SMC/IEC TC 114 Research Final Report

River Current Energy Conversion Systems: Direct Reliability Assessment and LRFD Load Factors at Different Safety Levels

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Summary of Scope and Objectives

This is the final Research Report for the project **Guideline for Reliability Assessment of Marine Energy Conversion Systems (MECs) and Design Parameters for River Current Energy Conversion Systems (RECs) for Different Safety Levels**, for work completed under a Contract between Marine Renewables Canada and the authors.

The scope of the research included the following:

- Development of a general methodology for the direct reliability assessment of a Marine Energy Conversion (MEC) system, for different limit states, to enable the use of an alternate design approach based on probabilistic methods. A River Current Energy Conversion system (REC) will be considered as a particular case of a MEC.
- Establishing relevant load factors for an River Current Energy conversion system (REC), for different safety levels, as defined in the IEC 62000-Part 2 CD, considering a generic Load and Resistance Factored Design (LRFD) concept.

The work in this Report addresses three objectives:

1. To describe a general methodology for the direct reliability assessment of a river current River Energy Converter (REC) system, for different limit states and performance levels; and to illustrate the methodology with an example using an operating REC;

2. Calibration of a Load and Resistance Factored Design (LFRD) procedure for a river current REC, to achieve minimum target reliability levels or maximum tolerable probabilities of failure, for different limit states, over the service life. To present results for load factors applicable to a combination of applied loads (a permanent load and up to two different live loads), taking into account the variability in system capacity, uncertainty in the loads and different definitions for the characteristic or design load values.

3. To recommend actions for future research.

Background

The development of Marine or River Energy Converters (MEC or REC) must incorporate the study of their reliability under mechanical and environmental demands over their service life.

In general, reliability studies imply consideration of all uncertainties, both in the demands as well as in the capacity of the structure of the MEC or REC to withstand those demands. Two types of applications must be considered:

Application 1: Direct assessment of the reliability of a specific system design for different limit states or modes of failure; assessment that could be part of a direct reliability-based design for the system;

Application 2: The design of a REC, determining design parameters so that the resulting structure achieves minimum target reliabilities (safety levels) for different limit states or modes of failure. The design procedure is to be based on the approximate LRFD approach, using a deterministic design equation incorporating characteristic values for the loads and the demands, and properly calibrated load and resistance factors.

Both problems fall within the scope of Reliability Theory, a general and well-developed application of probability theory to the design of engineering systems. Table 1 shows the target reliabilities for a MEC (expressed as maximum allowed annual probabilities of failure) as prescribed by the document IEC CD 62600 (2014), (Ref. 1), for three types of design safety levels (SL1, SL2 or SL3). A reliability-based study of the performance and design of tidal turbines, with objectives similar to those described in this report, is shown in Ref.(2). The work reported here was focused on REC applications for river currents.

The objective in the first application is to estimate the reliability of a MEC or REC in a given limit state, verifying that it meets the target requirement given in Table 1 for the desired safety level. For the second application, the design characteristics of the system must be obtained so that the achieved reliabilities match approximately the requirements shown in Table 1.

Table 1 - Safety Levels, IEC CD 62600-2 (2014)

Safety Level	Definition	Probability of Failure
SL1	Operating conditions where failure implies high risk of human injury, significant environmental pollution or very high economic or political consequences	$< 10^{-5}$ per year
SL2	For temporary or operating conditions where failure implies: risk of human injury, significant environmental pollution or high economic or political consequences. This level normally aims for a risk of less than 10^{-4} per year of a major single accident. It corresponds to a major incident happening on average less than once every 10,000 installation years. This level equates to the experience level from major representative industries and activities.	$<10^{-4}$ per year
SL3	Failure implies low risk of human injury and minor environmental and economic consequences	$<10^{-3}$ per year

River current applications may involve components easily replaceable, the failure of which may imply only minor economic or environmental consequences. For these components, a less stringent target safety level may be appropriate. Thus, in this Report, the scope for Table 1 has been augmented to include an additional safety level definition, **SL4**, with a maximum annual probability of failure of 10^{-2}.

Reliability and Performance Function

The reliability of a MEC or REC, in a given Limit State, is obtained by first defining a performance function G, expressing the margin of safety between the capacity and the demand. In general, the performance function G is written as

$$G = R\,\Omega - (D + L_1 + L_2) \qquad [1]$$

In which R, D, L_1 and L_2 are, respectively, the actual resistance, a permanent load effect and up to two live load effects that may be acting in combination. These are, in general, random variables. The parameter Ω, when multiplied by the resistance R, provides the capacity of the system. Capacity and load effects must be dimensionally consistent: for example, if the capacity is given as a maximum tolerable bending moment, the load effects must also be expressed as demand bending moments. In the particular case of fatigue limit state, the capacity would be the fatigue limit for the parameter Ω (or the corresponding cyclic stress range that could be applied without failure for an indefinite number of cycles) and the demand would be the magnitude of the actual, applied range.

The performance function G requires models for the capacity R or for the load effects R, L_1 or L_2 . These could be obtained from simple mechanical models or be the result of more complex analyses implementing finite elements or dynamic simulations.

The probability of non-performance (or failure) is then given by the probability of the function G being negative (P[G<0]). Knowing the probability distributions of the intervening variables in R, D, L_1 and L_2 , the probability P[G<0] can then obtained by the application of available software (e.g., RELAN, developed at the University of British Columbia by Foschi et al., 1990-2005). The probability P[G<0] can be obtained for different values of the design parameter Ω, which can then be adjusted to conform to a minimum reliability requirement.

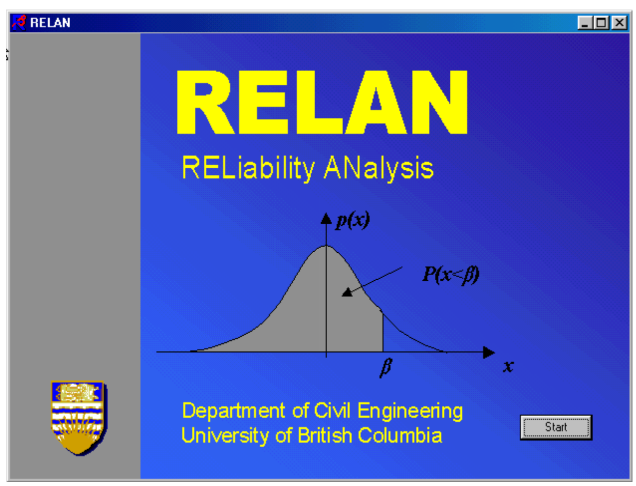

Figure 1. Opening screen of RELAN (Foschi et al., 1990-2005)

RELAN is one example of several such tools available now in the marketplace. All these programs, however, implement the same theory and all require the definition of the performance function G corresponding to the problem at hand. RELAN has been used for all the numerical results reported here. In RELAN, the performance function for the problem is specified in a subroutine called GFUN, which describes the models for both the capacity and the demands. RELAN has a Windows interface for input, which permits the specification of the number of random variables as well as the parameters of their probability distributions. RELAN computes the probability of non-performance, using FORM (First Order Reliability Method), or SORM (Second Order Reliability Method), or different simulation techniques (Importance Sampling or Standard Monte Carlo). The results in this study have been obtained using either FORM or Monte Carlo simulation for verification of FORM.

Assessing the reliability of a REC, Example and General Guidelines

Application 1 describes a general and direct approach to assess the reliability of a system. The objective in this project is to discuss the steps in this method, and to describe an example in detail. The assessment of other specific RECs, under different Limit States, will follow the same general guidelines.

The guidelines are described here by using a specific example, the case of fatigue design on an extruded aluminum river turbine blade. This example was developed in collaboration with Mavi Innovations Ltd., and is used here to illustrate the general steps that form part of the method for analysis in Application 1.

The river turbine is schematically shown in Figure 2, a rotor with airfoil blades of length L . A river current with speed V induces, through the blades, a rotation of the turbine with a rotational speed S. Figures 3 and 4 show the actual turbine being prepared for testing and river installation.

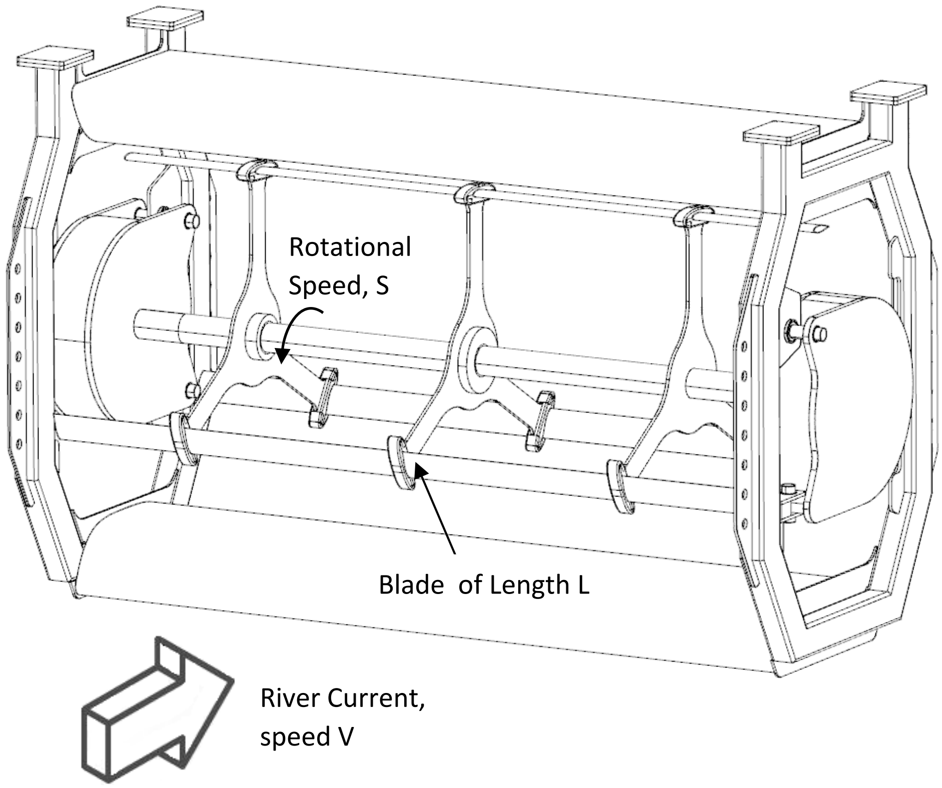

Figure 2. Schematic of the river turbine, rotating with speed S in a current with speed V

Figure 3. River turbine being readied for testing

Figure 4. The turbine being lowered into the river current

The following describes the general steps to be followed for the direct assessment of the reliability of the REC in a specific Limit State.

Step 1: Development of a model for the limit state and performance function

Reliability analyses require models to represent the system demand and capacity in the particular limit state of interest. The demand for blade fatigue requires the evaluation of the bending stresses produced by the different forces acting on the blades. Due to the changing angle of attack of the blade, the maximum bending stresses fully reverse in sign, from tension to compression, as the rotor completes a full rotation. The maximum total stress demand can then be compared with the fatigue characteristics of the blade material. In particular, the system capacity is given by the reversing maximum total tress that can be sustained for an indefinite number of cycles (fatigue limit).

As the turbine rotates with an angular speed S (rpm), in a river with current speed V (m/sec), the total stress effect F_{total} for blade bending (MPa) is given by three components as follows:

$$F_{total} = F_g(1g) + F_c(S_{ref})x\left(\frac{S}{S_{ref}}\right) + F_{hyd}(V_{ref}, TSR)x\left(\frac{V}{V_{ref}}\right)^2 \qquad [2]$$

in which:

F_{total} is the resulting (or net) maximum stress on the blade, MPa

$F_g(1g)$ is the stress due to gravity (or own weight), MPa

$F_c(S)$ is the stress due to the centripetal acceleration for rotation speed S (rpm),

$F_{hyd}(V, TSR)$ is the stress due to hydrodynamic loads, depending on the speeds S and V, interacting to provide *TSR*, the blade tip speed ratio:

$$TSR = \frac{V_{blade}}{V} = \frac{\pi \cdot D \cdot S}{60 \cdot V} \qquad [3]$$

in which D is the rotor diameter (m).

The stresses $F_c(S)$ and $F_{hyd}(V, TSR)$ require dynamic analyses of the blade rotating in the flow, and these are carried out under reference speeds S_{ref}, V_{ref}.

The hydrodynamic stresses F_{hyd} *(V, TSR)* depend on *TSR* due to changing angles of attack on the blades. They were evaluated by Mavi Innovations at a reference speed 2.0 m/sec and for several blade tip speed ratios TSR. The results were used to fit a polynomial relationship between TSR and F_{hyd} :

$$F_{hyd}\,(V_{ref},\,TSR) = -0.5555 + 30.7228*TSR - 1.2468*TSR**2 \qquad [4]$$

The speed of the turbine is a function of the current speed V, and is determined by the turbine controller. The turbine controller maximizes power output of the turbine at low flow speeds. At high flows, it will act to reduce power output by speeding up or slowing down the rotor. For this calculation, the rotor speed is held approximately constant after the turbine reaches its rated power. As shown in Figure 5, the speed S of the turbine, determined by the current speed, is controlled not to exceed a maximum S_{rated} .

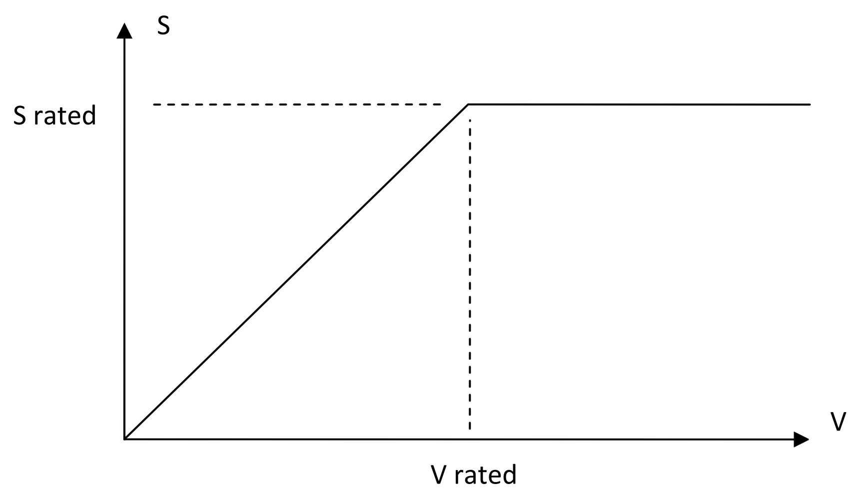

Figure 5. Control of rotor speed S to a maximum S_{rated}

S_{rated} and V_{rated} are parameters set in turbine rotor controller.

Blade performance in fatigue is described in terms of the fatigue limit F_{LIM} and the F_{total} from Eq.[2]. Thus, the ***Performance Function G*** is written as:

$$G = F_{LIM} - F_{total} \qquad [5]$$

Under F_{LIM} the blade could withstand an unlimited number of stress cycles. If F_{total} exceeds F_{LIM} the number of cycles to failure will be finite (that is, fatigue failure will occur at some point in time). Thus, when the performance function is negative (G<0) the turbine blade will not perform as intended, and the probability of non-performance will equal the probability of the event G<0.

Step 2: Identification of Random variables

The next step in the analysis is the identification of the intervening random variables and their corresponding statistical description. The random variables are taken as components of a vector **X**. In this case there are *5 random variables*, as follows:

1) **X(1)** , is the current velocity V. This is assumed to have an Extreme Type I distribution, representing (for example) the *maximum current speed in a year*. In this case, the probability of non-performance will approximately correspond to an annual probability. Two parameters must be given to describe an Extreme Type I distribution: its mean and its standard deviation. In the numerical results shown below, the mean V was assumed to be 3.0 m/sec and the standard deviation was 0.6 m/sec (a coefficient of variation of 0.20 or 20%). These statistics are chosen only to carry out the calculations for the example, other probability distributions or statistics could be used if deemed more appropriate. In a more complex model, the current could also be considered to have two components, one for a more steady flow and another, superposed, with higher variability due to phenomena like turbulence.

2) **X(2)** , is associated with the uncertainty in controlling of the maximum rotor speed S_{rated} . The actual speed is assumed to be

$$S_{rated} = S_{rated\ nominal} \ (1 + COV_{Srated} \ X(2)) \qquad [6]$$

The error or difference between S_{rated} and $S_{rated\ nominal}$ is assumed to have a Normal distribution having a zero mean and a coefficient of variation COV_{Srated} = 0.05. **X(2)** then has a Standard Normal distribution (zero mean, standard deviation = 1).

3) **X(3)** , is associated with uncertainty in the initial slope of the graph S/V (Figure 5). This slope is taken with a mean of 40.0 rpm/(m/sec), corresponding to a turbine design for a rated speed of 120 rpm in 3 m/sec flow. It is assumed that deviations from 40.0 have a Normal distribution, so that

$$S/V = 40.0 \ (1 + COV_{S/V} \ X(3)) \qquad [7]$$

with a coefficient of variation $COV_{S/V}$ = 0.02 and **X(3)** being a Standard Normal random variable.

4) **X(4)** , is associated with uncertainty in the value of the fatigue limit F_{LIM} . Thus,

$$F_{LIM} = F_{LIM\ nominal} \ (1.0 + COV_{FLIM} \ X(4)) \qquad [8]$$

Implying a Normal distribution around the nominal fatigue limit $F_{LIM\ nominal}$ and a coefficient of variation COV_{FLIM} . **X(4)** is a Standard Normal variable. For the numerical results the following values were used:

$$F_{LIM\ nominal} = 85.0 \text{ MPa and } COV_{FLIM} = 0.05 \qquad [9]$$

5) **X(5)** , is associated with overall model error. It is assumed that the formulation of the performance function, as per Eq. [2] and [5], is correct on the mean, but that there is a model error which is Normal, with a mean of 1.0 and a coefficient of variation 0.05.

In addition, the following deterministic parameters enter into the performance function and are therefore required:

6) $\mathbf{V_{ref}}$ = 2.0 m/sec and $\mathbf{S_{ref}}$ = 20.0 rpm , reference speeds used for the structural dynamic analysis of the turbine blade
7) $\mathbf{F_c(1g)}$ = stress produced by gravity (own weight) = 3.0 Mpa
8) $\mathbf{F_c(S_{ref})}$ = 0.2Mpa, stress produced by centripetal accelerations due to a S_{ref} = 20 rpm

Step 3: Calculation of Probability of Non-Performance and Results

The calculation of the probability of non-performance implies the estimation of the probability that the performance function G be negative. In the example studied here, G from Eq.[5] is a function of five random variables. Different methods can be used to estimate this probability. Among them, a simple simulation:

1) Select, randomly, a set of values for the variables X(1) through X(5) and verify the corresponding sign of the function G.
2) Repeat step 1 N times, counting the number of times N_f that G < 0.
3) Estimate the probability of non-performance by the ratio N_f / N

This simple procedure, a Monte Carlo simulation, becomes more accurate as N increases, but it could be time consuming as the number N of trials becomes large when the probability of non-performance is small.

Other procedures, more efficient, require specialized software. RELAN provides options for simulation as well as more efficient procedures like FORM (First Order Reliability Method). For this study, FORM was used to obtain the probability of non-performance, verified using simulation.

The following shows a detailed output from RELAN:

RELAN RELIABILITY ANALYSIS OUTPUT

PERFORMANCE FUNCTION: GIVEN EXPLICITLY FOR BLADE STRESSES NOT TO EXCEED FATIGUE LIMIT

ANALYSIS APPROACH: STANDARD FORM/SORM

CONVERGENCE TOLERANCE ON BETA = .00010

MAXIMUM NUMBER OF ITERATIONS = 100

VARIABLE	CODE	MEAN VALUE	STD. DEV.	
1	5	.30000E+01	.60000E+00	V (Extreme Type I)
2	1	.00000E+00	.10000E+01	Uncertainty, controlled rot.speed, Normal
3	1	.00000E+00	.10000E+01	Uncertainty, ratio S/V, Normal
4	1	.00000E+00	.10000E+01	Uncertainty, fatigue limit, Normal
5	1	.00000E+00	.10000E+01	Model error, Normal

NOTE: ALL THE BASIC VARIABLES ARE UNCORRELATED.

Scontrolled at = 24.0 rpm (mean, allowing a 5% coefficient of variation)

RESULTS:

BETA (FORM) = 3.544 G = .151576E-03

PROBABILITY OF FAILURE (FORM) = .19693010E-03

ITERATIONS TO CONVERGE = 3

STARTING VECTOR:

.58018E+01 .82645E+00 .00000E+00 -.20081E+01 .88935E+00

DESIGN POINT:

.63539E+01 .69115E+00 .00000E+00 -.72629E+00 .67697E+00

SENSITIVITY FACTORS (DIRECTION COSINES IN STANDARD NORMAL SPACE):

.93994E+00 .19501E+00 .00000E+00 -.20493E+00 .19101E+00

NOTES:

In this case, the probability of exceeding the fatigue limit is estimated at .19693010E-03

which corresponds to a reliability index Beta = 3.544

Sensitivity factors refer to the influence of the respective variable on the reliability

calculation. The closest the sensitivity is to 1.0 (in absolute value) the more the influence of that variable.

In this case, the first variable, V, is the most influential. Variable ranking of importance:

1) Current speed V
2) Fatigue limit uncertainty
3) Uncertainty in the rotational speed control
4) Uncertainty due to model error
5) Uncertainty in the ratio S/V (S < Scontrolled)

A common implementation in practice seeks to achieve the following objective:

Given a REC with a given rotor speed control parameter $S_{rated\ nominal}$, find the river current characteristic in which the REC can be used with a desired fatigue reliability.

<u>Results</u>:

The results are shown in Figure 6, for values of $S_{rated, nominal}$ of 80, 100 or 120 rpm, and using different mean maximum annual flow speeds from 1.0 to 1.8 m/sec, maintaining a fixed coefficient of variation of 0.20 (20%).

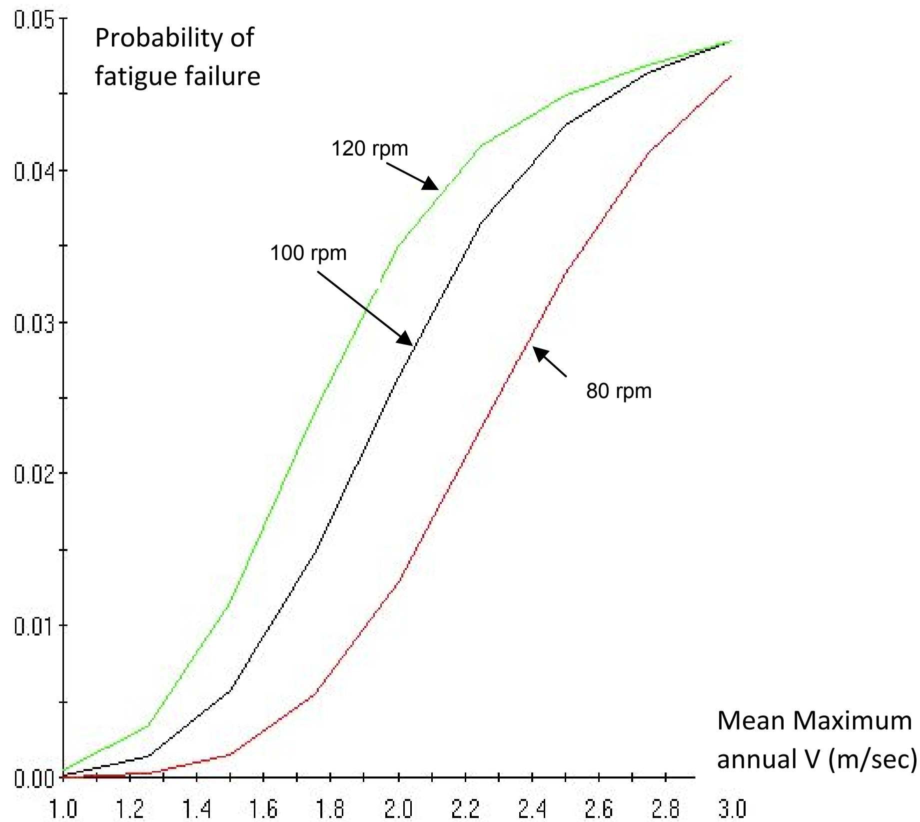

Figure 6. Probability of fatigue failure vs. mean maximum river current V, at different rotor controlled speeds

The results from Figure 6 show that the safety level SL4 (probability of failure not exceeding 0.01) is achieved for the combinations of 80rpm and V = 2.0m/sec, or 100rpm and V = 1.65m/sec, or 120rpm and V = 1.5m/sec.

Development of Load and Resistance Factors for a LRFD Design Equation

In LRFD, the design parameters are obtained through the use of a deterministic design equation, formulated in terms of characteristic loads and resistances, modified with load and resistance factors. Once the characteristic values are chosen, the load and resistance factors must be calibrated, to ensure that the resulting design achieves the desired reliability. The design equation in LRFD is normally meant to apply to a wide range of design situations. However, with a limited number of calibrated factors, the target reliability cannot be achieved exactly for all situations. Thus, this calibration implies that the LRFD design approach is an approximate method. The calibration is an optimization, seeking to minimize the error in the achieved reliability, which nevertheless will always vary from situation to situation.

1) Design equation and performance function

LRFD requires a choice for the format of the deterministic design situation. The results presented in this Report would be applicable to any REC system the performance of which can be described as in Eq.[1] or Eq.[11], with a proposed (generic) LRFD design equation of the form:

$$\alpha_D D_C + \alpha_1 L_{1C} + \alpha_2 L_{2C} = (R_C / \Upsilon) \ \Omega \qquad [10]$$

in which

$\alpha_D D_C$ = load factor and characteristic load effect for permanent loads;

$\alpha_1 L_{1C}$ = load factor and characteristic load effect for live load 1;

$\alpha_2 L_{2C}$ = load factor and characteristic load effect for live load 2;

Υ and R_C = resistance factor and characteristic value for the resistance R;

Ω = design parameter to be calculated from the equation (for example, turbine blade thickness).

Eq.[10] has the format normally adopted for LRFD structural design Codes, and it assumes the possibility of a combination of permanent load effects with up to two live loads. The design equation is deterministic, that is, it does not involve probabilities beyond the definition of the characteristic values for loads and resistances. The reliability achieved for the design parameter Ω is then estimated by the performance or limit state function G, as per Eq.[1]:

$$G = R\,\Omega - (D + L_1 + L_2) \qquad [11]$$

In which R, D, L_1 and L_2 are, respectively, the actual resistance, a permanent load effect and two live load effects that may be acting in combination. These are, in general, random variables.

The objective in the development of LRFD guidelines is the calibration of the factors α_D, α_1, α_2 and γ so that the calculated parameter Ω corresponds to a design with a probability of non-performance not exceeding a specified target. This probability is calculated for the event $G < 0$, using, for example, the software RELAN. The calibration is to be carried out for four target levels, SL1, SL2, SL3 and SL4, as described in Table 1.

Using the design Eq.[10], Ω is calculated as follows:

$$\Omega = (\alpha_D D_C + \alpha_1 L_{1C} + \alpha_2 L_{2C}) / (R_C / \Upsilon) \qquad [12]$$

for which the performance function G from Eq.[11] becomes:

$$G = (R/R_c)\,(\alpha_D D_C + \alpha_1 L_{1C} + \alpha_2 L_{2C})\,\Upsilon - (D + L_1 + L_2) \qquad [13]$$

The probability of $G<0$ is not changed if the function G is divided by a positive number. Thus, the function G can be written as follows, dividing by L_{1C}:

$$G = r\,[\alpha_D\,(D_C / L_{1C}) + \alpha_1 + \alpha_2\,(L_{2C} / L_{1C})]\,\Upsilon - [d\,(D_c / L_{1C}) + l_1 + l_2\,(L_{2C} / L_{1C})] \qquad [14]$$

in which $d = D/D_C$, $l_1 = L_1 / L_{1C}$ and $l_2 = L_2 / L_{2C}$ are the load effects normalized with respect to their respective characteristic values. Similarly, $r = R/R_c$ represents the normalized resistance. Finally,

$$G = r - [d\,(D_c / L_{1C}) + l_1 + l_2\,(L_{2C} / L_{1C})] / \{[\alpha_D\,(D_C / L_{1C}) + \alpha_1 + \alpha_2\,(L_{2C} / L_{1C})]\,\Upsilon\} \quad [15]$$

Eq.[15] allows the calculation of the probability of failure, P[G<0], as a function of the load and resistance factors, plus other parameters as discussed in the following section.

2) Intervening random variables

The random variables r, d, l_1 and l_2 determine the failure or non-performance probability P(G<0), or the reliability of the design. In addition, Eq.[15] shows that this probability is also controlled by the load and resistance factors ratios α_D , α_1 , α_2 and Υ, the characteristic load ratios D_c / L_{1C} and L_{2C} / L_{1C} , and the definition (return periods) chosen for the characteristic values of the live loads, L_{1C} and L_{2C} .

2.1) Permanent load effects:

When permanent load effects are considered, the random variable D is assumed Normally distributed, with mean D_m and standard deviation σ_D :

$$D = D_m + \sigma_D\, R_N \quad [16]$$

in which R_N is a Standard Normal random variable (mean = 0, standard deviation = 1). The characteristic value of D, D_c , is chosen equal to the mean D_m, or $D_c = D_m$. Therefore, finally,

$$d = D/D_c = 1.0 + V_D\, R_N \quad [17]$$

in which V_D is the coefficient of variation of the random, permanent load variable D.

2.2) System Resistance:

The resistance random variable R is assumed to obey a 2-parameter Weibull distribution, with scale parameter m and shape k , according to

$$R = m\,[-\ln(1 - p)]^{1/k} \qquad [18]$$

in which p is a random variable Uniformly distributed between 0 and 1. Weibull distributions are commonly used for the representation of material strengths.

The characteristic resistance R_c is associated with a lower percentile of R, corresponding to a probability level $p = p_c$. Thus,

$$R_c = m\,[-\ln(1 - p_c)]^{1/k} \qquad [19]$$

from which, the normalized variable $r = R/R_C$ results

$$r = [-\ln(1 - p_c)]^{-1/k}\,[-\ln(1 - p)]^{1/k} \qquad [20]$$

which is also a Weibull distribution, with a scale parameter $m^* = [-\ln(1 - p_c)]^{-1/k}$ and a shape $k^* = k$:

$$r = m^*\,[-\ln(1 - p)]^{1/k} \qquad [21]$$

Here p is a random variable Uniformly distributed between 0 and 1.

The shape parameter k is related to the coefficient of variation V_R of the resistance R, according to the following expression, using the Gamma function Γ:

$$V_R = \Gamma(1.0+2.0/k) / \Gamma^2(1.0+1.0/k) - 1.0 \qquad [22]$$

which can be approximated by $k \sim 1.2 / V_R$.

2.3) Live load effects:

The probability distribution of the live load effects L_1 and L_2 is assumed to be an Extreme Type I or a Gumbel distribution. This is generally used to represent maximum load effects (for example, in Canada it is used to describe maximum snow loads in a 30 or 50 year window). Here it is used to represent the maximum load effect in a *one year* window (annual maximum). An Extreme Type I distribution contains two parameters, A and B, as follows:

$$L_1 = B + (1.0/A)\,[-\ln(-\ln p)] \qquad [23]$$

in which p is a Uniform random variable between 0 and 1. For a Gumbel distribution, the product AB is related to the coefficient of variation V_1 of L_1 :

$$AB = [\pi/\sqrt{6}\;V_1] - 0.5772157 \qquad [24]$$

The mean of L_1, M_1 , and the corresponding standard deviation σ_1 are related to the parameters A and B,

$$M_1 = B + 0.5772157 / A$$

$$\sigma_1 = \pi/(\sqrt{6}\;A) \qquad [25]$$

The load corresponding to a return period of N_C years is obtained from the annual distribution of Eq.[23] using the probability level $p = (N_C - 1)/N_C$. For example, a 50-year return period load will correspond to a probability 49/50, or to a probability 1/50 of being exceeded on an annual basis. This load may be used as the characteristic load L_{1C} . Thus,

$$L_{1C} = B + (1.0/A)\,[-\ln(-\ln((N_C - 1)/N_C))] \qquad [26]$$

For design, and in correspondence with the characteristic value L_{1C} , L_1 is chosen here as the *maximum load effect that could occur over a window of Nc years*, which, using Eq.[23] , can be shown to be:

$$L_1 = B + (1.0/A)\,[\ln N_C - \ln(-\ln p)] \qquad [27]$$

From Eq.[26] and [27], the normalized design load effect $l_1 = L_1/ L_{1C}$ becomes:

$$l_1 = \{ AB + [\ln N_C - \ln(-\ln p)] \} / \{ AB + [-\ln(-\ln ((N_C - 1)/N_C)] \} \qquad [28]$$

which means that, since the product AB is directly related to the coefficient of variation V_1, the normalized live load effect variable l_1 can be obtained for different values of the random variable p, when V_1 and the definition of the return period N_C are given.

The same procedure is applied to the calculation of the normalized variable l_2 , in terms of V_2 , and the chosen corresponding return period Nc.

2.4) Ratios of Characteristic Load Effects

As shown by the performance function of Eq. [15], the probability of G<0 also depends on the characteristic load ratios D_C/L_{1C} , L_{2C}/L_{1C} . Using Eq.[26] and [17], it can be shown that these ratios can be written as follows:

$$L_{2C}/L_{1C} = (M_2/M1)(V2 / V_1) \{AB_1+ [-\ln(-\ln ((N_{C1}-1)/N_{C1})]\} / \{AB_2+ [-\ln(-\ln ((N_{C2} - 1)/N_{C2})]\}$$

$$D_C/L_{1C} = (D_m/M_1) [\pi / (\sqrt{6} V_1)] / \{AB_1+ [-\ln(-\ln ((N_{C1}-1)/N_{C1})]\} \qquad [29]$$

In which M_2 and V_2 are, respectively, the mean and the coefficient of variation of L_2 , while M_1 and V_1 are the corresponding values for L_1. Similarly, AB_1, from Eq.[24], corresponds to L_1 and depends only on V_1 , while AB_2 depends on V_2 and corresponds to L_2 . Load effects L_1 and L_2 could have different return periods N_{C1} and N_{C2} .

It is seen from Eq.[29] that the characteristic load ratios are determined when the ratios of means M_2/M1 and D_m/M_1 are given, along with the coefficient of variation V_1 and V_2 and the chosen return periods for defining the characteristic values L_{1C} and L_{2C}.

Finally, the intervening random variables were four (4):

- **X**(1) = Associated with the resistance R, Uniformly distributed between 0 and 1, Eq.[20];
- **X**(2) = Associated with the permanent load effect D, Standard Normal R_N, Eq.[17];
- **X**(3) = Associated with the live load L_1 , Uniformly distributed between 0 and 1, p in Eq.[20];

X(4) = Similar to X(3) but associated with the live load L_2 .

3) Procedure for calibration of the load and resistance factors

From the discussion in the previous section, the probability of non-performance associated with the performance function Eq.[15] depends on the following parameters:

- The return periods for the characteristics L_{1c} and L_{2c}
- The "*Design Situation*" defined by the ratios $(M_2/M1)$, (D_m/M_1), and the coefficients of variation V_R , V_D, V_1, V_2
- The set of "load and resistance factors" α_D , ϒ , α_1 , and α_2 .

V_R , V_D, V_1, V_2 are, respectively, the coefficients of variation of the resistance and the load effects, normalized with respect to their respective characteristic values. In the case of live load effects, V_1 and V_2 correspond to their respective distribution of annual maxima.

The computer program RELAN was adapted to calculate the probability of non-performance when the situation and the return periods are defined and the load factors are given. Probabilities were estimated by FORM (First Order Reliability Method).

A database was first developed for the different situations considered, either for only one live load (L_1) or two (L_1 and L_2). Appendix 1 shows the situations considered for the two cases, a total of 12 for only L_1 and 72 for L_1 and L_2.

The load factor for permanent load, α_D , and the resistance factor ϒ were both fixed at a value 1.10. The characteristic resistance were assumed throughout to be defined at the 25^{th}-percentile of the resistance distribution, or $p_c = 0.25$.

For each situation, the load factors α_1 , α_2 were assigned values between 1.0 and 4.0, with a step of 0.01. Thus, 301 values of α_1 were considered for the first case of only one load (L_1), and 90,601 combinations of α_1 and α_2 were used for the case of two (L_1 and L_2). RELAN was run for each combination, obtaining the probability of failure for the situation and the specified load factor(s). The results were stored in four files according to the achieved safety level:

File 1: Containing the set of factors leading to probabilities less or equal to 1.0×10^{-2} (level SL4)

File 2: Containing the set of factors leading to probabilities less or equal to 1.0×10^{-3} (level SL3)

File 3: Containing the set of factors leading to probabilities less or equal to 1.0×10^{-4} (level SL2)

File 4: Containing the set of factors leading to probabilities less or equal to 1.0×10^{-5} (level SL1)

- File 1 was then searched for the set of factors leading to the largest failure probability (in this case, the closest to 1.0×10^{-2}). This strategy enforces the minimum reliability required for the SL4 safety level while avoiding an over-conservative design. The same procedure was followed for Files 2, 3 and 4, searching for the set of factors leading to the largest probability (respectively, closest to 1.0×10^{-3} , 1.0×10^{-4} or 1.0×10^{-5}). The results for Files 1, 2, 3 and 4 are stored in a File 5, containing the parameters defining the situation and the corresponding set of optimum factors. Table 2 shows an example of typical results for File 5, for two live loads, for situation 1 as defined in Appendix 1 by the parameters

$(D_m/M_1) = 0.05$, $(M_2/M1) = 0.10$, $V_R = 0.05$, $V_D = 0.10$, $V_1 = 0.10$, and $V_2 = 0.10$.

The next four lines in Table 2 show the maximum probability of failure corresponding to the choice for the four factors α_D , ϒ , α_1 , and α_2 . Thus, the combination $\alpha_D = 1.1$, ϒ = 1.1 , $\alpha_1 = 1.3$, and $\alpha_2 = 2.92$ produces a maximum failure probability .99976910E-04 or very close 1.0×10^{-4} (SL2).

Table 2. Typical results: a situation and factors corresponding to the four safety levels.

1					
.050	.100	.050	.100	.100	.100
.99448833E-05	1.100	1.100	1.580	2.040	
.99976910E-04	1.100	1.100	1.300	2.920	
.99773155E-03	1.100	1.100	1.180	2.200	
.99582568E-02	1.100	1.100	1.120	1.360	

These calculations were then repeated for all the situations considered.

The results are presented for different choices of the live load return periods used to define the corresponding characteristic values. Results were obtained for the return period combinations shown in Table 3.

Table 3. *Return Periods (years) for Live Load Combinations*

Load L_1	Load L_2
50	25
50	1
25	25
25	1
50	- (only L_1)
25	- (only L_1)
1	- (only L_1)

4) Results, Load factor α_1, Permanent and only one Load L_1

Figure 8 and Table 4 show the load factor α_1 for the case of only one live load. This factor is discriminated by safety class (SL1, SL2, SL3 or SL4), and the return period used to define the characteristic value of the load. A return period of 25 years, for example, is associated with L_1 being the maximum load effect over a 25 year window.

The factor α_1 changes with the design situation. Ideally, this variability should be small, to increase the range of applicability of the LRFD approach. Table 4 gives the results, including the mean and standard deviation of the calculated factor α_1 considering all the situations described in Appendix 1. These statistics were obtained from lognormal fits of the α_1 data, and Figure 9 shows a typical example of this fit for the case SL4, 50 year return period.

It is seen that α_1 increases with the target failure probability required, that is, it is larger for SL1 than for SL4. Further, there is a moderate dependence on the choice for the return period, with α_1 increasing when the return period is shorter and the variability in the load correspondingly increases.

Figure 8. Load Factor α_1, case of only Load L_1

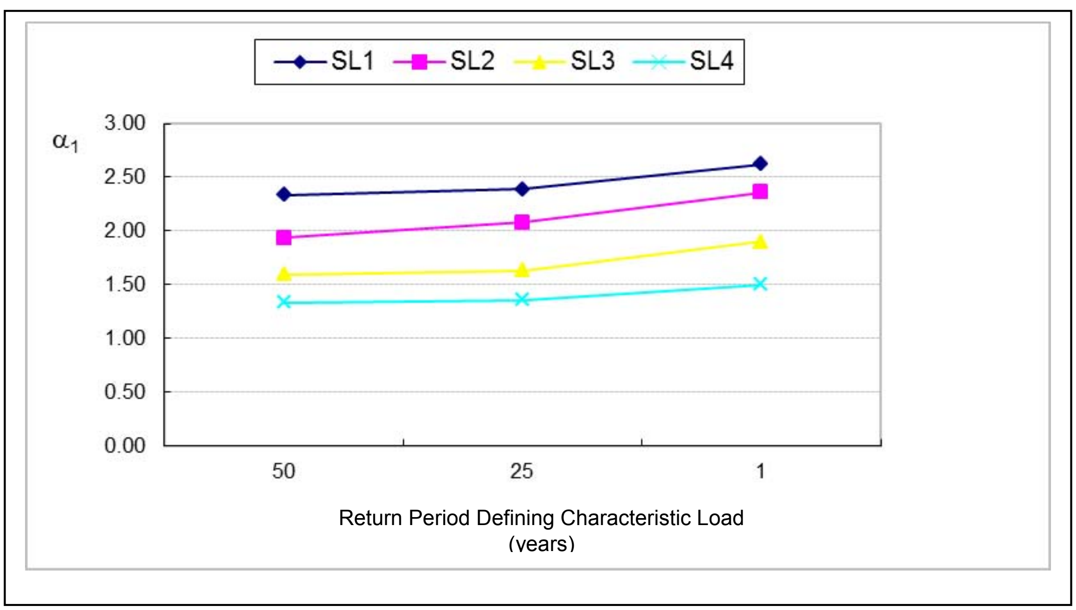

Table 4. Load and resistance factors, case of only one live load L_1 .

p_c		Return Period (years)	γ	α_D	$\alpha_{1(Mean)}$	α_1 (Std. Dev.)
0.25	SL1	50	1.10	1.10	2.34	0.38
		25	1.10	1.10	2.39	0.48
		1	1.10	1.10	2.62	0.77
	SL2	50	1.10	1.10	1.94	0.33
		25	1.10	1.10	2.08	0.39
		1	1.10	1.10	2.37	0.77
	SL3	50	1.10	1.10	1.59	0.18
		25	1.10	1.10	1.63	0.19
		1	1.10	1.10	1.90	0.40
	SL4	50	1.10	1.10	1.34	0.11
		25	1.10	1.10	1.36	0.13
		1	1.10	1.10	1.50	0.25

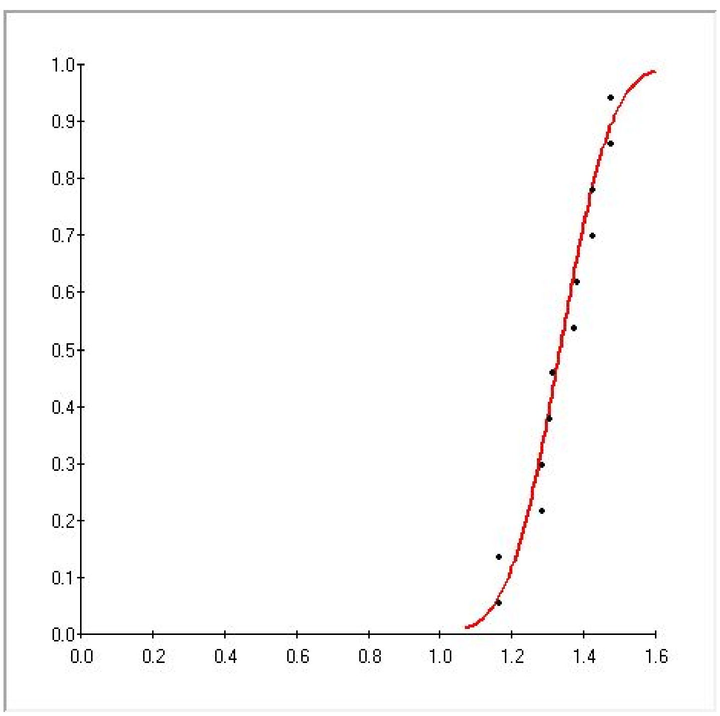

Figure 9. Lognormal fit of α_1 , SL4 level, 50 year return period

Table 4 shows the mean and standard deviation of **α_1** over all situations. Since these include the parameter V1, Table 5 shows the mean values of **α_1** discriminating by the coefficient of variation V1 of the load L_1 .

Tables 4 and 5 are reproduced in Appendix 2 as a summary for possible consideration by the TC114.

Table 5. Load factor α_1, only one live load L_1, influence of V1

α_1 (Mean)			V1		
			0.1	0.2	0.3
PCR	SL1	Return Period			
		50	2.15	2.53	2.58
		25	2.11	2.44	2.54
		1	2.08	2.55	3.85
0.25	SL2	50	1.69	1.91	2.22
		25	1.75	2.09	2.41
		1	1.75	2.41	3.49
	SL3	50	1.43	1.62	1.74
		25	1.45	1.64	1.82
		1	1.47	1.91	2.33
	SL4	50	1.22	1.34	1.45
		25	1.23	1.37	1.49
		1	1.23	1.49	1.79

5) Results, Load factors α_1 and α_2, Permanent and Loads L_1 , L_2

Table 6 and 7 show the results for the load factors α_1 and α_2 for the case in which a permanent load acts in combination with two live loads L_1 , L_2 . The return periods for these loads were as specified in Table 3. The Tables show the mean and the standard deviation of the load factors over all the 72 situations considered, as described in Appendix 1. The statistics for the factors were obtained with lognormal fits of the data, and Figure 10 shows a typical such fit for $\boldsymbol{\alpha_1}$.

Tables 6 and 7 are reproduced in Appendix 2, as a summary for possible use by TC114.

Table 6. Load factors α1 and α2, Permanent and Two Loads L_1 , L_2

Return Periods $N_{C1} - N_{C2}$ (years)	Safety Level	α_1(mean)	Std.Dev. α_1	α_2(mean)	Std.Dev. α_2
50 -1	1	**2.04**	**0.42**	**2.59**	**0.89**
	2	**1.75**	**0.35**	**2.53**	**0.88**
	3	**1.41**	**0.23**	**2.69**	**0.96**
	4	**1.16**	**0.13**	**2.43**	**0.88**
50 – 25	1	**2.04**	**0.47**	**2.44**	**0.99**
	2	**1.73**	**0.33**	**2.61**	**0.89**
	3	**1.38**	**0.22**	**2.55**	**0.84**
	4	**1.19**	**0.11**	**2.06**	**0.84**

Table 7. Load factors α1 and α2, Permanent and Loads L_1 , L_2

Return Periods $N_{C1} – N_{C2}$ (years)	Safety Level	α_1(mean)	Std.Dev. α_1	α_2(mean)	Std.Dev. α_2
25 – 1	1	**2.14**	**0.44**	**2.46**	**0.85**
	2	**1.86**	**0.40**	**2.46**	**0.82**
	3	**1.47**	**0.25**	**2.40**	**0.84**
	4	**1.20**	**0.12**	**2.26**	**0.99**
25 – 25	1	**2.04**	**0.52**	**2.98**	**0.96**
	2	**1.76**	**0.46**	**2.59**	**0.95**
	3	**1.35**	**0.25**	**2.71**	**0.91**
	4	**1.18**	**0.14**	**2.14**	**0.86**

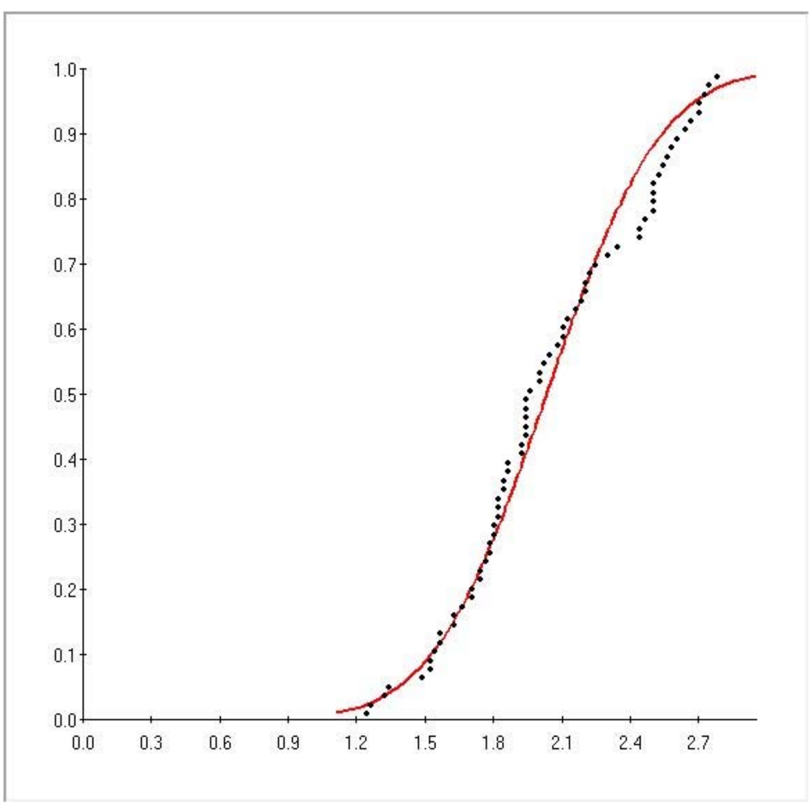

Figure 10. *Load factor α1,* Lognormal fit, Safety Level SL1, Return period of 50 years for L_1 and 1 year for L_2

Further Research

Several areas are highlighted for further research:

- To tie the outcome of this Report to the work of the resource assessment and performance groups.
- To discuss and provide guidance as to the random variables in the analysis, particularly standardization as to the types of probability distributions and sources and gathering of data.
- Consideration of specific loading situations and their characteristics: flow speed and influence of turbulence, ice loadings, debris impact. This could make use of data from some actual river sites that have been studied in detail (e.g. the CHTTC or test sites in Alaska). In this context, statistical information should be gathered on arrival and durations of events like ice loadings, or impacting debris.
- This report has considered the fatigue limit state for the turbine blades, but other limit states must be considered (e.g., anchoring of the turbine to the river bed) and calculation of the overall reliability regardless of the failure mode.
- The development of specialized software, freely available, for the reliability study of a REC or MEC system in the context of performance-based design and cost optimization.

References

1. IEC (International Electrotechnical Commission), TC 114, IEC 62600-2: Marine Energy - Wave, tidal and other water current converters - Part 2: Design requirements for marine energy systems, 2014.
2. Gaizka Zarraonandia, S., Piing Chen, and Bittencourt Ferreira, C., *Partial Safety Factors and Design Fatigue Factors for Design Requirements of Tidal Turbines, A Risk-Based Approach*, Proceedings of the 34th International Conference on Ocean, Offshore and Arctic Engineering OMAE2015, May 31- June 5, 2015, St. John's, NL, Canada.

Contribution to Technology Transfer

Dr. Gouri Bhuyan, “Guideline for Reliability Assessment and Calibrated Load & Resistance Factored Design (LRFD) Procedures: River Current Energy Conversion Systems”, SMC/TC 114 Committee, March 21, 2016.

Appendix 1. *Design Situations for Calibration*

Situations for L_1 only:

D_m/M_1	V_R	V_D	V_1
0.050	0.050	0.100	0.100
0.050	0.050	0.100	0.200
0.050	0.050	0.100	0.300
0.050	0.100	0.100	0.100
0.050	0.100	0.100	0.200
0.050	0.100	0.100	0.300
0.100	0.050	0.100	0.100
0.100	0.050	0.100	0.200
0.100	0.050	0.100	0.300
0.100	0.100	0.100	0.100
0.100	0.100	0.100	0.200
0.100	0.100	0.100	0.300

Total = 12

Situations for L_1 and L_2:

D_m/M_1	M_2/M_1	V_R	V_D	V_1	V_2
0.050	0.100	0.050	0.100	0.100	0.100
0.050	0.100	0.050	0.100	0.100	0.200
0.050	0.100	0.050	0.100	0.200	0.100
0.050	0.100	0.050	0.100	0.200	0.200
0.050	0.100	0.050	0.100	0.300	0.100
0.050	0.100	0.050	0.100	0.300	0.200
0.050	0.100	0.100	0.100	0.100	0.100
0.050	0.100	0.100	0.100	0.100	0.200
0.050	0.100	0.100	0.100	0.200	0.100
0.050	0.100	0.100	0.100	0.200	0.200
0.050	0.100	0.100	0.100	0.300	0.100
0.050	0.100	0.100	0.100	0.300	0.200
0.050	0.200	0.050	0.100	0.100	0.100
0.050	0.200	0.050	0.100	0.100	0.200
0.050	0.200	0.050	0.100	0.200	0.100
0.050	0.200	0.050	0.100	0.200	0.200
0.050	0.200	0.050	0.100	0.300	0.100
0.050	0.200	0.050	0.100	0.300	0.200
0.050	0.200	0.100	0.100	0.100	0.100
0.050	0.200	0.100	0.100	0.100	0.200
0.050	0.200	0.100	0.100	0.200	0.100
0.050	0.200	0.100	0.100	0.200	0.200
0.050	0.200	0.100	0.100	0.300	0.100
0.050	0.200	0.100	0.100	0.300	0.200
0.050	0.300	0.050	0.100	0.100	0.100
0.050	0.300	0.050	0.100	0.100	0.200
0.050	0.300	0.050	0.100	0.200	0.100
0.050	0.300	0.050	0.100	0.200	0.200
0.050	0.300	0.050	0.100	0.300	0.100
0.050	0.300	0.050	0.100	0.300	0.200
0.050	0.300	0.100	0.100	0.100	0.100
0.050	0.300	0.100	0.100	0.100	0.200
0.050	0.300	0.100	0.100	0.200	0.100
0.050	0.300	0.100	0.100	0.200	0.200
0.050	0.300	0.100	0.100	0.300	0.100
0.050	0.300	0.100	0.100	0.300	0.200
0.100	0.100	0.050	0.100	0.100	0.100
0.100	0.100	0.050	0.100	0.100	0.200
0.100	0.100	0.050	0.100	0.200	0.100

Appendix 1. *Design Situations for Calibration*

Situations for L_1 and L_2 (Continued)

Dm/M1	M2 /M1	VR	VD	V1	V2
0.100	0.100	0.050	0.100	0.200	0.200
0.100	0.100	0.050	0.100	0.300	0.100
0.100	0.100	0.050	0.100	0.300	0.200
0.100	0.100	0.100	0.100	0.100	0.100
0.100	0.100	0.100	0.100	0.100	0.200
0.100	0.100	0.100	0.100	0.200	0.100
0.100	0.100	0.100	0.100	0.200	0.200
0.100	0.100	0.100	0.100	0.300	0.100
0.100	0.100	0.100	0.100	0.300	0.200
0.100	0.200	0.050	0.100	0.100	0.100
0.100	0.200	0.050	0.100	0.100	0.200
0.100	0.200	0.050	0.100	0.200	0.100
0.100	0.200	0.050	0.100	0.200	0.200
0.100	0.200	0.050	0.100	0.300	0.100
0.100	0.200	0.050	0.100	0.300	0.200
0.100	0.200	0.100	0.100	0.100	0.100
0.100	0.200	0.100	0.100	0.100	0.200
0.100	0.200	0.100	0.100	0.200	0.100
0.100	0.200	0.100	0.100	0.200	0.200
0.100	0.200	0.100	0.100	0.300	0.100
0.100	0.200	0.100	0.100	0.300	0.200
0.100	0.300	0.050	0.100	0.100	0.100
0.100	0.300	0.050	0.100	0.100	0.200
0.100	0.300	0.050	0.100	0.200	0.100
0.100	0.300	0.050	0.100	0.200	0.200
0.100	0.300	0.050	0.100	0.300	0.100
0.100	0.300	0.050	0.100	0.300	0.200
0.100	0.300	0.100	0.100	0.100	0.100
0.100	0.300	0.100	0.100	0.100	0.200
0.100	0.300	0.100	0.100	0.200	0.100
0.100	0.300	0.100	0.100	0.200	0.200
0.100	0.300	0.100	0.100	0.300	0.100
0.100	0.300	0.100	0.100	0.300	0.200

Total = 72

Appendix 2.

SUMMARY OF LRFD LOAD FACTORS RESULTS FOR TC 114

Table 4. Load and resistance factors, case of only one live load L_1 .

p_c	Safety Level	Return Period (years)	γ	α_D	$\alpha_{1(Mean)}$	α_1 (Std. Dev.)
0.25	SL1	50	1.10	1.10	2.34	0.38
		25	1.10	1.10	2.39	0.48
		1	1.10	1.10	2.62	0.77
	SL2	50	1.10	1.10	1.94	0.33
		25	1.10	1.10	2.08	0.39
		1	1.10	1.10	2.37	0.77
	SL3	50	1.10	1.10	1.59	0.18
		25	1.10	1.10	1.63	0.19
		1	1.10	1.10	1.90	0.40
	SL4	50	1.10	1.10	1.34	0.11
		25	1.10	1.10	1.36	0.13
		1	1.10	1.10	1.50	0.25

Table 5. Load factor α_1, only one live load L_1, influence of V1

α_1 (Mean)			V1		
			0.1	0.2	0.3
PCR		Return Period			
0.25	SL1	50	2.15	2.53	2.58
		25	2.11	2.44	2.54
		1	2.08	2.55	3.85
	SL2	50	1.69	1.91	2.22
		25	1.75	2.09	2.41
		1	1.75	2.41	3.49
	SL3	50	1.43	1.62	1.74
		25	1.45	1.64	1.82
		1	1.47	1.91	2.33
	SL4	50	1.22	1.34	1.45
		25	1.23	1.37	1.49
		1	1.23	1.49	1.79

Table 6. Load factors α1 and α2, Permanent and Two Loads L_1 , L_2

Return Periods $N_{C1} – N_{C2}$ (years)	Safety Level	α_1(mean)	Std.Dev. α_1	α_2(mean)	Std.Dev. α_2
50 -1	1	**2.04**	**0.42**	**2.59**	**0.89**
	2	**1.75**	**0.35**	**2.53**	**0.88**
	3	**1.41**	**0.23**	**2.69**	**0.96**
	4	**1.16**	**0.13**	**2.43**	**0.88**
50 – 25	1	**2.04**	**0.47**	**2.44**	**0.99**
	2	**1.73**	**0.33**	**2.61**	**0.89**
	3	**1.38**	**0.22**	**2.55**	**0.84**
	4	**1.19**	**0.11**	**2.06**	**0.84**

Table 7. Load factors α1 and α2, Permanent and Two Loads L_1 , L_2

Return Periods $N_{C1} – N_{C2}$ (years)	Safety Level	**α_1**(mean)	Std.Dev. **α_1**	**α_2**(mean)	Std.Dev. **α_2**
25 – 1	1	**2.14**	**0.44**	**2.46**	**0.85**
	2	**1.86**	**0.40**	**2.46**	**0.82**
	3	**1.47**	**0.25**	**2.40**	**0.84**
	4	**1.20**	**0.12**	**2.26**	**0.99**
25 – 25	1	**2.04**	**0.52**	**2.98**	**0.96**
	2	**1.76**	**0.46**	**2.59**	**0.95**
	3	**1.35**	**0.25**	**2.71**	**0.91**
	4	**1.18**	**0.14**	**2.14**	**0.86**