User Organisation: CalWave Power Technologies UG

User Project: Taut Mooring Rope CBOS Testing

Project Acronym: TaMoRoCT

Project Reference Number: 2c

Infrastructure Accessed Ifremer - Materials Testing Facility

Infrastructure
Access
Reports

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MaRINET2

ABOUT MARINET

The MaRINET2 project is the second iteration of the successful EU funded MaRINET Infrastructures Network, both of which are coordinated and managed by Irish research centre MaREI in University College Cork and avail of the Lir National Ocean Test Facilities.

MaRINET2 is a €10.5 million project which includes **39 organisations** representing some of the top offshore renewable energy testing facilities in Europe and globally. The project depends on strong international ties across Europe and draws on the expertise and participation of **13 countries**. Over 80 experts from these distinguished centres across Europe will be descending on Dublin for the launch and kick-off meeting on the 2nd of February.

The original MaRINET project has been described as a *"model of success that demonstrates what the EU can achieve in terms of collaboration and sharing knowledge transnationally".* Máire Geoghegan-Quinn, European Commissioner for Research, Innovation and Science, November 2013

MARINET2 expands on the success of its predecessor with an even greater number and variety of testing facilities across offshore wind, wave, tidal current, electrical and environmental/cross-cutting sectors. The project not only aims to provide greater access to testing infrastructures across Europe, but also is driven to improve the quality of testing internationally through standardisation of testing and staff exchange programmes.

The MaRINET2 project will run in parallel to the MaREI, UCC coordinated EU marinerg-i project which aims to develop a business plan to put this international network of infrastructures on the European Strategy Forum for Research Infrastructures (ESFRI) roadmap.

The project will include at least 5 trans-national access calls where applicants can submit proposals for testing in the online portal. Details of and links to the call submission system are available on the project website www.marinet2.eu

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1 Introduction & Background

1.1 Introduction

CalWave Power Technologies UG (CPT) is developing a submerged pressure-differential wave energy converter (WEC) capable of precise load management, lowering capital costs and increasing capacity factor.

CPT is currently working towards a scaled ocean demonstration of the WEC technology.

Historically, primary testing at 1:50 scale was completed in January 2016, and limited testing at 1:20 scale was completed in August 2016 at the U.S. Navy MASK Basin. After significant redesign in 2017, CPT completed hydrodynamic system identification in Jan. 2018 at the LIR DOB with the support of Marinet2. Testing at DOB produced over 100 test cases, totalling over 20 hours of recorded data, providing a rich data set for hydrodynamic WEC characterization and feed-in to detailed PTO and PTO control design. Follow-up tank testing was conducted in August and November of 2019 with representative PTO/device controls.

CPT is interested in utilizing a winch mechanism in its WEC capable of high cycles and full system loads. Initially, this project was intended to be focused on the testing of synthetic mooring ropes. These ropes typically suffer from cyclic bend over sheave (CBOS) failures due to a high number of bending cycles causing individual rope fibers to rub against each other. After a design iteration, an HMPE webbing belt was instead selected to perform the linear to rotary power conversion with the expectation of superior CBOS performance. CPT collaborated with TTS-Innova on the selection of an appropriate HMPE webbing. This project sought to confirm the suitability of the selected belt under representative loads and a high number of cycles in preparation for the upcoming field deployment.

1.2 Development So Far

1.2.1 Stage Gate Progress

Device modelling and scaled tank testing for device has been previously completed and existing data was used to select belt experimental testing parameters.

Previously completed: ✓

Planned for this project: ➲

STAGE GATE CRITERIA	Status
Stage 1 – Concept Validation	
• Linear monochromatic waves to validate or calibrate numerical models of the system (25 – 100 waves)	✓
• Finite monochromatic waves to include higher order effects (25 –100 waves)	✓
• Hull(s) sea worthiness in real seas (scaled duration at 3 hours)	✓
• Restricted degrees of freedom (DofF) if required by the early mathematical models	✓
• Provide the empirical hydrodynamic co-efficient associated with the device (for mathematical modelling tuning)	✓
• Investigate physical process governing device response. May not be well defined theoretically or numerically solvable	✓
• Real seaway productivity (scaled duration at 20-30 minutes)	✓
• Initially 2-D (flume) test programme	✓
• Short crested seas need only be run at this early stage if the devices anticipated performance would be significantly affected by them	✓
• Evidence of the device seaworthiness	✓
• Initial indication of the full system load regimes	✓
Stage 2 – Design Validation	

STAGE GATE CRITERIA	Status
• Accurately simulated PTO characteristics	✓
• Performance in real seaways (long and short crested)	✓
• Survival loading and extreme motion behaviour.	✓
• Active damping control (may be deferred to Stage 3)	✓
• Device design changes and modifications	
• Mooring arrangements and effects on motion	✓
• Data for proposed PTO design and bench testing (Stage 3)	✓
• Engineering Design (Prototype), feasibility and costing	✓
• Site Review for Stage 3 and Stage 4 deployments	✓
• Over topping rates	
Stage 3 – Sub-Systems Validation	
• To investigate physical properties not well scaled & validate performance figures	➲
• To employ a realistic/actual PTO and generating system & develop control strategies	✓
• To qualify environmental factors (i.e. the device on the environment and vice versa) e.g. marine growth, corrosion, windage and current drag	➲
• To validate electrical supply quality and power electronic requirements.	
• To quantify survival conditions, mooring behaviour and hull seaworthiness	✓
• Manufacturing, deployment, recovery and O&M (component reliability)	➲
• Project planning and management, including licensing, certification, insurance etc.	
Stage 4 – Solo Device Validation	
• Hull seaworthiness and survival strategies	
• Mooring and cable connection issues, including failure modes	
• PTO performance and reliability	
• Component and assembly longevity	
• Electricity supply quality (absorbed/pneumatic power-converted/electrical power)	
• Application in local wave climate conditions	
• Project management, manufacturing, deployment, recovery, etc	
• Service, maintenance and operational experience [O&M]	
• Accepted EIA	
Stage 5 – Multi-Device Demonstration	
• Economic Feasibility/Profitability	
• Multiple units performance	
• Device array interactions	
• Power supply interaction & quality	
• Environmental impact issues	
• Full technical and economic due diligence	
• Compliance of all operations with existing legal requirements	

1.2.2 Plan For This Access

1.2.2.1 To investigate physical properties not well scaled & validate performance figures

Although often used for lifting slings, HMPE belts are not yet commonly used for linear to rotary power transmission. The focus of this access is to test the HMPE belt under representative loads for a high number of cycles and confirm tensile strength and expected cycles to failure. In a deployment, the belt would have to undergo millions of cycles in a single year due to the natural periods of ocean waves.

1.2.2.2 *To qualify environmental factors (i.e. the device on the environment and vice versa) e.g. marine growth, corrosion, windage and current drag*

Testing is performed "wet" with a water spray to appropriately simulate the thermal aspects of the belts being used in a marine environment. CBOS is in part driven by thermal effects of fibers rubbing against each other and thus the cooling effects of the water spray are expected to lead to more representative results for CBOS performance.

1.2.2.3 *Manufacturing, deployment, recovery and O&M (component reliability)*

HMPE belt sample to be tested will be that envisioned for the scaled ocean demonstration. By assessing the CBOS performance of an actual belt sample, a better understanding of the risk associated with this less common use case can be obtained.

2 Outline of Work Carried Out

2.1 Setup

2.1.1 HMPE Sample

A sample of HMPE belt was supplied for testing on a CBOS testing setup at Ifremer's Materials Testing Facility. The belt sample was nominally 6m long, 100 mm wide and 2.6 mm thick. The belt has a nominal breaking strength of 180 kN. End terminations were made by folding the belt end over and sewing the two sides together to create a loop, as shown in Figure 2.1.

Figure 2.1:HMPE belt construction showing end loop termination.

2.1.2 Custom Pulley Sheave

A new pully sheave was manufactured from Nylon MD Oil-Filled to allow the CBOS experimental set up to accommodate the belt sample. This pulley is shown in Figure 2.2. Due to bearing restrictions, the maximum pully width and minimum diameter the CBOS test machine could accommodate was 100 mm and 320 mm, respectively. The belt width that the sheave could accommodate between flanges was 94 mm. Due to a manufacturing error, the belt sample was produced wider than 94 mm and because of time restrictions, testing was conducted without reordering a belt of a more appropriate width. The 320 mm diameter is representative of the winch drum the belt will eventually be wrapped around during operation. A dimensioned drawing of the pulley can be found in Figure 2.3.

Figure 2.2: Custom pulley sheave machined from Nylon MD Oil-Filled.

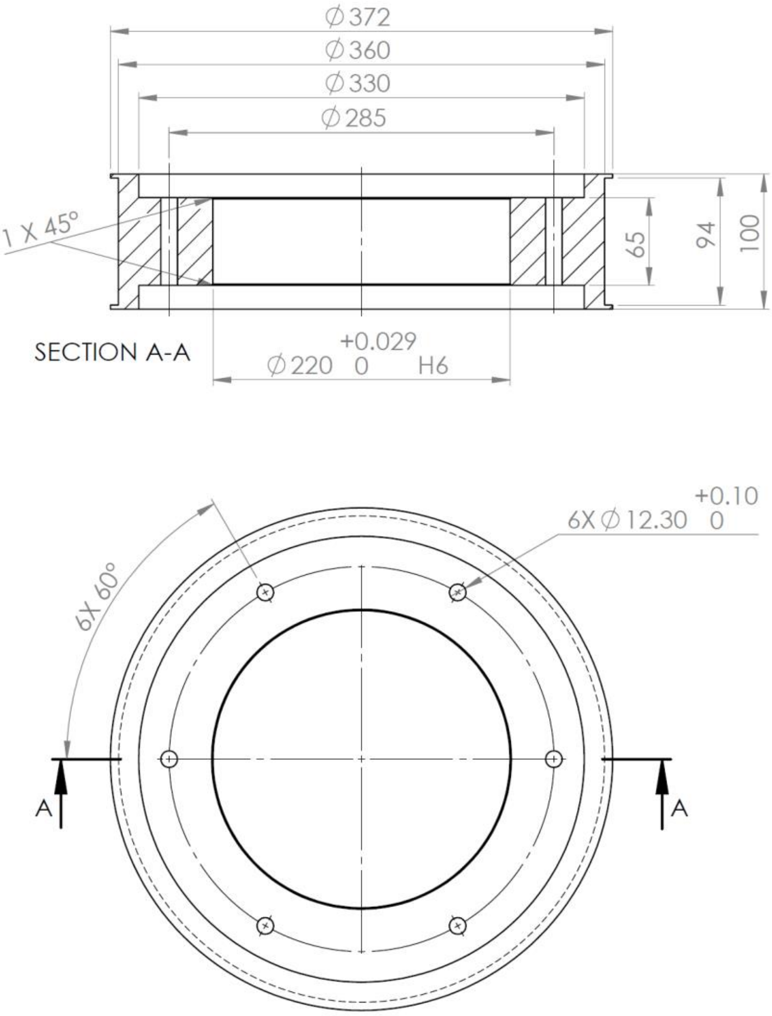


Figure 2.3: Drawing of machined custom pulley

2.1.3 Experimental Setup

The new sheave was mounted to the test machine followed by the HMPE belt sample. The HMPE sample is wrapped 180° around the sheave and the two loop ends are connected to two pistons that induce belt displacement relative to the sheave. The test machine utilizes a central piston to apply and maintain a specific load on the sheave, thus providing a near uniform tension in the belt sample. Displacements and loads are monitored by the machine. A water system allows tap water to be sprayed on the belt, keeping the areas of interest wet and simulating the thermal properties of a marine environment. An IR camera was used to measure surface temperature of the belt sample. This full experimental set up can be found in Figure 2.4 with detail of the belt loop termination connection shown in Figure 2.5.

Figure 2.4: Experimental set up with sheave and belt mounted to the test machine.

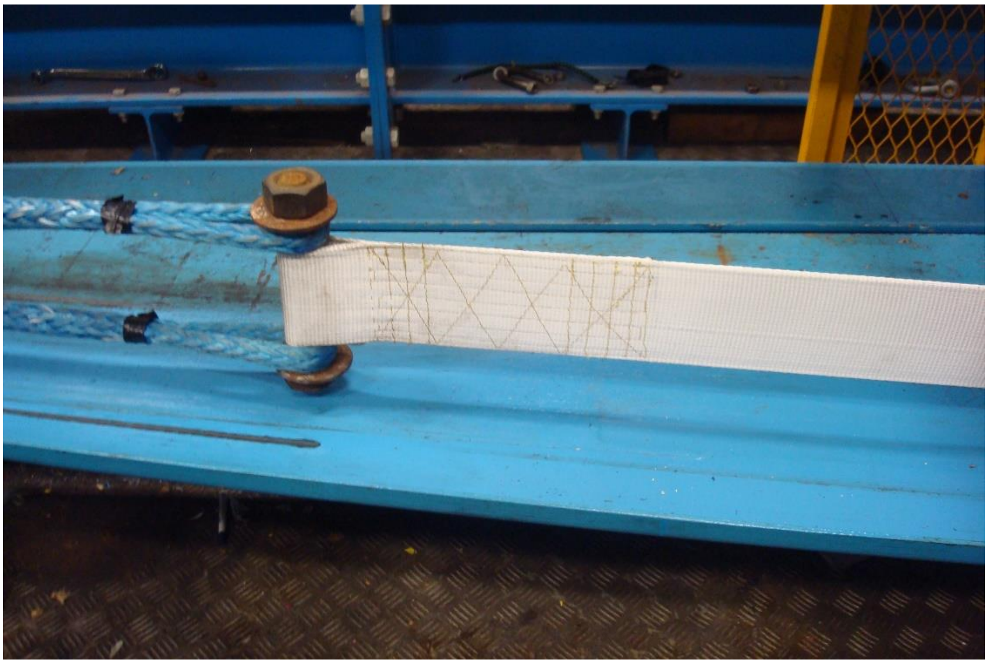


Figure 2.5: Belt loop termination connection to test machine.

2.2 Tests

2.2.1 Test Plan

A single endurance testing experiment was planned for the full duration of the access. A constant load of 90 kN was applied to the central piston, inducing a 45kN tensile load on the belt. 45kN is the expected peak load seen in the belts during the scaled deployment and this value was chosen to lead to a conservative estimate of cycles to failure. The belt was displaced sinusoidally with an amplitude of 320 mm at a period of 14s in order to have sections of the belt fully pass on and off the sheave during each cycle. Note that this leads to two bend-unbends per cycle, whereas a belt wrapping on and off a winch drum would only have one bend-unbend per cycle. It is notable that 14s is a longer period than would be seen in a scaled ocean environment and shorter periods would be desirable to accelerate wear testing and induce a larger number of cycles in a shorter period of time. Unfortunately, a 14s period was the limit of the machine's capabilities for the required displacement amplitude.

Experimental data, including applied and measured loads and piston displacements were recorded with a sampling frequency of 1 Hz. The IR camera was used to compare surface temperatures between 5 points on the belt and a reference point on the sheave at intervals throughout the test.

Testing was scheduled to continue constantly for 3 full weeks. If at the end of the 3 weeks, the belt was still undamaged, a tensile breaking test would be conducted to confirm belt strength after undergoing numerous bending cycles and compare with the breaking strength of a fresh sample.

2.3 Results

Experiments commenced on January 15th. When the belt was initially loaded, a single fiber element broke near the sheave, likely due to uneven load sharing in the stitched end terminations as shown in Figure 2.6. However, this did not appear to propagate. Additionally, due to the belt being 6mm wider than the sheave, one edge of the belt folded over on top of itself, as shown in Figure 2.7.

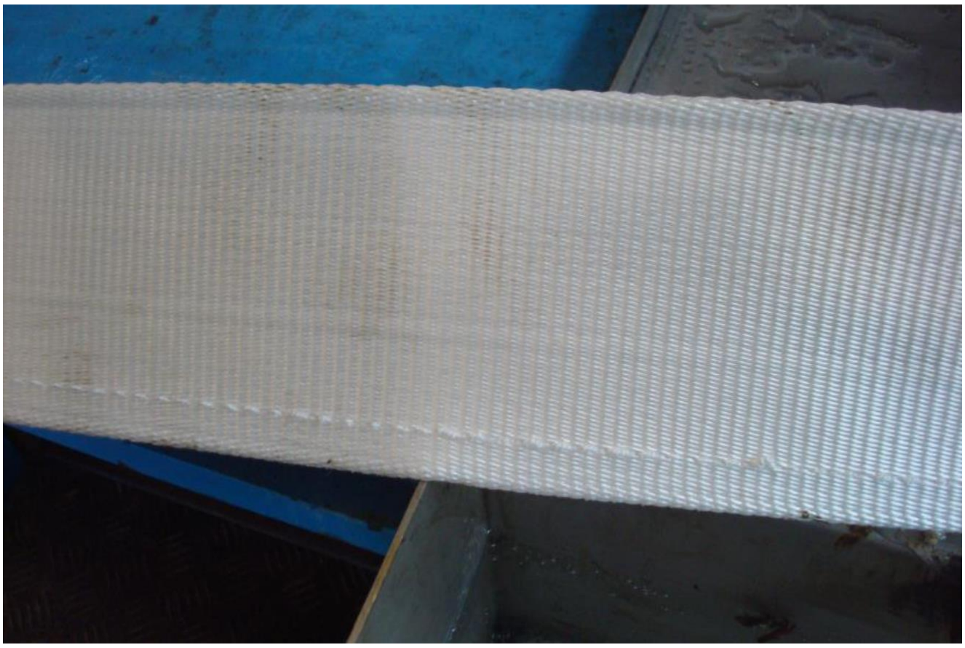


Figure 2.6: Belt showing single broken fiber after initial loading of the machine to 45kN.

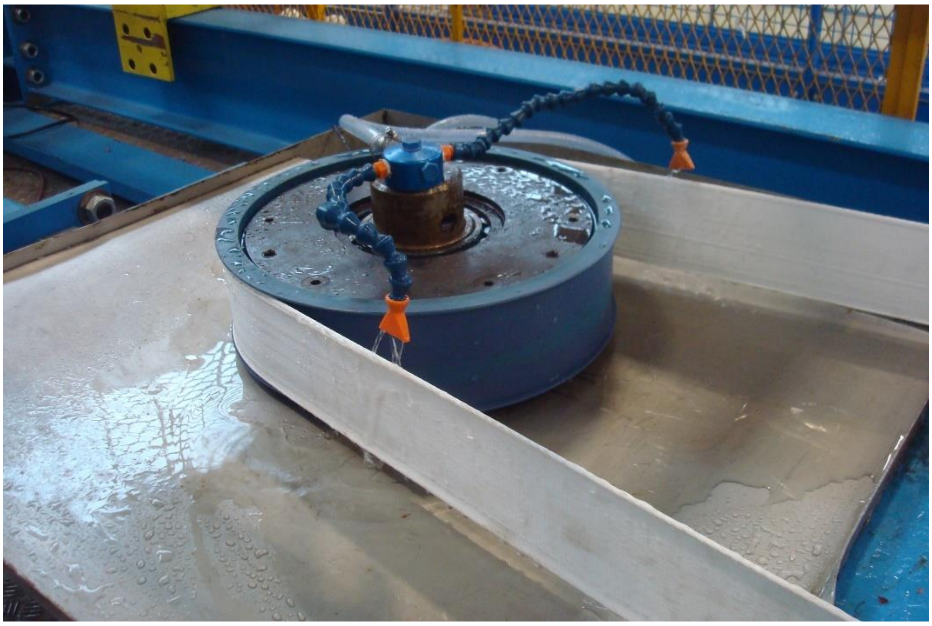


Figure 2.7: Belt showing slight folds at end due to not fitting well inside of the sheave width.

Consistent piston displacements and forces were achieved over multiple cycles. Representative forces and displacements can be found in Figure 2.8 and Figure 2.9. Unfortunately, due to a data recording issue, displacement data of the central piston is not available for this test.

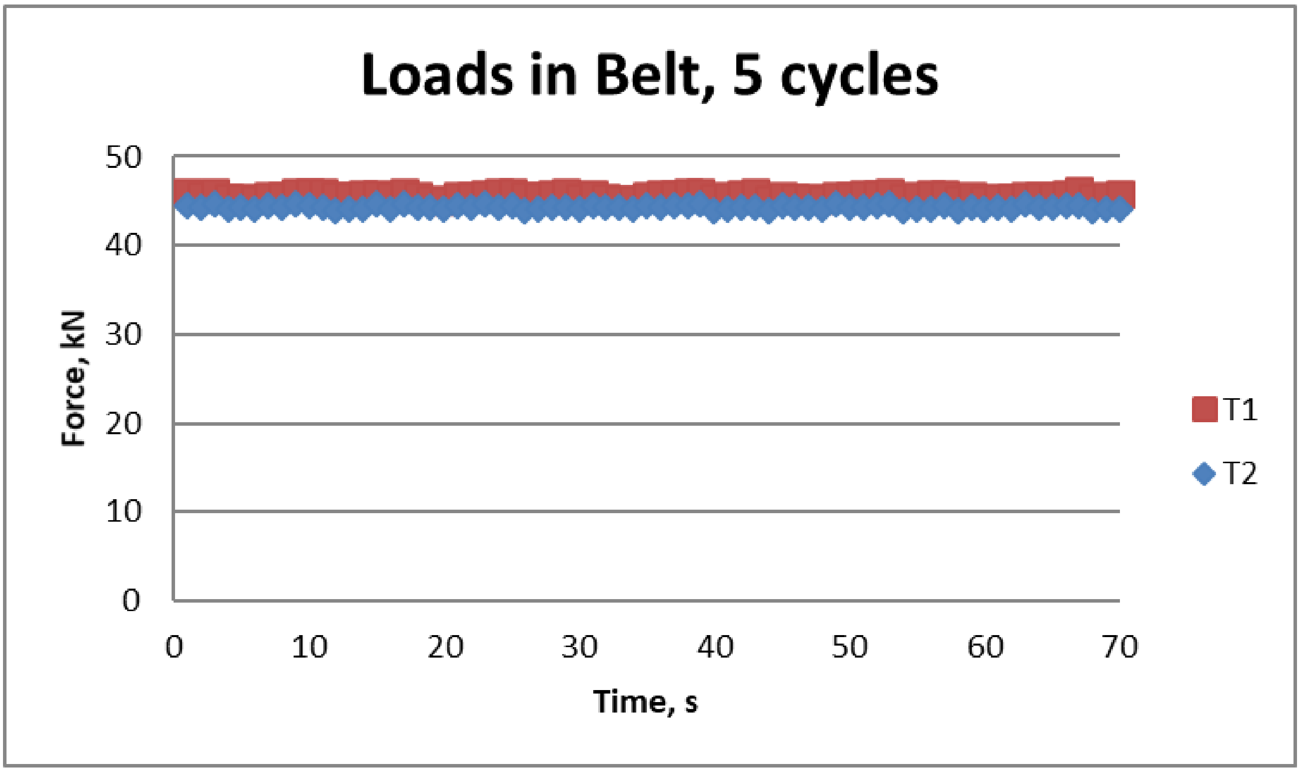


Figure 2.8: Representative belt tensions throughout experiment on each side of the sheave.

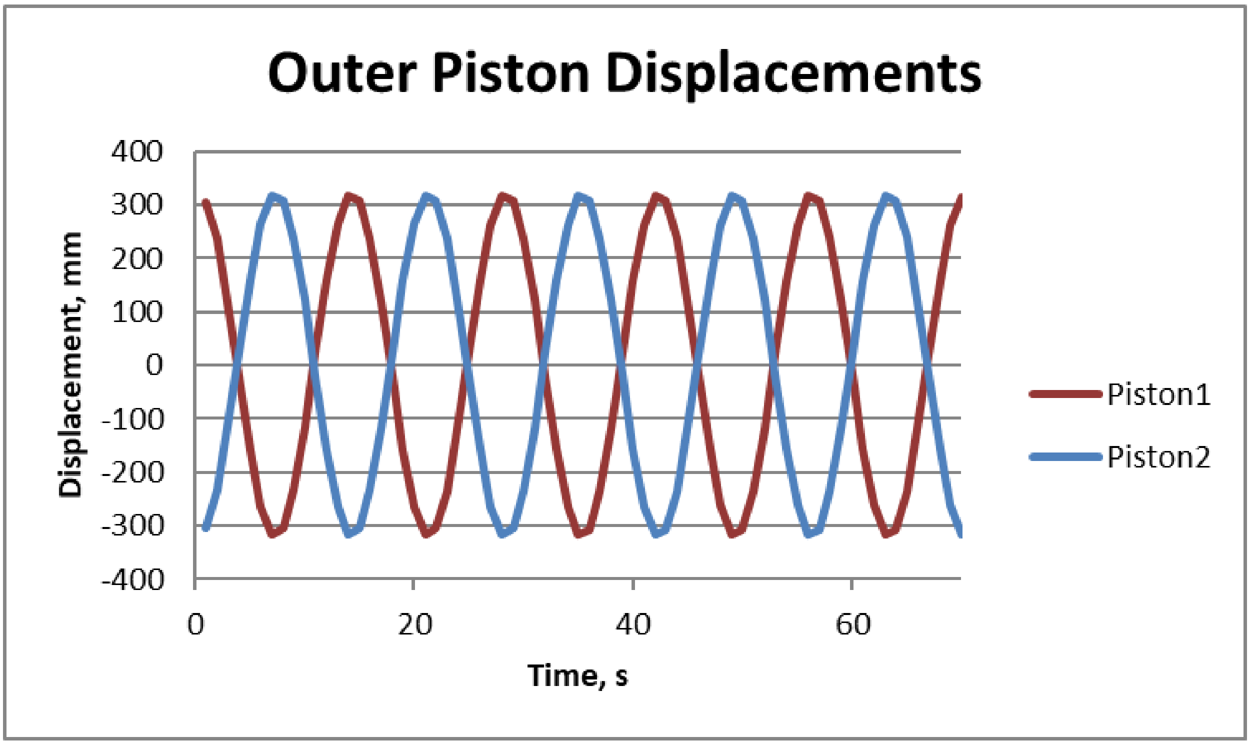


Figure 2.9: Representative piston displacements throughout experiment.

Aside from the single element fiber breaking noted in Figure 2.6, no additional damage was noted during the first 6 days of testing and the belt was able to adequately withstand the 45kN of constant tension. However, on January 22nd, significant visible damage was first observed after 41k cycles and this damage subsequently developed along the lower belt edge. This damage can be seen in Figure 2.10.

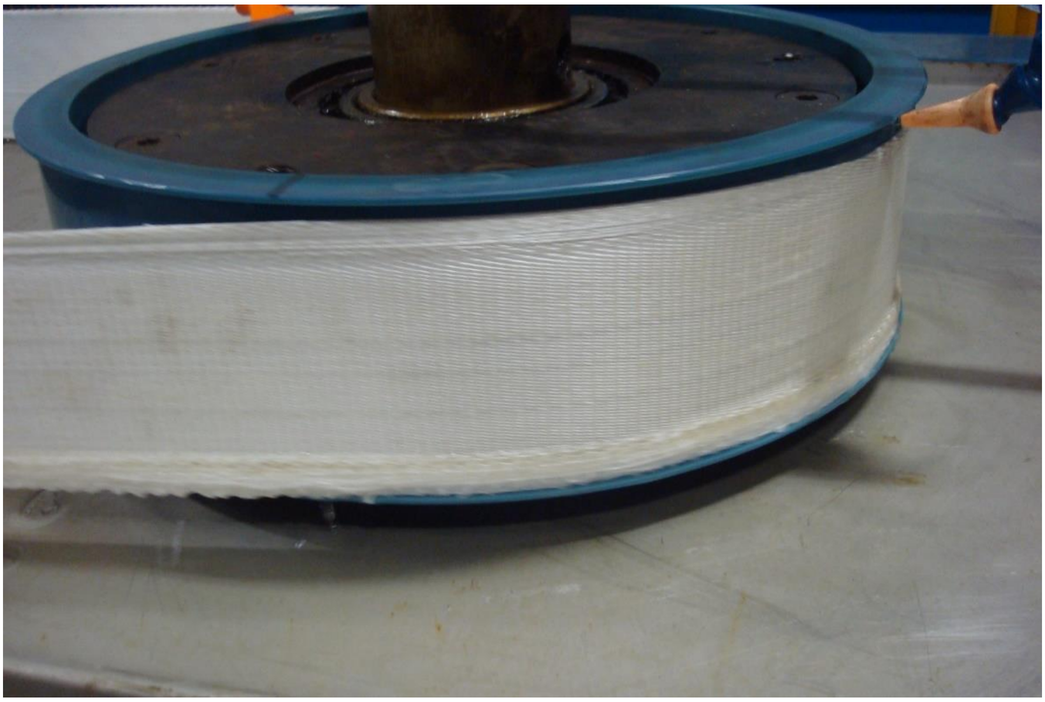


Figure 2.10: Significant visible damage to the bottom edge of the belt noted after 6 days of testing.

On January 24th, the lower flange of the sheave was found to be partially torn off, as shown in Figure 2.11. As a result, the belt began to move down the sheave, causing further damage and causing it to fold over itself near the edge, as shown in Figure 2.12.

Figure 2.11: Sheave with partial lower flange failure.

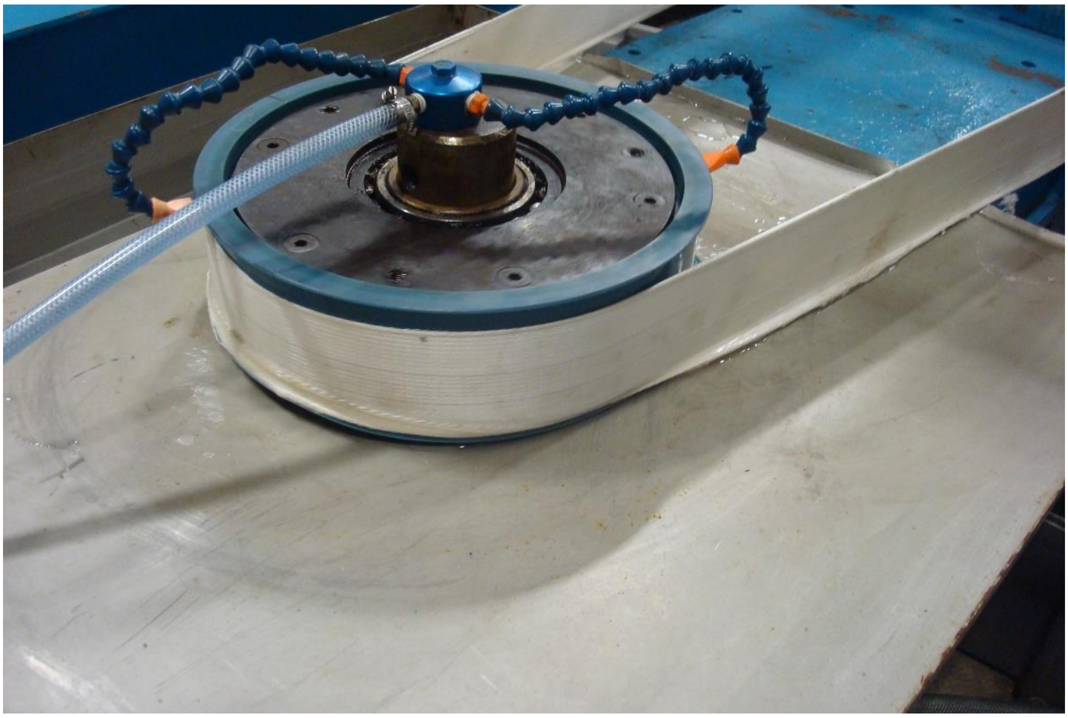


Figure 2.12: Belt moving down the sheave vertically due to the flange failure.

Representative temperature data is shown in Figure 2.13. The surface temperature of the belt never exceeded 22° C throughout the experiment.

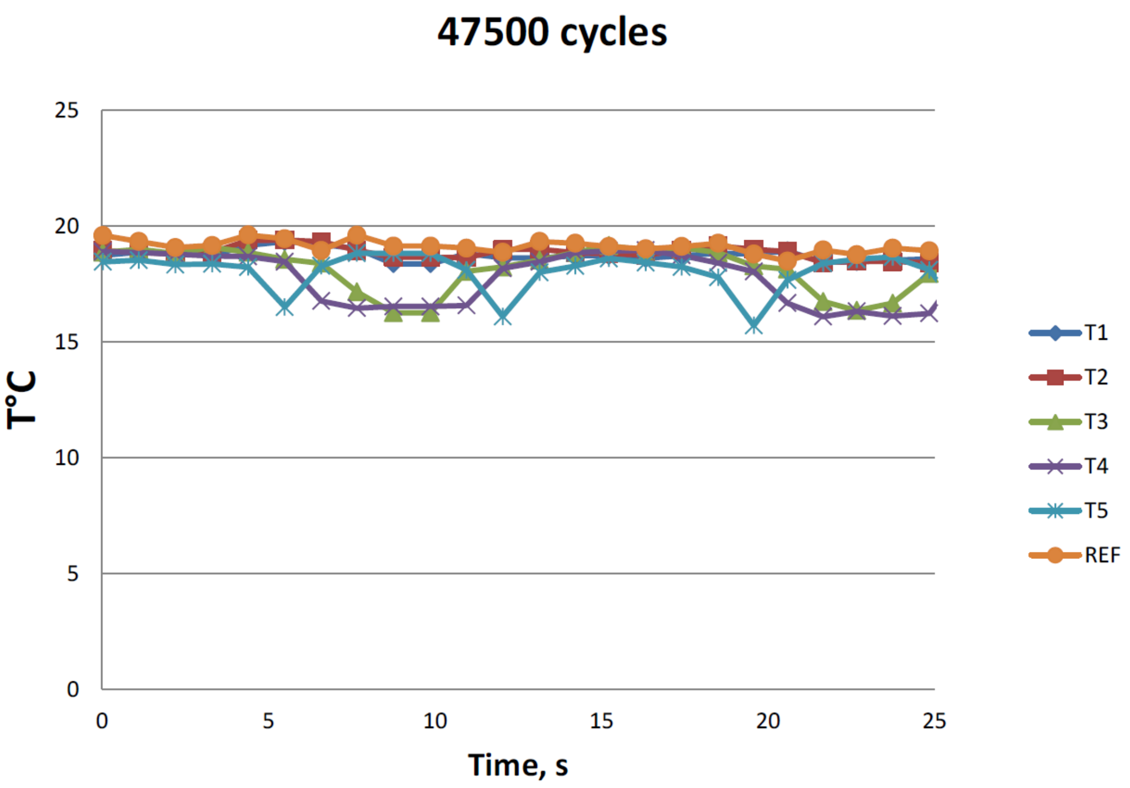


Figure 2.13: Representative belt surface temperature data throughout the experiment.

The test was stopped on January 25th after a total of 61k displacement cycles. The damage to the belt at this time is shown in Figure 2.14. Over a third of the belt displayed visible damage at this time and only 80 mm of the original 100 mm belt was still engaged with the sheave due to the remaining folding over.

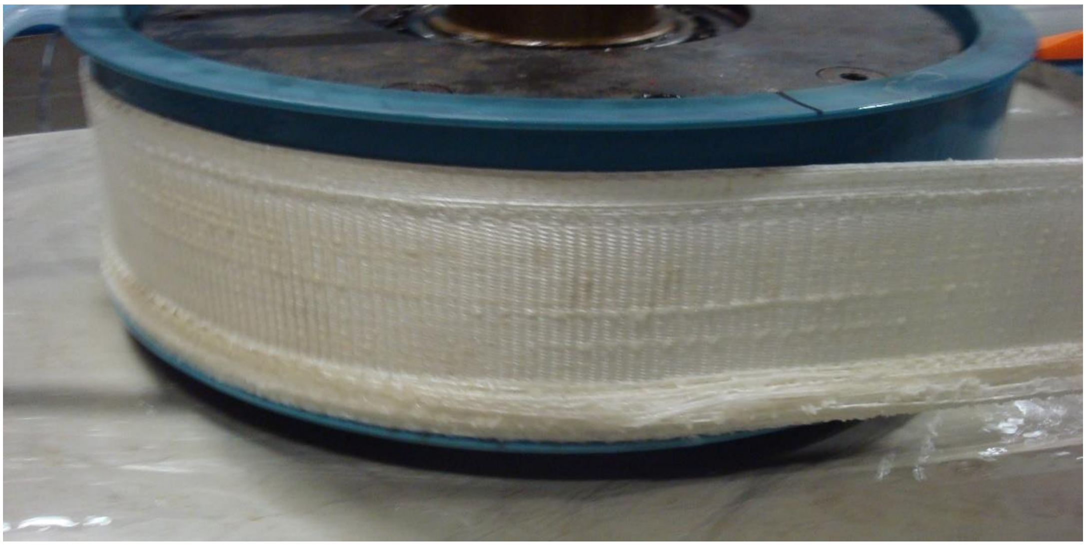


Figure 2.14: Damage to belt at the end of the first test. Note that the belt had also significantly slipped down the sheave.

The belt was removed for inspection. It had become very stiff in the area subjected to the cyclic bending load. Although the damage was primarily localized along the bottom edge, the upper edge also showed some signs of damage and wear, as shown in Figure 2.15.

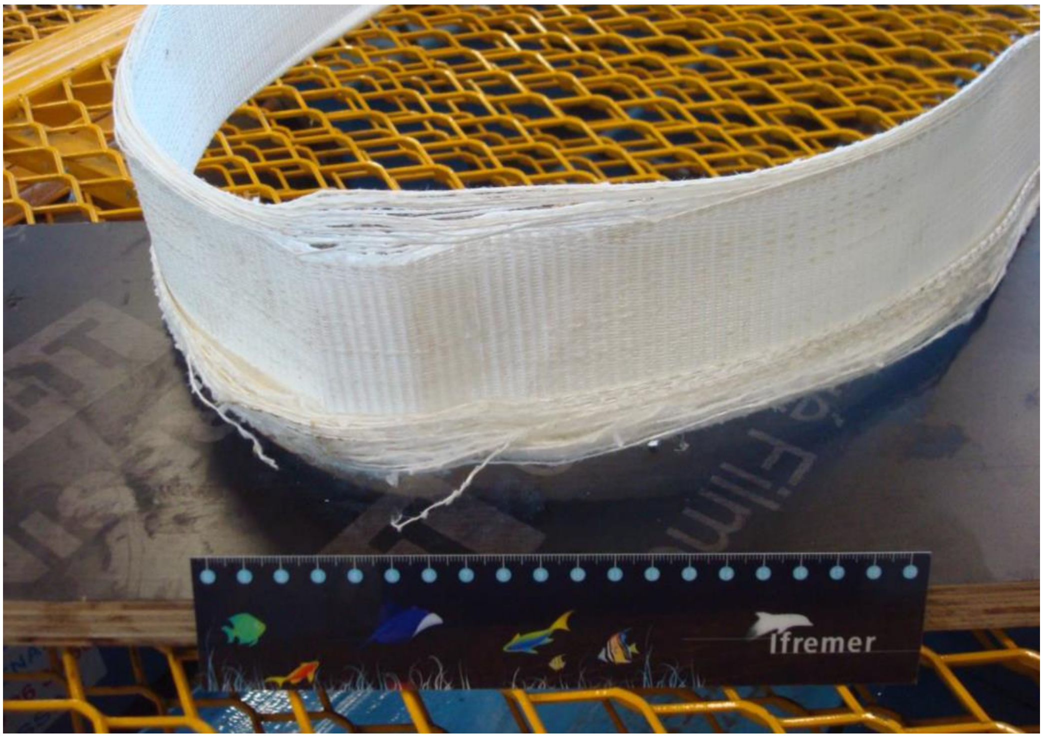


Figure 2.15: Belt sample after removal from the test machine.

To continue to make use of the 3 week allotted testing time and acquire more data, the sheave and belt were both flipped such that the damaged ends were on the top and reinstalled onto the machine. Testing was then restarted on January 30th following the same testing conditions. Complete belt failure occurred after 78,600 total machine cycles (157,000 bending-unbend cycles) after an additional 18k cycles since restarting the experiment caused the belt to break along its full width. The torn areas of the belt can be seen in Figure 2.16. The belt also exhibited some delamination upon failure, as shown in Figure 2.17, suggesting a layered cross section construction as opposed to fully weaved.

Figure 2.16: Belt after complete failure.

Figure 2.17: Delamination of belt suggesting a layered cross-section construction.

Displacement data was successfully recorded for the central piston during this second test. Elongation of the central piston during the final 70 hours of testing to failure is shown in Figure 2.18.

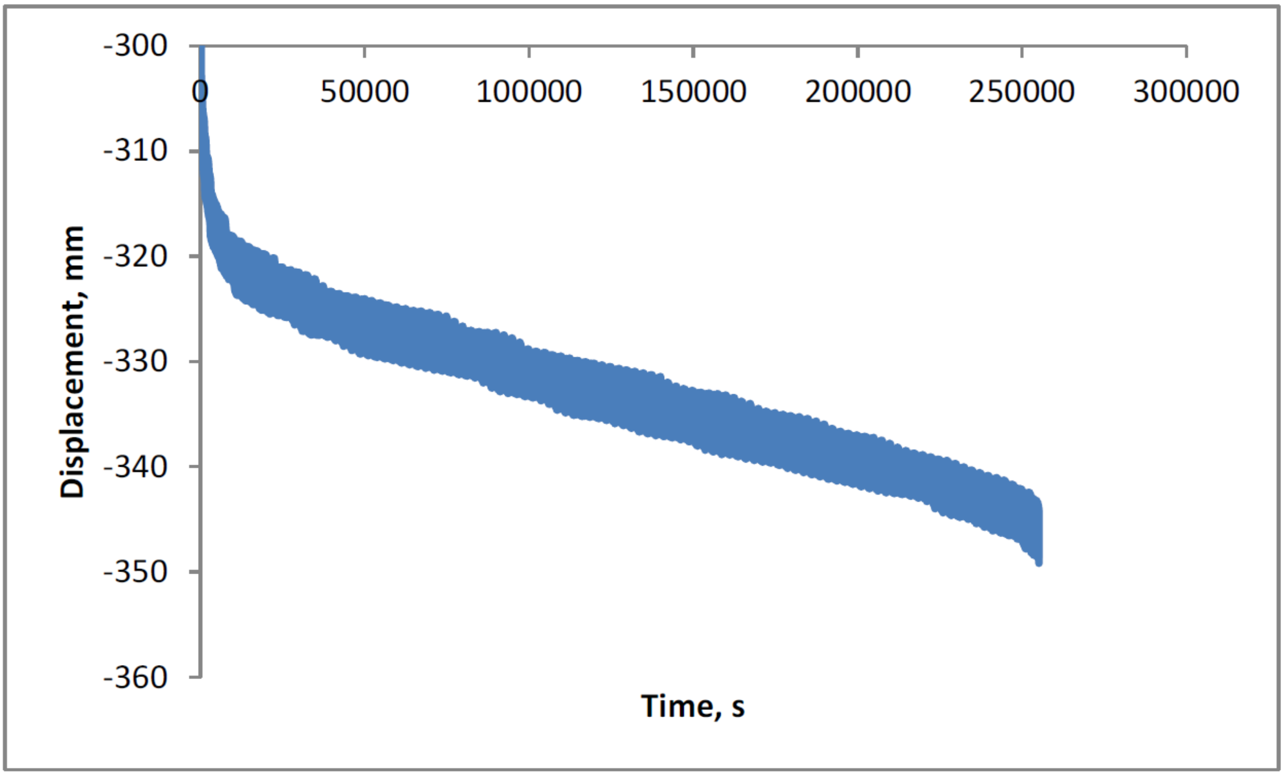


Figure 2.18: Displacement of the central piston during the continued experiment.

2.4 Analysis & Conclusions

The belt failed prior to enduring 100k cycles and fell short of the targeted millions of cycles. However, although the intent of the experiment was to test the CBOS performance of the HMPE belt, the actual failure mechanism appeared to be caused by abrasion along the belt edges due to the belt not fitting properly inside the sheave. A properly sized belt and sheave pair is expected to significantly increase the belt life. The delamination of the belt noted in Figure 2.17 also brings to question whether a fully woven cross section would be more robust than the layered one. It is also expected that upgrading to a branded fiber, such as DSM's Dyneema or Honewell's Spectra, could increase fiber performance. Fiber manufacturers also have developed special coatings such as DSM's XBO coating which claim improved CBOS performance. Additional testing on an improved belt and sheave that incorporates the learnings is considered before the technology can be implemented in the scaled deployment reliably.

As a secondary result, load levels and temperatures caused by this testing induced very little creep elongation of the fibers. It is possible that with a shorter oscillation, the belt would reach higher temperatures than found in this experiment. Never the less, the low temperatures recorded are thought to leave sufficient margin before heating of the fibers becomes a real concern.

3 Main Learning Outcomes

3.1 Progress Made

3.1.1.1 To investigate physical properties not well scaled & validate performance figures

Cycles to failure for the belt was tested and found to be unsatisfactory in the current embodiment.

3.1.1.2 To qualify environmental factors (i.e. the device on the environment and vice versa) e.g. marine growth, corrosion, windage and current drag

The "wet" testing was successful and showed that in an actual marine environment, minor increases in belt temperature can be expected.

3.1.1.3 Manufacturing, deployment, recovery and O&M (component reliability)

The belt that was currently selected was tested. Due to the unsatisfactory results, specific fiber and belt construction will likely be revisited.

3.1.2 Progress Made: For This User-Group or Technology

Given that the belt was unable to endure 100k cycles and it is desired to withstand millions of cycles, a revision of the design is needed followed by a second round of testing.

3.1.3 Progress Made: For Marine Renewable Energy Industry

This experiment provides for some general guidance in future testing of HMPE belts for rotatry to linear power conversion. It was the first belt tested at Ifremer's Material Testing facility allowing staff to also gain experience that can be conveyed to other future users. The belt pully sheave may also be reused or upgraded with minor improvements.

3.2 Key Lessons Learned

- Forcing a belt that is 6mm wider than the accompanying space on the sheave will accelerate wear and lead to unsatisfactory wear testing results.
- Large testing machines may have limits on the oscillation periods at which they are capable of conducting leading to fewer than initially expected cycles achieved during a set amount of time.
- Sheave flanges used to constrain a belt should be adequately designed to withstand expected side loading.
- Knowledge of specific fiber used in belt construction can be important and usage of well characterized fibers is recommended for high value applications.
- When conducting a single experiment over multiple days, it is good to have a way of confirming all desired data is being saved so that you are not surprised by missing data at the end of an experiment.

4 Further Information

4.1 Scientific Publications

List of any scientific publications made (already or planned) as a result of this work:

- none

4.2 Website & Social Media

Website: http://calwave.energy

YouTube Link(s):

LinkedIn/Twitter/Facebook Links: Twitter - https://twitter.com/calwaveberkeley

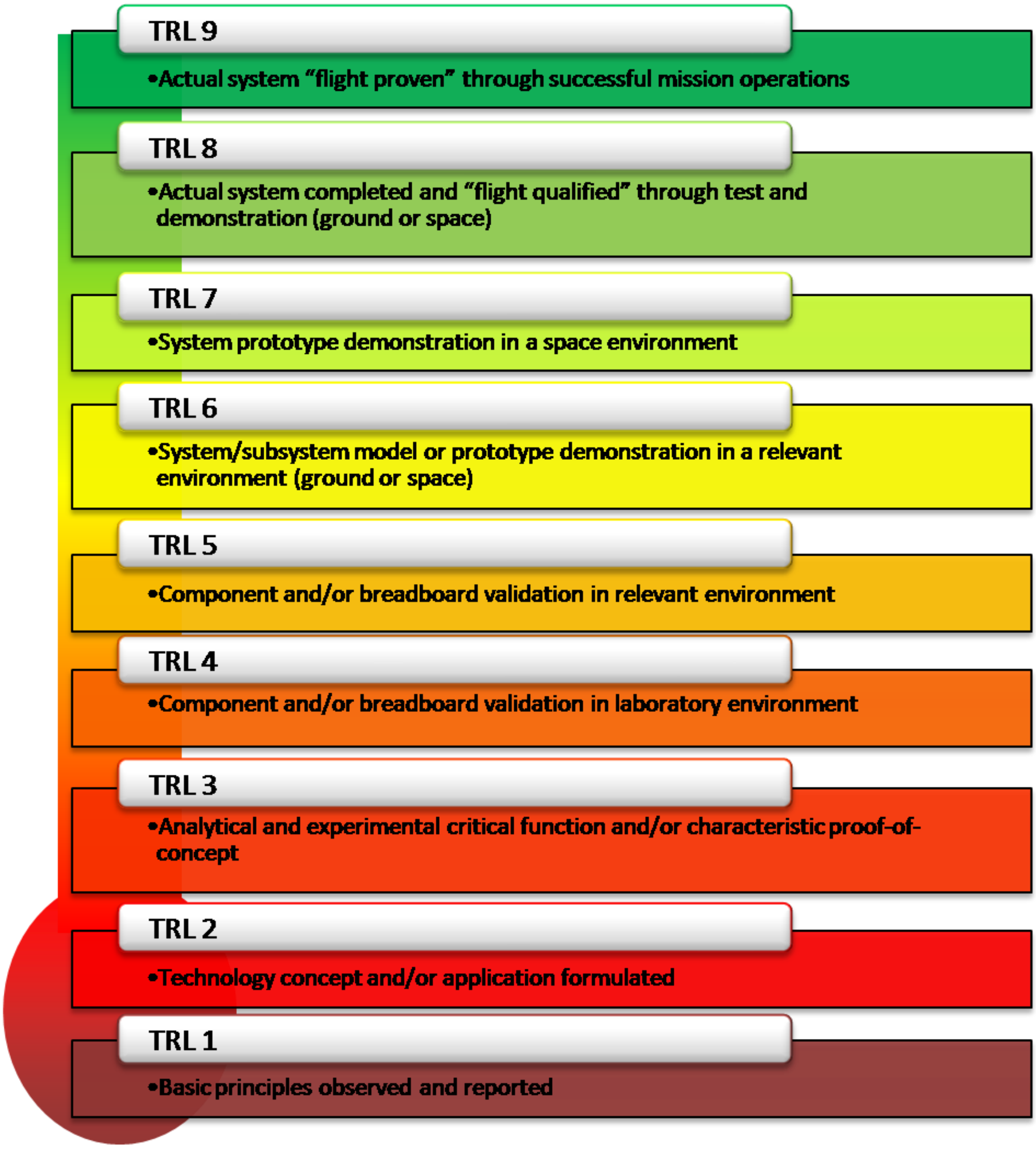
Online Photographs Link:

5 references

6 Appendices

6.1 Stage Development Summary Table

The table following offers an overview of the test programmes recommended by IEA-OES for each Technology Readiness Level. This is only offered as a guide and is in no way extensive of the full test programme that should be committed to at each TRL.



TRL 9

- Actual system “flight proven” through successful mission operations

TRL 8

- Actual system completed and “flight qualified” through test and demonstration (ground or space)

TRL 7

- System prototype demonstration in a space environment

TRL 6

- System/subsystem model or prototype demonstration in a relevant environment (ground or space)

TRL 5

- Component and/or breadboard validation in relevant environment

TRL 4

- Component and/or breadboard validation in laboratory environment

TRL 3

- Analytical and experimental critical function and/or characteristic proof-of-concept

TRL 2

- Technology concept and/or application formulated

TRL 1

- Basic principles observed and reported

NASA Technology Readiness Levels[1]

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[1] https://www.nasa.gov/directorates/heo/scan/engineering/technology/txt_accordion1.html

NASA TRL Definition Hardware Description Software Description Exit Criteria

TRL	Definition	Hardware Description	Software Description	Exit Criteria
1	Basic principles observed and reported.	Scientific knowledge generated underpinning hardware technology concepts/applications.	Scientific knowledge generated underpinning basic properties of software architecture and mathematical formulation.	Peer reviewed publication of research underlying the proposed concept/application.
2	Technology concept and/or application formulated.	Invention begins, practical application is identified but is speculative, no experimental proof or detailed analysis is available to support the conjecture.	Practical application is identified but is speculative, no experimental proof or detailed analysis is available to support the conjecture. Basic properties of algorithms, representations and concepts defined. Basic principles coded. Experiments performed with synthetic data.	Documented description of the application/concept that addresses feasibility and benefit.
3	Analytical and experimental critical function and/or characteristic proof of concept.	Analytical studies place the technology in an appropriate context and laboratory demonstrations, modelling and simulation validate analytical prediction.	Development of limited functionality to validate critical properties and predictions using non-integrated software components.	Documented analytical/experimental results validating predictions of key parameters.
4	Component and/or breadboard validation in laboratory environment.	A low fidelity system/component breadboard is built and operated to demonstrate basic functionality and critical test environments, and associated performance predictions are defined relative to the final operating environment.	Key, functionally critical, software components are integrated, and functionally validated, to establish interoperability and begin architecture development. Relevant Environments defined and performance in this environment predicted.	Documented test Performance demonstrating agreement with analytical predictions. Documented definition of relevant environment.
5	Component and/or breadboard validation in relevant environment.	A medium fidelity system/component brassboard is built and operated to demonstrate overall performance in a simulated operational environment with realistic support elements that demonstrates overall performance in critical areas. Performance predictions are made for subsequent development phases.	End-to-end software elements implemented and interfaced with existing systems/simulations conforming to target environment. End-to-end software system, tested in relevant environment, meeting predicted performance. Operational environment performance predicted. Prototype implementations developed.	Documented test performance demonstrating agreement with analytical predictions. Documented definition of scaling requirements.
6	System/sub-system model or prototype demonstration in an operational environment.	A high fidelity system/component prototype that adequately addresses all critical scaling issues is built and operated in a relevant environment to demonstrate operations under critical environmental conditions.	Prototype implementations of the software demonstrated on full-scale realistic problems. Partially integrate with existing hardware/software systems. Limited documentation available. Engineering feasibility fully demonstrated.	Documented test performance demonstrating agreement with analytical predictions.
7	System prototype demonstration in an operational environment.	A high fidelity engineering unit that adequately addresses all critical scaling issues is built and operated in a relevant environment to demonstrate performance in the actual operational environment and platform (ground, airborne, or space).	Prototype software exists having all key functionality available for demonstration and test. Well integrated with operational hardware/software systems demonstrating operational feasibility. Most software bugs removed. Limited documentation available.	Documented test Performance demonstrating agreement with analytical predictions.
8	Actual system completed and "flight qualified" through test and demonstration.	The final product in its final configuration is successfully demonstrated through test and analysis for its intended operational environment and platform (ground, airborne, or space).	All software has been thoroughly debugged and fully integrated with all operational hardware and software systems. All user documentation, training documentation, and maintenance documentation completed. All functionality successfully demonstrated in simulated operational scenarios. Verification and Validation (V&V) completed.	Documented test performance verifying analytical predictions.
9	Actual system flight proven through successful mission operations.	The final product is successfully operated in an actual mission.	All software has been thoroughly debugged and fully integrated with all operational hardware/software systems. All documentation has been completed. Sustaining software engineering support is in place. System has been successfully operated in the operational environment.	Documented mission operational results

DEVELOPMENT PROTOCOL	*STAGE 1* *CONCEPT VALIDATION*			*STAGE 2* *DESIGN VALIDATION*	*STAGE 3* *SYSTEMS VALIDATION*		*STAGE 4* *DEVICE VALIDATION*		*STAGE 5* *ECONOMICS VALIDATION*
	TRL 1: Confirmation of Operation	**TRL 2: Performance Convergence**	**TRL 3: Device Optimisation**	**TRL 4: Sub-Systems Assessment**	**TRL5: Sub-Assembly Bench Tests**	**TRL 6: Full System Sea Trials**	**TRL 7: Solo, Sheltered, Grid Emulator**	**TRL 8: Solo, Exposed, Grid Connected**	**TRL 9: Multi-device Array (3-5)**
Objectives/ Investigations	Op. Verification Design Variables Physical Process Validate/Calibrate Maths Model Damping Effect Signal Phase	Real Generic Seas Design variables Damping PTO Natural Periods Power Absorption Wave to Devise Response Phase	Hull Geometry Components Configurations Power Take-Off Characteristics Design Eng. (Naval Architects)	Final Design Accurate PTO [Active Control] Mooring system Survival Options Power Production Added mass	PTO Method Options & Control Inst. Power Absorption Electricity Production & Quality	Scale effects of Overall Performance Characteristics Mooring & Anchorage Security Environmental Influences & Factors	Oper & Mains Procedures Electrical Output Quality Grid Supply, Stability & Security PTO Performance at all phases Control Strategy Seaworthiness, Survival & Lifecycle Analysis Device Array Interaction (Stages 1 & 2)		Grid Connection Array Interaction Maintenance Service Schedules Component Life Economics
Output/ Measurement	Vessel Motion Response Amplitude Operators & Stability Pressure / Force, Velocity RAOs with Phase Diagrams Power Conversion Characteristic Time Histories Hull Seaworthiness; Excessive Rotations or Submergence Water Surface Elevation Abeam of Devices			Motion RAOs Phase Diagrams Power v Time Wave Climates @ *head, beam, follow*	PTO Forces & Power Conversion Control Strategies	Incident Wave Field 6 D of F Body Motion & Phase Seaworthiness of Hull & Mooring [Survival Strategies]	Full On-Board Monitoring Kit for Extended Physical Parameters Power Matrix Supply forecasting	Array Interaction Annual Power Prod. Elec. Power Perfrm. Failure Rates Grid EIA reviews	Service, Maintenance & Production Monitor, Telemetry for Periodic checks & Evaluation
Primary Scale (λ)	$\lambda = 1 : 25 - 100$ ($\therefore \lambda_c = 1 : 5 - 10$)			$\lambda = 1 : 10 - 25$	$\lambda = 1 : 2 - 10$		$\lambda = 1 : 1 - 2$		λ = 1:1, Full size
Facility	2D Flume or 3D Basin			3D Basin	Power Electronics Lab	Benign Site	Sheltered Full Scale Site	Exposed Full Scale Site	Open Location
Duration –*inc Analysis*	1-3months	1-3months	1 3 months	6 – 12 months	6 – 18 months		12 – 36 months		1 – 5 years
Typical No. Tests	250 - 750	250 - 500	100 - 250	100 - 250	50 - 250		Continuous		Statistical Sample
Budget (€,000)	1 – 5	25-75	25-50	50 - 250	1,000 – 2,500		10,000 – 20,000		2,500 – 7,500
Device	Idealised with Quick Change Options Simulated PTO (0-∞ Damping Range) Std Mooring & Mass Distribution		Distributed Mass Minimal Drag Design Dynamics	Final design (internal view) Mooring Layout	Advanced PTO Simulation Special Materials	Full Fabrication True PTO & Elec Generator	Grid Control Electronics or Emulator Emergency Response Strategies Pre-Production Pre-Commercial		Operational Multi-Device
Excitation / Waves	Monochromatic Linear (10-25Δ*f*) (25-100 waves)	Panchromatic Waves (20min scale) +ve 15 Classical Seaways Spectra Long crested Head Seas		Deployment -Pilot Site Sea Spectra Long, Short Crested Classical Seas Select Mean wave Approach Angle		Extended Test Period to Ensure all Seaways inc.	Full Scatter Diagram for initial Evaluation Continuous Thereafter Time & Frequency Domain Analysis		
Specials	DofF (heave only) 2-Dimentional Solo & Multi Hull	Short Crest Seas Angled Waves As Required	Storm Seas (3hr) Finite Regular As required	Power Take-Off Bench Test PTO & Generator	Device Output Repeatability Survival Forces	Salt Corrosion Marine Growth Permissions	Grid Emulator Quick Release Cable Service Ops	Stakeholder Consult. Health & Safety Issues	Small Array (Up-grade to Generating Station)?
Maths Methods (Computer)	Hydrodynamic, Numerical Frequency Domain to Solve the Model Undamped Linear Equations of Motion		Finite Waves Applied Damping Multi Freq Inputs	Time Domain Response Model & Control Strategy Naval Architects Design Codes for Hull, Mooring & Anchorage System. Economic & Business Plan			Economic Model Electrical Stab. Array Interaction	Grid Simulation Wave forecasting	Array Interaction Market Projection for Devise Sales
	EVALUATION [Stage Gates]								
Absorbed **Power** [kW]									
Converted									
Weight, [tonnes]									
Manufacturing Cost [€]									
Capture [kW/tonne] or [kW/m^3]	[200-50 m^3]								
Production [c/kW]	< 25 €c / kW			≤ 15 €c / kW			≤ 10 €c / kW		≤ 5 €c / kW

6.2 Any Other Appendices