OCEAN POWER TECHNOLOGY DESIGN OPTIMIZATION

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BACKGROUND

Ocean waves are a potentially vast renewable energy resource, with roughly 2 TW available globally [1]. Yet, compared to other renewable energy technologies, such as wind and solar, wave energy technology is immature, with the majority of wave energy converters (WECs) still in the research and development stage. As with any early technology, one of the obstacles to further development is a lack of proven design tools and methodologies. To fill this need, the National Renewable Energy Laboratory (NREL) and Sandia National Laboratories (SNL) have developed WEC-Sim (Wave Energy Convertor Simulator), an open-source, dynamics simulator for WECs. To validate the accuracy of WEC-Sim, its results must be compared with reliable WEC test data, which are limited and typically proprietary. Ocean Power Technologies (OPT) [2], a leading developer of wave energy convertors, however, has conducted extensive wave tank and periodic ocean testing of their PowerBuoy® WEC. Furthermore, OPT is continually working to optimize their PowerBuoy design to maximize performance while maintaining or improving manufacturability. This convergence of NREL and OPT objectives led to the subsequent collaborative study, with the following goals; 1) validate WEC-Sim using OPT's PowerBuoy tank test data, 2) develop a design optimization methodology for WECs utilizing WEC-Sim, 3) and finally, using this methodology, compare several design variations of OPT's PowerBuoy.

OPT'S POWERBUOY

Based on prior design experience and wave tank tests conducted in 2010 and 2012 [3], OPT was interested in evaluating and comparing several promising float and mooring design variations of their PowerBuoy. The floats selected for further evaluation were a symmetric float, '*F1*,' and a rhombus float, '*F3*.' The moorings selected for further assessment were a fixed monopile configuration, '*MP*,' and a compliant spar-plate configuration, '*SP*.' These components are shown schematically in Figure 1 for the *F3-MP* and *F1-SP* configurations. The mooring for the spar-plate design is applied via four symmetric lines attached below the surface. In these simulations, a linear power-take-off (PTO) was assumed, a control system was not implemented, the PTO stiffness was set to zero, the PTO damping was optimized for power output at each sea state, and no end stops were imposed.

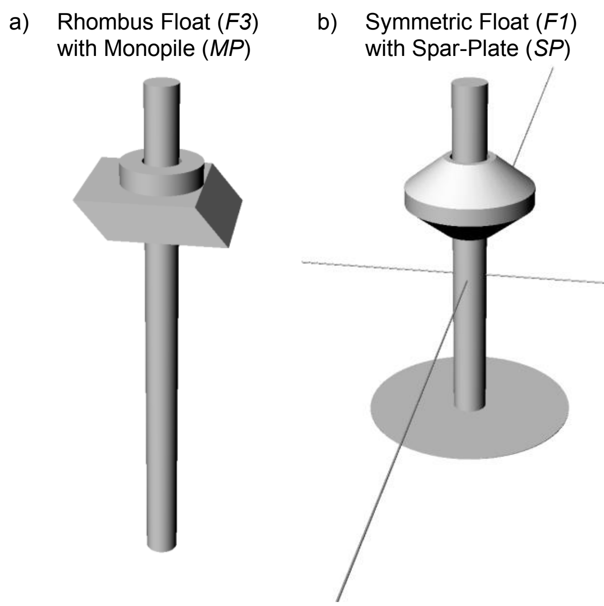

FIGURE 1. OPT POWERBUOY GEOMETRIES.

WEC-SIM

As discussed previously, the numerical model used and validated in this study is WEC-Sim. WEC-Sim is a WEC simulator that utilizes the multi-dynamics solver SimMechanics in MATLAB/SIMULINK. A detailed description of the theory and use of WEC-Sim is provided in the online documentation [4], but in short, WEC-Sim is able to simulate devices that are made up of rigid bodies, PTO mechanisms and mooring systems by solving the WEC equations of motion in the time domain for six degrees-of-freedom (DOF). Among other inputs, WEC-Sim requires the input of the system's hydrodynamic force coefficients prior to running. Typically, the linear radiation and excitation force coefficients are obtained with a frequency-domain boundary element method (BEM). In this study, the BEM code WAMIT [5] was used to obtain the linear hydrodynamic coefficients for each PowerBuoy float-mooring combination: *F1-MP*, *F3-MP*, *F1-SP*, and *F3-SP*.

In addition to the linear BEM hydrodynamic coefficients, WEC-Sim requires estimates of the viscous drag coefficients, C_D, for each body and DOF. C_D's may be obtained from experimental measurements, numerical simulations, or from previously reported values. In this case, C_D for *F1* and *F3* in heave, the primary DOF, were calculated with the CFD code STAR-CCM+ [6]. All other component and DOF C_D were estimated based on typical values reported in literature, specifically C_D = 1.2. C_D for *F1* and *F3* were calculated by simulating a free-decay response. From the free-decay response, a total damping coefficient, c, may be calculated from the logarithmic decrement of each decay amplitude [7]. c, however, includes both linear, ($c_v + b$), and quadratic components, c_d, as indicated in Equation 1. To extract c_d, c_d is replaced with an equivalent linear damping coefficient, $8c_d\omega z_a/3\pi$, as shown in Equation 1 [7], where ω is the oscillation frequency and z_a is the oscillation amplitude. c_d is then calculated based on the slope of the c values with respect to $8\omega z_a/3\pi$. And lastly, $C_D = c_d / (½\rho A_{ref})$, where A_{ref} is the float's reference area in heave.

$$F_{damping} = c\dot{z} = (c_v + b)\dot{z} + c_d|\dot{z}|\dot{z} = (c_v + 8c_d\omega z_a/3\pi)\dot{z} \quad (1)$$

The free-decay response was modeled in STAR-CCM for the heave DOF with the float centered in a square computational domain (with applicable symmetries applied), two wavelengths to each side, and a damping zone of one wavelength at the periphery. The simulations were run with a k-ω turbulence model and second-order temporal discretization. The free-decay response was realized by giving the float an initial displacement and then releasing it at t = 0 s. Each simulation was run for ~2.5T, where T is the oscillation period (after which, the grid resolution is insufficient to accurately resolve the small amplitude oscillation forces). Following grid resolution studies, the horizontal grid resolution used was 68-79 cells per wavelength (λ), 10 cells per smallest $2z_a$, and the time step was dictated by $\Delta t \leq 0.5\Delta z_{min}T/\lambda$. This resulted in 4.9×10^6 and 13.5×10^6 cells for the *F1* and *F3* simulations, respectively. The resulting ratio of drag coefficients for *F3* and *F1* was, $C_{D,F3}/ C_{D,F1}$ = 1.8.

DESIGN OPTIMIZATION

Once the 6 DOF WEC-Sim models have been setup, and the hydrodynamic coefficients obtained, the various PowerBuoy configurations can be simulated and compared. To compare the different float-mooring configurations, WEC-Sim was used to simulate the average power production, fatigue loads, extreme condition response, and effect of directional waves. As a basis for these comparisons, the joint probability distribution of Humboldt Bay [8] was used, as illustrated in Figure 2, where H_s is the significant wave height and T_e is the wave energy period.

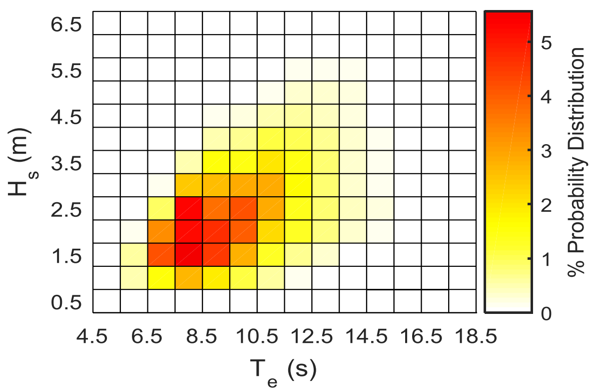

FIGURE 2. HUMBOLDT BAY JOINT PROBABILITY DISTRIBUTION [8].

Power Production

To first validate WEC-Sim's model of OPT's PowerBuoy, the power production predicted by WEC-Sim for the *F1-MP* and *F3-MP* configurations were compared to experimentally measured tank test values [3]. For these simulations WEC-Sim was run with a Bretschneider wave spectrum (for which, $T_e = 1.206T_a$, where T_a is the average period) for a 3 hr simulation time, plus a $5T_e$ ramp up period, with $\Delta t = T_e/400$. The average power predicted by WEC-Sim is compared to OPT's measured values in Figure 3, where the power has been normalized by P_o, the experimental value for the *F1-MP* configuration at T_a = 7 s and H_s = 2 m.

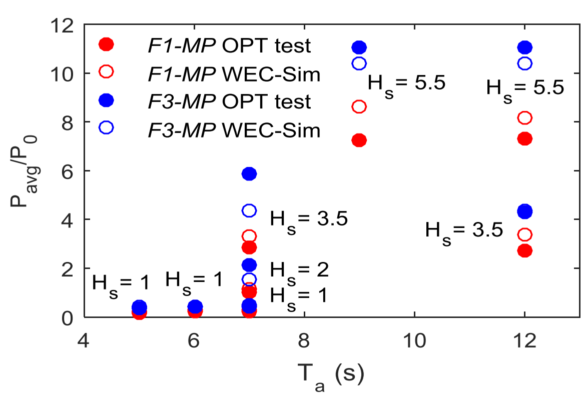

FIGURE 3. COMPARISON OF OPT TANK TEST AND WEC-SIM COMPUTED NORMALIZED P_{avg}.

For the sea states examined, WEC-Sim over predicts P_{avg}/P_0 by 0.45 for *F1-MP* and under predicts P_{avg}/P_0 by 0.38 for *F3-MP*, on average. However, the overall agreement is good, particularly at lower H_s where the response is linear, as is assumed in the WEC-Sim model (the test and WEC-Sim symbols are overlapping for the $H_s = 1$ data in Figure 3). Given these results, WEC-Sim can be employed with some confidence in predicting the power production of the different PowerBuoy design configurations.

Using the same WEC-Sim setup parameters and as described for the validation simulations, power matrices for the Humboldt Bay probability distribution were produced for each PowerBuoy configuration: *F1-MP*, *F3-MP*, *F1-SP*, and *F3-SP*. Multiplying the simulated power output at each sea state by the corresponding probability, and summing the results for all sea states, gives the expected annual average mechanical power (assuming no losses), P_{avg}^{1yr}. The resulting P_{avg}^{1yr} for each configuration, normalized by the *F1-MP* value, is given in Table 1. These results indicate that the *F3-MP* configuration produces the most power, on average; and that the use of *SP* mooring, for either float, reduces the expected P_{avg}^{1yr}.

TABLE 1. NORMALIZED AVERAGE ANNUAL POWER.

$\frac{P_{avg,F1-MP}^{1yr}}{P_{avg,F1-MP}^{1yr}}$	$\frac{P_{avg,F3-MP}^{1yr}}{P_{avg,F1-MP}^{1yr}}$	$\frac{P_{avg,F1-SP}^{1yr}}{P_{avg,F1-MP}^{1yr}}$	$\frac{P_{avg,F3-SP}^{1yr}}{P_{avg,F1-MP}^{1yr}}$
1.000	1.120	0.871	0.836

Fatigue Loads

To estimate the effect of fatigue loads on the PowerBuoy PTO system, damage equivalent loads were calculated using Miner's rule, Equation 2 [9].

$$F_{eq} = \sqrt[m]{\sum F_i^m n_i / N} \qquad (2)$$

Where, F_{eq} is the equivalent load for N cycles; F_i is the load range for bin i; n_i is the number of rain flow cycles for load range bin i; m is the *S-N* (stress with number of cycles) curve slope; and N is the total number of cycle repetitions. The load considered in this study was the PTO force, F_{PTO}, and, m was assigned a value of 6 (the value used for m was somewhat arbitrary; $m \approx$ 3-4 for welded steel, $m \approx$ 6-8 for cast iron, and $m \approx$ 9-12 for composites [9]; however, for the purpose of design comparison, the exact value is inconsequential). Based on the Humboldt Bay probability distribution, the annual average number of cycles for a three-hour period is N = 1,491, and for the entire year, the expected number of cycles is N = 4,353,644. Using these cycle repetitions, three-hour equivalent fatigue loads, F_{eq}^{3hr}, were calculated for each sea state in the Humboldt Bay's probability distribution; and, a cumulative annual equivalent fatigue load, F_{eq}^{1yr}, was calculated for the entire distribution. Fatigue calculations for the different PowerBuoy configurations were completed with the same WEC-Sim simulations used to generate the power matrices and annual average power. The normalized F_{eq}^{1yr} values are compared for each PowerBuoy configuration in Table 2. The results in Table 2 indicate that *F3*, when combined with *MP*, results in the largest loads, on average; but, when combined with *SP*, results in the smallest loads, on average.

TABLE 2. NORMALIZED ANNUAL FATIGUE LOAD.

$\frac{F_{eq,F1-MP}^{1yr}}{F_{eq,F1-MP}^{1yr}}$	$\frac{F_{eq,F3-MP}^{1yr}}{F_{eq,F1-MP}^{1yr}}$	$\frac{F_{eq,F1-SP}^{1yr}}{F_{eq,F1-MP}^{1yr}}$	$\frac{F_{eq,F3-SP}^{1yr}}{F_{eq,F1-MP}^{1yr}}$
1.000	1.068	1.027	0.914

To provide further validation of the WEC-Sim model, wave tank $F_{PTO}(t)$ data provided by OPT for the *F3-MP* configuration were also used to calculate F_{eq}^{3hr}. F_{eq}^{3hr} derived from the experimentally measured time series are compared to the WEC-Sim derived F_{eq}^{3hr} in Figure 4, were the loads are normalized by F_o, the experimental F_{eq}^{3hr} for *F3-MP* at T_a = 7 s and H_s = 2 m. This comparison shows reasonable agreement for all points, again, particularly at lower H_s, with an average difference in experimental and WEC-Sim F_{eq}^{3hr}/F_0 of 0.515.

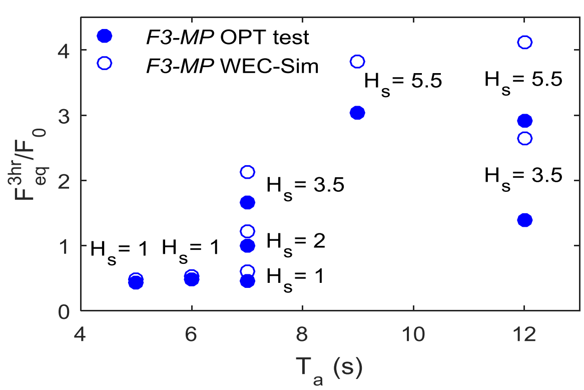

FIGURE 4. COMPARISON OF OPT TANK TEST AND WEC-SIM COMPUTED NORMALIZED F_{eq}^{3hr}.

Extreme Conditions

WEC-Sim is based on linear BEM hydrodynamics, and consequently, cannot accurately simulate nonlinear extreme load scenarios. However, using a design approach adopted from the naval and offshore oil and gas industries, linear based models, such as WEC-Sim, may be used to approximate the extreme condition loads and the scenarios in which they occur; and then, high-fidelity models, such as CFD, may be used to evaluate the extreme loads in more detail at a later stage in the design process. The focus of this study is on the early stage WEC design process, in which, extreme load approximations are appropriate for the purpose of design comparison. To compare the extreme condition response of the various PowerBuoy configurations, five points from the Humboldt Bay 100-year wave contour [8], as specified in Figure 5, were examined with WEC-Sim. In these simulations, the PTO damping coefficient was set to zero, allowing the float to move freely. The loads selected to quantify the extreme condition response were the heave displacement, *z*, the *x*-direction relative force between the float and the mooring body, F_{float}, and the *x*-direction mooring force, $F_{mooring}$ (which is zero in the *MP* configurations).

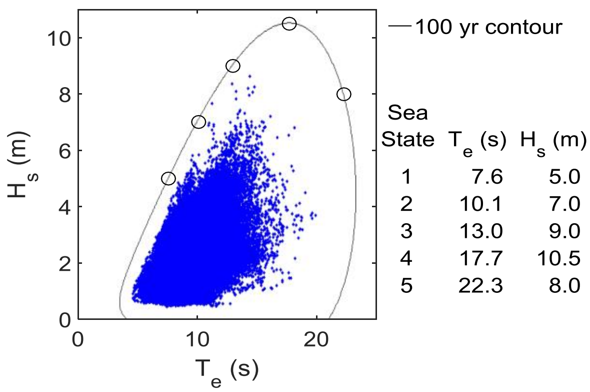

FIGURE 5. HUMBOLDT BAY 100-YEAR CONTOUR [8].

Maximum extreme loads are often in response to a particular, instantaneous position and wave elevation, which does not necessarily correspond to the largest wave height. As such, to determine the most likely extreme load with an irregular sea state model, the occurrence of the extreme load is treated stochastically. Each extreme sea state was simulated 200 times in WEC-Sim using a Bretschneider wave spectrum, with a different initial random wave phase, for 3 hours plus a $25T_e$ ramp up period, using $\Delta t = T_e/200$. The maximum loads during each simulation were recorded and utilized to generate probability distributions (PDFs), and from the PDFs, cumulative distributions (CDFs), as illustrated for an example maximum heave displacement in Figure 6. From the CDF, the 99% load was then identified as the most likely maximum design load for that sea state, as indicated in Figure 6. This approach of estimating the extreme response is a variation of the block maxima method, which requires the most significant number of simulations, but also provides the most accurate short term extreme response estimate [10]. Other approaches could have potentially been employed, such as the all-peaks Weibull method, which estimates the extreme response based on a single simulation, but results in a less accurate extreme response estimate [10].

The resulting most likely normalized maximum loads for each PowerBuoy configuration and extreme sea state are plotted in Figure 7. The peak extreme response for all loads and configurations correspond to the sea state with the largest wave height, Sea State 4, except F_{float} in the *MP* configurations, which occurred at T_e = 10.1 s. From these results, it appears that the particular float-mooring combination has little effect on the maximum heave displacement. However, the maximum F_{float} was 1.3-1.7 times larger for the *MP* configurations than the *SP* configurations, since the mooring lines take much of the total surge load.

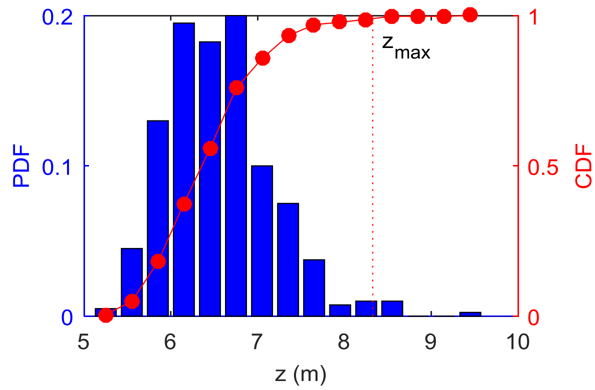

FIGURE 6. EXTREME HEAVE CDF AND PDF EXAMPLE.

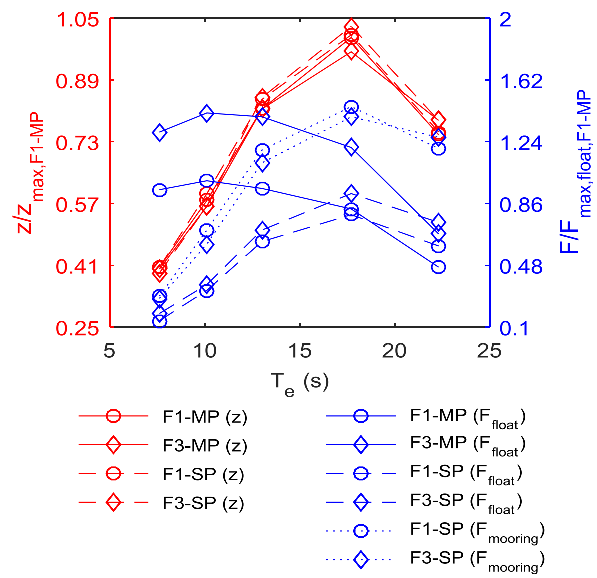

FIGURE 7. NORMALIZED EXTREME CONDITION MAXIMUM LOADS.

Directional Waves

Thus far, all power production and load estimates were made assuming a 0^0 wave heading. However, the wave environment at the deployment site will change with the wind direction and bathymetry. The effect of varying wave headings may result in higher design loads and lower power extraction efficiencies for the asymmetric *F3* configurations. To quantify any directional effects, WEC-Sim (and necessarily WAMIT), was used to reevaluate the *F3-MP* and *F3-SP* power production and loads with a 30^0 wave heading. Table 3 compares the resulting normalized annual average power, cumulative annual equivalent load, and extreme condition loads for the 0^0 and 30^0 wave headings.

TABLE 3. DIRECTIONAL EFFECTS FOR *F3* AT 30^0.

	$\frac{P^{1yr}_{avg,30°}}{P^{1yr}_{avg,0°}}$	$\frac{F^{1yr}_{eq,30°}}{F^{1yr}_{eq,0°}}$	$\frac{z_{30°}}{z_{0°}}$	$\frac{F_{float,30°}}{F_{float,0°}}$	$\frac{F_{mooring,30°}}{F_{mooring,0°}}$
F3-MP	0.963	0.991	0.994	1.017	-
F3-SP	0.988	1.031	0.976	0.918	0.966

With a 30^0 wave heading, compared to the 0^0 wave heading, there is a slight drop in the expected power production, 1–4%, but the directional effect on the fatigue and extreme loads was minimal. These limited results indicate that directional effects are fairly insignificant for the *F3* configurations. However, before this can be stated conclusively, a thorough analysis of the complete wave spectrum, and additional fatigue analyses, for loads that are likely to be strongly affected by directional waves, such as the mooring loads, should be carried out.

CONCLUSIONS

NREL provided technical support to industry partner OPT in the capacity of design optimization. NREL employed WEC-Sim to simulate and compare various PowerBuoy configurations. As part of this process, WEC-Sim was validated with experimental data provided by OPT, and C_D were acquired via CFD for the two floats studied. WEC-Sim was then utilized to estimate the power performance and loads for operational conditions, extreme conditions and directional waves, assuming the wave environment of Humboldt Bay.

The final power to weight, P^{1yr}_{avg}/W_{disp}, power to fatigue load, $P^{1yr}_{avg}/F^{1yr}_{eq}$, power to maximum extreme load, P^{1yr}_{avg}/F_{float}, power to water plane area, P^{1yr}_{avg}/A_{plane}, and power to wetted surface area, P^{1yr}_{avg}/A_{wetted}, ratios are given in Table 4, where the best case is highlighted for each parameter. In calculating these ratios, the weight was approximated as the total static buoyancy force. The extreme condition heave displacements were not considered, since the maximum value did not change significantly between the different configurations. The mooring forces were also not considered, since they are only applicable in the *SP* configurations, and the mooring stiffness could potentially be modified without significantly changing the mooring design or cost. Based on the ratios given in Table 4, the best configuration for the power to weight ratio, and the power to maximum extreme load is *F1-SP*; the best configuration for the power to fatigue load is *F3-MP*, even considering a 30^0 wave heading; and, the best configuration for the power to area ratios is *F1-MP*.

Although, this study provides a fundamental design analysis of the OPT PowerBuoy, these analyses have not considered manufacturing and installation costs, the impact of further design optimizations, or the implementation of a control system, all of which could vastly change any conclusions drawn. Nonetheless, the WEC-Sim model has been validated with experimental results, and processes have been established to evaluate the power production, fatigue loads, extreme condition response and directional effects. Hence, the results and methodologies summarized in this report provide a basis for further WEC design development and optimization.

TABLE 4. SUMMARY AND COMPARISON OF RESULTS FOR THE VARIOUS POWERBUOY CONFIGURATIONS.

	$\frac{P^{1yr}_{avg}}{W_{disp}}$	$\frac{P^{1yr}_{avg}}{F^{1yr}_{eq}}$	$\frac{P^{1yr}_{avg}}{F_{float}}$	$\frac{P^{1yr}_{avg}}{A_{plane}}$	$\frac{P^{1yr}_{avg}}{A_{wetted}}$
	$\frac{kW}{MN}$	$\frac{kW}{MN}$	$\frac{kW}{MN}$	$\frac{kW}{m^2}$	$\frac{kW}{m^2}$
***F1-MP* (0^0)**	8.23	161.65	40.21	**0.482**	**0.089**
***F3-MP* (0^0)**	7.80	**169.52**	31.76	0.470	0.086
***F3-MP* (30^0)**	7.51	164.64	30.09	0.452	0.082
***F1-SP* (0^0)**	**9.13**	137.15	**44.23**	0.419	0.045
***F3-SP* (0^0)**	7.12	147.81	36.47	0.350	0.039
***F3-SP* (30^0)**	7.03	141.71	39.21	0.346	0.039

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