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THE PURPOSE of the California Steam Bus Project* was to demonstrate the feasibility of the external combustion engine (ECE) as a low-emission, quiet propulsion system for a city bus. Emphasis was on the early demonstration of potential, rather than extensive development or technical perfection. The inquiry was an outgrowth of hearings held by the California State Assembly in early 1968, dealing with possibilities of steam automobiles. An initial grant of research funds to the Assembly was approved in February 1969 by the Urban Mass Transportation Administration of the U.S. Dept. of Transportation. Design and development work was begun in June 1970 by three engineering contractors, each in cooperation with a California fleet operator: William M. Brobeck and Assoc., Berkeley, Calif., with the Alameda-Contra Costa Transit District (A-C) based in Oakland; Lear Motors Corp., Reno, Nev., with the San Francisco Municipal Railway (MUNI); Steam Power Systems, San Diego, Calif., with the Southern California Rapid Transit District (SCRTD) of Los Angeles.

All three contractors completed installations of power systems into standard 40 ft urban coaches (Fig. 1), and provided maintenance support during the period of engineering tests and public service demonstrations. While many other forms of ECE have been suggested (such as Stirling cycle engines) the contractors all chose Rankine cycle systems for early exploration. The program evaluation covered engineering, operational, and nontechnical aspects of the use of steam power for city buses.

Exhaust emissions were evaluated by the California Air Resources Board. Sound level measurements were conducted by the California Highway Patrol. Supporting services were also provided by the Assembly Office of Research, the State Dept. of Public Health, and the Division of Highways.

Overall project management was by the Scientific Analysis Corp. of San Francisco. The International Research and Technology Corp., Washington, D.C. provided technical management and evaluation services through a California field office. Another California firm, Instrumentation Associates of Castro Valley, assisted with instrumentation and services in road testing.

The project was completed in September 1972. It was found that the ECE can compete with diesel power for city bus propulsion in terms of road performance and system weight. Exhaust emissions are low, and are well below the levels permitted by the 1975 California Heavy Duty Vehicle

ABSTRACT

The California Steam Bus Project demonstrated the potential of low-emission, quiet external combustion engines in public transit service. Three contractors supplied and installed steam powerplants in urban buses, replacing the original diesel engines. Exhaust emissions were found to be considerably lower than the 1975 California requirements for heavy-duty vehicles. Substantial reductions in sound levels were measured in one of the buses. Powerplant weights can be lower than present diesel engines. Road performance was similar to that with diesel engines, but very high fuel consumption was experienced with these nonoptimized demonstration vehicles. Prospects for future improvements are given in this paper, including the outlook for large reductions in fuel consumption and exhaust emissions.

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*A project sponsored by the California State Assembly with a grant of funds from the Urban Mass Transportation Administration of the U.S. Department of Transportation.

Fig. 1 - A 40 ft urban coach converted to steam power. (Southern California Rapid Transit District, with powerplant by Steam Power Systems, Inc. Illustration courtesy SPS, Inc.)

Standards in terms of carbon monoxide (CO), hydrocarbon (HC), and oxides of nitrogen (NO_x). The NO_x, in particular, are sharply reduced below current diesel levels. The potential for considerably quieter operation was shown, but interior noise levels proved more difficult to reduce than was the noise emitted to the outside environment. Fuel consumption at best (at the present level of development) was considerably higher than that of diesel units. Substantial improvement in fuel economy is a foreseen probability, but will require basic redesign of the power systems. Not surprisingly, many breakdowns were experienced with these early and rudimentary powerplants, but there seems no reason to believe that an acceptable level of system reliability would not be reached with future evolution. While freezing was not a problem in the California test environment, one of the contractors (Lear) exhibited a small heater that could keep a bus engine compartment warm.

The project staff has endeavored to evaluate the steam buses with an eye to the untapped potential remaining in the future. While the state-of-the-art in steam-propelled vehicles is not advanced enough to warrant immediate introduction into fleet service, the ECE has now been identified as one of the more promising candidates for the "clean engine of the future." Accordingly, guidelines were prepared for the Urban Mass Transportation Administration for possible future development.

HISTORY OF STEAM BUSES

Steam-propelled road vehicles have existed for over 200 years. The French engineer Cugnot demonstrated a 3-wheeled artillery tractor during the 1760s. Steam-powered stage coaches (the first steam buses) were operated commercially in England in the first half of the nineteenth century, although they were rapidly superceded by faster and more efficient rail conveyances.

The birth of the true automobile occurred during the 1890s. Until around 1910, many observers regarded steam power as superior for road transport. Lightweight, high-torque, and silent steam engines were invented and manufactured by the thousands. Steam cars were displaced by the gasoline-fueled internal combustion engines (ICE) when the latter evolved into forms that were cheaper, simpler, and more convenient to use.

Fig. 2 - Historical photograph of a Henschel-Doble bus operated by Suburban Railway of Bremen, Germany during late 1930s

Interest in the latent possibilities of steam was not totally forgotten, however. The work of Doble, Besler, Williams, and others (1)* in the interim years may yet prove to be forecasts rather than of historical interest only.

Returning to bus applications, the London public transit system operated some hundreds of Clarkson steam buses until 1919 (2). These vehicles were fueled by kerosene, and employed condensers for the recycling of the water.

The Doble technology (3) found its way into city buses, presaging the present California experiment. During the early 1920s, the Detroit Motor Bus Co. operated two Doble-powered buses for over 30,000 miles. These vehicles had an acceleration rate which was greater than that of contemporary gasoline buses, and with a fuel consumption which was competitive (4). In 1929, the Doble Co. installed a steam system in a General Motors Yellow Coach.

During the mid-1930s, high-grade motor fuels were in short supply in the German Third Reich. Warren Doble worked closely with the Henschel works at Kassel to introduce "Dampfomnibusse," which could burn fuel oils derived from coal. One such bus prototype is shown in Fig. 2. The direct-drive and reversible steam engine developed a rear-wheel torque which was greater at all road speeds than the competing ICE with 4-speed transmission (5).

Much more could be said about the background of steam-powered motor vehicles, but those interested may review additional referenced literature (6-9). It may suffice to state that some of the works past embodied considerable merit, and we are still relearning many of the pertinent lessons. Much engineering remains to be done before the full potential will be shown.

DESCRIPTION OF THREE POWER SYSTEMS

During this exploratory work, the three contractors were encouraged to develop their own individual design approaches.

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*Numbers in parentheses designate References at end of paper.

Each contractor seriously considered or implemented more than one design, and so the project benefited from the evaluation of a rather broad set of choices. Reciprocating, rotary, and turbine expanders all reached the preliminary bench test stage. A number of working fluids other than water were examined and some were used in bench-test powerplants. Several variations of control systems, auxiliary drives, feed pumps, and burners, went on to the expensive junk pile.

The present systems have some features in common. All use water as the working fluid. All generate the steam in forced-circulation, continuous-coil tubular steam generators. Final control of the steam temperature is by the "normalizer" principle, in which supplemental feed water is injected into the superheater as required. Condensing is by fan-cooled, finned tubular radiators. As an expedient in this short-term endeavor, all three buses use commercially available multi-ratio automatic torque converter transmissions. In each case, the main expander (engine or turbine) drives auxiliaries and accessories at idle. While a variety of liquid fuels may be used, most testing was conducted with No. 1 diesel. Specific features of each system follow.

WILLIAM M. BROBECK & ASSOC. - The Brobeck system is an outgrowth of the automatic monotube steam generators and compound-expansion piston engines developed earlier by Doble and Besler (10). The steam generator and its automatic controls are mounted in the original engine compartment at the rear of the bus. As shown in Fig. 3, the other systems elements are located amidships under the floor. All accessory and auxiliary units are belt driven from pulleys on the forward end of the engine crankshaft. Condenser fans are remotely driven by hydraulic motors. The transmission is a Dana-Spicer model 184 2-speed torque converter unit, locking up into direct drive at 29 mph.

Approximately one-quarter mile of tubing is used in the steam generator, varying from 0.50 in OD in the economizer section, to 1.0 in OD in the superheater. In order to reduce pressure drop through the generator, two parallel tube paths are used in the economizer and most of the evaporation zone. These are merged into a single monotube coil in the final evaporation and superheating regions. Both tangential and axial burner firing were tried, with the former yielding better results in this generator configuration. The burner uses a single air-atomizing nozzle, with automatic switching among four steady-states: off, idle, low fire, and high fire.

The engine (expander) has three double-acting cylinders (Fig. 4). Compound expansion is utilized, with one high-pressure cylinder exhausting into two low-pressure cylinders. As an expedient for this early demonstration, a nonreversible fixed cutoff valve gear is used.

By locating the system components in existing spaces, the original seating capacity (51 passengers) was retained.

LEAR MOTORS CORP. - The Lear power system differs strikingly from the other two, in the use of a turbine as an expander. All major components are placed in the original rear compartment. It was necessary, however, to enlarge this compartment because of the shape of the steam generator and to accommodate regenerators.

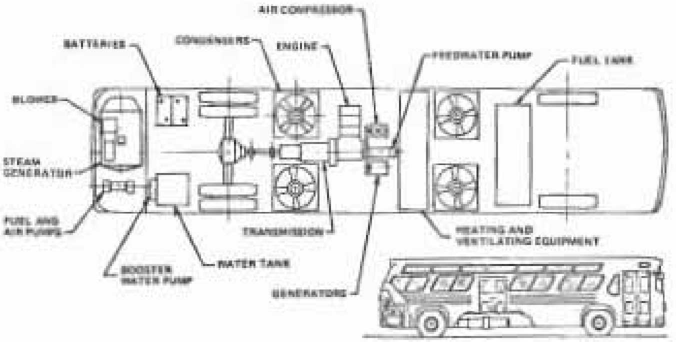

Fig. 3 - Location of powerplant components in vehicle (courtesy William M. Brobeck and Assoc.)

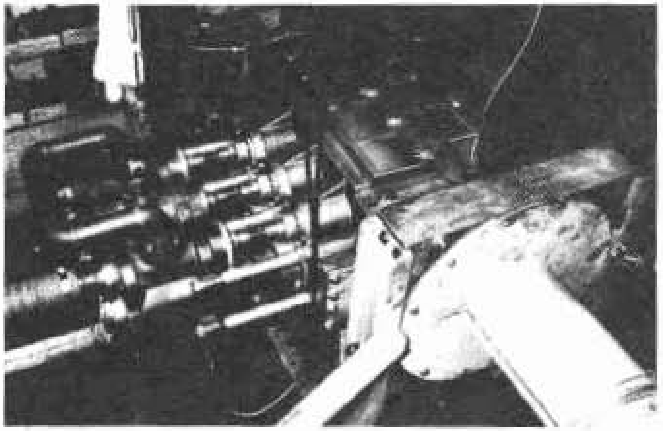

Fig. 4 - Brobeck steam engine on test stand (courtesy William M. Brobeck and Assoc.)

Lear's steam generator features a radial outflow of the hot gases through the tube bundle. During the development period, several types of burner were tried, including vaporizing mechanical atomizing, and air atomizing. An air-atomizing burner was finally adopted.

So far as is known, this vehicle is the first in history to be successfully propelled by a steam turbine. Originally, this turbine was designed to operate on an alternate working fluid having antifreeze characteristics and a molecular weight greater than that of water. During bench testing, however, it was found that this fluid deteriorated chemically at the required operating temperatures. Steam was then substituted, with redesigned turbine nozzles. The single-stage impulse turbine is very small in size (wheel diameter 5.6 in) and rotates at high speeds (to 65,000 rpm). Reduction gearing of 24:1 ratio connects the turbine, via an Allison HT-740 D 4-speed automatic transmission, to the rear axle. Most of the auxiliaries are also driven from the speed-reducing gearbox, including the feed water pump, two condenser fans, and the burner blower. The general arrangement of the powerplant is shown in Figs. 5 and 6.

STEAM POWER SYSTEMS, INC. - The SPS powerplant (11) features a 6-cyl double-acting compound-expansion engine. The steam is reheated between the two expansion stages. Steam generation is by a series-parallel tubular boiler, with an additional section for the interstage resuperheating. The

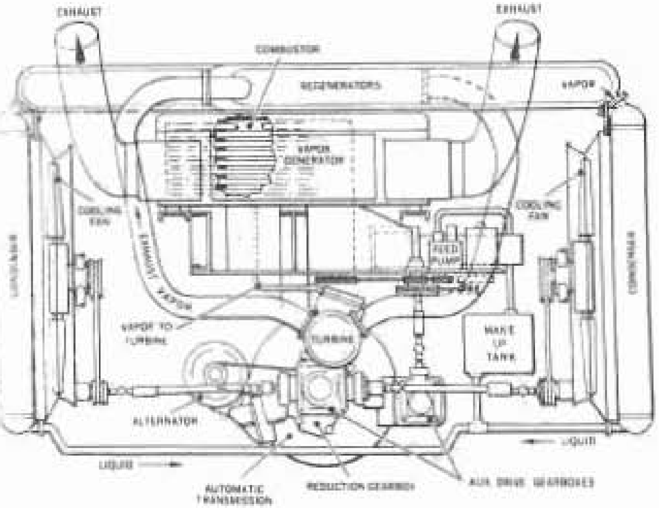

Fig. 5 - Lear component arrangement and flow diagram, as viewed from rear of bus (courtesy Lear Motors Corp.)

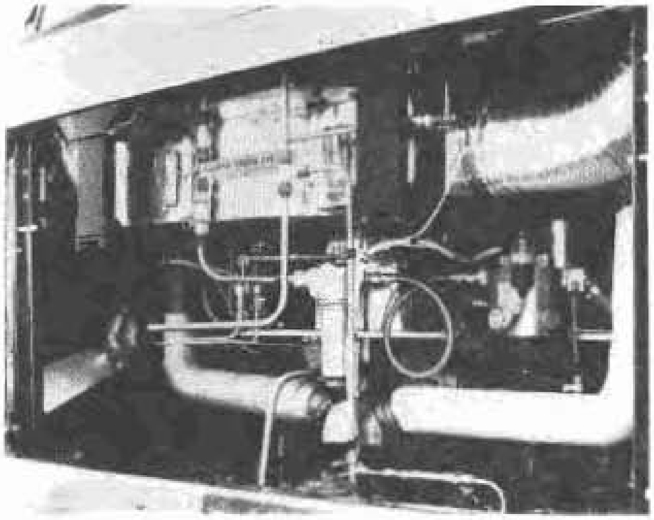

Fig. 6 - Lear vapor turbine system installed in bus (courtesy Lear Motors Corp.)

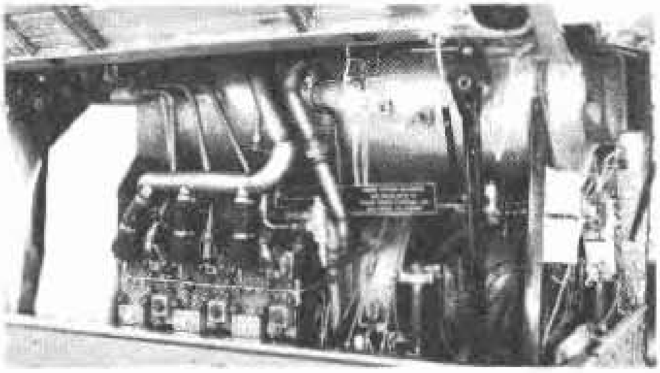

Fig. 7 - Powerplant installation by Steam Power Systems, Inc. (courtesy SPS, Inc.)

steam generator, expander, auxiliaries, and one of the condensers, are located in an enlarged rear-engine compartment. Three additional condenser cores are located under the bus, just behind the front axle. Fig. 7 shows the system installation.

Table 1 - Powerplant Specifications

	Brobeck	Lear	SPS
Expander type	Reciprocating	Turbine	Reciprocating
Max expander gross bhp	240	250*	275
Max auxiliary load, hp	40	40	50
Rated net system bhp	200	180	225
Max expander rpm	2,100	65,000	1,850
Max steam rate, lb/h	2,500	2,340	3,600*
Max fuel rate, gal/h	30	30	47*
Boiler heating surface, ft^2	180.2	275	356**
Combustion intensity, Btu/h ft^3	0.5×10^6	1.25×10^6	1.1×10^6
Condenser frontal area, ft^2	34.5	19.4	32.2
Steam pressure, psi	1,000	1,000	1,000†
Steam temperature, F	850	1,000	750†
Lowest bsfc, lb/net bhp·h	0.985	1.13	1.18
Approx. wt, lb:			
Boiler with burner	920	890	850
Expander	965	110††	1,250
Condensers with fans	750	420	800
Transmission	625	700	600
Auxiliaries	491	392	800
Other	1,026	590	400
Total system dry weight (a)	4,777	3,102	4,700

*Derated from figures shown for actual use in bus system.

**Including reheater section.

†In the SPS system, the steam leaving the reheater is 240 psi at 650-750 F.

††With gearbox.

(a)Present 6-cyl diesel powerplants weigh approximately 3800 lb, including transmission and auxiliary items.

Of the three buses, this is the only one to retain the original transmission (GM-Allison Super V) and angledrive rear axle. It is also the only bus equipped with air conditioning.

Two significant innovations were carried to the bench test phase, but were laid aside temporarily when time did not permit sufficient development to allow installation into the bus. One of these was the use of infinitely variable cutoff valve gear, and the other was the elimination of oil lubricants in the steam cylinder. The first of these allowed engine speed control without a throttling valve and would be conducive to high-thermal efficiency. The second would avoid the old problem of oil carry-over into the condenser and boiler.

TABULATION OF SPECIFICATIONS - The specifications of the three powerplants are compared in Table 1. Because configurations changed many times during the project's history, values given may differ from those reported in earlier publications.

EVALUATION OF RESULTS

The technical results of this program are interesting because they represent an early point of departure, upon which future improvements may be based.

Table 2 - Urban Bus Road Performance

	Diesel, GM 6V-71*	Diesel, GM 8V-71**	Diesel, Cummins 903 V8†	Steam, Brobeck	Steam, Lear	Steam, SPS††
Gvw as tested, lb	25,320	26,860	28,000	30,580	28,470	30,900
Top speed, mph	52	65(a)	70+(a)	56	54	58(a)
Acceleration, s:						
0-10 mph	4.0	3.0	3.7	3.0	5.0	5.0
0-30 mph	18	12	19	20	22	25
0-50 mph	57	33	46	62	74	71
Gradeability	16% at 3 mph	19% at 7 mph (b)	16% at 8 mph	18% at 2 mph	20% at 2 mph	N.A.

*N-55 injectors.

**N-60 injectors.

†Derated engine.

††Steam temperatures were too low for best power output.

(a)Overdrive transmission used.

(b)35,000 lb gvw overload test.

CUMULATIVE EXPERIENCE - Many hours of bench testing of the systems served a primary purpose of "debugging," rework, and adjustments prior to installation. Another valuable contribution was the practical education of a cadre of engineers and technicians in relating theory to design.

Approximately 8372 miles of road testing and public service were accumulated under steam power during this program. The longest single trip was by the Lear bus, 235 miles from San Francisco to Reno.

ROAD PERFORMANCE - The road performance of the steam-powered buses was similar to buses powered by 6-cyl diesel engines. Obviously, the performance of such systems could be scaled upward or downward if desired. In actual passenger-carrying service, the steam buses could usually duplicate, to the minute, the time schedules achieved by diesel power.

Because torque-converter transmissions were used, not much advantage could be taken of the very favorable torque rise, and high-stall torques, and potential retarding effort inherent in steam engines.

Road performance data of steam versus diesel buses are summarized in Table 2.

EMISSIONS - Several tests were made of the exhaust emissions of diesel versus steam buses by the California Air Resources Board. Table 3 is a summary of the results which confirm that the external combustion engine (ECE) can produce very low exhaust emissions even under the handicap of significantly higher fuel rates. All steam buses easily met the 1975 California Heavy Duty Vehicle Standards. These standards limit CO emissions to 25 g/engine bhp·h and combined HCs and NO$_x$ to 5 g/bhp·h. Of special interest is the fact that the cleanest steam system emitted only 6% NO$_x$ as the cleanest diesel tested. It should be emphasized that the diesel emission test results are based on a random sampling from well-maintained fleets, and may or may not be "typical" of diesel engines generally.

The Air Resources Board used test procedures which will accompany the 1973 and 1975 California standards for heavy-duty vehicles (12, 13). Testing was done with a chassis dynamometer, with emissions sampled during 13 separate steady-state modes of speed and load, including idle. While road-load transients are not included during sampling in this procedure, any transients due to boiler and burner response to hold the given road loads are integrated into the results.

Table 3 - Exhaust Emissions of Steam and Diesel Buses*, Figures in Grams per Engine bhp-h

	CO	HC	NO$_2$**	HC + NO$_2$
Steam buses				
Brobeck (test 10-71)	2.0	1.2	1.2	2.4
Brobeck (5-72)	1.6	0.8	0.5	1.3
Lear (9-72)	7.9	1.1	1.6	2.7
Lear (9-72)†	5.6	0.2	1.6	1.8
SPS (5-72)	2.7	1.6	1.5	3.1
SPS (8-72)	4.4	0.6	4.2	4.8
Avg. steam	4.0	0.9	1.8	2.7
Diesel buses††				
A-C #678 (GM 6V-71)	4.4	2.5	9.0	11.5
STA #408 (GM 6V-71)	2.6	1.5	13.9	15.4
MUNI #3141 (GM8V-71)	7.9	0.9	8.4	9.3
SCRTD #7185 (CUM. 903)	2.3	0.5	10.2	10.7
Avg. diesel	4.3	1.4	10.4	11.8
California Heavy Duty Standards				
1973	40	—	—	16
1975	25	—	—	5

*All tests were performed by the California Air Resources Board.

**NO$_x$ was measured as nitric oxide (NO) and expressed as equivalent NO$_2$.

†The second Lear test was a composite of two tests, with an improved (but not optimized) idle setting between tests.

††Diesel results are from a very limited sampling of well-maintained vehicles, and may not be representative or typical of diesel engines in general service. Bus designated "STA" was loaned by Sacramento Transit Authority.

All emissions tests, as well as most of the experimental bus operation, were made with No. 1 diesel fuel. With proper

Table 4 - Exterior Sound Levels of Steam and Diesel Buses

	Steam Buses			Diesel Buses			
	Brobeck	Lear	SPS	A-C #678, GM6V-71	STA #408, GM6V-71	MUNI #3309, GM8V-71	SCRTD #7185, Cum. 903
Full-throttle drive-by, microphone at 50 ft	76	85	80.5	78.5	84	86	82
Full-throttle standing start, microphone at 15 ft	74	88	86	88	89	90	94.5
Idle, microphone at 15 ft	68.5	78	78	75.5	78	74.5	75.5

NOTE:

All figures are maximum sound-pressure levels in dB re 0.0002 microbar, "A" weighted scale.

All measurements by California Highway Patrol.

Microphone was placed alongside the roadway, with distances measured from the centerline of path of travel.

Table 5 - Interior Sound Levels of Steam and Diesel Buses

	Steam Buses			Diesel Buses			
	Brobeck	Lear	SPS	A-C #678, GM6V-71	STA #408, GM6V-71	MUNI #3309, GM8V-71	SCRTD #7185, Cum. 903
Full throttle acceleration, just prior to up-shift							
Front	75	74.5	76	75	75	79	73.5
Center	81	81	79	78	79	84	79
Rear	78	84	83	85	84	87.5	82
At idle							
Front	62	63	60	62	63	64	60
Center	67	65	66	68	67	66	65
Rear	66	71	72	72	68	72	69

NOTE:

All figures are maximum sound-pressure levels in dB re 0.0002 microbar, "A" weighted scale.

All measurements by California Highway Patrol.

Microphone positions were along the centerline of the aisle, midway between the floor and ceiling of coach.

adjustment, combustion is virtually smokeless. However, with improper control settings, puffs of exhaust smoke were sometimes observed during load changes. Light odors reminiscent of gas turbine or jet engine exhaust were sometimes noted.

NOISE - The California Highway Patrol made surveys of the sound levels both inside the buses and in the near-field outside environment. The following tests were made:

1. Drive-by, full-throttle tests. A microphone was placed 50 ft from the center of the roadway lane, in accordance with SAE Recommended Practice J366a. As the bus approached the microphone position, it was accelerated at full throttle within a speed range 20-35 mph. Sound levels were measured in both directions of travel.

2. Standing starts. With a microphone placed 15 ft from the center of the lane, sound levels were taken first at engine idle and then under full-throttle acceleration from a standing start. This procedure approximates the perception of a bystander near a bus stop.

3. Interior noise. Sound levels were taken along the centerline of the aisle, at the front, center, and rear of the bus.

Test results are summarized in Tables 4 and 5.

The quietest steam bus was 2.5-10 dB quieter than diesel buses during the 50 ft drive-by tests. Moreover, the quietest steam bus in the 15 ft tests (simulating curb side) was 6-14 dB quieter than the quietest diesel tested. On the other hand, interior sound levels were similar or higher than diesel in several cases. It appears that interior sound levels may be influenced as much by the construction of the bus as by the character of the powerplant.

The Lear system emitted a high-frequency sound characteristic of turbines. It is believed that the transmitted and radiated sound levels of this vehicle, now higher than diesel, can be reduced by techniques that have proved successful in gas turbine practice.

FUEL CONSUMPTION

The demonstration buses, in the present state of limited development, have a very high fuel consumption. The highest cruise fuel mileage of the Brobeck steam bus was 3.5 mpg at 40 mph. Under the same test conditions, a diesel bus can do at least 8-10 mpg. Under actual stop-and-go route conditions,

Table 6 - Fuel Consumption of Steam and Diesel Buses, gvw 25,000-30,000 lb

	Brobeck	Lear	SPS	GM 6V-71	GM 8V-71	Cummins 903 V8
Cruise fuel mileage, mpg						
20 mph	2.4	1.8	2.2	–	4.7	7.7
30 mph	3.5	2.2	2.3	10.2	7.1	11.8
40 mph	3.0	2.3	2.9	–	8.1	10.3
45 mph	–	–	–	8.9	–	–
50 mph	2.5	2.1	2.5	–	7.1	8.8
60 mph	–	–	–	–	–	7.5
Idle fuel consumption, gal/h	4.5	3.2	4.7	0.5	0.65	0.62
Examples of route fuel mileages, mpg						
A-C #58, local	1.1	–	–	3.58	–	–
MUNI #32, local	–	0.7	–	–	3.68	–
SCRTD #83, local	–	–	0.6	–	–	3.02

steam at 0.5-1 mpg was noted against the diesel at 2.3-3.7 mpg. (More characteristics of such routes will be discussed later.) The idle fuel consumption was 3.2-4.7 gal/h for steam, versus 0.5-0.7 gal/h diesel.

Table 6 gives some of the comparative statistics on fuel consumption.

These three steam systems did not achieve specific fuel consumption (sfc) as high as demonstrated possible during the Doble-Besler era. In the present project, bench tests yielded sfc exceeding 1.0 lb/net bhp·h. Ref. 1 cites a bsfc of 0.81 attained by a Doble engine in 1936, presumably based on gross expander output (0.93 possible, if on the basis of net system output). The many reasons for the present excessive fuel rates, and the hope for considerable future improvement, will be given in a later section.

OPERATING CHARACTERISTICS

Driver controls on all buses were arranged to be similar or identical to the original diesel buses. These included foot throttle, air brake treadle, and forward-neutral-reverse selector lever. In addition to the original panel of instruments, a tachometer and a steam-pressure gage were included, together with indicator lights signifying powerplant conditions or incipient problems.

All fire-up procedures were controlled from the driver's seat. Sufficient steam to start the expander can be raised within a minute from a cold switch-on. Careful warmup of the expander is then needed in the case of the reciprocating designs, and this can require an additional 2-5 min. The Lear turbine may be started just as soon as steam is available. All three systems must be driven a few blocks before the entire system is up to temperature and maximum power becomes available. Once the powerplant is hot, it may be restarted within a matter of seconds, even after a lapse of up to 1/2 h.

While all three power systems employed condensers for the recovery of water, none were completely sealed systems. By means of relief valves, excess steam exhaust could be relieved under overload conditions on a hot day. The buses have adequately sized condensers and sufficient fan horsepower, which should have provided a touring range at least equal to a normal day's operation. In practice, however, all the steam buses sometimes fell short of this goal. Earlier in the program, the Brobeck system suffered insufficient water recovery, due to the confined space in which the condensers were mounted. Later, however, the mounting configuration was changed and another condenser core was added, appreciably adding to the water mileage.

The waste heat release from a Rankine-cycle powerplant is appreciably greater than that of ICE. Therefore, much consideration had to be given to directing the heat flow away from the passenger compartment and from bystanders. In the future, much thought will no doubt be given to placing condensers on the rooftop of the vehicle, with both comfort and unimpeded airflow in mind.

SAFETY

Complete operational safety was a firm requirement in this demonstration project. Careful surveillance and control were exercised during all phases, and included design reviews, laboratory proof-testing, and frequent in-service inspections. The following areas of concern and criteria applied:

1. Working fluids which were toxic, flammable, or explosive were not permitted in this program.
2. The steam generators were required to be of inherently nonexplosive designs.
3. Several safety limiting devices were used, such as pressure and temperature limit switches in the automatic steam generator control circuits. Safety valves were also used.
4. Limiting governors were applied to prevent accidental expander overspeed.
5. Flame sensors were installed to stop fuel flow in the event of ignition failure.
6. Driver's controls were simplified and made as similar as possible to those of a standard diesel bus.

Concern is sometimes expressed regarding the possibility of "boiler explosions." In this project, large, pressurized vessels were not permitted as steam-generating apparatus. Hence, a sudden explosive release of the boiler's energy content is not possible with the designs adopted for these buses. A relatively small amount of steam and water is confined to a long, coiled length of tubing (Fig. 8). On a number of occasions, tube failures did occur on the experimental steam generators. These occurrences proved to be inconveniences, rather than presenting a hazard. Because of the large exhaust duct, steam from a tube failure would vent harmlessly to the atmosphere.

Overall, with good design practice and careful workmanship, the potential hazard level of these systems was judged to be similar to that of gas turbines, in which large quantities of fuel are burned in combustors outside of the "engine block."

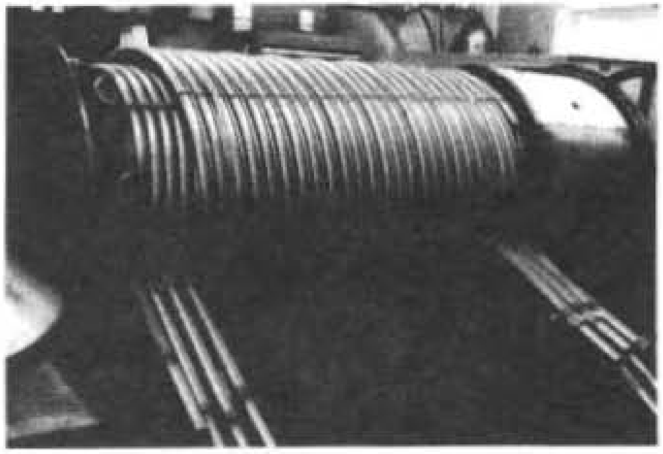

Fig. 8 - Interior view of a steam generator built by Steam Power Systems, Inc. Hot gases, produced in combustion chamber on right, pass through tube bundle. Tubing extensions shown are temporary, for hydrostatic proof testing (courtesy SPS, Inc.)

CONTEXT: URBAN DRIVING CYCLES

When a designer contemplates an unorthodox powerplant for a vehicle, some rather fundamental questions need to be answered. What are the average, maximum, and instantaneous values of power required over a driving cycle? How much time is spent at idle and at low power levels? What are the route profiles in terms of road gradients, speed, and accelerations? These and other characteristics must be understood in order to compile a reasonable set of objectives and specifications. Specifications for a new diesel bus can become almost a routine extrapolation based on recent experience; however, more study and analysis is desirable when the proposed powerplant is relatively unfamiliar. This is particularly true when the visualized power system has a substantial overload capacity, or if it can draw from a reserve of energy storage. A possible consideration with some future powerplants would be the conservation of some of the energy normally dissipated by the brakes.

During the course of this project, diesel- and steam-powered buses were fitted with portable instrumentation for measuring and recording a number of vehicular and route characteristics. Actual bus routes (or segments of routes) were experimentally driven with a constant ballast payload of 4500 lb (representing a partial load of 30 passengers). Simulated passenger stops were made at locations and for the durations observed during previous surveys of passenger-carrying runs. The driver made other stops as dictated by traffic conditions. After each driving cycle test, the portable recording instrument was removed from the bus, and data were fed into a computer. A detailed sequential record, in the form of a computer printout, described characteristics of the route and what the bus did in coping with conditions along the route.*

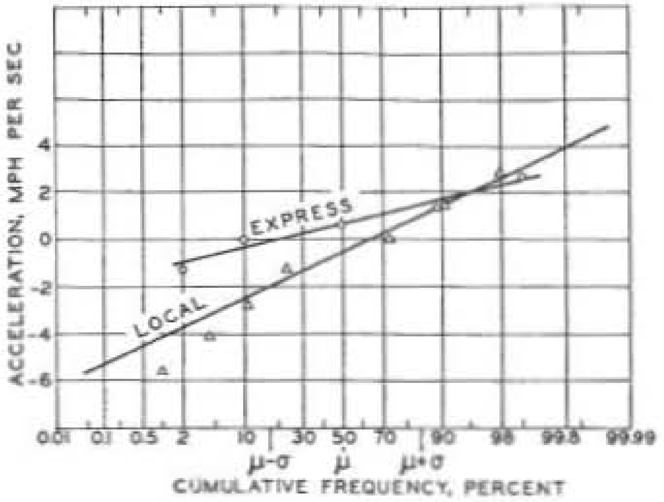

Fig. 9 - Statistical distribution of vehicular acceleration. Routes for Figs. 9-12 were A-C Transit No. 58 (local) and No. R-F (express)

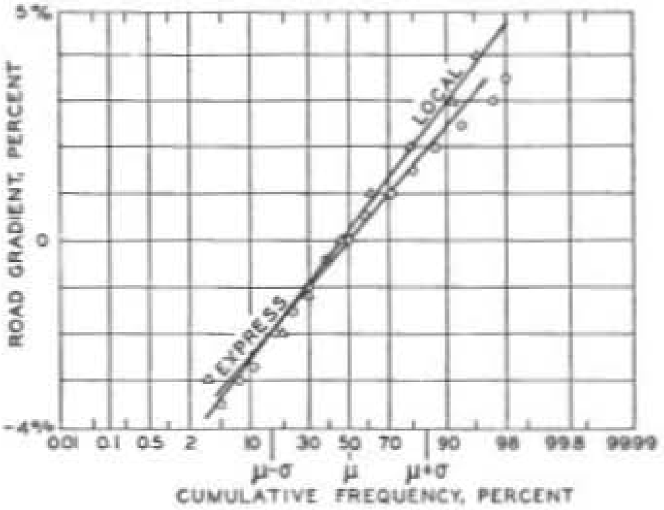

Fig. 10 - Statistical distribution of road gradient

Information on the printouts included these measured or computed values for each route tested: distance traveled, velocity, acceleration, road gradient, road horsepower, engine rpm, totalized propulsive energy, totalized braking energy, fuel consumption, interior sound level, and powerplant variables, such as pressure, temperatures, etc.

The data were also analyzed by statistical methods, for convenient assessment. Sample results are summarized in Figs. 9-12, for two contrasting types of route. The scale of such graphs has been contrived such that a straight-line fit to the data represents a Gaussian normal distribution. The assumption that such statistics as acceleration, road gradient, and horsepower requirements may be approximated by a Gaussian distribution appears well founded. Velocity, too, can be characterized as a Gaussian normal distribution, but only after transformation to log-squared velocity.

An overview of some of the characteristics of several of the routes tested is given in Table 7. It is interesting to observe, for local routes, the low average speeds, the rather low average power requirement (but with a capacity for high peak power being needed occasionally), and the high fraction of propelling energy that is ultimately dissipated in braking

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*Two papers (14, 15) give the rationale and procedures used in determining the properties of vehicular driving cycles.

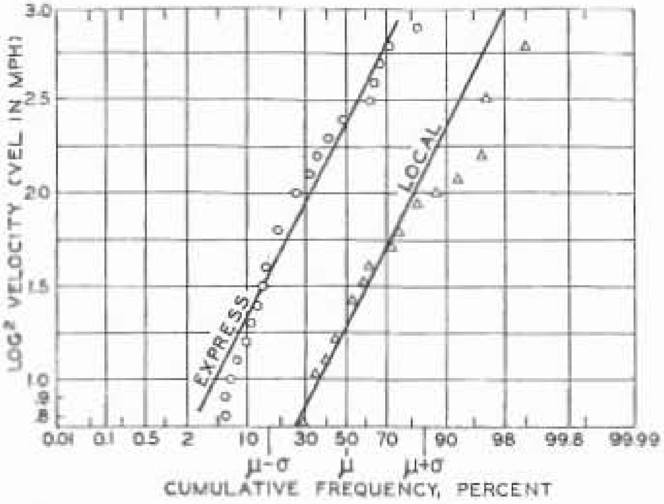

Fig. 11 - Statistical distribution of vehicular velocity, plotted as $\log^2 V$

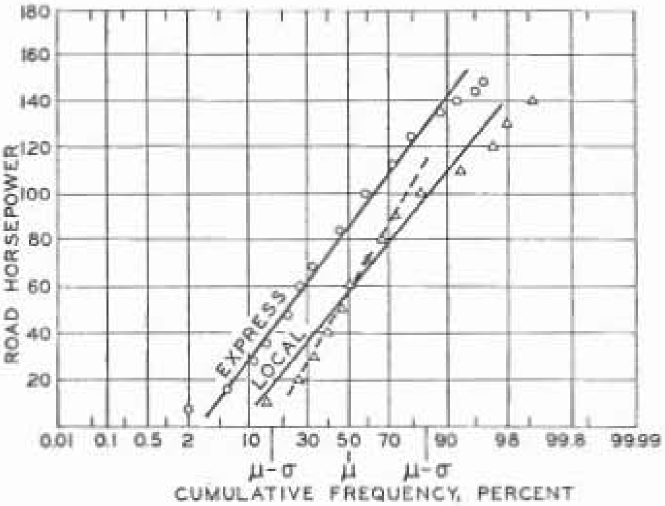

Fig. 12 - Statistical distribution of road horsepower. Dashed line is an optional fit over mid-range of local route data

Table 7 - Characteristics of Urban and Suburban Bus Driving Cycles

	Local, A-C 58	Express, A-C R-F	Local, MUNI 32	Local, MUNI 55	Local, SCRTD 83	Express, SCRTD 60-E
Average speed, mph	10.3	31.2	11.7	9.7	8.5	38.0
Stops per mile	7.1	0.64	4.6	10.2	9.1	0.6
Percent of time at idle	32	7	28	34	42	11
Max upgrade, %	6.1	8.8	8.4	19.3	6.9	8.7
Max downgrade, %	5.3	5.9	11.1	16.2	4.7	5.6
Max hp to rear wheels	138	169	181	210	166	213
Avg hp to rear wheels	24.3	58.7	22.4	42.4	25.9	78.8
Total energy delivered to wheels, hp·h	30.6	55.8	14.2	38.1	29.8	65.7
Energy dissipated by brakes and retarding, hp·h	15.7	11.1	4.1	20.9	13.7	7.8
Fuel mileage with diesel, mpg	3.58	6.15	3.68	2.28	3.02	6.50
Fuel mileage with steam, mpg	1.11	2.05	0.7	0.52	0.6	–

NOTE:
Figures are as tested with diesel coaches, except for comparative steam mpg.
Engines were: A-C, GM 6V-71; MUNI, GM 8V-71; SCRTD, Cummins 903 V8.

(up to 55%). The substantial fraction of the time spent at idle is also worth noting.

Realistic driving cycle data can be extremely useful in many ways:

1. As an aid to writing future powerplant specifications.
2. As background information in powerplant design.
3. Bus duty cycles may now be reproduced in the engine test laboratory. Moreover, power system properties may be simulated by computer for optimization studies.
4. Emissions under road conditions may be calculated, for instance, on the basis of grams per vehicle mission or grams per passenger mile.
5. The benefits of recovery of braking energy may be assessed.

SUMMARY OF PRESENT STATUS

Vehicles developed under this project matched expectations for road performance. It has been demonstrated that steam-powered buses can meet local route schedules to the minute. Acceleration, top speed, and hill climbing have been shown to approximate that of 6-cyl diesel buses. Powerplant output could be scaled to equal 8-cyl diesels, if desired. Exhaust emissions are very low, and comfortably meet the 1975 California Heavy Duty Vehicle Standards. Reductions in NO_x are particularly remarkable, with a sixteenfold reduction over the tested diesels having been observed in the cleanest steam bus. Some of the tests indicated that the ECE can provide greater quietness and smoothness under all operating conditions when compared to diesel power, although interior sound levels are difficult to reduce.

Two out of the three power systems were heavier than conventional diesel systems, and one (Lear) was lighter. All three occupied more space than the ICE. Because the several elements could be separately located, however, it was shown that passenger space need not be diminished (Brobeck).

Familiar and conventional driver's controls were used, so the need for special driver instruction was minimized. Special knowledge was required, however, for the powerplant maintenance. All three buses were used in revenue passenger service, and were demonstrated to be satisfactory in terms of operational safety and passenger comfort. The SPS bus includes air conditioning, effectively driven by shaft power taken from the main expander.

It should be remembered, however, that these converted buses were only intended for use in early demonstrations of potential. They are not preproduction prototypes, for much engineering development would be required before such power systems could measure up to the standards of the transit industry in terms of packaging, reliability, and operating economy.

The fuel economy of the present steam buses is poor when compared to the diesel power, though the discrepancy is not as great if compared with other fledgling systems such as the gas turbine and the spark-ignition engine fueled with natural gas (16, 17). Much can be done to improve fuel economy in the ECE, and this subject will be touched upon in the next section of this paper.

As with any new experimental devices, a great deal of inspection, rework, and maintenance was necessary in the field demonstrations of these vehicles. This led some observers to believe that steam engines would always require a great deal of maintenance, but such a conclusion is certainly not warranted at this early date.

At the present time, all three buses have been retired from active passenger-carrying service, and are being used as experimental test beds by the contractors.

FUTURE POSSIBILITIES

GENERAL OUTLOOK - With the ECE, the problem of air pollution control can be attacked at its roots, namely the physics and chemistry of the combustion process. It may not be an exaggeration to state that a well-perfected ECE would have the potential of being as clean as a fuel-burning engine ever can be. The Rankine-cycle ECE, with its possibilities for a smooth, quiet application of high-torque propelling energy, seems an excellent candidate for the urban vehicle operating under stop-and-go conditions.

Some years of progressive, persistent, and coherent engineering work will be required, however, before the ECE is ready for general application and acceptance. Obvious areas for improvement include those of fuel economy, operating reliability, packaging, combustor technology, automatic controls, and improved transmissions. Winterizing mobile steam powerplants is another important subject, though this would not be as difficult a problem in fleet operations as it would be with privately owned automobiles.

At the same time, much research needs to be carried forward if the appropriate lubricants, metallurgy, working fluids, and control components are to be ready for the ECE of the future.

AN IMPORTANT VIEWPOINT - While reducing fuel consumption may be singled out as a goal of high priority, the subject is important for reasons beyond its impact upon operation costs*. A great many characteristics would be improved if the ECE system thermal efficiency were raised. Some examples are:

1. Specific emissions (grams of pollutant per hp·h) would be decreased even further.
2. Lower steam consumption would reduce the size and weight of the boiler and condenser.
3. When the condenser load is reduced, condenser fan power requirements go down. The resultant parasitic power requirement then reflects back as a further improvement in overall system thermal efficiency.
4. Reduced fan power also means an even quieter powerplant.
5. Environmental heat pollution would be diminished.

Because of these and other crucial interactions, it would seem imperative to examine the ways in which fuel consumption can be reduced. If one can be convinced that fuel consumption can be brought into line, then there is an even greater justification in continuing development work on Rankine-cycle systems.

RANKINE-CYCLE THERMAL EFFICIENCY - Questions regarding the fuel economy of any power system may be analyzed in terms of the system's thermal efficiency. If a power system were placed on a bench test, the overall thermal efficiency could be determined using the following relationship:

$$E_{th} = \frac{\text{Actual net output power}}{\text{Rate of fuel energy input}} \quad (1)$$

E_{th} is obviously always lower in value than the efficiency of the ideal thermodynamic cycle, E_i, since the ideal cycle does not take into account friction, parasitic accessory loads, miscellaneous heat losses, and the like. Values of E_i for an arbitrary example of a Rankine cycle have been calculated and plotted on the upper curve of Fig. 13. These values are seen to increase when temperature of the feed steam is increased. (The calculations were based upon steam at an initial pressure of 1000 psi, expanded to 20 times initial volume in an ideal expander, and then returned to the boiler as condensed water at 200 F.)

Thermal efficiencies that can be realized in practice are shown in the shaded region of Fig. 13. For example, if steam at 800 F were used, the ideal cycle efficiency would be

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*Fuel costs are only about 3% of the total annual costs of urban transportation systems. Maintenance costs are around 15%.

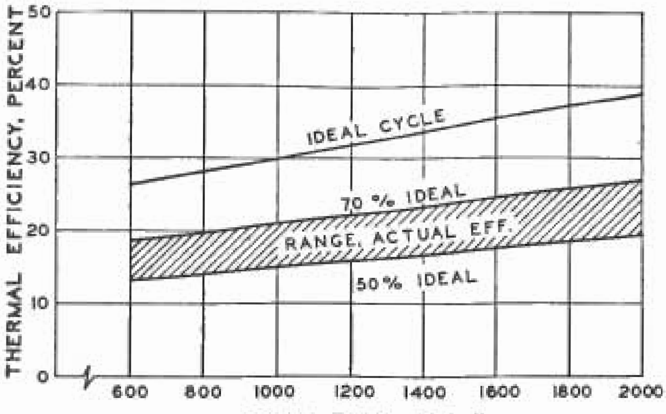

Fig. 13 - Range of ideal and actual Rankine cycle thermal efficiencies, as influenced by steam temperature

around 28%, but E_{th} of an actual system would be in the range of 14-20%.

Bench tests of the three nonoptimized bus systems showed full-load sfc of 0.985-1.18 lb fuel/net bhp·h, which corresponds to E_{th} = 11.7 - 14%. These values fall somewhat below the E_{th} range given in Fig. 13. This is partly because the ideal cycle efficiencies were less than those shown in the figure, but mostly because of incomplete expansion and very high parasitic loads.

When installed in the vehicles, E_{th} suffered even further. At high loads in the buses, exhaust (condenser) pressures rose, while at lower loads, parasitic effects took a proportionately higher toll. As installed, the systems could be characterized as E_i = 25%, and E_{th} = 10%, approximately. As presently will be discussed, many potential opportunities exist to greatly improve upon this state of affairs.

VEHICULAR EFFICIENCY AND FUEL ECONOMY - What really matters is the overall vehicular thermal efficiency, E_v, in terms of power actually delivered to the rear wheels. Fuel economy, in mpg, is determined primarily by the powerplant efficiency, E_{th}, multiplied by the power transmission efficiency, E_t. Values for E_t can vary from zero (a hydraulic torque converter at stall) to numbers approaching 90% (losses would be in gears, bearings, universal joints, etc.) If (as an estimate) the mean transmission efficiency in stop-and-go service were 60%, and the powerplant E_{th} were 10%, the overall E_v would only be 6%.

Another factor influencing route fuel economy is the idle fuel rate of the powerplant. We have seen from the route-cycle testing that up to one-third to one-half of the route time may be at idle.

OPPORTUNITIES TO IMPROVE FUEL ECONOMY - Having identified the causes of low efficiencies in the present steam vehicles, it should be possible to make substantial improvements in fuel economy in the near future. Fruitful areas for engineering development include:

1. Raising the ideal cycle efficiency (E_i). Obvious improvements can be made by increasing the temperatures of the steam or other working fluid. This route has been followed in gas turbines, with working fluid temperatures raised from 1500 to 2000 F in 15-20 years development (18, 19). Alternatives to simple Rankine cycles can also help, such as the use of reheat, regeneration, and binary vapor concepts. As-installed values of E_i can be increased from the present 25% to 30% in the near term, and 32-35% or more eventually.

2. Approaching the ideal more closely. Present actual thermal efficiencies are as low as 40% of the ideal. Sixty percent of E_i may be attainable in the near term, maybe 70% eventually. Major gains can be made in reducing parasitic auxiliary loads and by increasing expansion efficiencies. Smaller, but worthwhile, advances can be made in reducing boiler heat losses and mechanical friction. One example, for the reduction of powerplant auxiliary load, is the possible improvement in condenser fans. Over 30 hp is presently used to drive such fans in some of the installations. By the use of more efficient fans and fan drives, this can be reduced to 10-15 hp. It would also be possible, as in later Doble developments, to use exhaust blow-down turbines to drive condenser fans (3). This would not only reduce the consumption of premium shaft power even further, but would convert additional heat to productive work.

3. Reducing transmission losses. Heavy losses were suffered with the transmissions used in the present program, because available units were a poor match to expander characteristics. In the case of reciprocating steam engines, a direct drive (or at least to eliminate the hydraulic torque converter) would increase vehicular thermal efficiency appreciably. Transmission improvements are also possible for turbine expanders, which would allow the turbine to operate more of the time at peak efficiency.

4. Reducing idling fuel consumption. The use of a small auxiliary expander could reduce the idling fuel consumption to one third the present idle fuel rate.

5. Integrating energy services. Functions such as air conditioning and vehicular retarding could be integrated into the power system in ways conducive to energy conservation.

Some of the possibilities for improving the fuel economy of ECE-powered vehicles are given in Table 8.

POSSIBLE TRENDS IN REDUCING EMISSIONS - Even though the emissions demonstrated in this program were acceptably low, further reductions can be obtained by:

1. Reducing the amount of pollutants generated per pound of fuel burned (cleaner combustion).

2. Reducing, in turn, the amount of fuel burned per hp·h of work produced.

The burners produced in this early program were designed and built without the benefit of extensive combustion research. Meanwhile, a new body of pertinent research information is becoming available through contracts sponsored by the Advanced Automotive Power Systems (AAPS) program of the Environmental Protection Agency (20). One of the contractors has, in steady-state burner tests, demonstrated

Table 8 - Growth Potential for Efficiency and Fuel Economy of Steam Propulsion Systems for Buses, Compared with Present Diesel

	Steam, Present	Steam, Near Future	Steam, Eventual	Diesel, Present
Ideal cycle efficiency	0.25	0.30	0.35	-
System net thermal efficiency	0.10	0.15*	0.21*	0.30
System bsfc, lb/bhp·h**	1.38	0.92	0.66	0.46
Transmission efficiency, example	0.60†	0.85††	0.85††	0.60†
Vehicular thermal efficiency	0.06	0.13	0.18	0.18
Idle fuel rate, gal/h	4.5	1.5(a)	1.0(a)	0.5
Calculated fuel mileage, mpg, hypothetical local bus route (b)	1.0	2.3	3.3	3.5

*Sixty-seventy percent of ideal cycle efficiency may be attainable under test conditions in the near-term and eventual configurations, respectively. However, in vehicular applications, off-peak conditions will occur during some fraction of the operating time for either variable cutoff or turbine expanders. Therefore, the values of these modifiers have been reduced to an assumed mean of 50% and 60%, respectively.

**As-installed operating conditions.

† Assumed mean E_t with torque converter operating at high slip a substantial fraction of the time.

†† Direct-geared drive assumed, or high-efficiency transmission developed for turbine.

(a)Separate small expander maintains only essential idle load.

(b)One local route tested required 2.4 hp·h of propulsive energy per mile, and had 2 min of idle time per mile.

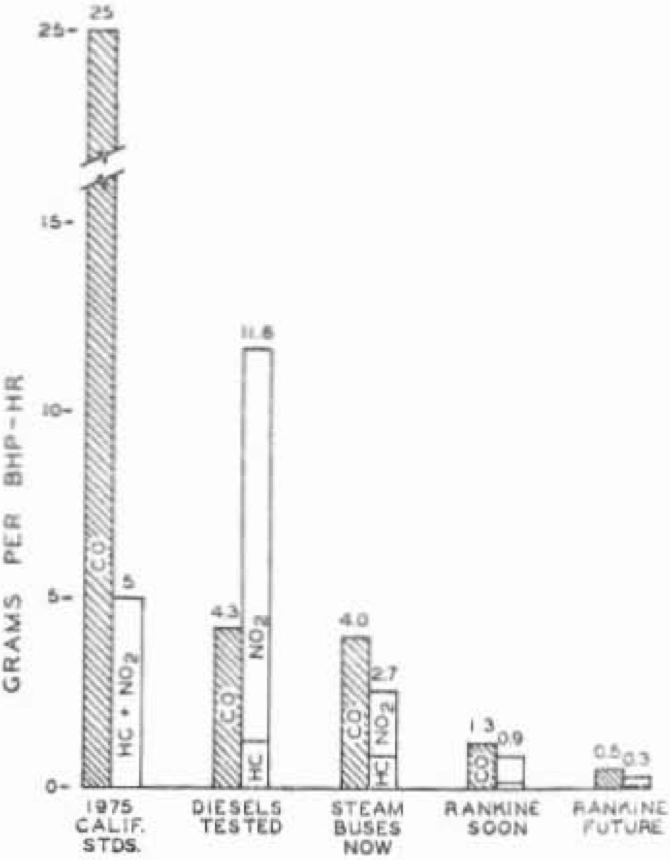

Fig. 14 - Exhaust emissions compared, together with future projections

less than one-fourth of the CO, one-tenth the HC, and one-third the NO_x found in some of the better steam bus test runs (on the basis of grams pollutant per unit mass of fuel burned). To be conservative in extrapolation, it might be expected that at least half of these indicated reductions could be obtained in the form of a system developed in the near future. The full reductions certainly ought to be feasible eventually in heavy-duty vehicle engines employing the Rankine cycle.

From Table 8, the projected bsfc can probably be reduced to 67% of present levels with near-term development, and to 48% eventually. Combining the effects of cleaner combustion and reduced fuel consumption, then, we may expect future reductions, as depicted in Fig. 14.

PROGRESS IN PACKAGING - Much was learned from the recent installations in regard to packaging, even though the work was conducted on the basis of ad hoc retrofit. It was found, for example, that the Rankine system offers considerable flexibility in the placement of the major elements in the chassis. While the total volume occupied by the ECE will probably always be greater than the space occupied by the present diesels, it has been shown that seating capacity need not be reduced. Powerplant weight can be less than diesel systems. Both volume and weight will diminish as the thermal efficiency is increased in the future.

Because of the large heat release from the condensers, consideration should be given to mounting these units on the roof in future designs. Under-floor mountings proved unsatisfactory from many points of view, including problems with cooling air circulation, the gathering of dirt, and heat release. The Lear side-mount condensers were much better, with outside air drawn inward by the fans. This led to engine compartment temperatures that were higher than desired, however.

Fig. 15 shows progress that is being made in the increase of specific output of Rankine power systems. Such trends, coupled with the visualized future increases in thermal efficiency, are indeed encouraging to those concerned with packaging.

COST PROJECTIONS - More engineering and testing must be done before such factors as first cost of powerplants can be accurately forecast. For the present, a fairly reliable guide is the cost per pound of manufactured products, with allowances made for any premium or nonstandard materials or fabrication techniques required (21). Steam systems are likely to cost somewhat more per pound than diesels, but may be lighter in weight. Even if the ECE remains higher in first cost, it is almost a certainty that future ICE systems will become more expensive as the demand for cleanliness and quietness increases. Unit costs are, of course, sensitive to the production quantities involved. Clearly, since the urban bus market represents less than 5000 units per year in the foreseeable future, commonality with other segments of

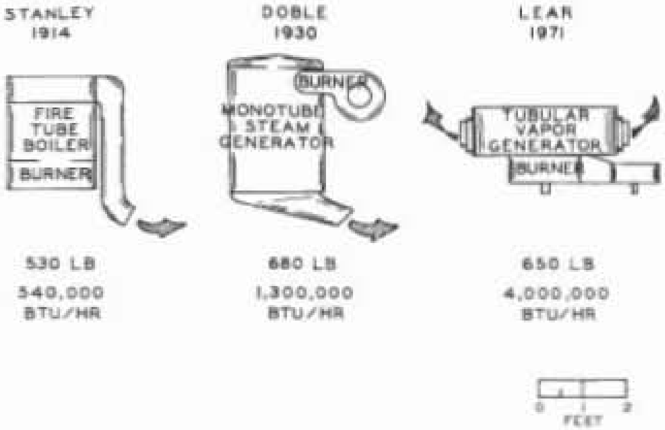

Fig. 15 - Trends in steam generator specific power outputs. Lear vapor generator shown is a research unit; vapor generator installed in bus was similar in size but somewhat heavier in construction

the heavy-duty engine market will be needed for the costs to become reasonable.

Eventual maintenance costs also remain a matter of speculation. A whole-vehicle comparison must be made, since a possible outcome might be reduced costs to service brakes and transmissions, but with new attention demanded by steam generators and controls. Expander maintenance (if a turbine) would be less than with the present basic engine block, but would be similar with reciprocating expanders.

Fuel costs can approach the economy of a diesel if the ECE becomes sufficiently well developed, but only for stop-and-go service where the present diesel and its transmission operate at a disadvantage. It does not seem likely that diesel fuel economy under steady cruise conditions (long-haul) will be exceeded for a long time to come.

It is not obvious that any cost advantage would result from the use of the ECE compared to the present diesel equipment. Costs over the vehicle's life would, with sufficient development, be similar. However, the benefits of cleanliness and quietness can greatly exceed those available with the diesel, while the diesel would almost certainly become considerably more costly, complex, and bulky in attempts to meet tighter standards.

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