EXTERNAL COMBUSTION ENGINES: PROSPECTS FOR VEHICULAR APPLICATION

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External combustion engines are discussed as possible alternatives to the internal combustion engine for vehicle propulsion. Potential advantages are low levels of exhaust pollution, quiet operation, high starting torque, and possible lower costs during a vehicle lifetime. Present experience with the California Steam Bus Project indicates that competitive road performance is obtainable with steam-powered city buses, but fuel consumption is higher than with a diesel engine. Opportunities remain open for the evolutionary improvement of thermal efficiency. Logical early applications include stop-and-go fleet vehicles.

•GASOLINE and diesel engines have been preferred prime movers for motor vehicles during a period of many years. Despite the almost universal application of the internal combustion engine (ICE), the criteria for vehicular power plants are now being seriously reexamined. Alternatives to the ICE are being reconsidered in a new light (1, 2).

The external combustion engine (ECE), of which the steam engine is the best known example, has been in use for more than 200 years. Steam power was popular for automobiles at the turn of this century. Prior to 1910, it was considered to be superior to the ICE for automobile propulsion in every way except first cost and convenience. Even then, the steam car was noted for its quietness and clean exhaust; freedom from gear shifting was also a decided advantage.

Now that air pollution, noise, and congestion are factors no longer to be ignored, both the role of the vehicle and its source of power are being evaluated anew. There is mounting evidence that the ECE can be significantly cleaner and quieter than the ICE (3, 4). Given accelerated (but expensive) development, the ECE could no doubt be applied to both private and public transit vehicles. This paper explores some of these possibilities.

Much of the present discussion will be supported by work now being done under the California Steam Bus Development and Demonstration Project (5, 6), described later in this paper.

The ECE may be defined as a power system in which the fuel is burned externally to the expander (cylinder with piston, turbine, or equivalent) and in which the products of combustion are not used as the expansive working fluid. This category includes engines using steam or other vapors as the working fluid (Rankine cycle). Stirling, Ericksson, and closed-loop Brayton cycle systems are also examples of the ECE. Technically, the open-cycle gas turbine does not fit the definition just given, for the combustion gases are used to drive the expander.

Another pertinent concept is that of the continuous combustion process. Such a process may be applied either to the ECE or to the open-cycle gas turbine. Contrasts with the ICE, in which ignition-to-extinction of the flame may take only milliseconds of time, are obvious. Opportunities for the beneficial tailoring and control of combustion processes in the ECE are a prime area for study during the next few years.

Important elements of the ECE include the following:

1. Source of heat (burner or combustor);
2. Means of transferring the heat to the working fluid (boiler, vapor generator, heater);

3. Expander, in which the heat of the working fluid is transformed into mechanical energy (turbines, piston engines, and rotary engines have all been applied);
4. Means of dissipating exhaust heat, such as a condenser, radiator, or other cooler;
5. Pump or compressor for returning the working fluid to element 2 above; and
6. Ancillary apparatus that may be required for starting, control, lubrication, speed reduction, and torque multiplication (auxiliary heat transfer apparatus such as feed-water heaters and regenerators may be used to increase the efficiency of the operating cycle).

CALIFORNIA STEAM BUS PROJECT

The California State Assembly, with a grant from the Urban Mass Transportation Administration of the U. S. Department of Transportation, is currently sponsoring a demonstration of the feasibility of ECE power for city buses. A major objective is to demonstrate a vehicle with a competitive level of road performance but with significant reduction of exhaust pollution, noise, smoke, and odor.

Development work was begun in June 1970 on 3 power system designs, each by a different engineering contractor. By the summer of 1971, extensive bench testing of complete power systems was under way. Installations into 51-passenger buses have now been made, and road test evaluation has begun.

Features of the 3 power systems are shown in Figures 1, 2, and 3. A brief description of each, a summary of preliminary data, and the project's outlook are discussed below.

William M. Brobeck and Associates

The Brobeck steam bus power plant is an outgrowth of the earlier and successful Doble designs. The steam generator, for example, is based on the Doble monotube concept (7). Unlike conventional boilers, no steam drums are used. A forced circulation of water and steam is induced through approximately 1,400 ft of coiled tubing. This requires, of course, the close automatic control of the flows of fuel and water to maintain the instant availability of steam under widely varying loads.

An engine (expander) having 3 double-acting cylinders with compound expansion is employed. Piston valves are employed that have fixed cutoff of steam admission during the stroke. Because the engine is coupled via a 2-speed automatic transmission to a conventional rear axle, the rated engine speed is the same as the diesel engine replaced—2,100 rpm.

The power system has a maximum rating of 250 hp at 2,100 rpm. Under normal operating conditions, up to 200 net hp are delivered to the transmission after auxiliary loads are deducted. Steam conditions are 800 to 1,000 psi and 850 F.

In the present bus conversion, the steam generator has been installed in the original engine compartment at the rear of the bus. The engine, condensers, and auxiliary apparatus are mounted midway under the floor. Cooling fans for the condensers are hydraulically driven.

Lear Motors Corporation

The Lear bus power plant is unconventional in design approach. It uses a single-stage impulse turbine as the expander. Turbines are much smaller and lighter than piston engines and also eliminate the problem of cylinder lubrication at high superheat temperatures. Although steam is being used as the working fluid during field tests, extensive bench testing has been done with substitute organic vapors in this system. (A low freezing point would be a considerable advantage in cold-weather operation.)

Much work has been done by the Lear organization toward optimizing combustion and heat transfer characteristics. As a result, the size and weight of the vapor generator (boiler) have been greatly reduced over traditional steam automotive practice. This, together with the use of the compact turbine, makes possible a power system that is lighter (by hundreds of pounds) than a diesel power plant of the same power output.

Steam Power Systems, Inc.

SPS is endeavoring to further the art of the steam reciprocating engine. A 6-cylinder, double-acting, compound-expansion engine of high specific output is coupled to a forced-circulation steam generator of the coiled-tube design. The steam is reheated between expansion stages. Electronics have been utilized to a maximum degree in the automatic controls. Because the engine delivers 12 power strokes per revolution of the crankshaft, there is an extremely smooth torque delivery over a wide range of speeds. Although piston valves with fixed cutoff are used as a design expedient in the first bus installation, a more advanced concept is under development. The advanced system uses poppet valves with variable cutoff, which should result in reduced fuel consumption.

In the SPS bus installation, the steam generator, engine, and one of the condenser cores are mounted in the original engine compartment, together with auxiliaries. Additional condenser cores are located under the floor. Each condenser core resembles a large automotive type of radiator.

Project Outlook

Although the final technical evaluation of this project will not be completed for some months, preliminary data are now available. We are reminded that this project is primarily to provide a public demonstration and to evaluate potential; it is not intended to be a developmental advancement of the art. To a large extent, this has been a learning process to determine where the basic point of departure lies. Much relearning has also taken place.

Road Performance—Good road performance seems ensured. City buses of this size are normally fitted with diesel engines rated at 180 hp and more. ECE systems being installed in this project have been bench tested at levels exceeding 200 hp net input to the transmission. Early road trials confirm that the experimental steam power plants can yield performance equaling or exceeding that of diesel power in terms of acceleration, hill climbing, and top speed.

Exhaust Emissions—Exhaust emissions were measured by the California Air Resources Board in early October 1971. The results, expressed in grams per brake horsepower hour, are given in Table 1. The information is from limited and initial test data and is not considered absolute or necessarily representative for this class of vehicle. Future California standards for heavy-duty diesel-powered vehicles are also given in Table 1 (8).

Laboratory experiments with advanced burner designs, at Lear Motors and elsewhere, show that even the low emissions given for the steam bus in Table 1 can be considerably reduced. Future steam bus emissions can be cut to levels of less than half those shown for carbon monoxide, hydrocarbons, and oxides of nitrogen.

Sound Levels—Sound levels in the near vicinity of the Brobeck steam bus have been found to be 3 to 10 decibels lower than those for diesel-powered equipment. Because the decibel scale is logarithmic, this represents a reduction in noise intensity by a factor of 2 to 8 or more. Sound levels inside the coach, however, were similar to diesel equipment because of the arbitrary locations of mechanical equipment below the floor of the steam bus.

Fuel Consumption—Fuel consumption for the steam systems is high, being roughly twice that of the diesel engine. Much improvement from the present rudimentary state of development is needed and possible.

Safety—The question of safety arises when high-pressure steam systems are discussed. Studies conducted prior to the hardware development phase showed that well-designed systems could meet stringent requirements for operational safety. Boiler explosions, in the dangerous or destructive sense, are not possible with the continuous-tube type of steam generator. All the pressurized steam and water are contained within small-diameter tubing; even if this tubing should rupture, the result would be more of an inconvenience than a hazard (9). Special safety studies are required when working fluids other than water are used. In the California Steam Bus Project, such fluids are limited to those that are nontoxic and those that have a low flammability potential.

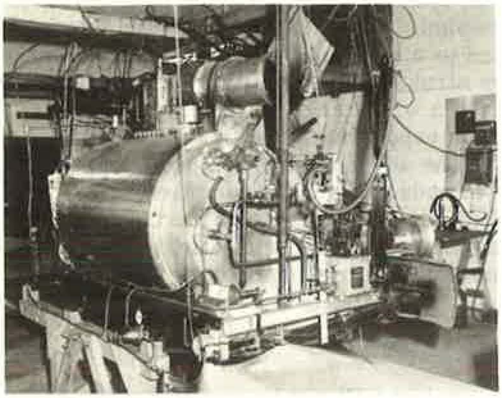


Figure 1. Brobeck steam generator under laboratory test.

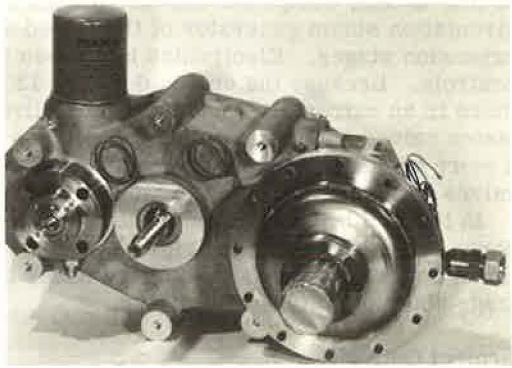


Figure 2. Prototype vapor turbine by Lear Motors Corporation.

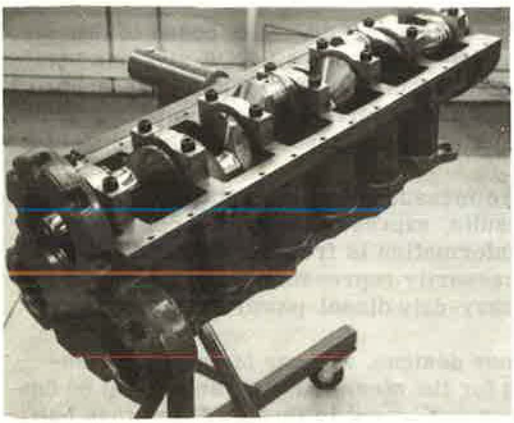


Figure 3. Crankcase assembly for reciprocating steam expander by Steam Power Systems, Inc.

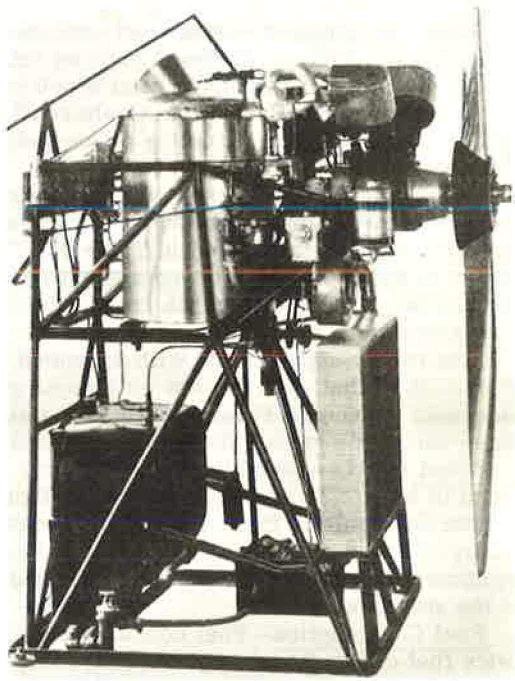


Figure 4. 1933 Besler steam aircraft engine.

Table 1. Steam and diesel bus exhaust emissions.

		Grams per Horsepower Hour			
Date	Vehicle	CO	HC	NO_2	HC + NO_2
October 1971 measurement	51-passenger steam bus (Brobeck power system)	2.0	1.2	1.2	2.4
	51-passenger diesel bus (V-6 engine)	4.4	2.5	9.0	11.5
	51-passenger diesel bus (V-8 engine)	7.9	0.9	8.4	9.3
1973 standard	Heavy-duty diesel-powered vehicle	40.0	—	—	16.0
1975 standard	Heavy-duty diesel-powered vehicle	25.0	—	—	5.0

Figure 5. Trends in development of automotive steam generators.

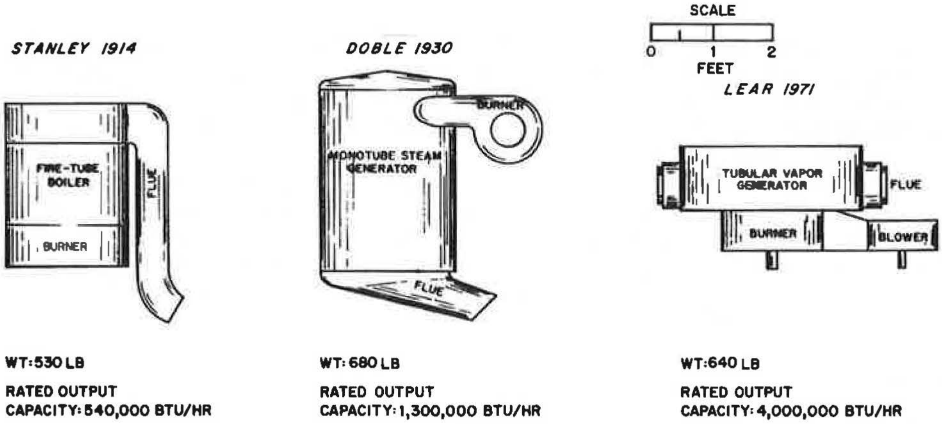
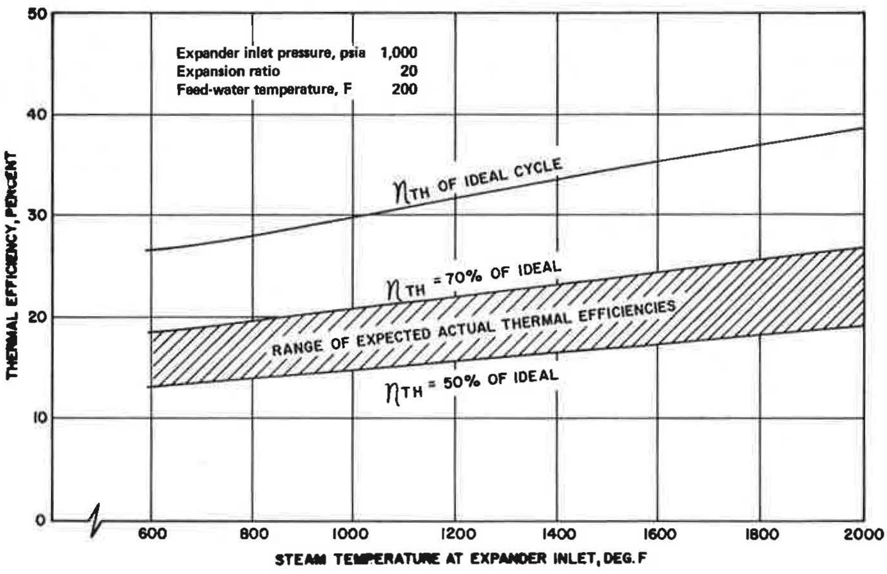


Figure 6. Influence of steam temperature on thermal efficiency (η th) of Rankine cycle system.



Size and Weight

The photograph shown in Figure 4 should dispel any notions that ECE systems are inherently heavy, clumsy machines. In 1933, William Besler flew an airplane powered by the steam system shown. The complete condensing steam power plant had a dry weight of less than 5 lb per shaft horsepower. It is certainly reasonable that even higher power-to-weight ratios could be evolved.

Although the ECE need not be heavier than the ICE of today, it seems certain that it will always be somewhat large. Space requirements are dictated to a major extent by the heat-transfer apparatus, namely the boiler and condenser. Hopes for reducing the size of these components hinge largely on 2 considerations: increasing the unit effectiveness of the heat transfer process and raising the efficiency of the system in converting heat energy into useful work. An encouraging trend is shown in Figure 5.

Fuel Consumption

When tested under ideal conditions, engines based on Otto or diesel cycles almost invariably show a maximum attainable thermal efficiency higher than that of vehicular Rankine engines. This should not inhibit inquiry into the really pertinent questions: How do well-designed systems compare under actual conditions of vehicular operation? What undeveloped potential remains for each of the candidate systems?

Regarding the first question, a modern gasoline automobile engine, under ideal test conditions, can attain a thermal efficiency of 25 to 30 percent. The internal-combustion-powered automobile as a system, however, may have a vehicular thermal efficiency of only 10 to 12 percent in an actual urban driving cycle (10). Inefficiencies are attributed to the transmission, to engine idling, and to poor part-load fuel economy.

Regarding the second question, none of the power system candidates has reached its ultimate potential in terms of efficiency. The ECE, even with its sporadic and undernourished growth, has already passed the following significant mileposts (the thermal efficiency is the estimated heat overall thermal efficiency based on net shaft output):

Period	Examples	Thermal Efficiency (percent)
1900	Steam carriages, Stanley and Locomobile	5
1907-1910	Steam cars, White	12
1920-1950	Doble and Besler	15
1950-1960	Experimental steam systems, McCulloch and Williams	18
1966	Developmental Stirling cycle engines, General Motors model CPU-3 (13)	21 to 27

The thermal efficiency of any heat engine is strongly influenced by the maximum cyclic temperature. Gas turbine developments in recent years serve as an excellent example of evolution beyond original expectations. By 1971, developmental gas turbines for military vehicles were being operated with gas temperatures of 2,180 F (11). Only 20 years earlier, limiting temperatures of 1,500 F seemed an almost insurmountable barrier.

For some years now, the automotive steam engine has been held to peak temperatures not exceeding 800 to 1,000 F. By and large, lack of developments in (or substitutes for) high-temperature valving, cylinder assemblies, and cylinder lubricants have been responsible for this state of affairs. Figure 6 shows the increase in thermal efficiency that could follow a rise in permissible steam temperatures.

There also remain good possibilities for bringing the efficiency of the actual cycle closer to that of the theoretical cycle. One of the ways is to reduce the parasitic load

of the power-plant auxiliaries, such as condenser fan, boiler feed pump, and combustion air blower.

A third realm of improvement involves the recovery of benefit from wasted low-grade heat. Regenerative heat exchangers can be used. There is also the possibility of saving fuel by the use of absorption air conditioning rather than mechanical refrigeration.

Operational Characteristics

Steam engines (and also electric motors) can exert a high starting torque and, hence, can move a heavy load from rest without the benefit of clutch or multiratio transmission. They can also be made reversible and can provide a substantial braking or retarding effort if desired. Although the vehicles converted for the California Steam Bus Project all employ an available automatic transmission (to simplify the design of demonstration engines), ECE power plants of the future may well eliminate or simplify the requirements for transmissions. In any event, smooth and rapid acceleration is a decided advantage gained by ECE-powered vehicles.

Emissions and Noise

It has yet to be determined just how clean the exhaust of an ECE can be. A reasonable argument can be made that an efficient ECE power plant with steady-state, carefully controlled combustion is potentially as clean as a fuel-burning engine ever can be. If this be true, then it seems preferable to obtain a clean exhaust by this fundamentally correct approach rather than to add corrective devices to the ICE.

More and more is being heard these days about noise pollution. Here again, the ECE is inherently advantageous, having a closed-cycle engine exhaust. The better steam automobiles of yesteryear were almost inaudible at around-town speeds. Tire and wind noises tend to become more dominant at highway speeds with any vehicle, however.

Our growing awareness of environmental intrusion includes the concept of heat pollution. Unfortunately, all heat engines—whether ICE, gas turbine, or ECE—must eject heat into their surroundings in order to function. More efficient engines and more efficient utilization of vehicles can help.

It is true that electric vehicles—drawing current from either a battery or a conductor—are extremely clean at their immediate location. However, they do depend on an engine, a nuclear reactor, or a power dam in someone else's neighborhood.

Economics

The various alternative power systems must be judged in the ever-changing arena of economics. Not surprisingly, it is believed that most substitutes for the ICE will involve a higher first cost, particularly if extensive retooling and other initiation costs are to be amortized. However, on the basis of total costs over the life of a vehicle, the ECE might be favored because of possibly lower maintenance costs (12), particularly if the competing ICE is burdened by emission control equipment requiring frequent attention.

PROSPECTS FOR APPLICATION

It would be tragically premature to conclude that the ECE cannot be competitive merely because it became outmoded under earlier forms and conditions. There is ample evidence that many desired attributes are potentially available in the ECE—including quietness, cleanliness, and great flexibility in torque delivery. There is a need for continuing careful studies regarding possible economic advantages in the long term. Such studies must include the benefits and disutility costs of the alternatives to society as a whole, in addition to the direct impact on supplier and user. Difficult technical problems are being identified, principally connected with raising the thermal efficiency of small Rankine cycle systems while at the same time keeping the mechanism simple.

If applications do become widespread, they are likely to appear first in heavy-duty, stop-and-go fleet operations. Here, the ECE might show some of its advantages under

conditions that have always been difficult for the ICE. Smaller, urban fleet vehicles such as taxicabs and delivery trucks might be subsequent candidates.

The future of the ECE for constant high-speed, high-power applications such as long-haul trucking is less distinct, unless the full-load fuel economy can approach that of the diesel. Perhaps the gas turbine will eventually fit here, although the fuel consumption for truck turbines has to date been about as high as for present experimental steam engines.

Will the ECE drive private automobiles of the future? The writer offers the opinion that it could do so within a decade if it were merely a matter of developing the technology. Physical scaling considerations (such as condenser frontal area available versus power requirements) seem to favor a small-to-medium-sized vehicle with a modest power level (say, around 100 hp). Whether it will do so involves matters of resolve and sense of priorities within our society.

The writer is optimistic that the more general goal will be reached: The steam engine now seems destined either to be a stepping-stone to the clean engine of the future or to become the standard by which the emissions of future systems are to be judged.

ACKNOWLEDGMENT

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