BAE HybriGen® Power Fuel Efficiency Evaluation

In-Use Testing of ACBL's High-Horsepower Hybrid Tow Vessel

MJB & A

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Contents

Acknowledgements

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This independent report, *BAE HybriGen® Power Fuel Economy Evaluation*, documents the in-use fuel study performed by M.J. Bradley & Associates in cooperation with BAE Systems (BAE) and American Commercial Barge Lines (ACBL) on their river vessel CHRISTOPHER M. PARSONAGE. MJB&A was responsible for overall development of the test plan; collection of fuel use data; and data evaluation and analysis. ACBL provided the vessel to be tested as well as vessel operating personnel and was responsible for coordination of vessel availability and installation of fuel metering equipment on their vessel. BAE assisted with coordination as well as monitoring of their HybriGen Power system during testing. The authors would like to acknowledge and thank the following individuals for their contributions to this project; without their help it would not have been possible:

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This report is available at www.mjbradley.com.

About M.J. Bradley & Associates

M.J. Bradley & Associates, LLC (MJB&A), founded in 1994, is a strategic consulting firm focused on energy and environmental issues. The firm includes a multi-disciplinary team of experts with backgrounds in economics, law, engineering, and policy. The company works with private companies, public agencies, and non-profit organizations to understand and evaluate environmental regulations and policy, facilitate multi-stakeholder initiatives, shape business strategies, and deploy clean energy technologies.

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Introduction

This in-use fuel consumption testing report represents a third-party evaluation of ACBL and BAE's joint engineering effort to hybridize a high-horsepower river tug. The project also received partial funding from the Maritime Administration under the Maritime Environmental and Technical Assistance Program.

The CHRISTOPHER M. PARSONAGE operates on the Mississippi River as a tow vessel, moving barges up- and down-river, between Cairo, Illinois and New Orleans, Louisiana. The vessel operates in near-constant operation with minimal stopping for barge pickup/delivery as well as maintenance.

For this project, data on engine fuel consumption was collected from the CHRISTOPHER M. PARSONAGE as the vessel transited the Mississippi River during normal in-use operation.

Test Vessel

The test vessel, the CHRISTOPHER M. PARSONAGE was built in 1998 and is part of ACBL's River Operations. This 180-foot pushboat has a total power rating of 8,000 hp from two (2) Electro-Motive Diesel (EMD) 16-cylinder 710G7B engines, each certified to EPA Tier 3 emissions standards. The vessel is also equipped with two (2) John Deere generator sets, capable of each producing 175 kW for vessel hotel load.

In 2016, the vessel's starboard EMD main engine was upgraded with a BAE Systems HybriGen® Power generator and associated equipment, thus converting the vessel to a hybrid configuration. The hybrid generator is connected to the main engine via a reduction gearbox and shaft arrangement and can be disengaged using its air clutch assembly.

As the EMD engine is running, the hybrid generator creates electrical power for the hotel load of the vessel (e.g., ship's power). When the hybrid system is operating, both auxiliary generators are disconnected from the main switchboard and turned off. BAE Systems designed the HybriGen system to reduce fuel consumption for hotel power generation in all operating conditions.

The vessel specifications and engine parameters for the CHRISTOPHER M. PARSONAGE are shown in Table 1.

Table 1 CHRISTOPHER M. PARSONAGE Specifications

Vessel Name	CHRISTOPHER M. PARSONAGE
Build Date	1998
Vessel Upgrade Date	2016
Propulsion Engines	
# of Engines	2
Model Year	2016
Manufacturer/Model	EMD 16-710G7B
Config/# of Cylinders	Vee / 16 cylinders
Power Rating (ISO Continuous)	4,000 BHP @ 900 RPM
Emission Standard	EPA Tier 3
BAE HybriGen® Power (mounted to Starboard EMD engine)	
Arrangement	Shaft-mounted via front engine flywheel and Reduction gearbox
Power Output	120 kW (idle) to 230 kW (full engine speed)

Auxiliary Generator Sets	
# of Generator Sets	2
Model Year	2015
Manufacturer/Model	John Deere 6090AFM85
Config/# of Cylinders	In-line / 6 cylinders
Power Rating (ISO Continuous)	298 BHP @ 1,800 RPM
Emission Standard	EPA Tier 3

Test Procedure

All testing performed on the vessel was done during normal in-use operation as it transited up and down the Mississippi River over the course of several weeks in the Summer of 2019. For this project, two distinct configurations were tested – "baseline" and "hybrid".

The baseline configuration consisted of both main engines and one (1) auxiliary generator set in operation. The HybriGen® system for this configuration was unclutched and disconnected from the main switchboard. In the hybrid configuration both main engines, as well as the HybriGen® system were active and both auxiliary generator sets were disconnected from the main switchboard and turned off.

Both configurations were monitored using fuel metering equipment, which logged fuel consumption of each engine. In addition, the main propulsion engines were fitted with non-contact RPM sensors to independently monitor engine speed. All fuel metering equipment and sensors were wired to a data acquisition system, which logged each parameter at 1 Hz (e.g., once per second).

Each configuration was logged for five (5) days headed southbound from Cairo, IL to New Orleans, LA and seven (7) days headed northbound from New Orleans, LA to Cairo, IL. Although the system was active during July, August and for parts of September, there was significant flooding along the Mississippi River over the summer that limited the amount of in-use data available. Additionally, there was an instance where data was collected, but determined to not be valid because one of the vessel's propellers was damaged.

In addition to capturing in-use river operation, a 20-minute idle test was performed while at the dock in Cairo, IL. The vessel was tested at idle in the baseline condition for 20 minutes and then swapped over to the HybriGen® Power system and tested for an additional 20 minutes. No changes, other than vessel power generation source, were made during the test.

Test Equipment

For this project, fuel use was measured using two (2) KRAL fuel flow meters installed on each engine. The meters are spindle-type meters with an accuracy of +/- 0.1% of measured flow. On each engine, one meter was installed in the fuel line on the inlet side of the engine fuel pump, and one was installed in the fuel return line between the engine and fuel tank. Figure 1 shows the inlet fuel meter installed next to the BAE HybriGen® Power generator on the starboard main propulsion engine. Figure 2 shows both inlet and return KRAL fuel meters installed on the auxiliary generator set.

Fuel use by the engine was calculated by subtracting measured fuel return flow from measured fuel pump inlet flow, as recorded by the meters. For these diesel engines, return fuel flow is expected to be approximately ten times engine fuel use; as such measured fuel use for this testing will have an accuracy of approximately +/- 1%. The specifications for each of the fuel meters are provided in Appendix A.

Figure 1 KRAL OMG20 Fuel Meter Installed on Starboard Main Engine

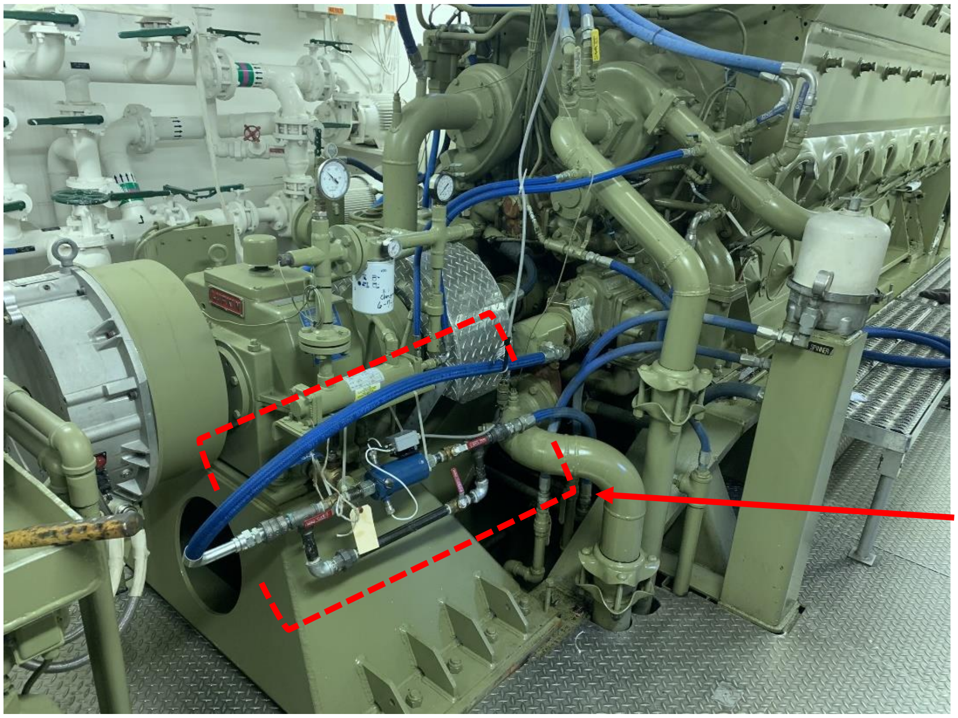
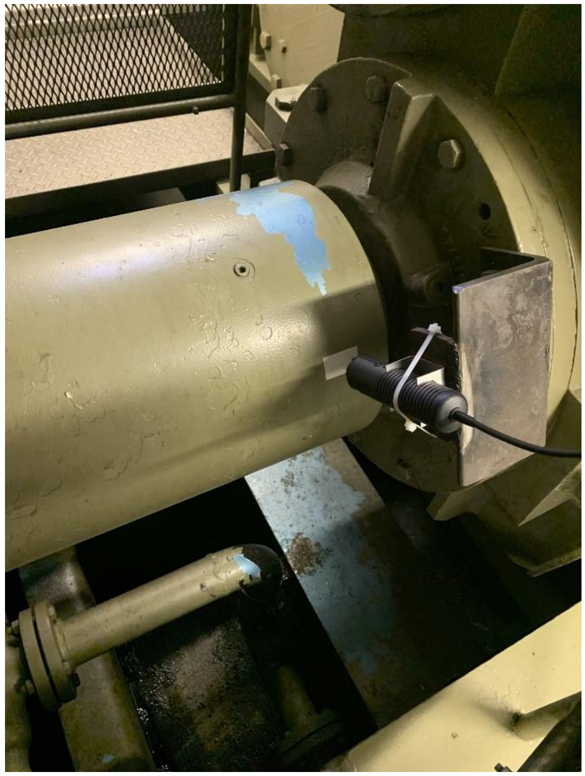


Figure 2 KRAL OME13 Fuel Meters Installed on Auxiliary Generator #1

In addition to the fuel meters installed on each engine, non-contact RPM sensors were installed on each main propulsion engine's stub shaft between the engine and gearbox. Each RPM sensor had an accuracy of +/- 1.5 RPM. The RPM sensor attached to the port main engine is shown in Figure 3.

Figure 3 RPM Sensor Installed on Port Main Engine Stub Shaft



Information from each fuel meter and RPM sensor was transmitted directly into a data acquisition system and recorded at a 1 Hz frequency. The datalogger used for testing is shown in Figure 4.

Figure 4 Data Acquisition System

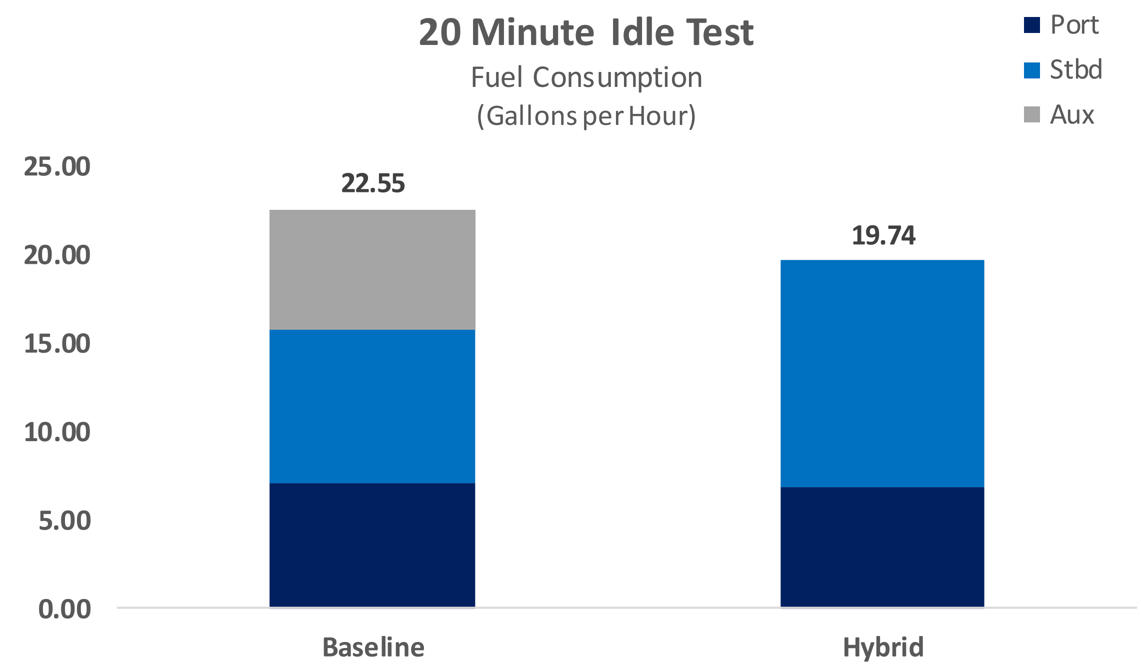
Results

The following section summarizes the results of the fuel testing for idle and in-use river conditions. All results compare the HybriGen® Power system against the baseline configuration.

Idle Test

As discussed previously, the idle test was performed over a 20-minute period under both configurations while dockside. No changes were made to the vessel hotel load or other conditions during the testing. The following chart (Figure 5) compares the baseline and hybrid configurations' average fuel consumption for the main and auxiliary engines.

Figure 5 20 Minute Idle Test (Gallons per Hour)



As shown, the HybriGen® Power system yielded a savings of 2.81 gallons per hour (~12.5% savings), when compared against both main engines and auxiliary generator set in the baseline condition. The power used to generate hotel load under the baseline condition is shown in gray, while under the hybrid condition, this hotel load is generated by the starboard main engine (light blue).

In-Use HybriGen® Power Testing

Under the baseline condition, auxiliary generator set fuel usage was measured for both the northbound and southbound directions. Average fuel consumption (gallons per hour) for the auxiliary genset in each direction were calculated, along with the port and starboard main engines. Auxiliary genset hotel load was consistent for the baseline test, resulting in only ± 5% between all testing days.

Variances in fuel consumption between the port and starboard main engines in the baseline condition were observed during the northbound and southbound trips. For the northern trip, the starboard engine burned 0.2% more fuel than the port, while on the southern trip, the starboard engine burned approximately 2.1%

more than port. On average for the entire test period, the starboard engine burned 0.9% more, compared to the port main engine. This average value was used to correct the port-to-starboard variance, which is discussed further below.

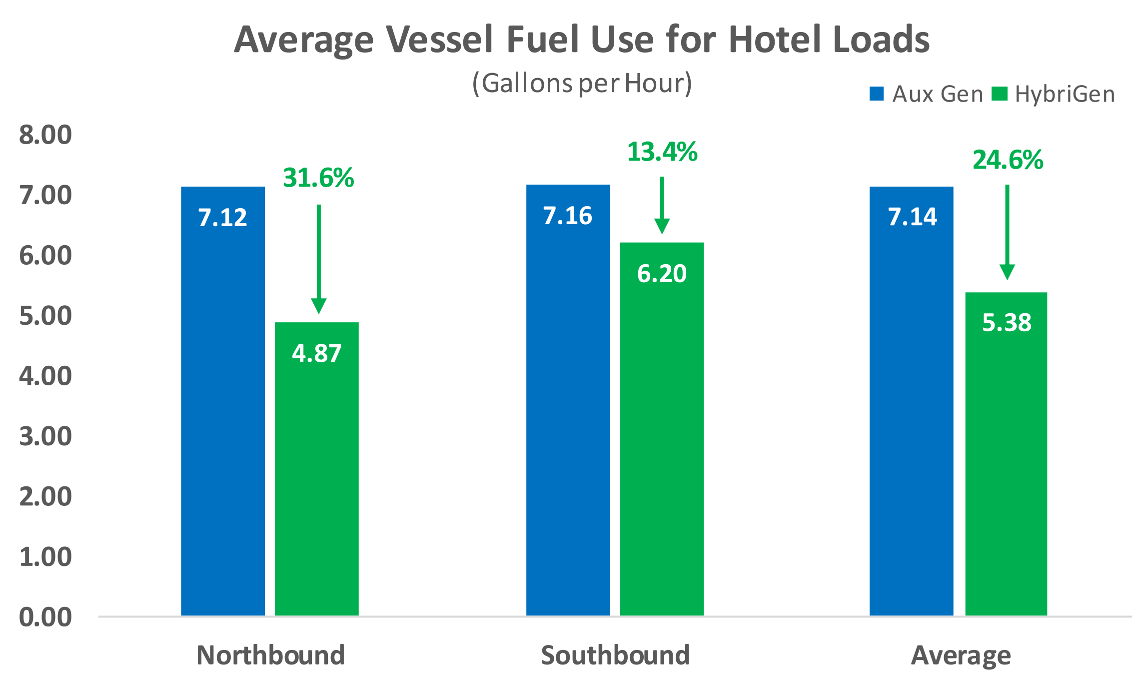
In an effort to understand variances between the baseline and hybrid test trips (e.g., tow load differences, river conditions, etc.), an analysis of the port main engine was performed. Since the port engine remains unaltered between baseline and hybrid configurations, fuel consumption for both tests were analyzed for variation. For the baseline test, the port engine averaged 88.6 gallons/hour, while during hybrid testing, the port engine average 92.5 gallons/hour, resulting in less than 5% variance between the two tests.

For the hybrid test, fuel consumption (gallons per hour) between the port main engine and the starboard main engine were compared for both the northbound and southbound directions. Using the average correction factor discussed above (0.9%), the port-to-starboard variance was adjusted to "normalize" the differential between both engines. The resulting difference between the starboard and port main engines represent the fuel consumption used to operate the HybriGen® Power system for hotel load.

Hotel load from the hybrid system was analyzed and the individual days were compared. Overall, hotel load during the hybrid test varied ± 6% between days and compared to the baseline trip, hotel load varied ± 5% compared to the hybrid test.

See Figure 6 for a comparison of the HybriGen® Power system to the baseline auxiliary generator set.

Figure 6 Average Vessel Fuel Use for Hotel Loads (Gallons per Hour)



As shown, the HybriGen® Power system provided a fuel consumption benefit ranging from 13% to 32% for hotel power generation. Over the entire test period, the hybrid system averaged a 25% decrease in fuel use for hotel load.

Conclusion[1]

As discussed in the Results section, the HybriGen® Power system can provide significant fuel savings, compared to a traditional auxiliary genset arrangement. In idle conditions, the system provided a 12% reduction in total vessel fuel use; while in river operations, the hybrid configuration averaged a 25% reduction in fuel consumption for hotel power generation.

On average for a typical 13-day roundtrip, it is estimated that the system could save more than 570 gallons compared against the baseline auxiliary genset. Assuming the vessel makes 26 roundtrips per year[2], total annual fuel savings could be more than 14,800 gallons.

In addition to the fuel savings discussed, the hybrid system can also offer co-benefits, including maintenance savings (with auxiliary generators turned off), as well as reduced greenhouse gas and criteria pollutants. This analysis did not contemplate full life-cycle cost and emission savings possible using the HybriGen® Power system.

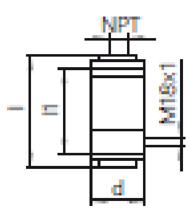
[1] The results shown are for discussion-purposes only; individual vessel results may vary.

[2] Assumes 20 days for maintenance and 5 days for miscellaneous delays (340 days ÷ 13 days per roundtrip) = ~26 trips.

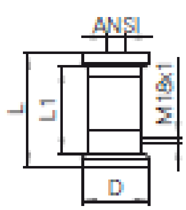
Appendix A Kral Fuel Meter Specifications

Kral OMG20 Fuel Meters (Main Engines)

Technical data.		OMG 13	OMG 20	OMG 32	OMG 52	OMG 68	OMG 100	OMG 140
Flow								
Q_{max}	gpm	4	12	40	135	270	790	2,000
Q_{nom}	**gpm**	2.7	8	27	90	180	525	**1,300**
Q_{min}	gpm	0.027	0.08	0.27	0.9	1.8	5.25	13
Pressure P_{max}	psig	3,600	3,600	3,600	2,300	1,450	600	600
Temperature $t_{min} \dots t_{max}$	°F	-4 to 400	-4 to 400	-4 to 400	-4 to 400	-4 to 400	-4 to 400	-4 to 400
Viscosity $v_{min} \dots v_{max}$	cSt	1 to $1x10^6$	1 to $1x10^6$	1 to $1x10^6$	1 to $1x10^6$	1 to $1x10^6$	1 to $1x10^6$	1 to $1x10^6$
K-Factor K1	pulses/gal	4,603	2,423	886	269	151	63.6	33.5
K2	pulses/gal	9,206	4,845	1,772	538	301	127	67.0
K3	pulses/gal	27,618	9,691	3,838	1,143	632	218	83.7
Frequency f1 at Q_{nom}	Hz	205	323	394	404	453	557	726
f2 at Q_{nom}	Hz	409	646	788	807	903	1,111	1,452
f3 at Q_{nom}	Hz	1,227	1,292	1,706	1,715	1,896	1,908	1,813



Dimensions/Weights.		OMG 13	OMG 20	OMG 32	OMG 52	OMG 68	OMG 100	OMG 140
NPT inch		½"	¾"	1"	1 ½"	2"	4"	6"
p	psi	3600	3600	3600	2300	1450	600	600
l	inch	5.71	7.28	10.43	11.61	13.98	18.9	25.39
d	inch	3.54	2.91	4.1	4.65	5.43	7.4	10.51
l1	inch	3.7	5.71	8.46	9.45	11.61	15.75	21.14
wt	lb	9.9	11.7	31.8	41.2	65.3	154	419



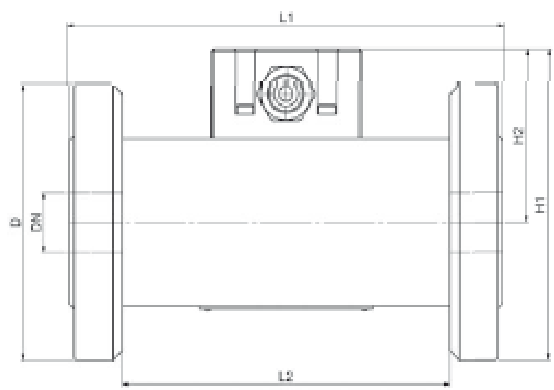
ANSI		½"	½"	¾"	¾"	1"	1"	1 ½"	1 ½"	2"	2"	4"	4"	6"	6"
Class		150	300	150	300	150	300	150	300	150	300	150	300	150	300
L	inch	5.71	5.71	7.30	7.64	10.43	10.63	11.22	11.61	13.58	13.58	18.31	18.31	23.62	26.5
D	inch	3.5	3.75	3.87	4.62	4.25	4.87	5	6.13	6	6.5	9	10	11	12.5
L1	inch	3.7	3.7	5.71	5.71	8.46	8.46	9.45	9.45	11.61	11.61	15.75	15.75	21.14	23.62
wt.	lb	10.8	12.1	13.6	17.4	32.0	35.3	40.6	47.8	65.0	67.5	165	184	397	461

Kral OME13 Fuel Meters (Auxiliary Genset)

Dimension Information.

Threaded and flanged flowmeter connections.

ANSI dimensions.		OME 13	OME 20	OME 32	OME 52
DN	[in]	1/2	3/4	1	1 1/2
Class		300	300	300	300
D	[in]	3.75	4.63	4.87	6.30
L1	[in]	4.13	5.71	7.68	12.40
L2	[in]	2.56	3.74	5.51	8.96
H1	[in]	4.21	4.95	5.27	6.77
H2	[in]	2.34	2.54	2.84	3.62
Weight	[lbs]	2.6	3.7	6.6	26.0



Technical Data.

The size to fit your application.

OME Compact series.		OME 13	OME 20	OME 32	OME 52
Flow					
Q_{max}	gpm	4	12	40	135
Q_{nom}	**gpm**	**2.7**	**8**	**27**	**90**
Q_{min}	gpm	0.027	0.08	0.27	0.9
Pressure					
p_{max}	psi	600	600	600	600
Temperature					
t_{min} to t_{max}	°F	-4 to +257	-4 to +257	-4 to +257	-4 to +257
Viscosity					
v_{min} to v_{max}	cSt	1 to $1x10^6$	1 to $1x10^6$	1 to $1x10^6$	1 to $1x10^6$
K-factor					
K	pulses/gal	4,596	1,215	295	67
Frequency					
f to Q_{nom}	Hz	202	161	130	104