IEA | OCEAN ENERGY SYSTEMS
ANNEX II REPORT 2003

Implementing Agreement on Ocean Energy Systems

SUMMARY

One of the main challenges within the development of Ocean Energy Systems is the fact that there is presently no predominant technology and several different approaches are trying to attract funding and investors. The common goal of developing technologies able to produce power from the ocean waves and tides at a low cost seems only achievable if developers on an international level can be motivated to provide and share comparable data and results.

Up to now it has been difficult to compare different systems, as the underlying assumptions with respect to power production, generator capacity and cost statements are based on very different assumptions.

In order to overcome this problem the Annex II of the IEA OES is focused to provide guidelines that could become standards for:

- Testing
- Preliminary costs assessment
- Presentation of results

The guidelines have been prepared based on principles developed as part of the Danish Wave Energy Program 1997 – 2001.

The first section of the Annex provides an overview of testing facilities in member countries where experiments with wave and tidal energy systems could be carried out.

Kim Nielsen, RAMBOLL, Denmark

April 2003

ANNEX II
Development of recommended practices for testing
and evaluating ocean energy systems

SUBTASK II.1
INSTITUTIONS

INSTITUTIONS

The list of hydraulic laboratories is presented to provide an overview of available facilities for model testing within Canada, Denmark, the UK, France, Portugal and Ireland. The list has been prepared from data made available by the Danish Hydraulic Institute via their cooperation under HYDRALAB (www.iahr.org/hydrolab). The testing facilities suitable for testing ocean current and wave energy systems are listed and data on the facility is presented in a table format:

1. Facility	2. Dimensions			3. Waves			4. Current		5. Remarks
	L[m]	B[m]	D[m]	H_s[m]	T_p[s]	D	v[m/s]	Q[m³/s]	

TYPE OF FACILITY

Wave basin

Flume

Towing tank

Cavitation tunnel

DIMENSIONS

Length	L[m]
Beam	B[m]
Depth	D[m]

WAVES

Maximum significant wave height	H_s
Corresponding maximum peak period	T_p
2 or 3 Dimensional waves	D

CURRENT

Towing speed or current velocity	v[m/s]
Volume flow	Q[m^3/s]
Cavitation flumes	

CANADA

NRC CANADIAN HYDRAULICS CENTRE, OTTAWA

Contact: Dr. Andrew Cornett, (613) 993 6690, andrew.cornett@nrc.ca
Web: www.chc.nrc.ca/ or www.chc.nrc.ca/English/Coastal/Facilities/CTest_facilities_e.html

1. Facility	2. Dimensions			3. Waves			4. Current		5. Remarks
	L[m]	B[m]	D[m]	H_s[m]	T_p[s]	D	v[m/s]	Q[m^3/s]	
MWB	50	30.0	3.0 (max15)	0-0.7	0.8- 4.0	3	Varies	Varies	Multidirectional WaveBasin with equipment for simulating winds, currents and multidirectional waves. 15m deep pit for deep-water structures. Easy access for model building, installation, etc.
CWB	63	14.0	1.5	0-0.5	0.8- 4.0	2	Varies	Varies	Coastal Wave Basin with computer controlled wave generator. Easy access for model building, installation, etc.
SWB	47	30.0	0.9	0-0.3	0.5-3.5	2	Varies	Varies	Shallow Wave Basin equipped with multiple mobile computer-controlled wave generators. Easy access for model building, installation, etc.
LWF	90	2.0	2.7	0-1.1	1.0-5.0	2	Varies	Varies	Large Wave Flume with computer controlled wave generator and active wave absorption.
HDF	10	2.7	1.4	-	-		Varies	0-1.7	High Discharge Flume.
SWF	63	1.2	1.2	0.3	0.5-3.5	2	Varies	0-0.2	Small Wave Flume with computer controlled wave generator and active wave absorption.
IT	21	7.0	1.2	0-0.3	0.5-3.5	2	-	-	Ice Tank with carriage in a large cold room for tests with freshwater and model ice.

BC RESEARCH INC., VANCOUVER

Contact: Gerry Stensgaard, P.Eng., gstensgaard@bcresearch.com
Web: www.bcresearch.com

1. Facility	2. Dimensions			3. Waves			4. Current		5. Remarks
	L[m]	B[m]	D[m]	H_s[m]	T_p[s]	D	v[m/s]	Q[m^3/s]	
Wave basin	30.5	26.5	2.4	0.50	2.1		N/A	N/A	
Tow-ingtank	67.0	3.7	2.4	0.25	2.4		N/A	N/A	Towing carriage, max. speed 6 m/s

NATIONAL WATER RESEARCH INSTITUTE, BURLINGTON

Contact: B. Taylor, taylor@ec.gc.ca

1. Facility	2. Dimensions			3. Waves			4. Current		5. Remarks
	L[m]	B[m]	D[m]	H_s[m]	T_p[s]	D	v[m/s]	Q[m^3/s]	
Wave flume	103	45.0	1.48	0.60					Height of waves: 0 to 0.6m, wave frequency: 0-2 H_Z
Tow-ing tank	122	5.0	3.00						Towing carriage, max. speed 6 m/s
Small wave flume	13	0.3	0.50						
Temporary basin	20	20.0	1.00	0.15					Height of waves: 0 to 0.15m,
	28	11.1	1.00						wave frequency: 0 to 2 H_Z.
	18	14.0	1.00						

DENMARK

DHI WATER AND ENVIRONMENT

Web: www.dhi.dk

Contact: dhi@dhi.dk

1. Facility	2. Dimensions			3. Waves			4. Current		5. Remarks
	L[m]	B[m]	D[m]	H_s[m]	T_p[s]	D	v[m/s]	Q[m^3/s]	
basin	30	20.00	3.00	0.25		3	0.2		
basin	37	25.00	0.80	0.25		3		1.2	
basin	32	30.00	0.45	0.17					
basin	30	30.00	0.75	0.25					
basin	62	30.00	0.45	0.17					
flume	35	11.00	0.80	0.25				1.2	
flume	28	0.74	1.20	0.28				0.6	Abs

THE TECHNICAL UNIVERSITY OF DENMARK, ISVA

Web: www.isva.dtu.dk/vb/laboratory.htm

1. Facility	2. Dimensions			3. Waves			4. Current		5. Remarks
	L[m]	B[m]	D[m]	H_s[m]	T_p[s]	D	v[m/s]	Q[m^3/s]	
wave	25	0.6	0.8						Flume no. 1
wave±current	28	4.0	1.0				2.00		Flume no. 2
wave±current	28	0.6	0.8				0.50		Flume no. 3
current	35	3.0	1.0				1.50		Flume no. 4
current	23	2.0	0.5				0.50		Flume no. 5
wave±current	23	12.0	0.6				1.00		Basin
current	10	0.3	0.3				0.05		Tilting flume
wave	10	0.4	0.4				2.00		Oscillating flume
wave±current	2 ø	0.2	0.2						Circular flume

FORCE TECHNOLOGY, DMI

Web: www.danmar.dk

1. Facility	2. Dimensions			3. Waves			4. Current		5. Remarks
	L[m]	B[m]	D[m]	H_s[m]	T_p[s]	D	v[m/s]	Q[m^3/s]	
wind tunnel	1.7	13.6	15.0				7.0		Wind tunnel no. 1
wind tunnel	0.7	1.0	2.6				80.0		Wind tunnel no. 2
wind tunnel	1.8	2.6	20.8				24.0		Wind tunnel no. 3
towing basin	240.0	12.0	5.5	0.9	3		?		Main Ship Model Basin
towing basin	25.0	8.0	0.8						Shallow Water Basin
cavitation tunnel	2.0	0.8	0.8				9.0		Cavitation tunnel

AABORG UNIVERSITY

Web: www.civil.auc.dk

Contact: Peter Frigaard, peter.frigaard@civil.auc.dk

1. Facility	2. Dimensions			3. Waves			4. Current		5. Remarks
	L[m]	B[m]	D[m]	H_s[m]	T_p[s]	D	v[m/s]	Q[m^3/s]	
basin	15.5	8.5	3.0						Wave basin 1
basin	12.0	18.0	0.7						Wave basin 2
flume	20.0	1.2	1.5						
flume	25.0	1.5	0.7						
flume	18.0	0.4	0.5						
water tunnel	30.0	7.0	3.0				1.5		Water tunnel

UNITED KINGDOM

HR WALLINGFORD

Web: www.hrwallingford-group.co.uk

Contact: jsd@hrwallingford.co.uk

1. Facility	2. Dimensions			3. Waves			4. Current		5. Remarks
	L[m]	B[m]	D[m]	H_s[m]	T_p[s]	D	v[m/s]	Q[m^3/s]	
basin	54.0	27.0	0.80	0.2			1.5		Coastal Research Facility
flume	98.5	1.5	0.80					0.80	Flood Channel Facility
duct	6.8	0.6	0.25				1.0		Sloping Sediment Duct
flume	20.0	3.0	0.70					0.30	Tilting Sediment Flume
flume	52.0	1.2	1.70	0.4					Deep Flume
flume	40.0	1.5	0.80	0.2					Absorbing wave flume
rotating flume	6.0 ø	0.4	0.35				0.6		Circular Mud Flume
flume	27.5	2.4	1.30					0.51	High Discharge Flume
flume	27.4	0.6	0.30					0.14	Reversing Flume
tank	24.0	24.0	2.00	0.5					Manoeuvering Tank

CAMBRIDGE UNIVERSITY ENGINEERING DEPARTMENT, CUED
Web: www.eng.cam.ac.uk
Contact: tbn@eng.cam.ac.uk

1. Facility	2. Dimensions			3. Waves			4. Current		5. Remarks
	L[m]	B[m]	D[m]	H_s[m]	T_p[s]	D	v[m/s]	Q[m^3/s]	
flume	8.0	0.9	0.50					0.36	Recirculating Flume
flume	15.6	0.6	0.90	0.2					Wave Flume (regular)
duct	3.7	0.3	0.45						Oscillating Flow Tunnel

ABERDEEN UNIV, ENG. DEPT.
Contact: T.O'Donoghue@eng.abdn.ac.uk

1. Facility	2. Dimensions			3. Waves			4. Current		5. Remarks
	L[m]	B[m]	D[m]	H_s[m]	T_p[s]	D	v[m/s]	Q[m^3/s]	
tunnel	16.0	0.30	0.75		2-16		1.9		Oscillatory Flow Tunnel
wave flume	20.0	0.45	0.70	0.22					Random wave flume
flume	12.5	0.30	0.50					0.10	Armfield Flume
flume	10.0	1.20						0.03	Flood channel
flume	11	0.4	0.2						Sediment re-circulation flume

BRISTOL, UNIV. OF BRISTOL
Contact: J.Loveless@bris.ac.uk

1. Facility	2. Dimensions			3. Waves			4. Current		5. Remarks
	L[m]	B[m]	D[m]	H_s[m]	T_p[s]	D	v[m/s]	Q[m^3/s]	
flume	20.0	1.50	1.10	0.2					Wave Flume
flume	14.0	0.75	1.00						Sed. Recirculation Flume
flume	7.2	2.40	0.60	0.2					Wide wave flume
flume	10.0	2.00	0.25				0.1		Flood channel facility
tank	1.8	1.80	3.00				0.1		Hydrobrake Test Facility

CARDIFF, CARDIFF UNIVERSITY
Contact: FalconerRA@Cardiff.ac.uk

1. Facility	2. Dimensions			3. Waves			4. Current		5. Remarks
	L[m]	B[m]	D[m]	H_s[m]	T_p[s]	D	v[m/s]	Q[m^3/s]	
basin	7.0	4.0	0.5				0.3		Tidal Basin
flume	10.0	1.2	0.3					0.1	Wide Flume
flume	14.0	0.5	0.5	0.15				0.1	wave-current flume
mechanical oscillator with current	4.5	0.5	0.5					0.1	orbital rig

GLASGOW, UNIVERSITY OF STRATHCLYDE

Web: www.strath.ac.uk/
Contact: contact-shipmarine@strath.ac.uk

1. Facility	2. Dimensions			3. Waves			4. Current		5. Remarks
	L[m]	B[m]	D[m]	H_s[m]	T_p[s]	D	v[m/s]	Q[m³/s]	
towing tank	96.0	6.80	2.75	0.50			6.0		Towing Tank
tank	16.5	8.27	3.00	0.40			6.0		Sea keeping Tank
towing tank	77.0	4.60	2.70	0.24			6.4		Towing Tank

EAST COWES, ISLE OF WIGHT, GKN WESTLAND

Web: www.gknplc.com
Contact: GeorgeD@gknwae.co.uk

1. Facility	2. Dimensions			3. Waves			4. Current		5. Remarks
	L[m]	B[m]	D[m]	H_s[m]	T_p[s]	D	v[m/s]	Q[m³/s]	
towing tank	188.0	2.40	1.20				4.6		Tow Tank No 1
towing tank	76.0	3.70	1.68				10.6		Tow Tank No 2
towing tank	196.7	4.60	1.37				15.0		Tow Tank No 3
towing tank	25.2	3.70	1.78				10.6		Tow Tank No 4
tank	54.8	14.60	0.60						Manoeuvering Tank
cavitation tunnel		0.25	1.20						Water Tunnel

HAMPSHIRE, DERA

Web: www.dera.gov.uk
Contact: idgrant@dera.gov.uk

1. Facility	2. Dimensions			3. Waves			4. Current		5. Remarks
	L[m]	B[m]	D[m]	H_s[m]	T_p[s]	D	v[m/s]	Q[m³/s]	
towing tank	270.00	60.00	5.50	0.86					Tow Tank
basin	120.00	60.00	5.50	0.60					Manoeuvring Basin
cavitation tunnel	5.35	2.40	1.20				7.9		Cavitation Tunnel
tunnel	4.57	ø 0.76					15.0		Quiet Water Tunnel
channel	5.00	1.40	0.84				5.0		Circulating Channel

NEWCASTLE, UNIVERSITY OF NEWCASTLE UPON TYNE

Web: www.marinetect.ncl.ac.uk / www.staff.ncl.ac.uk/mehmet.atlar
Contact: memhmet.atlar@ncl.ac.uk

1. Facility	2. Dimensions			3. Waves			4. Current		5. Remarks
	L[m]	B[m]	D[m]	H_s[m]	T_p[s]	D	v[m/s]	Q[m³/s]	
towing tank	37	3.7	1.52						Towing Tank
cavitation tunnel	60	0.4	0.15				8.0		Cavitation Tunnel

PORTSMOUTH, VOSPER THORNYCROFT (UK) LTD.

Web: www.vosperthornycroft.co.uk/

Contact: les.ives@vosperthornycroft.com

1. Facility	2. Dimensions			3. Waves			4. Current		5. Remarks
	L[m]	B[m]	D[m]	H_s[m]	T_p[s]	D	v[m/s]	Q[m^3/s]	
cavitation tunnel	2.2	0.5	0.5				12.0		cavitation tunnel

SOUTHAMPTON, UNIVERSITY OF SOUTHAMPTON

Web: www.soton.ac.uk/

Contact: steve.dalzell@solent.ac.uk

1. Facility	2. Dimensions			3. Waves			4. Current		5. Remarks
	L[m]	B[m]	D[m]	H_s[m]	T_p[s]	D	v[m/s]	Q[m^3/s]	
towing tank	30	2.4	1.2				2.5		Tow Tank No 1
towing tank	60	3.7	1.8				4.5		Tow Tank No 2

PORTUGAL

LISBON, LNEC

Web: www-dh.lnec.pt/npp/npp.html

Contact: treis@lnec.pt or jrocha@lnec.pt

1. Facility	2. Dimensions			3. Waves			4. Current		5. Remarks
	L[m]	B[m]	D[m]	H_s[m]	T_p[s]	D	v[m/s]	Q[m^3/s]	
wave basin	38.1	15.7	0.50	0.35					no carriage
wave basin	30.0	19.6	0.50	0.35					no carriage
wave basin	44.0	23.0	0.75	0.35					no carriage
wave channel	49.4	1.6	1.00	0.35					no carriage
wave channel	73.0	3.0	3.00	1.00					carriage for model
tilting flume	40.7	2.0	1.00				0.35	1.0	max tilt 2,5 %

PORTO, UNIVERSITY OF PORTO

Web: www.fe.up.pt

Contact: fpinto@fe.up.pt

1. Facility	2. Dimensions			3. Waves			4. Current		5. Remarks
	L[m]	B[m]	D[m]	H_s[m]	T_p[s]	D	v[m/s]	Q[m^3/s]	
wave basin	30	12	1	0.35					no carriage

LISBON, IST (TECHNICAL UNIVERSITY OF LISBON)

Web: www.civil.ist.utl.pt/cehidro/

Contact: hr@civil.ist.utl.pt

1. Facility	2. Dimensions			3. Waves			4. Current		5. Remarks
	L[m]	B[m]	D[m]	$H_s[m]$	$T_p[s]$	D	v[m/s]	$Q[m^3/s]$	
wave channel	21.5	0.7	0.5	0.25					
wave basin	11.5	6.6	0.4	0.20					
tilting flume	5.0	0.3	0.2						max tilt 5 %

FRANCE

PONT DE CHAIX, ALSTROM CERG

Contact: René Perret, rene.perret@ctg.alstrm.com

1. Facility	2. Dimensions			3. Waves			4. Current		5. Remarks
	L[m]	B[m]	D[m]	$H_s[m]$	$T_p[s]$	D	v[m/s]	$Q[m^3/s]$	
flume	18.0	3.0	0.8				0.6	1.5	
flume	14.5	1.2	1.2				1.0	1.5	
cavitation tunnel	3.0	0.9	0.9				10.0	8.0	
pump test								1.0	loop nº1
pump test								0.6	loop nº2
pumping station	4.5	2.5	1.2						testing tank nº1
pumping station									

NANTES, ECOLE CENTRALE DE NANTES

Contact: G.Delhommeau, Gerard.Delhommeau@ec.nantes.fr

1. Facility	2. Dimensions			3. Waves			4. Current		5. Remarks
	L[m]	B[m]	D[m]	$H_s[m]$	$T_p[s]$	D	v[m/s]	$Q[m^3/s]$	
towing tank	148.00	4.97	3.00	0.6					towing tank (1978)
basin	19.56	9.40	2.00	0.4					Wave basin (1985)
	3.50	2.00	2.10						Planar Motion Generator (1985)
channel	10.00	2.00	1.25				1.7		Circulating Water Channel (1978)
tower	5.00	4.00	4.00						Impact Tower (1981)
flume	40.00	0.50	1.00	0.4					Two Dimensional Wave Tank (1991)
tank	50.00	30.00	5.00	1.0					48 paddles-pit

PALAISEAU, ENSTA

1. Facility	2. Dimensions			3. Waves			4. Current		5. Remarks
	L[m]	B[m]	D[m]	H_s[m]	T_p[s]	D	v[m/s]	Q[m^3/s]	
flume	10.0	0.25	0.3						
coriolis tank	ø1.4								
basin	50.0	12.50	10 20	0.65					
flume	50.0	4.00	2.5	0.35					

BOULOGNE SUR MER, IFREMER

Contact: Jean.Pierre.Morel@ifremer.fr

1. Facility	2. Dimensions			3. Waves			4. Current		5. Remarks
	L[m]	B[m]	D[m]	H_s[m]	T_p[s]	D	v[m/s]	Q[m^3/s]	
return flow pipe	18	4	2				1	2	movable bottom (8 m length), velocity: 0 - 2 m/s

MARSEILLE, IRPHE

Web: www.coriolis-legi.org

Contact: gio@pollux.irphe.univ-mr.fr

1. Facility	2. Dimensions			3. Waves			4. Current		5. Remarks
	L[m]	B[m]	D[m]	H_s[m]	T_p[s]	D	v[m/s]	Q[m^3/s]	
flume	40	2.6	1				0.1		Large IRPHE/IOA wind-wave facility

TOULOUSE, IMFT CENTRE D'ESSAIS AERONAUTIQUE DE TOULOUSE (CEAT)

1. Facility	2. Dimensions			3. Waves			4. Current		5. Remarks
	L[m]	B[m]	D[m]	H_s[m]	T_p[s]	D	v[m/s]	Q[m^3/s]	
flume	114	4	4					20	Grand canal
tunnel									Aero-Hydrodynamic Tunnel

TOULOUSE, CNRM/ GMEI/ SPEA

Contact: Paul Billant, paul.billant@meteo.fr

1. Facility	2. Dimensions			3. Waves			4. Current		5. Remarks
	L[m]	B[m]	D[m]	H_s[m]	T_p[s]	D	v[m/s]	Q[m^3/s]	
channel	30	3	1.6				0.25		Large stratified water channel (Also Towing tank)

CHATOU, LNHE

Web: www.edf.fr

Contact: M. Benoit, E. michel.benoit@edf.fr; Ben Slama, e.ben-slama@edf.fr

1. Facility	2. Dimensions			3. Waves			4. Current		5. Remarks
	L[m]	B[m]	D[m]	H_s[m]	T_p[s]	D	v[m/s]	Q[m^3/s]	
basin	50	30.00	0.80	0.40				1.50	wave generator 56 paddles
	33	28.00	0.45	0.20				0.50	Grande cuve d'agitation
basin	20	10.00	1.10					0.25	Cuve bidimensionnelle
basin	20	6.00	0.50					0.25	cuve Moselle
flume	25	2.00	1.00					0.70	canal 1
tilting flume	20	0.78	0.70					0.25	canal 2
flume	72	1.50	1.20	0.70				0.80	canal 5
flume	33	0.60	0.60	0.35				0.25	canal 12
flume	25	6.50	1.20					0.55	canal 20
flume	18	2.00	0.50					0.25	canal 22
flume	50	0.40	0.50					0.05	canal 24

GRENOBLE, CORIOLIS-LEGI-UJF

1. Facility	2. Dimensions			3. Waves			4. Current		5. Remarks
	L[m]	B[m]	D[m]	H_s[m]	T_p[s]	D	v[m/s]	Q[m^3/s]	
coriolis tank	ø 13 m		1.2						plaque tournante Coriolis
flume	36	0.55	1.3						canal à houle n°1
flume	24	0.80	0.8						canal à houle n°2

LA SEYNE SUR MER, OCÉANIDE

Contact:: Jean Claude DERN; Jean Pierre AULANIER oceanide@wanadoo.fr

1. Facility	2. Dimensions			3. Waves			4. Current		5. Remarks
	L[m]	B[m]	D[m]	H_s[m]	T_p[s]	D	v[m/s]	Q[m^3/s]	
flume	24	1	1.80	0.5			1.5		mobile bottom
basin	27	12	0.18	0.5					rotating plate
basin	25	16	10.00	0.8			1.5		

PONT DE CLAIX, SOGREAH

Web: www.sogreah.fr/
Contact: Olivier Cazaillet, olivier.cazaillet@sogreah.fr

1. Facility	2. Dimensions			3. Waves			4. Current		5. Remarks
	L[m]	B[m]	D[m]	H_s[m]	T_p[s]	D	v[m/s]	Q[m³/s]	
Inclinable torrential flow	15.0	5.0	0.5					0.04	Torrential Platform
platform	41.0	1.0	1.4	0.30					Wave flume 1
Wave flume									
Wave flume	41.0	2.4	1.6	0.55					Wave flume 2
Wave basin	30.0	24.0	1.6	0.22					Stability wave basin
Multidirectional	22.5	30.0	1.0	0.25					Multidirectional wave basin
wave basin	32.0	20.0	0.8	0.25					Sedimentological basins 1, 2 &3
Morphology basins									
Sedimentological flume	18.0	0.5	0.6				0.6		Racetrack flume
Various fluvial and								0.80	
torrential flumes									
and basins									

VAL DE REUIL, BASSIN D'ESSAIS DES CARENES

1. Facility	2. Dimensions			3. Waves			4. Current		5. Remarks
	L[m]	B[m]	D[m]	H_s[m]	T_p[s]	D	v[m/s]	Q[m³/s]	
towing tank	160.00	9.80	4.0						
towing tank	155.00	8.00	2.0	0.3					
towing tank	220.00	13.00	4.0	0.5					
ship tank	30.00	7.00	2.4						
basin	ø 65.0 m		5.0						
cavitation tunnel	ø 0.8 m								
cavitation tunnel	0.60	0.15	- 0.6						
cavitation tunnel	0.60	0.15	- 0.6						
cavitation tunnel	1.14	1.14	6.0						
cavitation tunnel	2.00	1.35	10.0						

CAEN, UNIVERSITÉ DE CAEN

Contact: Michel Belorgey, belorgey@meca.unicaen.fr

1. Facility	2. Dimensions			3. Waves			4. Current		5. Remarks
	L[m]	B[m]	D[m]	H_s[m]	T_p[s]	D	v[m/s]	Q[m³/s]	
flume	23	0.8	1.0	0.4					canal bleu
flume + waves current	18	0.5	0.5	0.2			0.8		canal orange

IRELAND

CORK, HYDRAULICS AND MARITIME RESEARCH CENTRE, UNIVERSITY COLLEGE

Web: www.ucc.ie/research/hmrc
Contact: hmrc@ucc.ie

1. Facility	2. Dimensions			3. Waves			4. Current		5. Remarks
	L[m]	B[m]	D[m]	H_s[m]	T_p[s]	D	v[m/s]	$Q[m^3/s]$	
Basin	20	18	1.00	0.18	2.0	3			40 Padles
Flume	25	3	1.00	0.17	2.0	2			1 Flap
Flume	18	1	0.75	0.05	1.5	2			1 flap

JAPAN

JAPAN MARINE SCIENCE AND TECHNOLOGY CENTER

1. Facility	2. Dimensions			3. Waves			4. Current		5. Remarks
	L[m]	B[m]	D[m]	H_s[m]	T_p[s]	D	v[m/s]	$Q[m^3/s]$	
Basin	40.0	4.0	2.0	0.2	4.0				Wave Motion Tank
Basin	20.0	0.5	0.7	0.2	4.0		0.1	0.05	Water Circulation Tank

NATIONAL MARITIME RESEARCH INSTITUTE

1. Facility	2. Dimensions			3. Waves			4. Current		5. Remarks
	L[m]	B[m]	D[m]	H_s[m]	T_p[sec]	D	v[m/s]	$Q[m^3/s]$	
Basin	80.0	80.0	4.5	0.40	2.30				80m Square Tank
Towing Tank	400.0	18.0	8.0	0.30	3.10				400m Experiment tank
Towing Tank	150.0	7.5	3.5	0.30	2.00				Middle Towing Tank
Basin	40.0	27.0	2.0	0.27	1.80		0.3		Ocean Engineering Basin
Cavitation tunnel									
Flume	10.0	3.0	1.5	0.31	1.50				Pulsating Wind Tunnel with Water Tank
Basin	35.0	6.0	1.8	0.20	1.12				Ice Model Basin
Circular Basin	Diameter = 14.0 (Diameter of Deep pit = 6.0)		5.0 (Depth of Deep pit = 30.0)	0.50	2.00		0.2		Deep-Sea Basin

PORT AND AIRPORT RESEARCH INSTITUTE

1. Facility	2. Dimensions			3. Waves			4. Current		5. Remarks
	L[m]	B[m]	D[m]	H_s[m]	T_p[s]	D	v[m/s]	$Q[m^3/s]$	
Basin	40.0	30.0	1.0	0.25	2.0-5		0.25		Directional wave and current, Intelligent wave basin for maritime environment
Flume	184.0	3.5	12.0	3.50	6.0-8			20.0	Wave flume with 4m deep sandbed
Flume	105.0	3.0	2.5	0.80	0.5-10				Wave flume
Basin	50.0	20.0	4.0	0.60	1.5-4			10.0	Wave basin
Flume	25.9	0.5	0.9	0.40	0.5-4				Wave flume
Basin	9.0	8.0	1.5	0.10	1.5-3		0.30		Basin for tidal flat

ANNEX II
Development of recommended practices for testing
and evaluating ocean energy systems

SUBTASK II.2
TESTING PROCEDURES

1. MODEL TESTING

Model tests are conducted before building a construction in full-scale in order to gain information on how the construction will behave at sea. Model tests conducted in a systematic way can be used to establish generalities, for a larger range of principally identical constructions.

Within ocean engineering there is a tradition for model testing in order to provide information on loads and movements required to finalise a given structural design. For ships it can be issues like stability (safety against capsizing with or without leakage, with or without free surfaces) manoeuvrability, ship resistance, propeller flow and size, vibrations etc. For design of harbours it can be the shape of the breakwater, the wave conditions in the harbour basin, stability of the breakwaters or sedimentation of the harbour etc. For offshore platforms fixed or floating it could be the study of the mooring system (number of anchors, rope length and weights) design loads on the mooring system and stability of foundation.

For wave energy converters some and perhaps many of these issues are relevant to study in model scale before constructions are built in full scale.

Constructions planned for utilisation of wave energy are large structures (like ships and harbours) that can be optimised with respect to energy production and determination of design loads by model testing. On the basis of the test results it will be possible to evaluate the cost of construction and the potential income in the form of produced energy. The produced energy, i.e. over a period of a year, can be calculated by combining the model scale results of average energy production in a range of sea states with real sea ocean statistics.

MODEL LAWS

The model law most commonly used in connection with wave energy is the model law of Froude [1]. This law is valid when the following conditions are fulfilled.

- Inertial forces are dominating, i.e. forces proportional to the mass of the structure (not viscous forces proportional to the surface area).
- Fluid friction forces can be disregarded, i.e. the waves are unable to move the structure by friction.
- The model must be geometrically identical with the full-scale structure that means the model drawing in principle can be used for full-scale construction, by adjusting the scale.

Scale ratio

Model tests are conducted in a scale ratio. The scale depends partly on the model basin and its wave generating abilities, and on the issue that needs to be investigated. In the first place the wave conditions in full scale need to be scaled down to the waves that can be generated in the model basin. If e.g. the waves in nature are 20 metre high with a period of 10 seconds, and the wave flume can generate

20 cm high waves with a period of 1 second a scaling scale ratio of 1:100 would be suitable. The water depth in a model scale in this case must be the water depth in nature divided by 100. So if the water depth in nature is 50 metre the model basin should be filled up to a water depth of 50 cm.

> *Froude's model law says that all dimensions must be scaled up proportionally to the scale – whereas the time has to be scaled by the square root of the scale.*

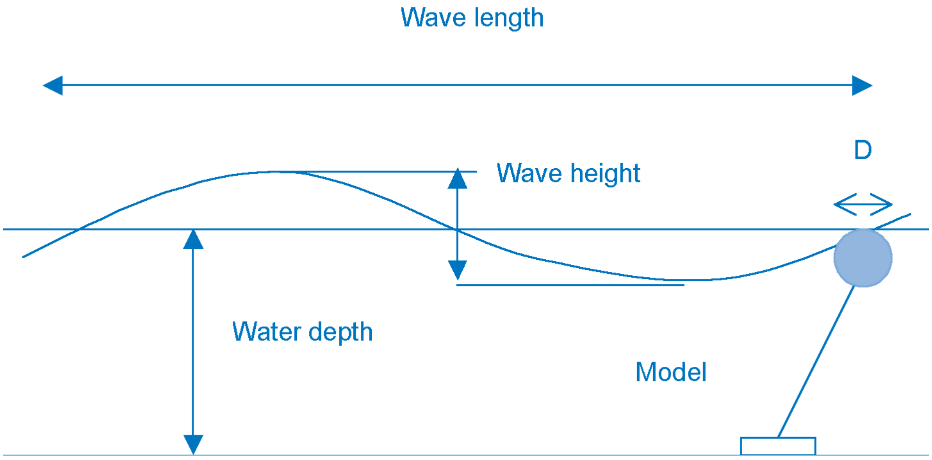


Figure 1.1

Figure 1.1 Definition sketch of typical dimensions that must retain the same relative relations in model and full scale.

On the basis of model tests, measured parameters like motion, forces and power production can be converted from the model to full scale as indicated in Table 1.1.

Conversion from model to full scale

Measured results and values obtained in the model scale can be presented in full-scale values. Typical parameters and values that have to be converted from model to full scale are shown in Table 1.1.

Parameter	Model	Full scale
Length	1	s
Area	1	s^2
Volume/Mass/Force	1	s^3
Time	1	$\sqrt{s}$
Speed (linear)	1	$\sqrt{s}$
Power	1	$s^{3,5}$

Table 1.1

Table 1.1 Conversion of measured values in model scale to full scale when model tests have been conducted in scale ratio 1:s

2. OCEAN WAVES AND WAVE POWER

WAVE CONDITIONS

Waves on the sea surface are irregular in nature – large waves, small waves, short waves and long waves follow each other, overtake and break. If a storm suddenly passes an ocean area, the sea will be set in movement the waves froths with foam while increasing in size. Depending on the speed of the wind and the available fetch the waves will grow to a certain size. The waves will spread in different directions and are therefore not unendingly long-crested. If e.g. a depression associated with winds from changing directions passes the ocean area waves with large directional spreading will occur. However waves moving out of the wind-affected area will form swells that can have several hundred metres long crests.

Waves however do not grow faster then it is fair to speak of stationary conditions within periods of time up to one to three hours. During such conditions one can speak of a prevailing sea condition (short-term distribution of waves). The sea condition is often described by the significant wave height H_s and a wave period - the average wave period T_z if the wave train is analysed statistically or the energy period T_e if the spectrum of the sea condition has been measured. The sea condition described by the significant wave height H_s and associated wave period T_z or T_e is relevant for ship and offshore constructions, but also for describing the sea condition in which the loads on the wave energy converter appears and under which conditions the converter produces a measured amount of power.

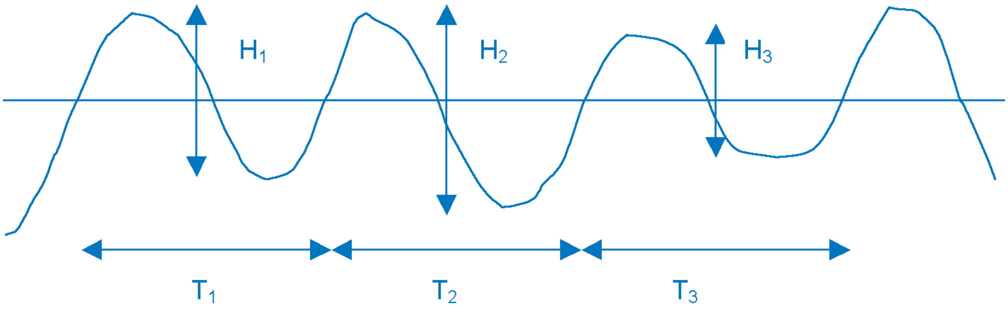


Figure 2.1

Figure 2.1 The sea condition described by H_s and T_z contains waves of different heights H_i and periods T_i.

SHORT TIME DISTRIBUTION OF WAVE HEIGHTS AND PERIODS (STATISTICALLY)

The wave train shown in figure 2.1 can be analysed statistically as the surface variation can be regarded as a number of individual waves, i.e. defined from the up crossing of the surface through mean still water level to over the crest down through mean level to the through and up to the mean water level. The time between two successive up crossings define the wave period T_i of the wave and the vertical distance from through to crest defines the wave height H_i.

The mean wave height H_m can be defined as the average of all measured individual heights H_i:

$$H_m = \frac{1}{n}\sum_{i=1}^{n} H_i$$

The significant wave height H_s derived on the basis of a statistical approach often is referred to as $H_{1/3}$. The significant wave height $H_s = H_{1/3}$ is about 1.6 times larger than the average wave height.

$$H_s = 1.6\, H_m$$

The significant wave height H_s is a measure for the wave conditions and in fact can be defined as the average of the largest 1/3 of the waves in a wave train.
The experience from ocean engineering shows that the waves over a short period of time (about 20 minutes) statistically can be described using a Rayleigh probability distribution function with H_s as parameter. This allows for predicting the fraction of waves that will be larger than a certain height h. One can also predict how many waves of different heights most likely will occur within a given (short) period of time. The Rayleigh function looks like:

$$P\{H \le h\} = 1 - \exp\left[-2\left(\frac{h}{H_s}\right)^2\right] \qquad (2)$$

The most likely largest wave H_{max} within a train of N waves in a sea condition with a significant wave height H_s can be calculated as

$$H_{\max} = H_s\sqrt{\tfrac{1}{2}\ln N} \qquad (3)$$

Example: The number of individual waves within intervals of 10 cm ranging from heights between 0 to 1.7 metres in a sea condition with a significant wave height of 1 metre and a wave train of 100 waves is shown on Figure 2.2. It is seen that most waves appear in the range 0.5–0.7 metres and the largest wave is about 1.7 metres high.

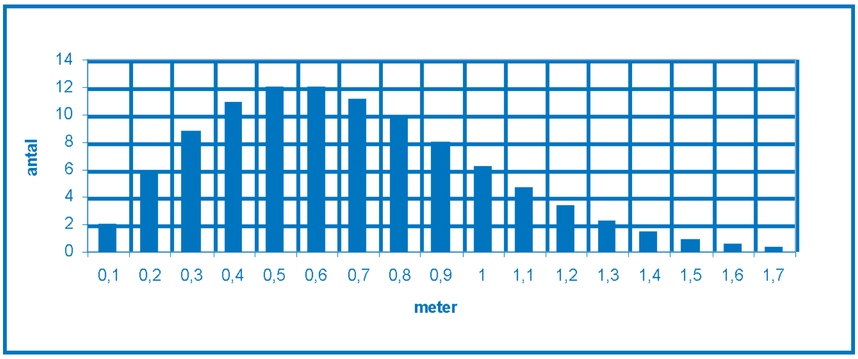


Figure 2.2

Figure 2.2 Distribution of 100 wave heights in 10 cm internals in a wave train with H_s = 1m.

Average wave period T_z

A sea condition is not only characterised by the significant wave height H_s but in addition the average period T_z. The wave period provides information on the average steepness of the waves and is also an important parameter in the study of resonance response of floating structures. The average wave period can be calculated based on the measured period between up or down crossing of the wave waves over mean water level and the average value is expected to be more or less the same T_z.

> *The average wave period is designated T_z*

> *The wave conditions can be defined by the significant wave height H_s and the mean wave period T_z*

THE WAVE ENERGY DISTRIBUTION IN A SEA CONDITION (SPECTRUM SHAPE)

The significant wave height can also be derived analytically by analysing the wave train. This involves determination of the energy content on the different frequencies in the wave train. Derived analytically the significant wave height is often designated H_{mo}. In a given wave condition with significant wave height $H_s = H_{mo}$ the surface variation can be interpreted as the superposition of a large number of monochromatic waves with different amplitudes, wave periods and phases. This means that the ocean surface in principle can be modelled by adding a number of sinusoidal monochromatic waves with different amplitudes, wave periods, directions and phases. The energy of each wave component is proportional to the square of its amplitude and the distribution over wave frequencies can be presented by the wave energy spectrum S(f) that describes how much energy is present on the different frequencies. A wave energy spectrum can be derived from a Fourier analysis of the surface elevation.

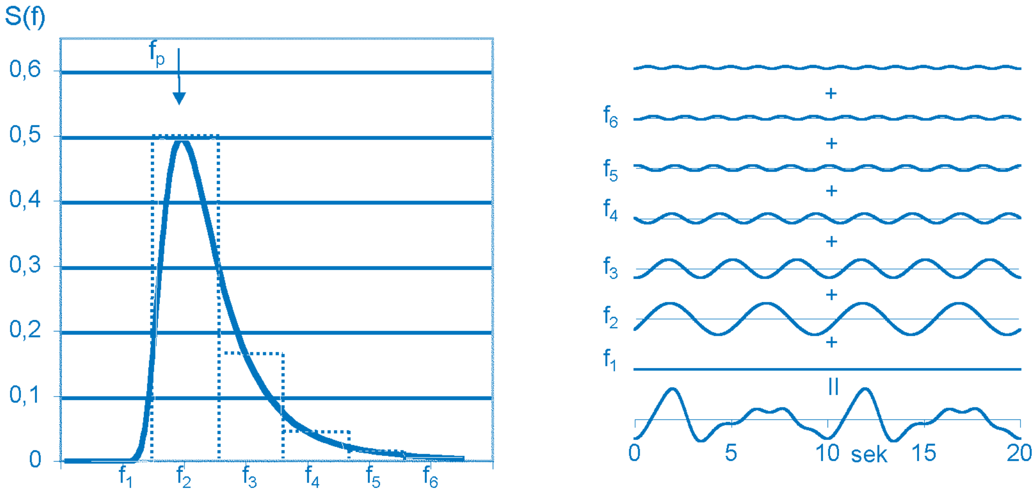


Figure 2.3

Figure 2.3 The wave energy spectrum shows the distribution of energy over frequencies.

The energy within each wave component is proportional to the square of the wave height. Waves within the frequency band $(f_1 - \Delta f/2)$ to $(f_1 + \Delta f/2)$ contain the energy Δ_{mo}, and the total energy is mo derived as the area under the spectrum. The spectrum often has a wall-defined peak value and the frequency at which the peak occurs is designated the peak frequency f_p. The corresponding peak wave period is $T_p = 1/f_p$. It turns out that the significant wave height is proportional to the square root of the area m_o (18) under the spectrum as:

$$H_s = H_{mo} = 4\sqrt{m_0} \tag{4}$$

> *The significant Hs = Hmo wave height derived from the spectrum is proportional to the square root of the area mo under the spectrum.*

> *The peak period Tp = 1/fp.is the wave period in the sea condition that contains most energy.*

PARAMETERS DERIVED FROM THE SPECTRUM MOMENTS

If the spectrum describing the wave surface of a given sea condition has been measured, it is possible to determine the energy spectrum and from this calculate the significant wave height, the average wave period and the power. This can be done from calculating the spectral moments mi:

$$m_i = \int f^i S(f)\partial f \tag{5}$$

The three moments that shall be used are:

$$m_o = \int S(f)\partial f \tag{6}$$

$$m_{-1} = \int f^{-1} S(f)\partial f \tag{7}$$

$$m_2 = \int f^2 S(f)\partial f \tag{8}$$

The significant wave height $H_s = H_{mo}$

The significant wave height can be derived from moment m_0 of the spectrum as:

$$H_s = 4\sqrt{m_0}[m] \tag{9}$$

The average wave period $T_z = T_{02}$

The average wave period T_z can be found from the spectrum moment m_0 and m_2

$$T_z = \sqrt{\frac{m_o}{m_2}}[Sec] \tag{10}$$

Peak period Tp

The peak period is found by differentiating the spectrum in order to find the frequency at witch it obtains its maximum value. The peak period T_p is approximately 1.4 times the average period T_z:

$$T_p = 1.4T_z[Sec] \tag{11}$$

The Energy Period T_e

The energy period T_e has been introduced in connection with wave power studies as it contains information on the integral m_{-1} proportional to the wave energy flux (14) of the sea state. The moment m_{-1} strongly depends on the lower frequency parts of the spectrum (longer wave periods). The energy period is defined as:

$$T_e = \sqrt{\frac{m_{-1}}{m_0}}[Sec] \tag{12}$$

The approximate relation between the energy period and the average period is about:

$$T_e = 1.2T_z[Sec] \tag{13}$$

Power per metre wavefront (Wave energy flux)

The average power in the sea condition (Watts per metre wave crest), describes the average wave power that passes through a one-metre-wide fictive vertical surface perpendicular to the direction of propagation and extending to the seabed. In deep water the wave energy flux can be calculated as:

$$P_w = \frac{\rho g^2}{4\pi} m_{-1} \tag{14}$$

$$P_w = \frac{\rho g^2}{64 \cdot \pi} H_s^2 \cdot T_e \tag{15}$$

The power per metre wave front can be expressed in kW/m using the formula below if the significant wave height H_s is inserted in metre and the energy period T_e is inserted in seconds (assuming ρ=1000 kg/m3):

$$P_{\text{inf}} = 0.577H_s^2 \cdot T_z \tag{16}$$

The power per metre wave front can be expressed in kW/m can also be expressed in terms of the significant wave height H_s (inserted in metre) and the average wave period T_z (inserted in seconds) (assuming ρ=1000 kg/m3) as:

$$P_{\inf} = 0.577 H_s^2 \cdot T_z [kW/m] \tag{17}$$

If the sea is fully developed i.e. the wind has been blowing over a large ocean area for a sufficiently long time so that the waves do not grow in size, a relation for calculating the average wave period T_z from the significant wave height H_s can be derived as:

$$T_e = 1.2 T_z [Sec] \tag{18}$$

In this case the power in the waves can be expressed in terms of the significant wave height alone:

$$P_{\inf.} = 2.05 \cdot H_s^{2.5} [kW/m] \tag{19}$$

Wind speed m/s	5.0	7.5	9.0	10.0	12.0	15.0
H_s (m)	0.5	1.2	1.7	2.1	3.1	4.8
T_z (sec)	2.6	3.9	4.7	5.2	6.2	7.8
T_e (sec)	3.1	4.7	5.6	6.2	7.4	9.3
P_w (kW/m)	0.4	3.2	8.0	13.1	33.8	103.2

Table 2.1

Table 2.1 Relations between the wind speed, the significant wave height H_s, the average wave period T_z, the energy period T_e and power P_w per metre wavefront derived for a PM spectrum.

Modeling of the sea surface

The significant wave height H_s is a well-known parameter to characterise a wave situation or a sea condition combined often with the additional information of the average wave period. To model the sea either numerically or in model wave basins the use of a few generic standard spectra are often used. These spectra have been derived from a large number of real sea studies and one of the most commonly known is the Pierson-Moskowitz (PM) spectrum. This spectrum was originally derived in order to describe fully developed sea conditions – that means sea conditions where there is a balance between the wind speed and the wave conditions – the wind has been blowing at a constant speed for a sufficiently long time and does not put additional energy into the sea with its speed.

The other spectrum derived is known as the JONSWAP spectrum. This has been derived as a result of a large measurement programme in the North Sea (Joint North Sea Wave Analysis Program). The primary difference between the two spectra is that the JONSWAP compared to the PM spectrum describes a sea with most of its energy concentrated around the peak frequency of the spectrum. The JONSWAP spectrum therefore provides a better description of seas growing that are not fully developed.

PM-spectrum

The PM spectrum describes the sea condition of a fully developed sea. There is a balance between the speed of the wind and the speed of the waves and the ocean area is unlimited.

The spectrum is named after two researchers Pierson and Moscowitz (PM) who derived a spectrum S(f), from numerous studies and measurements at sea as:

$$S(f) = \frac{A}{f^5}\exp(-\frac{B}{f^4}) \tag{20}$$

Where A is a pure constant and B depends on the wind speed U in m/s

$$A = \frac{8.1\cdot 10^{-3}\cdot g^2}{(2\pi)^4} = 5 * 10^{-4}\left[\mathrm{m}^2 s^{-4}\right] \tag{21}$$

$$B(U) = 0.74\cdot\left(\frac{g}{2\pi U}\right)^4 = 4.39U^{-4}\left[\mathrm{s}^{-4}\right] \tag{22}$$

The mathematical expression on which the PM-spectrum is based further provides the possibility to describe sea conditions with specified peak period s and significant wave heights.

To generate specified sea conditions as described later in this report, two parameters are given to determinate the shape of the spectrum:

- The peak period T_p ($f_p=1/T_p$)
- The significant wave height H_s.

The constant A is then determined from the desired significant wave height Hs and desired peak frequency $f_p=1/T_p$ and B depends on the peak frequency alone:

$$\mathrm{A} = \frac{5\cdot \mathrm{H}_s^2\cdot f_p^4}{16} \tag{23}$$

$$B = \frac{5\cdot f_p^4}{4} \tag{24}$$

The spectrum above is called the Brechsneider spectrum, but in view of its general similarity in shape compared to the PM spectrum, it will be referred to as the PM spectrum in the following.

JONSWAP spectrum

In ocean areas with limited fetch the JONSWAP-spectrum, (Joint North Sea Wave Program) (Hasselmann et al. 1973) is convenient. The spectrum has the same general mathematical formulation as the PM spectrum but it includes an additional factor around the peak frequency that describes the energy concentrated in that region.

$$S(f) = 0.205 \cdot H_s^{\,2} \cdot f_p^{\,4} \cdot f^{-5} \exp(-\tfrac{5}{4} \cdot (\frac{f}{f_p})^{-4}) \cdot 3.3^{a} \tag{25}$$

where

$$a = \exp\left[-\frac{1}{2} \left(\frac{(f - f_p)}{\sigma \cdot f_p} \right)^2 \right] \tag{26}$$

$$\sigma = \begin{cases} \sigma_a = 0{,}07 & \text{for} f < f_p \\ \sigma_a = 0{,}09 & \text{for} f \geq f_p \end{cases} \tag{27}$$

DIRECTIONAL SPREADING, SHORT CRESTED 3D WAVES

The ocean waves are not endlessly long-crested; waves are more or less short-crested. In order to express this in a mathematical form, the spectrum is multiplied with a spreading function f(q) that describes how much energy is moving in different directions (q) from the main direction of propagation.

$$S(f,\theta) = S(f) * f(\theta) \tag{28}$$

A spreading function often used is given by the following expression:

$$f(\theta) = \begin{cases} A\cos^{2s}(\theta) & \text{for} |\theta| < \pi/2 \\ 0 & \text{other wise} \end{cases} \tag{29}$$

The integral overall directions is unity:

$$\int_0^{2\pi} f(\theta) d\theta = 1 \tag{30}$$

A large value of the spreading parameter s gives the least spreading. The relationship between the spreading parameter s and the constant A is given by:

$$A = \frac{1}{\pi} \frac{2 * 4 * 6 * \ldots * 2s}{1 * 3 * 5 * \ldots * (2s - 1)} \tag{31}$$

It should be noted that real ocean waves often are quite difficult to model in terms of directional spreading especially in coastal areas.

LONG-TERM DISTRIBUTION OF WAVE CONDITIONS (SCATTER DIAGRAM)

The time span considered in connection with the long-term distribution of wave conditions is of a magnitude the lifetime of the structure. The distribution of the sea conditions can be shown in scatter diagrams in terms of how many hours per year or number per thousand observations different combinations of H_S and T_Z prevails over the year.

The scatter of numbers in each combination of H_S and T_Z depends on the position in the ocean, the water depth, the wind climate and the dimensions of the ocean area. In a sheltered shallow water area waves will rarely exceed $H_S = 1.5$ metre. In the North Atlantic Ocean in deep water, significant wave heights up to H_S 10 metre might prevail during extreme wind conditions.

In general there is an upper limit for the significant wave height at each interval of average wave periods. This is due to the fact that if waves get too steep they break and re-generate as longer waves. The limit for the significant wave height expressed in terms of the average period is in the order of:

$$H_s < 1.0\ T^2$$

This limit is shown in the diagram below.

Even in a relatively limited ocean area like the North Sea the distribution of waves depends on the position chosen in the North Sea. In general it is so that there is more annual wave energy at a site far from the Danish coast and increasing with growing water depth. This has been analysed in the wave energy atlas for the North Sea [1] prepared as part of the Danish wave energy programme. As an example Table 2.2 shows a scatter diagram of the distribution of waves at a site on 30 metre deep water near Horns Rev. The diagram shows how many hours per year a wave condition with a significant wave height within one metre intervals will occur combined with average wave periods within intervals of 1 second.

	Middelbølgeperiode Tz [sek.]									
Hs	2.0 -3.0	3.0-4.0	4.0-5.0	5.0-6.0	6.0-7.0	7.0-8.0	8.0-9.0	> 9.0	Sum	Pct
8.5-9.5										
7.5-8.5										
6.5-7.5							4	2	6	0,1%
5.5-6.5						2	26		28	0,3%
4.5-5.5						103	12		115	1,3%
3.5-4.5					208	154			362	4,1%
2.5-3.5			1	296	538	3		1	839	9,6%
1.5-2.5		1	635	1211	26	3		3	1879	21,4%
0.5-1.5	20	1741	2007	275	81	26	13	11	4174	47,6%
< 0.5	584	634	113	29	7	1			1368	15,6%
Sum	604	2376	2756	1811	860	292	51	15	8771	100,0%

Table 2.2

Table 2.2 Scatter diagram showing how many hours per year different combinations of H_s og T_z prevail

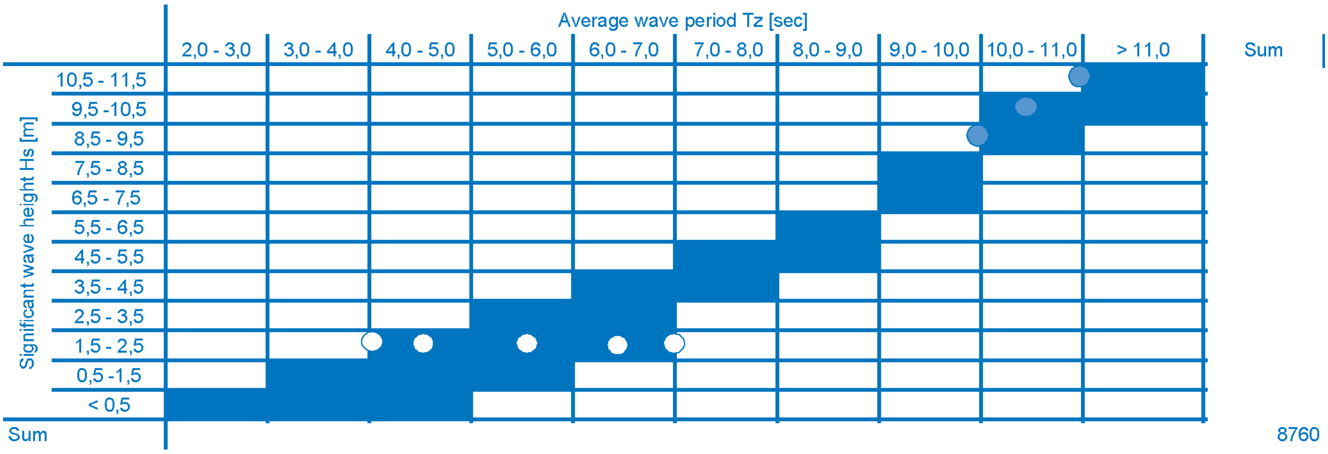
The long-term distribution of significant wave heights can be described using a Weibull distribution function with two parameters b and k. The parameters can be chosen to provide the best fit with observed data. This presentation however gives no information on the wave period. The likelihood to observe a significant wave height in the interval H_S ±0.5m can be calculated as:

$$Pi(H_s \pm 0.5) = \exp(-((\frac{H_s - 0.5}{b})^k)) - \exp(-((\frac{H_s + 0.5}{b})^k)) \quad (32)$$

When the long term distribution of sea states is know at a given site, the expected energy generated by a wave power converter at the site over a year can be calculated, based on experimental data providing information on the performance of the converter in the different sea states.

In order to provide uniform and comparable information on the ability of different wave power converters to convert energy, the advisory panel to the Danish Energy Agency have recommended a selection of representative sea states, to be reproduced in model basins in laboratories for testing the converters.

The selection is shown on the generic scatter diagram below and the procedure described in more detail in the next section.



Significant wave height Hs [m]	Average wave period Tz [sec]										
	2,0 - 3,0	3,0 - 4,0	4,0 - 5,0	5,0 - 6,0	6,0 - 7,0	7,0 - 8,0	8,0 - 9,0	9,0 - 10,0	10,0 - 11,0	> 11,0	Sum
10,5 - 11,5										■ ●	
9,5 -10,5									■ ●	■	
8,5 - 9,5									■ ●		
7,5 - 8,5								■			
6,5 - 7,5								■			
5,5 - 6,5							■				
4,5 - 5,5						■	■				
3,5 - 4,5					■	■					
2,5 - 3,5				■	■						
1,5 - 2,5		●	■ ●	■ ●	■ ●	●					
0,5 -1,5		■	■	■	■						
< 0,5	■	■	■								
Sum											8760

Table 2.3

Table 2.3 Generic scatter diagram

3. RECOMMENDED EXPERIMENTS FOR TESTING WAVE POWER CONVERTERS

INTRODUCTION

This section recommends a series of experiments in order to evaluate any wave energy concept with regard to energy production and design loads. The section contains a descriptive part followed by a list of recommended tests. In the descriptive part some considerations regarding the accuracy and documentation of wave conditions are described. Terms and parameters used refer to the previous chapter.

The recommendations have been made under the assumption that the North Sea was the location for operation at full scale. The recommendations can however be modified for application to a larger selection of ocean sites. The aim is to provide as realistic conditions in the model scale as possible including realistic parameters for wave heights, wave periods, directional spreading water depth etc. However it is accepted that some devices initially are tested in long-crested waves and that some systems are insensitive to directional short-crested waves. However it is important that a concise standard of reference is established in both short- and long-crested waves.

The wave conditions (prevailing within periods from 1 to 3 hours) are described using the traditional parameters for wave conditions: The significant wave height Hs and the average wave period T_z and the spreading parameter s.

ENERGY PRODUCTION

The wave energy converter is expected to produce power in sea conditions with significant wave heights up to about 5 metres. This will in general cover more than 90 % of all sea conditions on a yearly basis.

Based on experience and measured data from the central part of the North Sea [3], central estimates of the average wave period have been made for significant wave heights from 1 to 5 metres and are given in Table 3.1. For any chosen significant wave height a natural variation of sea conditions persists with a range of average wave periods (and corresponding peak period). The variation in wave periods is relatively large ±2 sec for values of the significant wave height below 2 metre and less about ±1 sec for significant wave heights above 3 metre.

Significant wave height H_s [metre]	1.0	2.0	3.0	4.0	5.0
Average wave period T_z [sec.]	4.0	5.0	6.0	7.0	8.0
Peak period T_p [sec.]	5.6	7.0	8.4	9.8	11.2
Wave power level [kW/m]	2.1	11.6	32.0	65.6	114.0

Table 3.1

Table 3.1 Test matrix 1, Sea conditions for performance evaluation.

It is difficult to decide if a standard test series should be conducted using a PM or JONSWAP spectrum. The PM spectrum is expected to be more correct during situations with constant and decreasing wind conditions whereas the JONSWAP spectrum is expected to be more correct during increasing wind conditions. In reality over the year the sea will change and in some cases even more complicated spectra, like twin-peaked spectra, will arise.

However, the difference in performance from any wave power converter whether it is tested in PM or JONSWAP is not expected to be decisive for the future applicability of the concept. In order to limit the standard testing regime it is therefore decided to use the PM spectrum for the standard testing of energy production, but test the influence of the spectral shape (JONSWAP) as part of a parameter study.

In general it is expected that most wave energy converters will demonstrate increased energy production if tested in a JONSWAP spectrum, as the energy is concentrated within a narrow band of frequencies.

Directional spreading

Directional spreading of short-crested waves is in the Danish part of the North Sea and has not yet been analysed in such detail that very firm recommendations can be given. It is however important for some wave energy converters to investigate how the energy production is influenced by the directional spreading of the sea in a given sea state. It is recommended that this can be included as a part of the parametric study.

A large value of s gives low spreading and a small value of s a wide spreading.

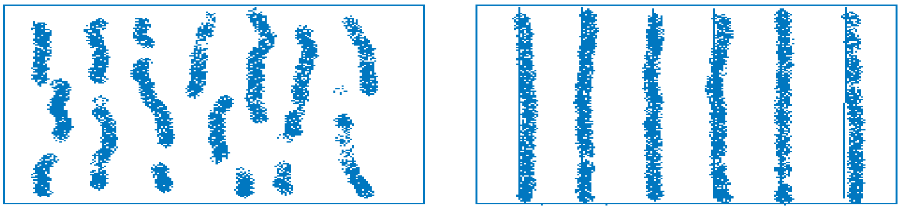


Figure 3.1

For storm conditions with significant wave heights up to about 10 metres a value of s = 15 seems to be representative. For smaller sea conditions a value between 1 and 2 is appropriate. Such values have however not yet been validated by measured data.

It is possible that future wave measurements including measurements of directionality can provide some approximate relations between the spreading parameter and the sea state. It is therefore recommended to measure the sensitivity of the converter to directional spreading.

Figure 3.1 Wave crests seen from above with and without directional spreading. (3D waves are short crested and 2D waves long crested).

RECOMMENDED STANDARD TESTS

Some concepts will show a very different behaviour depending on being tested in short crested 2D or long crested 3D waves. Other concepts like the single point absorber will hardly be affected and the required list of experiments, is series 1, 2 and 3 (see table 3.2). Concepts that are expected to be sensitive must be tested in wave basins able to generate 3D waves and the sensitivity to directionality can be obtained by comparing series 1 (conducted in 2D waves) with series 4 (in 3D waves).

Test	Wave flume	Wave basin
Series 1 - PM spectrum (long crested)	2D	2D
Series 2 - JONSWAP-spectrum	2D	3D
Series 3 - Variation of period	2D	3D
Series 4 - PM spectrum (short crested)		3D
Series 5 - Spreading parameter variation		3D

Table 3.2

The PM spectrum has been chosen for the basic tests in Series 1. The sensitivity to the spectral shape is tested in Series 2, and the sensitivity to the wave period is carried out in Series 3. The test in sensitivity to the wave period is not carried out because of uncertainties related to the wave period at the specific wave height, but carried out because different wave periods occur in nature in different wave conditions for the same values of significant wave height. In Series 4 the influence of the spreading compared to Series 1 is investigated, based on a predetermined set of parameters related to the sea conditions. Series 5 is carried out to monitor the effect of the spreading within the individual sea states of Series 4.

SURVIVAL TESTS

Test	Wave flume	Wave basin
Series 1 - PM spectrum (long crested)	2D	2D
Series 4 - PM spectrum (short crested)		3D

Table 3.3

Test	Wave flume	Wave basin
Series 6 - JONSWAP spectrum	2D	2D
Series 7 - PM spectrum variation of period	2D	3D
Series 8 - PM spectrum spreading parameter variation		3D

Table 3.4

Table 3.2 Test series for testing wave power conversion

Table 3.3 Test series for testing fatigue

Table 3.4 Test series for testing survival and design conditions

In order to determine fatigue, the numbers and levels of structural loads must be measured in all sea conditions. The loads can be measured in parallel with the energy production measurements or on a separate perhaps smaller model for testing the survival in both normal and extreme waves.

The test Series 6, 7 and 8 are in general extreme wave conditions with very large waves that occur once every 10, 20 or 50 years depending on the site.

Series 1: Basic tests in long-crested waves (PM Spectrum)

The first test series contains five sea states as indicated in table 3.5. The waves are long crested based on the PM spectrum. The shape of the PM spectrum (5) is generated by inserting the values of H_s and T_p in formulae (8) and (9) given in Chapter 1. Each test is recommended to last for a period of time corresponding to 60 minutes at full scale. The duration of the model experiment can be calculated by dividing with the square root of the scale s.

Test no.	Significant Wave Height	Average wave period	Peak period
	H_S [m]	T_Z [sec.]	T_P [sec.]
	1	4.0	5.6
	2	5.0	7.0
	3	6.0	8.4
	4	7.0	9.8
	5	8.0	11.2

Table 3.5

Table 3.5 Test Series 1, sea condition for testing energy production.

Series 2: Spectrum shape (JONSWAP)

In order to evaluate the influence of the spectral shape on the energy production tests at least two sea states are repeated using the JONSWAP formulation of the spectrum shape.

Test no.	Significant Wave Height	Average wave period	Peak period	Spreading parameter
	H_S [m]	T_Z [sec.]	T_P [sec.]	(If 3D is selected)
	2	5.0	6.5	
	3	6.0	7.9	

Table 3.6

Table 3.6 Test Series 2, sensitivity to spectral shape (JONSWAP).

Series 3: Variation of wave period (PM Spectrum)

It is of interest to know the how the energy production changes if the average wave period is changed for constant value of the significant wave height.

This can especially be important if a construction is tuned to resonate at a specific wave period in nature. The variation is suggested carried out in wave conditions with a significant wave height of 2 metre and variation of the average wave period Tz from 4 to 7 seconds.

Test no.	Significant Wave Height	Average wave period	Peak period	Spreading parameter
	H_s [m]	T_z [sec.]	T_p [sec.]	(If 3D is selected)
	2	4.0	5.6	
	2	4.5	6.3	
	2	5.5	7.7	
	2	6.5	9.1	
	2	7.0	9.8	

Table 3.7

For additional information it is recommended to add experiments to investigate the effect of wave periods for wave conditions with smaller and larger significant wave heights where the average wave period is changed ±1 second compared to the central period estimated in table 3.5.

For each significant wave height the energy production can be plotted as a function of the wave period.

Table 3.7 Test matrix 3, Variation of wave period to determine sensitivity in relation to energy production.

Table 3.8 Energy production in the sea with energy spreading on the spectrum (3D short crested)

Table 3.9 Energy production tests for determination of sensitivity to directional spreading

Series 4: Basic tests in short crested waves (3D PM-spectrum)

This test series will show how sensitive the system is to a short-crested sea compared to long-crested sea. Depending on the type of converter it is recommended to carry out tests in short-crested (3D) sea.

Test no.	Significant Wave Height	Average wave period	Peak period	Spreading parameter
	H_s [m]	T_z [sec.]	T_p [sec.]	(If 3D is selected)
	1	4.0	5.6	2
	2	5.0	7.0	3
	3	6.0	8.4	4
	4	7.0	9.8	6
	5	8.0	11.2	7

Table 3.8

Series 5: Variation of spreading parameter, (3D PM- spectrum)

The sensitivity to the directional spreading can be evaluated by changing the parameters from the previously tested value indicated in table 3.8 for a fixed value of the significant wave height chosen as 2 metre.

Test no.	Significant Wave Height	Average wave period	Peak period	Spreading parameter
	H_s [m]	T_z [sec.]	T_p [sec.]	(If 3D is selected)
	2	5.0	7.0	1.5
	2	5.0	7.0	4.5

Table 3.9

DURATION OF TESTS

It is recommended that the duration of each sea state corresponds to 60 minutes in full scale, i.e. a test in scale 1:25 will last for 12 minutes. With a pause of 10 minutes between each test the complete set of 19 experiments should be completed within 7 hours. The interval between two successive tests is often depending on how well the equipment and data acquisition work and if time is needed for the wave basin to calm down. If theoretically all experiments are carried out in one row the complete set of testing should take half a day.

OCEAN CURRENT

The effect of combined ocean current and waves is not expected to have a significant impact on the energy production of wave energy converters placed in the North Sea. In the North Sea currents are associated with tidal effects and the air pressure variation associated with the depressions and wind systems passing.

The current rarely exceeds 0.5 m/s at distances of a few kilometers off the coast in more than 20 metre deep water. The current may however have some influence on the orientation of systems proposed to float freely around a central mooring. In order to evaluate such concepts it is recommended to measure loads in the direction perpendicular to the main direction of the waves.

DESIGN AND SURVIVAL TESTING

The aim of developing wave energy converters, which are able to absorb and generate power at a low cost can only be done if the wave energy plant can survive at least until the investment has been returned, and if the structures can survive at sea for a longer period the energy is free except for maintenance costs. It is therefore useful to adapt the practice of offshore engineering and define the wave condition that only occurs approximately 3 hours every 100 years.

This wave condition depends on the ocean location and wave data obtained in the form of a scatter diagram can be the basis for evaluating the possibility for exceeding a particularly significant wave height. In this connection the Weibull distribution function describing the long-term distribution of significant wave heights can illustrate how the design situation is predicted.

If the waves at the site are distributed with the parameters b and k, the formula for significant wave heights exceeding 3 hours every 50 years is:

$$H_{s,50,3} = b \cdot [\ln(M)]^{1/k}$$
$$M = 365 * 24 * 50/3 \qquad (33)$$

The average period corresponding to this significant wave height can be approximated with

$$T_Z, 50,3 = 3,1 * [H_s, 50,3] \, 0,5 \qquad (34)$$

The Danish load and safety philosophy traditionally recommends design valuesthat corresponds to a once-every-50-years condition combined with relevant structural load coefficients. However in most other countries it is common to operate with a 100-year design situation.

The offshore wave energy systems are floating structures moored to the seabed. Due to the relatively large range of potential sites and large range of wave energy converters, it is presently recommended to test the concepts in a rather wide range of survival conditions in order to obtain a better understanding of the variability of the design loads in some detail. At a later stage this enables the designer to interpolate between measured data and design the system for a specific location with specific design rules and wave data. Approximate values for a range of survival and design waves are given in the tables:

Test no.	Significant Wave Height	Average wave period	Peak period	Spreading parameter
	H_s [m]	T_z [sec.]	T_p [sec.]	(If 3D is selected)
10 years	9	12.5	15.0	
	9	9.9	13.8	15 and 8
	9	14.3	15.0	
50 years	10	13.0	15.0	
	10	16.0	15.0	
	10	10.4	14.5	15 and 8
100 years	11	13.7	15.0	
	11	10.9	15.2	15 and 8
	11	16.7	15.0	

Table 3.10

Test no.	Significant Wave Height	Average wave period	Peak period	Spreading parameter
	H_s [m]	T_z [sec.]	T_p [sec.]	(If 3D is selected)
10 years	8	11.6	15	
8	9.4	13.1		15 and 8
8	8	14.6		15
50 years	9	12.5	15	
9	9.9	13.8		15 and 8
8	9	14.3		15
100 years	10	13.0	15	
10	10.4	14.5		15 and 8
8	10	16.0		15

Table 3.11

The measurement of loads on the structure in the combination of significant wave heights, average wave periods and spreading parameters as indicated in the tables above provides the opportunity to analyse the sensitivity of the measured loads to these parameters.

Each test has a duration corresponding to 3 hours at full scale. Measured load data from each sea state should be presented and analysed statistically using the Weibull distribution function in order to determine the load exceeded with a probability 0.1 % .

Table 3.10. Survival sea states on 40-60 metre deep water in the North Sea (JONSWAP spectrum)

Table 3.11 Survival sea states on 20-40 metre deep water in the North Sea (JONSWAP spectrum)

Ocean current in the survival condition

The design ocean current situation in the North Sea is not well defined. However wave power converter systems sensitive to ocean current should be tested in ocean current speed of 1 m/s with an angle of incidence between 0 and 90 degrees to the wave direction.

Fatigue loads

The wave energy converters are subject to oscillating loads over the years at operation. In order to determine the influence of fatigue the number and size of loads within each sea state must be known. A conservative estimate of the influence can be made by measuring the maximum load in each sea state and use the indicated number of oscillations in Table 3.12 for fatigue calculations.

Significant wave height H_S [metre]	**1**	**2**	**3**	**4**	**5**	**6**	**10**
Measured Load							
Cycles per year [$*10^4$]	450	170	71	25	7.5	2	0.5

Table 3.12

Table 3.12 Cycles per year in the range of selected sea states in the Danish part of the North Sea.

The cycles per year have been calculated based on the average wave period within each sea state. It might be expected that the fatigue loads could be a decisive part of the structural design.

REQUIRED ACCURACY AND DOCUMENTATION

The test conditions presented in the tables should be produced with an accuracy of:

> H_S : better than 5%
> T_z /T_p: better than 5%

s (spreading parameter): better than 10% within the interval of wave periods from $0.5^* T_p$ to $1.25^* T_p$.

The generated wave energy spectrum must be measured and presented in comparison with the theoretical spectrum.

The wave train must be generated so it does not repeat itself within the duration of the test time series. The time series of measured parameters should be presented.

Maximum and average values of measured parameters should be presented.

The statistical distribution of individual wave heights should be plotted and compared to the Rayleigh distribution function.

It should be noted if the test tank uses active absorption of the reflected waves.

Calibration of instruments should be carried out according to best laboratory practice.

4. MEASUREMENTS

INTRODUCTION

In this chapter suitable methods for measuring absorbed power on a few different types of wave power converters will be summarised. The review will provide an overview as to which methods have been used and recommended as suitable in connection with scale model tests of wave energy converters in wave tanks.

It is obvious that different methods of power measurements must be applied depending on how the wave power converter operates. Different wave power converters also might use a different number of steps in order to convert the wave energy to electrical power. The definition of Power Take-Off systems (PTO systems) is required and the measurements related to absorbed power and converted power will be described.

POWER TAKE-OFF SYSTEMS

Five main classes of PTO systems can be defined:

- Linear Mechanical systems (Mechanical power)
- Hydraulic power take-off systems (Fluid power)
- OWC systems (Air power)
- Overtopping systems (water power)
- Rotary Mechanical systems (Shaft Power)

FORCE AND SPEED MEASUREMENT

Linear mechanical systems utilise the direct linear movement between two parts in the wave power converter. The power absorbed in such a conversion system is calculated from simultaneously measured values of force F [N] and velocity v[m/s].

The force F [N] can be measured using a load cell (force gauge) and the movement by using a potentiometer. The velocity of the relative movement can be obtained by differentiation of the position measurement, x(t), as:

$$v(t) = \frac{dx}{dt} = \dot{x}(t) \tag{35}$$

The power can be obtained as the product of the two measurements:

$$P(t) = F(t) \cdot v(t) \tag{36}$$

HYDRAULIC POWER

The mechanical power can be converted into hydraulic fluid power if the load is applied to a hydraulic cylinder. The mechanical work is transformed into hydraulic pressure and flow.

The hydraulic pressure difference p(t) over the piston area A_s is related to the force F(t) (if friction is ignored) by:

$$p(t) = \frac{F(t)}{A_s} \tag{37}$$

The flow is related to the velocity of the piston and the piston area as:

$$Q(t) = A_s v(t) \tag{38}$$

The absorbed hydraulic power can be measured by measuring the flow and the pressure:

$$P(t) = Q(t) \cdot p(t) \tag{39}$$

The difference between mechanical power and hydraulic power is mainly due to friction losses in the hydraulic cylinder and flow losses in the hydraulic system.

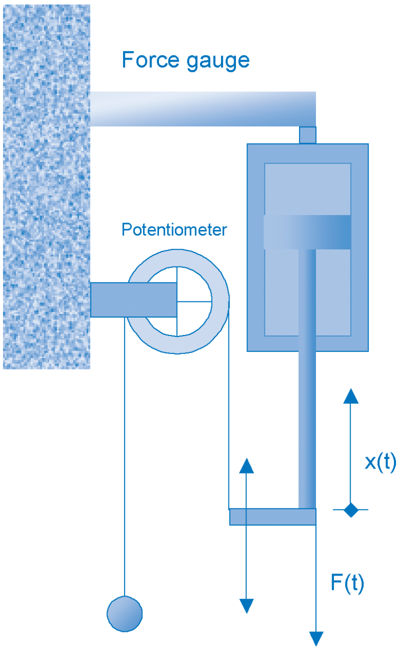


Figure 4.1 Schematic principle for measuring the power delivered to a piston.

OWC SYSTEMS

In the case of the OWC systems and overtopping systems, the wave power is coverted into flow Q [m3/s] and pressure p [N/m²] without a mechanical interface.The flow and pressure in OWC systems is pneumatic, i.e. air flowing forth and back through an air turbine. The air turbine can be simulated by an orificerestricting the air flow Q(t) [m3/s] and increasing the pressure p(t)[N/m²] in the airchamber. By calibrating the orifice it is possible to obtain a relation between pressure drop over the orifice and the flow,

$$Q(t) = \alpha \cdot p(t)^{\beta} \tag{40}$$

This means that the power measurement can be derived alone from measurement of pressure drop above the orifice.

$$P(t) = Q(t) \cdot p(t) = \alpha \cdot p(t)^{\beta+1} \qquad (41)$$

Depending on the final choice of air turbine and generator system (in full scale), the pressure drop can vary from linear to an exponential relation to flow.

In general applying an orifice provides a flow proportional to the square root of the pressure drop (β=0.5), whereas a linear variation (β=1) can be modelled by replacing the orifice with layers of felt.

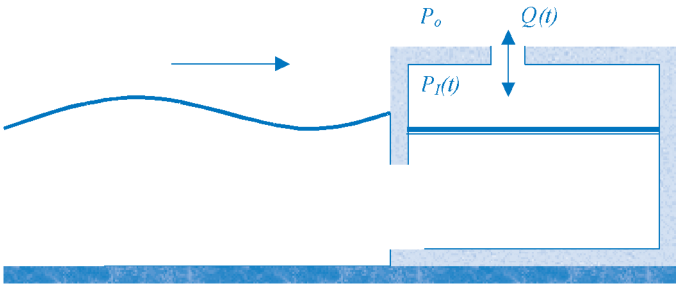


Figure 4.2 Schematic principle air flow and pressure in an OWC device

OVER TOPPING SYSTEMS

The power absorbed from over topping systems, i.e. systems where the waves run up a ramp elevated a distance ΔH over the mean sea surface and discharge a certain volume of water into the reservoir. If the water volume entering into the reservoir is pumped away, the average pump discharge Q_{ave} can be measured and the average absorbed power calculated:

$$P_{ave} = \Delta g Q_{ave} \Delta H \qquad (42)$$

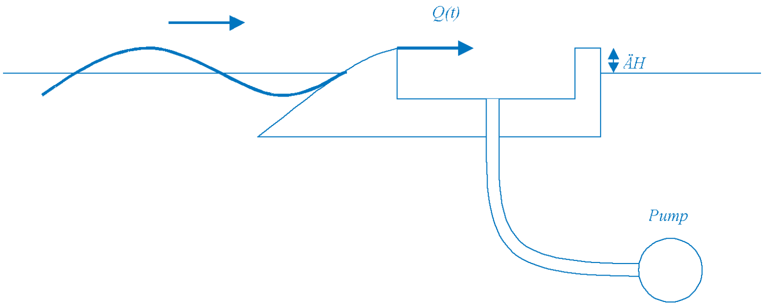


Figure 4.3 Schematic principle of flow and head in an over topping device Torque and rotation

Torque and rotation

The power delivered by a rotating shaft, i.e. to a generator, can be measured as the product of the shaft torque M(t) and the angular speed of rotation w(t).

$$P(t) = M(t)\omega(t) \qquad (43)$$

Where:

> $M(t)$ *Shaft Torque*
> $\omega(t)$ *Angular velocity*

Some systems like the wave mill directly converts the wave motion to a central rotating shaft. In other systems several conversion steps (some including flow rectification) are required before the rotation of the turbine is achieved.

OPTIMISATION OF POWER PRODUCTION

Finally a description on how the energy absorption of the wave power converter in a given sea state can be optimised by parametric changes within the PTO system. Conducting an experiment in irregular sea with a significant wave height Hs lasting for a period of time equivalent to 20 minutes in full scale provides a time series of the measured power as a function of time as illustrated in the figure below.

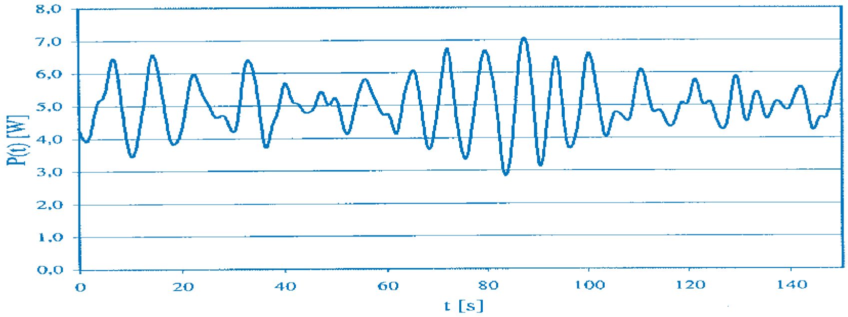


Figure 4.5

Figure 4.5 Illustration of the variation of absorbed power as a function of time t.

In general the power absorbed will depend on one or several parameters in the design that can be adjusted. This could be the orifice area, the height of the ramp in the overtopping system or the friction load applied to the linear mechanical systems. It is therefore recommended to carry out a number of experiments under the same sea conditions in order to find the optimum absorbed power in a specific sea state. In each experiment the average absorbed power Pm can be calculated from the time series of P(t) as:

Where the duration of the measurement period is T.

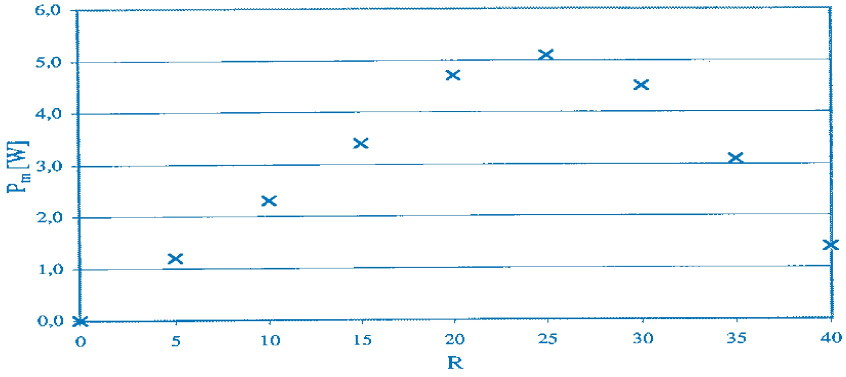


Figure 4.6

Figure 4.6 Example of a systematic change of resistance R in the power take-off system in order to find the optimum value of the average absorbed power Pm

5. PROTOTYPE TESTS

INTRODUCTION

Very few systems have yet been tested at sea and the main issue of this section is to propose some issues that could help comparisons between future prototype tests conducted at different sites within the EU and internationally.

Some standards with regard to the measurement of the incoming power seem to be very important and must be related to the measurements of absorbed and electrical power output on the individual systems.

Shoreline systems

The shoreline topography and the seabed slope will cause reflected and diffracted wave fields and waves will break at some distance from the coast, and the device itself might generate reflected waves. It would therefore seem natural to define the wave conditions facing the shoreline wave energy systems at some agreed minimum distance and water depth in front of the plant.

It could be recommended to measure the incoming waves at a depth contour of minimum 20 metre in the direction at least 1000 metre from the coastline.

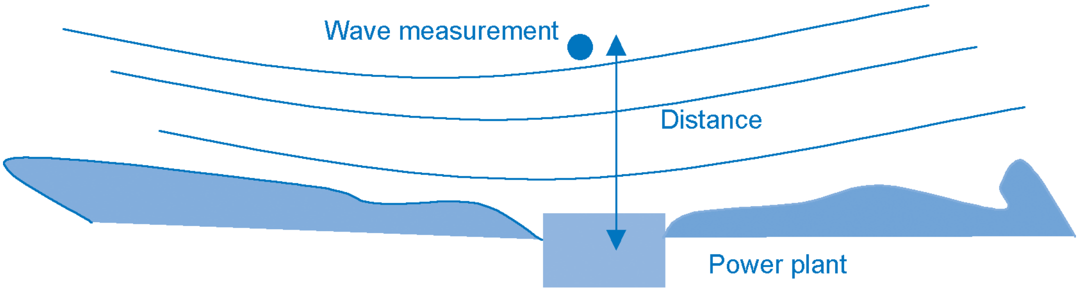


Figure 5.1

Offshore wave energy systems

Offshore wave energy plants will typically be located at some distance from the shore at water depths of about 40 - 50 metre. The reference wave data should be collected at some distance from the prototype plant e.g. at least 500 metre from the central position of the wave power plant.

Figure 5.1 Principle illustration of a shoreline wave energy plant seen from above.

Figure 5.2 Illustration oflocation of wave measurement related to an offshore wave energy plant (seen from above).

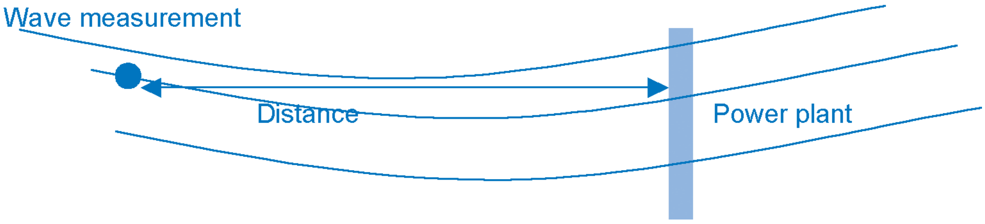


Figure 5.2

MEASUREMENTS RELATED TO THE OCEAN POWER CONVERSION

Building and installing prototypes of wave power converters at sea can provide information of how the converter perform at sea under real sea conditions.

In contrast to waves generated in laboratories real sea waves will be changing all the time and likely also be affected by tidal variation and currents. In order to relate the real sea performance to model scale tests it is necessary to measure these conditions regularly in order to monitor the performance. In addition to measurements of the generated electricity measurements of the absorbed power before conversion to electricity can help clarify the efficiency of the PTO system, both at full load and at part load.

Structural and mooring loads can provide information on the survival and fatigue conditions of the design. Such measurements are required in order to carry out future optimisation and provide documentation in relation to the safety of the system.

OWC systems

- Generated electrical power
- Absorbed Power (air pressure and flow)

Linear mechanical systems

- Generated electrical power
- Absorbed Power (Piston velocity and rod force)

Over – topping systems

- Generated electrical power
- Absorbed Power (Flow and average height of ramp above sea surface)

PRESENTATION OF THE MEASURED SEA STATES

The conditions of ocean changes with time – all the time – however the average conditions change only slowly and can in most ocean areas with sufficient fetch[1] be considered stationary for periods up to about 20 minutes. Ocean waves will be rather steep as the waves are generated by strong winds and after the storm has passed the waves propagate as swells, less steep and with a relatively larger wave period.

The single most important parameter needed to define the wave condition at the plant is the significant wave height: H_S (= 4*Hrms). The second piece of information that is important for understanding the sea condition at the site is the average wave period T_Z.

---

[1] - Fetch is the distance to shore in the direction of the incoming wind.

Duration of measurement periods and intervals between

The recommended duration of measurement is 20 minutes. This has been used as a standard period for ocean wave measurements in the past.

The interval between start of measurements is recommended to be 3 hours and to use Greenwich standard mean time. The identification of the time series is recommended to be:

- Pos_yymmdd_00
- Pos_yymmdd_03
- Pos_yymmdd_06
- Pos_yymmdd_09
- Pos_yymmdd_12
- Pos_yymmdd_15
- Pos_yymmdd_18
- Pos_yymmdd_21

Thus over a 24-hour period there will be 8 data points.

MEASUREMENTS RELATED TO THE ENVIRONMENT

A list of measurements related to the weather conditions that are associated with the incoming ocean power and the operational conditions of the converter.

Time date and position	
Sampling time	
The significant wave height: H_s (= 4*Hrms)	
The periods: T_z and T_e	
Direction of incoming waves: Deg	
Water level WL	
Mean water depth: d	
Current velocity V	
Current direction Vdeg	
Water density: ρ	
Water temperature	
Wind speed: U	
Wind direction: Udeg	
Atmospheric pressure	

INSTRUMENTATION FOR WAVE MEASUREMENTS

The practicality of instrumentation must be considered and the use of standard data acquisition systems recommended such as:

- Seabed mounted
- Floating Wave-rider buoy

Sampling frequency

The typical sampling frequency for measurements of wave conditions is 4 Hz and this is recommended as the default.

Preparation of wave data

Standard software is recommended for presentation of data and each time series should provide the following data:

- Identification
- Hmax
- Hmo
- To2
- Dir
- Spectrum
- Tp
- Te
- Pw

This data is required as reference for the performance and further useful in order to understand how the local wave parameters are related.

Site related scatter diagrams

The annual distribution of significant wave heights available from different sites can be presented in hours per year. To clarify the distribution, intervals of 0.5 metre are recommended. This corresponds to the standard most often used as in the case of the WerAtlas.

West of Orkney, at UKMO point 59.00°N 3.66°W, based on data from November 1986 – March 2001 Data in parts per hundred thousand.

Significant wave height H_s (m)	Mean wave period T_z (s)																Total
	0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12	12-13	13-14	14-15	15-16	
0.5	–	–	–	655	560	299	233	114	69	28	5	–	–	–	–	–	1963
0.5 to 1.0	–	–	–	3654	7426	3300	1109	423	138	62	36	5	2	–	–	–	16155
1.0 to 1.5	–	–	–	871	9076	5757	2358	886	332	126	33	5	2	7	5	–	19458
1.5 to 2.0	–	–	–	183	3310	8853	2702	1073	396	145	50	9	5	5	–	–	16731
2.0 to 2.5	–	–	–	–	368	7184	3796	1220	591	178	71	–	–	–	–	–	13408
2.5 to 3.0	–	–	–	–	26	1645	6472	1299	366	176	97	19	5	–	–	–	10105
3.0 to 3.5	–	–	–	–	–	221	4371	2049	342	150	74	21	2	–	2	–	7232
3.5 to 4.0	–	–	–	–	–	–	921	3269	415	107	38	17	19	5	–	–	4791
4.0 to 4.5	–	–	–	–	–	–	100	2296	748	102	14	17	2	–	–	–	3279
4.5 to 5.0	–	–	–	–	–	–	2	655	1339	109	31	17	5	5	5	–	2168
5.0 to 5.5	–	–	–	–	–	–	–	74	1052	192	38	14	9	–	–	–	1379
5.5 to 6.0	–	–	–	–	–	–	–	12	465	318	26	5	–	–	–	–	826
6.0 to 6.5	–	–	–	–	–	–	–	–	138	373	26	2	–	–	–	–	539
6.5 to 7.0	–	–	–	–	–	–	–	–	26	233	31	7	5	–	–	–	302
7.0 to 7.5	–	–	–	–	–	–	2	9	–	119	121	9	–	–	–	–	260
7.5 to 8.0	–	–	–	–	–	–	–	–	–	62	150	5	–	–	–	–	217
8.0 to 8.5	–	–	–	–	–	–	–	–	–	–	138	12	–	–	–	–	150
8.5 to 9.0	–	–	–	–	–	–	–	–	–	–	69	26	2	–	–	–	97
9.0 to 9.5	–	–	–	–	–	–	–	–	–	–	17	47	–	–	–	–	64
9.5 to 10.0	–	–	–	–	–	–	–	–	–	–	–	36	9	–	–	–	45
10.0 to 10.5	–	–	–	–	–	–	–	–	–	–	2	7	7	–	–	–	16
10.5 to 11.0	–	–	–	–	–	–	–	–	–	–	–	9	7	–	–	–	16
11.0 to 11.5	–	–	–	–	–	–	–	–	–	–	–	2	7	–	–	–	9
11.5 to 12.0	–	–	–	–	–	–	–	–	–	–	–	–	2	–	–	–	2
12.0 to 12.5	–	–	–	–	–	–	–	–	–	–	–	–	2	–	–	–	2
12.5 to 13.0	–	–	–	–	–	–	–	–	–	–	–	–	2	–	–	–	2
Total	–	–	–	5363	20766	27259	22066	13379	6417	2480	1067	291	94	22	12	–	99216

Directional presentation

The directionality of waves can be presented within angles between 30 and 45 degrees. From the point of view that the data shall be presented in a reasonable format, 8 main directions might be sufficient. However traditionally observations of wind and wave directions have been carried out from 12 directions.

West of Orkney, at UKMO point 59.00∞N 3.66∞W, based on data from November 1986 – March 2001 Data in parts per hundred thousand.

Significant wave height H_s (m)	Wave direction (centre of 30° wide sectors, °N)												Total
	0	30	60	90	120	150	180	210	240	270	300	330	
< 0.5	190	131	62	12	7	12	31	43	62	753	456	207	1966
0.5 to 1.0	1925	1104	437	347	392	451	446	489	814	4036	3732	1980	16153
1.0 to 1.5	2714	1396	437	311	522	646	556	598	1140	4385	3974	2780	19459
1.5 to 2.0	2308	1061	328	247	394	591	499	513	1254	3908	3659	1971	16733
2.0 to 2.5	1854	783	259	150	214	332	344	347	981	3438	2844	1864	13410
2.5 to 3.0	1230	646	119	62	104	183	138	216	902	2837	2348	1320	10105
3.0 to 3.5	838	311	55	31	52	59	40	121	696	2464	1757	807	7231
3.5 to 4.0	453	188	33	12	14	7	17	52	401	1821	1270	522	4790
4.0 to 4.5	287	102	19	5	7	5	7	14	190	1294	985	363	3278
4.5 to 5.0	214	31	2	–	–	–	–	–	90	838	762	230	2167
5.0 to 5.5	195	47	–	–	–	–	–	–	14	468	520	135	1379
5.5 to 6.0	59	17	–	–	–	–	–	–	9	361	266	114	826
6.0 to 6.5	40	33	–	–	–	–	–	–	–	185	192	88	538
6.5 to 7.0	14	14	–	–	–	–	–	–	–	102	121	50	301
7.0 to 7.5	21	14	–	–	–	–	–	–	–	78	114	33	260
7.5 to 8.0	19	24	–	–	–	–	–	–	–	45	102	26	216
8.0 to 8.5	–	5	–	–	–	–	–	–	5	28	93	19	150
8.5 to 9.0	17	–	–	–	–	–	–	–	–	21	47	12	97
9.0 to 9.5	5	5	–	–	–	–	–	–	–	9	36	9	64
9.5 to 10.0	–	–	–	–	–	–	–	–	–	9	26	9	44
10.0 to 10.5	–	–	–	–	–	–	–	–	–	–	12	5	17
10.5 to 11.0	–	–	–	–	–	–	–	–	–	5	12	–	17
11.0 to 11.5	–	–	–	–	–	–	–	–	–	–	7	2	9
11.5 to 12.0	–	–	–	–	–	–	–	–	–	–	2	–	2
12.0 to 12.5	–	–	–	–	–	–	–	–	–	–	2	–	2
12.5 to 13.0	–	–	–	–	–	–	–	–	–	–	–	2	2
Total	12383	5912	1751	1177	1706	2286	2078	2393	6558	27085	23339	12548	99216

ACKNOWLEDGEMENT

This report has been prepared on the basis of the standards prepared for the Danish Wave Energy Programme (1997 – 2001), supported by the Danish Energy Agency with contributions from Vagner Jacobsen, Danish Hydraulic Institute, Hans Burchart, Aalborg University and Michael Mcdonald Arnskov, Danish Maritime Institute

In addition many valuable comments has been incorporated from the international wave energy community.

ANNEX II
Development of recommended practices for testing
and evaluating ocean energy systems

SUBTASK II.3

PRESENTATIONS OF RESULTS

PRESENTATION OF RESULTS 50

PRESENTATION OF RESULTS

INTRODUCTION

The fuel driving the generator of the wave energy converter is free. It is therefore the aim to develop inexpensive converters that can drive a specific generator and withstand the impact of the ocean environment.

In order to compare different systems it is of primary importance to verify how much energy a given converter can generate on a yearly basis, and how much it is likely to be going to cost – and ensure that the system can it survive.

Windmills generate power as a function of the wind speed, and wave energy converters generate power depending on the sea state (H_s, T_z).

In a broad international development programme, the aim is to ensure comparable presentations of results between different types of wave energy converters. In order to achieve this, a set of standardised generic wave conditions for testing has been proposed in section 3. In the present section guidelines for presentation of results of measured data are described.

It is however very important to recognise that these guidelines are not intended to limit the testing or reporting – however the guidelines should be regarded as a minimum content required to evaluate the results.

In order to collate a summary of results in a precise short and standardised form some headings for reporting are recommended. The headings are:

- Background, previous R&D projects etc
- Information on test facility
- The wave energy converter, principle
- Drawing of converter at full scale
- Main dimensions
- Weight and materials involved at model and full scale
- PTO system conversion efficiency and storage options
- Experimental set-up
- Results and data from standardised Power-production-tests
- Results and data from standardised Survival tests
- Recommendations for further actions
- Supporting information, if any

BACKGROUND AND SCOPE OF THE STUDY

The aim of the project should be described and references made to previously conducted projects. A list of previous project reports should be made.

TEST FACILITY

In many cases the institute carrying out the testing will be responsible for the reporting. The table format used in Subtask 2.1 Institutions could be used in order to summarise the test facility used for the experiment.

1. Facility	2. Dimensions			5. Remarks
	L[m]	B[m]	D[m]	

The model scale sea states prepared for the experiment should be listed.

3. Waves		4. Current	
H_s	T_p	v[m/s]	Q[m3/s]

THE PRINCIPLE AND DRAWING OF FULL SCALE SYSTEM

A description of the operating principle of wave energy converter should be presented and a drawing of the full-scale design.

> *Drawing with dimensions of the full-scale converter*

MAIN DIMENSIONS AND WEIGHTS

A table of the main dimensions, weight and stability calculations can be included in this section. In general it is recommended that the device developers are associated with ship-designers, specialist engineers or ocean engineers in order to ensure a realistic design at this stage.

Data for the wave energy converter

The main data of the wave energy converter is presented.

Main data	
Length [m]	22
Beam [m]	22
Height [m]	13
Device volume [m^3]	80
Device float weight [tonne]	80
Device mooring substructure [tonne]	-
Total weight [tonne]	80

Materials involved

The weights of different materials included in the structural design are described.

Material types and weights	
Steel [tonne]	80
Concrete [tonne]	
Ballast concrete [tonne]	
Glass fibre [tonne]	

PTO system

The type of PTO system includes the conversion efficiency, and storage options are described and the rated power of the system assessed. For preliminary analyses and comparability of results the rated power is defined as the average absorbed power in a sea state of H_S = 5 metre.

Rated power [kW]	120

TEST PROCEDURE AND METHODOLOGY

In this section a description of the test and calculation procedures are described regarding

> *Experimental set-up*
> *Scale*
> *Drawing of the experimental model (reference number)*
> *Selected test series from the standard test regime*
> *Procedure for experimental measurement of absorbed power*
> *Design conditions and survival testing*
> *Calculation of design loads and parameters involved*

PRESENTATION OF POWER CURVE

In order to provide information on the power absorbed P_{abs} by a specific wave energy converter, it is recommended to produce a specific plot of the absorbed power in the 5 basic sea conditions specified in the basic test series in the range of H_S from 1 to 5 metre. An example of such a power curve is shown in figure 4.1.

Sea state Hs [metre]	1	2	3	4	> 5	sum
Average wave Period T_Z [sec] 4	5	6	7	8		
Absorbed Power P_{abs} [kW]	13	37	68	104	120	

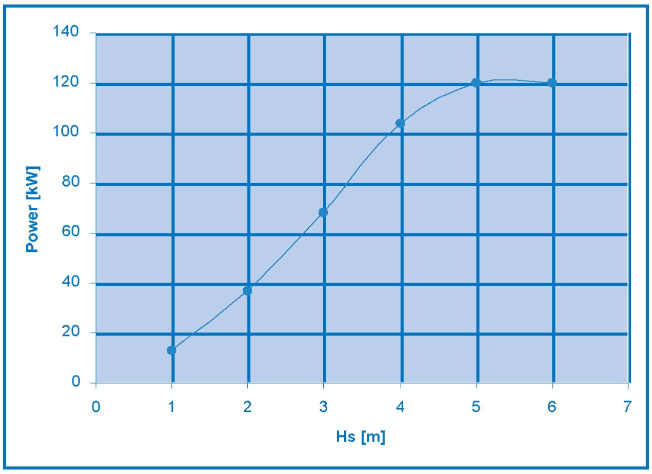


Figure 1 Power curve showing the measured relation between absorbed Power Pabs as a function of the significant wave height H_S in the five sea conditions specified in table 1.

Figure 1

ANNUAL ENERGY PRODUCTION

The annual energy production of the converter can be calculated by combining the information of the scatter diagram with the power curve. From the scatter diagram it is possible to see how many hours per year each sea state prevails. The annual energy production is therefore calculated as the sum of the product of the average absorbed power in each sea state and the number of hours per year this sea state prevails.

$$E_{ave} = \sum P_{abs}(H_s) \cdot dt(H_s)$$

The calculation is shown in the table below where the average absorbed power in each sea state is shown in (kW) and the number of hours per year this sea state prevails is shown.

Sea state Hs [metre]	1	2	3	4	> 5	sum
Absorbed Power Pabs [kW]	13	37	68	104	120	
Hours per year dt	4174	1879	839	362	149	
Energy production [kWh/year]	54.262	69.523	57.052	37.648	17.880	236.365 kWh

Table 2

Table 2 Energy contributions from the different sea states on a yearly basis.

ANNUAL AVERAGE CAPTURE WIDTH RATIO

The annual average capture width ratio denotes the ratio between the captured energy per year and the energy available to the wave power converter. The available wave energy is calculated as the energy passing through a fictive vertical cylinder with a diameter equal to the largest horizontal dimension of the wave energy converter (beam or length).

Example: The power curve in Table 4.1 is the result of measured data on a float in the shape of a flat vertical cylinder with a diameter of 10 metre. The annual captured energy is 236,365 kWh. The average annual energy at the site is 11.6 kW/m. The available energy over the year is therefore 8760 hours*11.6 kW/m*10 m = 1,016,160 kWh. The ratio between these two numbers gives the annual average capture width ratio

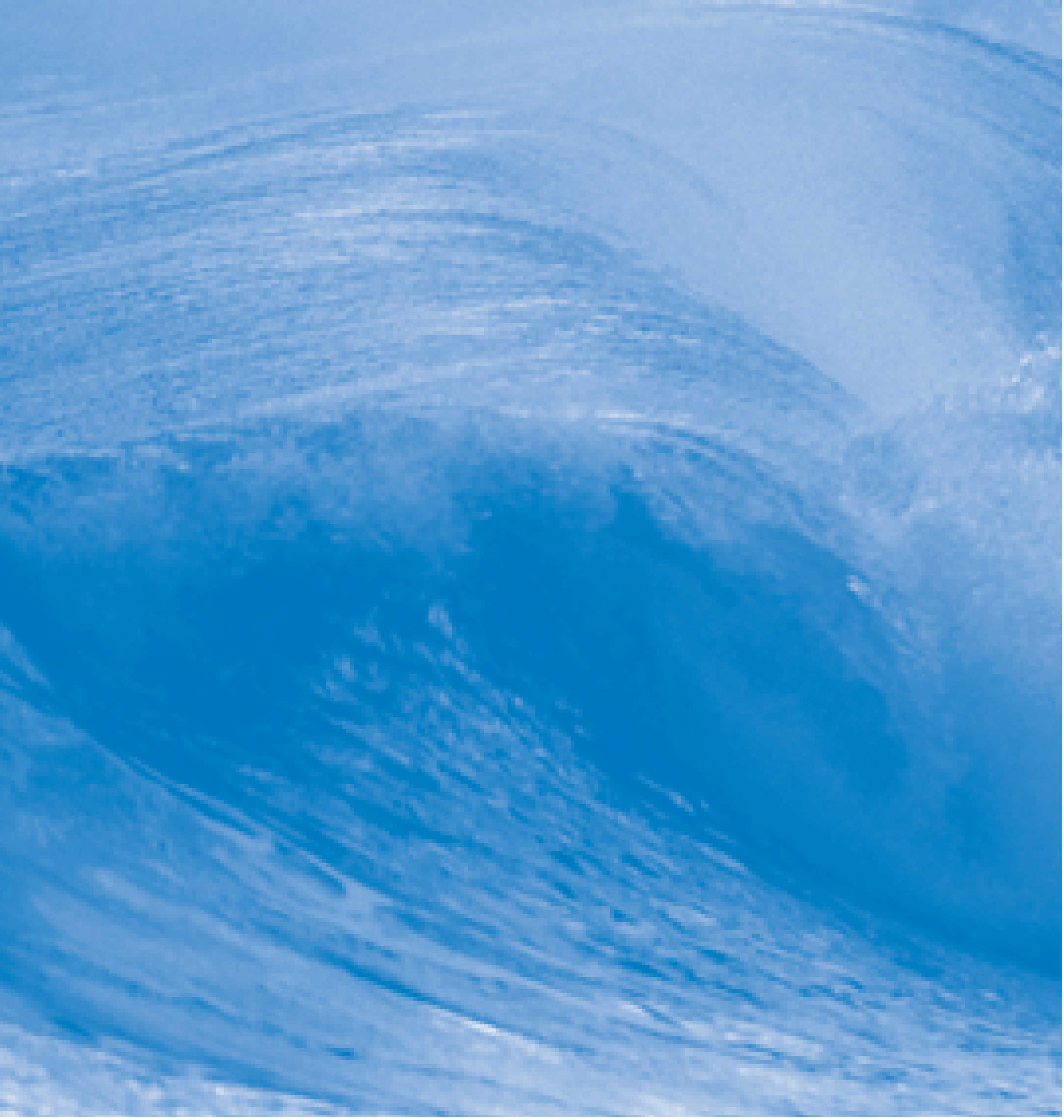
$$\eta_1 = \frac{E_{abs}}{8760 hours \cdot P_{\inf} \cdot D} = \frac{236365}{8760 \cdot 11{,}6 \cdot 10} = 23\%$$

In order to calculate the capture with a ratio for an array of converters, a similar approach can be adapted taking into account the total absorbed power and the array dimensions.

RECOMMENDATION FOR FURTHER R&D

Based on the results obtained during the completed project it is common that new related issues not envisaged at the start will require further R&D.

In example changes in experimental set-up can lead to improvements not foreseen at the project start – or the system design is behaving in an unintended way during survival conditions and that the cause for this calls for a redesign.



ANNEX II
Development of recommended practices for testing
and evaluating ocean energy systems

SUBTASK II.4

PERFORMANCE ASSESSMENT

PERFORMANCE ASSESSMENT

As a tool in the development process it is recommended to provide a few figures relating the performance of the wave energy converter to the costs associated with the weights and installed generating capacity of the system. This assessment is generic and does not take the cost of installation, maintenance and power transmission into account.

PRESENTATION OF TEST RESULTS

To provide a snapshot of the device development, the test results and specific design, can be presented in a standardised format as shown in table 8.1. The table can be used as an excel worksheet in order to automate the calculations. The weight and materials included in the structural design are combined with standardised unit costs, and the measured performance in the standardised wave conditions are combined with generic statistics representing different ocean sites. This way a few comparable cost figures are obtained.

K	Capital cost
P	Rated Power
E	Annual energy production

These figures are useful in order to establish a comparable and systematic presentation of the results in the form of:

K/E	"energy cost"
K/P	Cost per kW rated power
E/P	Full load hours per year

ABSORBED ENERGY PER YEAR

The measured average power production in the range of sea conditions from H_s =1 metre to H_s = 5 metre (at central estimates of the average wave period T_z) are presented in full scale. For preliminary assessment a unidirectional reference distribution of sea states (in hours per years) is recommended. The distribution below compares to the wave climate in Danish part of North Sea. 16 kW/m and the performance data from the example page 58.

Table 1 The annual energy production is calculated

H_s [m]:	1	2	3	4	5	Energy [MWh/year]
Tz [sec]	4	5	6	7	8	
Hours	4102	1981	944	445	326	
kW/m	2	12	32	66	115	
Pabs (Hs, Tz)	2.5	30	85	130	180	
Energy contribution MWh	10	59	80	58	59	266

Table 1

"RATED POWER"

Rated power P is defined as the average absorbed power in sea state Hs = 5m over a period of 20 minutes (in full scale). This definition is chosen for comparative reasons and the actual generator might in some cases be larger to cope with peak power.

UNIT COSTS

Based on the information provided in the project reports for the different systems regarding system mass and choice of materials, a few standard costs related to the choice of material are recommended. The unit costs should reflect:

Material	Unit cost €/tonne
Concrete	200
Ballast concrete	70
Steel	3400
Glass-fibre	9500

PTO SYSTEM AND RATED POWER

The power take-off system including turbine, gear and generator is assessed according to its rated power. The unit cost of the PTO system is estimated to about 340 _/kW independent of type. The average conversion efficiency of the different types of PTO systems has been estimated as shown below.

PTO system	Unit cost €/kW	PTO eff
Direct	340	95%
Air	340	54%
Water	340	83%
Hydraulic	340	65%

CAPITAL COST

The capital cost of the wave power converter is calculated on the basis of the unit cost information above and the data on materials included in the system as reported on the specific project.

Structural costs K €

ELECTRICAL ENERGY PRODUCTION

The annual electricity production is calculated by multiplying the annual absorbed energy with the average conversion efficiency of the PTO system.

$E = Eabs * PTO_{eff}$

E kWh/year Electrical Energy

ENERGY ABSORPTION PER DISPLACED VOLUME AND MASS

In comparison to other technologies the ratio between absorbed energy and construction volume and mass can be of interest.

Energy/volume E/V

Energy per structural mass E/M

Main data:

Length [m]	22
Beam [m]	22
Height [m]	13
Device volume [m^3]	80
Device float weight [tonne]	80
Device mooring substructure [tonne]	-
Total weight [tonne]	80

Material types and weights:

Steel [tonne]	80
Concrete [tonne]	
Ballast concrete [tonne]	
Glass fibre [tonne]	
Water ballast [tonne]	
Rated power [kW]	180

Cost calculation:

Material type	Unit prices €	Units	Material cost €
Steel [tonne]	3400	80	272000
Concrete [tonne]	200		0
Ballast concrete [tonne]	70		0
Glass fibre [tonne]	9500		0
Water ballast [tonne]	0		0
PTO system [kW]	340	180	61200
K Total structural cost €			333200

Performance power level at site 16 kW/m:

Power level at site	Wave distribution Hours/year	Hs[m]	Pabs [kW]
H_s=0.5m –1.5m	4102	1	2,5
H_s=1.5m – 2.5m	1981	2	30
H_s=2.5m – 3.5m	944	3	85
H_s=3.5m –4.5m	445	4	130
H_s> 4.5m	326	5	180[1]
Captured energy per year [kWh/year]			266.455
Wave energy per year over the largest dimension of the device (width or beam) [kWh/year]			3.083.520
Average capture width ratio			9%

Energy/volume [kWh/year/m^3]	3.331
Energy/mass [kWh/year/tonne]	3.331
Power take-off system average efficiency	81%
E Electrical Power production per year [kWh/year]	215.829
P Rated Power [kW]	180
Annual electrical production / volume [kWh/year/m^3]	2.698
Annual electrical production / mass [kWh/year/tonne]	2.698
E/P Full load hours [kWh/kW]	1.199
K/P €/kW	1851
K/E €/kWh	1.540

---

[1] - Defined as rated power

SUMMARY PRESENTATION OF RESULTS (AN EXAMPLE)

Applicant: DMI / Leif Wagner Smith	**Project name:** Wave Plunger

J.No.	Date:	Funding:	Institute / test site
51191/98-0016	02-07-98	150.000 DKK	DMI
51191/99-0039	21-07-99	425.000 DKK	DHI

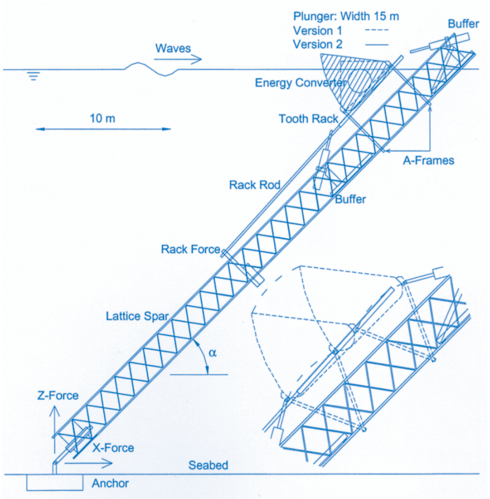
Reports

Feasibility Test with the "Plunger Wave Energy Converter", Danish Maritime Institute, 1999-02-06 Optimisation of the "Plunger Wave Energy Converter"
DMI 99133, 2001-11-23

Principle: The *Wave Plunger* is based on an asymmetric float moving along a sloped lattice tower, attached to a suction anchor on the seabed.

The float is intended to move along the sloped plane and thereby create waves to the lee of the structure. In theory this should enable the system to absorb the waves with a high capture width ratio.

Status: Model scale experiments in scale 1:25 have been completed at DMI March 1999. Further testing in 3D waves with a modified design of the guiding rails and float geometry was carried out at DHI in 2001.



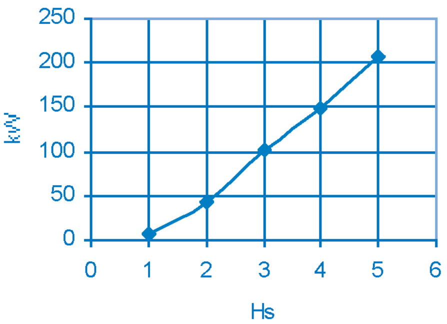
Main data:

Water depth:	
Length:	4.5 m
Beam:	15.0 m
Height:	4,5 m
Plunger Volume:	120 m^3
Float weight:	50 tonnes
Mast weight:	20 tonnes
Suction anchor:	50 tonnes

Choice and weight of materials:

Steel:	50 tonnes
Concrete:	50 tonnes
Ballast concrete:	50 tonnes

Power curve



Reference location:	North sea 16 kW/m
Power take-off:	
PTO efficiency (yearly average):	65 %
Rated Power:	207 kW
Annual energy absorption:	341.400 kWh
Annual electrical production:	222.900 kWh

Mooring system: directly to seabed
Lattice tower
Suction cup anchor
Maximum mooring force: 2.900 kN

Further R&D

- Structural and Mechanical design
- Power take-off

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FICHA TÉCNICA

PUBLISHED BY	IEA | Ocean Energy Systems
ACTING EDITOR	Dr. Kim Nielsen / RAMBOLL
DESIGNED BY	2&3D Design e Produção, Ltd
CIRCULATION	1000 exemplares
PRINTED BY	Textype, Artes Gráficas, Ltd
Depósito Legal	
ISBN	