New Trends in Turbine Modelling and New Ways of Partnership

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ABSTRACT

The purpose of this paper is to present a review of current tendencies regarding measurements on models of hydraulic turbines. We will discuss how such tests can be used to improve the overall performance of hydraulic turbines, taking into account overall efficiency, lifetime expectancy and environmental issues. We will also present new strategies for funding major R&D projects of current concern.

Present hydraulic market experience encounters strong pressures, both of a regulatory and a public driven nature, to mitigate environmental problems associated with hydraulic turbines, including reducing fish mortality by rendering existing or new units more “fish friendly” and compensating for dissolved oxygen depletion by turbine aeration. In addition, many powerhouses are ageing and in need of major overhauls. This means that manufacturers have to develop machines that can be installed within existing civil constraints, whilst still providing proven efficiency or power output, longer lifetime expectancy, and hopefully fulfilling new environmental requirements.

New trends in the energy market also include an increased concern to optimize the use and the benefits of existing hydro assets. To cover peak loads, turbines will be operated more and more frequently in transient and unsteady modes. There is therefore a need to understand the effects of start / stop cycles on the life expectancy of the runners. We also require a better understanding of the interaction between the rotating and stationary components of turbines and the effects of non-steady flows at partial load.

Major interdisciplinary research and development work has to be undertaken to achieve these objectives. Additional fundamental knowledge has to be garnered, at the frontier between biology, mechanics and fluid mechanics, on subjects as varied as fish and environmental responses, two phases flows, transient flows and fluid-structure interaction. A cooperative development of new experimental model tests and numerical simulations is required to get a better knowledge of the biological and physical phenomenon involved. The research literature shows for example that it is now possible to tackle some of these problems by measuring the velocity and turbulent fields inside model turbines using non intrusive methods such as PIV and LDV laser systems, and fast responding pressure measurements. Parallel prototype/model tests should allow us to develop better and more sophisticated scale-up formulae.

All the aforementioned efforts should greatly improve our comprehension of the fundamental phenomena involved and be helpful in achieving our overall aims. The tendency is now to form consortiums working on generic R&D projects, rather than specific ones, involving close partnerships between utilities, manufacturers, fluid researchers and environmentalists. Governmental funds are available to support these projects, but they are frequently poorly known or still quite complicated to put in place. In the present paper, we will examine some interesting new approaches to this problem and how university research laboratories, such as the LAMH at Laval University, can help in developing the appropriate partnerships and raising R&D money.

1. INTRODUCTION

In hydraulic energy production, R&D analyses are frequently performed for new prototypes to improve their performance and cavitation behaviour. However, the field would benefit from more research and development on certain subjects. Two interconnected examples are our understanding of the complex flow behaviour in hydraulic turbines and the subsequent description of the interaction between the flow and the structure. If these topics seem too academic and at first sight not too profitable, there are the problems of ascertaining the real effect of the refurbishment of an ageing power plant on efficiency and performance, or establishing cost operation strategies for peak energy and their related effects on the life expectancy of the unit, or understanding the effects on performance and efficiency of aeration, aimed at decreasing fish mortality.

Both old and emerging concerns arise when faced with the optimization of energy production taking into account environmental issues. These problems are very complex, as we will try to show in this paper. They would greatly benefit from the joint expertise of people coming from different organizations including power utilities, manufacturers, universities and government agencies; specialists using a variety of approaches to reach their aims, such as numerical simulations of engineering and environmental problems, in conjunction with model tests and test-site experimentation. This means that strategies for the protection of intellectual property and benefits must be devised, as well as an equitable sharing of R&D costs. In this paper, we will look more specifically at new ways to fund these programs.

2. STATE OF THE ART IN REFURBISHMENT

Upgrading and refurbishing ageing hydroelectric power plants will constitute the great majority of hydro projects in North America in the near future. When refurbishing plants equipped with Francis or Kaplan turbines, utilities will have the following goals in mind:

- To raise power production by increasing turbine-generator efficiency or installed discharge rate
- To maximize profits
- To protect their assets on a long-term basis
- To minimize associated costs in compliance with new environmental concerns and regulations

In some particular cases, major civil work may be required to achieve these goals, with the result that it is more economical to build a completely new adjacent powerhouse. However, refurbishment projects generally consist of a complete overhaul of the mechanical and electrical equipment, such as turbine and generator replacement and new control equipment.

When replacing the existing power units, the selection and design of the new turbines is entirely guided by civil constraints, including water passages, to avoid major concrete substructure modifications which could be excessively costly. This is why the best way is often to value existing assets and to conserve the external envelope of the turbine (spiral case and draft tube) and modify the internal geometry by inserting new wicket gates and new runners. The spiral case is usually kept as it is or slightly smoothed and coated. The runner diameter is generally maintained or slightly increased. The runner setting is unchanged or just slightly lowered and the draft tube geometry is maintained except for slight inner reshaping (piers, bottom and /or lintel).

When replacing old Francis turbines of medium to high head with new Francis units, one can expect an increase in discharge and power of about 10 to 15 %, an efficiency gain of a few percent and a corresponding increase in specific speed of 5 to 7 %. The old setting is however maintained as a result of an improved value of the cavitation number. Model studies are still of prime importance to predict the true gain accurately and evaluate the new turbine design. The best way to proceed is firstly to determine the true performance of the existing unit using an homologous model [2]. For this, the model has to be built based on the measured prototype geometry, considering 1) that probably the old runners have not been built exactly to the specifications of the original drawings, and roughness in the spiral case can be greater than indicated due to corrosion or riveted steel plates, and 2) that old model tests, if they do exist, were probably carried out employing older and less accurate procedures that we can now achieve. Geometry, roughness and tolerance controls are more tighter nowadays than in the past. Also, the standardized model test best efficiency requirement has increased from 0,4 % (IEC code 193, 1965) to 0,2 % (IEC code 60193, 1999), due to improvements in measurement techniques.

The scale-up formulas used nowadays may also differ from the old ones. In 1965, The IEC recommended the Hutton scale-up formula for Kaplan turbines and propellers and the Moody formula for Francis turbines. The new IEC code proposes a different formula. Typical performance curves of an old Francis turbine are represented in dark on figure 1. Prototype performance curves are often lower than the scaled-up model curves. Scale-up effects are significant and may represent differences of up to 2 % for large machines.

In a second phase, model studies remain the best tool for developing a new turbine [1, 2], capable of fulfilling all the technical and environmental requirements of the refurbished utility. On the one hand, model tests will determine with great accuracy the efficiency of cumulative improvements like a new runner, new wicket gates and modifications of the draft tube. A new runner may add 2%, or more, depending on the age of the old turbine. The wicket gates will typically provide an additional gain of the order of 0,5 to 1%. Draft tubes modifications can easily result in gains or losses of the same order of magnitude. The only pitfall is an eventual increase of kinetic energy losses at the outlet, that may become significant for a low head project. On the other hand, model tests are the only way to date to evaluate new environmental strategies such as aeration.

Typical performance curves of a new turbine are shown in figure 1.

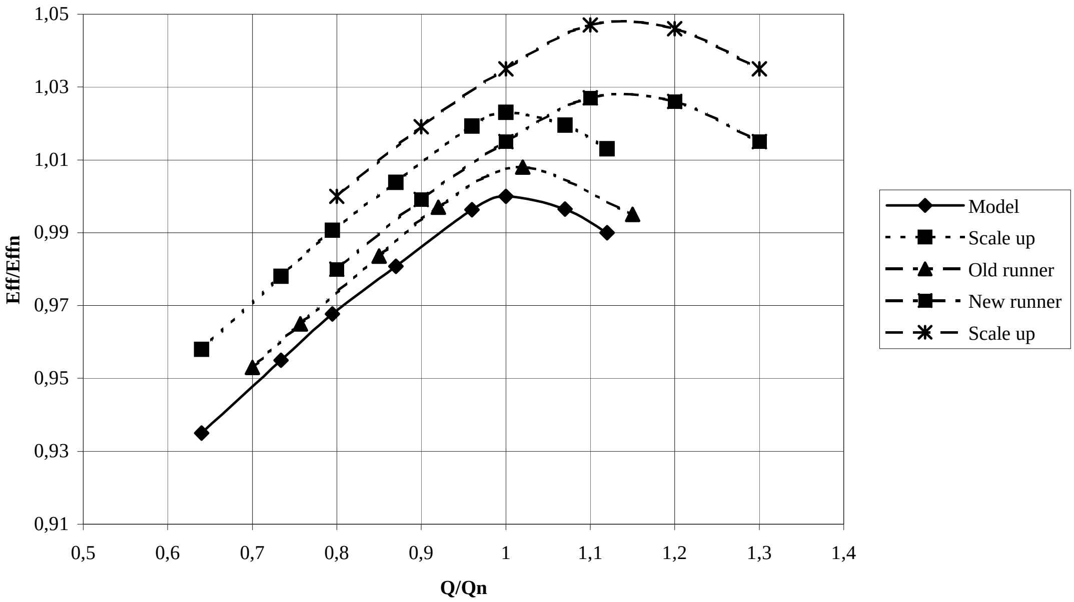

Figure 1: Typical performance curve of an old and new Francis runner

The refurbishment strategy for lower to medium head plants up to around 30 meters could involve replacing old Francis turbines by new Kaplan turbines. This could bring an attractive increase in power and discharge of up to 50 %. The corresponding increase in specific speed will then be about 25 %. This improvement will however be demanding since it will be difficult to accommodate the new turbine in the old setting.

3. EMERGING R&D FIELDS FOR PARTIAL AND FULL LOAD OPERATION

Besides providing information at the nominal operating point, model measurements can also ascertain machine performance, behaviour and efficiency at partial load and full load. Performance and efficiency curves are obtained for the complete operating range of the machine with good accuracy. Scale-up correction laws as per IEC code allow us to transpose results obtained from model tests to the prototype turbine but, strictly speaking, these laws are applicable only near nominal operating conditions. An important area of research and development should thus be to improve our knowledge about scale-up corrections for different parameters such as pressure fluctuations and establish new laws for partial and full load operating conditions. A complete comparison between model and prototype tests would be a good start to help establish improved scale-up laws.

The development of refurbished turbines is carried out nowadays by coupling model tests and numerical simulations (CFD analysis). This involves a similar process to the way we design new machines. We have witnessed extraordinary developments in the past 15 years, but so far these only indicate tendencies for use on a comparative basis. Numerical models, designed for full machine simulations on modern computers, are unfortunately still unable to predict absolute values of the efficiency with sufficient accuracy to replace model tests. According to reference [3] for example, the numerical simulation used for a particular Francis turbine overestimated the efficiency by 2 or 3 % at nominal load, while underestimating it by up to 7 % at partial load and overload. Existing numerical models in fact encounter difficulties to reproduce properly the swirls occurring in the draft tube [4]. Certain turbulent boundary layer models may also prove inappropriate near moving walls [5], such as rotating hubs or shrouds, or other areas where strong adverse pressures are present.

We must strongly emphasize that model tests and numerical simulations are not competitive techniques, but rather complementary tools. To determine the characteristics of a machine with good accuracy away from the nominal operating point, we still need to use model tests. For a good balance in resources utilisation, model tests can be used to calibrate and improve the numerical models, whilst numerical simulations can help us choose the critical operating conditions to be measured and extrapolate between these points at a lower cost. As mentioned previously, on the experimental side, techniques are now available [6] for measuring the complete mean velocity and turbulent fields inside model turbines using non intrusive methods like PIV and LDV laser systems, as well as unsteady pressure fields using fast responding pressure transducers.

Another consideration arises from the deregulated energy market. Due to the resulting increased fluctuations in the price of energy, the new trend is to try to maximize profits from hydro by changing the way turbine parks are managed. Traditionally, the North American way of producing energy was to run almost all units at nominal load, allowing very few start-stops (less than 100 per year), leaving a few machines to be “sacrificed” to follow the network demand. Nowadays the philosophy is completely different; the modern tendency being to promote peak load production involving many more start/stop cycles for each unit (the number may reach 500). This maximization of profits encourages both partial and full load turbine operation. However, even if the higher saleable price and its variations were known for peak energy, ancillary costs remain unknown, as we know very little about likely reductions in lifetime expectancy, due to frequent start/stop cycles and partial and full load operation. This could become another important research area in the near future.

Optimizing gains by using a unit at partial or full load requires much better knowledge on the negative effects on lifetime expectancy. Under certain operating conditions, pressure fluctuations have caused sufficiently high stress levels in the runner material, to lead to metal fatigue after let’s say 10^9 cycles [7, 8]. It would thus be useful to monitor the effects of the frequency and amplitude of such fluctuations on models, and be able to transpose them to prototypes [9]. In addition to model and prototype tests, we need to measure stress levels during the start and stop cycles of a production group. This whole field of unsteady fluid-structure interactions will also require important work on the numerical side.

4. ENVIRONMENTAL CONCERNS AND R&D

Besides the large scale environmental problems associated with the formation of the reservoir upstream of a dam, three very important ecological concerns may be alleviated while refurbishing turbines. These are, a reduction of oxygen depletion downstream of the reservoir, an increase in fish survival through the turbine passages and finally the guarantee of minimum flows to sustain fish habitats.

To comply even partially with these new requirements, we need model tests to improve turbine aeration and develop the best devices for maximizing oxygen transfer, whilst still maintaining high turbine efficiency. One aeration method, and probably the most economical, is auto venting through the turbine. Air is injected into the hub via the hollow shaft, or by other means, such as through the blades, or through the runner shroud, by benefiting from the depression occurring near the draft tube cone (cf. figure 2).

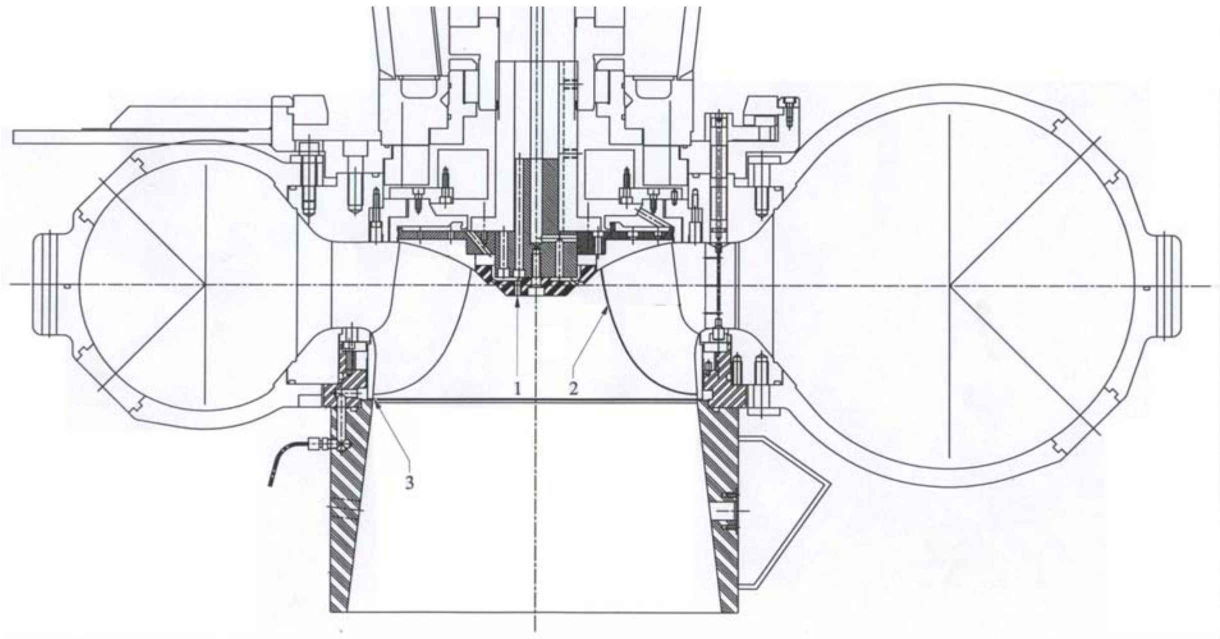

Figure 2: Air injection points in a Francis turbine

Model tests with air injection have been reported by Alstom Power in [10]. Air admission created a loss in efficiency at nominal and full load, increasing with the amount of air and the head, but indicating small gains at partial load. Losses can be minimised by improving the air injection device [11]. Oxygenation could also be optimized according to seasonal needs and turbine output levels.

The diffusion process of the air through the water can also be improved. Presently, the main difficulty resides in correlating the amount of air injected with the increase in oxygen in ppm, which is indeed the real goal. To improve our knowledge, we will require further research, using model tests combined with *in situ* monitoring and a two phase flow approach.

There has been great interest in recent years in determining the causes of turbine-induced trauma in fish [12]. Fish injuries are the result of mechanical injuries (abrasion, grinding and strikes) and pressure injuries. Fish are more sensitive to rapid pressure decreases than rapid pressure increases. We know that strong depressurisation is occurring through the runner and repressurisation in the draft tube. Cavitation, bubble collapse and associated strong bubble shock waves also cause injuries. Turbulent shear stresses developing in the flow field, due to high velocity gradients or vortices, can also cause injuries. Such zones of high turbulent shear stresses occur mainly near wicket gates, trailing edges, the outer shroud in Francis turbines, and close to the hub and blade tip gaps in Kaplan turbines.

It has also been shown that injuries are related to fish species and size [13]. Intensive test campaigns have determined biological criteria for different species. This should now allow the development of more fish-friendly turbines. Such a development can be done in two ways. Some groups are developing new fish-friendly turbines, such as the screw runner from ARL /NREC [14, 15]. Another approach is to improve the design of existing Francis, Kaplan and bulb turbines, in order to:

- reduce the rate of pressure decrease by lengthening the blades
- reduce cavitation by improving blade profiles
- reduce turbulent shear stress regions by reducing the number of wicket gates
- improve shroud geometry in Francis turbines and/or reduce the clearances of wicket gates

Some success in this direction has already been reported for new Kaplan units at the Bonneville Powerhouse on the Columbia river [16]. These replacements however demonstrated that the best fish survival rate does not correspond to the best efficiency point, as previously thought.

The development of fish-friendly units to replace old ones will necessitate a similar methodological approach to that described previously for improving performance. In a first phase, we will have to assess the existing situation concerning fish losses and injuries for a specific site. In a second phase, a mix of *in situ* measurements, model tests and numerical simulations should make it possible to develop new economical units with an increased rate of fish survival. It is clear that these developments need to be undertaken in partnerships involving the manufacturer, the utility and the regulatory bodies, in order to chose the best compromise between the traditional way of maximizing efficiencies (up to 94% or more) and environmental concerns. These new units will always involve a “balanced design” favouring certain species. *In situ* monitoring will also be necessary to ascertain progressively the right methodologies and biological criteria.

In order to preserve fish habitats downstream of power plants, continuous minimum flows are increasingly required in refurbished projects, while on the market side, peaking and on-off water regimes are being emphasized to increase profitability. To maintain these minimum flows without spilling, utilities will be tempted to operate some existing units at partial loads, with or without air admission, or to add new smaller units. It is important therefore that we gain a better knowledge of the consequences of such operating conditions on both fish survival and the lifetime expectancy of the unit.

5. R&D FUNDING POSSIBILITIES

It is difficult to put in place the collaborations necessary to carry out the various R&D projects proposed in the previous sections. It will require greatly improved comprehension of a variety of fundamental phenomena, needing consortiums working on generic projects rather that purely specific ones. Close partnerships will be required between utilities, manufacturers, fluid researchers and environmentalists. However, as we know, the market economy in which we function is full of pitfalls. We have seen for example that environmentalists and engineers have different perspectives: optimal machine efficiency does not necessarily mean fish-friendly turbines. It is also very difficult to reconcile partnerships with the competition for profit between companies, or for research funds between different university and government laboratories.

A number of both new and old strategies, involving governments, industries and universities, exist for financing these projects. Let us mention a few funding possibilities and examples.

Canadian governmental programs

Canadian governmental help falls into three main categories: fiscal benefits for private businesses involved in R&D activities, support programs by funding agencies such as the National Science and Engineering Research Council (NSERC, Canada) for collaboration between universities and their partners and finally support from specific programs such as the Canadian Foundation for Innovation (CFI) and others.

The Government of Canada has established a tax incentive program to encourage Canadian businesses of all sizes to conduct R&D that will lead to new or improved technologically advanced products or processes. This program is called the Scientific Research and Experimental Development (SR&ED) Program[1]. Different rules apply depending on the type of expenditure and business. But as a rule of thumb, between 40 % and 60 % of R&D projects are deductible. Similar programs also exist in some provinces of Canada.

NSERC is the main funding agency for scientific researcher in Canada. Besides sponsoring research groups and centres, it helps Canadian companies to compete in

[1] See www.adrc.gc.ca

today's economy by jointly funding collaborative R&D projects involving scientists and engineers in universities across the country. Other NSERC programs also provide individual research scholarships to undergraduate, graduate and post-doctoral students. The various programs are very useful. They help define projects that are relevant to industry and provide an academic background for students that one day may join the company. Similar initiatives exists at the faculty level with NSERC/Industry chairs, where both NSERC and an industrial partner invest in a specific research program.

In addition, the NSERC Research Partnerships Program (RPP)[2] offers a variety of grants whose common purpose is to promote closer collaboration between the university research community and other sectors, including government and Canadian industry. Let us mention a) the Collaborative Research Strategic Projects (CRSP), involving pre-commercial academic research on emerging technological problems with expected commercial or industrial impact within 10 years, b) the NSERC University-Industry Collaborative Research and Development program (CRD), offers NSERC funding of over 150 000$ a year for R&D projects with strong industrial relevance, c) the NSERC Technology Partnerships Program (TTP), can provide a maximum of 150,000$ annually, up to three years, for small and medium-sized Canadian businesses.

Regarding the development of research infrastructure, we should also mention the Canada Foundation for Innovation[3] (CFI). This is an independent corporation established by the Government of Canada in 1997 with a large budget of 3.15$ billion up to the year 2010. The Foundation’s goal is to strengthen the capability of Canadian universities, colleges, research hospitals, and other non-profit institutions, to carry out world-class research and technology development. This program provides help varying from the purchase of a specialized piece of instrumentation, such as a PIV for the LAMH at Laval University, to equipping a complete laboratory at a cost of several millions of dollars. The CFI also runs the Canada Research Chairs program.

It is useful to know that, in the hydro sector, CANMET Energy Technology Centre (CETC, Natural Resources of Canada) can act as an R&D partner or catalyser by providing access to programs such as the Renewable Energy Program (RETP), the Technology Early Action Measures (TEAM) of the Climate Change Action Fund (CCAF) or the Sustainable Technology Development Canada (SDTC) fund. The RETP in particular provides cost-sharing and technical assistance in support of technology development and field tests. Government Laboratories, such as the CETC, are also able to serve as contractors or provide in-kind support to industry on proposal submissions.

A glimpse at US formulas

The US Department of Energy (DOE), among other activities, funds research and development in various energy fields. Ongoing efforts include work on dam safety, the environment, fish protection and the development of computer technologies to improve

[2] See www.nserc.ca/programs/rpg_e.htm

[3] See www.innovation.ca

operations. The research work is carried out either through contracts or contribution agreements. However, the DOE acknowledges that the available governmental funding in hydro is likely to decline in the US, due to budget restrictions and increased deregulation of the electrical utility industry.

One also finds the "innovation co-enterprise'' formula, where an ad hoc company is created, co-sponsored by a manufacturer and a utility. The new entity does research work to develop and market new products for which they retain ownership and expect future revenues from sales. The Tennessee Valley Authority (TVA) and Voith Siemens have been working together in this way on the optimization of hydro energy production.

The EPRI (Electric Power Research Institute) is a non-profit organization that provides science and technology solutions for energy customers. In the field of hydro and renewable energies, work is co-sponsored by government and other stakeholders, who provide matching funding. EPRI has developed customized programs focusing on the most relevant issues such as emerging low-impact technologies.

International cooperation

Many programs exists in this category. We will mention only two, as interesting examples of partnership.

CEA Technologies Inc., a subsidiary of the Canadian Electricity Association (CEA) put in place a number of interest groups, whose members are the utilities. Each specific R&D project is supported by a sub-group of members who agree to co-fund the project and share the intellectual property of the final product. This may be a software, the results of engineering research or some technological product. The work is subcontracted to a specialist (manufacturer, engineering company, university ...). Co-founders provide their knowledge, data and expertise as input. Project funding ranges between 250 000$ and 1 000 000$. The CEA also provides access to operational machines for *in situ* experimentation and testing. The Hydraulic Plant Life Interest Group (HPLIG), who work on projects related to refurbishment, is a good example of this type of partnership and cooperation.

From abroad, let us mention SINTEF Energy Research (Norway) as another interesting example. This independent research organisation is engaged both in Norway and on the international market. Their R&D activities are focused on power production, including industrial processes and products. Projects are sponsored by industry and the utilities. SINTEF is directly linked to a university (Trondheim). It provides access to laboratories and places great emphasis on the training of graduate students and preparing future engineers and researchers for the hydro industry; a preoccupation of significant importance when one looks at the forthcoming shortage of trained personnel in Canada as well.

6. CONCLUSION

The main conclusion is that new R&D needs are emerging. These include the refurbishment, partial and full load operation and environmental concerns discussed in the paper.

It is common knowledge that funding of research and development in the hydro-industry remains very low both in absolute dollar terms and as a percentage of sales. To address the technological and environmental issues facing us, it is clear that we will have to develop new models of cooperation and funding between utilities, manufacturers, universities and governments. We need to create new and original ways of partnership, to share funding and to work together more closely and openly. A few examples have been developed in section 4, some well known, such as fiscal benefits, some less known, such as the Canadian or US government programs, and others addressing generic concerns such as the interest Groups of the CEA or the SINTEF of Norway.

These emerging R&D preoccupations aim at developing better turbines and plants - more efficient, more robust and more environmentally friendly - for the benefit both of industry and people in our communities. We believe that, by working in new ways and publicizing success stories, it will become possible to rejuvenate the image and perception of our hydro industry. This will attract the talented students and young engineers and researchers that are needed for our industry both in Canada and abroad.

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