RISK ASSESSMENT FOR FISH PASSAGE THROUGH SMALL, LOW–HEAD TURBINES

ETSU H/06/00054/REP

Contractor

Fawley Aquatic

Prepared by

A W H Turnpenny

S Clough

K P Hanson

R Ramsay

D McEwan

The work described in this report was carried out under contract as part of the New & Renewable Energy Programme, managed by ETSU on behalf of the Department of Trade and Industry. The views and judgements expressed in this report are those of the contractor and do not necessarily reflect those of ETSU or the Department of Trade and Industry.

First published 2000

EXECUTIVE SUMMARY

Small, low-head run-of river hydroelectric sites are often perceived as potentially damaging to fisheries interests, especially on migratory salmonid rivers. One of the main risks occurs during the downstream migration phase of salmonid smolts (mainly spring) and parr (mainly autumnal), as often a large proportion of the total river flow may be diverted through the turbine(s). Provision of fine-meshed smolt screens across the turbine inlets helps to reduce this risk, provided that the smolts are successfully directed back to the river. Unfortunately, they impose a heavy maintenance burden on hydroelectric operators and can reduce electricity production. Any requirement to fit physical screens could therefore jeopardise the economics of such schemes, especially small ones typical of those supported by the UK Government's NFFO (Non-Fossil-Fuel Obligation) and SRO (Scottish Renewables Order) initiatives. The use of fish screening alternatives, including behavioural screening (e.g. acoustic, louvre, bubble or electric screens) or even the no-screening option, may be acceptable in some circumstances, subject to the outcome of appropriate risk-assessment procedures which most fishery regulatory bodies now require.

An earlier ETSU-funded study undertaken by Fawley Aquatic Research Laboratories, Southampton (FARL) and National Engineering Laboratories, East Kilbride (NEL) investigated the risk of fish injury that might arise in tidal power schemes due to hydroelectric turbine passage. In that study, computational fluid dynamics (CFD) techniques were used by NEL to predict the potentially harmful conditions to which fish might be exposed. The key ones are hydraulic shear stress, caused when adjacent masses of water move at different velocities, and pressure fluxes, resulting from changes in hydrostatic head and hydrodynamic effects near the turbine blades. Cavitation (the formation of vapour pockets of low pressure) is potentially harmful to fish but mainly arises in turbines operating away from their design conditions. The FARL study also developed more accurate means of predicting fish injury rates based on the Von Raben statistical technique. The results of the earlier study have been used for predicting injury rates in a variety of medium-to-large sized turbines but are considered likely to under-predict injury rates in small turbines (<1 MW), in which the fish inevitably must pass closer to the mechanical components of the turbine (i.e. the water passages are narrower).

The present study was carried out by the FARL/NEL project team, assisted by Hydroplan UK, who provided information on representative small turbine designs. The stages of the project were as follows:

i) appropriate small, low-head Francis and Kaplan/ propeller turbine designs were selected;

ii) CFD modelling was carried out to estimate pressure fluxes and shear stresses;

iii) biological dose-response relationships were drawn from the earlier FARL study and from published information to describe responses of salmonid smolts and parr to pressure fluxes and shear stresses;

iv) a computer spreadsheet model, 'STRIKER', was developed to compute the likely smolt/parr injury rates from pressure flux and shear stress and to apply the modified Von Raben method for calculating injury rates arising from fish collision with the turbine runner.

v) field tests were carried out at two operating turbine sites to measure smolt/parr injury rates

for comparison with results generated by the computer model.

Conclusions

1. Results of the CFD analysis suggest that shear stress is of relatively minor importance in small, low-head Francis and Kaplan turbines, being predicted to account for injuries in <2% of smolts/parr passing through the turbines. This was confirmed by the field studies.

2. Pressure flux is potentially more damaging than shear stress, pressure-related symptoms accounting for up to 6.3% of observed injuries in the field tests. The main risk-areas of pressure-related injury were shown by the CFD study to be in the runner section and, where a significant siphonic fall exists, in the draft tube.

3. Runner-strike-related injuries were 3-4 times more important than the hydraulic effects (pressure, shear) in relation to smolt/parr passage. The rate of strike injury is highly dependent on the size of the fish and type of turbine, the runner diameter and rotation rate and the number of blades and the operating load (and hence flow rate).

4. The STRIKER program allows the computation of strike rate for smolts and parr and provides a good representation of the risk associated with hydraulic shear and pressure effects in small, low-head Francis and Kaplan/propeller turbines. The output from STRIKER provides a basis for risk assessment of turbine passage. Combined with information on the proportion of the river flow passing through the turbine(s) and the diversion efficiency of any intake screening system used, a full risk assessment for downstream-migrating salmonids can be achieved.

Contents

1. INTRODUCTION

The operation of hydroelectric turbines on rivers that support migratory fish populations may result in a risk of fish being entrained into the turbine water flow and of consequent injury or death. Turnpenny (1999) described a number of mitigation approaches that may be used to reduce or prevent the risk to migratory fish. These range from a variety of fish screening methods to more futuristic solutions involving ‘fish-friendly’ turbine designs (i.e. turbines that are designed to minimise the risk of hydraulically related or contact injuries).

A traditional method of preventing fish from entering turbine inlets is by the use of fine-meshed screening, usually in the form of flat panels placed across the water inlet that can be withdrawn for cleaning. Many older hydroelectric schemes lack fish screening but are required under existing or new regulations[1] to prevent fish entry. Options include manually cleaned or self-cleaning physical screens and behavioural barriers. The latter use e.g. a bubble curtain, flashing lights, an acoustic field or an electrical stimulus to deter fish. The efficiency of behavioural barriers is generally lower than that of physical screens but they may be more cost-effective and in general have a much lower impact on plant operation as they do not significantly impede water flow. In certain cases, turbine inlets are operate unscreened by agreement with the fishery regulators.

A previous ETSU study carried out by Fawley Aquatic Research Laboratories Ltd (FARL) reviewed this subject, describing legal requirements in the UK for fish screening, regulatory policy and available physical and behavioural fish barriers (Turnpenny *et al*, 1998). A recommendation of the study was that risk assessment procedures should be refined to improve confidence in estimates of fish injury rates in small hydroelectric turbines. This followed from discussions in particular with the Scottish Office (SO) and the Environment Agency (EA). Both of these bodies indicated that approval of the operation of turbines without fish screens, or of the use of behavioural screens, as preferred by some operators, should be subject to the satisfactory outcome of a suitable risk assessment. Such a procedure is already operated within the EA when assessing compliance of water intake fish screens with s.14 of the Salmon and Freshwater Fisheries Act 1975, but at present neither organisation has a procedure applicable to turbine water inlets.

A full risk assessment of the effect of turbine operation on fish populations would need to take account of several factors, including (Turnpenny and Hanson, 1997):

- the proportion of total river flow diverted to turbine;
- the efficiency of any fish screening system used and
- the injury or mortality rate of fish passed through the turbines.

---

[1] The Salmon and Freshwater Fisheries Act 1975 s.14 & 15 (as amended under The Environment Act 1995) [England and Wales], The Salmon (Fish Passes and Screens) (Scotland) Regulations 1994 and The Fisheries Act (Northern Ireland) 1966.

In respect of the last item, it is impractical to assess the survival prospects for an injured fish released into the wild and so the ‘worst case’ assumption is made that an injured fish equates to a dead fish. From this information, the overall scheme fish passage rate can be determined for any given combination of flow rates, turbine characteristics and screen deflection efficiencies.

The prediction of fish injury rates in hydroelectric turbines has been discussed by a number of researchers, with key works by Von Raben (1959), Monten (1980) and Turnpenny (1998). Other useful reviews are provided in Eicher *et al.* (1987), Solomon (1988) and Cada *et al.* (1997). The potential causes of fish injury in axial flow turbines include:

) collision with the fixed machinery (guide vanes, stay vanes etc.)

-**'strike'**) collision with the rotating runner blades

) TRAPPING OF FISH BETWEEN THE BLADE TIP AND THE RUNNER CASING

- **rapid pressure flux** (associated with passing through high, then low pressure zones across the runner)

- **hydraulic shear and turbulence** (close to fixed and moving surfaces and in the turbulent wake of the blade and in the draft tube)

- **cavitation** (at the blade tips and off the back of the blades).

The first three of these, known as 'strike' injury, represent the most important sources of injury for all but the smallest (≤10 cm) fish (Turnpenny, 1998). Of the three, collision with fixed machinery is least important, owing to the relatively low collision velocities and the thickness of these components. Runner strike is usually the most important, the probability of strike being greater, the larger the fish. Pressure, shear and cavitation effects are potentially important, especially for turbines that are operated off their design point.

Von Raben developed the probabalistic theory of fish collision with turbine runners and his approach has been refined by successors but remains fundamentally similar. The importance of strike and the other (hydraulic) effects was considered in an earlier study carried out by FARL (then part of National Power’s R & D department) and National Engineering Laboratories (NEL) for ETSU, as part of the UK Government’s tidal energy programme. This was entitled: “Experimental Studies Relating to the Passage of Fish and Shrimps Through Tidal Power Turbines”. The study was based on a 9m-diameter reference turbine design and investigated, separately, the effects of blade strike, hydraulic shear, cavitation and rapid pressure flux. The study began with a mathematical analysis of the relevant characteristics within an operating (9m) turbine, which was carried out by NEL. NEL used two proprietary computational fluid dynamics (CFD) programmes, PHOENIX and FLUENT. From the CFD analysis, the distributions of these physical attributes close to the turbine blading were computed. Biological ‘dose-effect’ experiments were then carried out at FARL to establish the tolerance of these ranges of conditions by various species of fish. This enabled FARL to assess the relative importance of different turbine-passage-related effects and to predict injury rates for turbines of known geometries and operating characteristics (head, speed, etc.). A summary of the work was reported by Turnpenny (1998). The method has been used in several risk assessments for new and existing hydroelectric sites, but it has been recognised that it is likely to give less accurate results the further the turbine departs from the 9m reference design. The greatest error would arise in turbines of <1 MW, typical of those used in the UK's NFFO/SRO[2] schemes. An opportunity to test the accuracy of the method arose during the testing of an acoustic fish barrier at Blantyre hydro-electric station (R. Clyde), when salmonid smolts that had passed through the turbine were collected in a tailrace net (Anon, 1996). The results showed that there was a good correspondence between predicted and observed strike rates (5.9% *cf.* 4.4% at full load, 7.7% *cf.* 7.5% at half-load), whereas non-strike-related injuries were under-predicted by factors of nearly 2-3. The discrepancy was considered most likely to be due to the effect of the smaller size of the turbine water passages, which means that fish must pass closer to the walls and blading (the passages get smaller but the fish stay the same size) and also, possibly, by the faster rotation rates of smaller turbines.

The study reported here set out to improve the accuracy of the prediction method for small, low-head (<30m) turbines, in the following stages:

i) selection of small, low-head turbine designs for analysis

ii) calculation of the hydraulic conditions within the selected turbine using CFD techniques;

iii) application of the biological experimental data generated by the earlier FARL study to assess the risk to fish ;

iv) development of a computer spreadsheet model, 'STRIKER', to allow computation of fish injury rates for different turbine arrangements;

v) validation of the model at two operating small turbine sites: one with a Francis turbine, one with a Kaplan/propeller type.

The project team included research staff from FARL and NEL, as in the original tidal power study, again with responsibilities for fish biology and CFD modelling, respectively. Engineering staff from Hydroplan also took part in the study and were responsible for turbine selection and specification of input parameters for the CFD modelling.

For reasons of confidentiality, it was agreed on behalf of the owners that the identity of the sites used for validation work would not be reported.

The output of study includes this Report and the associated Excel computer spreadsheet entitled "STRIKER" supplied with the Report. It is intended that these products can be used for calculation of potential injury rates for migratory salmonids (smolts). The development of a refined and validated risk assessment procedure for small turbine sites will enable:

the impacts on fish of existing sites that have no screening to be better assessed;

- the degree of improvement in overall scheme by-pass rate by fish to be predicted for different types of screens whose efficiencies are known;

rational decision-making on the appropriate level of efficiency required of a screening system in order to meet fishery management objectives under the principle of BATNEEC (Best Available Technology Not Entailing Excessive Cost).

---

[2] NFFO=Non-Fossil-Fuel Obligation; SRO = Scottish Renewables Order. Both are UK Government-sponsored schemes to promote renewable energy development.

A large number of hydroelectric schemes could benefit from the project, including many of the 84 sites listed under NFFOs 1-4 and 32 under the SRO. In addition, there are estimated to be >100 further small turbine sites (<1 MWe) in the UK, the vast majority of which use Francis or Kaplan turbines. It is also believed that the majority of these do not at present have smolt screens fitted and that they will need to address this problem in the very near future to comply with recent or new screening regulations (see Turnpenny *et al.*, 1998).

2. SELECTION OF TURBINE DESIGN PARAMETERS

For practical reasons associated with later field-testing, and because of the preponderance of small turbines, the turbine designs selected for study were of no more than a few cumecs (cubic metres per second) discharge capacity. The intention was to select low-head examples of (a) a Francis turbine and (b) a Kaplan or propeller turbine. These represent the most common types used historically and in new schemes in the UK today for run-of-river applications where migratory fisheries are principally at risk. The details of the designs selected are given below in Section 3.

3. CFD MODELLING

The full report of the CFD modelling study prepared by NEL and entitled "CFD Study of Fish Passage Through Small Turbines" contains turbine manufacturers' commercially confidential design information and hence is not included here in full. The key relevant information has been extracted and used in the STRIKER program. A summary of the key points and outputs is provided here. All modelling was carried out with the FLUENT™ v.5 CFD package.

3.1 Turbines studied

Three turbine configurations were examined.

The first was a Francis-type machine designed by a leading UK manufacturer in 1947, designated 'Francis 1'. This turbine has a Francis runner surrounded by a ring of adjustable guide vanes. The machine has no spiral casing and the whole assembly is situated at the bottom of a pit. The machine receives water from the river and discharges back into the river via a 90 degree bend and a short vertical conical diffuser. The manufacturer kindly supplied more detailed engineering drawings of the turbine and installation to enable computer modelling to take place. Drawings showing the format of the machine are given in Appendix 1. The only information they were unable to supply were details of the guide vanes, which they could not retrieve from their archives. NEL designed a set of vanes capable of guiding the flow for modelling purposes.

To provide a comparison with the above machine, flow in a Kaplan machine was studied. At the beginning of the study, details of a suitable machine were not available. The original plan therefore was for NEL to design a machine based on model turbines they had tested in the past. The machine would feature a Kaplan runner together with a spiral casing and a typical draft tube as these features were absent in the Francis 1 design. While the machine was more theoretical than the Francis 1 turbine the aim was to try and study as wide a range of specific speed as possible within the time and cost constraints of the project. After the draft tube and the spiral casing had been modelled but before the Kaplan runner had been designed, details of the runner on a hydro scheme were obtained by Hydroplan. It was decided to model and present the data from this runner separately and then to present the findings of the spiral casing and draft tube as they are often used in hydro schemes. The runner was designated Kaplan 1. Drawings are given in Appendix 2.

3.2 Francis 1

The first turbine is a Francis type with specific speed of 55 UK units or 244 metric units with the following performance data:

- Registered BHP 160
- Head 6.9 m
- Speed 200 rpm
- Output 100 KVA
- Flow 2 m^3s^{-1} at full capacity.

Appendix 1 gives a plan and side view of the installation. Water flows through the strainer to fill the pit or intake section. The water then flows radially through the guide vanes before entering the 0.9m diameter runner where the power is generated. The guide vanes are adjusted by governor control to compensate for changes in head. The water then enters the discharge bend and finally the conical draft tube before returning to the river.

Because of the nature of the installation and on limitations on computer power and memory, the whole machine could not be modelled as a total entity but had to be split into separate computational sections, the output of one section forming the input of the next. Due to the nature of the machine, some of the inlet and outlet sections had to be extended to ensure the transfer of suitable boundary conditions and hence there was a necessary overlap of computational sections resulting in some interpolation between sections. The analysis was further complicated by the nature of the technique used to handle the pressure in an incompressible flow regime. All pressures were calculated as a gauge pressure to remove numerical inaccuracies and in addition the pressure at one point in the flow was set to a reference pressure to prevent the values 'floating' during the iteration and solution phase of the mathematical model. This meant that whilst differences in pressure at various spatial locations within the model would be correct the absolute values of pressure had to be adjusted to give continuity of pressure when the associated domains are assembled. In the results presented this adjustment will have been carried out. With advances in computing power it is envisaged that it will soon be possible to model the whole site in one computer run making the above tasks unnecessary and hence simplifying the process.

The turbine was split into the following computational sections, the results from which are reported separately here.

- *The intake section*: This section is essentially the pit section of the machine. It starts at the discharge of the strainer and ends at the inlet to the guide vanes. The intake includes all the walls of the pit and the outer surface of the discharge pipe. It also includes the free surface of the water at the top of the pit.

- *The guide vane section*: This section is an annular region bounding the guide vanes.
- Both the upstream and downstream regions of the flow field were extended to accommodate boundary conditions. As suitable guide vanes were designed at NEL using an averaged output from the intake section only one blade was modelled.
- *The runner section*: This section comprises one blade passage of the runner. The upstream section was extended to accommodate boundary conditions.
- *The discharge section*: This section starts at the outlet of the runner and extends to the outlet of the conical diffuser.

3.2.1 The intake section

The geometry of the intake was taken from the drawings provided by the manufacturer. This geometry was input into the FLUENT pre-processor package GEOMESH, which is similar to a CAD package. The grid was input into FLUENT and the necessary water properties and boundary conditions set up to simulate a flow of 2 m^3s^{-1} through the machine. A converged solution was obtained.

As expected, the flow in the intake is fairly benign with the only area of interest being at the region next to the guide vane inlet and the outside of the discharge pipe. The general statistics are presented in Tables 3.1 and 3.2. The static pressure in the intake varied from atmospheric on the surface to a maximum of 30,795 Pascal at the bottom of the pit. As the pit is about 3 m deep, the pressure should be about 0.3 bar (atmospheres), i.e. 3 m of water or approximately 30,000 Pascal. In other words the rise in pressure is due to the depth of water, as expected. No reductions below atmospheric pressure occurred in this region.

The maximum velocity vector was 5.7 ms^{-1} and the maximum strain rate is 104 (ms^{-1}) per metre. Using the concept of effective viscosity and vorticity magnitude the maximum shear stress in this region was estimated to be 960 Nm^{-2}. Table 3.11 shows that the majority of the shear stress was in the 100-200 Nm^{-2} range, i.e. about 20% of the maximum, whilst Table 3.12 shows that the pressure distribution was fairly even, as one would expect in a pit where depth is the controlling factor.

3.2.2 The guide vane section

No details of the guide vanes could be found in the archives, but from the drawings it was possible to estimate the length and number of guide vanes. With this information and the estimated duty of the turbine it was possible to get a good estimate of the amount of swirl the guide vanes needed to create. With this value, using one of NEL's design programs, a typical set of blades was designed.

To ease analysis and because the blades were 'approximate' it was decided to assume axial symmetry and to analyse the flow in one blade passage using an average inlet flow field. As the variation in flow at the intake outlet section was not too great and because the inlet and outlet sections had to be extended to satisfy the boundary conditions, this technique is acceptable.

The geometry and grid were set up as for the intake. The grid comprised 55,000 cells, 114,000 faces and 12,000 nodes and a converged solution was obtained in about 2,700 iterations. Tables 3.3 and 3.4 give estimates of the probability of the occurrence of particular values of absolute pressure and shear stress in the intake. The majority of the shear stress was in the region of 200-500 Nm^{-2}, while pressures were mainly sub-atmospheric (i.e. negative).

3.2.3 The runner section

The manufacturer supplied details of the runner in the form of a pattern maker's drawing. This had to be converted into coordinate point, curves and radii for input into the GEOMESH modelling package. One blade passage was constructed and discretised onto computational cells. In total 80,000 tetrahedral cells were used comprising of 17,000 node points and 170,000 faces. A solution was sought for a number of flow conditions to check the model had been set up correctly and to assess the quality of the output. In all cases a converged solution was obtained.

Tables 3.5 and 3.6 estimate the probability distributions of shear and pressure. The majority of the shear was in the range 0-1000 Nm^{-2} while 40% of the pressure was in the –9 to –8 m range at the runner exit where the largest volume of water is located.

3.2.4 The draft tube section

The draft tube section was geometrically modelled and the grid generated from the drawings provided. 20,000 cells were used in the computer run. The outlet velocity profiles from the runner were used to generate a profile file that was directly input into the draft tube inlet. An outflow boundary condition was imposed at the outlet.

Again the range of pressures and shear stress were studied. The pressure ranged from -8 to 1 m (i.e. 2-9 m absolute). At the draft tube exit the pressure should be near atmospheric with a little dynamic head to account for the leaving losses and the maldistribution of flow. The maximum shear stress of 5000 Nm^{-2} occurred just at the runner exit and quickly dropped to a value of 0 to 200 Nm^{-2} through most of the diffusing sections. Tables 3.7 and 3.8 record the estimates of pressure and shear probabilities in the draft tube.

3.3 Kaplan 1 Runner

This scheme had two runner designs, one at 0.6 cumecs and one at 1.0 cumecs. Both designs were built to operate at 7 m head with a rotational speed of 700 rpm. The low-flow turbine was modelled here. The machine comprised an 800 mm diameter circular intake, with an approximately 120 degree bend (see Appendix 2). The flow was then guided by 12 fabricated vanes into the 500 mm diameter runner. The runner was of the propeller type with 4 blades on a 164.5 mm cylindrical hub. The flow then entered a circular diffuser type draft tube and finally passed through a circular-to-square transition diffuser back into the river

During this project Fluent decided to concentrate their geometry modelling efforts on a solid modelling packing they had developed called GAMBIT which they claim is easier to use than the more comprehensive GEOMESH package. It is their intention to scale down the use to GEOMESH and to develop GAMBIT further eventually producing a 'turbomachinery friendly' geometry front end. This runner was modelled in GAMBIT. As before one blade was modelled and rotational periodicity was employed. The geometry produced was meshed with 100,000 tetrahedral cells with 200,000 sides and 20,000 nodes. Boundary conditions, based on the information given by Hydroplan, were attached to the model and a converged solution was obtained. The pressure values from the solution were then adjusted as for the Francis 1 machine to match the plant conditions.

The maximum velocity in the model was approximately 18 ms^{-1}. Table 3.9 presents probably pressure values through the runner. The pressure in the model varied mainly from – 10 to 7 m water although there were regions at the tip where excessive pressures were obtained. The results suggest that the blades may be susceptible to cavitation at the leading edge tip and as cavitation is not modelled accurately this would explain these excessive pressure extremes and also the poor turning performance at the tip. At present cavitation can be modelled by FLUENT but only in simple cases.

The maximum shear stress in the runner (Table 3.10) was approximately 4000 Nm^{-2} although values higher than this (8000 Nm^{-2}) were seen at the tip leading edge and are likely to be a result of the excessive pressure at the tip. In the main most stress levels were below 1000 Nm^{-2}.

3.4 NEL Kaplan

As stated in the introduction the initial intention was to design and analyse a Kaplan machine complete with spiral casing, runner and draft tube until an actual Kaplan design became available. The spiral casing and draft tube of a model was analysed before the Kaplan 1 machine details became known. As these components are more 'theoretical' in nature than the other machines only brief details of these flows will be presented.

The spiral casing was used in a 350 mm model and designed to handle 0.65 m^3s^{-1} flow and is typical of many used in hydro schemes throughout the world. The spiral is used to smoothly guide the flow via a set of stay vanes into the machine's guide vane and runner assembly. The geometry was modelled and gridded using GAMBIT. The flow the spiral casing was found to be fairly smooth.

In a similar fashion a model draft tube was modelled for analysis. The draft tube was more typical of those used in hydro plants than the Francis 1 diffuser type. The draft tube consisted of a 90 degree bend which varied in section from circular to flattened elliptical and then a diffusing part which stretched the section into a rectangular outlet. The draft tube was from the same model as the spiral casing and hence designed for a 350 mm model runner with a flow of 0.65 m^3s^{-1}. Again the geometry was constructed in GAMBIT and then run in FLUENT using 180,000 cells with 365,000 faces with 34,000 nodes.

As the draft tube was not for any particular scheme the average static pressure at outlet was assumed atmospheric for analysis purposes. The pressure variation with this assumption varied from –1.5 m water (i.e. 8.5 m absolute) to 0 m (10 m absolute) at the discharge. Table 3.11 gives estimates of pressure occurrence probability which shows that most of the pressure was around atmospheric. Shear stress was also calculated and varied from 0 to 2,700 Nm^{-2}. Most of the high shear occurred in the inlet bend with shear values of less than 1,200 Nm^{-2} experienced in the outlet diffusing section. Again shear probabilities were calculated and are tabulated in Table 12.

Table 3.1 Probability of shear stress in Francis 1 intake

Shear stress range Nm^{-2}	Probability %
0-100	15.43
100-200	55.47
200-300	14.77
300-400	8.46
400-500	3.68
500-600	1.43
600-700	0.47
700-800	0.21
800-900	0.07
900-999+	0.01

Table 3.2 Probability of pressure (relative to atmosphere) in Francis 1 intake

Pressure range m water	Probability %
0-0.5	10.35
0.5-1.0	10.14
1.0-1.5	21.76
1.5-2.0	22.56
2.0-2.5	15.66
2.5-3.0	17.91
3.0+	0.40

Table 3.3 Probability of shear stress in Francis 1 guide vanes

Shear stress range Nm^{-2}	Probability %
0-200	25.41
200-400	32.49
400-600	16.46
600-800	10.88
800-1000	6.07
1000-1200	3.38
1200-1400	1.70
1400-1600	1.01
1600-1800	0.84
1800-2000	0.42
2000+	1.33

Table 3.4 Probability of pressure (relative to atmosphere) in Francis 1 guide vanes

Pressure range m water	Probability %
<-8	0.08
-8 to –7	0.03
-7 to –6	0.08
-6 to –5	0.42
-5 to –4	4.08
-4 to –3	33.61
-3 to –2	6.75
-2 to –1	1.86
-1 to 0	3.20
0 to 1	12.96
1 to 2	36.91
2+	0.00

Table 3.5 Probability of shear stress in Francis 1 runner

Shear stress range Nm^{-2}	Probability %
0-250	31.07
250-500	23.97
500-750	12.93
750.1000	9.53
1000-1250	8.49
1250-1500	6.50
1500-1750	4.66
1750-2000	1.48
2000-2250	0.43
2250-2500	0.23
2500-2750	0.13
2750-3000	0.12
3000+	0.46

Table 3.6 Probability of pressure (relative to atmosphere) in Francis 1 runner

Pressure range m water	Probability %
<-10	0.94
-10 to –9	5.33
-9 to –8	39.16
-8 to –7	5.89
-7 to –6	5.90
-6 to –5	8.13
-5 to –4	19.36
-4 to –3	15.24
-3 to –2	0.31
>-2	0.00

Table 3.7 Probability of shear stress in Francis 1 draft tube

Shear stress range Nm^{-2}	Probability %
0-100	48.10
100-200	15.55
200-300	4.87
300-400	3.23
400-500	2.10
500-750	4.76
750-1000	4.40
1000-1250	6.34
1250-1500	5.54
1500-2000	4.52
2000-2500	0.34
2500-3000	0.12
3000-3500	0.07
3500-4000	0.04
>4000	0.02

Table 3.8 Probability of pressure (relative to atmosphere) in Francis 1 draft tube

Pressure range m water	Probability %
<-10	0.00
-10 to –9	0.00
-9 to –8	0.07
-8 to –7	46.90
-7 to –6	18.68
-6 to –5	4.56
-5 to –4	2.61
-4 to –3	2.15
-3 to –2	4.49
-2 to –1	20.53
-1 to 0	0.00
>0	0.00

Table 3.9 Probability of pressure (relative to atmosphere) in Kaplan 1 runner

Pressure range m water	Probability %
<-10	0.16
-10 to –8	0.20
-8 to –6	0.95
-6 to –4	4.72
-4 to –2	30.27
-2 to 0	25.13
0 to 2	8.63
2 to 4	14.90
4 to 6	8.61
6 to 8	5.25
>8	1.17

Table 3.10 Probability of shear stress in Kaplan 1 runner

Shear stress range Nm^{-2}	Probability %
0-200	14.84
200-400	29.92
400-600	17.90
600-800	8.44
800-1000	4.40
1000-1500	7.52
1500-2000	4.72
000-2500	3.80
2500-3000	3.34
3000-3500	2.41
3500-4000	0.91
>4000	0.86

Table 3.11 Probability of pressure (relative to atmosphere) in NEL draft tube

Pressure range m water	Probability %
<-1.6	0.23
-1.6 to –1.4	0.27
-1.4 to –1.2	0.74
-1.2 to –1.0	1.29
-1.0 to –0.8	2.22
-0.8 to –0.6	4.05
-0.6 to –0.4	7.28
-0.4 to –0.2	14.65
-0.2 to 0	53.32
>0	15.94

Table 3.12 Probability of shear stress in NEL draft tube

Shear stress range Nm^{-2}	Probability %
0-200	35.93
200-400	24.60
400-600	11.25
600-800	7.40
800-1000	4.29
1000-1200	4.16
1200-1400	3.32
1400-1600	2.59
1600-1800	2.24
1800-2000	1.85
>2000	1.27

4. REVIEW OF BIOLOGICAL DATA

Prediction of the potential effects on salmonid smolts of the various stress-factors experienced during turbine passage relies on some form of 'dose-response' relationship. Although numerous studies have been carried out to estimate injury or mortality rates of fish that have passed through turbines, this type of data is not helpful here, as the causes of injury or mortality cannot be ascribed to the individual pressure-flux, shear-stress or other conditions defined within the CFD study. The main source of data on individual effects is the earlier FARL/NEL reported by Turnpenny *et al.* (1992), which dealt specifically with Atlantic salmon (*Salmo salar*) smolts as well as brown trout (*S. trutta*) and a variety of marine/estuarine fishes. A rather wider picture can be drawn from a review of similar experiments collated by the United States Department of Energy (USDOE) (Cada *et al*., 1997), which included species of Pacific salmon genus (*Oncorhynchus*) and other North American freshwater species. These data are worthy of consideration, in spite of the different species involved, as they generally reinforce the relationships observed in the UK studies. The USDOE undertook the review as part of a feasibility study for the development of 'fish-friendly' turbines (see also Odeh, 1999).

This section summarises the laboratory findings from these studies and develops the dose-response relationships used in the STRIKER programme. More detailed accounts of the derivation and interpretation of the information can be found in Cada *et al.*(1997), Turnpenny (1998) and Odeh (1999).

4.1 Pressure Flux

There is agreement within the literature cited above that pressure increases of the order that may be associated with low-head (<30m) turbines cause no discernible distress to fish. Pathologies associated with pressure flux are caused by rapid reductions in pressure. A major cause is rupture of the gas-filled buoyancy organ, the swimbladder, when a reduction of the external pressure leads to over-expansion and tearing of the delicate swimbladder tissue. Another is the formation of gas bubbles (embolisms) in blood vessels or the eyes (similar to 'the bends') due to out-gassing.

Two main types of swimbladder anatomy are found in fish. In *physostome* fish (including e.g. salmonids- salmon family- and clupeids- herring/shad family) the swimbladder is connected to the exterior by a pneumatic duct opening into the fore- or hind-gut and gas can be gulped at the surface to inflate the swimbladder or vented in the case of over-pressure. *Physoclist* fish, on the other hand, have no external connection (e.g. percid fish -perch, bass) and can only adjust the swimbladder volme by gas release from the bloodstream or reabsorption into the bloodstream. This process can take hours to complete. Rupture of the swimbladder is much more likely therefore in physoclist fish. In both types of fish the internal swimbladder pressure will, in time, adjust to achieve a constant volume (i.e. that which gives the fish neutral buoyancy) and the fish is then said to be adapted or 'acclimated' to the external pressure. It is therefore any reduction in pressure *relative to the acclimation pressure* that may be harmful.

Cada *et al*. (1997) presented data from laboratory experiments in which the fish's response to rapid pressure reductions (followed by a rapid return to the initial pressure) were investigated. Their data are presented in Table 4.1. Although these included FARL information taken from Turnpenny *et al.* (1992), a more comprehensive summary of the FARL results is shown in Table 4.1. Also, the physoclist and physostome fish are identified in the present listing of the data. Results from some 25 separate experiments are shown as mortality rates versus the ratio between exposure pressure (Pe) and acclimation pressure (Pa). Thus, a Pe/Pa ratio of, say, 0.2 would apply e.g. to a fish acclimated at 1 bar pressure and subjected to brief in pressure to 0.2 bar, or a fish that had been acclimated at 3 bar being exposed to 0.6 bar. In either case, the effect on the fish is expected to be the same.

The relationship between pressure flux (Pe/Pa) and percentage mortality is shown more clearly in Figure 4.1. A distinction is made here between physoclist and physostome fish. With no pressure change (Pe/Pa=1), mortality (measured relative to experimental controls) is (logically) zero in both cases. Mortality then increases as the exposure pressure drops (i.e. as Pe/Pa reduces). This effect is seen to be much more marked in the physoclist fish. The data are fitted by regression lines of the following form:

(i) Physoclists: $y = -38.83 \text{ Ln } (x) + 1.756$ (equation 1);

(ii) Phystostomes: $y = -3.997 \text{ Ln } (x) + 1.571$ (equation 2),

where y= mortality (%) and x=Pe/Pa.

Salmonid smolts are physostomes and hence equation 2 is used within the STRIKER programme to compute pressure-related mortality.

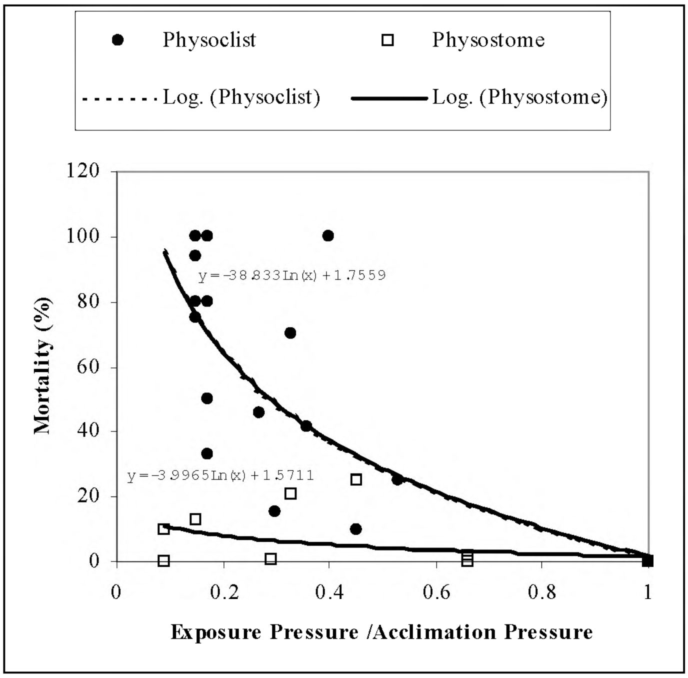


Figure 4.1 Observed mortality rates of physostome and physoclist fish species as a result of exposure to rapid pressure reductions in laboratory tests, darwn from data given in Table 4.1 (modified after Cada et al., 1997 with additional data from Turnpenny et al., 1992).

Table 4.1 Mortality rates of physostomes and physoclists exposed to rapid pressure reductions in laboratory tests

Fish Species	Swimbladder Form	Pressure Change Pe/Pa	Mortality (%)	Reference
Perch	Physoclist	0.33	70	Tsetkov *et al.* 1972
Largemouth bass	Physoclist	1	0	Feathers and Knable, 1983
Largemouth bass	Physoclist	0.53	25	Feathers and Knable, 1983
Largemouth bass	Physoclist	0.36	41.7	Feathers and Knable, 1983
Largemouth bass	Physoclist	0.27	45.8	Feathers and Knable, 1983
Bluegill sunfish	Physoclist	0.17	33	Hogan, 1941
Bluegill sunfish	Physoclist	0.17	50	Hogan, 1941
Crappie	Physoclist	0.4	100	Hogan, 1941
Crappie	Physoclist	0.17	50	Hogan, 1941
Largemouth bass	Physoclist	0.17	80	Hogan, 1941
Largemouth bass	Physoclist	0.17	100	Hogan, 1941
Largemouth bass	Physoclist	0.17	50	Hogan, 1941
Sea bass	Physoclist	0.15	94	Turnpenny *et al.*, 1982
Sea bass	Physoclist	0.3	15	Turnpenny *et al.*, 1982
Whiting	Physoclist	0.15	80	Turnpenny *et al.*, 1982
Whiting	Physoclist	0.45	10	Turnpenny *et al.*, 1982
Sand-smelt	Physoclist	0.15	100	Turnpenny *et al.*, 1982
Golden grey mulle	Physoclist	0.15	75	Turnpenny *et al.*, 1982
Sockeye salmon	Physostome	0.66	0	Harvey, 1963
Sockeye salmon	Physostome	0.29	0.5	Harvey, 1963
Sockeye salmon	Physostome	0.66	2	Harvey, 1963
Sockeye salmon	Physostome	0.33	21	Harvey, 1963
Brown trout	Physostome	0.45	25	Turnpenny *et al.*, 1982
Brown trout	Physostome	0.09	10	Turnpenny *et al.*, 1982

4.2 Shear Stress and Turbulence

Cada *et al.*(1997) reported no data that add significantly to the FARL data of Turnpenny *et al.* (1992). Although earlier experiments of a similar type had been carried out, e.g. by Groves (1970), analysis of the shear stresses generated by the apparatus was not undertaken. No further experiments of this type appear to have been reported. To provide data for the STRIKER model, salmonid data taken from Turnpenny *et al.* (1992) shown in Table 4.2. were used. These are presented in graphical form in Figure 4.2. For convenience of use in the program, regression lines of exponential form have been to yield the following continuous functions:

Salmon smolts: $y = 0.3414e^{0.0011s}$ (equation 3),

Trout (age 2+): $y = 0.0877e^{0.0017s}$ (equation 4),

where s is the shear stress (Nm^{-2}).

Table 4.2 Percentage observed mortalities and eye injuries in hatchery-reared Atlantic salmon smolts (age 1+) and brown trout (age 2+) exposed to different nominal shear-stress levels in the FARL jet test (Turnpenny *et al.*, 1992).

SHEAR STRESS	Survival % @ 7d	
$N.m^{-2}$	Salmon	Brown trout
0	96	100
206	100	-
774	100	100
1920	92	80
3410	88	90

Exponential rather than linear expressions were considered to give the most realistic representation of the biological response to shear stress. As hydraulic shear occurs in all natural moving bodies of water, it would seem unlikely that mortality would be a linear function over a wide range, and that mortality would be lower than predicted by such a model at low shear stress levels in the range typical of the stream environment of these fish. Cada *et al.* (1999) reviewed published data on naturally occurring shear stress levels in streams. In small to medium sized streams, shear stress levels at low flows were reported to be ≤30 Nm^{-2}, rising to >300 Nm^{-2} in flash floods. Within small stream basins, levels reached during flash floods ranged between 31 and 2,600 Nm^{-2}. Injuries and mortalities due to shear stress were not seen at levels of 774 Nm^{-2} or below and therefore this value was selected as the lower mortality threshold for the model. Equation 3, used in the model for smolts, therefore has a lower cut-off of 774 Nm^{-2}, i.e. exposure to levels below this value is taken to cause zero smolt mortality.

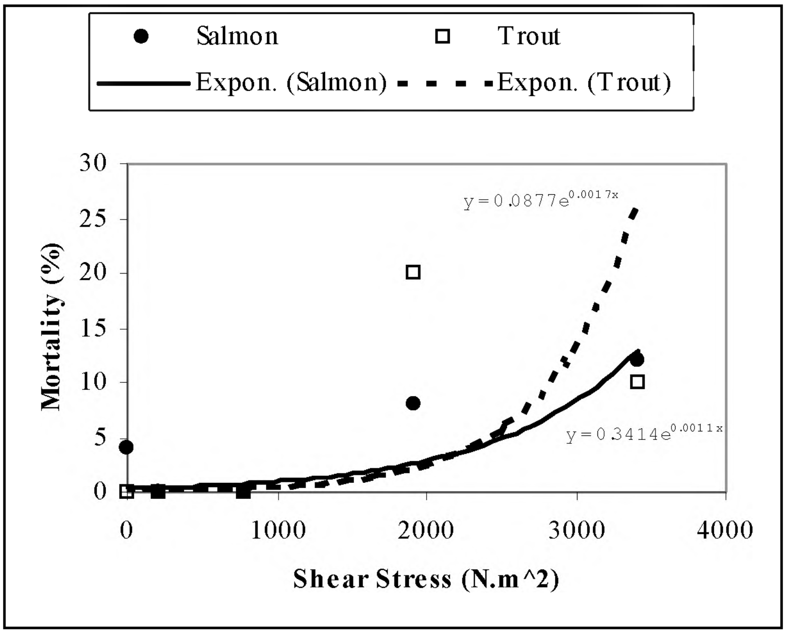


Figure 4.2 Observed mortality rates of salmon smolts and brown trout in relation to estimated shear stresses to which the fish were exposed in submerged jet experiments (derived from data in Turnpenny et al., 1992).

4.3 Collision

4.3.1 Kaplan/Propeller Turbines

Statistical calculation of runner strike probability for Kaplan/propeller turbines was first reported by Von Raben (1957) and has since been used by many other researchers. The principle is simple: for a fish to pass through the turbine on any given streamline without striking the runner, it must pass after the sweep of one blade and before the sweep of the next. Its chance of safe passage is increased if it is smaller or if it is moving quickly, or if it is orientated more in the direction parallel to the runner leading edge rather than that parallel to the turbine axis. Von Raben used the concept of 'water-length': i.e. the length of the streamline cut by successive blade passes: a fish which is longer than the water-length will be struck by one or more blade. Water-length, in turn, is determined by discharge through the turbine, which determines the velocity. The calculations are performed as follows:

Strike rate = Fish Length / Water-length (equation 5),

where:

Water-length = Axial Velocity / cos a.(No. of Blades x RPM of Runner /60) (equation 6),

and:

AXIAL VELOCITY = DISCHARGE / RUNNER SWEPT AREA (EQUATION 7),

and **a** is the angle formed between the water flow streamlines and the axis of the turbine at the runner leading edge.

In practice, this method is found to over-predict the strike damage, since not all strikes result in damage to the fish. For example, a strike near the tail of the fish is less likely to cause injury than one near the head or the centre of the body, as the tail can flex out of the way. Von Raben estimated the theoretical / observed fish damage rate of 0.43 for Kaplan turbines from numerous observations of fish passage. He termed this the mutilation ratio. He then calculated the damage rate as:

Injury rate = Fish Length x Mutilation Ratio / Water-length (equation 8).

Turnpenny (1998) showed that the Mutilation Ratio varied according to the mass of the fish. Collision with the blade is more likely with larger fish owing to their momentum carrying them towards the blade. In smaller fish, which have a larger surface area:mass ratio, the drag force exerted on the fish's surface by water passing around the blade tends to overcome the inertial force and pull the fish around the blade tip. Empirical results from the FARL study of Turnpenny *et al.* (1992) were used to develop a regression of Mutilation Ratio on length for salmonid smolts, as shown in Figure 4.3.

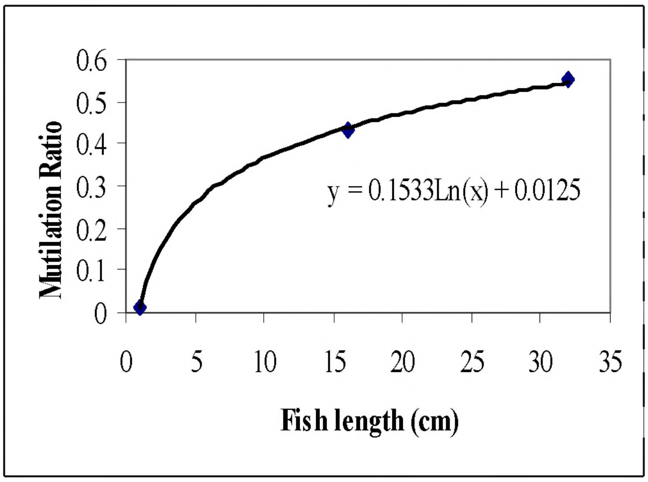


Figure 4.3 Regression of Mutilation Ratio (y) on Fish Total Length (x)

The equation shown in Figure 4.3 is used within STRIKER to predict collision rates.

Although fish collisions with other components of the machinery may occur, these are generally of relatively low velocity compared with the rotational velocity of the runner and are ignored within the STRIKER programme. The FARL experiments showed that collision velocities of $\leq 7ms^{-1}$ with the relatively blunt leading edge profiles typical of guide vanes and stays were unlikely to harm fish. Grinding of fish at the blade tip is also unlikely in small turbines, as the clearances between the blade and the casing is generally very small compared with the body dimensions of a smolt-sized fish. This aspect has also, therefore, been ignored. Such damage is, in any case, highly turbine-specific and therefore unpredictable in a general model of this kind.

4.3.2 Francis Turbines

Monten (1985) carried out extensive work on strike injury rates in Francis turbines. In a Francis machine, water enters the runner peripherally, via the guide vanes, the fish entering through the approximately rectangular opening formed by the trailing edgees of the adjacent guide vanes and the upper and theturbine casing. To use Monten's approach, a number of parameters must be known, including the blade velocity and pitch at the periphery of the runner (taken as the value measured at half the inlet height), the inflow velocity (flow divided by the open area at the outlet of the guide vanes) and the blade angle β. This then allows calculation of the relative opening, **s**, where:

s = blade pitch at periphery x sin β (equation 9).

Strike rate is calculated as:

Strike rate = 0.5 x Fish Length x **s** (equation 10).

For salmonid smolts, Monten found that a value of 0.465 in equation 10 gave a better fit to the data than the theoretical value of 0.5. In our formulation, the Mutilation Ratio, as shown in Figure 4.3 is used, so that equation 10 becomes:

Strike rate = Mutilation Ratio x Fish Length x **s** (equation 11).

This is an empirical rather than analytical approach, which has the effect of disproportionately reducing the probability of injury as the fish get smaller, in line with the laboratory observations made at FARL.

Monten further observed that at low inflow velocities,fish mortalities were often seen to be much lower than would be predicted by expression 11. For salmonid smolts, injury rates fell at contact velocities of <4 ms^{-1} and were neglible at values of <3ms^{-1}. The contact velocity is the *relative velocity* between the blade and the water, which depends on the blade velocity and direction and the water velocity and direction. The empirical relationship found by Monten is shown in Figure 4.4, which shows a factor by which the strike rate computed from equation 11 must be multiplied if the relative velocity is below 4ms^{-1}.

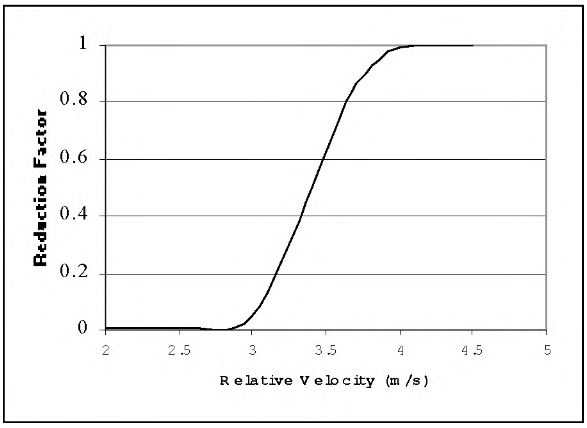


Figure 4.4 Reduction factor to be applied to predicted strike rates for Francis turbines at relative velocities of less than 4ms-1 (aftyer Monten, 1985).

To obtain accurate values for the angle β used to calculate **s** and for relative velocity requires a detailed knowledge of the blade geometry, usually only available from the turbine manufacturer. As this can be difficult to obtain, Monten showed that an approximation could be derived from the relationship between blade-tip velocity (**U**) divided by inflow velocity (**C**) and the angle β shown in Figure 4.5 From this, the relative velocity (**W**) can be calculated as:

W = **C**/sinβ (equation 12).

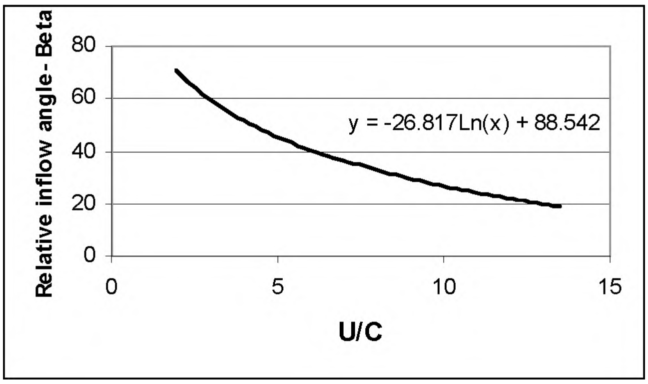


Figure 4.5 Correlation between angle β and the relationship U/C (after Monten, 1985).

5. THE 'STRIKER' EXCEL 97™ MODEL

5.1 The Model 'Engine'

STRIKER is a simple spreadsheet model formulated in Microsoft Excel 97™ to perform calculations using the equations described in Section 4. It separately predicts probabilities of death caused by pressure flux ($P_{pressure}$), shear/turbulence (P_{shear}) and blade-strike (P_{strike}). The resultant compound mortality rate ($P_{compound}$) is then calculated from the following product (Turnpenny, 1998):

$P_{compound} = 1 - (1 - P_{pressure}) * (1 - P_{shear}) * (1 - P_{strike})$ (equation 13).

The product rather than a sum is used here to account for that fact that a fish cannot be killed more than once, i.e. a fish that has been injured by pressure flux and shear may also be injured by blade strike and this would otherwise give rise to three separate predicted deaths. For pressure and shear effects, the tables of probabilities generated by the CFD analysis (Tables 3.1-3.12) for each section of the turbine (e.g. intake, guide vanes, runner, draft tube) are used to allow the calculation of mortalities associated with different pressure or shear-stress bands, the overall mortality due to each effect in each turbine section then being summated for the 1 to n observation classes. Thus, the shear-stress- and pressure-related effect in any given section of the turbine are calculated as:

Shear: $\Sigma_{I=1}^{n}\ (0.3414e^{0.0011s}) * F_I$ (equation 14),

Pressure: $\Sigma_{I=1}^{n}\ (-3.997\ Ln\ (Pe/Pa) + 1.571) * F_I$ (equation 15).

Examples are shown in Tables 5.1. The compound mortality rates for shear stress and pressure through the whole machine are then calculated using an expression similar to equation 13:

$P_{shear} = 1 - (1 - P_{shear:intake}) * (1 - P_{shear:guide\ vanes}) * (1 - P_{shear:runner}) * (1 - P_{shear:draft\ tube})$ (equation 16),

$$P_{pressure} = 1 - (1 - P_{pressure:intake}) * (1 - P_{pressure:guide\ vanes}) * (1 - P_{pressure:runner}) * (1 - P_{pressure:draft\ tube})$$
(equation 17).

Table 5.1 Calculation of smolt mortalities due to shear and pressure flux in Francis 1 intake using equations 10 & 11 and CFD data from Tables 3.1 & 3.2.

FRANCIS 1 INTAKE							
Shear stress				**Pressure**			
Nm-2	Mid-value	Probability	Mortality	m water	Pe/Pa	Probability	Mortality
		%	%			%	%
0-100	50	15.43	0.000				
100-200	150	55.47	0.000				
200-300	250	14.77	0.000	0-0.5	1.025	10.35	0
300-400	350	8.46	0.000	0.5-1.0	1.075	10.14	0
400-500	450	3.68	0.000	1.0-1.5	1.125	21.76	0
500-600	550	1.43	0.000	1.5-2.0	1.175	22.56	0
600-700	650	0.47	0.000	2.0-2.5	1.225	15.66	0
700-800	750	0.21	0.000	2.5-3.0	1.275	17.91	0
800-900	850	0.07	0.001	3.0+	1.325	0.4	0
900-999+	950	0.01	0.000				
Total			**0.001**				**0**

Table 5.2 Calculation of smolt mortalities due to shear and pressure flux in Francis 1 guide vanes using equations 10 & 11 and CFD data from Tables 3.3 & 3.4.

FRANCIS 1 GUIDE VANES							
Shear stress				**Pressure**			
Nm-2	Mid-value	Probability	Mortality	m water	Pe/Pa	Probability	Mortality
		%	%			%	%
%				%			
0-200	100	25.41	0.000	<-8	0.15	0.08	0.007
200-400	300	32.49	0.000	-8 to –7	0.25	0.03	0.002
400-600	500	16.46	0.000	-7 to –6	0.35	0.08	0.005
600-800	700	10.88	0.000	-6 to –5	0.45	0.42	0.020
800-1000	900	6.07	0.056	-5 to –4	0.55	4.08	0.162
1000-1200	1100	3.38	0.039	-4 to –3	0.65	33.61	1.107
1200-1400	1300	1.7	0.024	-3 to –2	0.75	6.75	0.184
1400-1600	1500	1.01	0.018	-2 to –1	0.85	1.86	0.041
1600-1800	1700	0.84	0.019	-1 to 0	0.95	3.2	0.057
1800-2000	1900	0.42	0.012	0 to 1	1.05	12.96	0.000
2000+	2100	1.33	0.046	1 to 2	1.15	36.91	0.000
				2+	1.25	0	0.000
			0.213				**1.584**

Table 5.3 Calculation of smolt mortalities due to shear and pressure flux in Francis 1 runner using equations 10 & 11 and CFD data from Tables 3.5 & 3.6.

FRANCIS 1 RUNNER							
Shear stress				**Pressure**			
Nm-2	Mid-value	Probability	Mortality	m water	Pe/Pa	Probability	Mortality
		%	%			%	%
%							
0-250	125	31.07	0.000	<-10	0.01	0.94	0.188
250-500	375	23.97	0.000	-10 to –9	0.05	5.33	0.722
500-750	625	12.93	0.000	-9 to –8	0.15	39.16	3.584
750.1	875	9.53	0.085	-8 to –7	0.25	5.89	0.419
1000-1250	1125	8.49	0.100	-7 to –6	0.35	5.9	0.340
1250-1500	1375	6.5	0.101	-6 to –5	0.45	8.13	0.387
1500-1750	1625	4.66	0.095	-5 to –4	0.55	19.36	0.767
1750-2000	1875	1.48	0.040	-4 to –3	0.65	15.24	0.502
2000-2250	2125	0.43	0.015	-3 to –2	0.75	0.31	0.008
2250-2500	2375	0.23	0.011	>-2	0.85	0	0.000
2500-2750	2625	0.13	0.008				
2750-3000	2875	0.12	0.010				
3000+	3125	0.46	0.049				
			0.513				**6.917**

Table 5.4 Calculation of smolt mortalities due to shear and pressure flux in Francis 1 draft tube using equations 10 & 11 and CFD data from Tables 3.7 & 3.8.

FRANCIS 1 DRAFT TUBE							
Shear stress				**Pressure**			
Nm-2	Mid-value	Probability	Mortality	m water	Pe/Pa	Probability	Mortality
		%	%			%	%
				%			
0-100	50	48.1	0.000	<-10	0.01	0	0.000
100-200	150	15.55	0.000	-10 to –9	0.05	0	0.000
200-300	250	4.87	0.000	-9 to –8	0.15	0.07	0.006
300-400	350	3.23	0.000	-8 to –7	0.25	46.9	3.335
400-500	450	2.1	0.000	-7 to –6	0.35	18.68	1.077
500-750	550	4.76	0.000	-6 to –5	0.45	4.56	0.217
750-1000	650	4.4	0.000	-5 to –4	0.55	2.61	0.103
1000-1250	750	6.34	0.000	-4 to –3	0.65	2.15	0.071
1250-1500	850	5.54	0.048	-3 to –2	0.75	4.49	0.122
1500-2000	950	4.52	0.044	-2 to –1	0.85	20.53	0.456
2000-2500	1050	0.34	0.004	-1 to 0	0.95	0	0.000
2500-3000	1150	0.12	0.001	>0	1.05	0	0.000
3000-3500	1250	0.07	0.001				
3500-4000	1350	0.04	0.001				
>4000	1450	0.02	0.000				
			0.099				**5.388**

Table 5.5 Calculation of smolt mortalities due to shear and pressure flux in Kaplan 1 runner using equations 10 & 11 and CFD data from Tables 3.9 & 3.10.

KAPLAN 1 RUNNER							
Shear stress				**Pressure**			
Nm-2	Mid-value	Probability	Mortality	m water	Pe/Pa	Probability	Mortality
		%	%			%	%
0-200	100	14.84	0.000	<-10	0.05	0.16	0.022
200-400	300	29.92	0.000	-10 to –8	0.1	0.2	0.022
400-600	500	17.9	0.000	-8 to –6	0.3	0.95	0.061
600-800	700	8.44	0.000	-6 to –4	0.5	4.72	0.205
800-1000	900	4.4	0.040	-4 to –2	0.7	30.27	0.907
1000-1500	1250	7.52	0.102	-2 to 0	0.9	25.13	0.501
1500-2000	1750	4.72	0.110	0 to 2	1.1	8.63	0.000
2000-2500	2250	3.8	0.154	2 to 4	1.3	14.9	0.000
2500-3000	2750	3.34	0.235	4 to 6	1.5	8.61	0.000
3000-3500	3250	2.41	0.294	6 to 8	1.7	5.25	0.000
3500-4000	3750	0.91	0.192	>8	1.9	1.17	0.000
>4000	4250	0.86	0.315				
Total			**1.442**				**1.716**

Table 5.6 Calculation of smolt mortalities due to shear and pressure flux in NEL draft tube using equations 10 & 11 and CFD data from Tables 3.11 & 3.12.

NEL DRAFT TUBE								
Shear stress				**Pressure**				
Nm-2	Mid-value	Probability	Mortality	m water	Mid-value	Pe/Pa	Probability	Mortality
		%	%				%	%
0-200	100	35.93	0.000	<-1.6	-1.7	0.83	0.23	0.005
200-400	300	24.6	0.000	-1.6 to –1.4	-1.5	0.85	0.27	0.006
400-600	500	11.25	0.000	-1.4 to –1.2	-1.3	0.87	0.74	0.016
600-800	700	7.4	0.000	-1.2 to –1.0	-1.1	0.89	1.29	0.026
800-1000	900	4.29	0.039	-1.0 to –0.8	-0.9	0.91	2.22	0.043
1000-1200	1100	4.16	0.048	-0.8 to –0.6	-0.7	0.93	4.05	0.075
1200-1400	1300	3.32	0.047	-0.6 to –0.4	-0.5	0.95	7.28	0.129
1400-1600	1500	2.59	0.046	-0.4 to –0.2	-0.3	0.97	14.65	0.248
1600-1800	1700	2.24	0.050	-0.2 to 0	-0.1	0.99	53.32	0.859
1800-2000	1900	1.85	0.051	>0	0.1	1.1	15.94	0.000
>2000	2100	1.27	0.044					
Total			**0.325**					**1.408**

5.2 Model Input Variables

STRIKER is designed to predict salmonid smolt mortality for low-head (<30 m) Francis and Kaplan/ propeller turbines (i.e. as for Kaplan but without adjustable guide vanes or runner angles). It is not feasible to represent all the design characteristics of different machines in a model like STRIKER (this would require the CFD analysis to be performed for every machine). Nevertheless it is possible to alter parameter values relating to predicted depressurisation conditons and to blade strike. Input values are required for the following variables:

Turbine type: (Francis or Kaplan)

Guide vanes: present/absent

Runner inlet height (Francis)

Turbine flow: at percentage load

Runner diameter

Runner speed: rpm

Number of runner blades

Angles of incidence (Kaplan/propeller);

Draft tube height: (see below)

Certain design parameters have been omitted, for example the inlet arrangement alternatives such as a spiral casing or a pit-type inlet. The CFD analysis showed this part of the turbine to be harmless to fish, hence there was no point in including it in the model.

The *angle of incidence* for a Kaplan/propeller design is defined as the angle relative to the axis of the runner at which the water strikes the leading edge of the blade. This may vary from the hub to the tip of the blade. The model therefore requires this angle to be entered for five equi-spaced points along the blade between the hub and the tip (divide the blade into five equal segments and take values for the centre point of each segment). This is specialist design information that is normally only available from turbine manufacturers on a confidential basis.

Draft tube height is used to account for the suction due to the hydrostatic head difference between the runner outlet and the tailrace water level (which will vary with river discharge). For horizontal-axis turbines, use the difference between the turbine axis level and the tailwater level. For vertical-axis turbines, use the difference between the vertical centre of the runner and the tailwater level. In applying equation 15, STRIKER uses the input value for draft tube height to adjust the pressure values in the runner and draft tube sections of the turbine relative to that of the reference machine studied in the CFD analysis.

5.3 Running the Model

Operating instructions and sample outputs are listed in Appendix 5. STRIKER requires a PC-type computer running Microsft Excel 97™. Outputs show the predicted compound mortality rates and their components (pressure-, shear- and strike-related) for salmonids ranging from pre-smolt (parr) size (down to 8 cm in length) to age 2+ smolt size of up to 22 cm. Although specific values of fish length are given in the STRIKER output tables, these can be overwritten with specific values if required.

For Kaplan machines, it is recommended that calculations are performed at a range of flow values corresponding to available load conditions (e.g. 100%, 50%, 25%). As the flow reduces, the effect is to reduce the *water length*, which has the effect of increasing the fish strike rate. This is because the turbine blades always spin at the same speed but the fish pass through more slowly at lower flow rates and are therefore more likely to be struck by the blade. *Relative velocities* are always high in Kaplan turbines and are seldom less than the critical $4ms^{-1}$ level below which blade strike is less harmful (Monten, 1985).

For Francis machines, estimating the *relative opening*, **s**, for lower operating loads and flows is not straightforward for the non-specialist and STRIKER does not attempt to do this. This should not generally be too much of a limitation as the injury rate is generally highest (worst case) at maximum load. This may seem unlikely, given that the value of **s** reduces as the guide vanes close but Monten (1985) showed that the relative velocities simultaneously reduce, making operation at low loads in small Francis turbines relatively safe for fish.

6. FIELD VALIDATION

6.1 Sites

The two operating turbines selected for field validation were included in the CFD modelling and their characteristics are described in Section 2, where they are designated 'Francis 1' and 'Kaplan 1'. For the field work, the sites chosen were selected on the basis of several criteria, viz.:

located within the UK

<0.5 MW capacity

<30 m net head

reasonably common0 design

located on a salmonid river

tailrace amenable to netting for fish capture

safe access for personnel

agreement of owner

agreement of local fishery agency

currently operating.

Meeting all these criteria presented some difficulty and the sites chosen were considered to be the best available. Both turbines were at the small end of the spectrum, being $\leq 2\ m^3s^{-1}$ flow, as this made fish capture less difficult than with a larger flow. The Francis 1 site was built in the late 1940's. It was not the same site from which the Francis 1 design drawings used in Section 2 were taken but it had an identical turbine and varied only in draft tube level. The Kaplan 1 site was modern, built within the last decade, and used three turbines, two rated at 1 m^3s^{-1} flow and one at 0.6 m^3s^{-1}, of which the latter was tested here.

In both cases, permission for the testing was obtained from the local fisheries agencies. We are also grateful to the owners of the schemes for their willing support during the project.

6.2 Methods

6.2.1 General Approach

The aim of the study was to collect fish that had passed through the turbines by attaching suitable nets across the draft tube exit or in the tailrace to capture the fish or fish remains. In both cases, the experiments were carried out during the spring season (Kaplan 1 site, May 1999; Francis 1 site, April 2000), to take advantage of fish incidentally migrating downstream. These were supplemented by introducing (for ethical reasons) freshly killed fish into the turbine inlet and recapturing them in the net.

6.2.2 Turbine Settings

Experiments were performed under standard operating conditions of the turbines, as found on the dates when work was carried out. It was established in each case prior to arrival that sufficient water was available to run the turbines at close to maximum discharge. In the case of the Francis 1 site, the operating range was ~80-90% of maximum load during the tests. The Kaplan 1 site was operating at full load on the smallest turbine; the turbines did not have variable guide vanes or runner blades and control at this site was enabled by using the different flow permutations available with the separate fixed turbine flows.

6.2.3 Fish Introduction

The supplementary fish were obtained from local hatchery sources. At the Kaplan 1 site, Atlantic salmon pre-smolts of average length around 10 cm were used. At the Francis 1 site, the introduction of alien salmon smolts was not approved by the fisheries agency and hatchery-reared brown trout were used instead. These were of similar size to the wild smolts present in the river system.

After transporting fish to the site, they were held in cages until ready for use. Prior to introduction, the fish were netted out and randomly allocated to batches containing 30 fish each.

The means of introduction into the turbine inlet differed at the two sites. For Kaplan 1, a 10 cm-diameter pipe was fixed in place with its lower opening submerged the turbine inlet mid-level. A large funnel was fitted to the top of the pipe and fish were tipped into the funnel and flushed down using 2 or 3 buckets of water. At the Francis 1 site, the fish were tipped directly into the intake pit.

Experimental handling controls were performed by introducing fish into the tailrace net through an opening at its mouth. In this way, they had been subjected to the same experimental handling as the turbine-passed fish, but had not been through the turbine.

6.2.4 Fish Collection

A netting arrangement was used that was similar to that used in a previous study at Blantyre hydroelectric station (Anon., 1996). Tapered nets, similar to trawl nets, were tailor-made to fit the outlets of each turbine. These had dimensions of ~3 m x 2 m at the inlet end and were 5 m long. The downstream end of the net was left open and fixed to an opening in the end of a 3 m x 3 m x 1 m deep live-car constructed of 6 mm aperture polyethlyene mesh (Netlon™). The net and live car were fixed in position by tensioned ropes so that the net remained open without bagging, to ensure that fish moved smoothly into the live car. This could be isolated periodically to net out the fish.

6.2.5 Fish Examination

Fish collected from the live car were first allocated to wild or introduced categories. They were then individually examined for the following external injury conditions:

Lacerations caused by runner blade contact

Eye injuries

Scale loss.

They were then carefully dissected to identify any internal injuries, specifically:

Swimbladder rupture

Spinal fracture.

In the presentation of the results, lacerations and spinal fractures have been included under one heading: 'body severed'.

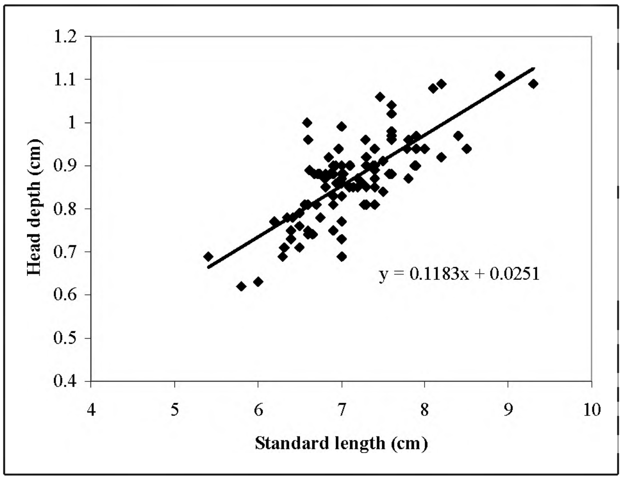


Figure 6.1 Regression analysis of fish standard length (x) against head depth (y) for salmon pre-smolts, used to calculate length for damaged fish.

Where possible, the length of the fish was estimated, either from the whole body or, where severed, from the head depth. For this purpose, an equation was used based on a regression analysis of data from whole fish (Figure 6.1).

6.3 Results

6.3.1 Francis 1 Turbine

Results for individual fish are listed in Appendix 3. A total of nine wild smolts (sea trout: *Salmo trutta* and salmon *Salmo salar*) of 8.5 –14 cm in length were collected in the tailrace net, having passed through the turbine. Of these, three were dead, as a result of strike injuries (body severed). The remainder were held for 48-h in a cage and were released back to the river live and unharmed.

Data were also obtained for 56 introduced brown trout that had been freshly killed by an overdose of the anaesthetic benzocaine. The average length was 10.9 cm (range 8.5-13.6 cm). A summary of the results is given in Table 6.1.

Table 6.1 Summary of findings for wild smolts and freshly killed brown trout that had passed through the Francis 1 turbine. (n=number of fish in sample).

Injury Type	Potential/Actual Fatal Injuries			
	Introduced (n=56)	Control (n=24)	Adjusted Result (n=56)	Wild (n=9)
Lacerations, spinal fracture	12.5%	0%	12.5%	33%
Swimbladder rupture	3.5%	0%	3.5%	?
Eye Injuries	1.8%	0%	1.8%	0%
Scale loss	7.1%	8.3%	0%	11%
Compound	23.2%	8.3%	17.9%	33%

This also includes data for 24 control fish and for the wild fish. The injury types shown are considered to be potentially fatal. In the case of scale loss, a minimum value of 20% loss is considered to be fatal (Kostecki *et al*, 1987). The percentage of the control fish batch in which scale loss exceeded this value was 8.3%, compared with 7.1% in the experimentally introduced batch. This indicates that the level of potentially fatal scale loss in the experimental batch can be explained in terms of handling alone. Scale loss was therefore discounted as a contributor to potential mortality. The finding does not mean that scale loss is necessarily unimportant, just that the experiment described here cannot differentiate the handling effect from any turbine-induced effect on scale loss. Allowing for this, the column in Table 6.1 headed 'Adjusted Results' gives the net potential mortality figures, excluding scale loss as a cause. The overall percentage of potentially fatal injuries in the introduced (freshly killed) trout was 17.9%. Of these potential fatalities, at least two-thirds were probably blade-strike-related, the remainder due to other causes. In the case of the nine wild smolts collected, all three (actual) fatalities were caused by blade strike.

6.3.2 Kaplan 1 Turbine

Eight batches of fish of between 7 and 21 fish were passed through the turbine and another three batches were used as handling controls. The average standard length of the fish was 7.2 cm (range 5.4-9.3 cm). Raw results from these are shown in Appendix 4. Table 6.2 provides a summary of the findings. Again, the column headed 'Adjusted Results' contains the data corrected by subtracting control injuries. In this case, the appearance of ruptured swimbladders in two of the control fish is likely to have been a handling artefact during dissection.

Table 6.2 Summary of findings for freshly killed salmon smolts that had passed through the Kaplan 1 turbine. (n=number of fish in sample).

Injury Type	Potential/Actual Fatal Injuries		
	Introduced (n=132)	Control (n=65)	Adjusted Results (n=132)
Lacerations, spinal fracture	27.8% (0-47.8%)	0%	27.8%
Swimbladder rupture	10.3% (94.3-16.6%)	4.0%	6.3%
Eye Injuries	1.3% (0-5.3%)	0%	1.3%
Scale loss	0%	0%	0%
Compound	39.4% (14.3-52%)	0%	35.4%

6.4 Comparison of Observed and Predicted Results

6.4.1 Francis 1 Turbine

Sample runs of STRIKER for the Francis 1 and Kaplan 1 turbines are shown in Appendix 5. Table 6.4 gives a summary of the predicted fish injury rates for the Francis 1 turbine, showing the overall rate of injury predicted for each cause (shear, pressure flux, strike), and the compound values for all three injury types together. The values are broken down also into those attributed to the various stages of the turbine, which shows clearly that the runner and draft tube are the most critical sections. In the case of the runner, strike-related injuries predominate but shear and pressure flux are also greater here than in any other part of thre machine. The predicted pressure-related damage in the draft tube are due to negative (siphonic) pressures in the descending limb down to the river.

A comparison with observed values from the field trials is given in Figure 6.2. For the sake of illustration, the simplifying assumptions have been made here that (a) lacerations equate to strike damage, (b) burst swimbladders equate to prsssure flux damage and (c) eye injuries equate to shear stresses. This may not be strictly true, as Turnpenny (1998) showed that e.g. eye injuries could be caused by pressure flux or blade contact, but those assumed are considered to be the most probable causes and effects.

Table 6.4 Potentially fatal injury rates calculated by the STRIKER model for fish of 12.4 cm total length, as used in the Francis 1 field tests.

POSITION IN TURBINE	% Potentially Fatal Injuries Due to:			
	Shear	Pressure	STRIKE	Compound
Intake	0.00	0.00	0.00	0.00
Guide vanes	0.213	1.58	0.00	1.8
Runner	0.513	4.36	12.3	16.6
Draft tube	0.099	3.33	0.00	3.42
Compound	0.82	9.90	12.3	21.8

It is evident from Figure 6.2 that STRIKER here correctly predicts the relative importance of shear, pressure and strike as observed in the field trials, although the actual values for pressure effects are overpredicted by the model. The prediction of strike-related injuries is remarkably close to that observed.

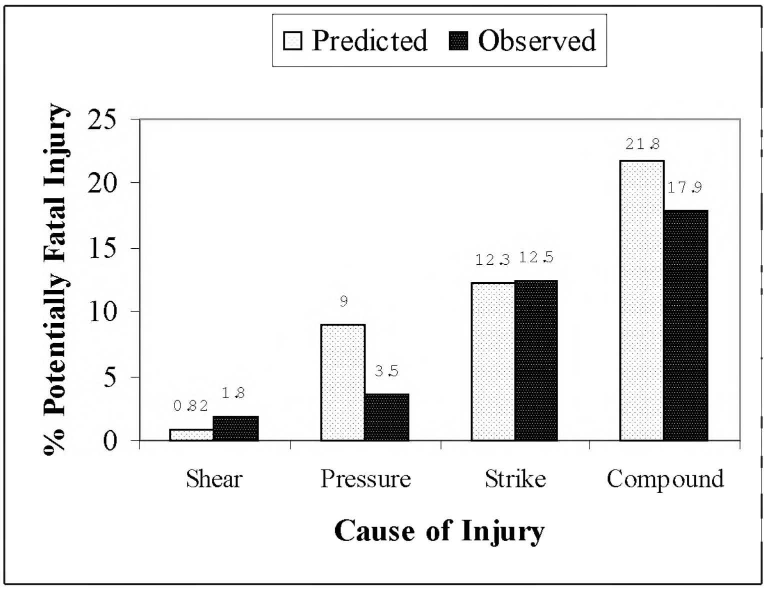


Figure 6.2 Comparison of observed injury rates and those predicted by the STRIKER program for the Francis 1 turbine.

6.4.2 Kaplan 1 Turbine

A printout showing a run of STRIKER for the Kaplan 1 turbine is given in Appendix 5. The results are summarised in Table 6.3.

Table 6.3 Potentially fatal injury rates calculated by the STRIKER model for parr/pre-smolts of 8.2 cm total length, as used in the Kaplan 1 field tests.

POSITION IN TURBINE	% Potentially Fatal Injuries Due to:			
	Shear	Pressure	STRIKE	Compound
Intake	0.00	0.00	0.00	0.00
Guide vanes	0.00	0.00	0.00	0.00
Runner	1.44	1.72	25.1	29.3
Draft tube	0.33	1.41	0.00	1.73
Compound	1.76	3.10	25.1	29.0

Again, assuming the partitioning of injury types to the causes as proposed above, a comparison of the observed values from the field study with the predictions made by STRIKER is shown in Figure 7.2. This shows that the relative importance of the different factors is correctly predicted by the model, with strike accounting for 75-85% of injuries, pressure 10-20%, and shear for <10% of injuries. Overall, the observed mortality was 35.4%, compared with a predicted value of 29%. Given the simplifications involved in the model and the relatively small number of fish observations available, the predictions correspond well enough with the observed values and should provide an adequate basis for risk assessment purposes.

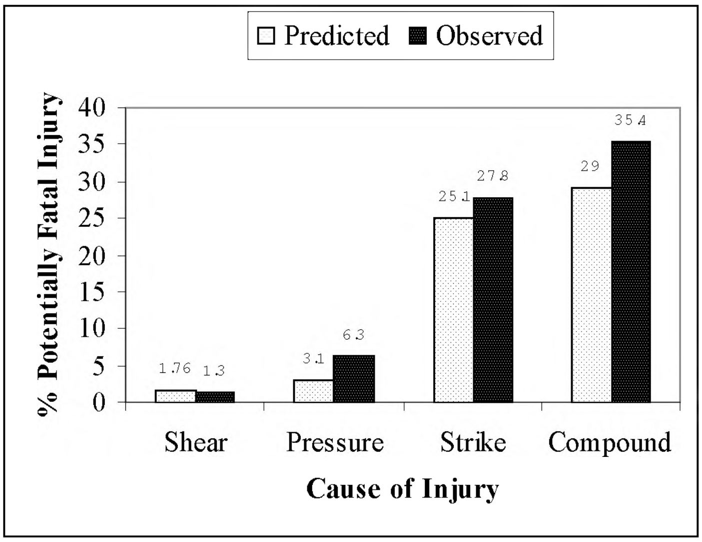


Figure 6.3 Comparison of observed injury rates and those predicted by the STRIKER program for the Kaplan 1 turbine.

7. DISCUSSION

The initial hypothesis underlying the study was that the hydraulic stresses associated with the restricted water passages in small turbines could generate high levels of shear stress and rapid pressure changes that would be potentially more harmful to fish than those associated with large turbines. Both the CFD study and the field trials indicated that shear stress levels remained low in the turbines studied, accounting for damage in a very small percentage of fish passing the turbines. Pressure fluxes caused by hydrodynamic effects in the turbines were also generally of minor importance, but depressurisation was predicted to be a more important effect in turbines where the draft tube outlet lies more than a metre or two below the runner outlet, as is the case in some older Francis turbines .Nevertheless, the pressure-related predictions can probably be considered 'worst case' for salmonid smolts, given their propensity to vent gas from the swimbladder without rupture in many cases. Runner blade strike therefore remains the main cause of mortality in most small turbines. Existing models of strike based on modified Von Raben and Monten formulations for Kaplan/propeller and Francis turbines respectively work well for this aspect.

The use of freshly-killed, hatchery-reared stock rather than live or wild fish in the majority of field observations within the present project will be considered by some to limit the validity of the findings. Ideally, live wild fish would have been used but this would have meant removing the fish screens/barriers to enable them to pass the turbine or manually introducing them. To do so was considered ethically unacceptable. The previous FARL laboratory study (Turnpenny *et al.*, 1992) anyway showed that most mortalities occurred as a result of identifiable lesions (wounds, ruptured swimbladders, gas embolisms, etc.) rather than through non-visible stress mechanisms. Consequently, examination of exposed fish for visible lesions is considered to be an adequate indicator of likely fatalities. Such lesions are found in exposed fish when freshly killed as well as in live fish. What neither the laboratory studies nor the field tests (with or without live, wild fish) can show is the viability of an unwounded fish once returned back to the river. The possibility remains that a fish disorientated by turbine passage may be more vulnerable to predation. This aspect merits further investigation.

The STRIKER model provides a convenient and simple method of computing the overall fish injury rate, suitable for risk assessment of downsteam migration past small hydro schemes. While it contains a number of simplifications, e.g. ignoring blade tip effects, cavitation (mainly associated with poor design or off-design operation), the model should be sufficiently accurate for risk assessment purposes.

The overall context into which the derived fish loss rate figures should be put for a particular scheme takes account of the proportion of the river flow passing through the turbine, and the efficiency of any screening/bypass system used to divert fish back from the generating flow into the river,as per the following expression (Turnpenny and Hanson., 1997):

Scheme Passage Rate (%) = $100*(1 - (\mathbf{P_{gen}} \,.\, (1 - \mathbf{e}) \,.\, \mathbf{I})$ (equation 18), in which $\mathbf{P_{gen}}$ is the proportion of descending fish that enter the generating flow, **I** is the fish injury rate in the turbine and **e** is the screen fish deflection efficiency. They gave the example of a high-flow scenario in which 50% of the descending fish passed directly over the weir and a behavioural barrier having a 90% diversion efficiency was used; injury rate in the turbine was 20%. The scheme passage rate then would be 100(1-0.5 x (1-0.9) x 0.2), = 99%. If no fish passed over the weir, then this would amount to a scheme passage rate of 98%.

The significance of the loss figure generated will depnd on sveral factors, including the conservation status of the river's fish population and the presence of other hydro schemes or alternative causes of smolt and parr loss elsewhere in the river system (see Turnpenny *et al.*, 1999). These are matter for public consultation and regulatory determination.

8. CONCLUSIONS

1. Results of the CFD analysis suggest that shear stress is of relatively minor importance in small, low-head Francis and Kaplan turbines, being predicted to account for injuries in <2% of smolts/parr passing through the turbines. This was confirmed by the field studies.

2. Pressure flux is potentially more damaging than shear stress, pressure-related symptoms accounting for up to 6.3% of observed injuries in the field tests. The main risk-areas of pressure-related injury were shown by the CFD study to be in the runner section and, where a significant siphonic fall exists, in the draft tube.

3. Runner-strike-related injuries were 3-4 times more important than the hydraulic effects (pressure, shear) in relation to smolt/parr passage. The rate of strike injury is highly dependent on the size of the fish and type of turbine, the runner diameter and rotation rate and the number of blades and the operating load (and hence flow rate).

4. The STRIKER program allows the computation of strike rate for smolts and parr and provides a good representation of the risk associated with hydraulic shear and pressure effects in small, low-head Francis and Kaplan/propeller turbines. The output from STRIKER provides a basis for risk assessment of turbine passage. Combined with information on the proportion of the river flow passing through the turbine(s) and the diversion efficiency of any intake screening system used, a full risk assessment for downstream-migrating salmonids can be achieved.

9. REFERENCES

Anon. 1996. Testing of an acoustic smolt deflection system at Blantyre Hydroelectric Power Scheme. ETSU H01/00046/REP, 90 pp..

Cada, G.F, Coutant, C.C. and Whitney, R.R., 1997. Development of biological criteria for the design of advanced hydropower turbines.. Report No. DOE/ID-10578. US Department of Energy, Idaho Operations Office, Idaho Falls, ID, USA, 85 pp.

Cada, G.F, Carlson, T., Ferguson, J., Richmond, M and Sale, M., 1999. Exploring the role of shear stress and severe turbulence in downstream fish passage. Proceedings of Water Power '99, Las Vegas, American Society of Civil Engineers, CD ROM No. 1-703-295-6163, 9 pp.

Eicher, G J, Campbell, C J, Craven, R E and West, M A, 1987. Turbine related fish mortality: review and evaluation of studies. Electric Power Research Institute, Palo Alto, California, Report No. EPRI AP-5480.

Feathers, M.G. and Knable, A.E., 1983. Effects of depressurisation upon largemouth bass. *North American Journal of Fisheries Management*, **3**, 86-90.

Harvey, H.H., 1963.Pressure in the early life history of sockeye salmon. PhD Thesis. University of British Columbia, Vancouver, B.C., Canada. 267pp.

Hogan, J., 1941. The effects of high vacuum on fish. *Transactions of the American Fisheries Society*, **70**, 469-474.

Kostecki, P.T., Clifford, P., Gloss, S.P. and Carlisle, J.C. ,1987. Scale loss and survival in smolts of Atlantic salmon (*Salmo salar*) after turbine passage. *Can. J. Fish. Aquat. Sci.*, **44**, 210-214.

Odeh, M., 1999. A summary of environmentally friendly turbine design concepts. Report No. DOE/ID/13741. US Department of Energy, Idaho Operations Office, Idaho Falls, ID, USA, 39 pp.

Solomon, D.J. (1988). Fish Passage Through Tidal Energy Barrages. Energy Technology Support Unit, Harwell. Contractors Report number ETSU TID 4056: 76 pp.

Tsetkov, V.I., Pavlov, D.S. and Nezdoliy, V.K., 1972. Changes in hydrostatic pressure lethal to the young of some freshwater fish. *Journal of Ichthyology*, **12**, 307-318.

Turnpenny, A.W.H., 1998. Mechanisms of fish injury in low-head turbines: an experimental appraisal. *Proc. Int. Conf. on "Fish Migration and Fish By-pass Channels*", Vienna, Austria, September 24-26th,1997. Fishing News Books, 300-314.

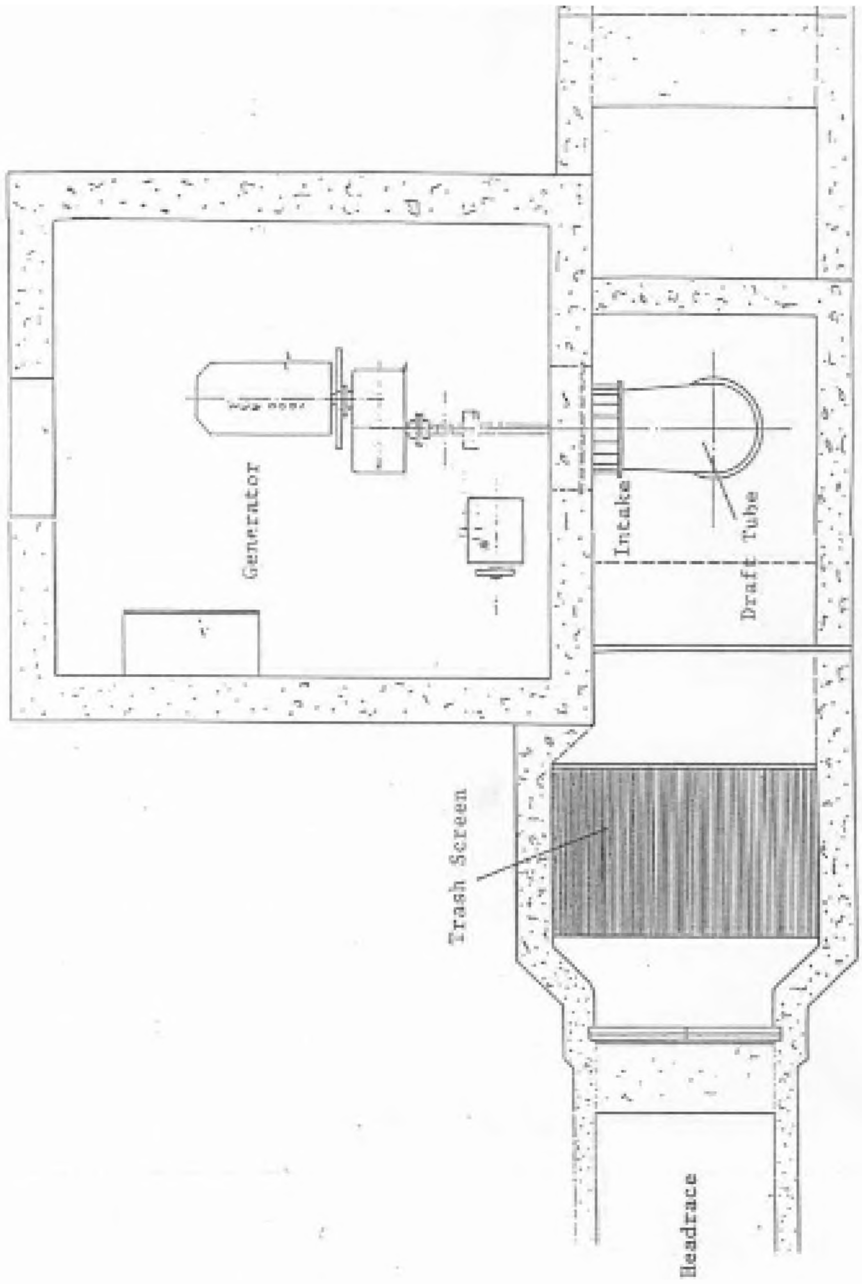
Turnpenny, A.W.H. and Hanson, K.P. (1997). Fish passage through small hydro-turbines: theoretical, practical and economic perspectives. Proceedings of the Hidroenergia 97 conference, September 29th – October 1st, 1997, Dublin, Ireland: 451-463.

Turnpenny, A.W.H., Struthers, G. and Hanson, K.P., 1998. A UK Guide to Intake

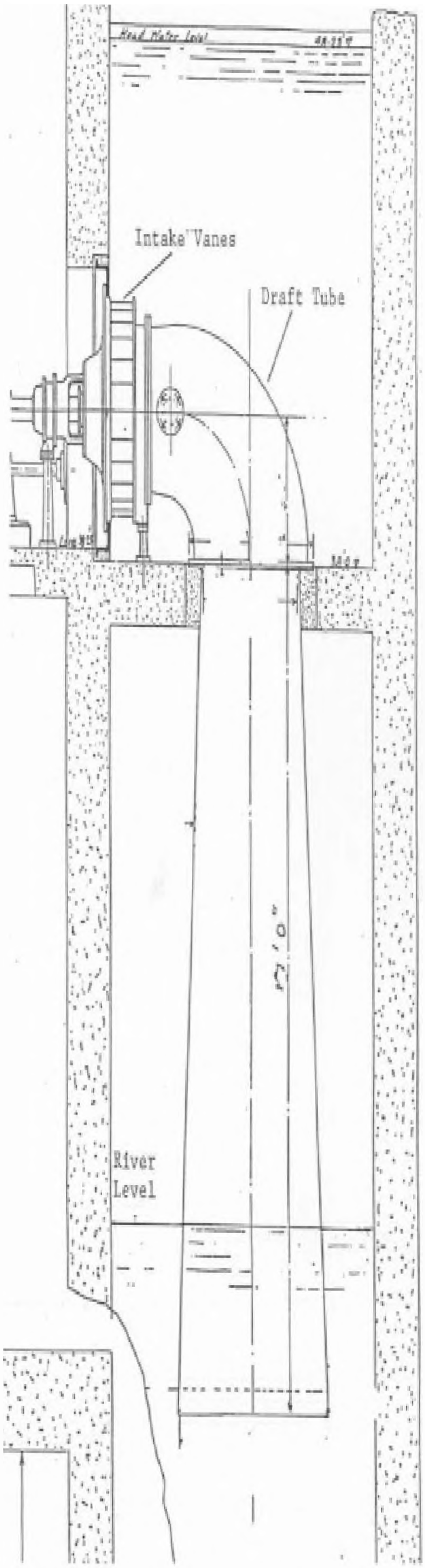
Fish-Screening Regulations, Policy and Best Practice. Final Report, ETSU Contract No. H/06/00052/00/00. Energy Technology Support Unit, Harwell, Oxon., OX11 0RA, UK.

Von Raben, K, 1957. Regarding the problem of mutilations of fishes by hydraulic turbines. *Die Wasserwirtschaft*, **4**, pp 97-100.

APPENDIX 1 Drawings of the Francis 1 Turbine Arrangement

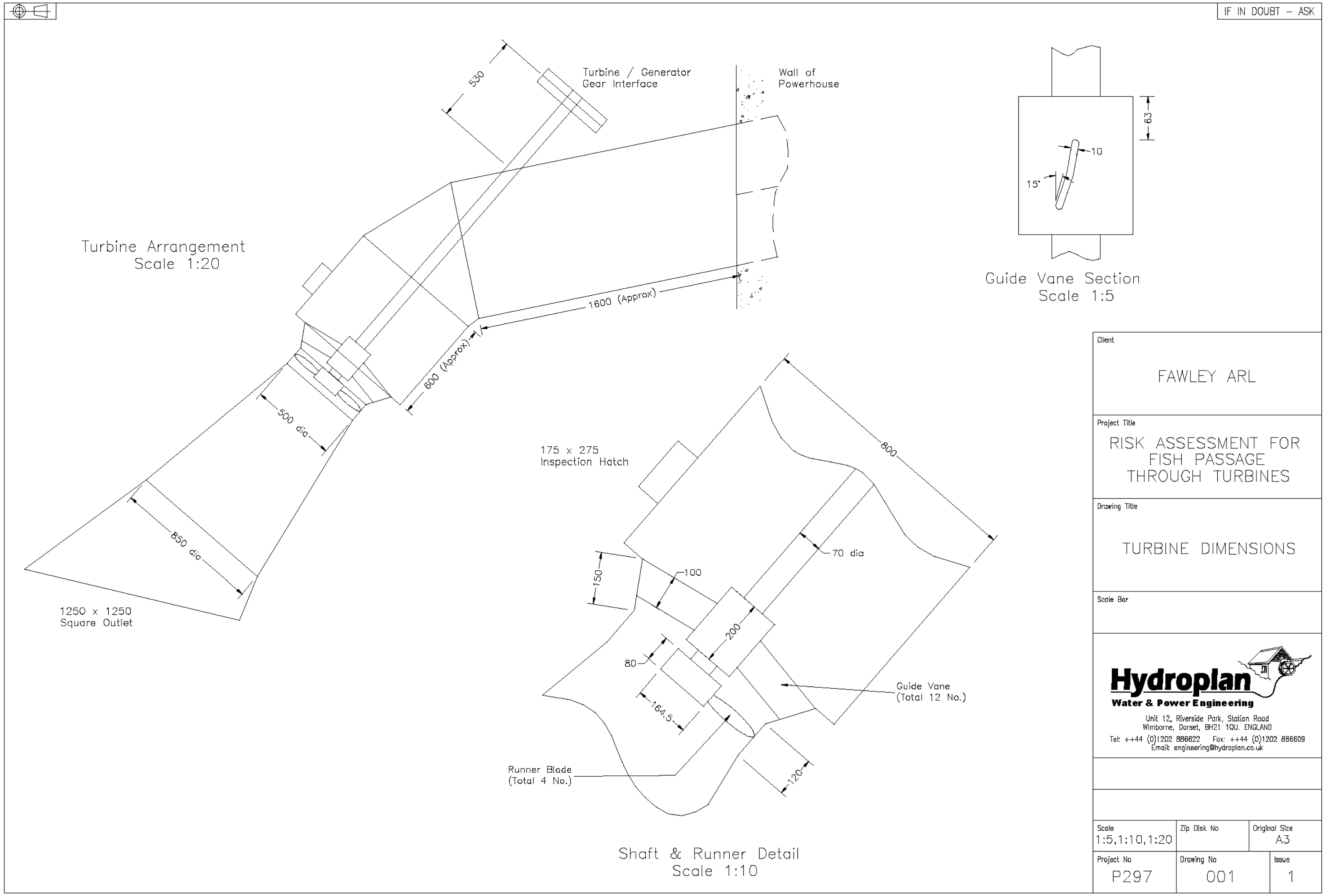


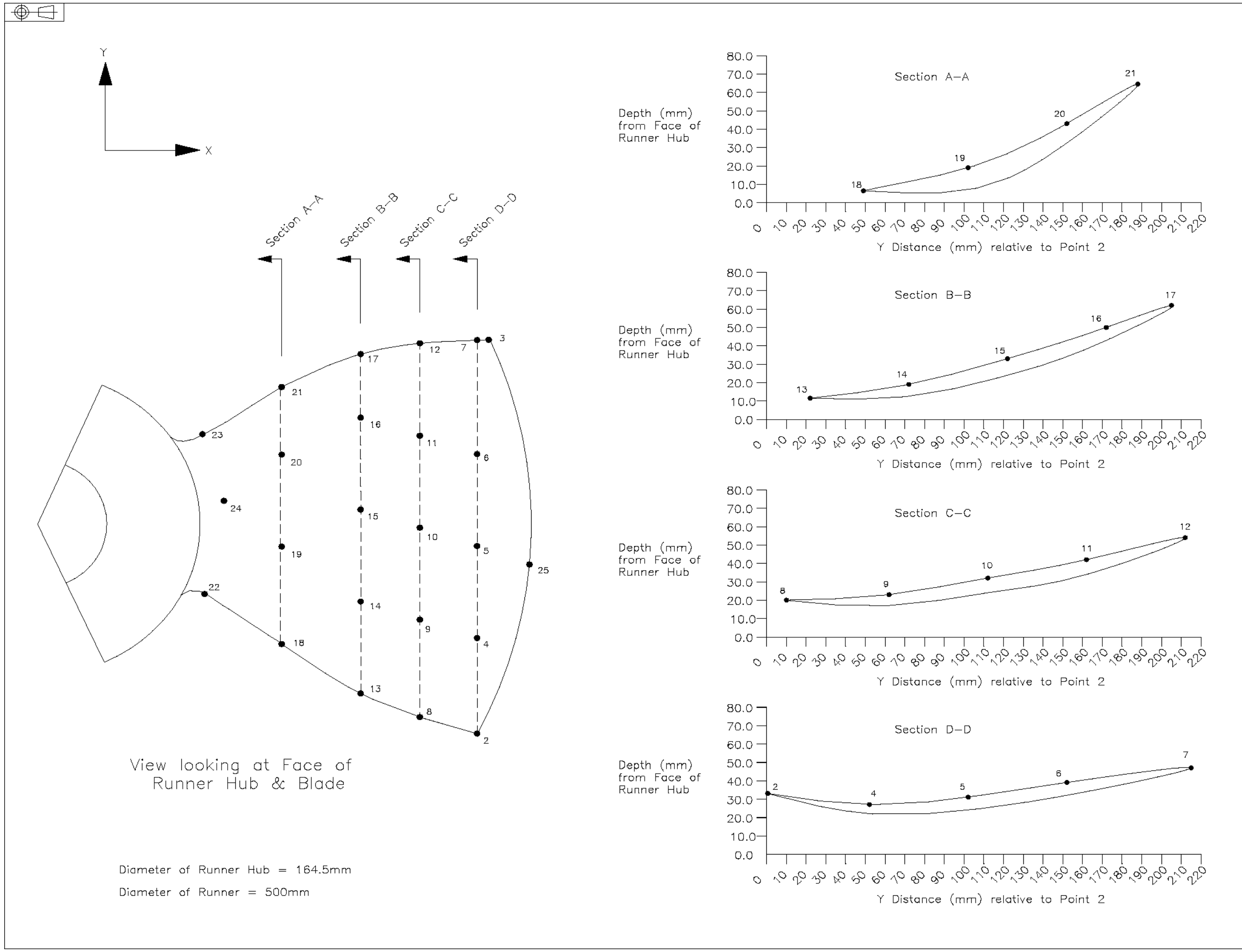
Francis 1 Site - Plan View



Francis 1 Site - Vertical Section

APPENDIX 2 Drawings of the Kaplan 1 Turbine - Reproduced with permission of Hydroplan


IF IN DOUBT – ASK
Turbine / Generator Gear Interface
Wall of Powerhouse
530
Turbine Arrangement Scale 1:20
1600 (Approx)
600 (Approx)
500 dia
850 dia
1250 x 1250 Square Outlet
Guide Vane Section Scale 1:5
63
10
15°
175 x 275 Inspection Hatch
800
70 dia
100
150
200
80
164.5
120
Guide Vane (Total 12 No.)
Runner Blade (Total 4 No.)
Shaft & Runner Detail Scale 1:10
Client
FAWLEY ARL
Project Title
RISK ASSESSMENT FOR FISH PASSAGE THROUGH TURBINES
Drawing Title
TURBINE DIMENSIONS
Scale Bar
Hydroplan
Water & Power Engineering
Unit 12, Riverside Park, Station Road
Wimborne, Dorset, BH21 1QU. ENGLAND
Tel: ++44 (0)1202 886622 Fax: ++44 (0)1202 886609
Email: engineering@hydroplan.co.uk
Scale
1:5,1:10,1:20
Zip Disk No
Original Size
A3
Project No
P297
Drawing No
001
Issue
1



Iss	Description	Drawn	Chk'd	Date
1	Runner Detail Amended	D.P.L	R.A.R	July'99
0	Original Drawing Issue	D.P.L	K.P.H.	July'99

Client

FAWLEY ARL

Project Title

RISK ASSESSMENT FOR FISH PASSAGE THROUGH TURBINES

Drawing Title

RUNNER BLADE PLAN AND CROSS SECTIONS

Scale Bar

Hydroplan
Water & Power Engineering
Unit 12, Riverside Park, Station Road
Wimborne, Dorset, BH21 1QU. ENGLAND
Tel: ++44 (0)1202 886622 Fax: ++44 (0)1202 886609
Email: engineering@hydroplan.co.uk

Scale	Zip Disk No	Original Size
1:2		A3

Project No	Drawing No	Issue
P297	002	1

APPENDIX 3: Results of the Francis 1 Fish Passage trials

[?=unknown; n/a = not applicable; 0=no injury, 1=injury]

Treatment	Species	Standard length (cm)	Body Severed	Swim Bladder Ruptured	Scale Loss	Eye Injury	Surival @48h	Potentially Fatal Injuries	Potentially Fatal Injuries, excl. scale loss
wild	sea trout	~14	0	?	0%	0	1	0	0
wild	salmon	9~10	0	?	0%	0	1	0	0
wild	salmon	9~10	0	?	0%	0	1	0	0
wild	salmon	9~10	0	?	0%	0	1	0	0
wild	salmon	9~10	0	?	0%	0	1	0	0
wild	salmon	9~10	0	?	0%	0	1	0	0
wild	sea trout	13.4	1	I	50%	0	0	1	1
wild	sea trout	9.8	1	I	5%	0	0	1	1
wild	sea trout	8.5	1	I	5%	0	0	1	1
introduced	brown trout	11.8	0	0	10%	0	n/a	0	0
introduced	brown trout	10.2	0	0	20%	0	n/a	1	0
introduced	brown trout	11.1	0	0	<5%	0	n/a	0	0
introduced	brown trout	10.1	0	0	5%	0	n/a	0	0
introduced	brown trout	11.2	0	0	10%	0	n/a	0	0
introduced	brown trout	10.5	0	0	20%	0	n/a	1	0
introduced	brown trout	10.3	0	0	5%	0	n/a	0	0
introduced	brown trout	10.8	0	0	5%	0	n/a	0	0
introduced	brown trout	10.2	0	0	5%	0	n/a	0	0
introduced	brown trout	10.4	0	0	5%	0	n/a	0	0
introduced	brown trout	9.1	0	0	10%	0	n/a	0	0
introduced	brown trout	9.2	0	0	15%	1	n/a	0	0
introduced	brown trout	-	1	0	0%	0	n/a	1	1
introduced	brown trout	10.9	0	0	0%	0	n/a	0	0
introduced	brown trout	13.6	0	0	5%	0	n/a	0	0
introduced	brown trout	11.9	0	0	0%	0	n/a	0	0
introduced	brown trout	11.8	0	0	0%	0	n/a	0	0
introduced	brown trout	11.5	0	0	5%	0	n/a	0	0
introduced	brown trout	12	0	0	0%	0	n/a	0	0
introduced	brown trout	11	0	0	0%	0	n/a	0	0
introduced	brown trout	11.3	0	0	10%	0	n/a	0	0
introduced	brown trout	10.5	0	0	0%	0	n/a	0	0
introduced	brown trout	12	0	0	0%	0	n/a	0	0
introduced	brown trout	12	0	0	0%	0	n/a	0	0
introduced	brown trout	10.5	0	0	0%	0	n/a	0	0
introduced	brown trout	11.5	0	1	0%	0	n/a	1	1
introduced	brown trout	11	0	0	0%	0	n/a	0	0
introduced	brown trout	12	0	0	90%	0	n/a	1	0
introduced	brown trout	11.1	1	0	0%	0	n/a	1	1
introduced	brown trout	12.5	0	0	0%	0	n/a	0	0
introduced	brown trout	10.5	0	0	0%	0	n/a	0	0
introduced	brown trout	10.8	0	0	0%	0	n/a	0	0
introduced	brown trout	10.4	0	0	0%	0	n/a	0	0
introduced	brown trout	11.8	0	0	0%	0	n/a	0	0
introduced	brown trout	10.8	0	0	0%	0	n/a	0	0
introduced	brown trout	10	0	0	5%	0	n/a	0	0
introduced	brown trout	10.9	0	0	20%	0	n/a	1	1
introduced	brown trout	11	0	0	0%	0	n/a	0	0
introduced	brown trout	10.3	0	0	0%	0	n/a	0	0
introduced	brown trout	10	0	0	0%	0	n/a	0	0
introduced	brown trout	11.3	0	0	0%	0	n/a	0	0
introduced	brown trout	9.8	0	0	0%	0	n/a	0	0
introduced	brown trout	10.9	0	1	0%	0	n/a	1	1
introduced	brown trout	10.5	0	0	5%	0	n/a	0	0
introduced	brown trout	10.5	0	0	0%	0	n/a	0	0
introduced	brown trout	10.1	1	0	0%	0	n/a	1	1
introduced	brown trout	11	0	0	0%	0	n/a	0	0
introduced	brown trout	10.4	0	0	0%	0	n/a	0	0
introduced	brown trout	10	0	0	0%	0	n/a	0	0
introduced	brown trout	10.5	0	0	0%	0	n/a	0	0
introduced	brown trout	9.2	1	0	0%	0	n/a	1	1
introduced	brown trout	8.7	0	0	0%	0	n/a	0	0
introduced	brown trout	10	0	0	0%	0	n/a	0	0
introduced	brown trout	8.5	1	0	0%	0	n/a	1	1
introduced	brown trout	-	1	0	0%	0	n/a	1	1
introduced	brown trout	-	1	0	0%	0	n/a	1	1
Total			**12.5%**	**3.6%**	**7.1%**	**1.8%**		**23.2%**	**17.9%**

Appendix 3 (continued)

Treatment		Standard length (cm)	Body Severed	Swim Bladder Ruptured	Scale Loss	Eye Injury	Surival @48h	Potentially Fatal Injuries	Potentially Fatal Injuries, excl. scale loss
control	brown trout	12	n/a	0	0%	0	n/a	0	0
control	brown trout	12.8	n/a	0	0%	0	n/a	0	0
control	brown trout	11.5	n/a	0	0%	0	n/a	0	0
control	brown trout	11.8	n/a	0	0%	0	n/a	0	0
control	brown trout	12.4	n/a	0	0%	0	n/a	0	0
control	brown trout	12.5	n/a	0	0%	0	n/a	0	0
control	brown trout	10.5	n/a	0	0%	0	n/a	0	0
control	brown trout	12.5	n/a	0	0%	0	n/a	0	0
control	brown trout	10.9	n/a	0	50%	0	n/a	1	0
control	brown trout	10.8	n/a	0	0%	0	n/a	0	0
control	brown trout	10	n/a	0	0%	0	n/a	0	0
control	brown trout	10.5	n/a	0	0%	0	n/a	0	0
control	brown trout	10.5	n/a	0	0%	0	n/a	0	0
control	brown trout	11.9	n/a	0	0%	0	n/a	0	0
control	brown trout	10.6	n/a	0	0%	0	n/a	0	0
control	brown trout	11.2	n/a	0	0%	0	n/a	0	0
control	brown trout	11	n/a	0	0%	0	n/a	0	0
control	brown trout	11.3	n/a	0	0%	0	n/a	0	0
control	brown trout	10	n/a	0	95%	0	n/a	1	0
control	brown trout	12	n/a	0	0%	0	n/a	0	0
control	brown trout	10.6	n/a	0	0%	0	n/a	0	0
control	brown trout	11.2	n/a	0	0%	0	n/a	0	0
control	brown trout	10	n/a	0	0%	0	n/a	0	0
control	brown trout	10.5	n/a	0	0%	0	n/a	0	0
Total				**0%**	**12.5%**	**0%**		**8.3%**	**0.0%**

APPENDIX 4: Results of the Kaplan 1 Trials

Treatment	Species	Standard length (cm)	Head depth (cm)	Body Severed	Swim Bladder Ruptured	Scale Loss	Eye Injury	Potentially Fatal Injuries
introduced 1	salmon	7.1	0.85	0	0	0%	0	0
introduced 1	salmon	6.3	0.71	0	0	0%	0	0
introduced 1	salmon	6.6	0.81	0	0	0%	0	0
introduced 1	salmon	6.7	0.88	0	0	0%	0	0
introduced 1	salmon	6.4	0.78	0	0	0%	0	0
introduced 1	salmon	6.9	0.88	0	0	0%	0	0
introduced 1	salmon	7.8	0.94	0	0	5%	0	0
introduced 1	salmon	7.0	0.88	0	0	0%	0	0
introduced 1	salmon	6.7	0.88	0	1	0%	1	1
introduced 1	salmon	7.6	0.88	0	0	0%	0	0
introduced 1	salmon	7.4	0.9	1	0	5%	0	0
introduced 1	salmon	6.8	0.85	0	1	10%	0	1
introduced 1	salmon	6.8	0.78	0	0	0%	0	0
introduced 1	salmon	7.9	0.9	0	0	0%	0	0
introduced 1	salmon	6.9	0.92	1	0	0%	0	1
introduced 1	salmon	6.9	0.83	0	0	0%	0	0
introduced 1	salmon	*6.8*	0.83	1	-	-	0	1
introduced 1	salmon	*6.4*	0.78	1	-	-	0	1
introduced 1	salmon	*8.6*	1.04	1	-	-	0	1
introduced 1	salmon	*7.6*	0.92	1	-	-	0	1
Total				**31.5%**	**13.3%**	**0.0%**	**5.3%**	**36.8%**
introduced 2	salmon	7.2	0.85	0	0	0%	0	0
introduced 2	salmon	6.5	0.71	1	0	5%	0	1
introduced 2	salmon	7.0	0.73	0	0	0%	0	0
introduced 2	salmon	6.6	0.75	0	0	0%	0	0
introduced 2	salmon	7.5	0.91	0	0	0%	1	1
introduced 2	salmon	7.0	0.86	0	0	5%	0	0
introduced 2	salmon	6.5	0.76	0	0	0%	0	0
introduced 2	salmon	6.2	0.77	0	0	0%	0	0
introduced 2	salmon	7.4	0.81	0	0	0%	0	0
introduced 2	salmon	6.3	0.69	0	0	5%	0	0
introduced 2	salmon	6.5	0.79	0	0	0%	0	0
introduced 2	salmon	6.9	0.81	0	0	0%	0	0
introduced 2	salmon	7.6	1.02	0	0	0%	0	0
introduced 2	salmon	7.0	0.9	0	1	0%	0	1
introduced 2	salmon	*6.2*	0.76	1	-	0%	0	1
introduced 2	salmon	*7.3*	0.89	0	0	0%	0	0
introduced 2	salmon	*6.9*	0.84	0	0	0%	0	0
introduced 2	salmon	*7.6*	0.92	0	0	0%	0	0
introduced 2	salmon	*7.1*	0.87	0	0	0%	0	0
introduced 2	salmon	*5.6*	0.69	0	0	0%	0	0
introduced 2	salmon			1	-	5%	0	1
Total				**14.3%**	**4.8%**	**0.0%**	**4.8%**	**23.8%**
introduced 3	salmon	7.0	0.94	0	0	0%	0	0
introduced 3	salmon	6.7	0.88	0	0	0%	0	0
introduced 3	salmon	6.7	0.74	0	0	0%	0	0
introduced 3	salmon	7.3	0.96	0	0	0%	0	0
introduced 3	salmon	6.9	0.9	1	0	5%	0	1
introduced 3	salmon	6.6	1	0	0	10%	0	1
introduced 3	salmon	6.6	0.89	0	0	0%	0	0
introduced 3	salmon	6.8	0.88	0	0	0%	0	0
introduced 3	salmon	7.3	0.81	0	1	0%	0	0
introduced 3	salmon	5.4	0.69	0	0	0%	0	0
introduced 3	salmon	7.5	1.06	0	0	0%	0	0
introduced 3	salmon	7.1	0.9	0	0	0%	0	0
introduced 3	salmon	*7.1*	0.87	1	-	0%	0	1
introduced 3	salmon	*7.0*	0.85	1	-	0%	0	1
introduced 3	salmon	*5.6*	0.69	1	-	0%	0	1
introduced 3	salmon	*8.1*	0.98	1	-	5%	0	1
introduced 3	salmon	*6.8*	0.83	1	-	0%	0	1
introduced 3	salmon	*7.6*	0.93	1	-	0%	0	1
introduced 3	salmon	*7.5*	0.91	1	-	0%	0	1
introduced 3	salmon	*7.4*	0.9	1	-	0%	0	1
Total				**45.0%**	**8.3%**	**0.0%**	**0.0%**	**50.0%**

Appendix 4 (continued)

Treatment	Species	Standard length (cm)	Head depth (cm)	Body Severed	Swim Bladder Ruptured	Scale Loss	Eye Injury	Potentially Fatal Injuries
introduced 4	salmon	7.9	0.9	0	0	0%	0	0
introduced 4	salmon	7.4	0.87	0	0	0%	0	0
introduced 4	salmon	8.5	0.94	0	0	0%	0	0
introduced 4	salmon	7.4	0.85	0	0	0%	0	0
introduced 4	salmon	7.3	0.81	1	0	0%	0	1
introduced 4	salmon	7.3	0.92	1	1	5%	0	1
introduced 4	salmon	7.5	0.84	0	0	5%	0	0
introduced 4	salmon	7.1	0.9	0	0	0%	0	0
introduced 4	salmon	*8.2*	1	1	-	5%	0	1
introduced 4	salmon	*7.6*	0.92	1	-	5%	0	1
introduced 4	salmon	7.2	0.87	0	0	0%	0	0
introduced 4	salmon	7.0	0.87	0	0	5%	0	0
introduced 4	salmon	7.3	0.9	0	0	0%	0	0
introduced 4	salmon	7.6	0.96	0	0	0%	0	0
introduced 4	salmon	7.0	0.9	0	0	10%	0	0
introduced 4	salmon	*7.5*	0.91	1	-	5%	0	1
introduced 4	salmon	*7.6*	0.92	1	-	5%	0	1
introduced 4	salmon	*7.5*	0.91	1	-	0%	0	1
introduced 4	salmon	*8.1*	0.98	1	-	0%	0	1
introduced 4	salmon	*6.6*	0.81	1	-	0%	0	1
Total				**45.0%**	**7.7%**	**0.0%**	**0.0%**	**45.0%**
introduced 5	salmon	7.6		0	0	0%	0	0
introduced 5	salmon	6.6		0	1	0%	0	1
introduced 5	salmon	7.1		0	1	0%	0	1
introduced 5	salmon	6.7		0	0	0%	0	0
introduced 5	salmon	7.4		0	0	5%	0	0
introduced 5	salmon	7.3		0	0	5%	0	0
introduced 5	salmon	7.6		1	0	5%	0	1
introduced 5	salmon	7.8		1	0	5%	0	1
introduced 5	salmon	7.2		0	0	0%	0	0
introduced 5	salmon	6.8		0	0	0%	0	0
introduced 5	salmon	6.9		0	0	0%	0	0
introduced 5	salmon	6.8		0	0	0%	0	0
Total				**16.6%**	**16.6%**	**0.0%**	**0.0%**	**33.3%**
introduced 6	salmon	8.0		0	1	0%	0	1
introduced 6	salmon	7.6		0	0	0%	0	0
introduced 6	salmon	6.6		0	0	0%	0	0
introduced 6	salmon	7.7		0	0	0%	0	0
introduced 6	salmon	8.6		0	0	0%	0	0
introduced 6	salmon	8.2		1	0	5%	0	1
introduced 6	salmon	7.0		0	0	0%	0	0
introduced 6	salmon	8.5		0	0	5%	0	0
introduced 6	salmon	8.2		1	0	0%	0	1
Total				**22.0%**	**11.0%**	**0.0%**	**0.0%**	**33.0%**
introduced 7	salmon	8.4		0	0	0%	0	0
introduced 7	salmon	6.7		0	1	0%	0	1
introduced 7	salmon	7.0		0	0	0%	0	0
introduced 7	salmon	7.3		0	0	0%	0	0
introduced 7	salmon	7.5		0	0	0%	0	0
introduced 7	salmon	7.4		0	0	5%	0	0
introduced 7	salmon	7.6		0	0	10%	0	0
Total				**0.0%**	**14.3%**	**0.0%**	**0.0%**	**14.3%**

Appendix 4 (continued)

Treatment	Species	Standard length (cm)	Head depth (cm)	Body Severed	Swim Bladder Ruptured	Scale Loss	Eye Injury	Potentially Fatal Injuries
introduced 8	salmon	6.7		1	0	5%	0	1
introduced 8	salmon	7.5		1	0	0%	0	1
introduced 8	salmon	7.4		1	0	0%	0	1
introduced 8	salmon	8.7		1	0	5%	0	1
introduced 8	salmon	7.7		1	0	0%	0	1
introduced 8	salmon	7.8		1	0	0%	0	1
introduced 8	salmon	7.3		0	0	5%	0	0
introduced 8	salmon	7.5		0	0	0%	0	0
introduced 8	salmon	8.2		1	0	0%	0	1
introduced 8	salmon	7.4		1	0	0%	0	1
introduced 8	salmon	7.6		1	0	5%	0	1
introduced 8	salmon	7.9		0	0	0%	0	0
introduced 8	salmon	7.7		0	0	5%	0	0
introduced 8	salmon	7.2		0	0	0%	0	0
introduced 8	salmon	6.9		0	1	0%	0	1
introduced 8	salmon	7.0		0	0	5%	0	0
introduced 8	salmon	7.6		0	0	5%	0	0
introduced 8	salmon	7.5		0	0	0%	0	0
introduced 8	salmon	6.8		0	0	0%	0	0
introduced 8	salmon	7.9		1	0	0%	0	1
introduced 8	salmon	7.2		0	0	0%	0	0
introduced 8	salmon	8.0		1	0	0%	0	1
introduced 8	salmon	7.4		0	0	0%	0	0
Total				**47.8%**	**4.3%**	**0.0%**	**0.0%**	**52.0%**
Average				**27.8%**	**10.0%**	**0.0%**	**1.3%**	**36.0%**

Appendix 4 (continued)

Treatment	Species	Standard length (cm)	Head depth (cm)	Body Severed	Swim Bladder Ruptured	Scale Loss	Eye Injury	Potentially Fatal Injuries, excl. scale loss
control 1	salmon	6.7		0	0	0%	0	0
control 1	salmon	6.8		0	0	0%	0	0
control 1	salmon	6.0		0	0	0%	0	0
control 1	salmon	8.6		0	0	0%	0	0
control 1	salmon	7.5		0	0	0%	0	0
control 1	salmon	8.3		0	0	0%	0	1
control 1	salmon	6.0		0	0	0%	0	0
control 1	salmon	6.7		0	0	0%	0	0
control 1	salmon	6.4		0	0	0%	0	0
control 1	salmon	7.3		0	0	0%	0	0
control 1	salmon	8.5		0	0	0%	0	0
control 1	salmon	6.6		0	0	0%	0	0
control 1	salmon	7.2		0	0	0%	0	0
control 1	salmon	6.9		0	0	0%	0	0
control 1	salmon	7.1		0	0	0%	0	0
control 1	salmon	7.5		0	0	0%	0	1
control 1	salmon	7.6		0	0	0%	0	0
control 1	salmon	6.9		0	0	0%	0	0
control 1	salmon	7.0		0	0	0%	0	0
Total				**0%**	**0%**	**0%**	**0%**	**0%**
control 2	salmon	7.0	0.83	0	0	0%	0	0
control 2	salmon	7.9	0.97	0	0	5%	0	0
control 2	salmon	6.8	0.87	0	0	0%	0	0
control 2	salmon	8.0	0.94	0	0	0%	0	0
control 2	salmon	7.6	1.04	0	0	0%	0	0
control 2	salmon	8.1	1.08	0	0	0%	0	0
control 2	salmon	7.6	0.97	0	0	0%	0	0
control 2	salmon	7.9	0.94	0	0	0%	0	0
control 2	salmon	7.0	0.88	0	0	0%	0	0
control 2	salmon	9.3	1.09	0	0	0%	0	0
control 2	salmon	6.9	0.9	0	0	5%	0	0
control 2	salmon	7.4	0.9	0	0	0%	0	0
control 2	salmon	8.4	0.97	0	0	0%	0	0
control 2	salmon	7.8	0.96	0	0	0%	0	0
control 2	salmon	7.3	0.92	0	0	0%	0	0
control 2	salmon	7.3	0.86	0	0	0%	0	0
control 2	salmon	6.4	0.78	0	0	0%	0	0
control 2	salmon	6.9	0.86	0	0	0%	0	0
control 2	salmon	8.9	1.11	0	0	0%	0	0
control 2	salmon	7.4	0.89	0	0	0%	0	0
Total				**0%**	**0.0%**	**0%**	**0%**	**0.0%**
control 3	salmon	7.1	0.85	0	0	0%	0	0
control 3	salmon	7.6	0.98	0	0	0%	0	0
control 3	salmon	7.0	0.77	0	0	0%	0	0
control 3	salmon	7.2	0.85	0	0	0%	0	0
control 3	salmon	5.8	0.62	0	1	0%	0	1
control 3	salmon	6.7	0.81	0	0	0%	0	0
control 3	salmon	6.4	0.75	0	0	0%	0	0
control 3	salmon	6.6	0.81	0	0	0%	0	0
control 3	salmon	6.0	0.63	0	0	0%	0	0
control 3	salmon	6.6	0.74	0	0	0%	0	0
control 3	salmon	8.2	0.92	0	0	0%	0	0
control 3	salmon	7.3	0.85	0	0	0%	0	0
control 3	salmon	6.4	0.73	0	0	0%	0	0
control 3	salmon	7.3	0.85	0	0	0%	0	0
control 3	salmon	6.9	0.75	0	0	0%	0	0
control 3	salmon	7.8	0.87	0	0	0%	0	0
control 3	salmon	7.6	0.88	0	0	0%	0	0
control 3	salmon	7.0	0.69	0	0	0%	0	0
control 3	salmon	6.9	0.88	0	0	0%	0	0
control 3	salmon	7.9	0.94	0	0	0%	0	0
control 3	salmon	7.6	0.96	0	0	0%	0	0
control 3	salmon	7.4	0.94	0	0	0%	0	0
control 3	salmon	6.6	0.96	0	0	0%	0	0
control 3	salmon	8.2	1.09	0	0	0%	0	0
control 3	salmon	7.0	0.99	0	0	0%	0	0
Total				**0%**	**0%**	**0%**	**0%**	**0%**

APPENDIX 5 STRIKER Instructions and Sample runs of STRIKER for the 'Francis 1' and 'Kaplan 1' turbines

Getting Started

General familiarity of the user with the MS Excel 97 spreadsheet program is assumed.

Having booted the Excel program, the STRIKER program disk is first inserted into the floppy-disk drive and loaded from the A: drive or alternative, as appropriate.

STRIKER has a number of pages that can be accessed by selecting (using the mouse) the tabs marked: 'Title Page', 'Instructions', 'Description' 'Francis', 'Kaplan' etc., at the bottom of the screen. The 'Instructions' are as printed here. A number of other pages exist but are hidden to avoid excessive clutter. They can be revealed using the 'Format/Worksheet/Unhide' function.

Each page (spreadsheet tab) is designed to be viewed in one screen width. The 'Zoom' setting within Excel's 'View' drop-down menu can be adjusted to fit the width of the pages to the screen. This will depend on the computer's video driver settings. A zoom value of 75% is a good place to begin. This must be set separately for each of the selected tabs. The pages are generally taller than the screen view allows in one go. Use the page-up, page-down, up-down arrow keys or the mouse-driven scroll bar to move up and down the page, as required.

All of the spreadsheet pages are protected, except for the data entry cells. This is to prevent accidental corruption of the program, which could lead to erroneous results.

Entering Data

The requirement is to select either the 'Kaplan' or 'Francis' spreadsheet, as required. The Kaplan sheet is also used for propeller turbines.

The cells within each spreadsheet are colour-coded. Mostly, the colours are used for visual effect only but the light-green cells denote data-entry cells.

Warning: Data should be entered in all the green cells on the spreadsheet that is being used. Otherwise, data will be carried over from the previous run, giving erroneous results.

The required values included the Project Title, a number of Fixed Turbine Parameters and Variable Turbine Parameters. The specific requirements for these may be found in the text of the report. It is recommended that the user should read the report before attempting to use STRIKER.

Output

The program operates instantly, generating the results as the input data are entered. The results are presented in Tables 1 and 2 of the program. These are to be found by scrolling down the page on the 'Kaplan' or 'Francis' spreadsheets, as appropriate. Table 1 contains the main output, comprising calculated smolt/parr injury rates for different sizes of fish. These are broken down into injuries related to shear, pressure and blade-strike respectively, along with a 'compound' value representing the combined effect of all three causes.

The program's Table 2 (below Table 1), gives a more detailed breakdown of the values derived from the CFD analysis for the various turbine zones (intake, guide vanes, runner section, draft tube). Strike injuries, of course, are all ascribed to the runner section so are not included in the program's Table 2.

Note that Table 1 of the program contains light-green shaded cells for fish length. This enables the user to enter different values from those initially shown, allowing more accurate predictions for intermediate fish lengths.