CALIFORNIA STEAM BUS PROJECT FINAL REPORT

Assembly Office of Research
California Legislature
Sacramento
January 1973

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This report is the product of a project sponsored by the California State Assembly and financed in part by the U.S. Department of Transportation, Urban Mass Transportation Administration. The contents of this report reflect the views of the Assembly Office of Research which is responsible for the facts and accuracy of the data. The contents do not necessarily reflect the official views or policy of the Department of Transportation, nor does the report constitute a standard. specification or regulation.

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INTRODUCTION

Since 1959, the California Legislature, mindful that motor vehicles are a major source of air pollution, has developed increasingly stringent automotive emission standards. A vital part of such legislative action is the development of factual data, in support of tight but realistic standards.

During 1967-68, studies and hearings by both state and federal agencies revealed that certain alternatives to the internal combustion engine (ICE) might be feasible as low-emission automotive powerplants. One alternative is the external combustion engine (ECE), in which fuel is burned continuously and completely to generate power. There are several types of ECE, but the most familiar is the steam engine, technically known as a Rankine cycle engine. The studies and hearings suggested that the ECE, far from being an outmoded concept, could become a workable alternative to the ICE, with the aid of modern technology. With this in mind, the California State Assembly decided to sponsor the demonstration and evaluation of ECE propulsion systems. This work was supported in part by a grant of funds from the Urban Mass Transportation Administration of the U.S. Department of Transportation.

The purpose of the California Steam Bus Project was to evaluate the technical feasibility and public acceptance of the ECE as a low-emission, quiet propulsion system, using city buses as demonstration vehicles. Emphasis was to be placed on the early demonstration of potential, rather than extensive development or technical perfection. The title "Steam Bus" was adopted after the project's engineering contractors chose Rankine cycle systems to exemplify the ECE.

Engineering development work began in June, 1970. Three contractors developed and installed steam propulsion systems in three 40-foot urban transit coaches, replacing the original diesel engines. The three steam buses were tested and demonstrated in the metropolitan areas of Oakland, San Francisco, and Los Angeles. The buses traveled 8,372 road miles under steam power, including about 800 miles in revenue passenger service. The program ended on September 30, 1972.

FINDINGS

The following is an abstract of the findings of the Steam Bus Project. Tables of supporting data are presented in the Appendix.

Performance. Steam bus acceleration, top speed and hill climbing were equal to or exceeded road performance of buses powered by six-cylinder diesel engines.

Emissions. In tests by the California Air Resources Board, all steam buses were well below the 1975 California emission standards for heavy duty vehicles, but none of the diesel buses tested came close to meeting the requirements for hydrocarbons and nitrogen oxides combined. When the cleanest steam bus was compared to a composite of the cleanest diesels tested, the steam bus produced 30.5 percent less carbon monoxide (CO) and 86 percent less hydrocarbons (HC) and nitrogen oxides (NO_x). The cleanest steam bus registered a 94 percent reduction in NO_x when compared to the cleanest diesel tested.

Noise. In measurements by the California Highway Patrol, the quietest steam bus was 2.5 to 10 decibels below the quietest diesel buses in drive-by tests and 6 to 14 decibels below in curb-side tests. On the other hand, interior sound levels were similar or higher than diesels.

Fuel Consumption. In the steam bus' state of limited development, fuel consumption was high. Diesel fuel consumption rates during actual stop-and-go route conditions were more than three times lower than the best steam bus. Diesel fuel mileage at a steady 30 m.p.h. was two to three times better than the best steam bus. Idle fuel consumption rates showed even a wider margin for diesel buses. Although fuel economy of present steam buses is poor when compared to diesel power, the discrepancy is not as great when compared to fledgling systems, such as the gas turbine and spark-ignition engines fueled with natural gas.

Operating characteristics. Conventional driver controls were used, minimizing the need for special driver instruction. Water recovery was inadequate, but startup times, performance and drivability were equivalent to fleet requirements for existing diesel equipment. Special knowledge and extensive attention were required, however, for powerplant maintenance.

Revenue service. Steam buses usually were able to duplicate time schedules of diesel buses in actual revenue passenger service. All buses demonstrated satisfactory performance in terms of operational safety and passenger comfort. One bus provided air conditioning, which was effectively driven by shaft power taken from the main expander. Riders interviewed on the steam buses indicated a high degree of user acceptance for these experimental vehicles.

Composite picture. Although not all three installations showed every potential attribute of an ECE, a composite picture demonstrated that steam buses can equal road performance of diesel buses. One bus was considerably quieter than the diesels. One system was lighter in weight than present diesel powerplants. Although all three systems occupied more space than diesels, one bus demonstrated that passenger space need not be diminished if the several components of the powerplant are located separately. Another system met almost all space requirements within the existing engine compartment. As with any experimental device, a great deal of inspection, rework and maintenance was necessary in field demonstrations. It must be emphasized, however, that these buses were converted only for use in an early demonstration of feasibility and potential. They are not pre-production prototypes, and much engineering development would be required before such power systems could meet transit industry standards for system layout, reliability and operating economy.

Potential for fuel consumption improvement. With progressive engineering over a two-year period, the fuel consumption of steam buses could be improved until it is only 52 percent more than present diesel in stop-and-go service. Improvements in the transmission and powerplant would be required to achieve this reduction. Eventually, fuel consumption could be improved until it is only 6 percent more than present diesels.

Potential for emissions improvement. Emissions of steam buses could be reduced significantly by developing cleaner burners and by consuming less fuel. Within two years, present steam bus emissions of CO could be reduced by 68 percent and HC plus NO_x by 67 percent. Eventually, steam bus emissions of CO could be reduced by 88 percent of present levels and HC plus NO_x by 89 percent.

CONCLUSION

The California Steam Bus Project successfully achieved its goals. Both the mission and the organization may appear unorthodox, but the involvement of many concerned private and public entities at an early date was very beneficial.

Steam propulsion systems were the first alternate power systems to be visibly supported by the public sector. Continued research and development is essential, if not for steam alone, then to legitimize other possible alternatives. This is the only way to insure that the sources of vehicular air pollution can be corrected, if attempts to control existing power systems fail. Acceleration of low-emission engine development appears to be among the more pressing needs in society. Public agencies have responsibilities to support both the technology and the market. Buses are, in a sense, merely symbolic of the variety of vehicles that could benefit from needed powerplant improvements.

RECOMMENDATIONS

Rankine cycle engines were found to have attributes that are needed in urban transportation. With further development, present drawbacks, such as high fuel consumption, can be eliminated or considerably reduced. Advantages, such as engine braking, can be developed in the future. The Assembly Office of Research, therefore, recommends the following:

1. We recommend the continued exploration of the Rankine cycle by developing an application for heavy duty vehicles in a basic research and development program.

2. We caution that many years of progressive and persistent engineering will be needed to make Rankine cycle powerplants technically feasible. Such a program should consist of the following elements:

(1) A frontal attack on technical problems identified by the California Steam Bus Project and other programs.

(2) Stress on design engineering and bench testing, rather than studies and demonstrations.

(3) Exploration of both turbine and reciprocating expanders, because it is not yet clear which form is superior for heavy-duty, stop-and-go vehicles.

(4) Use of the research work on Rankine cycle components and systems currently sponsored by the Environmental Protection Agency for automotive application.

(5) Funding at no less than $20 million over a four-year period.

3. If the above development phase clearly indicates the potential of this alternate system, we recommend that the federal government make the policy decisions that will be required to achieve the reality of low emission vehicles for urban areas, including automobiles, trucks and buses.

4. We encourage all state legislatures to follow California's lead by considering the need for market support if a suitable alternate propulsion system is developed. Such a need could be addressed by the following threefold legislative program:

(1) Establish low emission vehicle certification programs that rank propulsion systems by their cleanliness and performance.

(2) As a matter of public policy provide incentives, such as subsidies or tax relief to heavy duty vehicle users for purchasing low emission fleet vehicles, especially because such vehicles may be available only at premium prices.

(3) Legislate more stringent heavy duty vehicle emission standards for urban areas when clean alternatives are available, after fleet operational feasibility is demonstrated and low emission experience is validated.

PROJECT HISTORY

The California State Assembly submitted a grant application to the Urban Mass Transportation Administration (UMTA) of the U.S. Department of Transportation on December 17, 1968, seeking funds to demonstrate and test ECE systems in city buses. This application was approved on February 17, 1969, making this the first major research grant made to a state legislative body.

Qualified suppliers of ECE systems were sought by means of a Request for Proposals issued on May 1, 1969. Replies from potential suppliers revealed that ECE systems, far from being available off-the-shelf, would require extensive engineering development before any demonstration could be scheduled. With this knowledge, the program was restructured to provide time and funds for development and new proposals were solicited.

On September 20, 1969, a panel of eight experts appointed by the Assembly selected the three best qualified system vendors.

The actual work of designing and developing these steam power systems began with the signing of engineering contracts in June, 1970. Each system vendor was paired with a transit district as follows:

1. William M. Brobeck & Associates, Berkeley, California with neighboring Alameda-Contra Costa Transit District (AC Transit) headquartered in Oakland.
2. Lear Motors Corporation, Reno, Nevada with the San Francisco Municipal Railway (S.F. Muni).
3. Steam Power Systems (SPS), San Diego, California, with nearby Southern California Rapid Transit District (SCRTD) in Los Angeles.

Overall direction was provided by the Assembly Office of Research. This office was assisted by two systems management firms. The first was Scientific Analysis Corporation (SAC), a non-profit research firm in San Francisco, which was to administer the project on a daily basis, conduct public and patron attitude surveys and supervise making of a documentary motion picture. The second was International Research & Technology Corporation (IR&T), a Washington, D.C. firm, which was to monitor and report technical progress and evaluate bus performance through a field office in San Ramon, California. Kerry Napuk was made project manager by SAC and Roy Renner became project technical manager for IR&T. These system managers represented the Assembly on all matters of administration, coordination and evaluation.

AC Transit and SCRTD contributed late model coaches to be retrofitted to steam power. Lear Motors furnished its own bus and powerplant for lease to S.F. Muni. The Bay Area Educational Television Association, KQED, in San Francisco, was selected to film project activities. Exhaust emissions were tested and evaluated by the California Air Resources Board. The California Highway Patrol measured sound levels and performed motor carrier safety inspections. Support also was provided by the Assembly Rules Committee staff, the Auditor General's Office, Division of Highways, Department of Public Health and the Office of Insurance. During special demonstrations, assistance was provided by D.C. Transit and the Sacramento Transit Authority.

William Brobeck & Associates was the first to complete installation work and have a steam bus operational, in September, 1971. This bus was delivered to AC Transit on September 27, 1971. The Lear installation was first operated in January, 1972 and delivered to San Francisco on July 20, 1972. Steam Power Systems completed installation in March, 1972 and brought the bus to Los Angeles on August 7, 1972.

In addition to participating in engineering testing and fleet trials, these experimental vehicles were involved in two major demonstrations.

The Brobeck-AC Transit steam bus was demonstrated in Washington, D.C. on November 17, 1971, in conjunction with a Steam Bus Symposium sponsored by UMTA and the U.S. Department of Transportation. During its stay in the nation's capitol, the first modern steam bus traveled more than 75 miles and carried nearly 500 people in showings to Department of Transportation officials, members of Congress and symposium guests.

On April 26, 1972, all three steam buses were demonstrated before members of the California Legislature in Sacramento.

Financially, the original grant application requested $450,000. This figure proved to be inadequate and California made application for added funds which were subsequently approved. At the end of the program, federal funds totaled $2,294,525. Local contributions of about $5.7 million were made to the project by the state, the transit districts, and by the system contractors. Thus, the total project cost was approximately $8 million. The largest share was the local contribution made by the system contractors, approximately $5.5 million.

TECHNICAL EXPERIENCE

Introduction

During the experimental period, the three contractors were encouraged to develop their own design approaches. Each vendor considered or implemented more than one design which benefited the project. Reciprocating, rotary and turbine engines reached preliminary bench test stages. A number of working fluids other than water were examined. Several variations of control systems, auxiliary drives, feed pumps and burners went onto an expensive junk pile before vehicles became operational.

The final systems had some features in common. All used water as the working fluid. All vendors generated steam in forced-circulation, continuous-coil tubular steam generators. Steam temperature control was by the "normalizer" principle in which supplemental water is injected into the superheater as required. Condensing was by fan-cooled, tinned tubular radiators. While a variety of liquid fuels may be used. No. 1 diesel was selected because it was the standard fuel of the industry.

Because time was an important factor, many technical compromises had to be accepted. As an expedient, commercially available multi-ratio automatic torque converter transmissions were used, even though these converters were not well matched to steam expanders. Fixed cut-off was used in the piston engines instead of the more difficult but much more efficient variable cut-off types. The main expanders were used to drive accessories at idle, although more efficient methods were known. Development of engine retarding with a piston engine, although desirable. was bypassed in this program. Complete operational safety, on the other hand, was a mandatory requirement, which all vendors met satisfactorily.

System descriptions

William M. Brobeck & Associates. The Brobeck system was an outgrowth of the automatic monotube steam generators and compound-expansion piston engines developed earlier by Doble and Besler. The steam generator and its automatic controls were mounted in the engine compartment at the rear, while other system elements were located amidships under the floor as shown in Figure 1. All accessory and auxiliary units were belt driven from pulleys on the forward end of the engine carnkshaft. Condenser fans were remotely driven by hydraulic motors. The transmission was a Dana-Spicer model 184 with two speed torque converter unit, which locked up into direct drive at 28 m.p.h.

Brobeck's steam generator was of the continuous-coil, forced-circulation type, using about one quarter mile of small diameter tubing which is shown installed in Figure 2. Both tangential and axial burner firings were explored, with the former yielding better results in this configuration. The burner used a single air-atomizing nozzle, with automatic switching among four steady state levels: off, idle, low fire and high fire.

Brobeck's expander had three double acting cylinders. Compound expansion was used, with one high pressure cylinder exhausting into two low-pressure cylinders. As an expedient, a non-reversible fixed cut-off valve gear was used. By placing the system components in existing spaces, the original seating capacity for 51 passengers was retained. AC Transit's coach was a 1969 General Motors bus, which, like all other vehicles in this program, was 40 feet long and 102 inches wide, weighing between 21,000 and 22,000 pounds unladen.

Lear Motors Corporation. The Lear system differed strikingly from the other two in its use of a turbine as an expander. All major components are placed in the engine compartment, which had to be enlarged to accomodate the steam generator configuration and regenerators and, thereby, reduced the original seating capacity by five passengers. Lear Motors supplied their own 1970 General Motors bus.

Lear Motors' steam generator featured a radial outflow of hot cornbustion gases through the tube bundle. During development. several types of burners were tried. including vaporizing, mechanical atomizing and air atomizing, with the latter finally adopted.

This vehicle appears to be the first in history to be successfully propelled by a steam turbine. The single stage impulse turbine was small, with a wheel diameter of 5.6 inches, and rotated at high speed, up to 65,000 r.p.m. Reduction gearing of 34 to 1 connected the turbine through an Allison HT-740 four-speed automatic transmission to the rear axle. Most auxiliaries also were driven from the speed reducing gearbox, including the feed water pump, two condenser fans and burner blower. Figures **3** and 4 show the general arrangement of this powerplant and its installation in the demonstration bus.

Steam Power Systems, Inc. The SPS powerplant featured a six-cylinder, double-acting compound-expansion engine. Steam was reheated between the two expansion stages. Steam generation was by a series-parallel tubular boiler, with an additional section for the inter-stage re-superheating. The steam generator, expander, auxiliaries and one condenser were located in the rear engine compartment, which was enlarged at the sacrifice of five rear seats for passengers. Three additional condensers were located under the bus, just behind the front axle. Installed components in SCRTD's 1968 Flexible bus are shown in Figures 5 and 6.

Of the three buses, the SPS bus was the only one to provide air conditioning and retain the original transmission, a GM-Allison Super V, and angle-drive rear axle. Two significant innovations were carried to bench test, but were laid aside when time did not permit development. One attempted innovation was the use of infinitely variable cut-off valve gear, which would allow engine speed control without a throttling valve while being conducive to high thermal efficiency. Another attempt was the elimination of oil lubricants in the steam cylinder, which would avoid the problem of oil carryover into the condenser and boiler.

Safety. Complete operational safety was a firm requirement with surveillance and control exercised during all phases, such as design review, laboratory proof-testing and frequent in-service inspections. The following criteria were applied:

1. Toxic, flammable or explosive working fluids were not permitted.
2. Steam generators were designed to be inherently nonexplosive.
3. Several safety limiting devices were used, such as pressure and temperature limit switches in the automatic steam generator control circuits, as well as safety valves.
4. Limiting governors were applied to prevent accidental expander overspeeding.
5. Flame sensors were installed to stop fuel flow in the event of ignition failure.
6. Driver controls were simplified and made as similar as possible to those for a standard diesel coach.

In this project, large pressurized vessels were not permitted for steam generation, which eliminated any possibility of a sudden explosive release of the boiler's energy content. A relatively small amount of steam and water is confined to a long coiled length of tubing as shown in Figure 5. On a number of occasions, tube failures did occur in these experimental steam generators, but they proved to be inconveniences rather than hazards.

Because of good design practice and careful workmanship by system vendors, the potential hazard level of these systems was judged to be similar to that of gas turbines, which have large quantities of fuel burned in combustors outside an engine block.

Road performance. These steam powered vehicles are capable of equaling or exceeding road performance of buses powered by six-cylinder diesel engines. Steam buses could usually duplicate, to the minute, time schedules achieved by diesel power during revenue passenger service.

Because torque-converter transmissions were used, there was little opportunity to take advantage of the favorable torque rise, high stall torque and potential retarding effort inherent in steam engines.

Emissions. Several tests were made of exhaust emissions of diesel and steam buses by the California Air Resources Board. Results confirm that the ECE can produce low exhaust emissions even though the steam buses consumed significantly more fuel. All steam buses met the 1975 California heavy duty vehicle standards, which limit carbon monoxide emissions to 25 grams per brake horsepower hour (bhp/hr) and hydrocarbons and nitrogen oxides combined to 5 grams per bhp/hr. While diesel buses tested easily met the CO requirements, none came close to meeting the combined HC and NO_x limits.

When the cleanest steam bus was compared to a composite of the cleanest diesel bus test data, the steam bus produced 30.5 percent less CO and 86.0 percent less HC and NO_2. Of special interest was a 94.0 percent reduction in NO_2 recorded by the cleanest steam bus. Testing was done with a chassis dynamometer, with emissions sampled during 13 separate steady-state modes of speed and load. This procedure does not include any road load transients during sampling, but transients from boiler and burner to hold a given road load were integrated into test results.

All emissions tests were made with Number One diesel fuel. With proper adjustment, combustion is virtually smokeless. During testing, smoke opacity numbers were similar to that of well-maintained diesels, with readings generally of one to three percent except for occasional visible smoke when loads were changed. Light odors reminiscent of gas turbine or jet engine exhaust were sometimes noted.

Noise. The California Highway Patrol made surveys of sound levels both inside the buses and in the near-field outside environment. Three types of tests were conducted: first, drive-by, full throttle: second, standing start: and third, interior.

Test results are in the form of decibel readings, which are comparative measures ofsound-pressure levels. A logarithmic scale is used; thus, a reduction of three decibels corresponds to a 50 percent reduction of sound levels.

During drive-by tests, the quietest steam bus was 2.5 to 10 decibels below diesels at a distance of 50 feet. Moreover. the quietest steam bus in simulated curb-side tests was 6 to 14 decibels below the quietest diesels tested. On the other hand, interior sound levels were similar or higher than the diesels, with the exception of the latest results for the Brobeck powerplant installation.

The Lear system emitted a high frequency sound characteristic of turbines. It is possible, however, that transmitted and radiated sound levels of this vehicle, now higher than diesels, can be reduced by techniques proven successful in gas turbine practice.

Fuel consumption. Steam buses had very high fuel consumption. The best cruise fuel mileage of the Brobeck power plant was 3.5 miles per gallon (mpg) at 30 m.p.h., while a diesel bus can achieve 7 to almost 12 mpg under the same conditions. During actual stop-and-go route conditions. steam fuel rates of 0.6 to 1.1 mpg were noted compared with diesel rates of 3.02 to 3.68 mpg. Idle fuel consumption was also high, with steam systems using 3.2 to 4.7 gallons per hour compared with diesel figures of 0.5 to 0.65 gallon per hour.

Operating characteristics. Driver controls on all steam vehicles were similar to those on the diesel coach before conversion. These controls included a foot throttle. air brake treadle and forward-neutral-reverse selector lever. In addition to the original panel instruments, a tachometer and a steam pressure gauge were included along with indicator lights signifying powerplant conditions and incipient problems.

All fire-up procedures were controlled from the driver's seat. Sufficient steam to start the expander was available within a minute from a cold switch-on. While careful warm-up of the expander required an additional two to five minutes for systems with reciprocators, the Lear turbine could move as soon as steam was ready. All three steam systems had to be driven for a few blocks before the entire system reached proper temperatures and maximum power was available. Once the powerplant is hot, however, it may be restarted within a matter of seconds. even after a lapse of 30 minutes.

Although all three power systems employed condensers for recovery of water, none was a completely sealed system. By means of relief valves, excess steam exhaust could be relieved under overload conditions on a hot day. The original goal was a touring range at least equal to a normal day's operation for diesel buses. **In** practice, however, all steam buses sometimes fell short of this goal. because of unfavorable condenser mounting configurations (Brobeck and SPS) and periods of insufficient turbine operating speed (Lear).

Waste heat release from a Rankine cycle powerplant is appreciably greater than that of internal combustion engine systems. Much consideration. therefore, was given to directing heat flow away from the passenger compartment and bystanders.

Urban driving cycles. During the project. diesel and steam buses were fitted with portable instruments for measuring and recording a number of vehicular and route characteristics. Urban bus routes were then experimentally driven with a constant ballast payload of 4.500 pounds. representing a partial load of 30 passengers. Several types of driving cycles encountered by urban and suburban buses were thereby identified and used as a basis for evaluating bus performance.

PUBLIC SERVICE EXPERIENCE

Steam buses entered revenue passenger service in the cities of Oakland, Berkeley, Hayward, San Francisco and Los Angeles. The longest individual public service was eighteen operating days; the shortest was two. Several special demonstrations were provided, however, before and after delivery of the steam buses to their assigned transit districts. These three vehicles accumulated a total of 8,372 road miles, including about 800 miles while carrying paying passengers.

Public experience on a district-by-district basis was as follows:

AC Transit. On January 23, 1972, the AC Transit steam bus entered its first day of public service, operating from East Oakland to Berkeley and back. While completing its third round trip of the day, an engine failure, involving a broken crosshead, forced the vehicle to retire only three blocks from completing its day's service.

On May 25, 1972, the steam bus returned to public service making one round trip per day between Oakland and Berkeley. On June 5, the bus operated from downtown Hayward to Oakland and back. During eight days of public service, 13 one-way trips were completed and three were aborted. Numerous operating problems were encountered, including control instability, a blower motor failure, a feed water pump failure, relief valve bellows failure and poor water consumption. The steam bus was withdrawn from public service on June 9 to undergo improvements.

On September 19, 1972, the AC Transit steam bus returned to public service, operating between downtown Hayward and downtown Oakland, a distance of 39 miles. It operated on this route for nine continuous days without any operational problem, ending service on September 29, the last day of operation under the project terminated on September 30. Operating at much reduced noise levels, coach Number 666 traveled 353 miles during this period, accumulating a total of 3,465 miles under steam power from September 1971 through September 1972. No stops were required for water or fuel, and only occasional odors from an improper fuel/air ratio marred its otherwise perfect service.

S.F. Municipal Railway. On August 7, 1972, the Muni Railway steam turbine bus began its revenue service between the Southern Pacific Station and Fisherman's Wharf and back. On August 9 through 11, it was withdrawn from service to make a boiler repair and to adjust the burner which emitted noticeable smoke. From August 14 through 18, the coach operated as a commuter shuttle between the Ferry Building and the S.P. Station, making up to four trips a day with a maximum of 98 passengers on board. From August 22 through 25, it operated on a more rigorous route involving ten miles of freeway and a six percent grade. On August 25, during the last day of public service, the steam turbine bus attempted two round trips with full loads and lost a fan belt on the combustion air blower on a freeway during rush traffic. This was the only operational problem during eleven days of revenue service, and the bus returned to the barn under its own power.

On at least two occasions, once with a simulated payload of 4,500 pounds and once with fifteen passengers, the bus successfully traversed the Sacramento Street route, which includes San Francisco's steepest bus grades of 16 and 19 percent. Underscoring its relatively trouble-free time in San Francisco. the steam bus was driven from San Francisco to Reno under its own power on August 31 and September 1, traveling 230 miles over the Sierra Nevada without major problems. During its brief exposure, therefore, the bus provided early indications of the potential for high system reliability. In eight months of operation since January, this bus traveled 3,900 miles.

SCRTD. During its first week of public service, the SCRTD steam bus encountered numerous difficulties. Its first two days of attempted public service on September 5 and 6 were aborted, because a bolt sheared on the conibustor air fan assembly and a gear mechanism in the oil pump failed. On September 7, the bus entered public service, but it completed only a one-way trip of 7.3 miles because a pulley slipped which prevented the fan from turning inside the boiler. On September 8, the bus was withdrawn from public service when a boiler leak was detected; however, the bus traveled 86 miles on September 11 during performance testing until the boiler leak deteriorated.

After the bus was towed to San Diego and the repaired boiler was installed, the bus returned to Los Angeles on September 28 and re-entered public service on September 29, operating on Wilshire Boulevard. It completed a successful 15-mile round trip with air conditioning operational and favorable performance, except for a loose battery terminal which caused a 27-minute delay. The bus thereby completed its second and last day of public service, because vendor and fleet operator contracts expired on September 30. In 5.5 months since March, this bus logged 1,007 road miles.

PUBLIC ATTITUDES

Part of the project evaluation involved measuring public understanding and acceptance of steam propulsion systems. The attitudes of four groups were surveyed: the general public, diesel and steam bus riders, transit district managers and steam bus drivers.

Community attitude surveys. Three surveys conducted by the Survey Research Centers at the University of California at Berkeley and at Los Angeles were designed to measure public concern about air pollution and the need for alternative transportation systems. Standard nietropolitan surveys were conducted in Los Angeles County in October and November 1970 and in March and April 1971. The San Francisco Bay Area was tested May and June 1971.

In the Los Angeles County studies, air pollution ranked as the third most serious domestic problem facing Americans today (53%). Concern over the seriousness of air pollution held constant for variables of age, income, education and ethnic background, except for blacks who placed property taxes, race relations and quality of schools ahead of air pollution. Moreover, 85% of those sampled felt air pollution had reached a point where it was dangerous to human health.

When asked to identify the causes of air pollution, 67% of respondents blamed the automobile. When asked whether or not steam buses would help reduce smog, 42% of those surveyed thought steam buses would help a great deal and 38% thought they would help some. More than 85% of the respondents would ride a bus powered by steam, if they had an opportunity to do so. An insignificantly small number (1.3%) expressed fear about riding steam buses.

A survey was conducted in the San Francisco Bay Area with similar results.

Patron surveys. Rider reaction of steam buses was measured by surveying 239 passengers on the three steam buses and 307 riders of conventional diesel buses traveling the same routes at the same times in Oakland, Hayward, San Francisco and Los Angeles. Because of carefully controlled selection procedures, the diesel and steam bus riders shared similar characteristics, which insured a high reliability for comparisons. Interviews were spaced throughout the day.

Steam bus riders were asked about their reactions to the experimental vehicle itself. Overall acceptance was high. Almost 65% said they noticed some difference in performance. Most riders felt the bus provided a smoother ride (63%), produced less smoke (74%) and generated less air pollution than a diesel (83%). Opinions on odors, noise and vehicular power varied dramatically with each steam bus.

On the important question whether riders felt steam buses would help reduce air pollution, 47% of the steam bus riders felt it would help a great deal, 44% said it would help somewhat and only 1.7% felt it would be of little help. Diesel bus riders saw less impact, with 32% believing it would help a great deal and 44% that it would help somewhat.

Transit manager surveys. Sixty-five transit managers who operated at least 100 buses were mailed questionnaires. The 48 responses represented public and private ownership of about 86% of all city buses. The relatively large response rate allows the data to be considered both representative and reliable.

Nearly all transit managers, both public and private, expressed concern over air pollution. About 54% felt it was very serious and 40% believed it was fairly serious. When asked if it had reached a point to be dangerous to health, 42% said that it had and 40% thought it might have.

The majority of managers (67%) believed the transit industry needed to adopt a clean propulsion system. If steam buses offered quieter and cleaner operation, would transit managers purchase them? About 54% said yes, 12.5% said no and one-third had no opinion. When asked if they thought steam buses would help reduce air pollution, however, only 2% said a great deal and 27% said it would help some, but about 54% believed it would be of little help.

If steam buses were available only at a higher price than diesels, how much would transit managers pay? Only 4% were willing to pay one-fourth more and 20% were willing to pay one-tenth more. One-third of the managers were not willing to pay any premium. Another two-fifths wanted to wait for more information on operating costs or expressed no opinion.

Steam bus driver attitudes. An in-depth personal interview was conducted with five drivers who operated both diesel and steam buses, and who had between nine and 43 years of service. Three drivers were regular operators and two were instructors.

When asked which bus they would choose to operate on a daily basis, all five drivers said they would prefer the steam bus, because if provided a smoother, quieter ride and was less polluting; however, all drivers recognized that many improvements would have to be made in steam buses before a choice of vehicles became a reality.

POTENTIAL FOR IMPROVEMENTS

General outlook. The External Combustion Engine attacks the problem of air pollution at its roots, which are the physics and chemistry of the combustion process. Almost by definition, the ECE can have the cleanest combustion system possible. With its smooth, quiet application of high torque propelling energy, the Rankine cycle appears to be an excellent candidate for urban vehicles operating under stop-and-go conditions.

Some years, perhaps less than a decade if funding is adequate, of progressive engineering work will be required before the ECE is ready for general application and acceptance. Obvious areas for improvement are fuel economy, operating reliability, system layout, combustor technology, automatic controls and improved transmissions. Winterizing mobile steam powerplants is another important consideration.

Fuel Consumption. High fuel consumption in the steam buses has been identified as the largest obstacle to the potential acceptance of these alternate systems. Such concern goes beyond the economics of fleet operations, since fuel costs are only about three percent of the total costs of operating bus systems. An additional consideration is an impending national energy crises. Other important reasons to improve fuel economy are as follows:

1. The already low total emissions of the ECE would be reduced even further.
2. Waste heat released into the environment would be reduced.
3. Boilers and condensers would become smaller and lighter.

4. Condenser fan power requirements also would decrease. increasing system efficiency and reducing noise.

Improvements in fuel consumption can be made in a number of separate areas as follows:

1. Basic improvements can be made by increasing temperatures of steam or other working fluids. Values of ideal Rankine cycle efficiency can be raised from the present 25% to about 30% in the short term of two years and to 32 to 35% or more eventually.

2. The present thermal efficiencies are as low as 30% of the ideal cycle efficiency. Sixty percent of the ideal efficiency may bc attainable in the short term and possibly 70% eventually. Major gains can be made by reducing parasitic auxiliary loads and by increasing expansion efficiencies. One example for auxiliary load reduction is improvement in condenser fans, which consume 30 horsepower in present systems but could be reduced to 10 or 15 horsepower with more efficient fans.

3. The present method of sustaining the whole steam powerplant at idle is wasteful. The use of a small auxiliary expander for essential idle loads could reduce idle fuel consumption by two-thirds.

3. Heavy power losses incurred with transrnissions used in this project, because available units were poorly matched to expander characteristics. In the case of reciprocating steam engines, direct-drive or, at least, elimination of the hydraulic torque converter would appreciably increase vehicular efficiency. Transmission improvements also are possible for turbine expanders, whichwould allow the turbine to operate more of the time at peak efficiency.

The above improvements would have a major impact on fuel consumption. At present, diesel buses average around 3.5 mpg under local route conditions, and the best present steam bus about 1 mpg. It should be possible, however, to raise the fuel mileage of steam buses to about 2.3 mpg with two more years of development and to 3.3 mpg within a decade's time. Eventually, then, there would be a differential of only six percent between steam and diesel vehicles.

Emissions. Although emissions demonstrated in this program were acceptably low, they were not optimized. Further reductions can be obtained by two actions: first, reducing the amount of pollutants generated per pound of fuel burned through cleaner combustion; second, reducing, in turn, the amount of fuel burned per horsepower hour of work produced.

Burners produced in this early demonstration were designed and built without the benefit of extensive cornbustion research. Since that time, a new body of pertinent research information became available through contracts sponsored by the Advanced Automotive Power Systems (AAPS) program of the Environmental Protection Agency. One of their contractors, in steady-state burner tests, demonstrated, on the basis of grams pollutant per unit mass of fuel burned, less than one-fourth the CO, one-tenth the HC and one-third the NO_x found in some of the better steam bus emission test runs.

Figure 7 portrays the magnitude of projected future reductions.

System layout. Much was learned from these installations, even though work was on the basis of performing an ad-hoc retrofit. It was found, for example, that the Rankine cycle system offers considerable flexibility in the location of major components in the chassis. While the total volume occupied by the ECE probably always will be greater than space occupied by present diesels, it was shown that seating capacity need not be reduced. Both volurne and weight will diminish with future development. Substantial progress already was made in reducing the relative size and weight of system components. The Lear steam generator, for example, can deliver more than twice the power of earlier Doble units without increased size or weight.

Present diesel propulsion systems, with transmission and auxiliary items, weigh about 19 lbs. per net horsepower. The present Lear system weighs approximately 17 lbs. per net horsepower. Therefore, it is realistic to expect 15 lbs. per net horsepower would be possible in the short term and 10 or 12 lbs. per horsepower eventually.

Cost projections. More engineering must be done before initial cost of powerplants can be accurately forecast. Future steam systems will cost more per pound than diesels, but they will be considerably lighter in weight. Unit costs are sensitive to the production quantities involved. Because the urban bus market represents less than 5,000 units per year in the foreseeable future, commonality with other segments of the heavy-duty engine market might be needed to keep costs at reasonable levels.

Maintenance costs. Eventual maintenance costs also remain a matter of speculation. Costs to service brakes and transmissions may be reduced with steam systems, but attention would have to be devoted to steam generators and controls. Piston expander maintenance would be similar to present diesel engine blocks, but would be much less for a turbine. Maintenance costs for a diesel, however, may rise sharply if pollution control devices are added and if sophisticated chemical treatment is needed to reduce oxides of nitrogen.

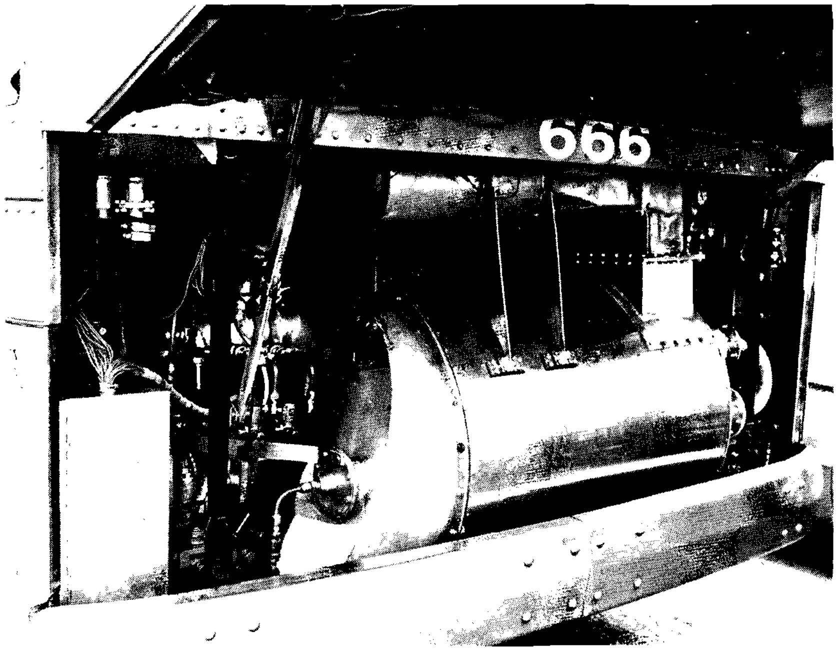
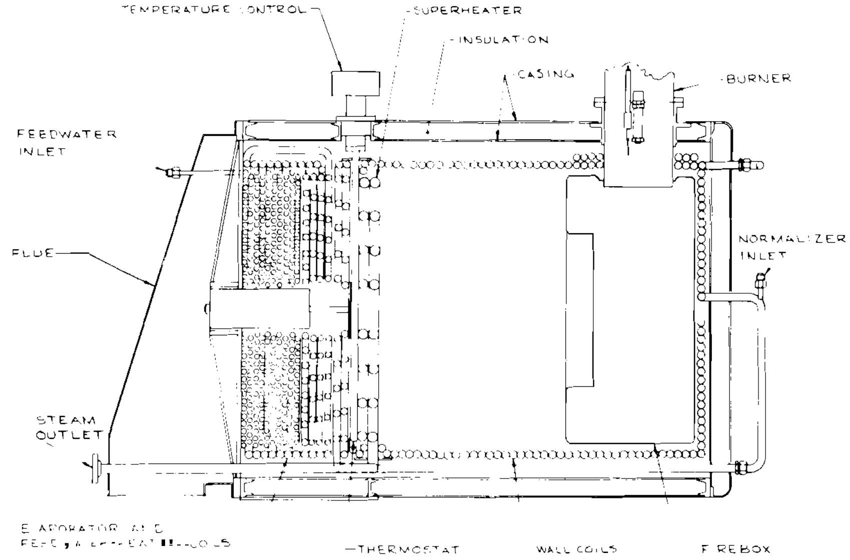


Figure 1. Installation of Boiler in William Brobeck & Associates Demonstration Bus.



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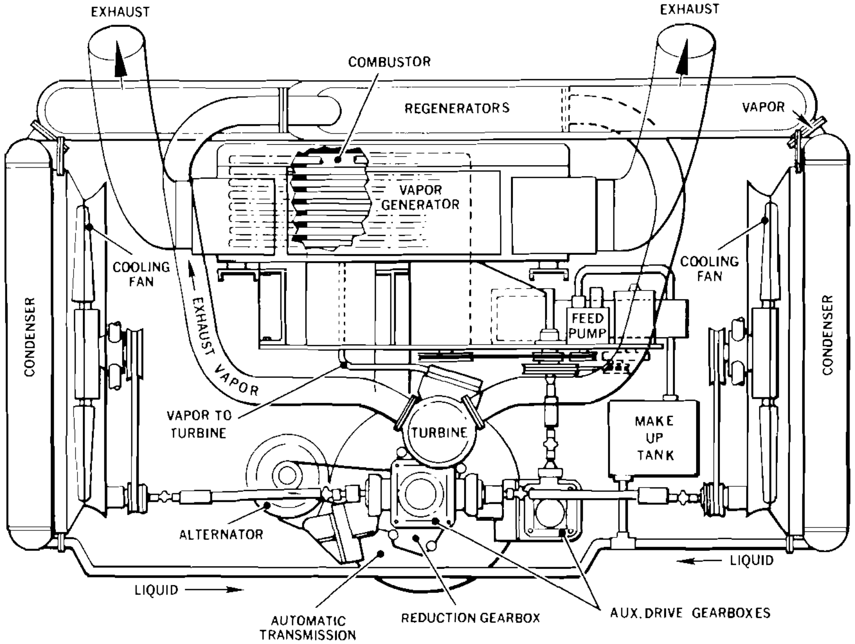

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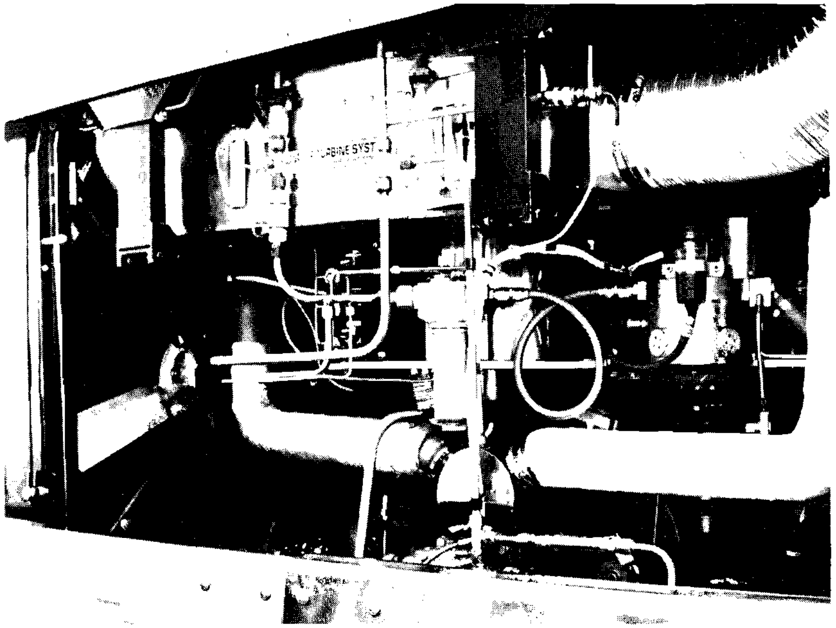

Figure 4. Actual Installation of Boiler and Turbine in Lear Rlotors Corporation Demonstration Bus (January 1972).

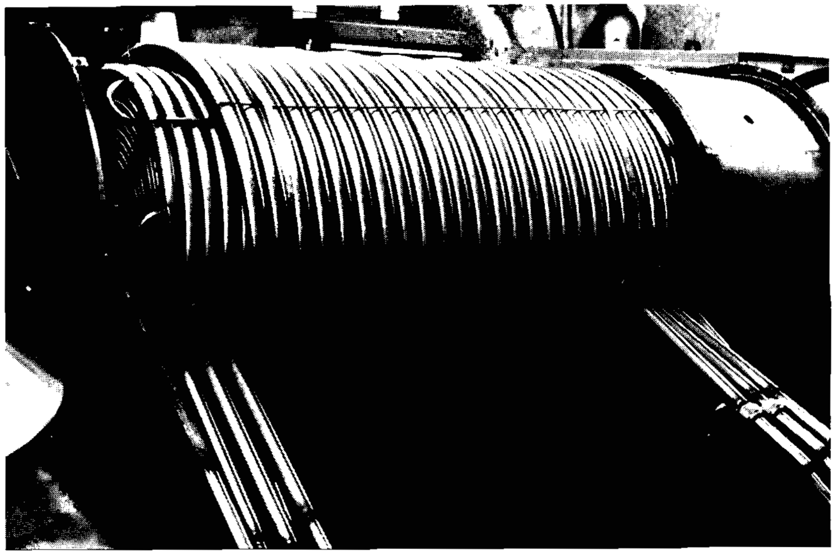

Figure 5. An interior view of a steam generator built by Steam Power Systems, Inc. Hot gases, generated in the combustion chamber on the right, pass through the tubing bundle to produce a superheated steam. The tubing extensions shown are temporary, for hydrostatic proof testing.

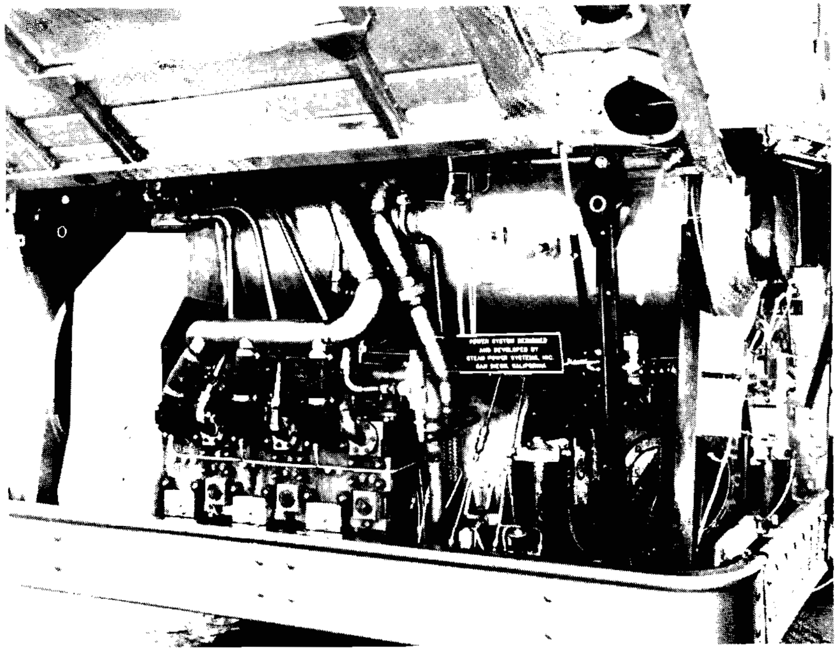

Figure 6. Actual installation of Boiler and Engine in Steam Power Systems Demonstration Bus (March 1972).

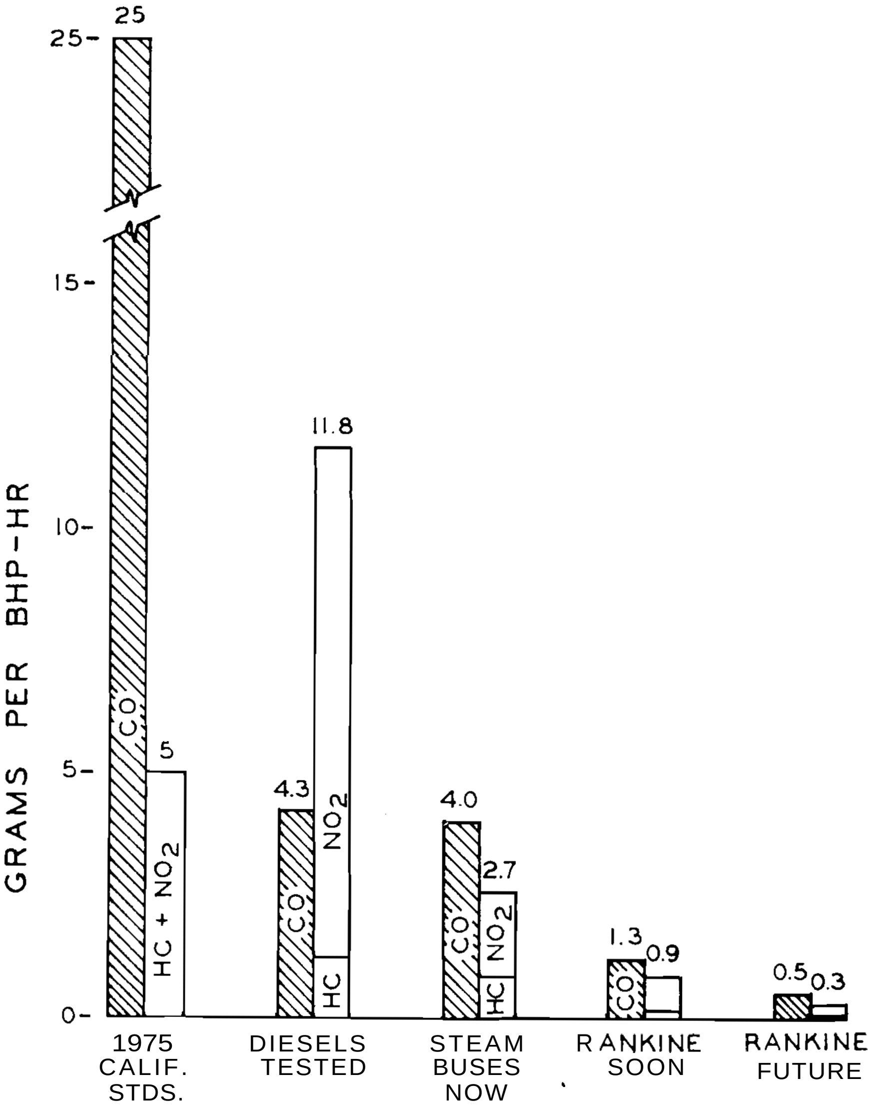

Figure 7. **Comparison** and projections: exhaust emissions from **heavy-duty** vehicle engines.

APPENDIX

TABLE I

COST SHARING IN THE CALIFORNIA STEAM BUS PROJECT

(As of August 31. 1972)

Project Participants	Federal Funds (UMTA)	Local Contributions*	Total Costs
Brobeck & Associates	$518,304	$ 60,256	$ 578,560
Lear Motors Corporation	649,782	3,473,205	4,122,987
Steam Power Systems	553,500	1,957,668	2,511,168
AC Transit	— — —	55,365**	55,365
S. F. Muni	— — —	10,793	10,793
SCRTD	— — —	35,039	35,039
IR & T	252,996	— — —	252,996
SAC	232,934	— — —	232,934
Film Producer, KQED	32,000	— — —	32,000
California State Assembly	— — —	49,724	49,724
California Air Resources Board	— — —	25,000**	25,000
California Highway Patrol	— — —	899**	899
Other Project Costs	55,009	— — —	55,009
TOTAL	$5,294,525	$5,667.949	$7,962,474

"Project contributions still outstanding for September 1972
**Through July 31, 1972

TABLE II

STEAM POWERPLANT SPECIFICATIONS

	BROBECK	LEAR	SPS
Expander type	Reciprocating	Turbine	Reciprocating
Max. expander gross bhp (Brake Horsepower)	240	249[a]	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/hr	2,500	2,340	3,600[a]
Max. fuel rate, gal/hr	30	30	47[a]
Boiler heating surface, ft2	180.2	275	356[b]
Combustion intensity. BTU/hr ft3	0.5×10^6	1.25×10^6	1.1×10^6
Condenser frontal area. ft^2	34.5	19.4	32.2
Steam conditions, psi/^oF (Pressure/Temperature)	1,000/850	1,000/1,000	1,000/750[c]
Lowest bsfc, lb/net bhp-hr. (Brake Specific Fuel Consumption)	0.985	1.13	1.18
Approx. weights, lbd			
Boiler with burner	920	890	850
Expander	965	110[e]	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	4.777	3,102	4,700

Notes:

a. Derated for installation in buses.
b. Includes reheater section.
c. Steam leaves the reheater at 240 p.s.i. and 650 to 750^oF.
d. A comparable 6-cylinder diesel power system, including transmission, radiator and auxiliaries, weighs approxirnately 3800 pounds.
e. With gearbox.

TABLE III

URBAN BUS ROAD PERFORMANCE

	Diesel GM 6V-71*	Diesel GM 8V-71**	Diesel Cummins 903 V-8	Steam Brobeck	Steam Lear	Steam SPS***
Weight as tested, lb (Gross Vehicle)	25,320	26,860	28,000	30,580	28,470	30,900
Top speed, mph	52	65[a]	70 plus[a]	56	54	58[a]
Acceleration, sec:						
Zero to 10 mph	4.0	3.0	3.7	3.0	5.0	5.0
Zero to 30 mph	18	12	19	20	22	25
Zero to 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.

Notes:

* Equipped with N-55 Injectors

** Equipped with N-60 Injectors

*** The SPS steam bus was tested under unfavorable engine operating conditions, with the steam temperature being too low for best power output.

a. Utilized overdrive transmission

b. 35,000 lb GVW (Gross Vehicle Weight) overload test

N.A., Not available because suitable test could not be scheduled.

TABLE IV

EXHAUST EMISSIONS OF STEAM AND DIESEL BUSES

(grams per engine brake horsepower hour)

	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
Average Steam	4.0	0.9	1.8	2.7
Diesel Buses:				
AC No. 678 (GM 6V-71)	4.4	2.5	9.0	11.5
STA No. 408 (GM 6V-71)	2.6	1.5	13.9	15.4
MUNI No. 3141 (GM 8V-71)	7.9	0.9	8.4	9.3
SCRTD No. 7185 (CUM. 903)	2.3	0.5	10.2	10.7
Average Diesel	4.3	1.4	10.4	11.8
California Heavy Duty Standards:				
1973	40	–	–	16
1975	25	–	–	5

Notes:

* These emissions were considered official test results for first complete emissions test without any tuning adjustments.

** The second Lear Motors test was a composite of the best results from both tests, with an improved but not optimized idle setting between tests.

1. All tests were performed by the California Air Resources Board.
2. Diesel results are from a limited sampling of well-maintained vehicles and may not be representative or typical of diesel engines in general service. No steam bus had burners or controls optimized for low emission results.
3. NO_x was measured as nitric oxide (NO) and expressed as equivalent NO_2.

TABLE V – EXTERIOR SOUND LEVELS OF STEAM AND DIESEL BUSES

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

		Steam Buses			Diesel Buses			
		Brobeck	Lear	SPS	AC No. 678 GM6V-71	STA No. 408 GM6V-71	MUNI No. 3309 GM8V-71	SCRTD No. 7185 Cum. 903
A.	Full-throttle, drive-by, microphone at 50'	76	85	80.5	78.5	84	86	82
B.	Full-throttle standing start, microphone at 15'	74	88	86	88	89	90	94.5
C.	Idle, microphone at 15'	68.5	78	78	75.5	78	74.5	75.5

Notes:

1. All measurements were perfornied by the California Highway Patrol.
2. In drive-by tests, a microphone was placed 50 feet from the center of the roadway lane. As the bus approached the microphone position, it was accelerated at full throttle within a speed range of 20 to 35 m.p.h. Sound levels were measured in both directions of travel.
3. In standing start tests, sound levels were taken at engine idle then under full-throttle acceleration from a standing start with a microphone placed 15 feet from the center of the lane. This test approximates perception of a pedestrian near a bus stop.

TABLE VI – INTERIOR SOUND LEVELS OF STEAM AND DIESEL BUSES

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

		Steam Buses			Diesel Buses			
		Brobeck	Lear	SPS	AC No.678 GM6V-71	STA No.408 GM6V-71	MUNI No. 3309 GM8V-71	SCRTD No. 7185 Cum. 903
A.	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
B.	At idle							
	Front	62	63	60	62	63	64	60
	Center	67	65	66	68	67	66	65
	Rear	66	72	71	72	68	72	69

Notes:

1. All measurements were perfornied by California Highway Patrol.
2. Microphone positions were along the centerline of the aisle, midway between the floor and ceiling of coach.

TABLE VII – STEAM AND DIESEL BUS FUEL CONSUMPTION

(Test Gross Vehicle Weight 25,000 to 30,000 lbs.)

	Brobeck	Lear	SPS	GM 6V-71	GM 8V-71	Cummins 903 V-8
Cruise fuel mileage, miles per gallon (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/hr:	4.5	3.2	4.7	0.5	0.65	0.62
Examples of route fuel mileages						
AC Route No. 58	1.1	–	–	3.58	–	
MUNI Route No. 32	–	0.7	–	–	3.68	–
SCRTD Route No. 83	–	–	0.6			3.02

TABLE VIII – CHARACTERISTICS OF URBAN AND SUBURBAN BUS DRIVING CYCLES"

	Local AC 58	Express AC RF	Local MUNI 32	Local MUNI 55	Local SCRTD 83	Express SCRTD 60-E
Distance tested, mi	12.9	29.7	7.4	8.7	9.8	31.6
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, percent	6.1	8.8	8.4	19.3	6.9	8.7
Max. downgrade, percent	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-hr	30.6	55.8	14.2	38.1	29.8	65.7
Energy dissipated by brakes & retarding, hp-hr	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	

*Data from tests with diesel coaches, except for comparative steam mpg. Engines were as follows: AC, GM 6V-71; MUNI, GM 8V-71; and SCRTD, Cummins 903 V-8.

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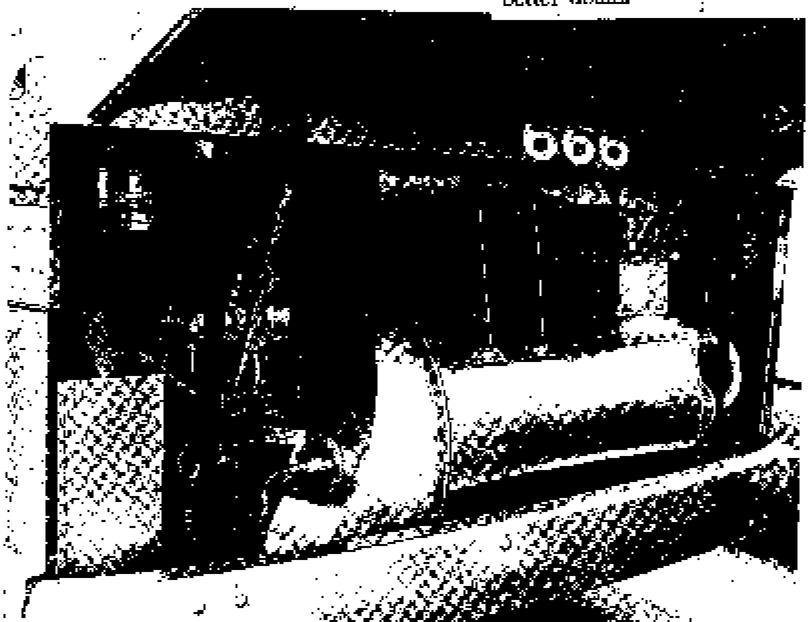

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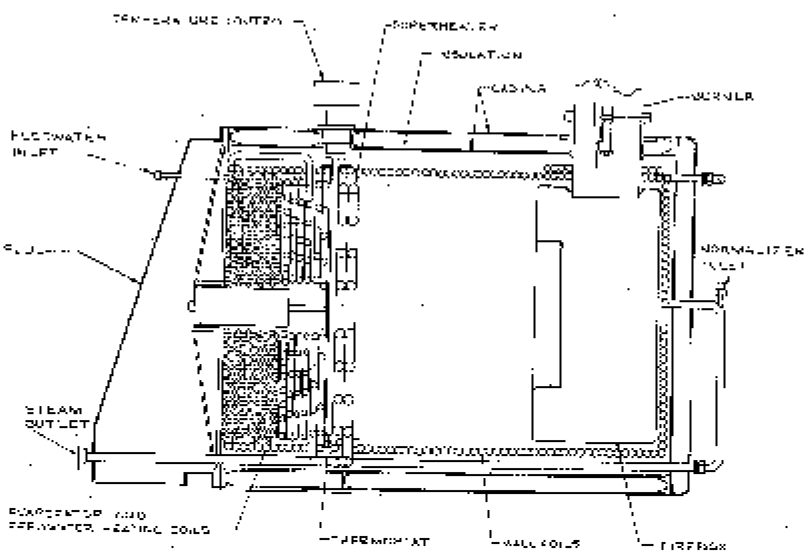

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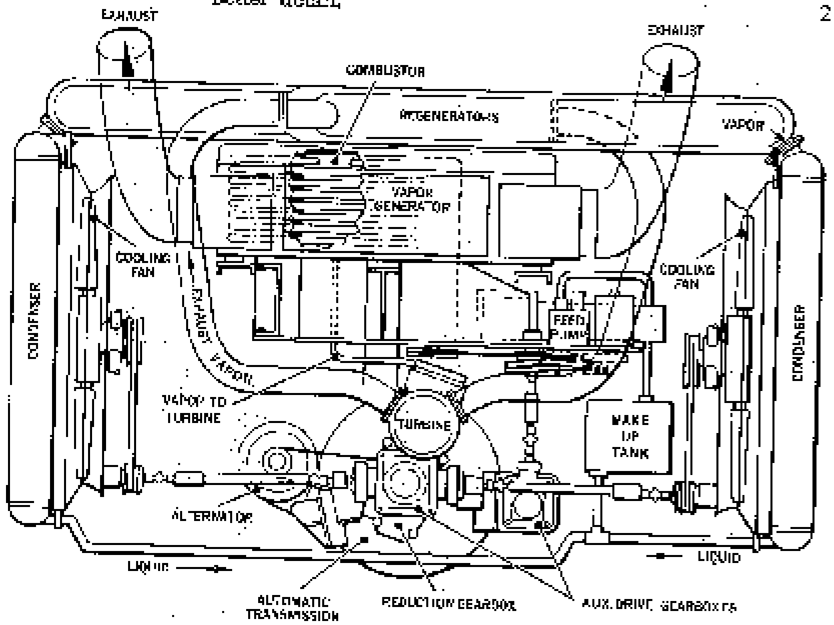

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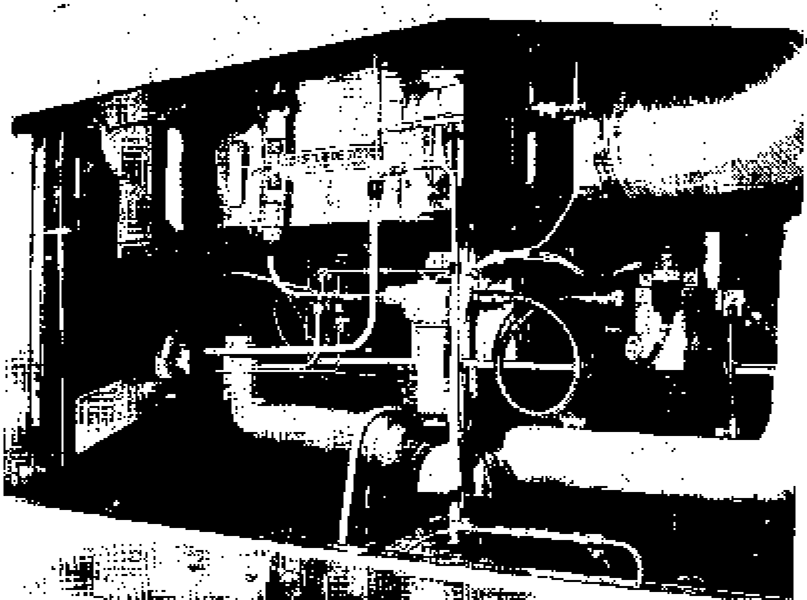
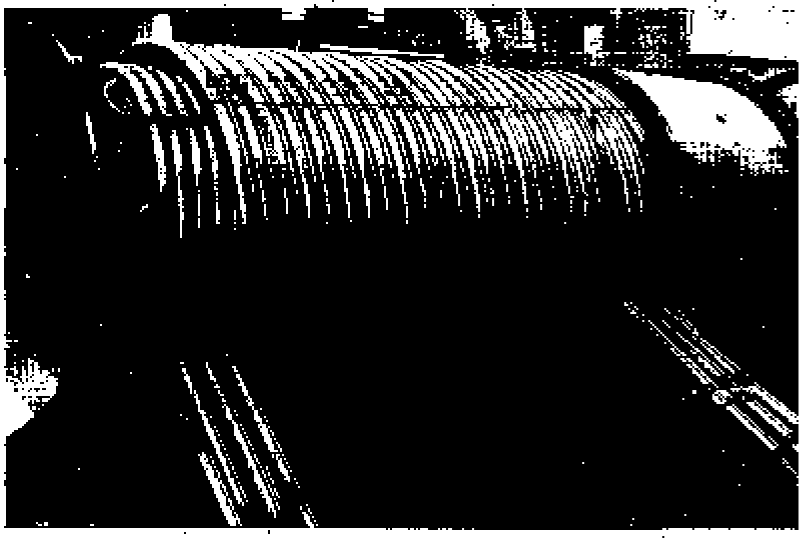


Figure 4. Actual Installation of Boiler and Turbine in Lear Motors Corporation Demonstration Bus (January 1972).



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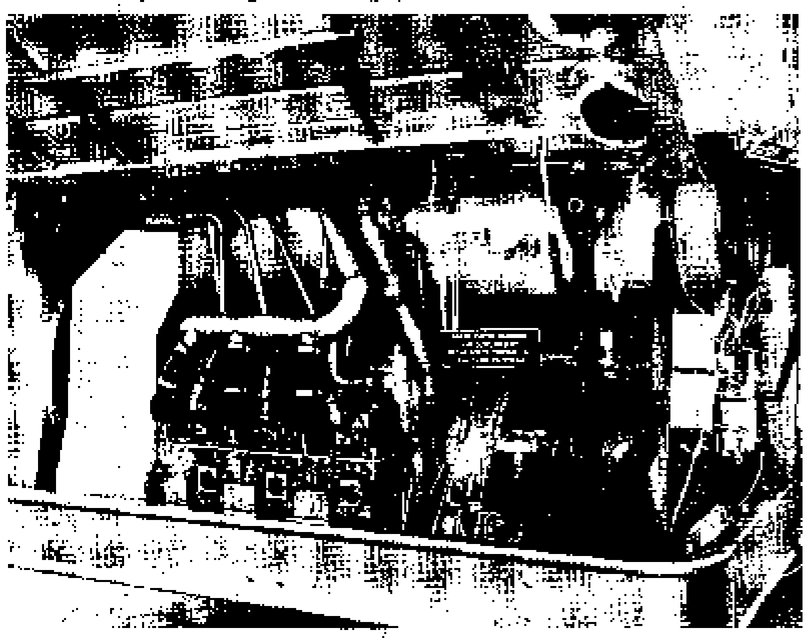

Figure 6. Actual installation of Boiler and Engine in Steam Power Systems Demonstration Bus (March 1972).