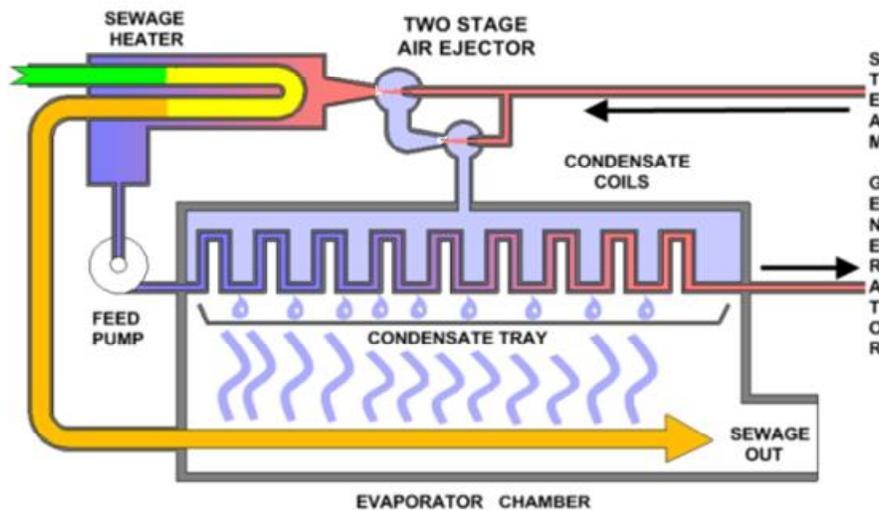


The short development period cannot be overemphasized; extensive (and time consuming) durability testing is needed with allowances made to incorporate test data back into the design as needed; minimizing the number and complexity of elements to be developed dramatically improves the likelihood of successful 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 more time may be allotted to explore a wider array of options.

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 directly. 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 flue gasses through perforated pipes submerged in the sewage; allowing the air to bubble upwards through the sewage, 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.

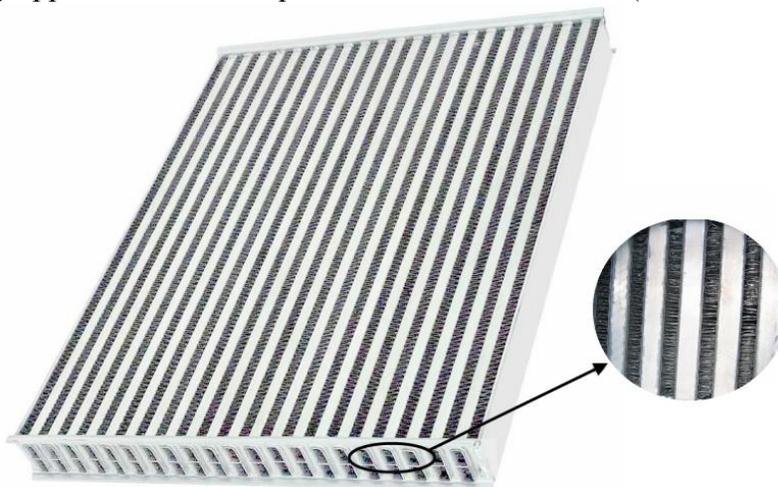
No matter what drying method is selected, I presume a mechanical separation scheme would first be employed to remove entrained water; home washing machines do a fine job with their “spin cycle”.

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:

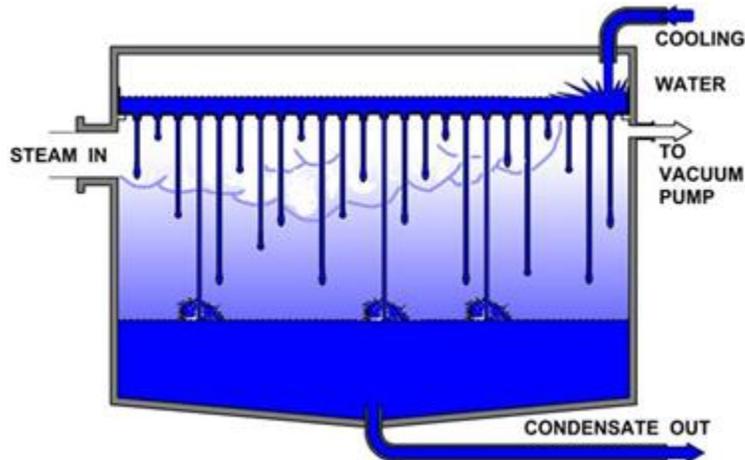
- Condensers may be subjected to higher exhaust pressures or vacuum, requiring stout construction
- Steam is a poor thermal conductor and doesn’t readily give up heat to its surroundings
- The latent heat of vaporization must be rejected as well as sensible heat.

Sub-atmospheric condensing (vacuum) enhances thermal efficiency, but poses challenges for the condenser. The reduced pressure causes the condensation temperature to drop results in dwindling heat exchanger effectiveness. 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)

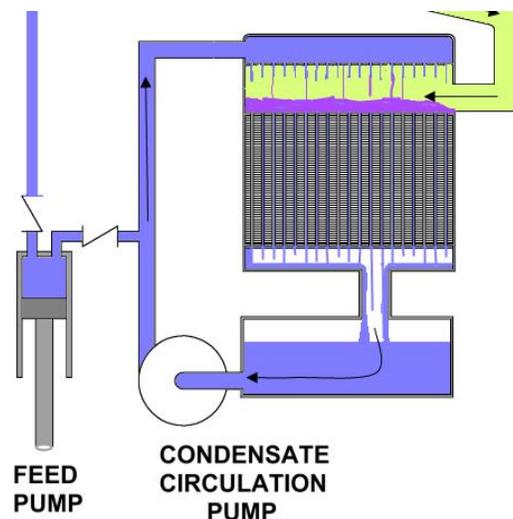


Jet condensers are the most common direct contact device, although the term covers a variety of hardware. The earliest jet condensers consisted of a box with a perforated pan on top, a steam entrance port beneath the pan and a drain port in the bottom. Cool water fed to the pan “rains” on the exhaust 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.



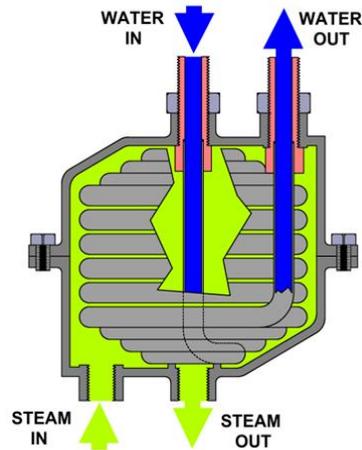
Air-cooled condensers have usually been of the direct contact variety, and almost invariably have been troublesome, but water cooling depends upon a secure water supply. I propose a two-step process: steam will be condensed in a direct contact device, the condensate and entrained steam will then descend 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

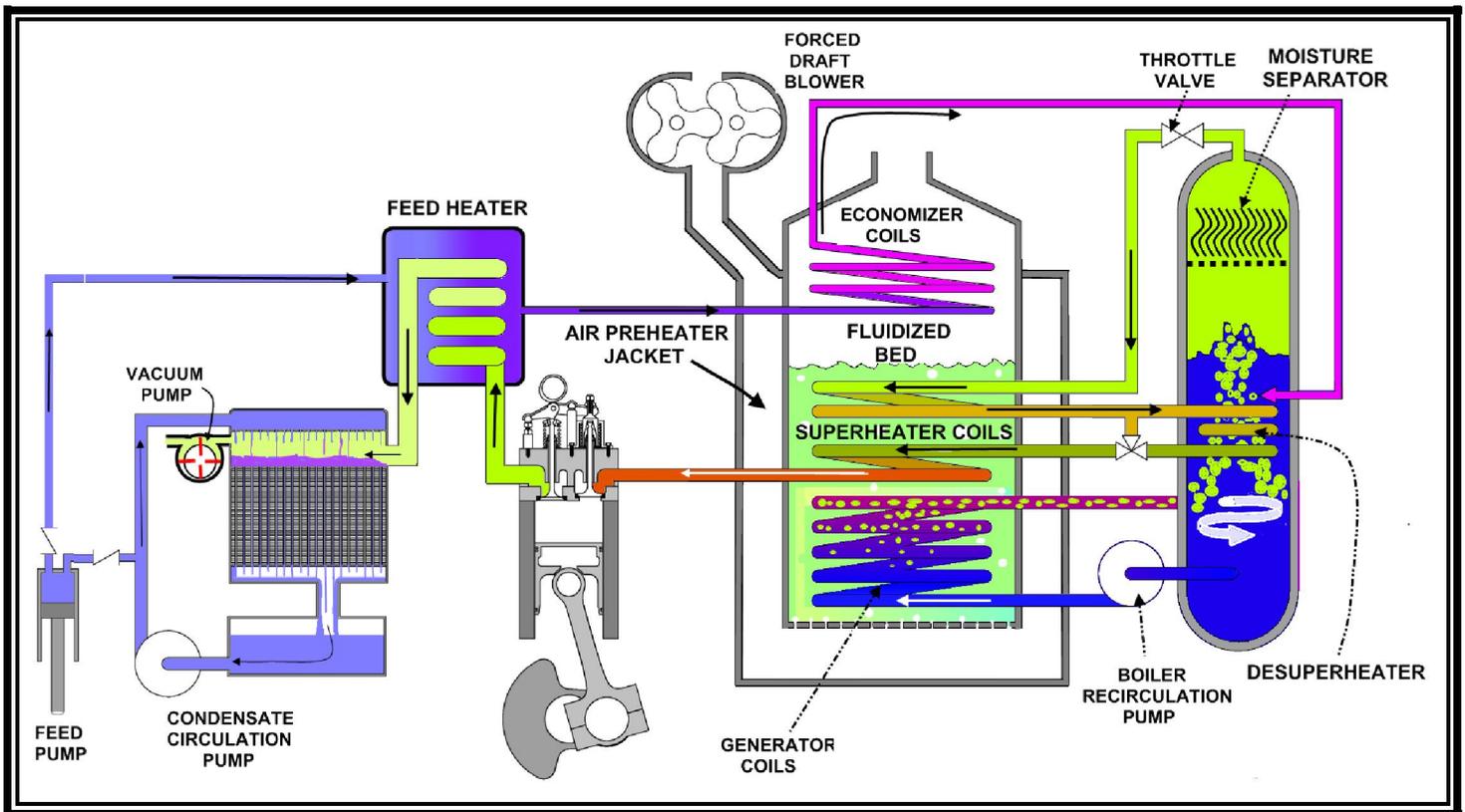
Steam power plants typically improve efficiency with a heat exchanger that transfers heat from the exhaust steam to the feed water. Should exhaust heat be used for drying or distilling, a finned heat exchanger might be employed to recover some otherwise lost energy by condensing the emitted vapors; otherwise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

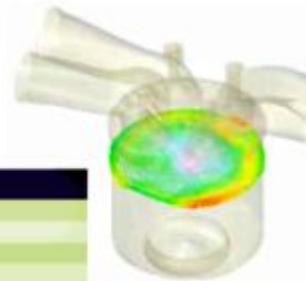
The Ricardo Proteus is a heavy-duty single cylinder research engine ideal for combustion system studies or advanced research as well as component and product development

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 (FW)
Valves	Two Four
Fuel Injection Equipment	Pump Driven Common Rail Electronic Unit Injector (EUI)

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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 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 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 for other than light hobby use. 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, 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.