THERMODYNAMIC IMPROVEMENTS TO A 0-4-0ST ENGINE IN 7 ¼" GAUGE

AN IMPLEMENTATION OF THE LEMPOR EJECTOR SYSTEM IN A LIVE STEAM LOCOMOTIVE

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CONTENTS

A NOTE ABOUT UNITS

In this paper as far as is possible the units that have been adhered to are the recognised units in current engineering practice in Australia.

Length:	millimetres	mm
Volume:	litres, cubic metres	l, m^3
Time:	second	s
Pressure:	Pascal	Pa
Angular measure:	Radians	Rad

For conversion factors to imperial equivalents there are many books and websites available on the internet for such a purpose.

INTRODUCTION:

This paper has been written to illustrate and to inform people about the possibilities that exist in improving steam locomotive performance. The main body of this paper is centred on the implementation of the late Ing. Livio Dante Porta's Lempor exhaust ejector.

In this case the subject for modification was a seven and quarter inch gauge 0-4-0ST locomotive owned by Mr. Gary Brown of Lewiston in South Australia. The locomotive was built by Mr Howard Bateup, also of South Australia in 1986.

Principal dimensions of the locomotive are listed below:
All dimensions in millimetres.

Length: 1333.5	Driving Wheel diameter: 196.85
Width: 521	Cylinders: (2) 60 x 102
Height: 675	valve gear: JMG

REASONS FOR MODIFICATION:

The reasons for this modification were twofold, firstly the structural integrity of the original 3mm thick mild steel smokebox had been breached by corrosion due to sulphur in the ash mixing with condensate to form sulphuric acid and corroding the steel, in some places to the extent that holes were starting to form. Secondly it formed part of an ongoing series of modifications to improve the performance of the loco to show what utilising many of the ideas available to improve performance could achieve.

PAST IMPROVEMENTS:

The locomotive had its first overhaul in 1997, basically an overhaul of the valve gear and balanced slide valve mechanism as well as the normal paint job. Photo 1 shows the locomotive in 1995 before any modifications, photo 2 is circa 1997.

Photo 1: “Tootles” in original condition 1995

In 1998 the locomotive had a major overhaul. A new boiler was built, of steel wetback design. It had a heating surface almost three times larger than the original heating surface. The original boiler was of the Briggs dry firebox design.

Photo 2: After the first overhaul, Easter 1997

The opportunity was also taken to sleeve the cylinders, manufacture new wheels and axles and replace the self aligning ball races in the axle boxes. A feedwater heating coil was installed in the smokebox made of stainless steel beer tube. Other improvements included a better lighting system for night running and a steel arch to improve combustion. A digital speedometer was fitted at this time as well. Photo 3 shows the locomotive after these modifications. The higher boiler centreline can be seen allowing for a deeper firebox and the firebox is also larger, extending further rearward into the cab

Photo 3: After second overhaul with the new steel wetback boiler and feed water Heater. The new boiler centreline is 40mm higher than the original facilitating a deeper firebox

<u>CURRENT IMPROVEMENTS:</u>

In July 2004 the smokebox had reached the end of its life and urgent action was needed. It was agreed that before the locomotive was transported to the workshop a trial would be undertaken, however the main topic to decide was to what extent the current round of improvements would cover new items or just a simple replacement. After some Discussion the following list was decided upon.

New smokebox shell and door all stainless steel
All items internal to the smokebox to be of stainless steel or bronze
Improved exhaust steam circuit
Improved live steam circuit
Lempor exhaust system, all internal components to be stainless steel or bronze
New blower
Lift boiler off chassis for internal cleaning
Valve gear overhaul (light, assessed on a joint by joint basis)
Overhaul crossheads
Retime valve gear
New boiler pressure gauge

Photo 4: The original smokebox and front end

Photo 4 shows the smokebox at the overhaul in 1998, the poor exhaust system can be seen. The exhaust from each cylinder hits a plain baffle plate before going up to the blast nozzle. Also the entry bell on the petticoat is only tapered not a proper bell type entry reducing vacuum generating efficiency.

TELEMETRY INSTALLATION:

Between the overhaul in 1998 and the overhaul in 2004 the intention of installing a Lempor ejector was formed, with this in mind and the need to establish a baseline for performance, telemetry was installed when time permitted. This started with the smokebox manometer in 2000, then in 2003 an exhaust backpressure gauge was installed. Together with the digital speedometer installed in 1998 and the steam chest pressure gauge that the locomotive possessed since it was built, formed the basis of the telemetry with which to gather data. (see Photo 5)

Photo 5: Locomotive's cab showing the instruments used for the trials

PRELIMINARY TRIAL

The preliminary trial was an important trial to perform as it provided crucial data on the original front end performance and a draughting curve that was ideal for the engine. The original front end provided enough draught for excellent steaming and the object of the modification was to at least equal this curve or better it but utilising a lower back pressure so the locomotive would gain horsepower for a given steaming rate. The regime of testing decided upon was to try to keep a constant steam chest pressure during the taking of other measurements. Full gear was maintained to simplify mean effective pressure measurement and mass flow calculations. Cut off in full gear being approximately 80% based on an elementary analysis of the valve gear travel.

Unfortunately time did not allow multiple runs at the same steam chest pressures and as a consequence the data gathered is quite limited. The results for the preliminary trial are shown in the spreadsheet and graphs in Appendix 1.

DESIGN ANALYSIS FROM THE TRIAL DATA

Once the trial was over and the locomotive stripped a dimensional analysis of the original front end was performed. It was found that the original was proportioned very closely to the American master mechanics front end. A table of the principle dimensions of the front end is shown below.

ORIGINAL FRONT END AREAS AND RATIOS		
Feature	**Area mm^2**	**% of tube gas area**
Petticoat choke	968	21.6
Blast nozzle	78	1.74
Area between nozzle & petticoat	5236	116.8

Table 1: Principle areas of the original front end.

Trial data analysis:

The data from the trial, in particular the calculated mass flow rates of steam were entered into a software program, Hall (2000). For calculating the properties and mass flow rate of steam through a convergent nozzle. A statistical analysis of this data against the software calculations enabled an estimation of the extent of the exhaust peaks and troughs in relation to the gauge reading from the locomotive.

The result showed that the gauge on average was reading 110% higher than the actual average back pressure should have been. This error was probably due to very high, short spikes in pressure at the moment of release keeping the mechanical gauge reading higher than it should have been, the snubber fitted to the gauge probably exaggerated the problem capturing the spike and taking longer to dissipate. It was decided to analyse the results after the trial with the Lempor as well to determine wether the spikes at release were smaller with a larger blast nozzle or “tuyere” area.

Once this data was established an arbitrary mass flow rate was decided which corresponded to the upper end of the envelope of locomotive power consistent with passenger hauling. The absolute top power of the locomotive was not picked as unlike full size models are operated normally well below the limit of power or adhesion.

The point that was picked was at a speed of 2.8 ms^{-1} which corresponds with the maximum allowable speed for public passenger hauling. From this the following calculations were performed to establish an approximate mass flow rate.
From operating experience the steam chest pressure used was 276kPa, the maximum that has been experienced using full gear on the locomotive while passenger hauling with a load of approximately 2500kg equal to 4 fully loaded carriages with adults. The absolute maximum load the locomotive in question has hauled though was in excess of 4.0t up a 1 in 75 gradient with a peak power output of approximately 2.5kW at the drawbar. It was interesting to note at this level of performance 250-500W was being used up to overcome a 75 kPa back pressure at a speed of 4.0ms^{-1}.

Determination of mass flow rate:

Cylinders: 60 x 102 (dia., D x stroke, S)
Steam chest pressure, p: 276kPa
Speed, v 2.8ms^{-1}
Wheel dia., w: 196.85
Max. Cutoff, Υ: 80%
Angular velocity, ω, of the wheels is required to find the number of cycles per second,

$$w = \frac{v}{0.5w}$$
$$w = \frac{2.8}{0.5 \times 0.19685}$$
$$w = 28.45 \text{ rad s}^{-1}$$

The number of strokes per second, *?* can be found using the equation,

$$h = \frac{v}{1/2p}$$
$$h = \frac{28.45}{1/2p}$$
$$h = 18.1 \text{strokes s}^{-1}$$

Then the volume of steam used per stroke needs to be calculated,

$$V_s = 0.25 D^2 pS 0.01g$$
$$V_s = 0.25 \times (30)^2 \times p \times 0.102 \times 0.01 \times 80$$
$$V_s = 2.307185 \times 10^{-4} \text{m}^3$$

The volumetric flow rate of steam can be now be calculated,

$$F_v = V_s h$$
$$F_v = 2.307185 \times 10^{-4} \times 18.1$$
$$F_v = 4.176 \times 10^{-3} \text{m s}^{-3}$$
$$F_v = 4.176 \text{ l s}^{-1}$$

Using steam tables the density of steam, *?*, at the steam chest pressure, p, 276kPa.

$$? = 0.4884 \text{ m kg}^{-3} = 2.047502 \times 10^{-3} \text{ kg l}^{-1}$$

Now the mass flow rate can be calculated,

$$F_m = F_v r$$
$$F_m = 4.176 \times 2.047502 \times 10^{-3}$$
$$F_m = 8.55 \times 10^{-3} \text{kg s}^{-1}$$

It is important to note that the above calculation is a simplification of the true mass flow rate of steam to the tuyere. However as this was a comparative exercise the approximation was suitable for the purpose. A paper by Hall(1999) gives a more accurate model for mass flow rate taking into account friction losses through the ports among other things.

Now that the mass flow through the tuyere was established at the maximum power used for public passenger hauling, the cross sectional area of the blast nozzle was to be increased to enable the backpressure to be at least halved needed to be established.

The basis for the modification was to halve the back pressure for a given mass flow rate. To do this the net area of the of the blast nozzle would need to be increased by 50% therefore the diameter of the nozzle orifice would have to increase by a factor of,

$$D_f = \sqrt{150/100}$$

$$\therefore D_f = 1.224$$

From this factor the new tuyere equivalent diameter was established. This worked out to be: 10 x 1.224 = 12.24mm

With this factor now established the Lempor nozzle diameters are exactly half for four nozzles i.e. 12.24/2 =6.12mm

Utilising the Appendix, A3 in Porta (1974) the proportions for the mixing chamber and diffuser were calculated. Before performing this however it was thought possible to drop the back pressure another 10% due to the inherently lower steaming rate of the boiler requiring a lower vacuum in coping with a lower power output due to a reduced backpressure. Although the nozzle would not be implemented with the larger holes immediately the mixing chamber and the diffuser would be proportioned on the slightly larger tuyere surface area it being unlikely there would be any undue effect on performance. Using the same formula again D_f =1.048 therefore tuyere equivalent diameter =12.24 x 1.048 = 12.8 mm
mm in diameter therefore each nozzle =6.4mm

From Porta's paper and recommendations in Wardale (1998) the following schematic drawing was developed.

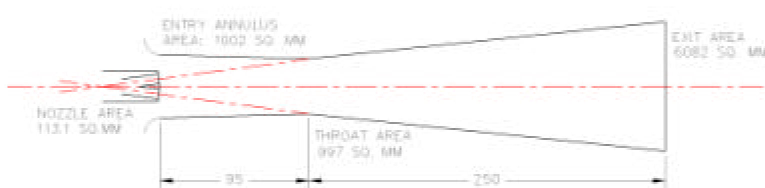

Figure 1: Schematic showing the principal areas of the Lempor ejector.

After developing the schematic the working drawing was drawn to enable manufacture of the new smokebox. This is shown in appendix 2

MANUFACTURE & ASSEMBLY

Once the drawing was completed manufacture began on the smokebox shell and door. All of these components were made from 316 stainless steel. The whole assembly was bolted together using 304 stainless steel high tensile fasteners and then sealed with GE high temperature Silastic (the same specification as used on aircraft gas turbine tailpipes). The diffuser section and its saddle being external components were machined from mild steel, the saddle was actually fabricated from plate and hollow bar and then hand worked and machined.

The mixing chamber was machined from a solid billet of 431 stainless steel and polished internally to a high finish. The exhaust pipes were formed from pre-welded sections of 25.4mm diameter x 1.6mm wall stainless steel tubing, the two elbows having been previously welded to straight sections of pipe. These were modified and then TIG welded together by a fellow club member to form the exhaust "tee" the whole idea was to get a nice sweeping bend for the least amount of turbulence and friction loss from the two gas streams. Unfortunately the length was a little too short to incorporate a kordina however the tuyere has a tapered entry to minimise turbulence. The tuyere is machined from solid bronze and has 4 x 6 mm nozzles, the area being kept a little small for trial steaming. The entries to the nozzles are hand ground to minimise turbulence as well. The tuyere is removable, being screwed into a threaded bush on top of the exhaust stand. A blower is fitted consisting of a copper tube with three 1.6mm diameter De Laval nozzles machined into it. Photo 6 shows the smokebox under construction.

Photo 6: the new all stainless smokebox under construction.
The mixing chamber and improved exhaust pipe work can be seen with a threaded bush at the top for the tuyere to screw into.

The steam circuit was also modified. The steam circuit from the dome to the cylinders was quite restrictive, however one particular point open to improvement as can be seen in the photo of the original smokebox was where the two dryer tubes converge into one tube, the bore of which had an area of only 127 mm^2. This area was only 2.22 % of the total cylinder sectional area. Wardale (2000) gives the ratio for the SAR 26class 3450 as 6.25%. The converging piece and the main inlet pipe were replaced with an improved design effectively increasing the steam inlet orifice area in each cylinder by 65% and effectively increasing steam chest volume by utilising a large diameter “manifold” arrangement between the two cylinders, (this can be s een in photo 7 under the smokebox). The original gasket flanges on the steam pipes were replaced to a heavier type utilising ‘o’ rings as primary sealing elements. Thus the new steam circuit arrangement at its worst has a cross sectional delivery area of 253mm^2. Giving a total cross sectional area in relation to the cylinders of 3.5%, Nowhere near ideal, however still an improvement. (this showed up later, very graphically on the steam chest pressure gauge when the oscillations it had in full gear, in the order of 50kPa when working hard pre modifications, almost disappeared entirely and became no more than a slight quiver!).

Once the locomotive was back together, a trial in the workshop was undertaken to ensure steam tightness. All was shown to be well. Photo 7 shows a view inside the completed smokebox after this run.

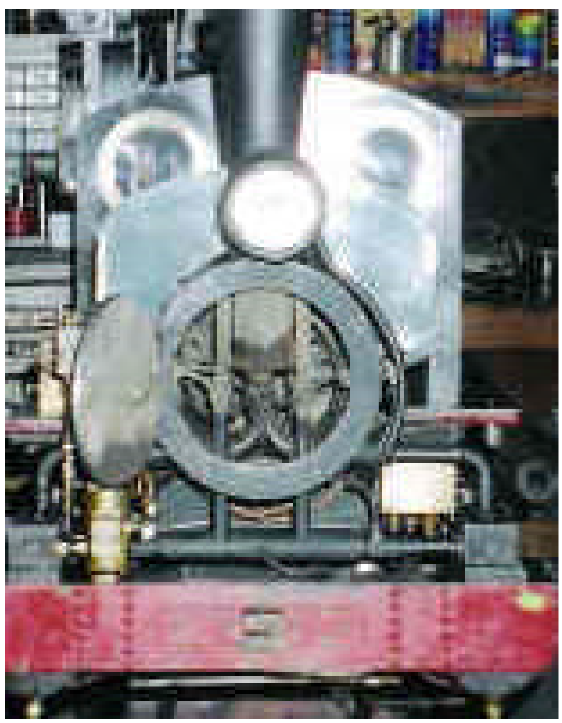

Photo 7: smokebox and Lempor ejector after installation and first firing. The large inlet manifold can be clearly seen under the smokebox.The outlets for the slide valves are on top as the slide valve design is balanced and allows the exhaust to go straight through. An elegant and thermodynamically superior design concept that has proven itself very well in practice.

POST MODIFICATION TRIAL(S)

As soon as it was convenient for all concerned the locomotive was taken up to the track at Roseworthy to check everything in normal operation. We had planned to do a trial, unfortunately one of the crossings on the track was blocked off for a major event on the oval the track is next to. (The track of the club I belong to, Roseworthy Railway is sited inside the Roseworthy Campus of the University of Adelaide next to the main oval.)This was very late October; this meant there would be no chance to do a trial before we went to Wagga with the loco the following weekend for 3 days running.

We ran on what track we could just to confirm there was nothing mechanically wrong with the locomotive after reassembly but performance characteristics under load would still be unknown.

The following weekend the loco was taken to Wagga, and much to the delight of all involved the locomotive ran flawlessly, steaming freely and producing an almost silent exhaust except when working very hard. The other thing that was noticed was a reduction in fuel used, it was definitely more efficient. The only drawback was that the chimney used so much of the energy out of the exhaust steam the steam became quite wet and barely lifted from the funnel, hampering visibility especially when it was a cooler day. Photo 8, taken by David head, a member of the Diamond Valley Railway shows the loco simmering in a siding at Wagga.

Photo 8: the locomotive after its modifications at the Wagga Wagga invitation run November 2004

After coming back from Wagga the trial was undertaken with the standard test load (photo 9 shows the loco coupled to this). This way there could be a direct comparison between the two trials the latter showing lower backpressure and horsepower with hopefully, a similar draughting curve and the same or better mean boiler pressure. The results of this trial are shown in appendix 1. The analysis of the difference between the gauge backpressure and calculated backpressure showed the error between the two had been reduced to 45%, less than half the original 110%. The tables for both are shown below.

Table showing anomoly between calculated and actual flow rates for modified front end

Gauge backpressure, Pa,Absolute	Calculated backpressure @ Calculated flowrate ,Pa, Absolute	Calculated flowrate,F_c	Calculated flowrate,F_a @ gauge backpressure,kg/s	Smokebox pressure,Pa, Absolute	F_a/F_c	%terms
103300	101442	0.001924763	0.00564	101202	2.930231	193.02%
105300	102485	0.004467096	0.0079	101172	1.768487	76.85%
106300	103250	0.005686931	0.00881	101114	1.549166	54.92%
108300	106480	0.008985739	0.0103	101084	1.146261	14.63%
112300	105800	0.008489299	0.0129	101006	1.51956	51.96%
119300	110700	0.012058085	0.0162	100810	1.343497	34.35%
143300	117500	0.015561606	0.0238	100417	1.529405	52.94%
149300	127760	0.019458617	0.0252	100319	1.295056	29.51%
					Average	**45.02%**

Table showing anomoly between calculated and actual flow rates for original front end

Gauge backpressure, Pa,Absolute	Calculated backpressure @ Calculated flowrate ,Pa, Absolute	Calculated flowrate,F_c	Calculated flowrate,F_a @ gauge backpressure,kg/s	Smokebox pressure,Pa, Absolute	F_a/F_c	%terms
105300	101483	0.001443572	0.00547	101202	3.789212	278.92%
108300	102180	0.002791935	0.00717	101114	2.568111	156.81%
112300	103700	0.004423169	0.00893	101025	2.018914	101.89%
119300	105260	0.005659533	0.0113	100859	1.996631	99.66%
129300	105150	0.005686931	0.0138	100711	2.426616	142.66%
146300	118000	0.011017766	0.017	100368	1.542963	54.30%
149300	124900	0.012904434	0.0175	100270	1.356123	35.61%
156300	140300	0.016024744	0.0185	100172	1.154465	15.45%
					Average	**110.66%**

Table 2: steam consumption table showing discrepancy comparisons caused by pressure peaks

CONCLUSIONS AND OBSERVATIONS

After analysing all the data the specific efficiency of the new front end is 30% above that of the original. It is also shown that the approximate increase horsepower available at 10-12km/h is 20%, a very significant amount. Subjectively loco runs much freer, steaming very freely and gets along quietly. The coal consumption has been reduced although that is only a subjective observation as no tests were performed to compare consumption rates. The supplementary calculations would suggest that the water consumption remains unchanged and the fact that no change in superheat or valve gear was made supports this.

The important thing to note about the results of these very limited trials is that the results show a significant ***trend.*** This is the important result. It confirms the practicality and suitability of the Lempor exhaust ejector on a miniature steam locomotive and it's ability to match or even improve the draughting curve of an engine utilising lower back pressure. The other effect the trial showed up was the importance of having a suitably large live steam circuit. Most models are limited to some extent by having too smaller steam circuits, limiting their high power performance, a small increase in limiting diameters of the steam circuit can make a large difference to the performance of a locomotive. Due to a lack of time a full analytical design analysis of the Lempor exhaust made was never performed, the proportions all being derived from the blast nozzle orifice. At some stage this will be done and a comparison done between that and a theoretical ideal Lempor, it shall be interesting to note what, if any differences there are.

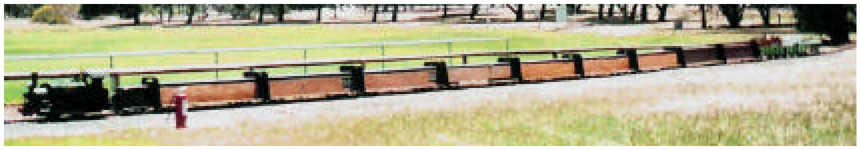

Photo 9: show the modified locomotive (with obligatory summertime fire extinguisher close by) with the standard test load behind. Weighing in at approximately1.25t, a modest but adequate load for this loco.

THE FUTURE

Currently I am studying mechanical engineering and without my workshop, so practical development is on hold. However design work has commenced on a 3 cylinder compound 0-4-0ST much the same size as “Tootles”. This “Tootles Mk II” will incorporate many of the improvements Chapelon, Porta, Wardale and others have designed to maximise the power to weight ratio and thermodynamic efficiency, it is hoped a doubling of available power is possible, this projects that the engine should be able to haul 10 -12 fully loaded carriages up a 1 in 70 gradient at 10 km/h , a feat most model 4-8-4’s are unable to achieve.

The results of this locomotive will then be used to design an updated model of Chapelon’s 3 cylinder compound 2-10-4 capable of hauling 18 carriages under the same conditions however both projects are some years down the track once my degree is out of the way.

“Tootles” is unlikely to receive any more modifications in the near future, however new cylinders and improved superheating are the most likely improvements to be implemented next. My final words for this paper are words of encouragement particularly to younger model engineers to give experimental improvements a go and document what they find scientifically so it may contribute to the pool of knowledge.

ACKNOWLEDGEMENTS

I would like to thank first and foremost Mr. Gary Brown for having faith in me to “rip” apart his loco and perform ‘surgery’ on it with no guarantee of success. Secondly Mr Bob Walladge, the president of Roseworthy Railway for plasma cutting out the larger components and TIG welding the Exhaust pipework. Also Mr Peter Armstrong for being my assistant and trial driver in the locomotive trials. I would also like to thank all the Authors of the documents I refer to in the references, in particular Mr. David Wardale, whose book changed the way I thought about steam locomotives. The book highlighted their unique position in the engineering world of being the most totally integrated machine man has invented, a quality that I think attracts most enthusiasts and engineers alike. And lastly I would like to thank anyone who has taken the time to sit down with an open mind and read this paper.

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APPENDIX 1: TRIAL DATA AND GRAPHS

PERFORMANCE DATA FOR "TOOTLES", AN 0-4-0T LOCOMOTIVE IN 7 1/4" GAUGE

Data for the Improved Front End

Steam Chest Pressure (kPa)	Boiler Pressure (kPa)	Back Pressure (kPa)	Manometer Reading (mm H_2O)	Smokebox Pressure (Pa)	Speedometer reading (km/h)	Angular Velocity of Wheels (RPM)
103	586	2	10	101202	4	108
138	655	4	13	101172	8	216
172	655	5	19	101114	9	243
207	620	7	22	101084	12	323
258	655	11	30	101006	11	296
310	620	18	50	100810	13	350
362	620	42	90	100417	15	404
413	620	48	100	100319	17	458
Average boiler pressure for runs:	**629**					

Data for the Original Front End

Steam Chest Pressure (kPa)	Boiler Pressure (kPa)	Back Pressure (kPa)	Manometer Reading (mm H_2O)	Smokebox Pressure (Pa)	Speedometer reading (km/h)	Angular Velocity of Wheels (RPM)
103	655	4	10	101202	3	81
138	620	7	19	101114	5	135
172	620	11	28	101025	7	189
207	655	18	45	100859	8	216
241	690	28	60	100711	9	243
275	448	25	70	100613	10	270
345	586	45	95	100368	11	296
380	586	48	105	100270	12	323
413	551	55	115	100172	14	377
Average boiler pressure	**601**					
Overall average for ALL	**615**					

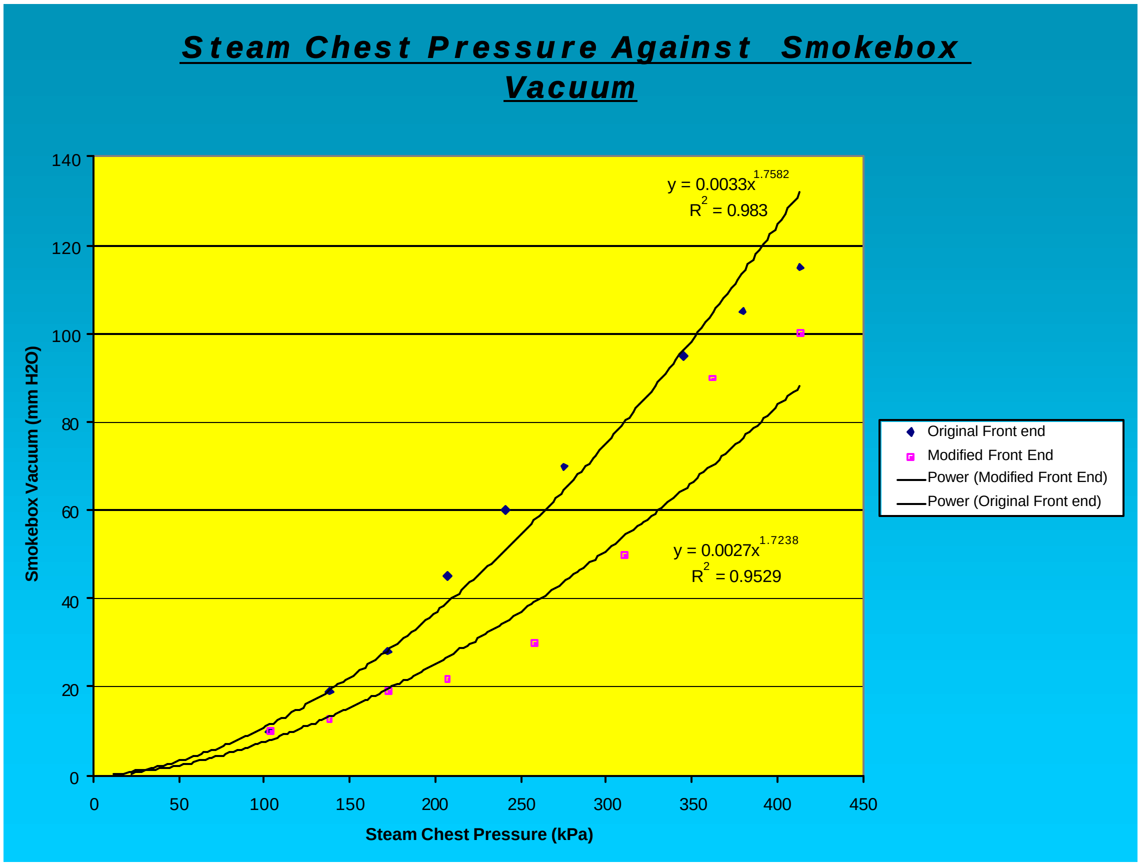
Supplementary Calculated Data

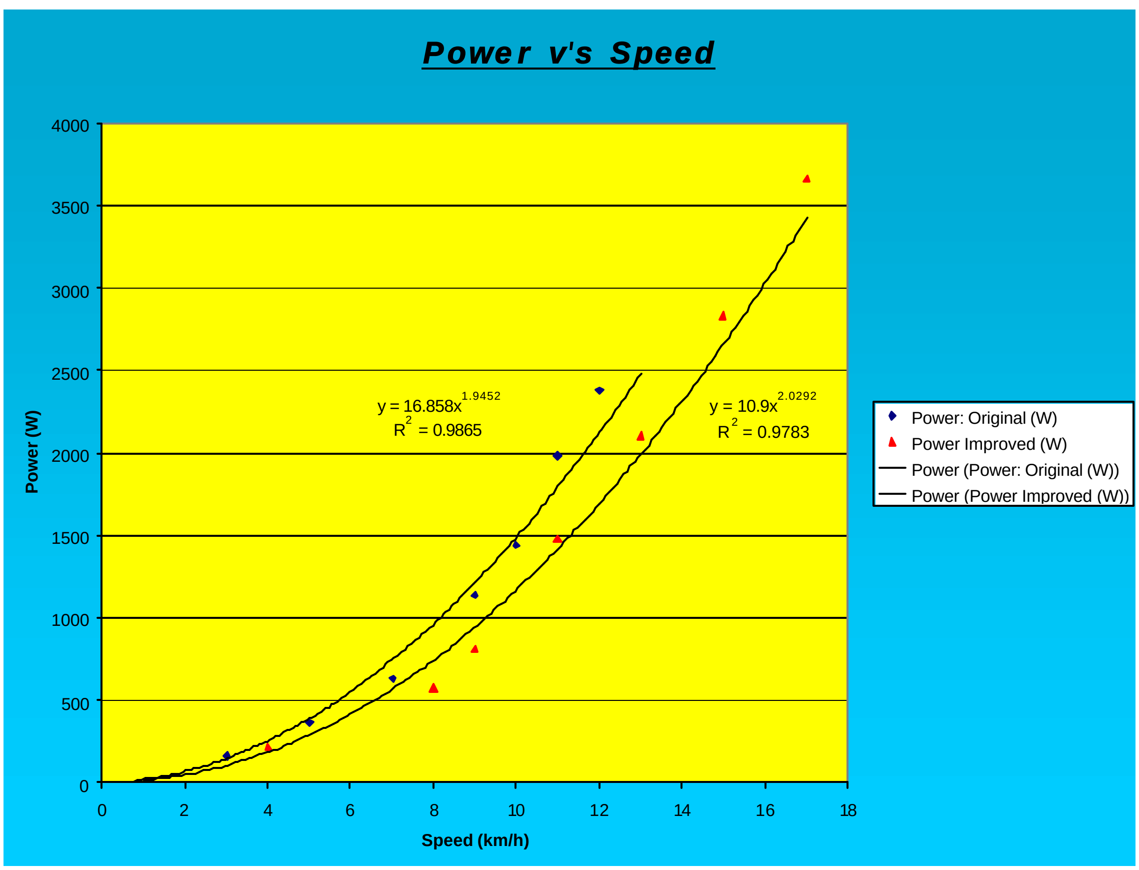
Speedometer reading (km/h)	Power: Original (W)	Speedo (km/h)	Power Improved (W)
3	161	4	215
5	360	8	576
7	628	9	808
9	1132	11	1481
10	1435	13	2103
11	1980	15	2833
12	2379	17	3663

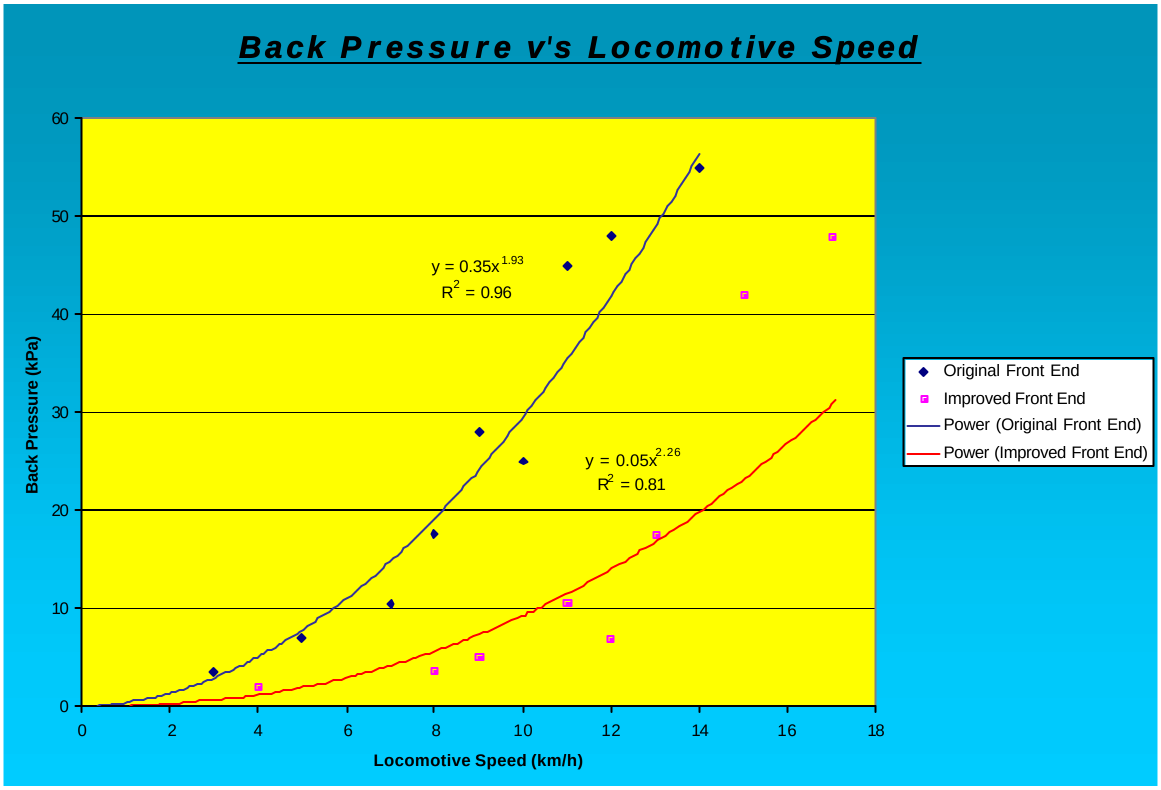
Original nozzle efficiency rate, Pa/kPa	efficiency rate, Pa/kPa	Increase in specific efficiency
Area: $78 mm^2$	Area: $113.1 mm^2$	Area increase: 45%
28.02857143	49.05	
26.62714286	36.43714286	
26.16	37.278	
25.22571429	30.83142857	
21.02142857	28.02857143	
27.468	28.02857143	
20.71	21.02142857	
21.459375	20.4375	
20.51181818		
24.13	**31.39**	**30.06%**

Steam flow calculations

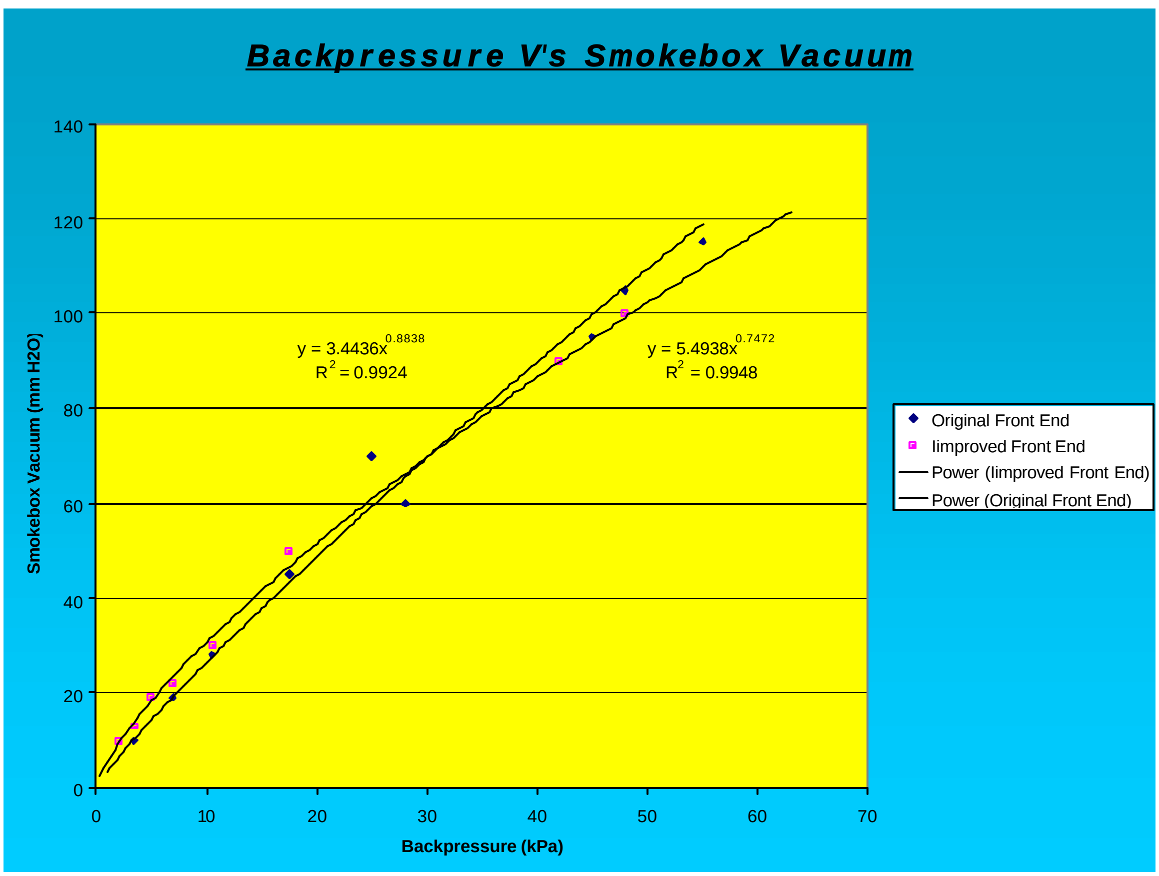
Speed km/h	Improved front end: Mass flow for engine @80% cutoff in kg/s	Improved front end: Steam Chest Pressure kPa Absolute	Improved front end: Density of steam, in kg/l	Original engine: Mass flow for engine @80% cutoff in kg/s	Original engine: Steam Chest Pressure kPa Absolute	Original engine: Density of steam, in kg/l
1						
2						
3				0.001443572	204.3	0.001152074
4	0.001924763	204.3	0.001152074			
5				0.002791935	239.3	0.001336898
6						
7				0.004423169	273.3	0.001512859
8	0.004467096	239.3	0.001336898	0.005659533	308.3	0.001693767
9	0.005686931	273.3	0.001512859	0.00702497	342.3	0.00186881
10				0.008530913	376.3	0.002042484
11	0.008985739	369.3	0.001955799	0.011017766	446.3	0.002398082
12	0.008489299	308.3	0.001693767	0.012904434	481.3	0.002574665
13	0.012058085	411.3	0.002220742			
14				0.016024744	514.3	0.002740477
15	0.015561606	463.3	0.002483855			
16						
17	0.019458617	514.3	0.002740477			
18						
19						
20						
Average	**0.009579017**		**Average**	**0.007757893**		
Average per km/h	**0.000912287**		**Average per km/h**	**0.000912693**		


Steam Chest Pressure Against Smokebox Vacuum
y = 0.0033x^1.7582
R^2 = 0.983
y = 0.0027x^1.7238
R^2 = 0.9529
Smokebox Vacuum (mm H2O)
Steam Chest Pressure (kPa)
0
20
40
60
80
100
120
140
0
50
100
150
200
250
300
350
400
450
Original Front end
Modified Front End
Power (Modified Front End)
Power (Original Front end)

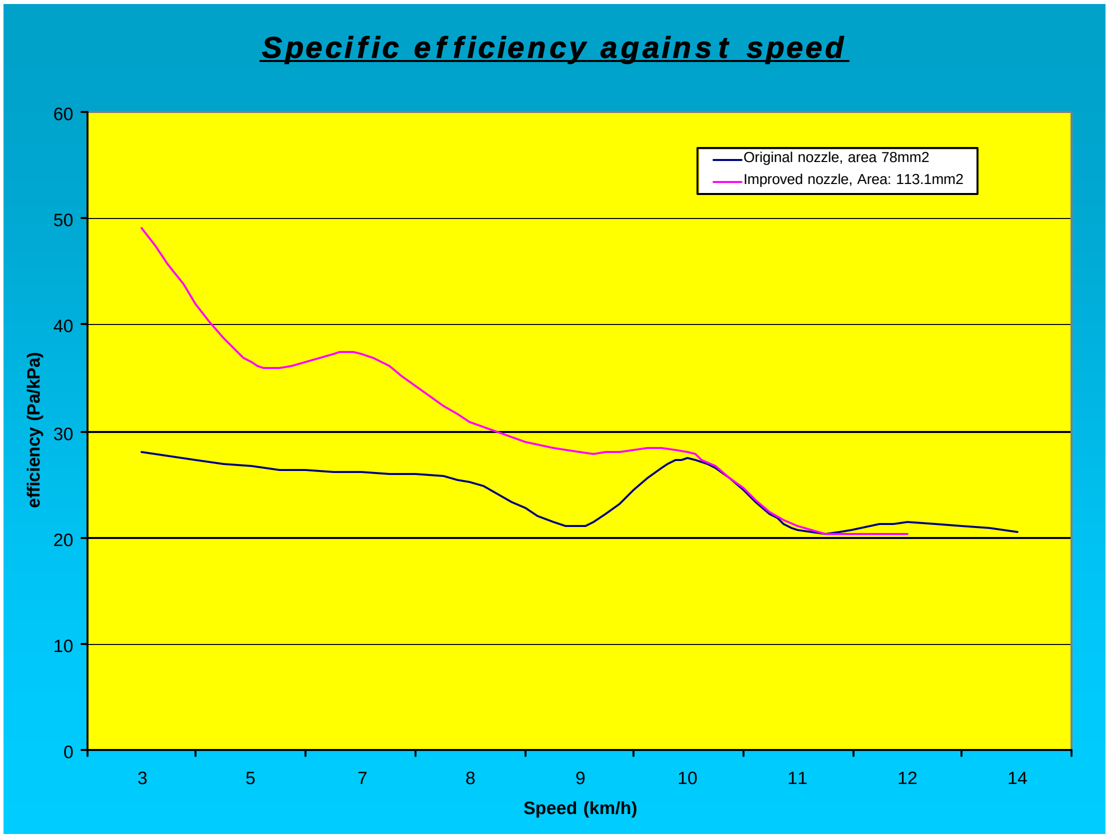

Power v's Speed
y = 16.858x^1.9452
R^2 = 0.9865
y = 10.9x^2.0292
R^2 = 0.9783
Power (W)
Speed (km/h)
0
500
1000
1500
2000
2500
3000
3500
4000
0
2
4
6
8
10
12
14
16
18
Power: Original (W)
Power Improved (W)
Power (Power: Original (W))
Power (Power Improved (W))

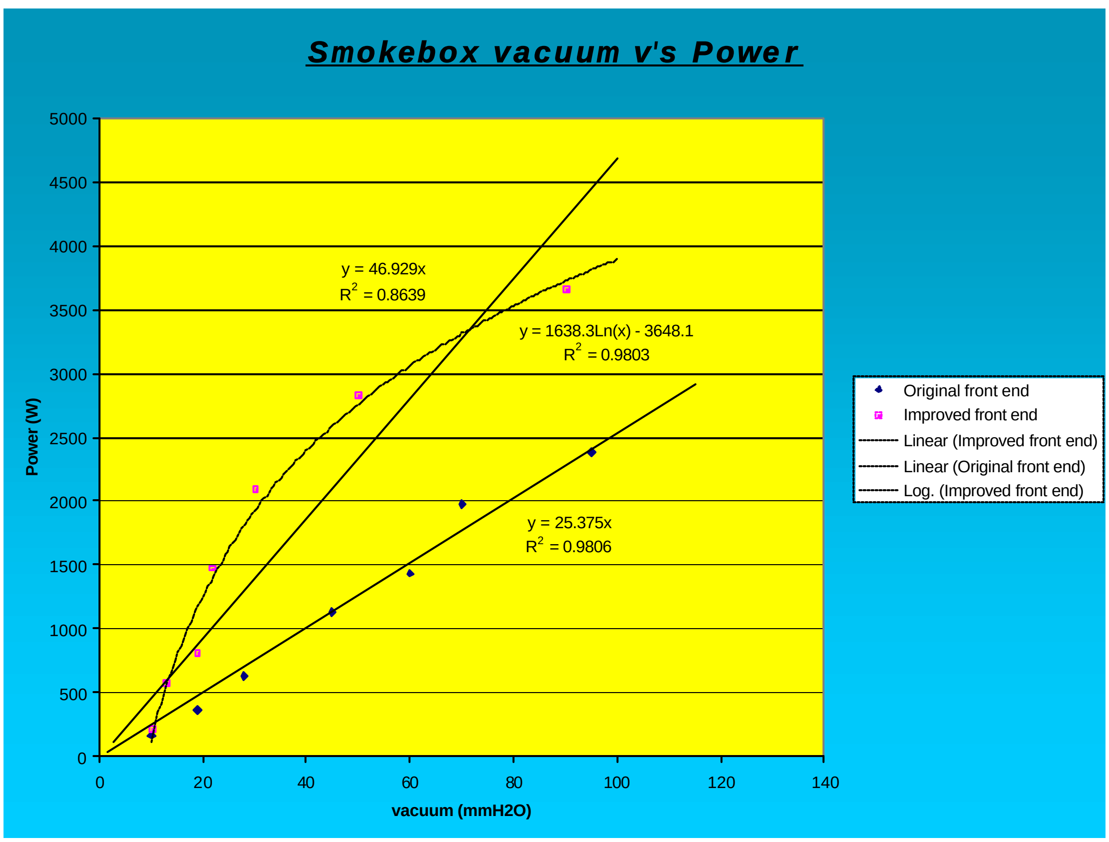


Back Pressure v's Locomotive Speed
Back Pressure (kPa)
Locomotive Speed (km/h)
0
10
20
30
40
50
60
0
2
4
6
8
10
12
14
16
18
y = 0.35x^1.93
R^2 = 0.96
y = 0.05x^2.26
R^2 = 0.81
Original Front End
Improved Front End
Power (Original Front End)
Power (Improved Front End)

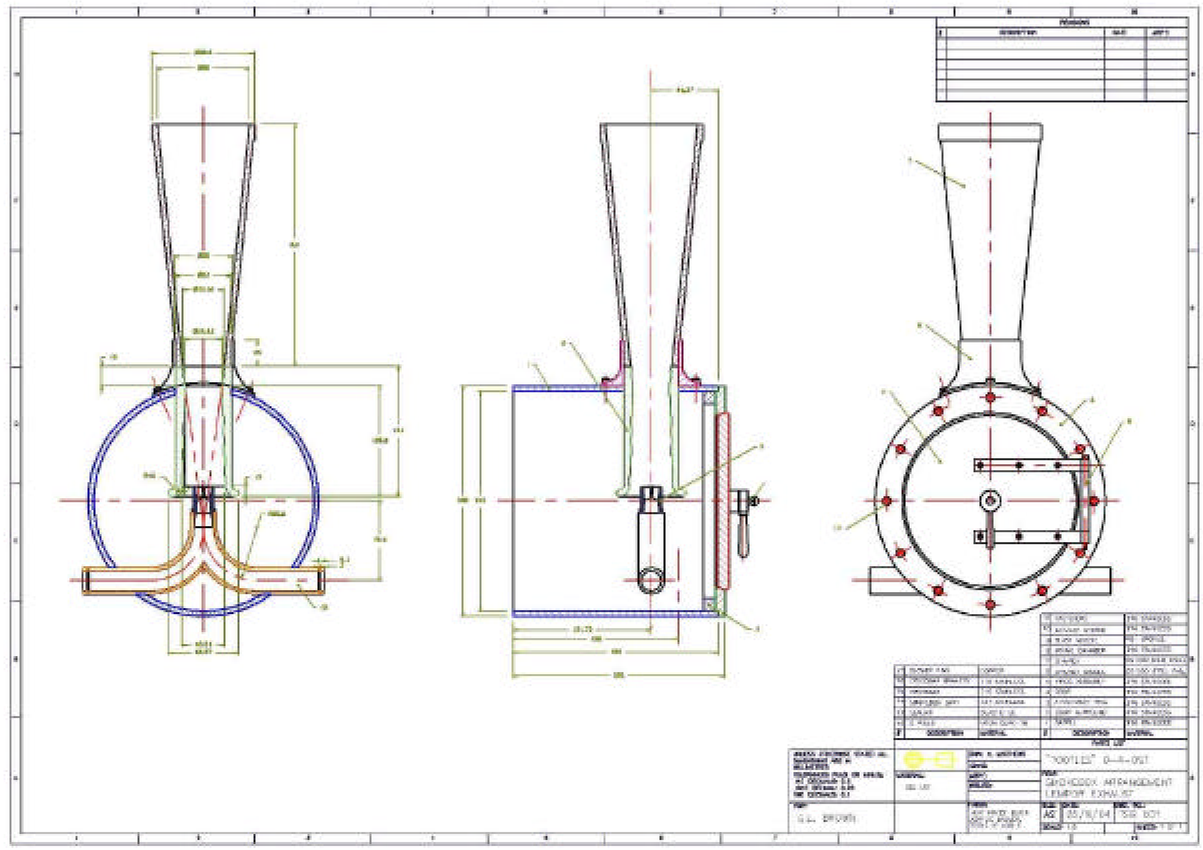


Backpressure V's Smokebox Vacuum
Smokebox Vacuum (mm H2O)
Backpressure (kPa)
0
20
40
60
80
100
120
140
0
10
20
30
40
50
60
70
y = 3.4436x^0.8838
R^2 = 0.9924
y = 5.4938x^0.7472
R^2 = 0.9948
Original Front End
Iimproved Front End
Power (Iimproved Front End)
Power (Original Front End)


Specific efficiency against speed
Original nozzle, area 78mm2
Improved nozzle, Area: 113.1mm2
efficiency (Pa/kPa)
60
50
40
30
20
10
0
3
5
7
8
9
10
11
12
14
Speed (km/h)


Smokebox vacuum v's Power
y = 46.929x
R2 = 0.8639
y = 1638.3Ln(x) - 3648.1
R2 = 0.9803
y = 25.375x
R2 = 0.9806
Original front end
Improved front end
Linear (Improved front end)
Linear (Original front end)
Log. (Improved front end)
Power (W)
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
0
20
40
60
80
100
120
140
vacuum (mmH2O)

APPENDIX 2: SMOKEBOX DESIGN



The plan above shows the smokebox design and the the materials list for the components. The smokebox was bolted together due to not having easy access to TIG welding equipment.