# Purpose

The aim of these series of reports is to give an update of the AAU Testbench concerning its performance and reliability. The overall goal is to mature the digital hydraulic PTO such that it can be implemented in the next generation of Wavestar's WEC. A status of the Testbench is given together with a list of recommended topics to further improve the performance and reliability.

# Executive summary

- The new weighted efficiency(*) calculations yield an ***annual*** **manifold efficiency with Bucher+Parker valves of 84%** instead of the previous calculated efficiency of 79%.
- The new weighted efficiency(*) calculations yield an *annual* manifold efficiency with Parker valves of 77% instead of the previous calculated efficiency of 57%.
- After extensive tests it is concluded that the lower efficiency of Parker valves is due to defect valve sealings.
- Leak measurements show that the current Testbench has tolerable leak levels (below 0.1[L/min]).
- No evidence found that the manifold efficiency depends on the oil temperature.
- The Parker valves were controlled as if they were Bucher valves (discrete control signals instead of analogue ditto) and no difference was observed in the manifold efficiency.
- Reference measurements to check the sensor outputs are included.

(*) The new weighted efficiency refers to as the average efficiency where the efficiency in each seastate is weighted with the annual energy generated at the seastate in question.

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## New definition of weighted efficiency

A power matrix measurement was performed with Bucher and Parker valves and documented in the previous report (status report 13-jan-2015). The calculated overall efficiency of the manifold was weighted with the probability of the seastates. However, a more relevant way of calculating the efficiency is weighting it with the generated energy of each seastate. The new weighted efficiency allows therefore to directly multiply the annual harvested energy with the efficiency to calculate the annual output energy of the manifold.

| | Old efficiency (13-jan-2015) | New efficiency |
|---|---|---|
| **9x Parker** | 57% | 77% |
| **6x Parker + 3x Bucher** | 79% | 84% |

**Table 1:** *Weighted manifold efficiencies.*

Code to calculate the weighted efficiency:

```
% seaState number    SS11 SS12  SS14  SS15  SS16  SS17  SS18  SS19  SS20
seaStateprob       = [23.3 14.6  8.3   20.6  13.3  7.1   3.8   4.9   4.1];
pAvgOutBucher_kW   = [2.2  6.5   3.2   9.3   17.6  26.6  16.1  26.0  34.5];
pAvgOutParker_kW   = [0.9  4.9   1.5   7.5   16.0  24.9  14.8  24.2  32.6];
pAvgInBucher_kW    = [3.1  8.2   4.4   11.6  20.8  30.8  18.5  29.6  38.7];
pAvgInParker_kW    = [3.0  8.1   4.4   11.0  20.0  30.0  18.7  29.0  38.4];

yearH              = seaStateprob/100*365*24;
pAvgOutBucher_kWh = pAvgOutBucher_kW .* yearH;
pAvgOutParker_kWh = pAvgOutParker_kW .* yearH;

weightedEtaBucher = sum(pAvgOutBucher_kW ./ pAvgInBucher_kW .*
(pAvgOutBucher_kWh./sum(pAvgOutBucher_kWh)));

weightedEtaParker = sum(pAvgOutParker_kW ./ pAvgInParker_kW .*
(pAvgOutParker_kWh./sum(pAvgOutParker_kWh)));
```

## Parker valves controlled as if they were Bucher valves

Previous measurements (status report 01-dec-2014) reveal that the manifold with 3x Bucher valves + 6x Parker valves performs better than the manifold with 9x Parker valves. One possibility could be that the control signal to the Bucher valves (which is discretized) by chance results in a better control strategy. Therefore an experiment was made to control the Parker valves in the same way as Bucher valves are controlled, that is, by discretizing the control signal to Parker valves.

The seastate 6 (Hm0 = 1.5[m], T02 = 5.5[s]) was tested and as Table 2 shows there is no difference in the measured efficiency (despite the slight differences in the averaged input and output power).

| | **Pin [kW]** | **Pout [kW]** | **Efficiency [%]** |
|---|---|---|---|
| **Analog control signal to Parker valves** | 15.6 | 13.3 | 85 |
| **Discretized control signal to Parker valves** | 15.0 | 12.8 | 85 |

**Table 2:** *Manifold efficiency (SS6) with analog and discretized control signal to Parker valves.*

The measurements indicate that discretizing the control signals to Parker valves does not affect the measured efficiency of the manifold.

## Manifold efficiency as a function of oil temperature

In this section it is investigated whether the manifold efficiency depends on the oil/fluid temperature. The seastate 5 (Hm0 = 1.25[m], T02 = 5.5[s]) was tested with 3 different oil temperatures (28[ºC], 40[ºC] and 60[ºC]).

| | **Pin [kW]** | **Pout [kW]** | **Efficiency [%]** |
|---|---|---|---|
| **Oil temp = 28[ºC]** | 11.7 | 9.8 | 84 |
| **Oil temp = 40[ºC]** | 11.7 | 9.8 | 84 |
| **Oil temp = 60[ºC]** | 11.7 | 9.8 | 84 |

**Table 3:** *Manifold efficiency (SS5) as a function of oil temperature.*

As Table 3 shows, there is no difference in the measured efficiency despite the wide range of the oil temperature.

## Leakage investigation

As the previous status reports show, the manifold efficiency is higher with [6xParker + 3xBucher] than with [9xParker]. In the following, two different investigations are made in order to find out why the manifold efficiency is lower with 9xParker.

### *Leakage test with old Parker sealings (9 valves) and no Bucher valves*

The manifold efficiency was recorded to be higher after upgrading the manifold with 3xBucher valves. After several tests, it was discovered that specially one Parker valve (V01h) was not able to close completely, leading to a significant leak which over time resulted in a low manifold efficiency. The Parker valve was swapped with one connected to the low pressure line and better efficiencies were achieved. The Parker sealings were under suspicion and the presumed defect sealings were replaced with new ones.

In order to be sure that the sealings were in fact the cause of the problem (low manifold efficiency), the old sealings and original Parker locations were restored to see if the low efficiency numbers could be reproduced. If the low efficiency numbers could be reproduced, the sealings would be considered as the main factor of the low efficiency.

| Seastate | Measurement | Pin [kW] | Pout [kW] | Efficiency [%] |
| --- | --- | --- | --- | --- |
| SS2 | Original | 1.9 | -0.5 | -26 |
| | Reproduced | 2.4 | 0.8 | 33 |
| SS6 | Original | 14.8 | 11.3 | 76 |
| | Reproduced | 14.3 | 10.7 | 75 |

**Table 4:** *Manifold efficiency with original Parker configuration and with reproduced Parker configuration.*

The efficiency in the seastate SS2 in Table 4 is rather different between the original measurements and the reproduced measurements. This is mainly due to the low power levels where small differences yield large deviations. The power levels in seastate SS6 are sufficiently high and the efficiency results are comparable between the original and reproduced measurements which indicate that the efficiency measurements can be reproduced by restoring the old sealings and original Parker locations. Hence the sealings are the main contributor to the low manifold efficiency.

### *Leakage test with new Parker sealings (6 valves) and with 3x Bucher*

Being aware that the valves may have a certain leak, a set of tests under different conditions was made to estimate the leak in the manifold. In general, if there is no leak, an entrapped volume of oil shall be able to maintain the pressure indefinitely. However in practice the pressure falls over time and the leak can be estimated by considering the initial and final pressure together with the volume of the entrapped oil. A mathematical model of the chambers was made in Simulink and the simulations were fitted to the measurements by adjusting the leak factor of each chamber/valve. *Appendix: Leakage investigation (measurements*) shows the measured and estimated leaks.

The tests are not able to identify the leak of a specific valve. Instead the leak is estimated for a group of valves, for example "*all the  valves connected to the high pressure line*", or "*all valves connected to the middle pressure line*".

Common for all the estimated leaks is that the values are below 0.1[L/min]. All in all it can be concluded that the current Testbench has tolerable leak levels.

## Appendix: Leakage investigation (measurements)

### *Leakage Test #1*

**Description**:
Hp pressure set to 180bar during 2 min. V17 + V01h, V02h and V03h closed to measure leakage at B side of Hp valves.

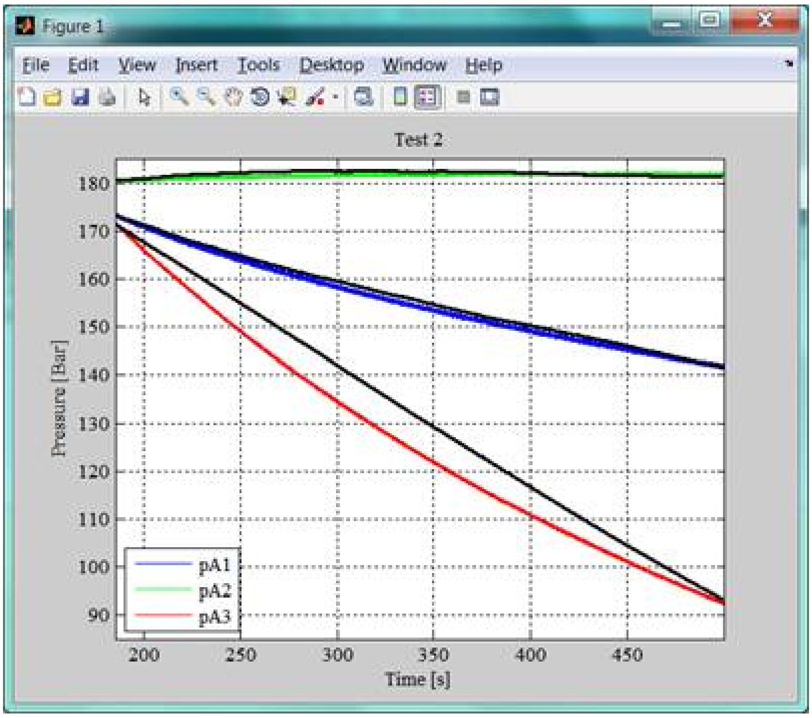
**Result:**
There is no measurable leakage at side B of Hp valves.

## *Leakage Test #2*

**Description:**
(V01h, V02h and V03h open to equalize pressure (approx. 180bar) and then closed again, V18 open and system pressure set to 23bar, to measure leakage at A side of all valves and cylinder sealings during 5 min. Afterwards the valves are open again to equalized pressure (approx 20bar)

**Result:**
leak1 = -0.054/6e4; % [m^3/s]
leak2 = 0.038/6e4; % [m^3/s]
leak3 = 0.042/6e4; % [m^3/s]

Insignificant leakage levels measured/estimated.
Measurements in color and fitted curve (model) to estimate leakage in black.

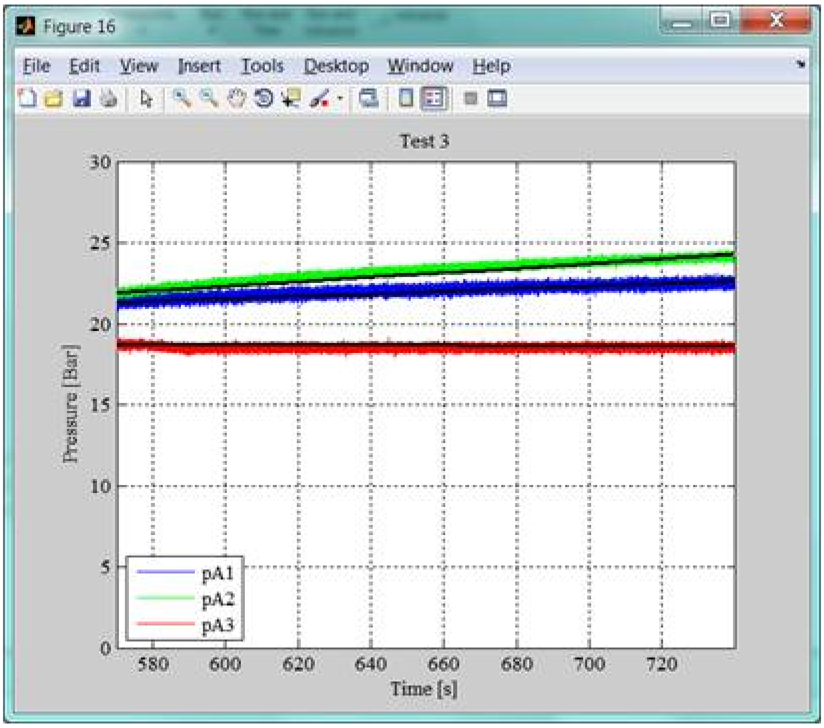


## Leakage Test #3

**Description:**
System pressure set to 100bar and V17 open, V18 closed to equalize pressure at Hp and Mp. Leakage at B side of V01m, V02m and V03m investigated during 3 min.

**Result 3:**
leak1 = -0.066/6e4; % [m^3/s]
leak2 =  0.023/6e4; % [m^3/s]
leak3 =  0.015/6e4; % [m^3/s]

Insignificant leakage levels measured/estimated.
Measurements in color and fitted curve (model) to estimate leakage in black.

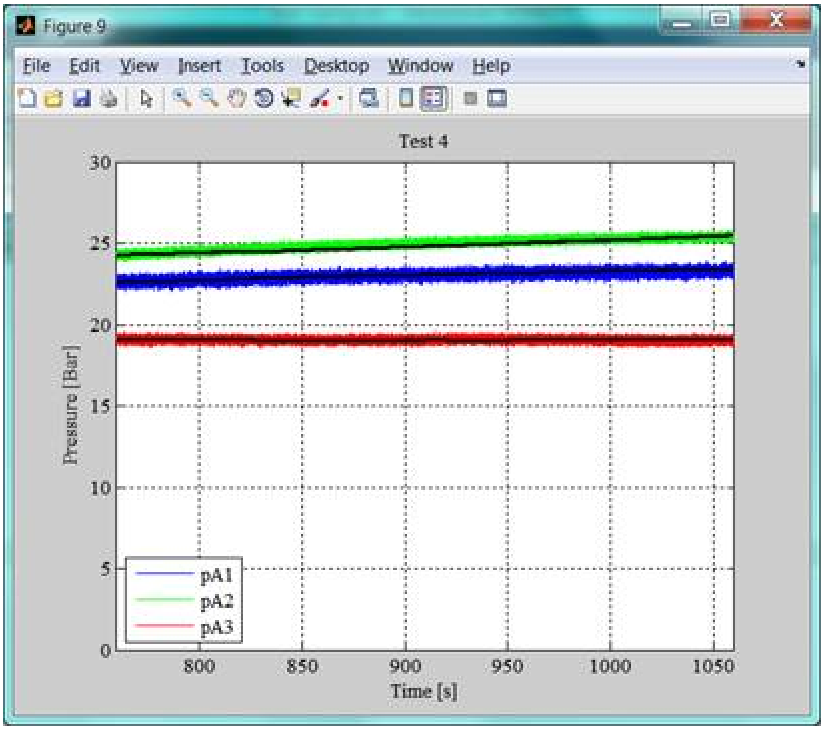


## *Leakage Test #4*

**Description:**
V17 and V18 closed and system pressure set to approx. 23 bar to measure leakage at V17 and V18.

**Result 4:**
leak1 = -0.062/6e4; % [m^3/s]
leak2 = 0.029/6e4; % [m^3/s]
leak3 = 0.015/6e4; % [m^3/s]

Insignificant leakage levels measured/estimated.
Measurements in color and fitted curve (model) to estimate leakage in black.



| WAVESTAR | Testbench Status 08-apr-2015 | Date: 08-04-2015<br>Created: |
|---|---|---|
| | | By:EVS, MPE |
| | | Checked by: |

## Appendix: Reference measurements to check sensor outputs

The measurements together with the HMI settings can be found in the excel file (*Sensor check - 03-02-2015*). In this appendix only the sensor readings with the statistical values are presented, which can be used for future reference.

| 08-12-2014 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Status: | | Testbench Stopped | Idle; V01m, V02m, V03m open 40% | Idle; V01m, V02m, V03m open 40%, V17 og V18 open 100%, Semi-aut. tilt Control | Idle; V01m, V02m, V03m open 40%, V17 og V18 open 100%, Semi-aut. tilt Control | Idle; V01m, V02m, V03m open 40%, V17 og V18 open 100%, Semi-aut. tilt Control | Idle; V01m, V02m, V03m open 40%, V17 og V18 open 100%, Semi-aut. tilt Control | Idle; V01m, V02m, V03m open 40%, V17 og V18 open 100%, Semi-aut. tilt Control |
| Sensor: | | | | | | | | |
| | | Read | Read: | Read: | Read: | Read: | Read: | Read: |
| Flow: | Tilt: | 0,000 | 0,004 | 0,230 | 0,530 | 0,840 | 1,040 | 0,050 |
| QFM01 | l/min | 0,000 | 0,000 | 19,469 | 53,087 | 87,187 | 109,972 | 0,000 |
| QFM02 | l/min | 0,000 | 0,000 | 19,469 | 52,798 | 87,476 | 110,261 | 0,000 |
| QFM03 | l/min | 0,000 | 0,000 | 19,469 | 52,798 | 87,764 | 110,550 | 0,000 |
| min. | | 0,000 | 0,000 | 19,469 | 52,798 | 87,187 | 109,972 | 0,000 |
| max. | | 0,000 | 0,000 | 19,469 | 53,087 | 87,764 | 110,550 | 0,000 |
| Max. Deviation | l/min | 0,000 | 0,000 | 0,000 | 0,289 | 0,577 | 0,578 | 0,000 |
| % Deviation | | | | | 0,54 | 0,66 | 0,52 | |

| 03-02-2015 | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Status: | | In operation, V17 & V18 open, **SP: 20 Bar** | In operation, V17 open , V18 closed, **SP: 50 Bar** | In operation, V17 open , V18 closed, **SP: 75 Bar** | In operation, V17 open , V18 closed, **SP: 100 Bar** | In operation, V17 open , V18 closed, **SP: 125 Bar** | In operation, V17 open , V18 closed, **SP: 150 Bar** | In operation, V17 closed V18 open, **SP: 180 Bar** | In operation, V17 closed, V18 open, **SP: 200 Bar** |
| Pressure: | | Read | Read | Read | Read | Read | Read | Read | Read |
| MA1 | bar | 23,7 | 53,1 | 77,8 | 102,4 | 126,9 | 151,1 | 181 | 200,2 |
| MA2 | bar | 23,6 | 52,6 | 78,5 | 101,4 | 126,1 | 150,8 | 181,1 | 199,5 |
| MA3 | bar | 23,6 | 53,1 | 77,8 | 102,3 | 127,1 | 151,6 | 181,1 | 200,1 |
| MC1 | bar | 23,9 | 53,3 | 78,7 | 102,5 | 127,6 | 152 | 181,9 | 201,2 |
| MC2 | bar | 22,9 | 52,3 | 77,3 | 101,2 | 125,9 | 150,2 | 179,9 | 199,2 |
| MC3 | bar | 22,8 | 52,4 | 76,7 | 101,3 | 126,1 | 149,9 | 179,5 | 198,6 |
| MC4 | bar | 23,1 | 52,7 | 77,2 | 101,6 | 126,5 | 150,2 | 179,6 | 199 |
| MPh | bar | 23,3 | 52,9 | 77,4 | 102,7 | 127,2 | 151,5 | 180,2 | 200,1 |
| MPm | bar | 23,6 | 53,2 | 77,9 | 102,5 | 127,2 | 151,5 | - | - |
| MPl | bar | 23,1 | - | - | - | - | - | - | - |
| M17B | bar | 24,2 | 51,9 | 78,4 | 102,4 | 125 | 150,1 | 179,4 | 200,4 |
| M18B | bar | 24,5 | 52,2 | 79,3 | 102,7 | 125,5 | 150,4 | - | - |
| middel | | 23,5 | 52,7 | 77,9 | 102,1 | 126,5 | 150,8 | 180,4 | 199,8 |
| min | | 22,8 | 51,9 | 76,7 | 101,2 | 125 | 149,9 | 179,4 | 198,6 |
| max | | 24,5 | 53,3 | 79,3 | 102,7 | 127,6 | 152 | 181,9 | 201,2 |
| Max. Deviation | | 1,7 | 1,4 | 2,6 | 1,5 | 2,6 | 2,1 | 2,5 | 2,6 |
| Max. deviation from Average: | | 1,0 | 0,8 | 1,4 | 0,9 | 1,5 | 1,2 | 1,5 | 1,4 |
| % deviation | | | 2,7 | 3,3 | 1,5 | 2,1 | 1,4 | 1,4 | 1,3 |
| MW01 | bar | 1,3 | 290,3 | 289,7 | 289,4 | 291,1 | 290,0 | 291,1 | |
| MW02 | bar | 0,1 | 0,2 | 0,2 | 0,2 | 0,2 | 0,3 | 0,2 | |
| MW03 | bar | 1,0 | 208,1 | 210,7 | 213,1 | 215,1 | 214,0 | 215,1 | |
| MW04 | bar | -0,4 | 200,9 | 199,9 | 201,8 | 200,5 | 200,2 | 200,5 | |
| MW05 | bar | 1,1 | 218,2 | 217,3 | 220,1 | 218,8 | 217,3 | 218,8 | |
| MW06 | bar | 0,4 | 207,8 | 212,3 | 213,2 | 214,5 | 214,4 | 214,5 | |
| MW07 | bar | 0,3 | 202,4 | 202,8 | 202,7 | 202,0 | 202,2 | 202,0 | |
| F_WaveCyl | kN | -0,2 | -12,8 | -22,3 | -24,9 | -29,6 | -28,9 | -29,6 | |
| F_Chart | kN | | | | | | | | |
| F_Sum | kN | -0,9 | 22,3 | 33,8 | 26,0 | 17,6 | 28,8 | 17,6 | |
| v_cyl_MTS | m/s | 0,000 | -0,002 | -0,002 | -0,002 | -0,002 | -0,002 | -0,002 | |
| x_cyl_MTS | mm | 902,0 | 892,0 | 832,0 | 713,0 | 549,0 | 632,0 | 549,0 | |