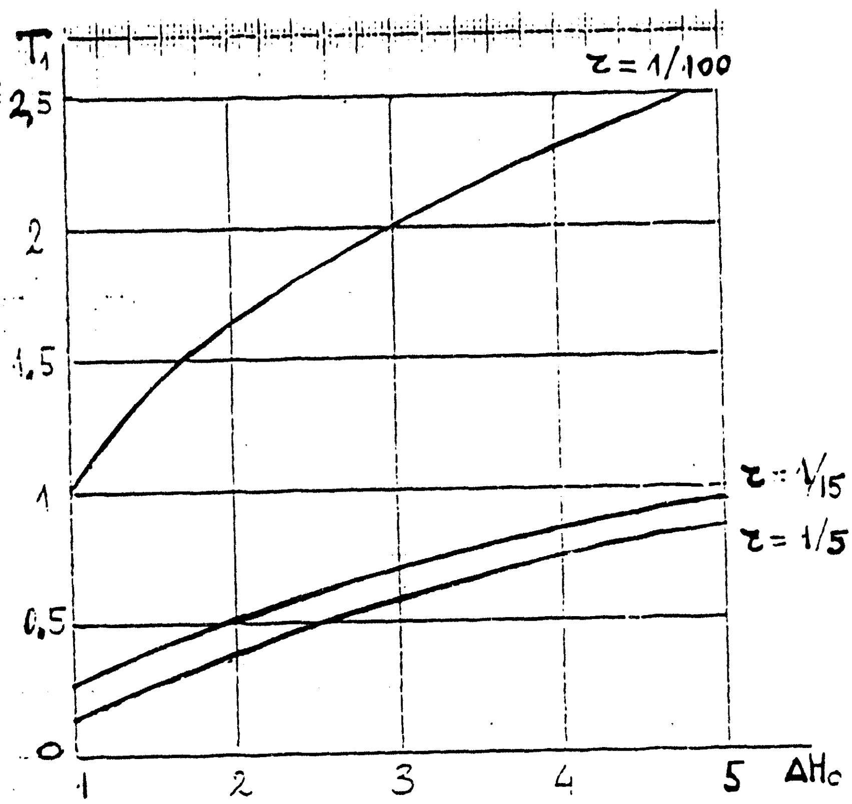


Fig. 4 Cycle time T_1 versus water heads for different r.

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