PROPOSAL

LIGHT STEAM POWER SYSTEM

PREPARED FOR PRESENTATION TO JANICKI INDUSTRIES FOR CONSIDERATION IN FULFILLMENT OF GATES FOUNDATION GRANT

May 15, 2012
Kenneth Helmick

INTRODUCTION

Steam enthusiasts tend to have pet projects, cherished ideas and strong opinions, often not compromising or working well with others and striving to prove ideas long after prudence dictates change (see the entire career of Abner Doble). This enthusiasm has created a longstanding cycle of overly optimistic claims followed by inevitable disappointment; perhaps grounded in the belief that a successful demonstration justifies all. “Once you get something running, anyone can take over and get it into production.” Experience indicates the opposite; sufficient complexity can achieve results, after a fashion, refining those results into a simple, elegant, reliable, economical and buildable form is often the greater challenge. Fixing the ideas of simplicity and practicality firmly in mind at the project outset improves the likelihood of eventual success.

Universal simple solutions or spectacular results are suspect; often best practice is tailored to the application and ideal theoretical answers may be less practical. I cheerfully admit having pet projects and ideas but refrain from presenting them, as much as I would like to. Advocating untried solutions, when I feel the allotted time is too short for more than direct and abbreviated development, would be unprofessional.

Light steam engines have a long history but, I submit, are not a mature technology because development slowed to a crawl around a century ago with the advent of gasoline and diesel engines; little from that era classifies as “modern”. I understand a system must be presented in about 2 ½ years, a very short period for even automotive manufacturers to develop an engine from “the ground up”. Engine manufacturers possesses dedicated equipment, trained specialists, enjoy existing vendor support and institutional experience; lacking this full range of resources, a different approach to tackling the problem is necessary. Fortunately, products similar to our needs are readily available for modification; it may be possible to collapse the work load to a manageable level by “borrowing” off-the-shelf hardware and **limiting development to only the most critical ‘steam-specific items’**. Even borrowing liberally, a successful outcome depends on disciplined project planning, management and scheduling. The dearth of successful light steam product launches suggests a historical lack of strong planning, discipline and focus; by vigorously adopting project management tools (such as PERT charts) the needed discipline can be imposed. “Modern steam” programs often seem dedicated to proving personal theories rather than producing a marketable product; forging ahead on a fixed course regardless of time or cost until running out of one or both. The successful program will exercise strong discipline and adherence to the critical development path but will also allow a degree of flexibility and encompass “Plan B’s” to ensure ongoing progress rather than stagnation when advancement stalls.

More than efficient manufacture is needed; at some point the customer takes possession and this transfer must be planned to promote a happy outcome. To this end extensive testing is necessary to:

- Verify performance or provide the necessary data to correct deficiencies
- Verify reliability or provide necessary data to make corrections
- Aid in establishing warranty policies
- Aid in determining what portion of revenues must be set aside to fund warranty repairs
- Establish correct operating procedures
- Establish effective and simple maintenance routines

Ease of operation and maintenance after the sale are critical to ensuring customer satisfaction; representative test subjects working with the hardware during the test phases may be needed to develop tools and materials suitable to the target customer.

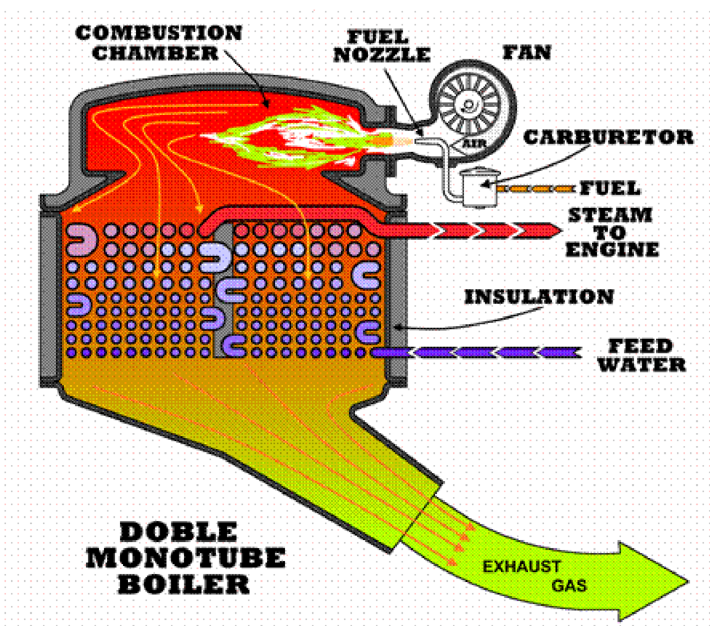
SYSTEM

My initial understanding was that program contemplated converting a diesel engine into a compound steam engine of about 75 horsepower which would turn an electrical generator. The furnace was to be fired by solid fuel, combusted in a fluidized bed. Process waste steam derived from the engine was to provide heat for some unspecified drying or distillation apparatus and the entire system was to be fitted on a trailer. Since that time the information has changed slightly, the output has increased to 100 horsepower and a triple expansion compound with inter-stage reheat is projected to be built up from two joined diesel engines. The following proposal reflects the original goal of 75 horsepower as the changes needed for greater output are immaterial to the discussion.

Steam Generator

The steam generator will be one the two major technical challenges in the system, the other being the steam expander (engine). The fire tube boiler is inadvisable for any number of reasons such as slow startup, the need for a heavy pressure vessel and incompatibility with the proposed fluidized bed combustion system. It is mentioned merely to acknowledge that the alternative exists and to rapidly dismiss it.

Water tube boilers can be divided into a number of categories; once-through versus recirculation being a good starting point. Once-through boilers admit water in one end and emit steam at the other, the flow being a straight line. The monotube is a once-through boiler with only a single flow path; other once-through boilers may have multiple parallel paths. Recirculation boilers contain a larger weight of steam and water; the fluid travels a loop with water being added, then heat applied and some steam produced, the steam is then extracted and the remaining water shuttles back to the beginning of the loop for another pass.



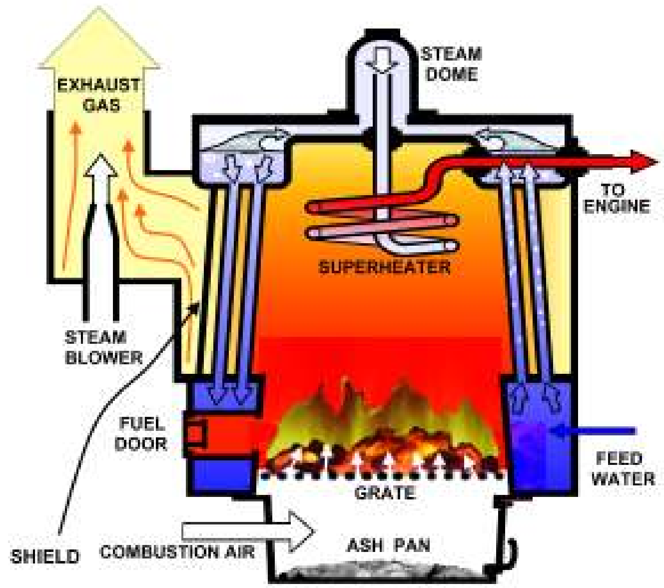
Recirculating boilers have some advantages over once-through designs such as monotubes.

- Greater water weight and flow velocity permit higher safe firing rates.
- Submerged steam generator surfaces make control is simple; steam pressure regulates burner firing rates while the water level regulates the water feed rate.
- Saturated circulating water readily turns to steam when pressure falls, dampening pressure fluctuations.
- Non-volatile contaminants generally remain in solution throughout the circulating loop rather than depositing on the superheater. The risk of tube burnout, corrosion and scale damage to the engine are

lessened. Occasional top and bottom blow-downs along with occasional chemical treatments remove contaminants.

Recirculation comes in two flavors, natural and forced. Natural circulation occurs because a volume of cold water is heavier than a similar volume of mixed hot water and steam; the cold water will sink, displacing the hot water and steam upwards. Forced circulation boilers use a pump to move the working fluid.

Natural recirculation becomes more rapid as the boiler becomes taller, the weight difference between hot and cold columns increases with height, accelerating circulation. Natural circulation boilers must orient the flow paths generally upwards and, due to friction losses, work better when bends and turns are kept to a minimum.



NATURAL CIRCULATION BOILER (THORNYCROFT)

Forced flow boilers, such as once-through or forced recirculation, are usually wound into coils but readily utilize straight lengths and hairpin bends. Orientation is immaterial and need only conform to the boiler shell.

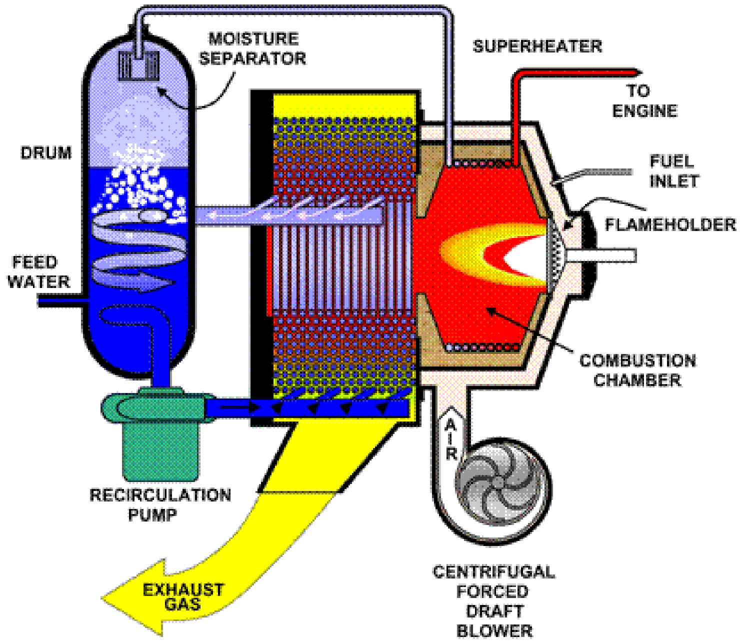
I recommend against once-through boilers, such as monotubes because, regulation of such boilers is difficult and depends on well calibrated controls, making them less suitable for use in the field. Natural circulation may prove less than ideal because boilers supplying a 75 or 100 horsepower engine are small and less likely to circulate strongly.

Forced recirculation is recommended. Positive circulation permits greater steam output and added burnout protection while the development experience is transferrable to future higher performance steam systems.

At some point, steam and water must be separated, steam being directed to the engine and water returning to the generator tubes. This separation occurs in a drum, or in drumless boilers, through the agency of specialized separators. Drumless boilers are smaller, lighter and cheaper but more difficult to control properly and lacking in reserve. The drum presents the more straight-forward option and is recommended for the following reasons:

- The pipes to and from the steam generator tubes and recirculation pump should be tangential to the drum walls so as to produce a spinning action in the steam/water mix. Centrifugal force produced by spinning improves steam and water separation; and reduces water carryover into the superheater, minimizing thermal shock and deposition of harmful deposits on the superheater wall.
- The recirculation pump suction pipe can be positioned in the drum to act as a ram intake, reducing the energy spent to operate the pump.

- The weight of hot, pressurized working fluid in the drum serves as a buffer against fluctuations in burner heat output and power demand, assuring more stable operation.



FORCED RECIRCULATION BOILER (VAPOR CORP)

Superheaters

Elements heated by convection become hotter with increases in firing rate while those heated by radiation become cooler, by combining proper proportions of radiation and convection heated elements we can produce a superheater with better inherent temperature stability. Such units are called 'uncontrolled superheaters' to distinguish them from those with thermostatic regulation. Presumably, fluidized beds provide primarily convective superheat, causing temperatures to rise with firing rate increases.

Increased superheat temperature is desirable to promote higher efficiency but steam temperatures may potentially rise to damaging levels. Active superheat control of superheat is desirable because it permits use of higher and more efficient temperatures without swings that exceed safe limits. Three methods of control are:

- **Controlled superheat furnaces** are primarily dedicated to superheating steam and the firing rate is thermostatically controlled by the outlet temperature.
- '**Normalizers' or 'attemperators'** inject cooling water midway into the superheater path under control of a thermostat positioned at the superheater outlet. Like the de-superheater that follows, the normalizer requires a superheater that is a bit over-sized and prone to overheating, permitting temperature control by regulating the amount of cooling supplied.
- **Surface contact de-superheaters** control temperature like a car thermostat. A sensor at the superheater outlet directs a valve to split the fluid flow into two paths, directing one path to a cooling heat exchanger in the drum. Recombining the paths produces a cooler mix which passing through the remaining superheater emerges at the correct temperature. Positive feedback occurs because transferring heat to the drum vaporizes a portion of the saturated water therein, raising the pressure and causing the controls to reduce the firing rate which in turn tends to reduce the superheat.

Choosing between these options one must note that controlling superheat temperature by throttling a furnace has proven difficult, superheated steam has no moisture content and lacks the moderating effect of latent heat, making rapid temperature swings more common. Adding water into the steam is a very effective, undoubtedly why Doble adopted the normalizer. Being so effective, the flow of cooling water is necessarily small and must be carefully regulated through a small tube or orifice. Normalizers are light and compact, but precise operation is important and clogging of the small orifice will disrupt correct functioning. Other potential problems include risk of the coolant creating thermal shock in hot piping and the sudden cooling causing contaminants to suddenly drop out of suspension and form harmful deposits on the superheater wall.

The surface de-superheater cooling process is less effective than the normalizer because steam is a poor thermal conductor and a relatively large flow through the desuperheater is needed to produce the same temperature change. This isn't necessarily bad; the equipment can be less precise and delicate while still providing close temperature regulation. While larger and heavier than the normalizer, it is also robust and reliable. Given the service this system is meant to see, the surface de-superheater is probably a better choice.

Currently Projected Expander

As I understand it, the current contemplated design comprises a three stage compound engine composed of two 4 cylinder diesel engines connected to run in series operation with one piston in the first engine being the High Pressure stage, the following three pistons being the Medium Pressure and the second engine in its entirety comprising the Low Pressure. Admission steam pressures of 2000 psi and very low RPM operation on the order of 500 rpm is required to achieve efficient expansion while limiting output to about 100 HP.

This configuration contemplates an HP stage utilizing admission steam pressures on the order of 2,000 PSIA to achieve high efficiencies.

I have a number of reservations about achieving the level of efficiency expected:

- Steam "blow-by" past piston rings is a function of Mean Effective Pressure (MEP) and duration of steam playing against the rings (residence). The Dutcher Industries compound expander used similar pressures and despite attempts to control loss consistently reported HP stage blow-by on the order of ten percent; this poses a serious practical limit to efficiency and significant lubrication challenge.
- Using two diesel engines to achieve three expansion stages involves more mechanism than is traditional; the result should be a minimum of twice the typical friction losses.
- The large number of cylinders creates unfavorable surface area-to-volume ratios; heat loss through the cylinder walls appears to be on the order of 2.5 times greater than purpose built engines.
- Both the engine block and cylinder head may require cooling to control expansion and protect lubricants, the large surface areas present greater potential for cooling losses.
- Transferring steam between stages takes energy. Assuming 20 milliseconds to fill the cylinder at 500 rpm, steam velocities from 50-100 feet per second are probably reasonable, attaining this velocity requires diverting steam energy from other purposes. Single acting engines only suffer this loss once.
- Given that the boiler is less than 100% efficient, inter-stage reheating is also less than 100% efficient. We can expect losses to compound, offsetting some of the expected benefits.
- Piping between the expander and reheater increase the potential for radiative and convective losses.

Admittedly, not all of these losses are large, but the effects are cumulative. The proposed compound design leads to some other concerns:

- A 4 cylinder, 4 stroke engine divided into 1 HP and 3 Medium Pressure (MP) cylinders will produce torque very unevenly; leading to greater cyclical fatigue than the crankshaft manufacture contemplated when setting the maximum torque specifications and possibly leading to premature failure.
- Diesel engines use steel shell bearings coated with anti-friction metals and forced oil lubrication. Crankshaft rotation forms the oil into a supporting wedge upon which the shaft floats and the strength

of the wedge depends upon the shaft speed. Operating at the envisioned 500 rpm may place the engine at severe risk of "lugging" and premature bearing failure.

- Commercial electric generators of the projected output typically operate at higher speeds than 500 rpm, mandating the use of a speed increaser which adds size, weight and cost to the unit while at the same time increasing friction and lowering overall efficiency.
- Mating two expanders directly is difficult, extremely tight tolerances are needed to achieve correct alignment. Flexible couplings are simpler but increase the overall size as the mated units must be spaced out; couplings requires periodic inspection and maintenance, presents an increased likelihood of failure and add extra friction to the system.
- The LP stage requires a second donor engine of larger displacement, greatly raising overall size, weight, cost and complexity.
- Compound design really demands adjustable valve cutoff on each stage. The larger LP engine will require an entirely different cylinder head and valve assembly, while the variable cutoff adds more components. All the added hardware raises cost, complexity and increases likelihood of component failure.
- Lubricating oil carried between stages may decompose in the resuperheaters, forming insulating carbon deposits that can cause superheater failure or break loose and damage the following valves or cylinders.

Proposed Expander

My initial conversation led me to believe the project is facing a fairly tight time-line of about 2 ½ years, which led to the notion of converting existing diesel engines in the interest of expediency. I concur with this assessment; development "from the ground up" of a fully tested, industrial grade system suitable for mass production is not likely in this amount of time with the resources at hand.

I firmly believe a successful power plant must be very simple and durable, two approaches stand out:

1. Convert Detroit Diesel 2 stroke engines to uniflow operation. These were produced for a number of years and in four different numbered series: 53, 71, 92 and 149. They can be obtained as remanufactured Detroit Diesel models while some variants are still available as newly built units for military applications by MTU Detroit Diesel, Inc.
2. Purchase complete diesel gen sets, possibly marine units, and remanufacture critical components to convert them into steam power plants.

The Detroit Diesel option promises greater theoretical efficiency because the uniflow expander obviates passing cool exhaust through the cylinder head, which in turn cools incoming steam. The two stroke crankshaft layout produces very smooth torque when operated under steam. To the best of my knowledge, these engines employ pushrod operated valves actuated by a single camshaft and, in some models, contain a balance shaft; with some effort this balance shaft provides the opportunity to serve as a second cam, permitting separate and controllable admission and exhaust events. The marine gen set option has the advantage of purchasing an entire power plant with the engine and electrical elements being fully integrated and proven; minimizing risk and effort. Both approaches have much to commend them and the choice might come down to factors other than pure suitability as an engine. I settled on the marine gen set option because the engine, generator, frame and supporting hardware come as a tested and packaged unit; simplifying overall development. The uniflow engine itself may be a bit easier to convert to steam, so the choice really comes down to which option promises the more rapid, certain and economical outcome. While uniflow engines are typically more efficient, counterflow engines using separate exhaust and admission valves narrow the gap greatly by not pre-cooling the steam admission passage. Such counterflow engines can significantly delay the onset of compression while still achieving full recompression, and do so with less clearance volume than many uniflow designs, which increases the power output per cylinder and further negates some of the uniflow efficiency advantage.

Let me reiterate that although I chose the counterflow design based on the availability of existing donor gen sets, I am not critical of converting the “Jimmy” Detroit Diesel into a uniflow steam engine. In any case, the engine parameters for either uniflow or counterflow diesel to steam conversions are relatively similar and the following is generally applicable for either decision.

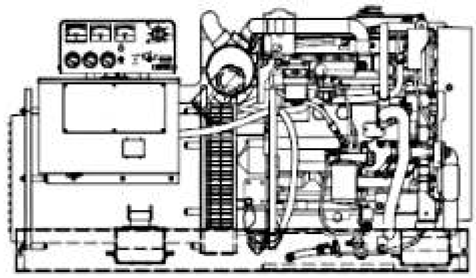
My initial conversation with you in March revealed a need for output of about 75 horsepower, a short internet search identified a packaged diesel gen set meeting this basic parameter; the Kohler Power Systems 55EFOZ (50 Hz) Marine Generator Set which is powered by the John Deere 4045TFM Marine Engine. (Note: A similar V-8 powered gen set built by the same manufacturer is available for inspection at Tom Kimmel’s nursery.) I did not intend this as a specific product recommendation, other products might be considered more suitable for technical or economic reasons which we have not had time to examine; it does seem to serve as a representative sample of commercial offerings, however. A more recent conversation suggests a desired engine output of perhaps 100 horsepower; this can be accommodated by similar 6 cylinder models of the same engine family and points out that the basic features of such steam systems should be readily scaled within certain power ranges.

Model: 65EOZ (60 Hz)
55EFOZ (50 Hz)

KOHLER POWER SYSTEMS

3-Phase Diesel

ISO 9001 CE



Marine Generator Set

Generator Features

- Remote control connector
- Class H insulation
- Reconnectable voltage
- 60/50 Hz field adjustable generator set
- One- or three-phase reconnectable alternator
- Voltage regulation of ±2%
- Frequency regulation of ±5%

Optional Accessories

- Sound shield
- Power takeoff (PTO)
- Electronic governor
- Paralleling governor
- Circuit breakers

Application Data

Engine

Engine Specifications	60 Hz	50 Hz
Manufacturer	John Deere	
Model	4045TFM	
Type	Inline, 4-cycle	
Number of cylinders	4	
Firing order	1-3-4-2	
Aspiration	Turbocharged	
Displacement, L (cu. in.)	4.5 (276)	
Bore and stroke, mm (in.)	106 x 127 (4.19 x 5.00)	
Compression ratio	17.0:1	
Combustion system	Direct injection	
Rated rpm	1800	1500
Maximum power at rated rpm, HP	95	76
Cylinder block material	Cast iron	
Cylinder head material	Cast iron	
Piston rings	2 compression/1 oil	
Crankshaft material	Forged steel	
Connecting rod material	Forged steel	

Lubrication

Lubricating System	60 Hz	50 Hz
Oil pan capacity with filter, L (U.S. qt.)	14.0 (14.8)	
Type	Pressure	

Operation Requirements

Air Requirements	60 Hz	50 Hz
Engine combustion air requirements, L/min. (cfm)	4502 (159)	3738 (132)
Cooling air required for generator set at 14°C (25°F) rise, m³/min. (cfm)	N/A	N/A
Exhaust gas flow, m³/min. (cfm)	14.2 (502)	11.9 (419)

Fuel Consumption	60 Hz	50 Hz
Diesel, Lph (gph) at % load		
100%	17.4 (4.6)	14.4 (3.8)
75%	13.2 (3.5)	10.6 (2.8)
50%	9.8 (2.6)	7.6 (2.0)
25%	5.7 (1.5)	4.2 (1.1)

Light steam power plant temperatures of 1000 to 1200 degrees F have been long proposed as a way to attain thermal efficiencies competitive with internal combustion. Unfortunately, use of such temperatures has led to engine failures from lubricant breakdown and metallurgical challenges in the boiler. A thorough program of performance and reliability testing will readily consume a minimum of 6 months, and possibly over a year, leaving 1 to 1 1/2 years actual development time. This constraint, and the requirement to operate in remote areas with minimal technical support, suggests initial steam temperatures of no more than 850 F with changes being based on test results. Previous steam systems have proven reliable at this temperature and efficiency should be "good enough" for our purposes. Development of "new and improved" models operating at higher conditions could be examined when the initial program has been completed.

Some years back, I wrote an Excel spreadsheet using IAPWS-97 add-ins to estimate expander behavior assuming isentropic steam properties. Using the John Deere bore, stroke and rpm I juggled variables to calculate an output of about 75 horsepower while assuming losses of about 70%. Starting with 1000 psi as a working pressure the resulting calculations revealed a solution having a clearance volume of about 2% and cutoff of about 3.6% with recompression to near the admission pressure in order to improve efficiency. Yielding the desired power, a nice calculated water rate around 10 lbs. per horsepower-hour was had. However, the T-V diagram indicates the expansion curve intercepts the saturation line around 40% of full stroke, leading me to believe it is probably unrealistic to expect this level of performance and efficiency.

STEAM ENGINE PERFORMANCE CALCULATOR

ASSUMES OVERCOMPRESSION RELIEVES TO STEAM CHEST

DATA ENTRY BLOCK

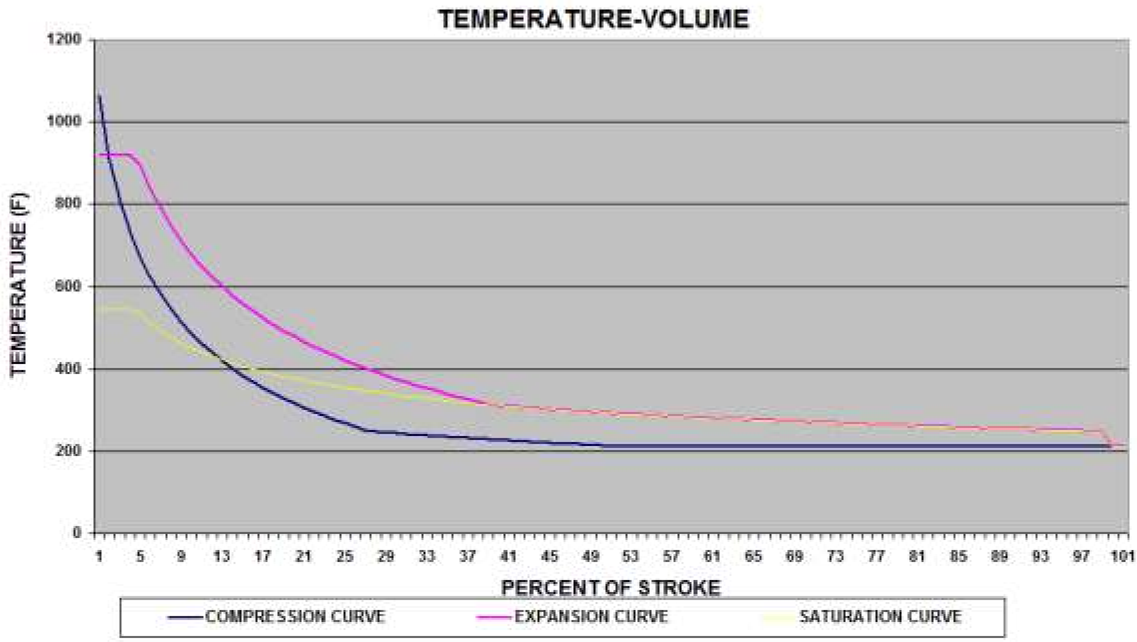
Steam Pressure (psia)	Steam Temp (F)	Exhaust	Jimmy factor
1,000	850.00	15.000	70.000
305.35 F superheat		30.54" Hg	
Bore (ins)	Stroke (ins)	Cylinders (#)	RPM
4.190	5.000	4	1500
Clearance (% of stroke)	Cutoff (% of stroke)	Release (% of stroke)	Cmprssn start (% of stroke)
2.175	3.600	98.000	50.000

Note: Check TV graph, expansion curve in saturation region.

MECHANICAL DATA			
Horsepower	76.55	Total MEP (PSI)	104.69
Expansion MEP:	151.06	Compression MEP:	46.37
Water Rate (lbs/hp-hr)	10.06	Efficiency (%)	17.82
Max piston thrust (lbs)	13,788.53	Average Torque (ft-lbs)	268.03
Water used (lbs/hr)	770.21		

EXPANSION DATA			
Expansion ratio	17.35 : 1	Release PSI	28.71
Release Temp (F)	247.79	Exhaust Temp (F)	212.99
Nominal Cutoff (%)	3.67	Stm Used (lbs/hr)	770.21

COMPRESSION DATA	
Compression ratio: 23.98	Nominal clearance (%) 2.22
Mixing temperature: 919.7	Yields superheat of: 375
Compression temp: 1063.7	Yields superheat of: 540.6
No overcompression	
Inches Admiss press reached: 0.0145	after TDC
Steam wt recycled (%): 38.47	
Peak pressure (psia): 833.849181	



Reselecting for 400 psi and a doing a bit of juggling, the computer produced an engine that delivers about the same power with 2.0% clearance and about 11.5% cutoff. The water rate is a “good enough” 11.65 pounds per horsepower-hour, similar to Doble Series E compound engines. The steam temperature at release is just approaching the saturation line, so over-expansion does not seem to be a problem. The cutoff is still short enough to be challenging but not to the level of the 1000 psi engine. These parameters seem to make a decent starting point from which to develop an engine, an ongoing test program would include fine tuning the details.

STEAM ENGINE PERFORMANCE CALCULATOR

ASSUMES OVERCOMPRESSION RELIEVES TO STEAM CHEST

DATA ENTRY BLOCK

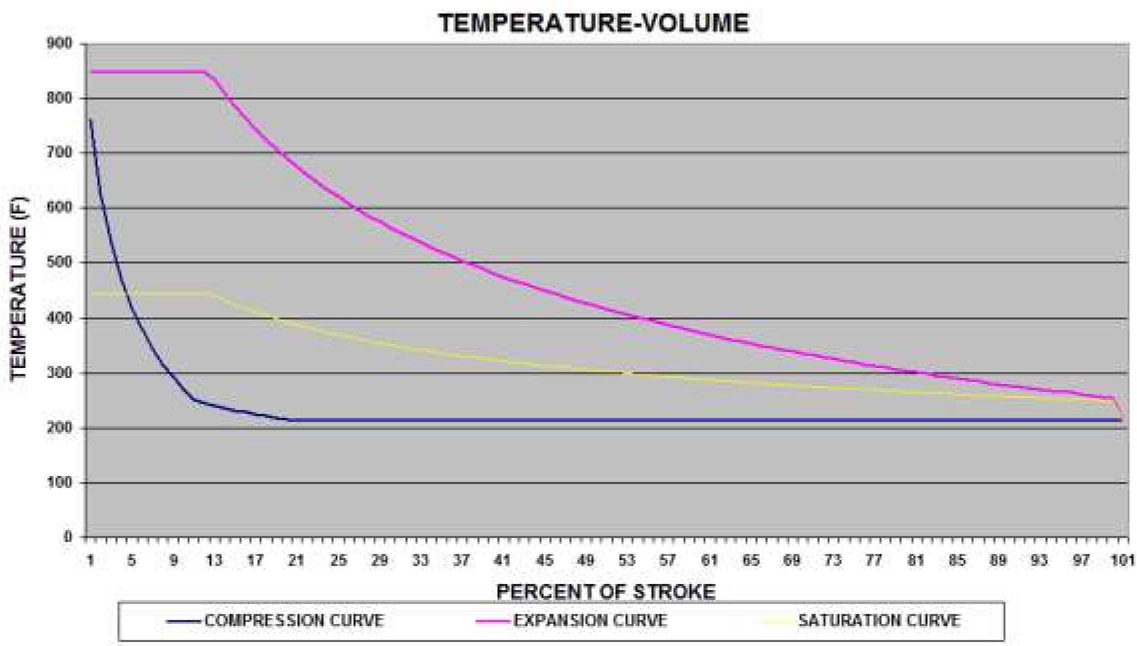
Steam Pressure (psia)	Steam Temp (F)	Exhaust	Jimmy factor
400	850.00	15.000	70.000
405.37 F superheat		30.54" Hg	
Bore (ins)	**Stroke (ins)**	**Cylinders (#)**	**RPM**
4.190	5.000	4	1500
Clearance (% of stroke)	**Cutoff (% of stroke)**	**Release (% of stroke)**	**Cmprssn start (% of stroke)**
2.000	11.500	99.000	20.000

MECHANICAL DATA			
Horsepower	77.11	Total MEP (PSI)	105.45
Expansion MEP:	128.45	Compression MEP:	23.00
Water Rate (lbs/hp-hr)	11.65	Efficiency (%)	15.13
Max piston thrust (lbs)	5,515.41	Average Torque (ft-lbs)	269.97
Water used (lbs/hr)	898.37		

EXPANSION DATA			
Expansion ratio	7.48 : 1	Release PSI	29.37
Release Temp (F)	254.24	Exhaust Temp (F)	212.99
Nominal Cutoff (%)	11.62	Stm Used (lbs/hr)	898.37

COMPRESSION DATA			
Compression ratio: 11		Nominal clearance (%) 2.02	
Mixing temperature: 848.3		Yields superheat of: 403.7	
Compression temp: 762.1		Yields superheat of: 342.3	
No overcompression			
Inches Admiss press reached:		0.0184	after TDC
Steam wt recycled (%): 13.91			
Peak pressure (psia): 307.867657			

Note: TV curve generally superheated.



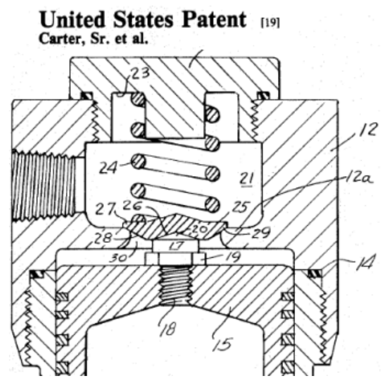
With a water rate of about 12 pounds/hp-hr., at 100 horsepower the water consumption would be 1200 pounds per hour; making allowances for performance degradation over time and auxiliary uses, a minimum steam generator capacity of 1500, and preferably 1800, pounds per hour would be needed to meet contingencies.

Suitable donor engines will probably be ‘cast enbloc’, the cylinders all comprising one casting; such designs also contemplate use of a single cast cylinder head. Thermal expansion of a long cylinder head can bow the engine block, leading to crankshaft and possibly even block failure. Internal combustion engines address this problem with cylinder and head cooling, a steam conversion may have to do likewise and may use the cooling jackets already provided with the donor engine. Selective use of internal insulation may reduce the amount of heat to be carried away, as would careful design of the head to minimize the surface area exposed to steam. An unexpected consequence is that the “uniflow advantage” may diminish; the cool counterflow exhaust cooling the head may reduce the need for applied cooling in comparison to uniflow.

The counterflow exhaust valve poses no particular difficulties; a stock diesel valve should be satisfactory, in both cases the cylinder pressure pushes the valve head against the seat, making for a tight seal until the valve is opened by applying downwards force on the valve stem. The steam admission valve poses a few more challenges, the steam pressure seeks to pop open a stock diesel valve rather than seal it shut. There are a few simple remedies for this situation:

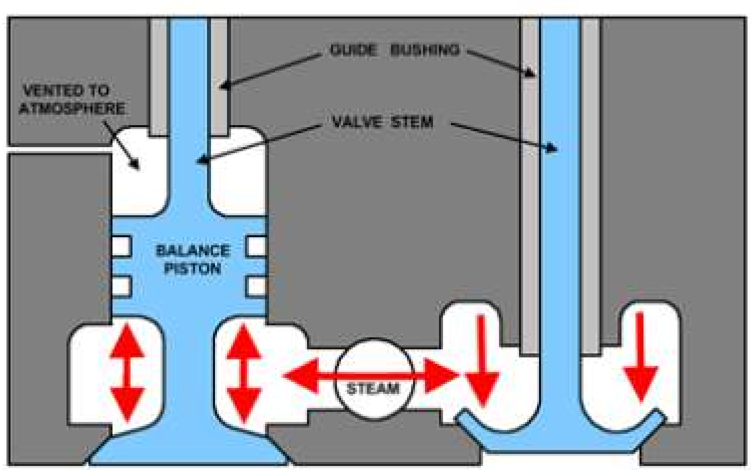
- Employ a bump valve with recompression to cancel the closing pressure.
- Use a very stout valve with an immense spring to withstand the pressure
- Add a counterbalance piston to the valve, causing the steam pressure to work in two directions and cancel out axial thrust
- Build a poppet valve that opens by lifting rather than depressing.

Bump valves are contact the cylinder head under spring pressure and lifted by a pin fitted directly to the piston top. The abrupt contact gives rise to the term "bump valve" although some detractors consider the term "bash valve" more descriptive. Bump valves potentially operate at very short cutoff operation and may be tuned to reach a 'sweet spot' around some fixed rpm, a nice trait for a generator. Jay Carter used them to advantage in his steam automobile of the 1970s and as a subject for development in future projects they show great promise. My concern is the relative lack of data regarding long term operational reliability. Constant failure of the valve due to the combination of high temperatures and continuous impact led Jay Carter to high strength, non-metallic valve disc materials and specially heat treated, super-alloy springs.



To the best of my knowledge, only the only engine to accumulate a large number of hours using bump valves was the White Cliffs solar steam, according to Graeme Vagg they had at least one valve failure although I am unsure under what conditions. While bump valves have their passionate advocates and present a promising subject for development, I am not convinced that, at this time, the bump valve is a certain enough proposition.

The second option requires extremely stout valve stems, springs, rocker arms and cams; in this scenario the operating forces are high and potential for wear is great. We can probably safely dismiss it as an acceptable option. The next two solutions appear more competitive and are illustrated as follows:



A valve with a balance piston is shown to the left, steam pressure applied through the central passage works equally on the bottom of the piston and top of the poppet valve, creating similar opposing forces when the space above the piston is vented to atmosphere and the cylinder is exhausted. As in most engines, the valve stem is lifted shut by a spring and depressed by the cam to open. Recompressing prior to admission presses the valve upwards and a strong force must be applied to the steam to cause it to open.

The valve to the right is simply forced shut against the seat when steam is supplied. Recompressing steam in the cylinder counteracts the pressure on the valve head and reduces the needed operating force.

The counterbalance piston design operates like the exhaust valve and simplifies design of the valve train; a similar valve was used by Dutcher. The lifting valve operates more easily, is more compact and being lighter is subjected to less acceleration forces, making for increased longevity. The lifting valve presents fewer challenges to suppliers of poppet valves. For all these reasons a lifting design poppet valve is recommended. Similar valves are found in the GM SE-101 steamer and the Art Gardiner PSL engine.

Unlike compound engines, the power output of both the uniflow and simple counterflow engine can be controlled by the simple expedient of throttling the admission steam pressure; in the counterflow engine this is accompanied by an efficiency penalty as the pressure is reduced.

STEAM ENGINE PERFORMANCE CALCULATOR

ASSUMES OVERCOMPRESSION RELIEVES TO STEAM CHEST

DATA ENTRY BLOCK

Steam Pressure (psia)	Steam Temp (F)	Exhaust	Jimmy factor
200	850.00	15.000	70.000
468.19 F superheat		30.54" Hg	
Bore (ins)	Stroke (ins)	Cylinders (#)	RPM
4.190	5.000	4	1500
Clearance (% of stroke)	Cutoff (% of stroke)	Release (% of stroke)	Cmprssn start (% of stroke)
2.000	11.500	99.000	15.000

MECHANICAL DATA

Horsepower	32.20	Total MEP (PSI)	44.03
Expansion MEP:	64.19	Compression MEP:	20.16
Water Rate (lbs/hp-hr)	13.33	Efficiency (%)	13.15
Max piston thrust (lbs)	2,757.71	Average Torque (ft-lbs)	112.73
Water used (lbs/hr)	429.19		

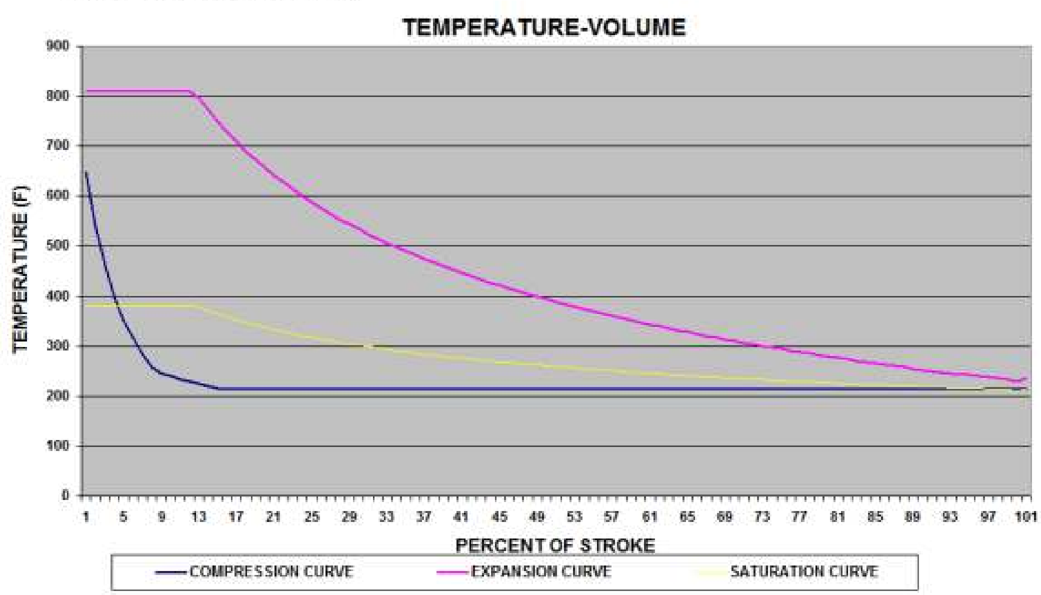
EXPANSION DATA

Expansion ratio	7.48 : 1	Release PSI	14.54
Release Temp (F)	229.49	Exhaust Temp (F)	212.99
Nominal Cutoff (%)	11.62	Stm Used (lbs/hr)	429.19

COMPRESSION DATA

Compression ratio: 8.5	Nominal clearance (%) 2.02
Mixing temperature: 809.9	Yields superheat of: 428.1
Compression temp: 648	Yields superheat of: 266.1
Overcompression Steam chest temp raised to: 846.4	
Inches Admiss press reached: 0.008 before TDC	
Steam wt recycled (%): 22.49	
Peak pressure (psia): 200	

Note: TV curve generally superheated.



Note that the recompression starts at 15% of stroke rather than 20% to prevent excessive recompression that might reduce efficiency; the solution appears reasonable as the expansion curve still generally avoids the saturation line. This is change in compression can be achieved by either shifting the cam to another profile or by advancing or retarding the exhaust cam timing through the use of an automotive camshaft phaser. Other options exist for dealing with over-compression ranging from auxiliary clearance volumes to check valves which vent over-compression to the steam chest.

If a single camshaft is employed, power modulation can be achieved solely through throttling and compression controlled by aux. exhaust or a check valve to vent the excess pressure either to the cylinder head although another, more advantageous, option may exist that I haven't examined thoroughly yet.

One misapprehension is that effective cutoff (the mass of steam admitted to the cylinder) is directly tied to the portion of the stroke during which the admission valve is open. We dismissed that, to some extent, by noting flow around TDC will be slight when recompression negates the differential pressure across the valve. The speed of valve movement is also important as we realize by acknowledging that the mass of admitted steam depends partly upon the passage size. Slowly opening and closing the admission valve increases the period when the valve passage chokes flow and effectively shortens cutoff. This choking can be accentuated with changes to the valve shape. The opening duration as well as speed is influential. Like all matter, steam has inertia and takes time to accelerate, as valve speed increases and the opening duration shortens we reach a point where the acceleration lag begins to interfere with steam passing through the valve. This steam acceleration is further complicated if we have recompressed the steam in the cylinder to around the admission pressure and no longer have sufficient differential pressure across the valve at TDC to promote steam flow. Testing may be necessary to determine a cam profile that is sufficiently gentle, provides the correct amount of lift and opening time while still admitting the optimum steam mass at the desired steam pressure and rpm.

Many traditional steam engines inject oil into the steam to lubricate both the valves and cylinder. Poppet valves have very little side loading and function well with a minimum of lubrication, usually a wiper is needed to remove the excess oil deposited on the valve stem by proximity to the rocker arms. However, steam cleaners are built to remove oily buildups, suggesting lubricants may function a bit differently than in an IC engine. Occasional tear downs during testing will reveal whether cylinder, piston, ring and valve wear is excessive; injecting additional oil at the admission valve stem may be necessary.

Piston ring "blow by" can lead to water in the crankcase, which demonstrably shortens bearing life; synthetic oils of high demulsibility, combined with appropriate methods of separation, will require attention and testing.

A simple means of bolting on efficiency would be to add a turbocharger to the steam engine exhaust manifold. The pressurized air produced from the expander steam exhaust can be used to feed the burner and efficiency will rise a bit as this load is no longer derived from the crankshaft.

Miscellaneous Hardware

Condenser

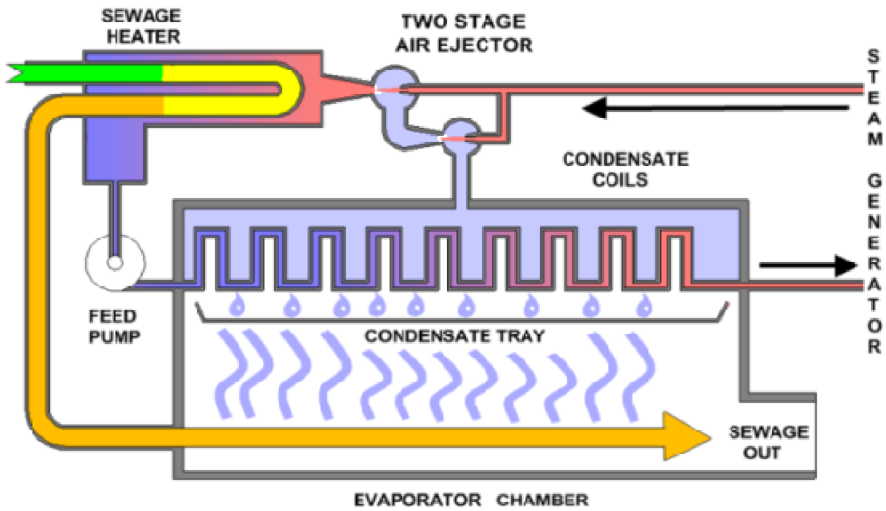
The feed water should be clean (distilled) and chemically treated, this is only economically feasible if the exhaust is condensed and reused.

Compressive condensation is rumored to be under consideration; an idea extensively patented and tested by Harry Percival Harvey Anderson and John McCollum in the 1920s and 30s. Compared to atmospheric condensing, the "Anderson System" reportedly improved system efficiency by about 29%. I would not expect comparable results because the Anderson-McCollum testing was done with locomotives which are less efficient than the engine I am proposing and so there is less scope for improvement.

The short development period cannot be overemphasized; extensive (and time consuming) durability testing is needed with allowances made to incorporate test data back into the design as needed; minimizing the number and complexity of elements to be developed dramatically improves the likelihood of successful on-time project completion. Despite strong theoretical advantages, compressive condensation has often been proposed but never adopted on any scale; such non-implementation hints that the technology has proven problematic. Since compressive condensing is not integral to operation of a successful generator set, I submit the development time and effort represents an unnecessary risk at this point. Experimentation with this technology would seem best suited for potential inclusion in later product generations, when the penalties for failure are not so high.

Expander exhaust pressures of about 50 PSIA have been suggested, the saturation temperature being used to dry sludge and sewage for use as fuel. This approach obviously limits overall engine expansion and reduces efficiency. Heat sources other than exhaust seem readily at hand including boiler flue gasses, hot exhaust gasses from the condenser and live steam. This last heat source bears close scrutiny as it is extensively used by shipboard distilling units to convert salt water into potable in some variant of the following process:

- Steam is fed to an air ejector (a form of jet pump), producing vacuum in the distilling chamber.
- Steam exiting the ejector heats sea water entering the chamber via a heat exchanger, in turn condensing the steam.
- The heated sea water flashes into steam at reduced temperature due to the vacuum.
- The condensed ejector steam is pumped through a heat exchanger on its way back to the boiler. The cool condensate is warmed by the flashed steam and in turn condenses the steam into water which collects in trays and is removed from the distilling unit. Such distillate may provide a good source of boiler makeup feed water after treatment.



The intertwined steam and water paths serve to minimize the energy expended to evaporate the water in a few different ways. Ejector produced vacuum reduces the evaporating heat requirement, this heat derived from the ejector itself. The condensed ejector discharge is reheated by the evaporated water, returning some of the heat lost in evaporating; the act of condensing causes pressure to drop in the chamber, reducing the amount of steam used by the ejector.

It seems preferable to develop a steam evaporator rather than use exhaust heat. This opens the door for vacuum condensing of engine exhaust, improving expander efficiency. Steam systems are very integrated, each component having some effect on the portion of the steam cycle preceding and following; care should be taken to avoid disrupting any portion of the system as such disruptions have the potential to inflict unforeseen consequences which may compromise performance and delay development. A separate system has the advantage that it doesn't adversely affect the steam system, and can be built in a more optimized form. If developing a separate steam generator is objectionable, a compromise could be considered where the saturated steam-water mix in the boiler recirculation loop is routed to a “re-boiler” in which lower pressure saturated steam is produced. Such re-boilers are common in naval nuclear power systems; they provide process steam yet prevent contamination in the primary loop by acting as a fire wall.

Tom Kimmel proposes use of a “solar chimney” to dry sewage and I would suggest this be given strong consideration. Boiler flue gasses can augment his proposal without any potential negative impact on the steam power plant other than, perhaps, increasing the blower pressure somewhat. A very effective method of augmenting a solar drier might be to simply force the flue gasses through perforated pipes submerged in the sewage; allowing the air to bubble upwards through the sewage and warming it. The hot air leaving the condenser could also be routed to the tower to improve performance, perhaps the trays holding the sewage could be ribbed to improve heat transfer.

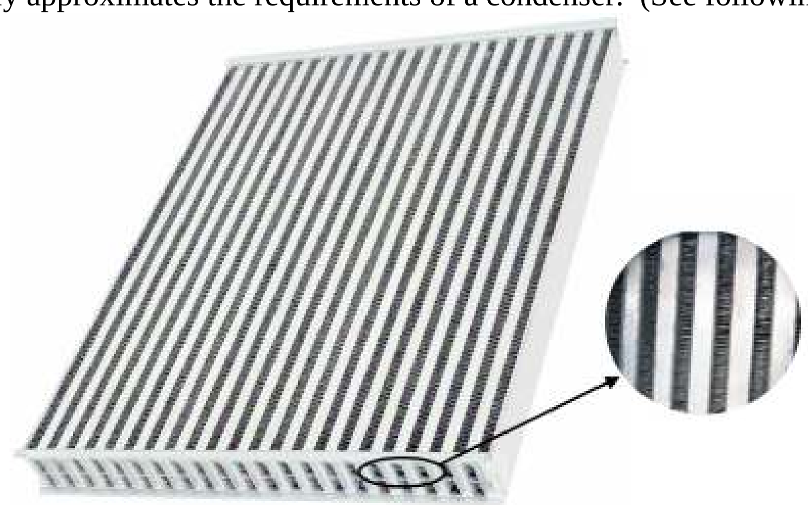
No matter what drying method is selected, I presume a mechanical separation scheme would first be employed to remove entrained water; home washing machines do a fine job with their “spin cycle”.

The most straightforward way to recycle exhaust steam to the boiler is to transfer the latent heat of vaporization to a coolant, i.e., to use a condenser. While water cooled condensers are preferable, the need to haul the system by trailer suggests air cooling is a necessity. Although traditional steam automobile air-cooled condensers and automotive radiators looks much the same, the condenser is more problematic:

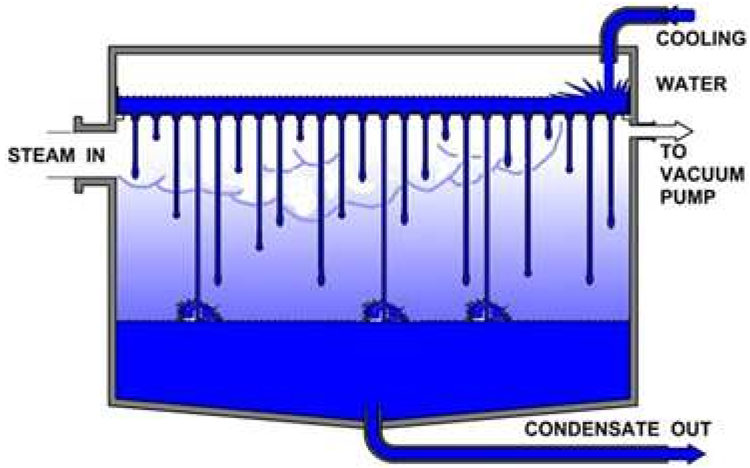
- Condensers may be subjected to higher exhaust pressures or vacuum, requiring stout construction
- Steam is a poor thermal conductor and doesn’t readily give up heat to its surroundings
- The latent heat of vaporization must be rejected as well as sensible heat.

Sub-atmospheric condensing (vacuum) enhances thermal efficiency, but poses challenges for the condenser. The reduced pressure causes the condensation to drop and causing heat exchanger effectiveness to dwindle. This can be compensated, to some degree, by using larger condensers and increasing air flow.

Condensers fall into two categories, surface contact and direct contact. Surface contact devices force steam to condense against cool surfaces while direct contact mixes the steam with a coolant (usually water). Steam cars surface condensers resemble IC radiators, leading to the idea that radiators may replace condensers. This really isn’t practical; condensers are exposed to pressures that radiators are not built to withstand. Condensers need a greater internal to external surface area ratio than radiators because the relative thermal capacities of steam and air are closer than those of water and air. Internal combustion engine intercoolers provide a potential source of condensers; their rugged construction resists pressures far better than radiators while their greater internal surface area more closely approximates the requirements of a condenser. (See following)

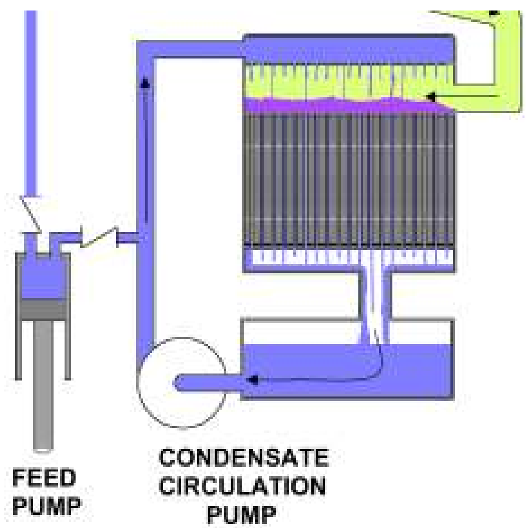


Jet condensers are the most common direct contact device, although the term covers a variety of hardware. The earliest jet condensers consisted of a box with a perforated pan on top, a steam entrance port beneath the pan and a drain port in the bottom. Cool water fed to the pan "rains" on the exhaust steam admitted directly below, the resulting condensate falls to the bottom of the box and exits out the drain. The collapse in volume as steam condenses creates a partial vacuum in the chamber, but also causes air dissolved in the steam to leave solution. A vacuum pump can be connected to the box to remove accumulated air and other non-condensable gases, although condensation is the main source of vacuum. Later jet condensers (eductor condensers) employ high velocity water to act as jet pumps, drawing steam into contact; this method is a bit more compact but also more energy hungry.



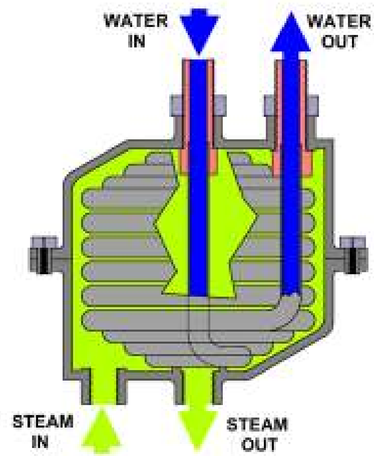
Air-cooled condensers have usually been of the direct contact variety, and almost invariably have been troublesome, but water cooling depends upon a secure water supply. I propose a two-step process: steam will be condensed in a direct contact device, the condensate and entrained steam will then descend through a heat exchanger and be cooled by the air. The two step process appears favorable because compared to steam; water is a superior thermal conductor and better suited to transfer heat.

I propose building a simple experimental assembly consisting of a simple jet condenser housing sitting atop a large diesel intercooler, or assembly of intercoolers. A pump will return cooled condensate to the jet condenser chamber while a Gast (or similar) vacuum pump removes air and other non-condensable gases from the condenser chamber... While perhaps not an ideal solution, it has the advantages of low cost, simplicity and rapid fabrication; at the very least it can serve as a starting point for condenser development.



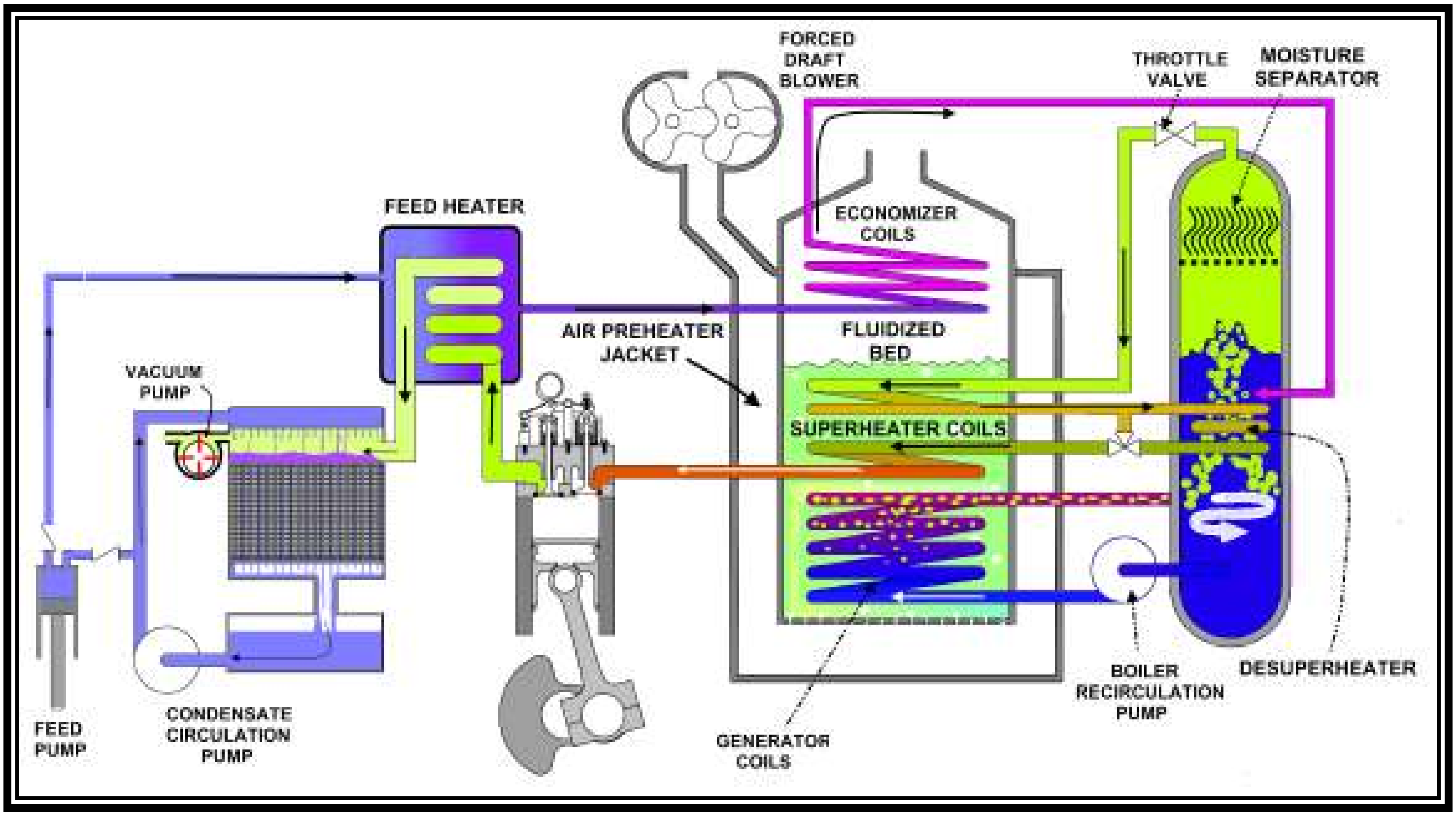
Feed Water Heater

Steam power plants typically improve efficiency with a heat exchanger that transfers heat from the exhaust steam to the feed water. Should exhaust heat be used for drying or distilling, a finned heat exchanger might be employed to recover some otherwise lost energy by condensing the emitted vapors; otherwise a feed water heater should be employed at the exhaust to transfer some of the exhaust steam heat to the boiler feed water.



Feed Pump

Pressure washers are now ubiquitous and reasonably priced. I would suggest a commercially available pump be used and also suggest that perhaps one or even two backup pumps be installed to permit continued operation in case of failure and replacement of the other unit. A variety of pumps are available from a number of manufacturers, a selection should be tested to ensure best compatibility with this system.



SIMPLE STEAM SYSTEM SCHEMATIC

Air Pre-heaters

Preheating is often used to insulate boilers; heat is kept from escaping by passing air over the boiler shell to absorb escaping heat and then directing the air into the burner, where the heat is recycled. I presume some similar scheme is used to improve the economy of fluidized bed combustors and can only note that in boilers care must be taken with air preheating to avoid excessive NOx production.

Coalescer

Coalescers are filters that trap oils and are usually constructed with lipophilic (oil loving) materials such as polypropylene. A coalescer embedded in the condensate piping might successfully trap oils before they reach the boiler, reducing boiler drum contamination. Polypropylene fibers are used in the floating rope used at pools and beaches, and thus are cheap and readily available. A reusable filter would be desirable, a task that might be simplified because most oils are detergent soluble. Coalescer elements which can be refurbished locally by installing new fibers would also be desirable, old filter material might be burned in the boiler furnace.

PROJECT MANAGEMENT

Compact reciprocating steam power plants have not been manufactured in great numbers for a long time. The environments in which they will now work are much different; operators and local repair facilities will be less knowledgeable and capable simply because the technology is no longer very familiar. Mass production, along with ever-improving reliability and access to rapid delivery, has encouraged the shift from local fabrication and fitting of replacement parts to installing those purchased from the manufacturer; which in turn demands greater involvement with the customer after sale. A successful light steam generator set will need to be largely automatic in operation and normally require only light routine maintenance; historical steam engines probably make a poor model from which to draw.

Organization

This project will likely entail quite a bit of experimentation and evolution to provide a modern system; particularly in areas such as durability testing, human-machine interfaces, water-oil separation, feed water testing and chemistry plus assorted detail efforts such as refining the design to minimize steam leakage. Compared to historical light steam plants; the steam pressure, temperature and rpm are higher, the cutoff and clearance volume are smaller, the boiler is lighter and circulates more rapidly, and a condenser is to be fitted. The closest approximations are found in steam automobiles, these being neither particularly inexpensive nor usually meant for use by relatively unskilled operators. Solving issues of automatic control, reliability, improved efficiency and size reduction is bound to require a program of testing and modification.

Steam power plants, much more than internal combustion, lend themselves to parallel development. I would suggest using teams to concurrently tackle various aspects of the project to speed the development process. A possible breakdown might be along the lines of the steam cycle itself:

- Expander team
- Boiler team
- Combustion team
- Auxiliaries team

- Dyno testing and pre-manufacturing are other areas that may benefit from special attention.

Although the various components can be developed in tandem, they must fit together easily and eventually work in unison, regular and ongoing co-ordination between teams will be needed to minimize integration problems later in the program.

Expander team

The expander team would be responsible for developing the steam engine itself. I would recommend buying one (preferably two) single cylinder research engines of appropriate size on which to experiment before moving to conversion of a production multi-cylinder diesel engine.

One or more dynamometers are virtually mandatory for any serious testing program. Along with price and features, the degree of personnel training provided should be taken into account when purchasing.

Research engines are quite common in commercial powertrain development because they are very rugged and tolerant of abuse, are readily modified to permit rapid refinement of designs and because limiting tests to a single cylinder make it much easier to gather data, make modifications, locate and solve problems. Although the initial cost is high, such engines are long-lived, usually being modified over time to assist in a number of projects. Research engines are typically fitted with simplified components designed to gather information which assists production hardware designers; for example, a series of dynamometer runs with a research engine can lead to development of near optimum cam profiles. Other uses are also valuable, such as testing piston rings for blow by, valve stem wear, valve stem leakage, cylinder wall lubrication and wear. All this testing can be performed concurrently with design of production components, usually a more lengthy process involving consultation with subcontractors and very careful refinement.

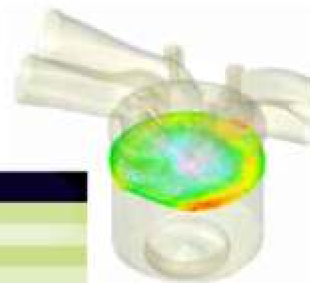
Heavy-duty Proteus

The Ricardo Proteus is a heavy-duty single cylinder research engine ideal for combustion system studies or advanced research as well as component and product development

Ricardo provides engine arrangements and technologies that meet its customer's current and future needs. The recently upgraded MK2 Proteus is designed for modern heavy duty diesel combustion and can withstand combustion pressures of up to 250bar.

The heavy duty engine in standard or custom design is available with bores from 100mm to 150mm and strokes up to 165mm, although an engine of approximately 2.0 litre displacement is typically used. The Proteus is of modular construction, which enables a selected combustion system to be built in a range of bores and strokes with valvetrain, FIE and other options chosen by the customer. Ricardo forms close collaborative relationships with the suppliers of the specialist systems (eg. Test equipment, FIE, valvetrain etc.). Of modular construction, it can be operated on gasoline, diesel and alternative fuels, including compressed natural gas (CNG), ethanol and hydrogen.

Proteus MK2



Feature	Options
Bore	Min 100mm - Max 150mm
Stroke	Min 120mm - Max 165mm
Pmax	Up to 250 bar
Combustion System Options	Diesel (DI or IDI) Alternative Fuels
Combustion Cycle	Four Stroke Two Stroke
Valve Operation	Push Rod Single Overhead Camshaft (SOHC) Double Overhead Camshaft (DOHC) Variable Valve Actuation (VVA/VVT) Cam Phasing Camless (HVA)
Valves	Two Four
Fuel Injection Equipment	Pump Driven Common Rail Electronic Unit Injector (EUI)

Design

FEV Single Cylinder Engine Program

FEV offers a single cylinder engine program for basic research, testing and development work over a wide range of engineering areas. It is possible to configure the FEV systemmotor to operate on gasoline, diesel and alternative fuels such as CNG and H2. All of the FEV Single Cylinder Engines are characterized by a modular architecture and a very robust yet flexible structure, to serve as the basis for a variety of engine set-ups. The main modules are:

- Base module with crankcase, cranktrain, flywheel and mass balance system
- Intermediate module with water jacket, cylinder liner and timing drive system
- Top end module with cylinder head, valvetrain, valve cover, intake and exhaust system.

A modular design enables the customization of each engine set-up in all engine classes, even for very special investigations, such as engines with optical combustion chamber access or engines utilizing production parts.

Three base engine platforms serve the most common engine classifications:
FEV Systemmotor – small, high-speed, passenger car and light-duty commercial engine classes
FEV HD Single Cylinder – medium, heavy-duty truck and industrial engine classes
FEV Large Bore Single Cylinder – locomotive, marine and industrial engine classes

FEV Systemmotor – Technical Data
Bore: 50 – 115 mm
Stroke: 60 – 135 mm
Rated Speed: Max. 6000 rpm (with full mass balance)
Max. 8000 rpm (with 1st order mass balance)

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The cylinder head will be a primary source of concern, especially the admission valve, and extensive testing may be needed to refine designs. As noted earlier, cam profiles will benefit from testing. The first prototype engine should benefit from lessons learned in research engine tests.

Lubrication is critical to any engine and is also a recurring source of trouble in light steam reciprocating engines. Steam blown by the piston rings tends to emulsify with natural mineral oils in the churning environment of the crankcase, rendering it unfit. A combination of tactics will probably be necessary to combat this problem. As discussed earlier, higher MEP and longer residence time lead to increased blow-by, single stage expanders operating at higher speeds strongly reduce the problem. Some synthetic oils exhibit superior demulsibility, use of such oils which are also compatible with the diesel manufacturer's requirements should be required as part of the warranty. Even small amounts of water degrade oil performance; efforts should be made to eliminate such contamination by such means as evaporation, settling and centrifugal separation.

Lubricant decomposition in the presence of high steam temperatures is also a concern and is one reason for recommending only moderate steam temperatures are employed in the first generation engine. Occasional tear down of the engines during testing can help determine whether this is an issue and also indicate whether exposure to live steam is stripping oil from the cylinder walls prematurely. Solving issues of oil selection and purification seem to fall under the purview of the expander team.

If engine development is concurrent with boiler development, it will not be possible to initially test with steam derived from a project built boiler. A shop boiler should be obtained capable of supplying enough flow at adequate pressure and temperature. Both Vapor Power International and Clayton Industries offer boilers with adequate flow and pressure output, but peak temperatures seem to be from about 650 to 750 F, I do not know if either company could be induced to build a model capable of higher temperature. If not, perhaps a custom build unit could be found or perhaps a stand-alone superheater could be fabricated to provide some extra temperature. Tom Kimmel has experience winding boiler coils and a number of automotive steam generator examples at hand from which to crib ideas; his expertise may save some aggravation.

Boiler team

The boiler team would have responsibility for determining the physical boiler structure that promises the best combination of performance, cost, ease of manufacture and durability; this would include examining such issues as finned or plain tubing, internal ribs or smooth, single path or parallel flow, stainless or alloy steel and so on.

Other duties would include:

- Designing the boiler. Fabricating and testing of prototype hardware.
- Determining the most suitable water chemistry tests and treatments compatible with the boiler construction and skill level of the operators.
- Developing hardware and procedures to minimize boiler water contamination.
- Ensuring the needed operator and maintenance skills are consistent with the available labor sources and providing tools and procedures necessary for performing these actions.
- Development of the forced circulation system, burner and feed water controls may be shared with the Auxiliaries team.

Combustion team

The fluidized bed combustor is somewhat of an unknown to me, and I am uncertain just how developed such systems are in units of this small size and what issues exist regarding maintenance of the fluidized bed itself. I would presume a separate group would work on the combustion system and also examine alternate combustion methods such as a rotary combustor and modifications to a down draft producer gas generator. The functionality and reliability of the forced draft blower will be important.

Firing with solid fuel may present some significant challenges to both steam plant operations and steady power production. Assuming fuel is a mixture of biomass and trash, the number of BTU per pound of fuel may vary widely across small periods of time. Large solid fuel fired power plants include support equipment to break the fuel into a small, regular size, permitting automatic feeding and relatively predictable heat production. Such pre-processing would appear overly complex, expensive and trouble prone for a plant this light, making hand feeding the natural choice. People tending coal or wood fires soon expertly judge the rate of heat release based on flame and coal colors, stoking and adjusting dampers to obtain good control over production of heat and control over ash and clinkers. Fluidized bed combustion seems less intuitive, automatic control over air flow is probably needed to maintain proper output and some sort of audible or visible prompt to regulate the stoker might be desirable.

Besides designing and perfecting a furnace, the Combustion team would be tasked with establishing methods to operate, regulate, maintain and repair the furnace. These tasks imply close cooperation with the Boiler and Auxiliaries groups.

Auxiliary team

The "Aux team" works on the 'stuff' that is needed to turn separate components into a power plant. Pumps, blowers, piping, controls, condensers, filters, feed heater and air heaters and so on all come under this heading. These components can make or break the expander, boiler or combustor, and thus must be tailored to work effectively with the primary components. Auxiliaries can be a challenge, electrically driven hardware makes for easy start up and control but engine driven auxiliaries may be cheaper and more efficient. It might be possible to consolidate some of the hardware into a single package for ease of installation and repair. A unified package might be able to use both shaft and electric motor drives through judicious use of clutches.

A strong ability to anticipate the needs of and to work closely with the other teams is vital for this team.

Shop

Even if it is envisioned to use subcontractors for most of the fabrication, an in-house machine shop is invaluable for performing the kind of small repairs, modifications and fabrication that otherwise stalls such programs.

TESTING

Though spelled out to the point of nauseum, I simply cannot over-emphasize the importance of testing. The history of light steam development has been one of hard work designing and building a prototype followed with perfunctory testing designed seemingly to only to prove the original goals were met and usually followed by silence when the product turns out to actually be inadequate due to insufficient development.

Depending on the degree of complexity in the project, established engine manufacturers may assemble one or more single cylinder research engines to test actual performance of the concept while changing a number of key variables in order to optimize the concept. This is typically followed by fabrication of 'alpha' generation prototypes that use whatever components are unique to the new engine and incorporate lessons derived from the research engines, extensive testing of these units provides lessons on performance and reliability that are embodied in a 'beta' generation of pre-production engines that matches the expected final design. A final group of 'gamma' pre-production engines are then built incorporating any changes implied by the previous generation; these engines are basically shop built clones of the production design because it is too expensive to authorize construction of production tooling before the design is verified. This generation is the most extensively tested, they establish characteristics of the production engines used to measure compliance with EPA and CAFÉ rules, verify power, economy and reliability. Such testing also provides solid data for projecting warranty costs, creating advertising, writing maintenance and repair standards and any other activity requiring hard information. The company might start taking definitive steps to put an engine into operation by the beginning of the 'beta' phase but delivery of the final production tooling is contingent upon successful 'gamma' tests.

I am not suggesting that this project can afford the full gamut of development and testing that established manufacturers implement (this is one reason for converting donor engines), but it is important to realize that successful manufacturers take little for granted and repeatedly check their work. Given that recalls still happen, one can only imagine the situation if such tight controls were not in place.

It isn’t enough to test just to verify a facet of performance; it must reveal performance across a spectrum of conditions. To provide customers with a credible product, testing must also be done to destruction, repeatedly.

In order to produce data in a timely fashion, engine developers typically run a number of dynamometer test cells almost continuously….24/7/365. Such expenditures on dynamometers are probably greater than this project can afford, but gen sets by their nature can serve as a dynamometer stand-in for some kinds of tests. The electric utility power grid is in effect an almost infinitely large, extremely cheap test load (less than cheap, you can sell the power to them). While dynamometers are superior for analyzing nuances in performance, the gen sets themselves are more than adequate for long duration durability testing because they perfectly replicate the intended running condition. Data capture cards for personal computers are now affordable to facilitate testing a number of units simultaneously; one operator can watch a number of engines at night if audible alarms, easily accessed shutdown switches and installed firefighting equipment are provided.

If a production IC engine such as a Deere, Jimmy or Caterpillar is used for the “core” engine, I would suggest contacting the manufacturer to explore the possibility of having their personnel perform tear-downs of the engine during the testing phase. Having long experience with the basic engine, they would be the most qualified resource to determine wear and note any irregularities in the crank, pistons and bores. Since they would not be affiliated with the project, their objectivity would be greater. It might be worth exploring the possibility of eventually having the manufacturer construct engines with specific modifications for steam engine use.

MANUFACTURING

All too often steam programs have worked on the premise that “once we get it to work; any idiot can clean it up and build it”. This attitude kills more products, of all varieties, than can be imagined. All too often, it is even exactly backwards, the skill and effort required to cobble a working device together may often be far less than that needed to refine the idea to bare essentials and produce it efficiently. A team familiar with machine tooling, manufacturing and vendor contracting must be working with the development teams from the very beginning to ensure the efforts are being channeled in a viable direction. To whatever degree is possible, the test hardware should accurately emulate final production hardware. This team should be in constant contact with vendors to ensure manufacturing snags don’t become embedded into the design; or they should be responsible for arranging tooling and training if any part of the manufacture is contemplated in house.

SUMMARY

It has been generations since a successful, packaged, portable light steam power system has been successfully manufactured. Prior practice isn’t indicative of a product that meets modern conditions: a new power plant will be needed. Extreme reliability is vital, efficiency is important but given the relative lack of current competition and the short time frame allocated, some liberties can be taken.

Time is the driving factor, the project should be tightly scheduled and some type of project management system such as PERT charts employed to enforce necessary discipline. Developing all the hardware from scratch and testing it simply does not look feasible in the allotted span an off the shelf equipment will have to be utilized to the greatest degree feasible to take advantage of those manufacturers expertise. Prototype and pre-production power plants need to be ready possibly as much as a year before delivery to provide time for the necessary development and reliability tests and thus novelty should be avoided wherever possible; the potentially lost time may be fatal to the project. Concurrent development and testing of hardware may aid in meeting a tight schedule.

I see no glaring reasons why the proposal to convert a diesel to steam can’t be achieved if care is taken to recognize the differences in the two forms of prime mover and make allowances; care should be taken to restrict operation to conditions approaching those contemplated by the original builder to reduce the likelihood of failure. Initial expander testing of single cylinder research engines makes possible rapid refinement of the overall specifications and simplifies design of the final product.

Forced recirculation provides a sound basis for steam production, permitting a light and compact boiler amenable to automatic control.

A manufacturing-savvy element needs to be involved from the very beginning to aid in keeping development on track for earliest production startup.