THE CALIFORNIA STEAM BUS PROJECT:
Technical Evaluation

IR&T
INTERNATIONAL RESEARCH &
TECHNOLOGY CORPORATION
1225 Connecticut Avenue, N.W.
Washington, D.C. 20036 · 202-293-3190

IRT-301-R

THE CALIFORNIA STEAM BUS PROJECT:
Technical Evaluation

FINAL REPORT

Roy A. Renner
International Research and Technology Corporation
1225 Connecticut Avenue, N.W., Suite 600
Washington, D. C. 20036

January 1973

IRT-301-R

THE CALIFORNIA STEAM BUS PROJECT: Technical Evaluation

FINAL REPORT

Prepared By
International Research and Technology Corporation
1225 Connecticut Avenue, N.W., Suite 600
Washington, D. C. 20036

Roy A. Renner, Project Technical Manager

January 1973

This report is the product of a project sponsored by the California State Assembly, financed in part by the U.S. Department of Transportation, Urban Mass Transportation Administration. Report prepared for the California State Assembly under Contract LCB 13292.

Project No. CA-06-0031
Urban Mass Transportation Administration
U.S. Department of Transportation

TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
IRT-301-R		

4. Title and Subtitle
The California Steam Bus Project
Technical Evaluation

5. Report Date October 1972

6. Performing Organization Code

7. Author(s)
Roy A. Renner

8. Performing Organization Report No. IRT-301-R

9. Performing Organization Name and Address
International Research & Technology Corp.
1225 Connecticut Avenue, N.W., Suite 600
Washington, D.C. 20036

10. Work Unit No.

11. Contract or Grant No. CA-06-0031

12. Sponsoring Agency Name and Address
Urban Mass Transportation Administration,
U.S. Department of Transportation
Washington, D.C.

13. Type of Report and Period Covered
Final Report, Technical work, April 1969-October 1972

14. Sponsoring Agency Code

15. Supplementary Notes
Demonstration project was sponsored by the California State Assembly, with a grant of funds from the Urban Mass Transportation Administration.

16. Abstract

The California Steam Bus Project demonstrated the potential of low-emission, quiet external combustion engines in public transit service. Work was sponsored by the California State Assembly, with a grant from the Urban Mass Transportation Administration of the U.S. Department of Transportation. 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 non-optimized demonstration vehicles. Prospects for future improvements are given, including the outlook for large reductions in fuel consumption and exhaust emissions.

17. Key Words
External combustion engines; rankine cycle engines; steam engines; mass transportation; bus technology; exhaust emission controls.

18. Distribution Statement
Availability is unlimited; document may be released to the public.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified		

Form DOT F 1700.7 (8-69)

ACKNOWLEDGEMENTS

The author wishes that it were possible to personally acknowledge the hundreds of individuals who contributed to the success of this project. James Lane, Project Director, should be thanked for his guiding role in this complex endeavor. Much credit is also due Kerry Napuk, Michael Wenstrom, and Albert Monighan for their capable administration. Richard Lawhorn and Carl Walker provided much-needed assistance in engineering evaluation. The good advice of Robert Ayres and Charles Daniels in regard to project formulation has been much appreciated. Patrons of the project among lawmakers and legislative staff were many, including Assembly Speaker Bob Moretti, Assemblyman Frank Lanterman, and William Lipman, Director of the Legislature's Federal Office. The tangible results of this program are directly attributed to the perseverance and leadership of William Brobeck, William Lear, and Cornelius Dutcher. Excellent cooperation was received from many organizations, including the following:

- Urban Mass Transportation Administration
- California State Assembly
- William Brobeck and Associates
- Lear Motors Corporation
- Steam Power Systems, Inc.
- Alameda-Contra Costa Transit District
- San Francisco Municipal Railway
- Southern California Rapid Transit District
- State of California:
  - Air Resources Board
  - Highway Patrol
  - Division of Highways
  - Department of Public Health
  - Office of Insurance
  - Auditor General's Office
- Bay Area Educational Television KQED
- International Research and Technology Corporation
- Scientific Analysis Corporation
- Sacramento Transit Authority
- D-C Transit

FOREWORD

The following report represents the conclusion of one phase of one strategy of a multi-strategy attack on the urban air pollution problem. The strategy in question is to reduce pollution by bringing about a modification of the basic vehicular power plant, of which the diesel engine, currently used in buses, is one species. The fact that diesel engines are not the worst pollutants might argue against using buses to demonstrate the potential of alternative engines. Against this, however, must be weighed the fact that buses are highly visible and that bus service represents a very rigorous and demanding test of an engine's capabilities. In any event the demonstration was undertaken to allay once and for all any possible lingering doubt in the public mind with regard to the key issues of safety, noise, emissions, and performance. On these issues all three of the experimental buses ranged from adequate to outstanding. None failed. Only with regard to fuel consumption did the steam engines show up a serious disadvantage--not very surprising in view of the lack of time or resources for development or design optionalization. In any case we believe this report will be of significant value in guiding future actions aimed at solving the vehicular emissions problem.

-- Robert U. Ayres
Vice President
International Research and
Technology Corporation

TABLE OF CONTENTS

INTRODUCTION

Project Background

During March 1968, the Transportation and Commerce Committee of the California State Assembly held hearings to determine the potential feasibility of alternative low-polluting vehicular powerplants. The External Combustion Engine (ECE)* appeared to be among the more promising candidates. Desiring to investigate further, the State initially considered a number of possible test-bed vehicles for a demonstration of feasibility, including police cars for the California Highway Patrol. The city bus was finally chosen as the symbolic test-bed, since the vehicles could be made available from publicly owned fleets; furthermore, the ECE appeared to ideally match the arduous requirements of the heavy-duty, stop-and-go vehicles. Accordingly, the Assembly submitted a grant application to the Urban Mass Transportation (UMTA) during the latter half of 1968 for the funding of a program to demonstration and test external combustion engines in city buses.

The federal government was investigating the automobile and air pollution during this same time period. A study sponsored by the U.S. Department of Commerce recommended, in 1967, that the federal government sponsor research on power systems with low-emissions potentials, such as the ECE (1).** This was followed by hearings, May 27-28, 1968, in the U.S. Senate on the automobile steam engine and other external combustion engines (2). Highlighting these hearings was the demonstration of two modern steam cars, one constructed by Charles Keen of Madison, Wisconsin, and the other by the Williams Engine Company of Ambler, Pennsylvania.

An initial grant of UMTA research funds to the California Assembly for the Steam Bus Project was approved in February 1969. The state issued a Request for Proposals in May of 1969 for the installation of demonstration powerplants. Replies from potential suppliers revealed that ECE systems,

---

*The steam engine is the most familiar example of ECE.

**Numbers in parentheses designate references listed at the end of this report.

far from being available off the shelf, would require extensive engineering development before demonstrations could be scheduled.* With this knowledge, the program was restructured to include more time and more funds for engineering development (as opposed to fabrication and demonstration only). And yet, because time was a constraining factor, it was decided to limit the objectives, with the recognition that a high degree of evolution or technical perfection was (for the moment) beyond reach.

The actual work of designing and developing the ECE systems commenced with the signing of the engineering contracts in June 1970. The engineering contractors were each paired with a California Fleet Operator:

1. William M. Brobeck and Associates (Berkeley, California) with the Alameda-Contra Costa Transit District (A-C) based in Oakland, California.
2. Lear Motors Corporation (Reno, Nevada) with the San Francisco Municipal Railway (MUNI).
3. Steam Power Systems (San Diego, California) with the Southern California Rapid Transit District (SCRTD) of Los Angeles.

The Brobeck installation was completed in September 1971, and road trials were begun. This was followed by the Lear bus in January 1972, and the SPS bus in March 1972. The Brobeck bus was brought to Washington, D.C. for demonstration in November 1971, and all three buses were operated in Sacramento in late April 1972. All three buses are of current design, 40' long x 102" wide and originally configured to seat 51 passengers. (See Figure 1.)

Because time was an important factor, many technical compromises had to be accepted. As an expedient, existing transmissions were employed, even though the torque converters were not well matched to the steam expanders (turbine or piston engine). Fixed cut-off engines were used in lieu of the

---

*As it later developed, the enthusiastic testimony of steam car advocates tended to overstate the availability of such technology and to underestimate the present drawbacks and development difficulties. The potential for a clean exhaust was correctly identified, however.

Fig. 1 - A forty foot urban coach converted to steam power. (Southern California Rapid Transit District, Power Plant by Steam Power Systems, Inc.)

more difficult to develop (but more efficient) variable cut-off types.* The main expanders were used to drive accessories at idle, even though more efficient methods were known. The development of engine retarding (though very desirable) was bypassed for the moment. Complete operational safety, however, was a mandatory requirement of the program.

Exhaust emissions were evaluated by the California Air Resources Board. Sound level measurements and motor carrier safety inspections were performed by the California Highway Patrol. Supporting services were also provided by the Assembly Office of Research, the Division of Highways, and the State Department of Public Health.

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

The Outcome in Brief

The project was completed in September 1972. All three of the buses were demonstrated in actual revenue service. About 8,372 miles of road testing and service were accumulated under steam power. As a composite evaluation, it was found that the ECE can compete with diesel power for city bus propulsion in terms of road performance. System weight can also be competitive. Exhaust emissions are low, and are well within the limits set by the 1975 California Heavy-Duty Vehicle Standards in terms of CO, HC, and NO_x. The oxides of nitrogen, 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 (with present level of development) was considerably higher than that of diesel units. Substantial

*The "cut-off" of a steam engine refers to the point at which the steam inlet valves are closed during the stroke of the piston. If the steam admission is cut off early in the stroke, good fuel economy is achieved during periods of moderate loads. If variable cut-off is employed, that same engine can also exert extremely high efforts for starting and hill climbing with late cut-off and temporarily increased fuel consumption.

improvement in fuel economy is a foreseen probability, but will require basic redesign of the power systems. Not surprisingly, system reliability was poor with these early and rudimentary powerplants, but there seems no reason to believe that an acceptable level of 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-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, a set of technical goals and guidelines has been drafted for future development of the ECE for urban buses and for other heavy-duty applications.

Why Steam Power?

This question is often posed by those who believe serious interest in steam propulsion to be anachronistic. Were it not for the large potential remaining for improvement, and the possibilities for exceedingly low levels of exhaust pollution, there would indeed be little justification for further inquiry into the steam engine. A brief orientation into the reasons for the low emissions may be in order here so that we may then proceed with the question of the past, present, and future of Rankine cycle systems.*

The burning of a pure hydrocarbon fuel with oxygen yields only non-poisonous and "natural" combustion products: carbon dioxide and water vapor. (These are the products that humans exhale.) All heat engines (whether internal combustion, gas turbine, external combustion) exhaust these substances in the main. However, they also emit greater or lesser quantities of offensive or poisonous materials. In the aggregate, the motor vehicles are presently the largest single source of air pollution. With the ECE, the amount of such pollution can be greatly reduced.

---

*ECE is the generic or family name; it includes specific varieties, which may be based upon the Stirling, closed Brayton, or Rankine thermodynamic cycles. The Rankine cycle, in which the working vapor is condensed before being recycled back to a boiler, may employ either steam or some other working fluid.

The problems inherent with the Internal Combustion Engine (ICE) are:

1. The fuel is ignited and quenched within milliseconds, resulting in incomplete combustion and the exhausting of poisonous carbon monoxide (CO) and of hydrocarbon residues (HC). This effect is particularly pronounced in carburated spark-ignition engines, which require the induction of homogeneous mixtures relatively rich in fuel. On the other hand, the diesel engine can be operated quite lean (excess air) and therefore can have low emissions of CO and HC.

2. The peak flame temperatures are so high that some of the normally inert nitrogen of the combustion air is also burned, with the formation of oxides of nitrogen (NO_x).

By contrast, a well-designed ECE burns a lean fuel mixture under continuous, controlled conditions. This virtually eliminates CO and HC in the exhaust. Also, the combustion temperatures can be moderate so that only very small quantities of oxides or nitrogen are generated.

In theory, one might suspect that the ECE would be the cleanest possible form of heat engine. And the cleanest possible form of engine, if applied to a mass transit vehicle that is efficient in people-moving, should be an asset in the urban community. Whether the ECE can be both clean and practical for motor vehicles is the question being addressed here.

HISTORY OF STEAM VEHICLES

The Rise and Fall of the Steam Car

Private cars powered by steam enjoyed a brief popularity during this century's opening decade. Silent operation, freedom from gear shifting and hand cranking, and "stored power" were advantages. Equally obvious were the problems associated with high water consumption and tedious procedures in "firing up" from cold. Also damaging to the steamer's reputation was the common notion that the boiler might explode. So, even though all of these faults were overcome by later developments, interest in steam cars dwindled when gasoline engines became simple, cheap, and convenient to use.

A Steam Bus Heritage

A fascinating history could be compiled in the application of steam power to buses. Some brief highlights include:

- 1906-1912: The Darracq-Serpollet Omnibus Co., Ltd., produced buses in Paris. Flash boilers were used.
- 1903-1919: Clarkson steam buses, fueled by kerosene and employing condensers, were operated in England (3).
- 1920's: Coal-burning Sentinel buses (England) failed to overwhelm the market, possibly because they required two men to operate.
- 1920's: Two Doble-powered steam buses were tested by the Detroit Motorbus Co., accumulating over 32,000 miles of experimental service (4).
- 1929: A Doble steam power system was installed in a Yellow Coach for General Motors.
- 1930's: Henschel buses, powered by Doble steam systems, were operated in Germany. The intent was to reduce national dependence on high-grade fuels (5).
- 1944: William B. McGorum, General Manager of the Lehigh Valley Transit Co., Allentown, Pennsylvania, wrote on the advantages of steam power for city buses (6):

  > "Steam is the only power medium other than electricity which can deliver silent motion.
  > ...As a practical matter exhaust fumes will be nonexistent.
  > ...The driver will have power braking at his disposal (from reversed engine torque).
  > ...The amount of brute maintenance work will begin to decrease sharply."

We may, at long last, soon have the opportunity to verify these predictions. Other interesting accounts of steam-powered buses may be reviewed in a referenced article (7).

Significant Interim Technology

During the years since 1920, development of light steam-power systems has been sufficient to show that some of the earlier objections can be overcome, and to serve as an indicator of future potential. It is a matter of record that mobile steam systems have been built that:

- Develop 100 to 700 hp.
- Weight less than 5 lb. per hp.
- Are in the range 15 to 20 percent overall thermal efficiency.
- Have very low levels of noise and chemical pollution.
- Can move the vehicle in less than one minute after a cold start.
- Are of inherently safe design.
- Have automatic control of the steam-generating functions.

Not all of the above attributes have necessarily been embodied in the same prototype. However, the level of technology of the interim period was sufficient to form the beginning of the present project.

The specific cases that follow are cited, in order that the reader may have a broader base from which to judge the future potential of this form of power.

Doble Steam Motors -- During the 1920's, this California corporation produced around two dozen experimental steam cars. While this venture failed in the marketplace, the legacy of fine engineering may yet make its impact on transportation science (8,9). The heart of the Doble system was the monotube steam generator, combining the virtues of high power output and fast response with good efficiency and inherent safety. Electrical ignition and automatic controls were also important innovations. A key feature was the condenser, which allowed the same tank of water to be used over and over again. Condenser fans, in some of the later models, were driven by exhaust steam turbines.

Besler -- In the early 1930's, the Besler Corporation became the successor to Doble. April 1933 saw a most remarkable demonstration: William Besler flew a Travelair airplane powered by a steam engine (10). This condensing powerplant, with a dry weight of only 4.5 pounds per horsepower, is believed to be the lightest ever built for its output. One feature of the aircraft was its unusual silence: the pilot was able to converse in shouts with observers on the ground.

Besler also applied high-pressure steam to drive a two-car commuter train, operated by the New Haven Railroad in the late 1930's. Utilizing steam at 1,500 psi and 750°F, the powerplant delivered 500-700 horsepower and was operated for almost a million miles. Because this was a condensing system, the train could be run 500 miles before replenishment of the water was needed. Overall thermal efficiency at the wheels was said to approach 20 percent.

Henschel -- Shortages of high-grade motor fuels in prewar Germany led to experiments with steam-powered commercial vehicles. During the period 1932-34, Warren Doble was retained as a consulting engineer by the Henschel Works at Kassel, to aid in such developments. Doble steam-power systems were subsequently installed in buses, trucks, railcars, and motor launches.

Henschel-Doble buses were used by the Suburban Railway of Bremen (Figure 2). High torque characteristics at the rear axle provided smooth, rapid acceleration. Another advantage was the ease of operation; the absence of a transmission eliminated the needs for thousands of gear changes per day in city traffic.

With the approach of World War II, German steam vehicle developments were suspended. Henschel did, however, continue to supply Doble-type automatic steam generators for industrial applications until at least 1952.

The Yuba Steam Tractor -- Immediately following World War II, there was an increasing demand for large tractors suitable for earthmoving, logging, and other off-road activities. Sensing this growing market, the Yuba Manufacturing Company (San Francisco) developed a steam-powered, pneumatic-tired, all-wheel-drive prime mover during the years 1946-51. While production plans did not materialize, the prototype tractor represented a significant advance in this branch of engineering (11).

The prototype tractor used a separate steam engine to drive each wheel. Since the front wheels could be cramped 90° either side of center, an extremely short turning radius was attainable. A two-speed transmission allowed a choice of high tractive effort (up to 32,000 pounds drawbar pull) or maximum road speed (40 mph). The tractor had a rating of 200 drawbar horsepower.

McCulloch Corporation -- The McCulloch Corporation of Los Angeles is well known for the manufacture of chain saws and lightweight gasoline engines. Not so well known is the fact that this company built an experimental steam automobile in 1951-54. With the help of Abner Doble, a system was evolved that was considerably smaller, lighter, and potentially more efficient than earlier Doble designs. The steam pressure was 2,000 psi -- the highest ever

Fig. 2 - Historical: Herschel-Doble steam bus operated by the Suburban Railway of Bremen, Germany during the late 1930's.

used in an automobile, so far as is known. And yet, because the steam was generated entirely within a continuous coil of small-diameter tubing (monotube boiler), the system was considered to be entirely safe (12).

Williams Steam Car -- The Williams Engine Company of Ambler, Pennsylvania has, with experiments over a few decades, evolved high-speed steam engines of very good thermal efficiency. A Williams car was demonstrated to the writer in 1968; adequate performance was achieved with an engine displacing only 43 cubic inches. Judging from the rather small size of the condenser on this car, thermal efficiencies are higher than normally expected from steam cars.

Williams engines can be used as retarders; a worthwhile saving in brake wear and an increase in operational safety would result if this principle were applied to buses and trucks.

Emissions testing on this car in 1966 formed the basis for testimony given by the Williams Company to the California Assembly and the U.S. Senate in 1968 (2,9).

Recent Developments

A new body of technical information is becoming available through contracts sponsored by the Advanced Automotive Power Systems (AAPS) program of the Environmental Protection Agency (13). One branch of the AAPS work is concentrating on Rankine cycle component and system development. Three automobile power systems are, at the time of this writing, approaching the bench-test phase:

1. The Aerojet General Corporation (Sacramento, California) is developing a vapor turbine powerplant using an organic working fluid.
2. Steam Engine Systems Company (Watertown, Massachusetts) is developing a piston expander system using steam as the working fluid.
3. Thermo Electron Corporation (Waltham, Massachusetts) is working on a piston expander system. The working fluid is 85 mole percent trifluoroethanol, 15 percent mole percent water.

After initial bench-testing of the above preprototype systems, a maximum of two systems will be selected for continued development through the prototype and vehicle demonstration phases. Vehicle development and testing is planned for the period 1974-75.

The AAPS program, in addition to sponsoring system development, is endeavoring to build a technological base in the form of component development and allied research. Combustors, condensers, feed pumps, lubricants, and working fluids have been among the subjects covered.

Learning from History

Some of today's technologists assert that they see little worth in the works of the past. Such a viewpoint, however, leads to costly and time-consuming re-invention. And yet, new vistas are also desperately needed, and Rankine cycle developments will require more than mechanical cleverness to become competitive.

The most valuable lesson to be drawn from steam vehicle history, however, is virtually nontechnical. It has to do with recognizing the magnitude of support that is required if the ECE is actually to be applied to social needs. This in turn relates to a new awareness of "public technology," in which the government takes a role in nurturing those technologies that are needful in society but which are unlikely to survive if left solely in the care of the private sector. Why did the steam vehicle fail in the past? The first time it passed away, in 1910, the benefits (criteria were less demanding than today) were accompanied by rising costs for the steamer (while ICE engines were getting better and cheaper). However, in every succeeding attempt to resurrect steam power, the pattern became repetitious: Just when good technical progress was imminent, programs failed when the high cost of product development was faced. It is noteworthy that none of the sponsoring industrialists had sufficient resources to carry the burden alone. In this light, the role of government support in partnership with the engineering resources available within industry becomes more apparent.

PROJECT OBJECTIVES

Overview

The California Assembly's original statement of project objectives was embodied in its Request for Proposals (RFP) dated May 1, 1969 (14):

> "The objective is to determine complete operational feasibility, potential advantages, public understanding and acceptance of an external combustion engine propulsion system for urban mass transit buses. Project will demonstrate the ECE system's principle performance advantages, fleet operational characteristics and lower pollution levels when compared with the internal combustion engine system."

The purpose in sponsorship was to provide the Legislature with essential information necessary in considering legislation to protect California's natural resources and the well-being of its citizens. It is to be noted that not all of the evaluation was to be of technical considerations. The work of the Scientific Analysis Corporation in evaluating the nontechnical aspects of the project is reported separately.

Originally, the project was to involve four buses,with two each demonstrated by the Alameda-Contra Costa Transit District ("A-C," serving Oakland and environs) and by the San Francisco Municipal Railway (MUNI).

The schedule initially published included nine months to develop the vehicle, a three-month initial trial period, and a nine-month public transit service phase (this euphoria was shortly to be corrected).

Without pausing to relate all the details, the program structure was greatly modified during succeeding months. The need for more development time and funding became apparent. It was likewise found necessary to limit the objectives and expectations to match attainable goals. Engineering optimization and technical perfection of the demonstration vehicles were declared to be beyond the goals of the project.

Eventually, only three power system installations were ordered, and in order to broaden the participation of the transit industry, a third fleet operator joined the project. The Southern California Rapid Transit District of Los Angeles became the third host property.

Technical Objectives

Goals of the project were specified in the state's RFP. Technical objectives are paraphrased and summarized below:

1. Definition -- The ECE is an engine in which the combustion process is separated from the working cylinders or turbine. Unlike the ICE, it does not use the combustion gases as the expansive working fluid.
2. Bus Configuration -- Installation was to be made into standard urban buses of 51-passenger seated capacity, 40' long x 102" wide.
3. Operating Conditions -- Severe terrain (grades to 19 percent) and congested traffic were noted. Freezing was not a problem locally.
4. Safety -- Complete and design-inherent safety was the highest priority technical requirement. Explosion-free steam generators, safe working fluids, and freedom from combustor malfunctions (firebox explosions) were among the requirements.
5. Road Performance -- Performance equal to or exceeding that afforded by diesel engines was desired (55 mph top speed, 5 mph on a 19 percent grade with a gross weight of 35,000 pounds).
6. Retarding -- It was desired that the power system be able to serve as a retarder, to slow the vehicle on downgrades.
7. Starting Time -- The vehicles were asked to be able to move within two minutes of cold switch-on, and to have full power available within five minutes.
8. Emissions -- Reference was made to Assembly Bill 356 of 1968 (Chapter 5, Section 39201 of State Code) defining a "low-emission motor vehicle":

   CO ----- not to exceed 11 grams per mile.

   HC ----- not to exceed 0.5 grams per mile.

   NO_x ---- not to exceed 0.75 grams per mile.

   Recognizing that the above figures related to passenger cars, it was desired that the buses conform to the above goals after multiplying by the ratio of bus/automobile fuel consumption.

9. Odor Levels -- To be limited.
10. Discharges -- Discharges of oil, soot, and fuel residues into the street were not to be permitted.
11. Noise Levels -- Sound levels were to be below those of diesel powerplants.
12. Heat Rejection -- Heat was not to be released in such a manner as to cause discomfort or danger to passengers, bystanders, motorists, or maintenance personnel.
13. Size and Weight -- The powerplant was to be enclosed; length and width of the bus were not to be increased. Powerplant weight and axle loadings were not to be greater than with diesel.
14. Controls and Instruments -- Operator's controls were to be uncomplicated and as similar as possible to conventional equipment. Instrumentation and warning devices were to be adequate to insure safe and efficient operation.
15. Fuel, Working Fluid, and Lubricants -- No. 1 diesel fuel was preferred. Fluids and lubricants were to be available on the open market or else supplied by the contractor.
16. Condensing -- Condensers were required to recover exhausted working fluid. Total recovery was required for working fluids other than water.
17. Bus Interfaces -- Safe and effective operation of brakes, steering, heating, ventilating, and electrical supply functions was to be retained.
18. Maintenance Obligation -- The contractor was to be responsible for field maintenance of the power system for the duration of the program.

Special Note

Recognizing that technical perfection could not be attained in the short term, the state considered its objectives as desiderata rather than firm requirements. The only exception was complete operational safety, which was a mandatory requirement of the project.

PROJECT CHRONOLOGY

It is of interest to note the plans, events, and changes that took place during the course of the program. Some of the more important junctures are listed chronologically below:

December 17, 1968:	Grant application for Steam Bus Project submitted to UMTA by Assemblyman John Francis Foran, Chairman of the Committee on Transportation and Commerce. The federal grant requested was $450,000.
February 17, 1969:	Grant application approved by Paul Sitton, then UMTA Administrator. First phase funding approved, $244,250.
April 1:	Work begun on technical plans and specifications by IR&T.
May 1:	State Assembly issues RFP to prospective system vendors. Scheduled ending date for project -- July 31, 1971.
July 14:	Being informed by prospective system vendors of inadequacies in time and funding proposed, State issues amendments to RFP. Scheduled ending date -- December 31, 1972. (UMTA had committed an additional $300,000 from contingency funds.)
September 20-21:	Selection panel meets and chooses four contractors: Brobeck, Lear, Steam Power Systems, and General Steam Corporation (the last of these went out of business).
November 24:	Assembly requests an augmentation of funding, with options of one to three systems to be developed.
March 3, 1970:	UMTA Administrator C. C. Villarreal approves total federal funding of $1,121,000 for the project.

June	Three engineering contracts signed, and work begins on system design and development.
September 16:	Experimental Lear steam generator demonstrated.
September 28:	First instrumented route-cycle test performed by Instrumentation Associates and IR&T, to quantify duty-cycle data of a diesel bus in local route service.
December 18:	Brobeck bus steam generator fired up for the first time.
January 21-22, 1971:	Project participants meet for a review and planning symposium at Bijou, California.
February 3:	Lear helical-screw expander operated on steam for first time.
Early February:	Steam Power Systems (SPS) fired up first version of bus steam generator.
February 23:	First dozen revolutions of SPS expander.
March 3-4:	Administrator Villarreal briefed on State's Phase II (bus testing and public service) proposal. Total federal funding requested for Phases I and II -- $1,611,484. Project now scheduled to end April 30, 1972.
April 1:	Lear petitions State for major design change: Screw expander to be replaced by a turbine driven by an organic vapor.
April 5:	Brobeck bus expander first operated on steam.
May 28:	UMTA approves Phase II.
June 4:	Brobeck expander reaches 200 gross horsepower in bench tests.
August 5:	Brobeck system tests completed.
September 9:	Brobeck system installed in bus, first moved under its own power.
October 1:	Brobeck bus turned over to A-C Transit.
October:	Laboratory tests conducted on Lear vapor turbine system.

October 4, 5:	Exhaust emissions tests, Brobeck bus, by California Air Resources Board (ARB).
November 16:	California Assembly proposes Phases III and IV to UMTA, engineering development to lead to pre-production prototypes.
November 17:	Brobeck bus demonstrated in Washington, D.C.; UMTA sponsors Steam Bus Symposium.
November 17:	Lear switches back to water.
November 22:	SPS changes expander design to fixed cut-off mechanically driven valves, laying aside hydraulic valve drive for the moment.
December 13:	Lear turbine reaches 249 gross horsepower.
January 6, 1972:	SPS expander reaches 275 gross horsepower.
January 24:	Brobeck bus enters public service in Oakland, but suffers engine failure after the third round-trip.
January 27:	Lear bus installation completed; bus driven 13 miles under steam with loads up to 58 passengers.
February 10:	California Assembly proposes Phase II.5 to UMTA (engineering improvements to present systems). Time is extended through September 30, 1972; total grant funding to be increased to $2,294,525.
March 17:	SPS bus operated under its own power for the first time.
April 10:	UMTA approves Phase II.5.
April 26:	All three steam buses demonstrated to Legislature in Sacramento.
April 27 - May 2:	Sound level and emissions tests in Sacramento.
May 25 - June 9:	Brobeck in public service, Hayward - San Leandro-Oakland - Berkeley.
July 20:	Lear bus delivered to San Francisco.
August 4:	Lear bus officially turned over to MUNI.
August 7-25:	Lear bus in public service, San Francisco.
August 7:	SPS bus delivered to Los Angeles.

August 22-25:	SPS bus and a diesel bus tested for emissions, North Hollywood.
August 30:	SPS bus officially turned over to SCRTD.
September 7:	SPS bus enters public service in Los Angeles. One trip made. Further service postponed to repair system.
September 13-15:	Lear bus tested for emissions at North Hollywood.
September 19-29:	Brobeck completes public service with A-C Transit. Final nine days were flawless performance, one run per day.
September 29:	SPS bus returns to public service in Los Angeles for a final day of operation.
September 30:	Technical work on the project completed.
October 1, 1972 - January 31, 1973:	Analysis and final reporting.

DESCRIPTION OF POWER SYSTEMS

Approach to the Problem

During this exploratory work, the three contractors were encouraged to develop their own individual design approaches. Moreover, 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. For example, reciprocating, rotary positive displacement, and turbine expanders all reached the preliminary bench test phase. A number of working fluids other than water were examined. Several variations of control systems, auxiliary drives, feed pumps, and burners were tested. By the time the project was over, some fairly large and expensive junk piles had come into being. Because time was short, there was not much opportunity for basic research or optimizing development. At times, outside criticism was leveled at the contractors' work, with the assertion that better approaches (such as variable cut-off expanders not requiring transmissions) were known. It required considerable discipline on the part of the contractors to avoid "improvements" and to stick to strictly limited objectives. Safety was mandatory. Low emissions and good road performance were primary goals. It was generally assumed that even an ad hoc system would be quiet (a bad assumption, as it turned out). Fuel consumption, powerplant packaging, and reliability were forced to lower positions on the agenda.

The very framework of this project was precedent-setting. Because legislative purpose was commingled with technological objectives, the intent was early demonstration, not product development. The vehicles were demonstrators, not prototypes. The mission was also a fact-finding one, to establish at long last a documented base for departure in ECE technology. Viewed in this light, it is believed that the program was highly successful.

Common Features

As finally developed, the three systems have some features and characteristics in common. All now use water as the working fluid. All generate steam in forced-circulation, continuous-coil tubular steam generators. The burners are of the air-atomizing type, in which compressed air is mixed with fuel in nozzles to create a fine spray. Condensing is by fan-cooled finned tubular radiators. As an expedient in this short-term endeavor, all three buses use commercially available automatic transmissions embodying hydraulic torque converters. In each case, the main expander (engine or turbine) drives auxiliaries and accessories at idle. While a variety of liquid fuels may be burned, most testing was conducted with No. 1 diesel fuel.

While the automatic steam generator control systems differ from each other, all three powerplants employ the "normalizer" principle to control steam temperature. As originated for the Doble steam cars, this involves sensing the temperature of the steam leaving the boiler, and injecting a supplemental amount of feed water into the superheater as required. This, of course, requires the proportioning of fuel and primary feed water such that the steam temperature would have a rising characteristic.

Because of the stringent requirements on system safety, similar features were adopted for the control of potential hazards:

1. The automatic steam generator controls are arranged to shut off the fuel to the burner, should pre-set limits on steam pressure and temperature be exceeded.

2. Safety valves of adequate flow capacity are installed, in the event that pressures rise above the automatic control settings.
3. Flame sensors are employed to prevent fuel flow in the event of ignition failure.
4. Overspeed governors will shut the systems down in the event of expander overspeed.
5. Drivers' controls are all very similar to those in the original diesel buses.

Specific features of each system are given below.

William M. Brobeck & Associates

The Brobeck system (15) is an outgrowth of the automatic monotube steam generators and compound-expansion piston engines developed earlier by Doble and Besler (8,9,10). The steam generator and its automatic controls are mounted in the original engine compartment at the rear of the bus. As shown in Figure 3, the other system elements are located amidships under the floor. By locating the system components in existing spaces, the original seating capacity (51 passengers) was retained. The bus used was loaned to the project by A-C Transit, and is a General Motors Model T6H5305. 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 two-speed torque converter unit, locking up into direct drive at 29 mph.

A general view of the Brobeck steam generator is given in Figure 4. Approximately one-fourth mile of tubing is used, varying from 0.50" O.D. in the feedwater heating (economizer) section to 1.0" O.D. 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:

1. Burner off.
2. Idle, fuel rate 8.9 gal./hr.

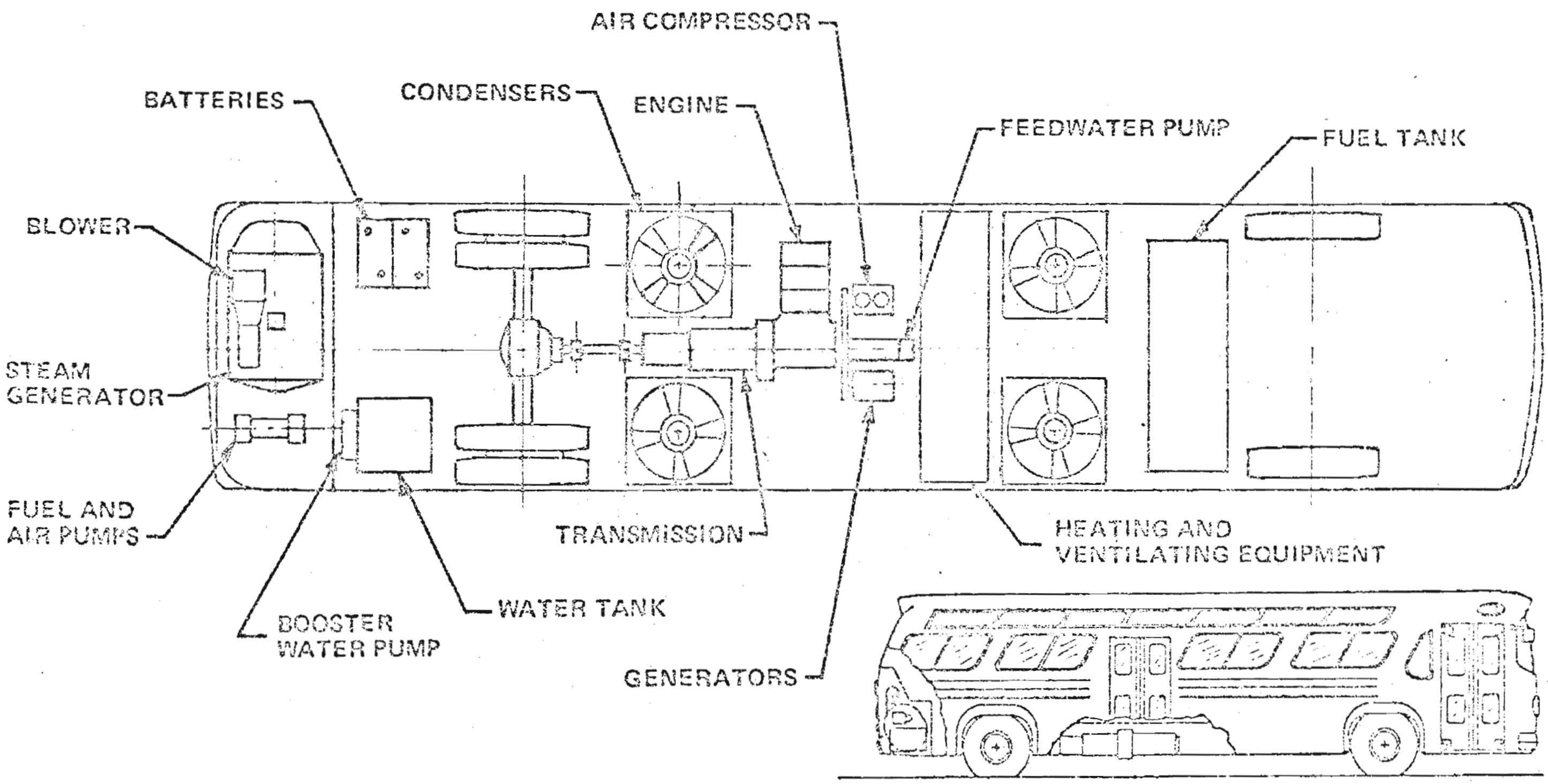

Fig. 3 - Location of Brobeck power system components in bus.

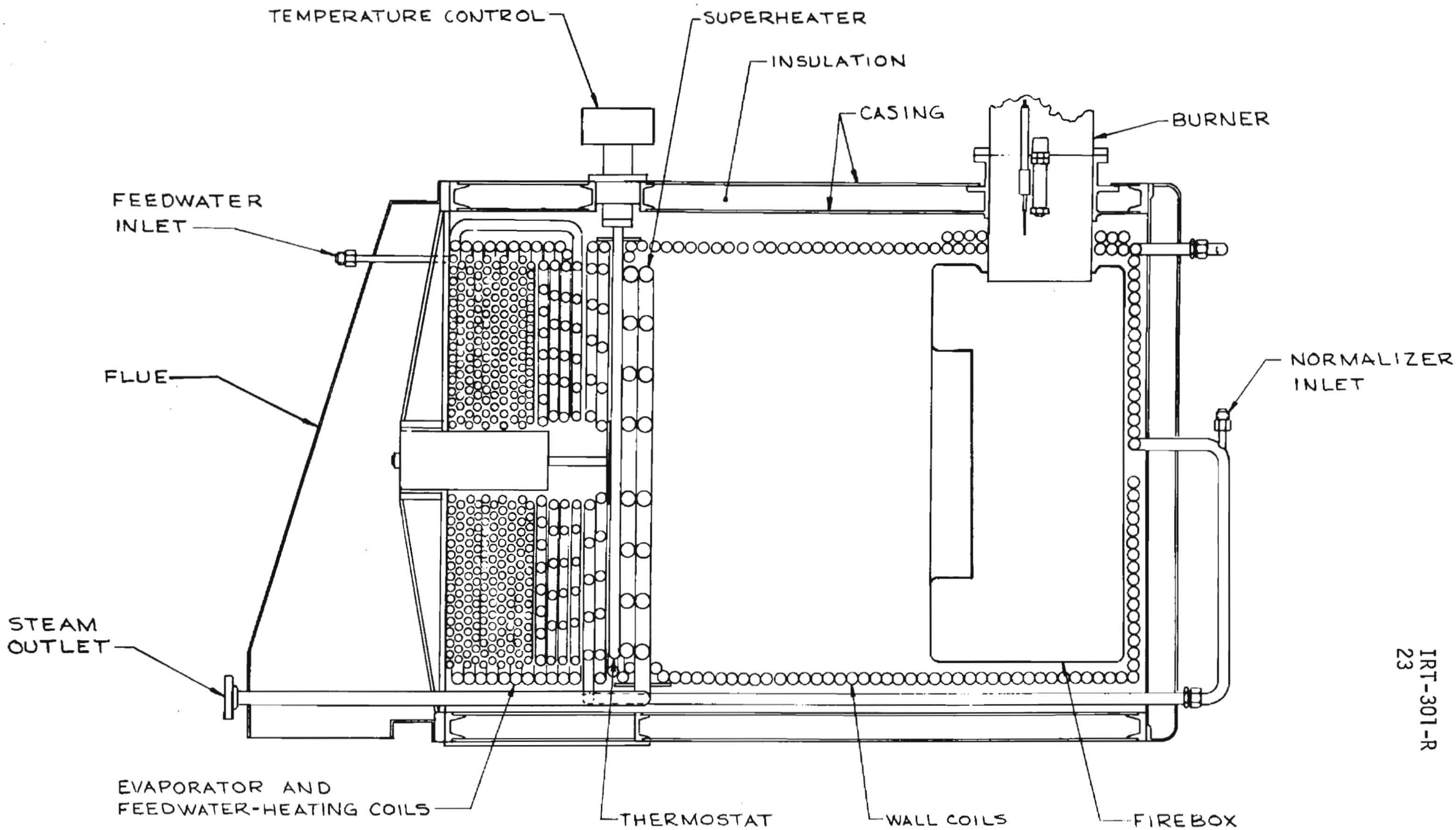

Fig. 4 - Brobeck steam generator

3. Low fire, 15 gal./hr.
4. High fire, 30 gal./hr.

The average idle fuel consumption is 4.44 gal./hr., with the idle fire cycling on-off about 50 percent of the time each. The firing rate is determined automatically by changes in boiler pressure. If the idle fire is on and a pressure switch senses that the pressure has dropped to a preset value, the low fire level comes on. If the load is such that the pressure falls below a second preset value,the burner is increased to high level.

The engine (expander) has three double-acting cylinders (Figures 5 and 6). 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 cut-off valve gear is used. The valves themselves are of the sliding "piston valve" type, with inside admission. The three-cylinder configuration was chosen as the simplest engine that can be balanced with one counter-rotatint shaft. This balance shaft also serves to drive the valves. In this type of engine, a compromise must be made between equal power in each cylinder and equal power between the two stages of expansion. The division of power in the Brobeck expander is 40 percent in the one high-pressure cylinder, and 30 percent in each of the lows.

The crankcase and cylinders are separately lubricated. Ordinary motor oil is used in the crankcase, and this is in theory never contaminated. A small amount of high-temperature steam cylinder oil is pumped into the steam line near the engine. This oil is later removed (it is not reused) by a combination of centrifugal action, filtration, and flotation lest it bake out in the boiler's superheater.

Lear Motors Corporation

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 engine compartment. It was necessary, however, to enlarge this compartment because of the shape of the steam generator and to accommodate regenerators. Because of this enlargement, seating capacity was reduced by five passengers. The bus was provided by Lear Motors, a GM Model T8H5305A.

Lear's steam generator features a radial outflow of the hot gases through the tube bundle. Finned tubing is used in portions of the generator, to extend

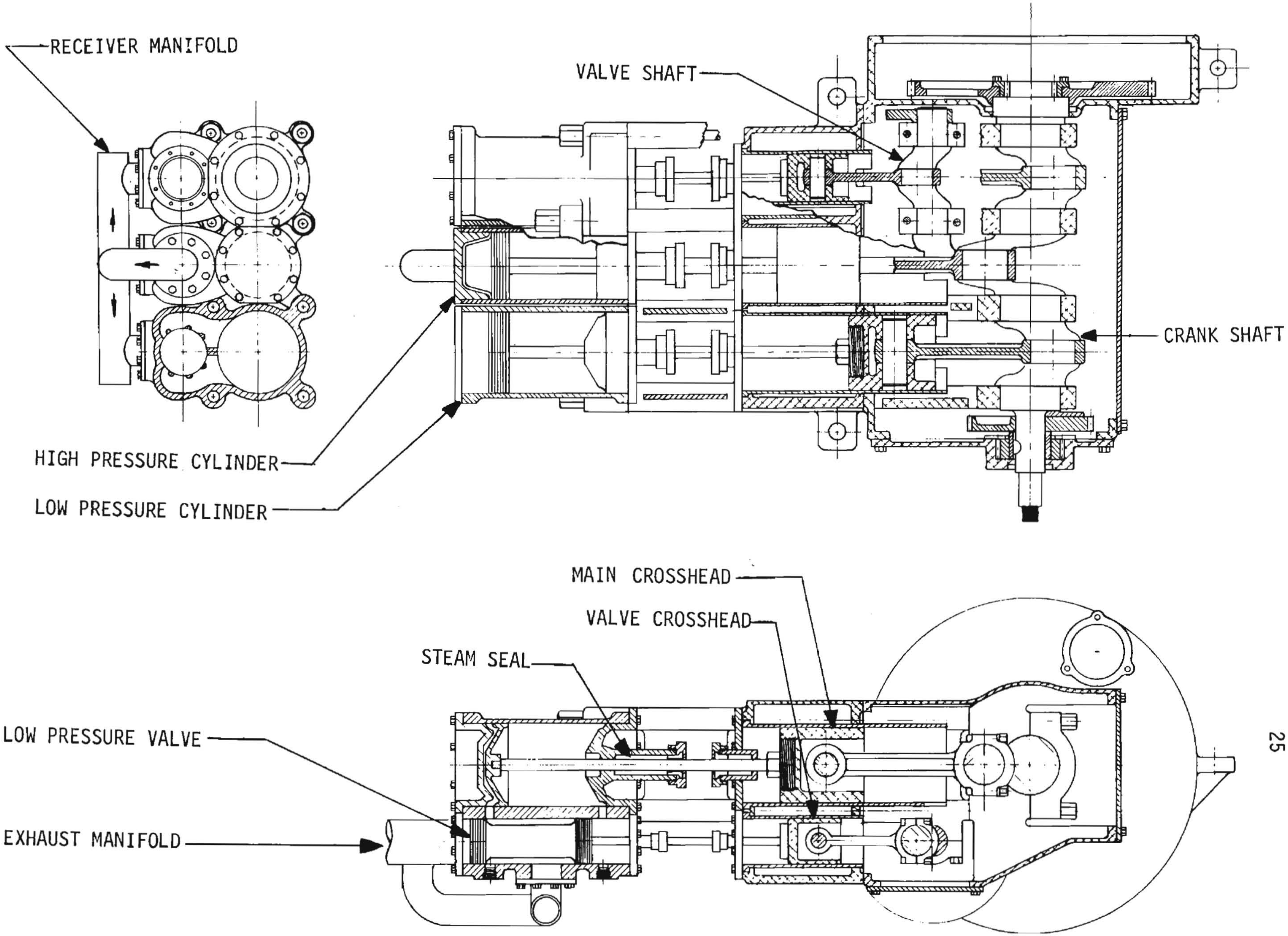

Fig. 5 - Sectional view of Brobeck reciprocating expander

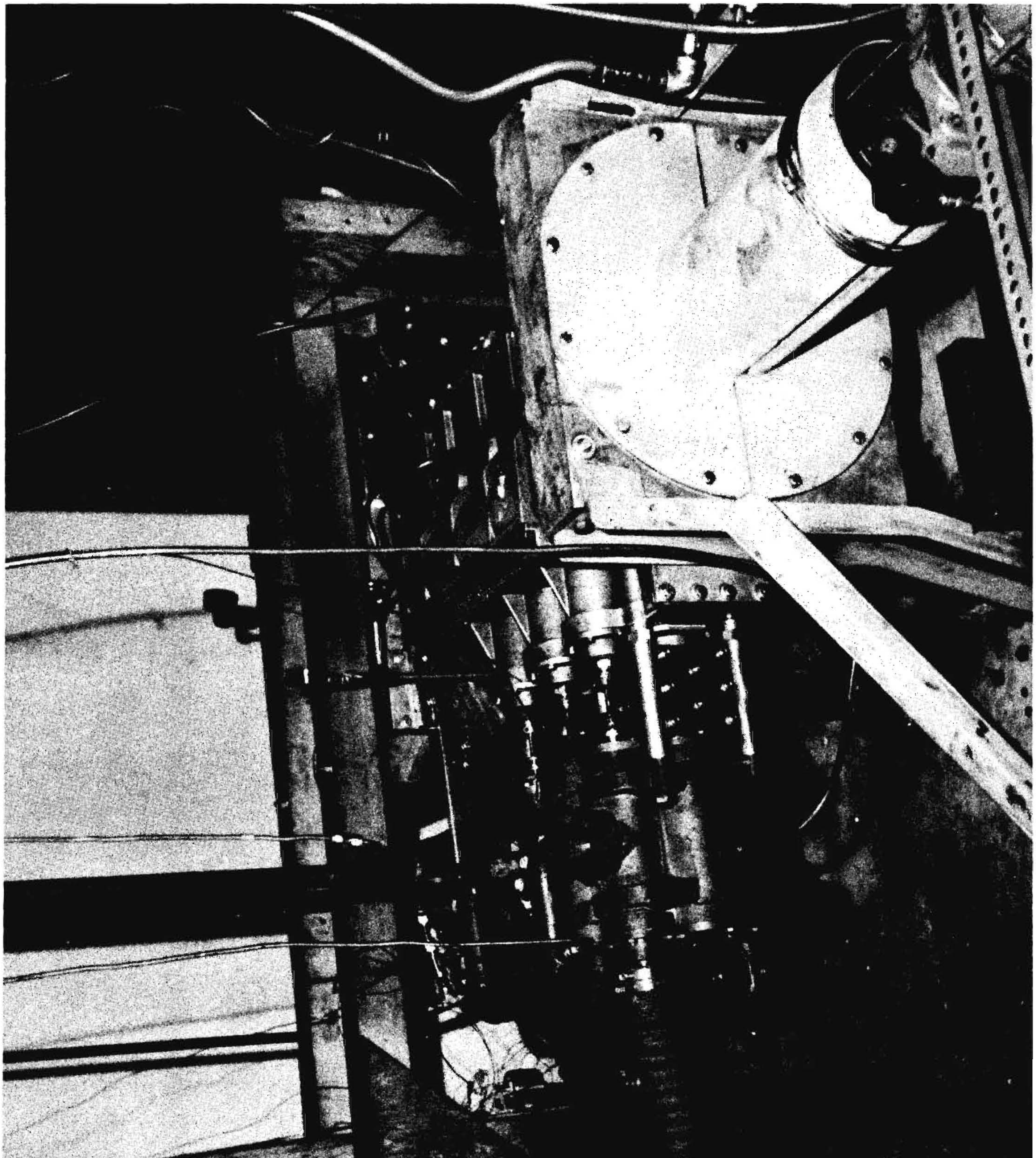

Fig. 6 - Brobeck expander during dynamometer testing

the gas side heat transfer surface area. During the development period, several types of burners were tried, including vaporizating, mechanical atomizing, and air atomizing. An air atomizing burner was finally adopted, although most of the bus operation was conducted with a mechanically atomizing burner, of the spinning cup variety.

So far as is known, this vehicle is the first in history to be successfully propelled by a steam turbine. The single stage impulse turbine is very small in size (wheel diameter 5.6 inches) and rotates at high speed (to 65,000 rpm). Reduction gearing of 23.1 ratio connects the turbine via an Allison HT-740 four-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 Figures 7 and 8.

Early in the program, Lear considered the use of positive displacement expanders, both reciprocating and rotary types. Figure 9 shows the screw expander. A device of this type was bench tested during the program and appeared to have satisfactory performance and efficiency from a technical point of view. Positive displacement expanders were set aside, however, with the viewpoint that turbines could be simpler, lighter in weight, and less expensive to produce.

The first turbine tests were with an organic working fluid instead of steam. Advantages included resistance to freezing and higher turbine efficiencies (when a vapor having a higher molecular weight than water is used). However, the use of steam was elected to bypass problems of chemical decomposition at elevated temperatures and problems in field servicing. When the change was made to steam, the turbine nozzles were redesigned. The regenerators (feed water heaters) were retained in the system, however.

Figure 10 shows the single-stage impulse turbine with the exhaust collector removed. The reduction gearbox is shown attached.

Servomechanisms with electronic information processing are used for steam generator control. Control of the burner and feedwater is proportional rather than "on-off."

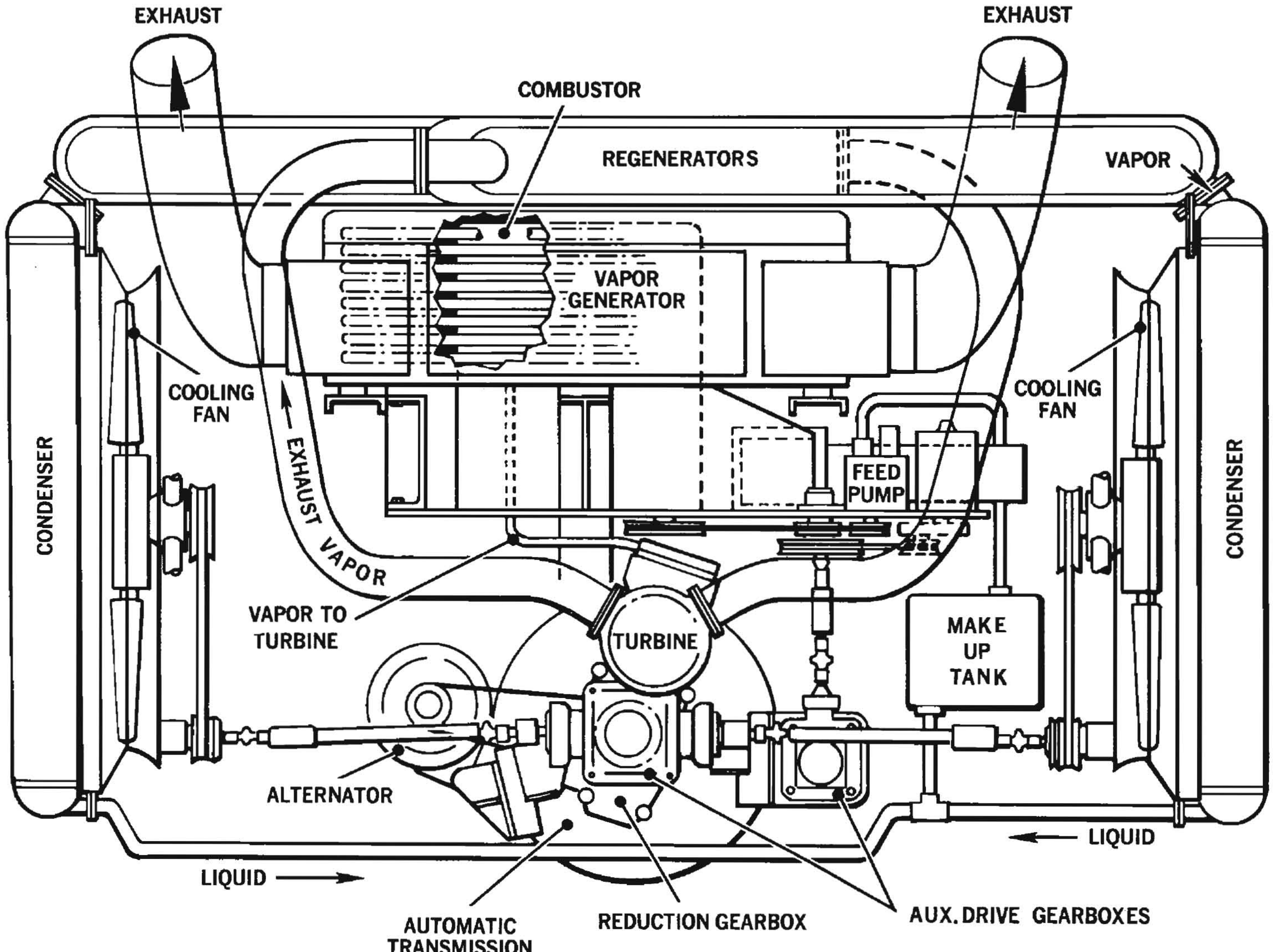

Fig. 7 - LEAR VAPOR TURBINE SYSTEM (GM COACH) INSTALLATION
Components & Flow Diagram
(rear view)

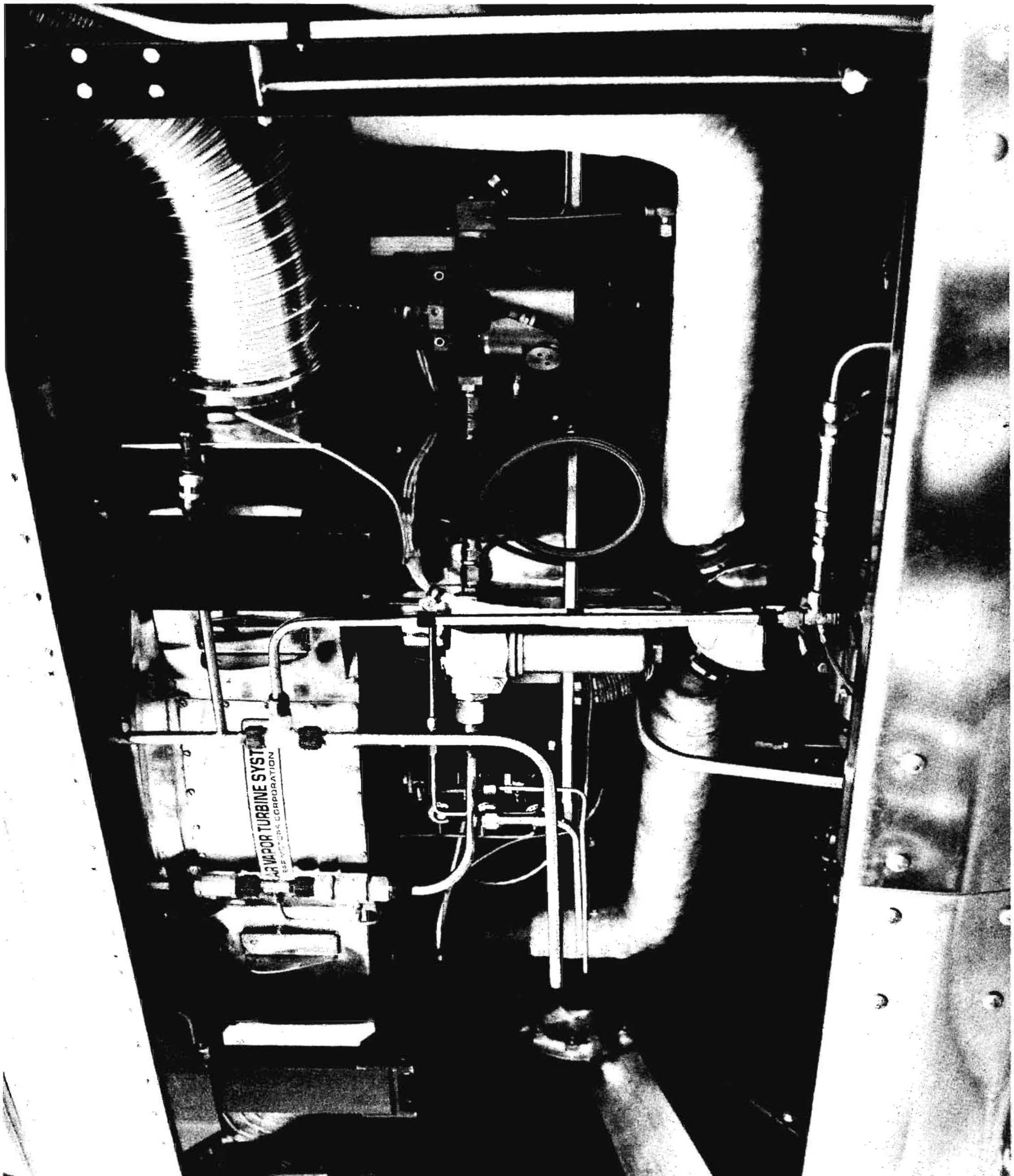

Fig. 8 - Lear vapor turbine system installation

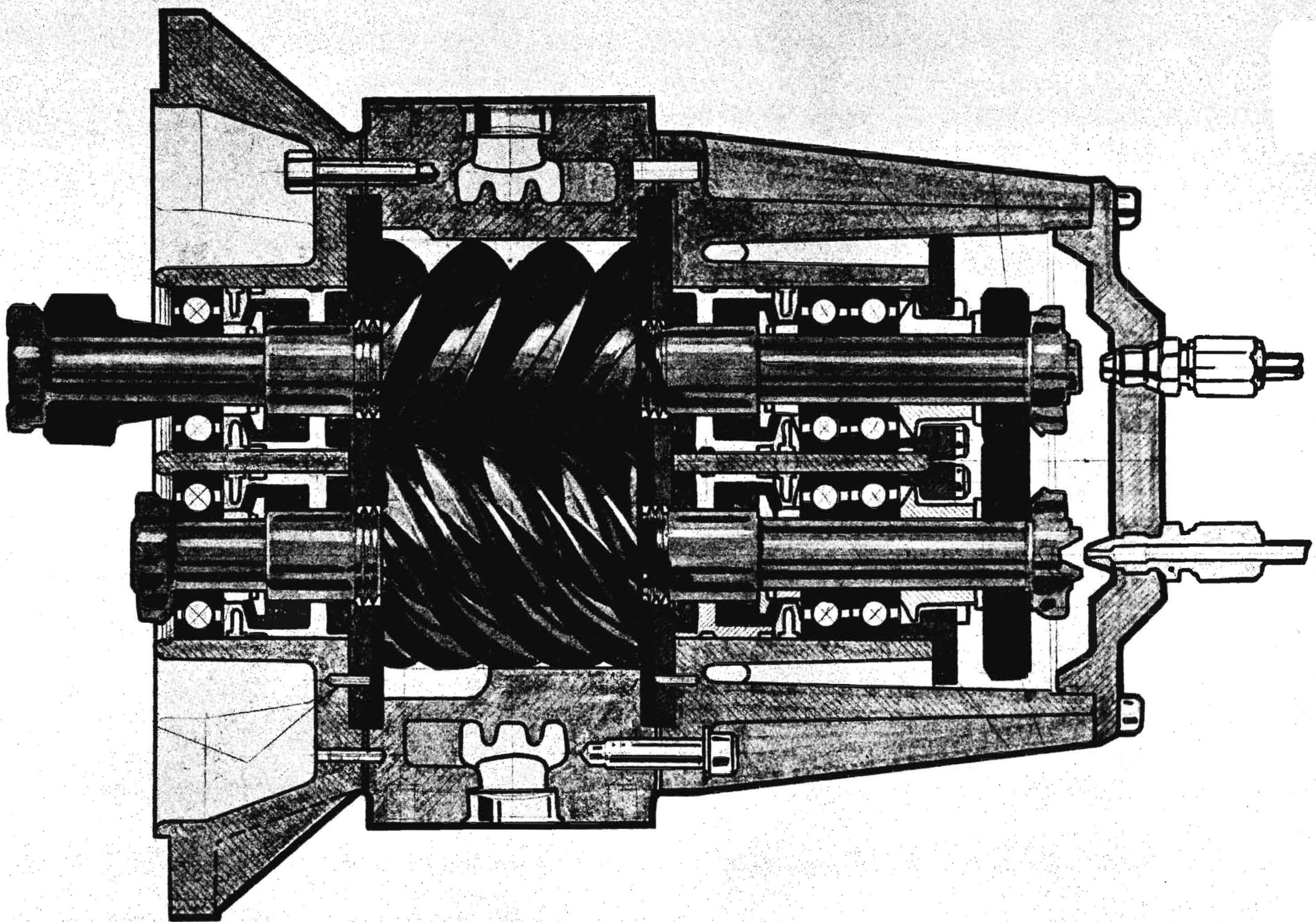

Fig. 9 - Historical: Lear involute screw expander originally considered for bus application

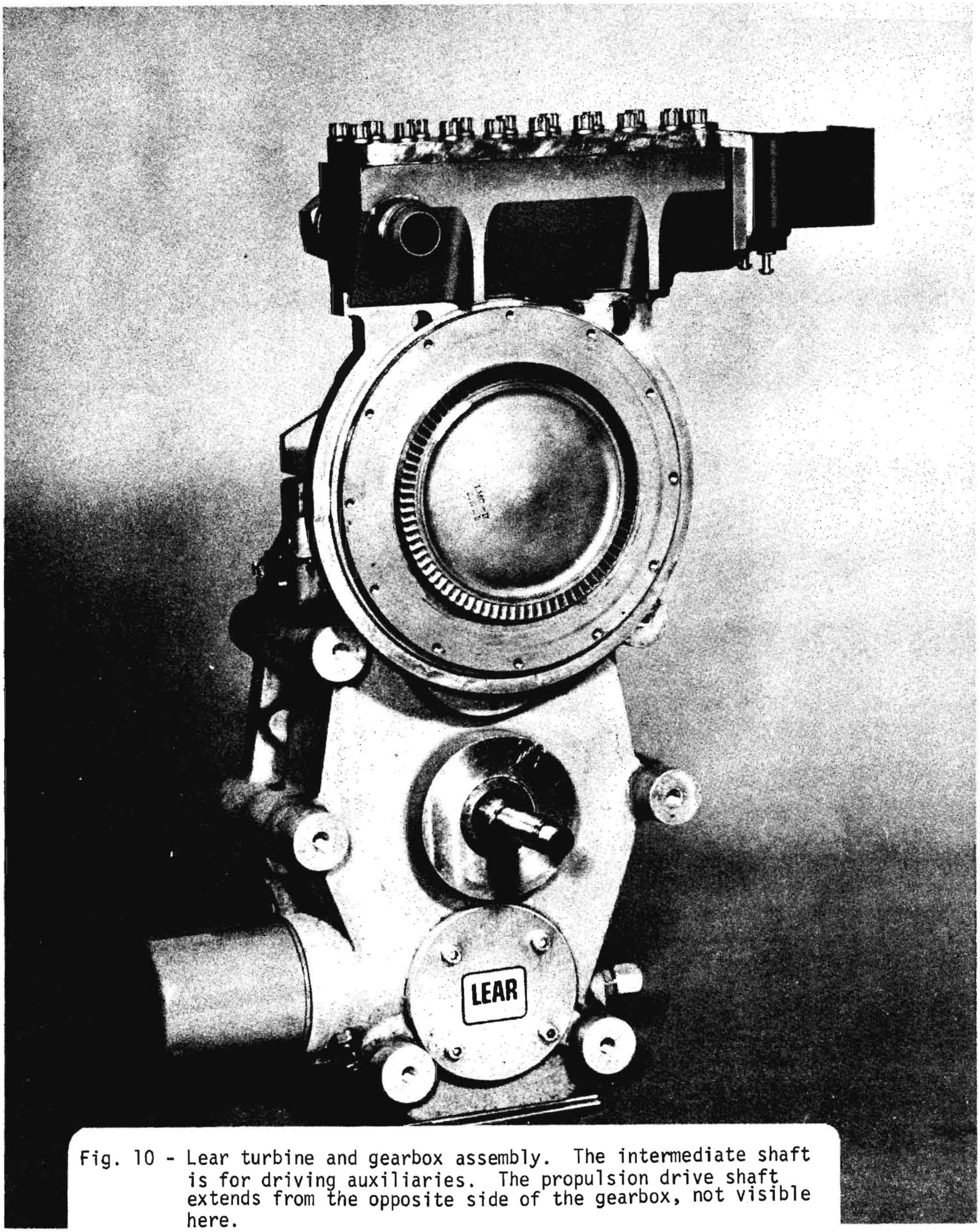

Fig. 10 - Lear turbine and gearbox assembly. The intermediate shaft is for driving auxiliaries. The propulsion drive shaft extends from the opposite side of the gearbox, not visible here.

Steam Power Systems, Inc.

The SPS powerplant (16) features a six-cylinder 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 inter-stage re-superheating. The steam generator, expander, auxiliaries, and one of the condensers are located in the rear engine compartment. Three additional condenser cores are located under the bus, just behind the front axle. Figures 11 and 12 show the system arrangement and installation. The SPS system is installed in a Flxible Model 111 CC-D51 coach supplied by SCRTD. The rear engine compartment has been enlarged, diminishing passenger space by five seats.

Of the three buses, this is the only one to retain the original transmission (GM-Allison Super V) and angle-drive 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 when time did not permit sufficient development. One of these was the use of infinitely variable cut-off 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 increased thermal efficiency. The second would avoid the old problem of oil carry-over into the condenser and boiler.

The use of a reheat cycle is interesting. The purpose is to increase overall thermal efficiency by reducing condensation within the low-pressure cylinders when high expansion ratios are employed. Unfortunately, it was not possible to verify the efficacy of this process in bus service, because the original variable cut-off valving had to be set aside to meet time schedules. An interesting sidelight to the reheat question is the fact that a greater total enthalpy (heat) drop in the expander is possible per pound of steam since the same steam is heated twice. The resultant decrease in specific steam rate lightens the burden on the feed pump, among other effects.

The steam generator is fitted with proportional controls, with a design turn-down ratio of 10:1. Air, fuel, and feedwater rates are coordinated to one another. The control system senses steam pressure to actuate an air damper. Airflow is then measured, reflecting in a command to a fuel-regulating control and the primary feedwater rate control. As described

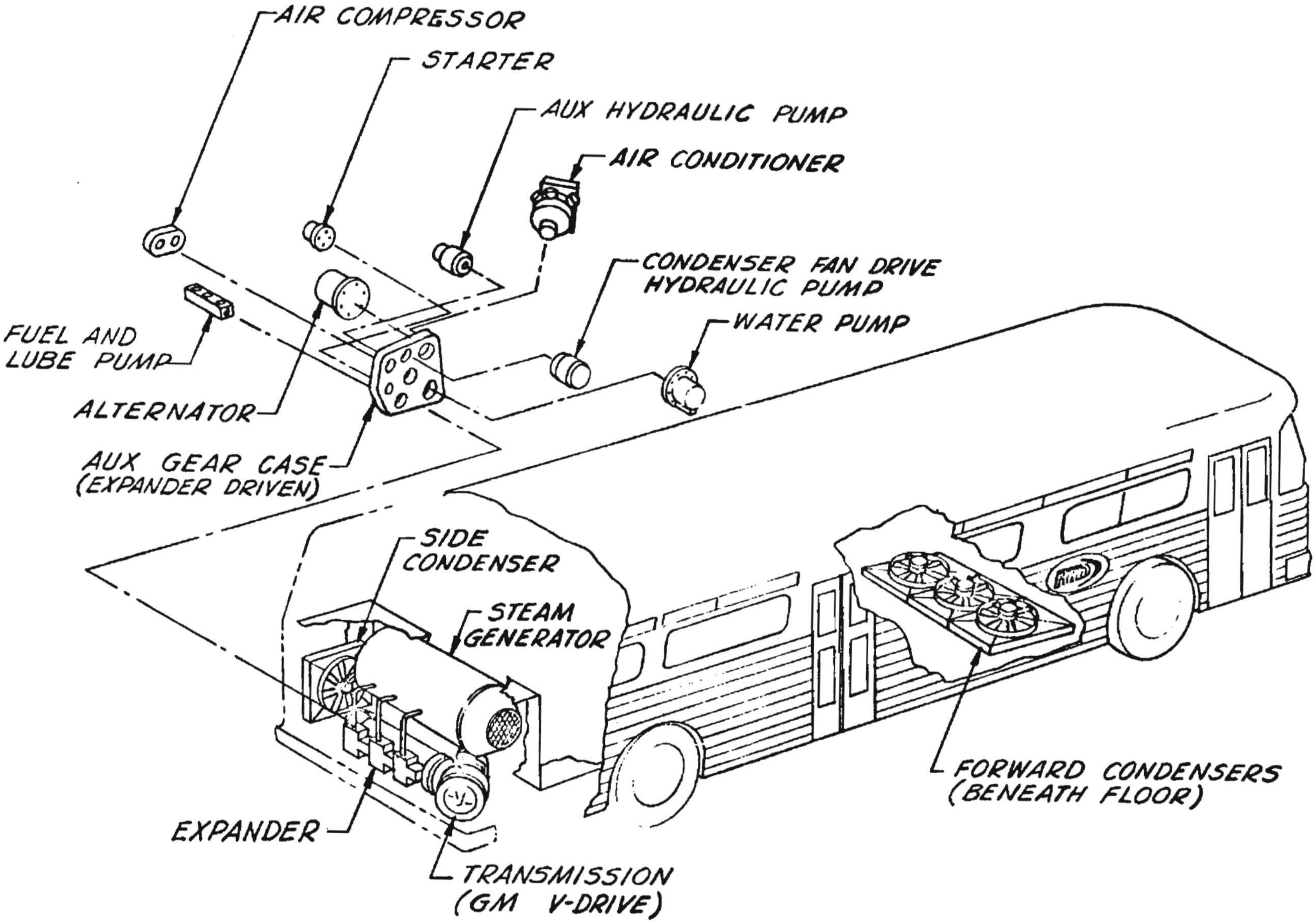

Fig. 11 - Installation layout, Steam Power Systems, Inc.

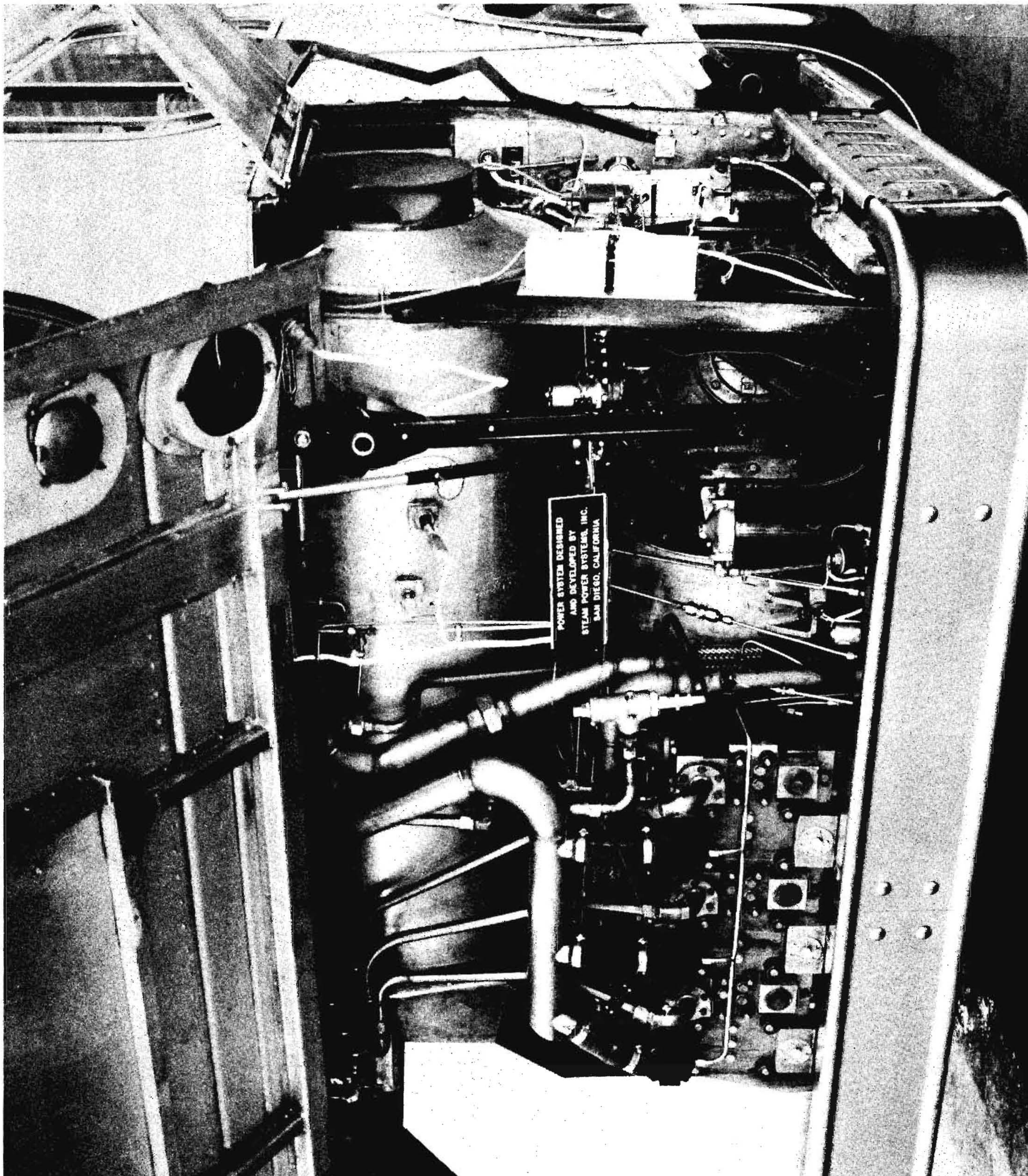

Fig. 12 - Installation of powerplant by Steam Power Systems, Inc. into a Flxible coach

previously, a normalizer set-up provides control of steam temperature. Figure 13 is a simplified diagram of system components and control schematic.

With similarities to the Brobeck expander, SPS separates the lubrication of the crankcase components from the steam cylinders. Sliding piston valves are used to time steam admission and exhaust events, with an arbitrarily fixed cut-off. (At SPS, the development of hydraulically actuated, variable cut-off puppet valves has been resumed as an adjunct to the bus project. The work is being carried out with a small two-cylinder research expander.)

To minimize expense and experimental down-time, the SPS expander is of modular construction. This allows, for example, experimental changes in engine valving without redesigning the entire engine block.

Tabulation of Specifications

The specifications of the three powerplants are compared in Table I. Because configurations changed many times during the project history, values given may differ from those reported in earlier publications. It is interesting to note the power system weights, which may be compared with a complete six-cylinder diesel power system weighing about 3,800 lbs., including transmission and other auxiliary items.

TEST METHODS AND INSTRUMENTATION

Scope of Technical Evaluation

Testing, evaluation, analysis, and documentation were major activities of this project. System safety, exhaust emissions, sound levels, road performance and operating characteristics, endurance, and the consumption of water and fuel were all subjects of measurement and evaluation. These and other aspects were compared to bus operation with conventional diesel engines. IR&T had the responsibility of coordinating all technical evaluation work. Some of this work was performed by public agencies such as the California Air Resources Board and California Highway Patrol. Other tests were performed by IR&T directly. Instrumentation and testing to determine the characteristics of bus driving cycles were provided under subcontract by Instrumentation Associates.

Powerplant bench testing was performed by the System Contractors, and key tests were witnessed by IR&T's Project Technical Manager.

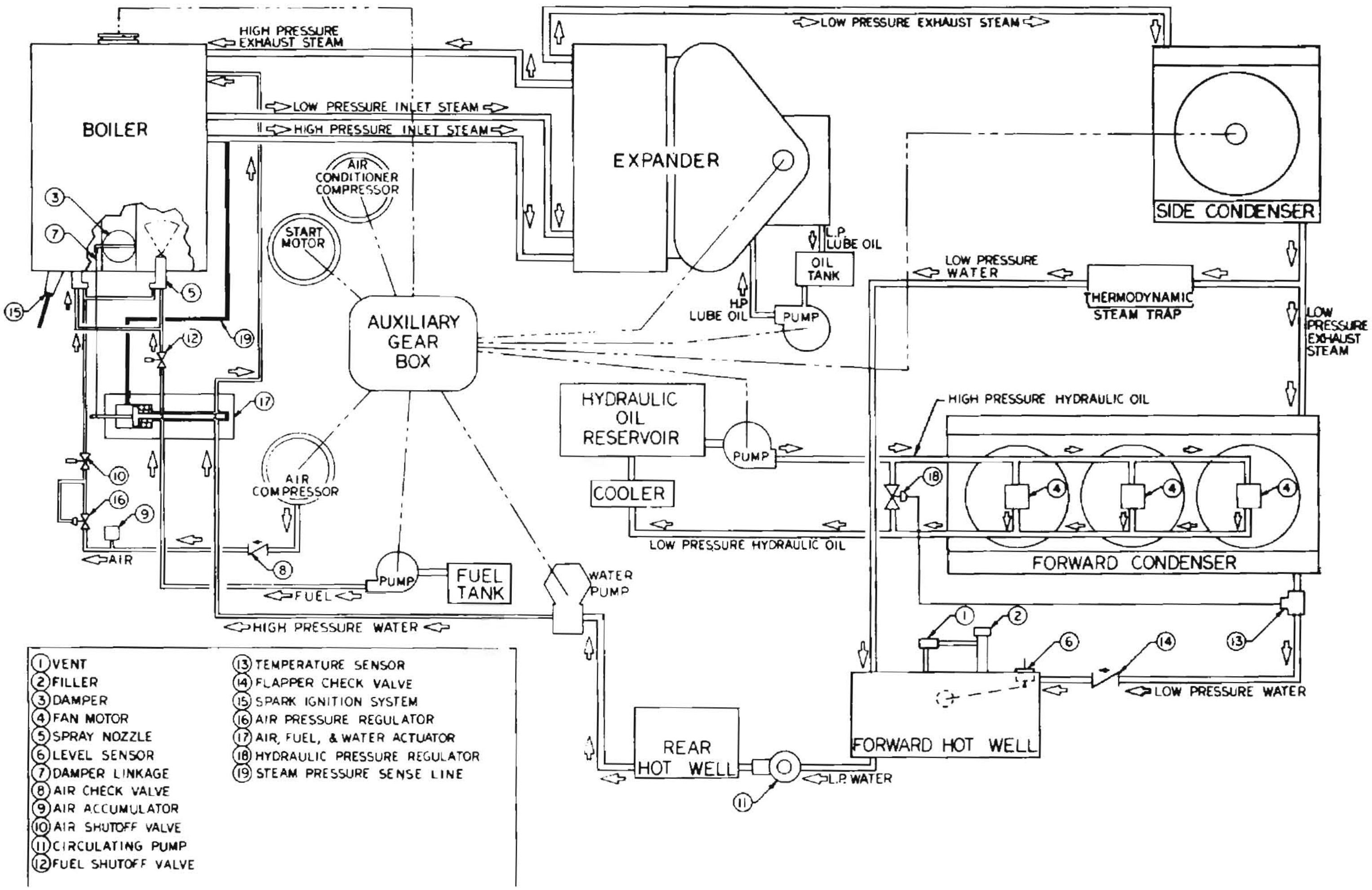

Fig. 13 - Flow diagram and control schematic, SPS system

TABLE I

POWERPLANT SPECIFICATIONS

	BROBECK	LEAR	SPS
Expander type	Reciprocating	Turbine	Reciprocating
Max. expander gross bhp	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, ft.^{2}	180.2	275	356 (b)
Combustion intensity, BTU/hr.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 (c)
Steam temperature, ^oF	850	1,000	750 (c)
Lowest bsfc, lb./net bhp-hr.	0.985	1.13	1.18
Approximate weights, lb.:			
Boiler with burner	920	890	850
Expander	965	110 (d)	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 from figures shown for actual use in bus system.
(b) Including reheater section.
(c) In the SPS system, the steam leaving the reheater is 240 psi at 650 to 750° F.
(d) With gearbox.

Safety

Determinations of operational safety were made at the Contractor's site during powerplant development and initial road trials. Safety tests included:

1. Proof Tests -- The boiler or vapor generator and other pressurized parts of the systems were hydrostatically proof tested. Boiler proof tests were conducted by completely filling the boiler with water, and then pumping additional water into it until the desired test pressure was reached. The use of cold water in applying a test overpressure minimizes damage or hazard should a failure occur. In order to insure a suitable margin of operational safety, proof tests are taken to pressures higher than the normal operating pressure. In this project, the proof pressure, P_p, was determined by the following formula:

$$P_p = 1.5\ P_s\ \left(\frac{Y_R}{Y_T}\right) .$$

Where

P_s = Pressure at which safety valve is set.

Y_R = Yield strength of boiler material at normal room temperature.

Y_T = Yield of the same material at the maximum elevated temperature under actual operating conditions.

For example, an SPS boiler was tested on January 15, 1971. P_s was 1,200 psi. The boiler tube material was a stainless steel alloy having a yield strength of 45,000 psi at room temperature. However, the metal temperature in the superheater section reached approximately 1,100° F, at which temperature the yield strength is only 20,000 psi. Accordingly,

$$P_p = (1.5)(1{,}200)\left(\frac{45{,}000}{20{,}000}\right)$$

$$= 4{,}050 \text{ psi.}$$

In the actual test, a pressure of 4,300 psi was applied by means of a hand-powered hydraulic pump. The pressure was held for five minutes. No leaks, failures, or incipient weaknesses were observed.

Similar tests were also performed on boilers and other components at the other two contractors' facilities.

2. Controls and Safety Devices -- All automatic controls and safety devices were tested in the as-installed condition for correct functioning.

3. Motor Carrier Safety -- The California Highway Patrol inspected each vehicle after conversion to assure compliance with the California Vehicle Code and applicable motor carrier regulations. The Project Technical Manager observed the operation of the vehicles to determine that safe handling, steering, braking, and visibility were not impaired.

Exhaust Emissions

All exhaust emissions test work was performed by the California Air Resources Board (ARB). The procedures are those outlined for the 1973 and 1975 exhaust emissions standards for heavy-duty diesel-powered vehicles (17,18). The test procedures specify a 13-mode test sequence in which a series of steady-state loads and speeds are imposed by a dynamometer. Road-load transients are not imposed by the test, although the steam powerplants tested did experience boiler control transient states in order to hold steady dynamometer loads. While the primary procedures are written for the certification of engines with the use of an engine dynamometer, the buses in this program were tested under an alternate chassis dynamometer procedure. All of the tests were conducted in the field, with real-time sampling and analysis of the exhaust (no bagged samples were used) by means of the ARB mobile laboratory. Chart recordings were taken of CO, CO_2, HC, and NO in terms of concentrations (ppm). Later, these readings were converted to grams of pollutant per brake horsepower hour (g/bhp-hr). Measurements of engine speed, "road speed," chassis dynamometer horsepower, fuel and air flow rates, and smoke opacity were made during the runs.

Instrumentation used by the ARB included:

1. Dynamometer. Three different Clayton Chassis dynamometers were used on the various test dates:
   a. Model C-61, at San Francisco Municipal Railway, October 1971.
   b. Model CT-400-200-OG, at Division of Highways, Sacramento, April-May, 1972.
   c. Model CT-400, at Division of Highways, North Hollywood, August-September, 1972.

2. Emission Analyzers.
   a. Three Beckman Model 315A nondispersive infrared analyzers for carbon monoxide (CO), carbon dioxide (CO_2), and nitric oxide (NO).
   b. A Beckman Model 402 flame ionization detector for hydrocarbons (HC).
   c. An Atlantic Research Model 101 opacity meter for smoke monitoring.
3. Fuel Flow. Various fuel quantity or rate measurement devices were used:
   a. During the October 1971 tests, two rotameters in connection with a fuel return surge tank and manual regulating valve were used. This apparatus was subsequently used in all tests of diesel buses.
   b. For the May 1972 test of the Brobeck bus, a Conoflow Model DP-31-1453 positive displacement meter was used to measure totalized fuel flow to the burner nozzle.
   c. For both tests of the SPS bus, a Potter Model 3/16-37D turbine flow-meter was built into the fuel line.
   d. During the August-September 1972 tests of the SPS and Lear steam buses, totalized fuel flow measured by an apparatus supplied by IR&T. In this apparatus, fuel suction and return lines may be switched instantaneously from the vehicle's tank to a two-liter glass cylinder (and back) against stop-watch timing.
   e. During the September 1972 tests of the Lear bus, a turbine meter was built into the fuel line.
4. Air Flow. The following instruments were used:
   a. For the diesel bus tests, a Meriam Model 50 MC2-6P laminar flow meter with a 5" inclined manometer and a U-tube.
   b. For the Brobeck steam bus, a 5.70" diameter thin-plate orifice with manometer.
   c. For the SPS bus, a 6" diameter flow duct with pitot tube (May 1972)(replaced by an 8" duct in August 1972).
   d. For the Lear bus, a 6" diameter flow duct with pitot tube.

Thirteen test modes are included in the California Heavy-Duty Test Cycle. Full-load (100 percent), 75, 50, and 25 percent, and no-load runs were made at each of two "road speeds" (approximately 50 mph and 30 mph). In addition to the above ten modes, three idle periods are tested.

Sound Levels

Sound level tests were performed by the California Highway Patrol at four testing sites:

1. Parking lot, Oakland Coliseum.
2. Parking lot, CAL-EXPO State Fairgrounds, Sacramento.
3. Parking lot, Candlestick Park, San Francisco.
4. Parking lot, Great Western Exhibit Center, Los Angeles.

Both external and internal sound fields were measured. All measurements were taken with a General Radio Type 1565-A, with the microphone separated from the meter by means of an extension cord. For all external measurements, the microphone was placed on a tripod in an area free from interfering objects at a height of four feet above the ground. A sound level calibrator was used at intervals to insure accurate readings. Test set-ups and procedures were as follows:

Drive-by Tests -- The microphone was placed on a tripod, and located fifty feet from the center of the lane to be traveled. Five readings were taken in each direction of travel, with the bus under full-throttle acceleration as it passed the microphone. The transmission gear was selected such that engine speed was at two-thirds maximum-rated speed or less upon entering the 100 foot test course, but without exceeding 35 mph at the end of the course (to accentuate powerplant noise, rather than the effects of tire and wind noise). Maximum observed values were used for project reporting purposes. The test procedures were in accordance with the CHP Sound Measurement Procedures Manual HPM 83.3, Annex B, and comply with Article 10, "Vehicle Noise Measurement," of the California Administrative Code Title 13. These procedures are patterned after SAE Recommended Practice J366a (19).

Curb-Side Simulation -- Using the same test course, the tripod-mounted microphone was moved up to a position fifteen feet from the center of the lane to be traveled. The rear bumper of the bus was placed even with the microphone. Sound level measurements were then made with the bus stationary and the engine idling. A second reading was taken as the maximum value observed when the bus accelerated at full throttle, starting from rest. A number of tests were made in each direction until repeatable maximum values were obtained.

Interior Noise -- Values were read at idle, and also the maximum observed during full-throttle accelerations in the transmission gear normally used for starting on a level roadway. Usually, the maxima occurred just prior to upshift. The microphone stations were along the center line of the aisle, midway between the floor and the ceiling. Readings were taken in the rear, center, and front of the bus, with the microphone always facing the rear of the bus.

Tractive Resistance

Tractive resistance (the sum of rolling resistance and air drag forces) was determined for some of the buses by the coasting method (20, 21). The vehicle was put into neutral gear at some suitably high cruising speed (like 50 mph) and the time interval to decelerate through increments of velocity was measured with a stopwatch. Making an allowance for the inertia of rotating parts, the total drag force at any given speed was equated to the vehicle's mass and rate of deceleration. Tests were by two-way runs over a level road.

Road Performance

Road performance measurements were done with the aid of either a trailing fifth wheel and precision survey speedometer, or by the vehicle's speedometer. In the latter case, the speedometer error was determined by timing methods or against the survey speedometer. Level-road tests were made in two directions to cancel minor effects of wind and gradients.

Fuel Consumption

The measurement of fuel consumption of diesel engines (and some of the steam systems) was complicated by the fact that not all the fuel pumped from the tank is consumed. These are termed bypass fuel systems, in which a surplus of fuel is bypassed by the injectors or burner controls and returned to the tank. Thus, what must be determined is the difference between two flows. Should these two flows be at different temperatures, or non-simultaneous, additional difficulties arise.

Two types of fuel-metering apparatus were used by IR&T. Either type could be used in single-flow or two-flow systems by modifications to the flow circuits:

- For the determination of total net flow over a known distance or a given time interval, a graduated test reservoir with two synchronized three-way valves was used. This apparatus, with a two-liter graduate cylinder, is shown in Figure 14. The three-way valves are switched in unison by a single lever, from the vehicle's fuel tank to the test reservoir for the test interval and then back again. Thus, by switching the suction and return lines simultaneously, the net fuel used over an interval may be measured. A deduction must be made for the volume of the two tubes immersed in the test reservoir, and a further correction is made for temperature. (All fuel measurements in this project were corrected to a standard 60°F.) This same switching apparatus was used in conjunction with a ten-gallon test container when measuring fuel consumption over longer time periods.
- A second type of fuel meter was a positive-displacement mechanism, so arranged as to give 1,000 electrical pulses per gallon of fuel. This unit, a Conoflow Model DP-31-1453 meter, contains a small four-piston motor driven by the fuel flow. The crankshaft carries a permanent magnet, opening and closing an electrical circuit with a reed switch. Data was recorded either on magnetic tape or on an electromagnetic visual counter. The data from magnetic tape could be processed to yield either instantaneous rate information or totalized flow. This Conoflow meter was very accurate (considerably less than one percent error at most flow rates tested) when used in single-flow systems. For two-flow systems, the meter was used with another device marketed by the Conoflow Corporation, known as a "two-pipe ratio regulator," part # DH-1484. This analog device is used to connect the meter into a supply line and the return-flow line such that only an amount of fuel equal to the net fuel consumed passes through the meter. Accurate results could not be obtained with the use of this flow regulator, however, and so it was only used to indicate approximate instantaneous fuel

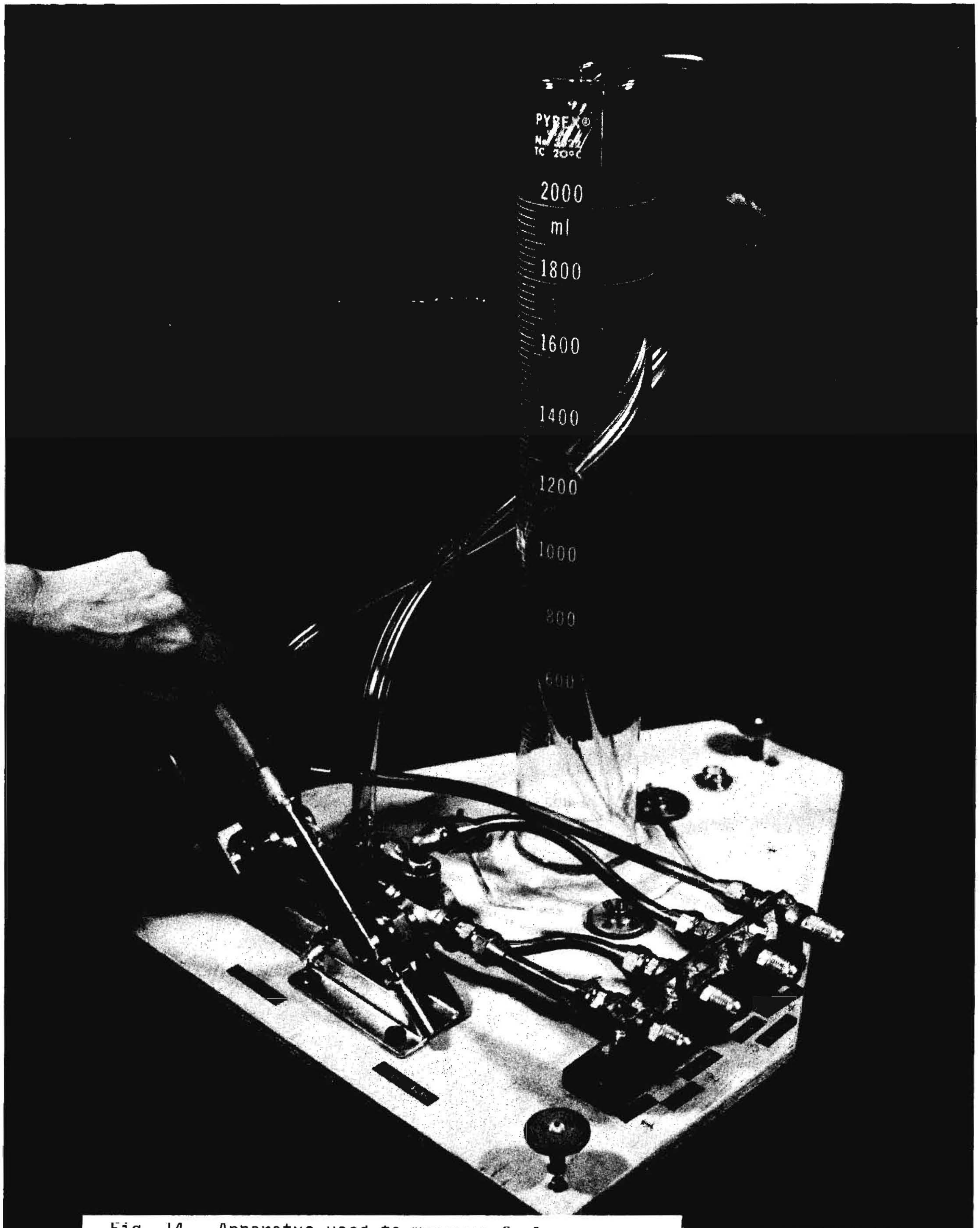

Fig. 14 - Apparatus used to measure fuel consumption

rates. When so used, other back-up apparatus was also employed to determine total integrated net consumption.

DRIVING CYCLE TESTS

The Nature of the Problem

The familiar city bus is taken for granted by the public, and often even by transit operators. Such vehicles, together with their diesel powerplants, have been developed by steady evolution over a good many years. Consequently, the specifications for new vehicles have usually been simple extensions based on past experience.

When contemplating an unorthodox powerplant, however, the designer requires answers to some very fundamental questions, such as: "Just what does an urban transit bus need to accomplish in its daily work routine?" Consider the problem of power requirements, for example. It is no longer sufficient merely to know the maximum or peak power required (although this is a ruling factor in the selection of internal-combustion engines). One now needs to understand how the power requirement at the rear wheels can vary moment by moment. What is the average power required? What is the frequency, magnitude, and duration of peak power needs? How much of the route time is spent at idle and at low power levels? These considerations are of particular importance when the visualized power system has a substantial overload capacity, or if it can draw from a reserve of energy storage. An additional possibility with some future powerplants is the conserving of some of the energy normally dissipated by the brakes.

During the course of the California project, the interactions between standard city buses and a variety of actual bus routes were measured and analyzed. Portable equipment was used to sample and record the characteristics of the "driving cycles." After a "driving cycle test" was completed, the recording apparatus was removed from the bus and connected to a computer for the reduction and analysis of the data. In this way, the detailed character of the route was obtained, plus knowledge of what the bus did to cope with the route conditions. The route cycle tests were conducted with diesel buses first, forming a basis for comparison with subsequent tests of steam buses.

Increasing use is being made of driving cycles in the evaluation of automotive performance and emissions. Driving cycles are intended to represent a combination of events or modes included in some typical regional driving experience. If the driving cycle can be defined in quantitative terms, it can be used as a basis for repeatable or comparative testing. One familiar example is the Federal Driving Cycle used in testing exhaust emissions, in which a schedule of simulated road loads is imposed upon a motor vehicle by means of a chassis dynamometer (22).

It would appear desirable to completely define a route cycle or vehicular mission in terms of a small number of variables to be measured or reproduced. Smith, Meyer, and Ayres (23) advanced and tested a hypothesis that a vehicular driving cycle can be adequately characterized in terms of only three independent statistical distribution functions. These three parameters are vehicular acceleration, speed, and road gradient. Given that the vehicle's mass and its tractive resistance as a function of velocity are known, it would then be possible to calculate the power and energy requirements of a vehicle over a driving cycle. Reference (23) gives an example of an automobile tested over a driving cycle in Pittsburgh, Pennsylvania, while reference (24) cites some of the early bus tests in this program.

Driving cycle tests, as outlined in this report, could be useful in a variety of ways:

1. The primary purpose for the tests in this program was as a basis for comparing performance and fuel consumption of diesel vs. steam buses over well-defined and realistic route conditions.
2. Early tests in this program provided background information for the steam powerplant designers.
3. The data is useful as an aid in writing future powerplant specifications.
4. Bus duty cycles may now be reproduced in the engine test laboratory. Moreover, power system properties may be simulated by computer and matched to realistic conditions in optimization studies.

5. Emissions under road conditions may be estimated, for instance on the basis of grams per vehicle mission or grams per passenger mile.
6. The benefits of recovering braking energy may be assessed.

Parameters Studied

Vehicle Motion -- A trailing fifth-wheel device was used to accurately measure the distance traveled from the start of the driving cycle. The distance information was transmitted to the recorder in terms of electrical pulses, and velocities were calculated from the pulse rate. Similarly, vehicle acceleration was obtained as the second derivative of distance/time. Vehicle stops were identified by the computer when $V = 0$; by summing up the times involved, the cumulative time at vehicle idle during a driving cycle was determined.

Road Gradient -- A sensitive accelerometer was mounted such that forces in the fore-and-aft direction could be measured. Such an accelerometer would measure, of course, the algebraic sum of the acceleration of the bus itself plus a component of the gravitational force representing the steepness of the grade. Since the acceleration of the bus was independently determined from odometer data, the vehicular acceleration component was then subtracted from the total accelerometer reading to yield the net value representing road gradient. A damped pendulum, attached to a potentiometer, was used to calibrate the grade-sensing accelerometer during stops.

Engine Speed -- An electrical tachometer sending unit was attached to an engine accessory drive. A continuous record of engine rpm was printed out on the same time base as were vehicular motions and road gradient. Periods of engine idle and transmission shift points could be ascertained from this record.

Power and Energy -- The instantaneous power manifested at the wheels may be expressed as:

$$P_i = P_r + P_a + P_g + P_{acc} \quad .$$

Where:

P_i = Instantaneous power delivered to drive wheels or absorbed by retarding.

P_r and P_a = Components of power required to overcome rolling and air resistances, respectively.

P_g = Power to overcome grade resistance.

P_{acc} = Power to accelerate vehicle (linear acceleration plus angular acceleration of rotating parts).

It is important to recognize that P_r and P_a are always positive values, while P_g and P_{acc} may be either positive or negative. Consequently, whenever the overall value P_i is positive, there is a net propelling force being delivered by the drive wheels; a negative value is indicative of power that is absorbed (and ultimately dissipated, in vehicles without regenerative braking) by the brakes or other retarding means. By an integration of P_i over time, cumulative values of propulsive and braking energy (say in horsepower-hours) over the driving cycle may be calculated.

Prior to measuring the properties of the driving cycles, it was necessary to determine the tractive resistance of the vehicles. Level-road tractive resistance (rolling plus air resistance) was ascertained by the coast-down method, making allowance for the inertia of rotating parts. The tractive resistance force, as a function of vehicle velocity, became an input to the computer code for the calculation of total propulsive power and energies. As an example, level-road retarding forces were a good fit to the expression:

$$R_t, \text{lb} = 238 + 0.179\ (V, \text{mph})^2$$

for A-C coach No. 665 operating over concrete pavement, with a gross vehicle weight (gvw) of 25,630 lb. The constant term 238 lb. is essentially the low-speed rolling resistance, while the quantity 0.179 V^2 is composed mainly of the air resistance component. It was unnecessary, for our purposes, to make a precise separation of the two effects.

<u>Fuel Consumption</u> -- The fuel consumed over a given driving cycle was measured volumetrically by the use of a calibrated auxiliary tank. Corrections were applied for the change in fuel density with temperature. A pair of synchronized three-way valves allowed the switching of feed and return lines

from the vehicle's tank to the research container at the start of a cycle, and back again at the end of the test. In some of the driving cycle tests with diesel buses, the Conoflow positive displacement fuel meter was used in conjunction with the "two-pipe ratio regulator" described previously. This allowed the recording of approximate instantaneous fuel rates along the route. For the tests of the Brobeck and Lear steam buses, the positive displacement meter was used in a single fuel line and the "ratio regulator" was not required. With the more accurate measurements resulting, accurate results were obtained in both fuel rate and totalized flow all along the route.

Interior Sound Level -- A General Radio Model 1565-A sound level meter was mounted at a location approximately ear-height of a passenger occupying an aisle seat. The microphone was 6.5 feet to the rear of the centerline of the vehicles' rear-exit doors. The sound meter was modified to allow a cable to feed the analog voltage level to the recording apparatus.

Powerplant Variables -- For tests of the A-C/Brobeck steam bus, recordings were made of the boiler pressure, steam temperature at the outlet of the boiler, and the temperature of the boiler coils at a selected location. The state of the burner and normalizer controls were also monitored and recorded. During route cycle tests with the MUNI/Lear steam bus, the boiler outlet pressure and temperature were recorded, together with the position of the driver's throttle pedal. The air-fuel ratio was also recorded. All powerplant variables on both steam buses were sensed by transducers furnished by the contractors.

Preparations were made for fully instrumented route cycle testing of the SCRTD/SPS steam bus, but the tests could not be scheduled because of mechanical difficulties with the bus. Instead, a route cycle test was conducted with this bus using manual data-taking in lieu of the recording apparatus.

Data Recording and Processing

Figure 15 shows the self-contained data recording system developed by Instrumentation Associates and used in the driving cycle tests. With this apparatus, a number of operating variables (nominally, up to twelve) can be sequentially monitored and recorded on magnetic tape. Any variable that can

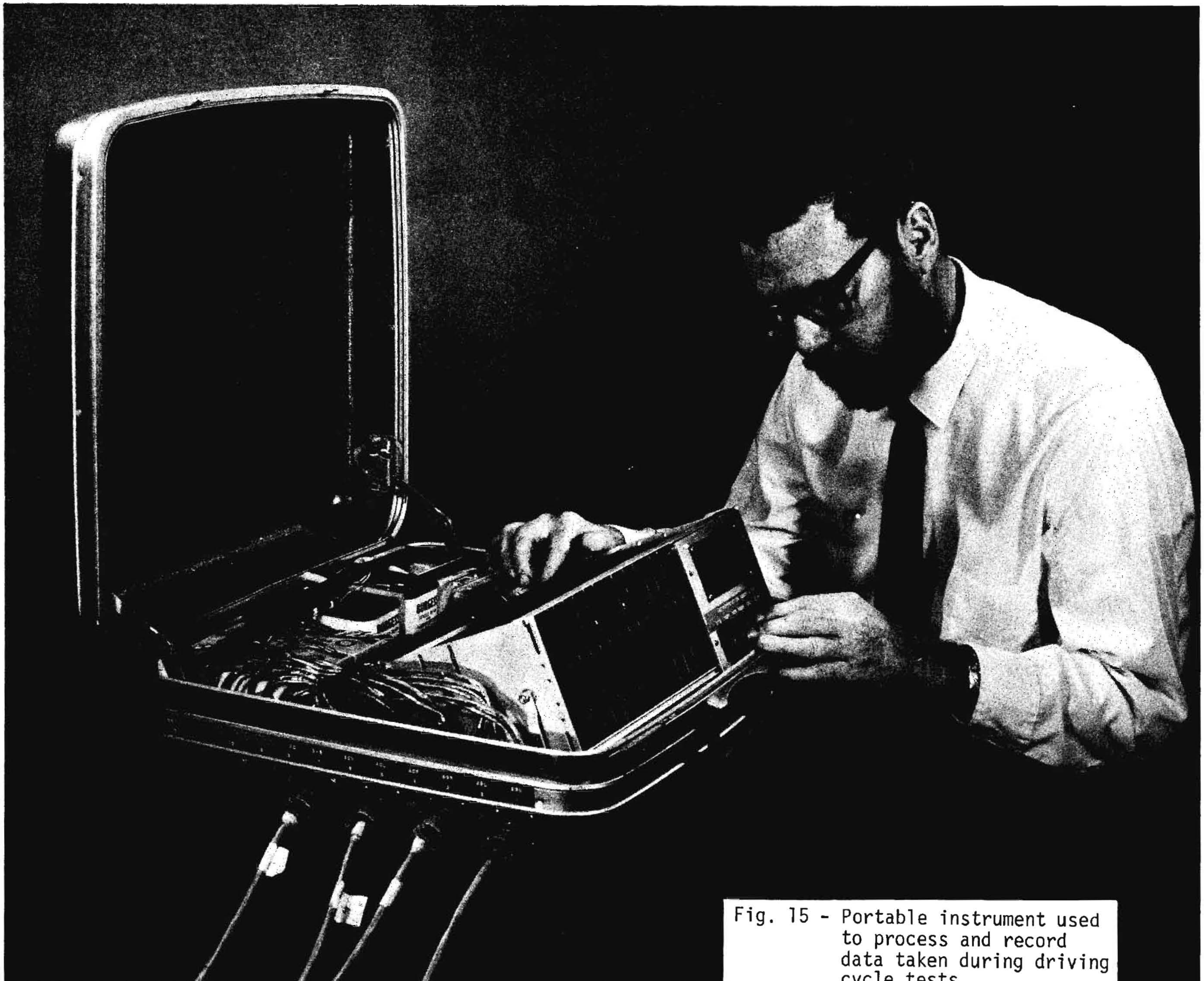

Fig. 15 - Portable instrument used to process and record data taken during driving cycle tests.

be translated into a suitable electrical signal can be recorded. This portable data system contains a battery power supply, a tape recorder, and signal processing circuitry. Such signal processing consists of impedance matching, amplification or signal scaling, data smoothing if required, and sequencing prior to analog-to-digital conversion. Versatility of the "Suitcase System" is enhanced by plug-in circuit cards for each channel, allowing the package to be tailored to different combinations of inputs.

Processed signals are encoded in digital format and recorded as a series of audio tones on the recording tape. These tones are compatible with equipment with which computers communicate over telephone lines. Data can be given to the computer from a field location by playing the recorder into a telephone headset. Printouts of raw data or results of calculations may be received at teletype remote stations. A sample page from a typical printout is shown in Figure 16. In this particular test, vehicular motion and road gradient information was sampled every 3.2 S, and road horsepower was computed with the same frequency. Values that changed less rapidly were printed out at intervals of 6.4 S. Other sampling rates were used in earlier tests, up to every 0.8 S.

The frequency of sampling is determined by the number of channels to be included in the sequence, the coarseness that can be tolerated when computing rates of change in the data, and some practical considerations in computer charges and thickness of printout.

Routes Tested

Thirteen route cycle tests were conducted over seven routes in three transit districts. Seven of the tests were conducted with diesel-powered buses and six with steam power. A driving time of around one hour was considered long enough to obtain valid statistical data (over 1,100 data points for those channels sampled each 3.2 seconds). Thus, for some of the shorter routes, a driving cycle consisted of one round trip; for a route of intermediate length, the driving cycle was taken as a one-way run; and for very long routes, a segment of a one-way run was tested.

A brief description of the routes, by district, is given below:

A-C Transit -- This district serves the metropolitan portions of Alameda and Contra Costa Counties, in the East Bay region. The district

PAGE 5 BERK .OUT

TIME-SEC	DIST-MI	VEL-MPH	VDOT-F/S2	ACC-F/S2	GRADE-%	POWER-HP	EENG-HPHR EBRK-HPHR	FLOW-GAL FDOT-GPH	SOUND-DB ENG RPM	ELEV-FT BLRTMP-F	PRESS-PSI PRITMP-F	ONHL BB-5
377.6	0.91	0.00	0.00	0.44	1.01	0.0	2.3	1.316	68.	46.	928.	1.
380.8	0.91	0.00	0.00	0.69	1.01	0.0	0.5	0.000	696.	794.	537.	26.
384.0	0.91	3.20	1.47	2.32	1.33	20.4	2.4	1.336	76.	47.	769.	11.
387.2	0.92	8.60	2.48	2.45	1.05	58.6	0.5	11.250	1268.	789.	549.	26.
390.4	0.93	11.49	1.32	1.85	1.41	60.2	2.5	1.385	78.	48.	831.	11.
393.6	0.94	13.93	1.12	1.66	1.58	66.3	0.5	27.562	1422.	809.	563.	26.
396.8	0.96	16.32	1.09	1.49	1.37	71.0	2.6	1.441	79.	50.	997.	100.
400.0	0.98	17.99	0.77	1.10	1.15	60.7	0.5	31.500	1364.	857.	567.	26.
403.2	0.99	16.23	-0.81	-0.66	0.71	-16.8	2.6	1.455	66.	52.	997.	100.
406.4	1.00	9.54	-3.07	-2.80	0.73	-61.3	0.6	7.875	672.	844.	558.	26.
409.6	1.00	3.44	-2.80	-2.03	1.06	-15.6	2.6	1.455	65.	52.	988.	0.
412.8	1.00	0.00	-1.57	0.10	1.06	0.0	0.6	0.000	581.	824.	553.	26.
416.0	1.00	0.00	-0.00	0.33	1.06	0.0	2.6	1.455	69.	52.	951.	1.
419.2	1.00	0.00	0.00	0.31	1.04	0.0	0.6	0.000	554.	809.	553.	26.
422.4	1.00	0.00	0.00	1.57	1.04	0.0	2.7	1.480	75.	52.	774.	11.
425.6	1.00	7.89	3.62	2.84	1.04	62.2	0.6	14.063	1256.	810.	566.	26.
428.8	1.02	11.66	1.73	2.11	1.13	68.9	2.8	1.528	80.	53.	882.	111.
432.0	1.03	14.71	1.40	1.83	1.26	76.5	0.6	27.000	1467.	838.	563.	26.
435.2	1.05	15.90	0.54	1.49	2.32	68.2	2.9	1.573	76.	56.	989.	101.
438.4	1.07	17.59	0.77	0.57	1.26	37.2	0.6	25.312	1072.	862.	550.	26.
441.6	1.08	12.96	-2.12	-1.84	1.01	-52.1	2.9	1.595	65.	58.	997.	100.
444.8	1.09	4.03	-4.09	-3.81	0.99	-36.1	0.7	12.375	617.	855.	547.	26.
448.0	1.08	0.00	-1.85	-0.03	0.99	0.0	2.9	1.595	66.	58.	998.	100.
451.2	1.08	0.00	0.00	0.63	0.99	0.0	0.7	0.000	572.	840.	543.	26.
454.4	1.08	0.00	0.00	0.69	1.22	0.0	2.9	1.595	64.	58.	977.	1.
457.6	1.08	0.00	0.00	0.71	1.22	0.0	0.7	0.000	608.	826.	541.	26.
460.8	1.08	0.00	0.00	1.50	1.22	0.0	2.9	1.610	74.	58.	822.	11.
464.0	1.08	0.00	0.00	2.36	1.22	0.0	0.7	8.438	1114.	819.	543.	26.
467.2	1.09	8.58	3.93	2.73	1.22	65.8	3.0	1.628	76.	59.	697.	11.
470.4	1.10	12.11	1.62	1.98	1.17	67.8	0.7	10.125	1373.	803.	541.	26.
473.6	1.12	13.93	0.84	1.46	1.65	59.2	3.1	1.668	79.	61.	750.	11.
476.8	1.13	15.21	0.59	1.38	2.17	61.4	0.7	22.500	1431.	796.	483.	26.
480.0	1.15	15.98	0.35	0.73	1.54	39.0	3.1	1.711	68.	63.	986.	1.
483.2	1.16	11.66	-1.98	-1.89	0.74	-48.1	0.7	24.187	717.	810.	503.	26.
486.4	1.15	6.06	-2.57	-3.07	0.28	-42.5	3.1	1.731	66.	64.	997.	0.
489.6	1.16	0.00	-2.77	-0.41	0.28	-0.0	0.7	11.250	602.	813.	509.	26.

Fig. 16 - Sample page from printout, driving cycle test of A-C Route 58, with steam bus No. 666

headquarters are in Oakland. Three lines were tested:

58 (Local) was tested one way. Starting at the Southern Pacific depot at Third and University Avenue in Berkeley, the line climbs a slight and uniform gradient up University Avenue, skirts the University of California campus, and then descends to downtown Oakland via College Avenue and then Broadway. Passing through the underwater tube to Alameda, the line then proceeds through the business and residential districts of that city. Alameda is almost perfectly level. The end of the line is on Fernside Boulevard at High Street. Both residential and business districts are traversed, with a mixture of hilly and level terrain. Traffic congestion is often encountered in Berkeley and Oakland.

41-A (Local) was likewise tested on a one-way basis. Beginning in East Oakland at Seminary Avenue and Foothill Boulevard, the terrain is moderately rolling toward downtown Oakland along Foothill (mostly residential). From downtown Oakland, the route is along a moderate upgrade via Telegraph Avenue to Berkeley. The end of the line is on Shattuck Avenue at University Avenue.

R-F (Trans-Bay Express) was tested one-way from southern Hayward (Fairway Park), along Mission Boulevard/East 14th Street to 164th Avenue, and thence non-stop via MacArthur Freeway (San Leandro and Oakland) to the Bay Bridge. After crossing the Bay Bridge, the line ends at the San Francisco Transit Terminal. Passengers are picked up along the first seven miles in Hayward. The remaining 23 miles are without passenger stops. During the morning commute hour, passengers are taken aboard only until a full-seated load is obtained; the bus then proceeds without further passenger stops.

S.F. MUNI -- The San Francisco Municipal Railway operates motor coaches, street railways, trolley coaches, and cable cars. Many of the routes are extremely hilly with steep grades. Lines serving the downtown area often meet very heavy traffic congestion in narrow streets. Passenger loads on some lines are very heavy, 100 passengers aboard a 51-passenger coach not being unusual. Two local lines were used in route cycle testing, having very different properties.

32 - The 32 line is short, lightly traveled except during commute hours, and for most of the distance is over level streets. Route cycle tests consisted of a round trip over the line. Starting northbound from the Southern Pacific depot at Third and King Streets, the route is via the Embarcadero, past the Ferry Building, and ends on Hyde Street near Beach Street, in the vicinity of Fisherman's Wharf.

55 - The 55 line is notorious for having the steepest gradient traveled by motor coaches in San Francisco (19.3%). Route cycle tests consisted of a round trip. Tests were begun at the foot of Sacramento Street near Drumm Street. The line becomes steeper as it progresses up Sacramento Street, past the Financial District and Chinatown. It is very heavily traveled throughout the day, with stops to serve passengers virtually every block over the first half of the trip. Oftentimes, stops are required in the middle of the block, on steep grades, because of traffic congestion. Starting from rest on grades of 14 to 19.3% are often required. Drivers state that six-cylinder diesel buses previously used over the route sometimes stalled on these hills and could not make headway until some of the passenger load had been lightened. Eight-cylinder buses now serving the line are able to negotiate the grades easily, but with high noise levels. In the Westbound direction, the line follows Sacramento, Lake Street, and Sixth Avenue to the corner of Sixth and Clement Street. The route then returns eastbound via Clement, Seventh Avenue, California Street, Sixth Avenue, Lake Street, and Sacramento Street. When Sacramento becomes one-way outbound, the line jogs one block north and follows Clay Street on the return downtown. The descent along Clay is virtually as steep as the earlier ascent up Sacramento, and the later model buses are equipped with engine retarding devices (Jacobs "Jake" brakes) to assist in controlling speed downgrade.

SCRTD - The Southern California Rapid Transit District serves Los Angeles County and some of the environs. At the present time, the operation is entirely by motor coach. Two lines were tested:

83 (Local) - This is a very long route, starting on Seventh Street at Main Street in downtown Los Angeles. Outbound, it follows Seventh to Figuroa Street, where it steps one block north to Wilshire Boulevard. The route then follows Wilshire to Ocean Avenue in Santa Monica, passing

through Beverly Hills enroute. Because of the length of the route, only a segment of a one-way run outbound was used as a driving cycle test route. This segment was from the point of origin, downtown Los Angeles to Wilshire and Santa Monica Boulevards, Beverly Hills.

60-E (Freeway Flyer) was also a very long route, so only a segment of the outbound line was used for testing. This is virtually a station-to-station run, starting from the SCRTD Station, downtown Los Angeles at 6th Street and Maple Avenue. Only a few passenger stops are made downtown, and then the bus proceeds via the San Bernardino Freeway (Eastbound) to the Pomona Station. Here the tested segment ended. When traffic conditions permit, speeds of 70 mph or more are sometimes reached.

Test Methods

A ballast load of 4,500 lb (sandbags or iron billets) simulated a "typical" partial payload of 30 passengers. The weight of instrumentation and at least two observers added at least 500 lb, bringing the total "payload" to 5,000 lb, the equivalent of 33-plus passengers. Gross vehicle weights varied from 25,570 to 31,290 lb depending upon the empty weight of the vehicle selected. Tests were with full tanks of fuel and water. The GVW was considered to remain constant during a given test, thus simplifying the computations. Tire inflation pressures were in accordance with standard practice within the district where the tests took place.

An arbitrary schedule of simulated passenger stops was compiled in advance, from surveys previously made aboard passenger-carrying runs. Such a schedule included the duration of each stop to be made, in seconds. During a route cycle test, the driver made the stops indicated on the test schedule, plus other stops as dictated by traffic conditions. Drivers were also instructed to follow published time schedules as closely as possible.

Much redundant information was noted during tests, and was found useful in applying corrections to the electronically-recorded data. Observers took note of times, distances, traffic conditions, and speeds. Topographic maps were used to check some of the grades, elevations, and distances. Preliminary computer printouts were visually scanned to eliminate "wild points" and to debug the program as required. After such reconciliations were completed, final printouts were obtained.

Results

The results of the driving cycle tests will be summarized and discussed at this point, and will serve as a frame of reference for steam bus test results in the following section of this report.

Summary of Tests

Table II is a concise summary of thirteen driving cycle tests over seven different routes. All tests were with the use of the portable data recording system except the test of the SPS steam bus over SCRTD Route 83. Because of limited availability of this vehicle, a segment of the route was tested with limited instrumentation and manual recording of data.

The two tests of the Lear bus were re-runs. On August 1, 1972, this bus was tested over the 32 and 55 lines. Unfortunately, the data recordings for both runs were found to be incoherent because of a defect in the data system. On that first occasion, the Lear bus performed very well, completing the 55 line including the steepest upgrade (19.3%) of any line served by motor coaches in San Francisco. On the re-run August 30, however, the turbine powerplant was not developing its maximum power and the test run was abridged by bypassing that portion of the line containing the steepest upgrade.

The R-F line test with the Brobeck bus was also a re-run, an earlier test having been aborted because of a mechanical failure in the engine. In general, it was found difficult to have an experimental instrumentation system ready simultaneously with the development of optimal performance by experimental vehicles.

Several interesting observations may be gleaned from Table II:

- The ratio of average to peak power requirements in urban bus service is rather low. For example, with diesel power over A-C Route 58, the average power required for propulsion was only 24.3 hp at the rear wheels. The maximum power of 138 hp was needed only once during the run of 1.25 hr. (Further study revealed that power exceeding 100 road hp was only required about 10% of the time the bus was in motion; requirements exceeded 120 hp less than 2% of the time in motion.)

- The peak road hp reached in express service more nearly approximated the maximum available from the engine. For example, the maximum power required at the rear wheels for SCRTD Route 60-E was 213 hp. This is closely reconciled with the 265 hp listed for the de-rated diesel engine, the difference being in accessory loads and power transmission losses.

TABLE II - PART I

SUMMARY OF DRIVING CYCLE TESTS

Route	Coach No.	Engine	Date Tested	Gross Wt, lb.	Schedule Period Simulated	Distance Tested, Miles	Net Elapsed Time, Min.(d)
A-C 58 (Local)	666	GM Diesel 6V-71 N-55	9-28-70	25,570	midday	12.9	75.5
A-C 58 (Local)	666	Brobeck Steam	3-24-72	28,660	midday	13.1	73.8
A-C 41-A (Local)	665	GM Diesel 6V-71 N-55	4-21-72	26,280	midday	10.7	57.5
A-C 41-A (Local)	666	Brobeck Steam	3-29-72	28,910	midday	10.7	61.2
A-C R-F (Express)	665	GM Diesel 6V-71 N-55	5-12-71	25,630	AM commute	29.7	57.0
A-C R-F (Express)	666	Brobeck Steam	5-11-72	29,140	AM commute	29.4	58.0
MUNI 32 (Local)	3318	GM Diesel 8V-71 N-60	7-21-72	27,340	AM commute	7.4	38.0
MUNI 32 (Local)	5000	Lear Steam	8-30-71 (c)	29,170	AM commute	7.2	38.7
MUNI 55 (Local)	3318	GM Diesel 8V-71 N-60	7-21-72	27,340	midday	8.7	54.0
MUNI 55 (Local)(a)	5000	Lear Steam	8-30-72 (c)	29,170	midday	7.0	57.5
SCRTD 83 (Local)	7185	Cummins Diesel 903 V-8	9-12-72	28,400	PM commute	9.8	69.0
SCRTD 83 (Local)(b)	6200	SPS Steam	9-28-72	31,290	PM commute	4.4	35.0
SCRTD 60-E (Express)	7185	Cummins Diesel 903 V-8	9-12-72	28,400	midday	31.6	50.0

TABLE II - PART 2

SUMMARY OF DRIVING CYCLE TEST (continued)

Route	Avg Speed, mph	Max. Speed, mph	Number Simul. Passgr Stops	Number Traffic Stops	Total Number Stops	Stops per Mile	Cum. Time at Idle, min.	Percent of Time at Idle
58 Diesel	10.3	51.2	57	35	92	7.1	24.1	32
58 Steam	10.7	48.0	57	20	77	5.9	26.8	36
41-A Diesel	11.2	35.0	55	21	76	7.1	20.6	36
41-A Steam	10.5	36.6	55	24	79	7.4	19.8	32
R-F Diesel	31.2	53.3	10	9	19	0.64	4.0	7
R-F Steam	30.5	55.2	10	9	19	0.64	5.5	9
32 Diesel	11.7	27.9	18	16	34	4.6	10.5	28
32 Steam	11.2	27.6	16	21	37	5.2	11.7	30
55 Diesel	9.7	30.6	62	27	89	10.2	18.2	34
55 Steam	7.3	24.8	45	21	66	9.4	19.6	34
83 Diesel	8.5	37.5	44	45	89	9.1	29.3	42
83 Steam	7.6	N.A.	24	21	45	10.2	10.0	29
60-E Diesel	38.0	68.5	3	16	19	0.60	5.4	11

TABLE II - PART 3

SUMMARY OF DRIVING CYCLE TESTS (continued)

Route	Final Elev., feet above starting pnt	Max. Upgrade, Percent	Max. Downgrade, Percent	Power to Rear Wheels, hp:		
				Max.	Avg Over Time	Avg During Motion
58 Diesel	-4	6.1	5.3	138	24.3	35.7
58 Steam	-4	6.1	5.3	119	22.5	35.4
41-A Diesel	+130	4.3	4.6	122	33.2	51.7
41-A Steam	+130	4.3	4.6	129	31.4	46.3
R-F Diesel	+10	8.8	5.9	169	58.7	63.2
R-F Steam	+10	8.8	5.9	146	55.7	61.5
32 Diesel	0	8.4	11.1	181	22.4	31.0
32 Steam	0	8.4	11.1	78	21.0	30.0
55 Diesel	0	19.3	16.2	210	42.4	63.8
55 Steam	-227	15.1	17.0	88	19.7	30.0
83 Diesel	+21	6.9	4.7	166	25.9	45.0
83 Steam	-40	6.9	4.7	N.A.	N.A.	N.A.
60-E Diesel	+630	8.7	5.6	213	78.8	88.5

TABLE II - PART 4

SUMMARY OF DRIVING CYCLE TESTS (continued)

Route	Cumulative Energy at Wheels, hp-hr: Propul.	Brkg(e)	Propul. Energy /mile, hp-hr	Fuel Consumed, gals(f)	Fuel Mileage, mpg	Specific Vehicle Fuel Consump., lb/hp-hr	Vehic. Thermal Effic. % (g)
58 Diesel	30.6	15.7	2.38	3.60	3.58	0.797	17.3
58 Steam	27.7	16.6	2.12	11.88	1.11	2.90	4.8
41-A Diesel	31.8	12.4	2.97	3.27	3.27	0.695	19.8
41-A Steam	32.0	13.4	3.00	12.00	0.89	2.53	5.4
R-F Diesel	55.8	11.1	1.88	4.83	6.15	0.584	23.6
R-F Steam	53.8	11.0	1.83	13.17	2.23	1.65	8.35
32 Diesel	14.2	4.1	1.92	2.01	3.68	0.958	14.4
32 Steam	13.5	5.4	1.88	10.40	0.69	5.21	2.64
55 Diesel	38.1	20.9	4.38	3.81	2.28	0.677	20.3
55 Steam	18.9	11.9	2.70	13.60	0.52	4.87	2.8
83 Diesel	29.8	13.7	3.04	3.24	3.02	0.735	18.7
83 Steam	N.A.	N.A.	N.A.	7.46	0.59	N.A.	N.A.
60-E Diesel	65.7	7.8	2.08	4.86	6.50	0.50	27.5(h)

TABLE II - PART 5

SUMMARY OF DRIVING CYCLE TESTS (continued)

NOTES ON TABLE II:

(a) Operation of Lear bus over Route 55 not comparable with diesel because route segments taken were different. Performance problems on the day of testing precluded operation over entire route.

(b) Operation of SPS bus over Route 83 not comparable with diesel because route segments were different. This was not a fully instrumented test.

(c) The Lear bus was originally tested over Routes 32 and 55 on 8-1-72. The data recording was found to be unusable because of faults in the recording apparatus. Both tests were re-run on 8-30-72. Unfortunately, the bus performance levels were not as high on the second test date. (On the original test date, the entire Route 55, including the steepest grade of 19.3%, was negotiated. It was decided to bypass that grade during the second test because of considerations of reduced performance and heavy traffic congestion.)

(d) Net Elapsed Time denotes the time to cover the distance tested, but deducting time out for technical adjustments to instrumentation.

(e) Cumulative energy dissipated by braking includes both by vehicle brakes and engine retarding. Retarding effect of rolling resistance and air drag is not included in this figure.

(f) All fuel volumes are corrected to 60°F, representing a density of 6.75 lb per gallon.

(g) Vehicular Thermal Efficiency is based on a lower heating value of the fuel of 18,500 BTU per lb.

(h) This value for vehicular thermal efficiency is believed to be too high, possibly because of undetected errors in the measurement of energy or fuel.

- The energy dissipated by brakes and engine retarding during local route service is significant, being up to 55% of the energy supplied to the rear wheels in the routes tested. This reflects the frequent stops and hilly terrain. By contrast, only 12 to 20% of the energy was so dissipated in the express runs. This suggests that methods for recovering braking energy should be seriously considered for some classes of service, but may not be worthwhile for others.
- The propulsive energy required at the rear wheels per mile of travel averaged 2.31 hp-hr/mi. The most notable deviation from this average was the diesel bus traversing MUNI Route 55, with 4.38 hp-hr/mi. This is an indication that if a high power capability is provided, the driver will use it to obtain maximum speeds on grades and for brisk acceleration.
- A very high fraction of the time spent on local routes is at engine idle. This suggests that a low idle fuel comsumption is a very desireable characteristic.
- The concept of vehicular thermal efficiency (Ev) is a very interesting and useful measure of the overall efficiency with which fuel energy is converted into useful work at the rear wheels. These values were computed by dividing the total energy delivered to the rear wheels by the energy content of the fuel consumed (lower heating value of 18,500 BTU/lb). As would be expected, Ev was higher for express service than for local runs, primarily because power transmission efficiencies are higher under cruise conditions than they are for stop-and-go and low speed driving. Ev varied from 2.64% for a steam bus in local service to over 23% for a diesel bus in express service. The value of 27.5% calculated for an SCRTD bus in express service is higher than realistic expectations, but thus far the source of possible error has not been found.

Statistical Evaluation

The large volume of data obtained from the route cycle tests is difficult to assess without the aid of statistical methods. Such methods were described in detail in a referenced report (23).

One interesting test is to determine whether or not certain key data are reasonable fits to gaussian normal distributions. Sample results from two contrasting types of routes are summarized in Figures 17-20. The scale of these graphs has been contrived such that a straight-line fit to the experimental 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. In the case of velocity, a straight-line fit to the raw data was not obtained. However, it was found (but not necessarily explained) that velocity data could fit a normal distribution if transformed to log-squared velocity. For all of the plots, distortions were avoided by rejecting values that were recorded at idle (V=0).

From the plots given in Figures 17-20, it is possible to determine graphically the statistical mean values of the variables, and the values of the standard deviations from these means. For example, the mean values (μ) for vehicular acceleration (Fig. 17) were -0.58 mph/sec for the local route and 0.7 mph/sec for the express route (-0.85 and 1.0 ft/sec^2 respectively). Comparing the two routes, it might be inferred that a greater proportion of the samplings for this particular local route involved hard braking.

In statistics, a standard deviation (σ) is defined as the square root of the average value of the squares of the deviations from the arithemetic mean. The span $\pm\ \sigma$ includes a trifle over 68% of the observations. Thus, using the local route as an example, about 34% of the observations involved accelerations up to 1.5 mph/sec higher than the mean, and 34% were up to 1.5 mph/sec lower than the mean.

It should be noted that the mean velocities inferred from Fig. 19 are higher than the average speeds listed in Table II, because the statistics plotted excluded zero velocity samples. Plotted distributions of road horsepower (Fig. 20) included only those samplings for which values of power were positive. Hence, mean values on this basis will also be higher than average values listed in Table II.

---

*Such a distribution has been found to describe a great many probabilistic processes in the actual physical world, and is usually plotted as the familiar bell-shaped curve.

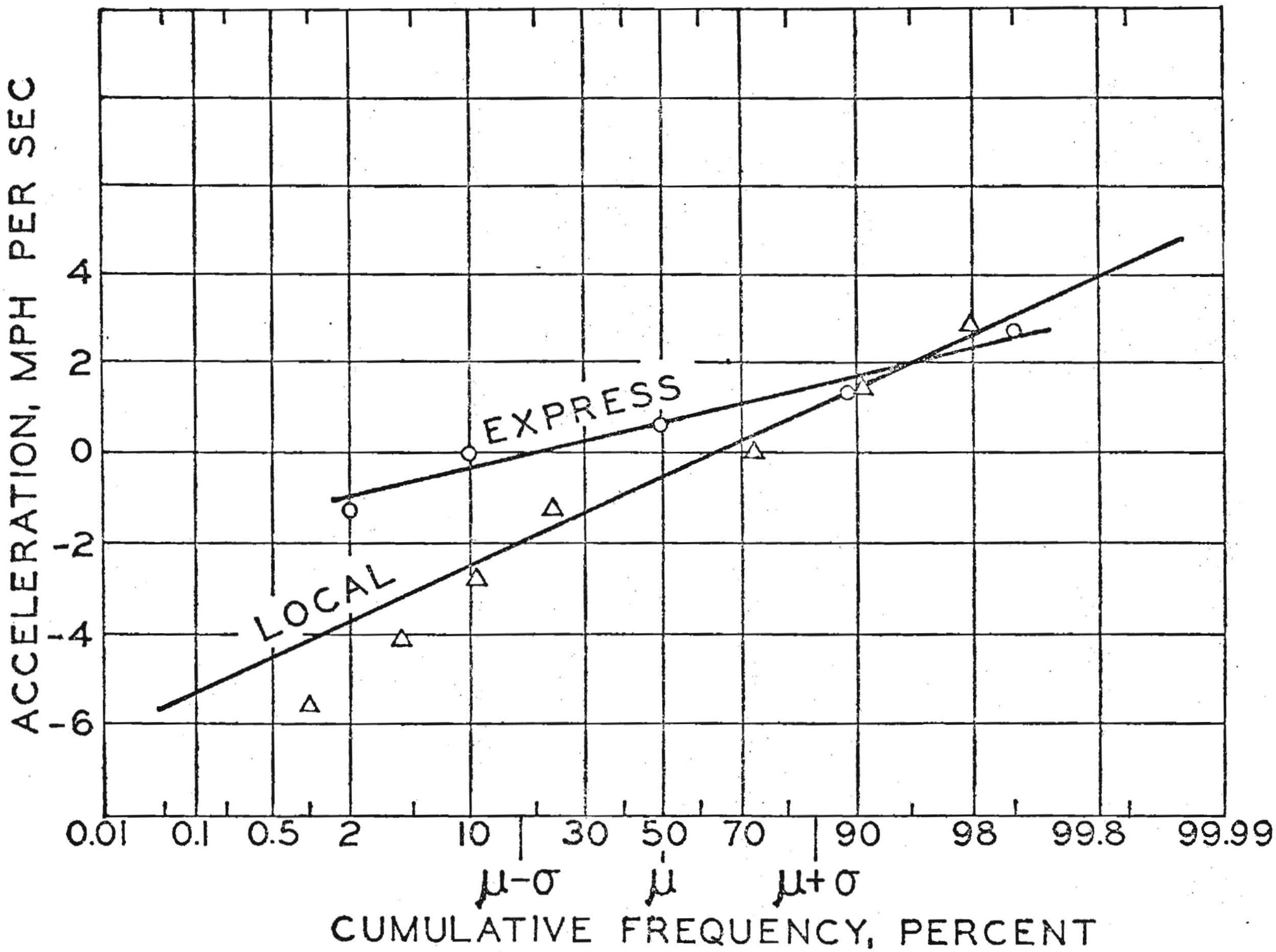

Fig. 17 - Examples of statistical distribution of vehicular acceleration over driving cycles. Routes for Figures 17-20 were A-C Transit No. 58 (local) and No. D-E (

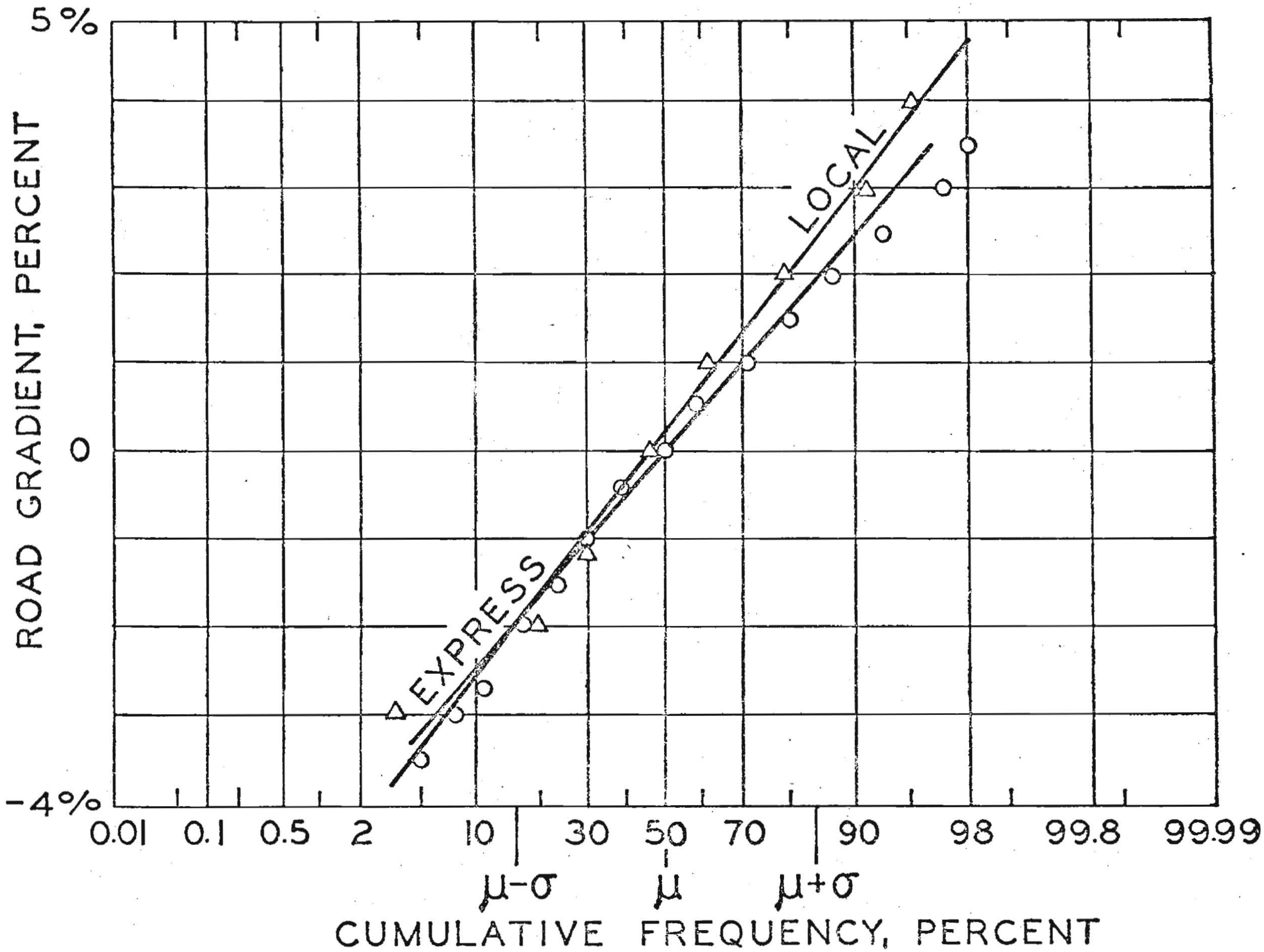

Fig. 18 - Examples of statistical distribution of road gradient

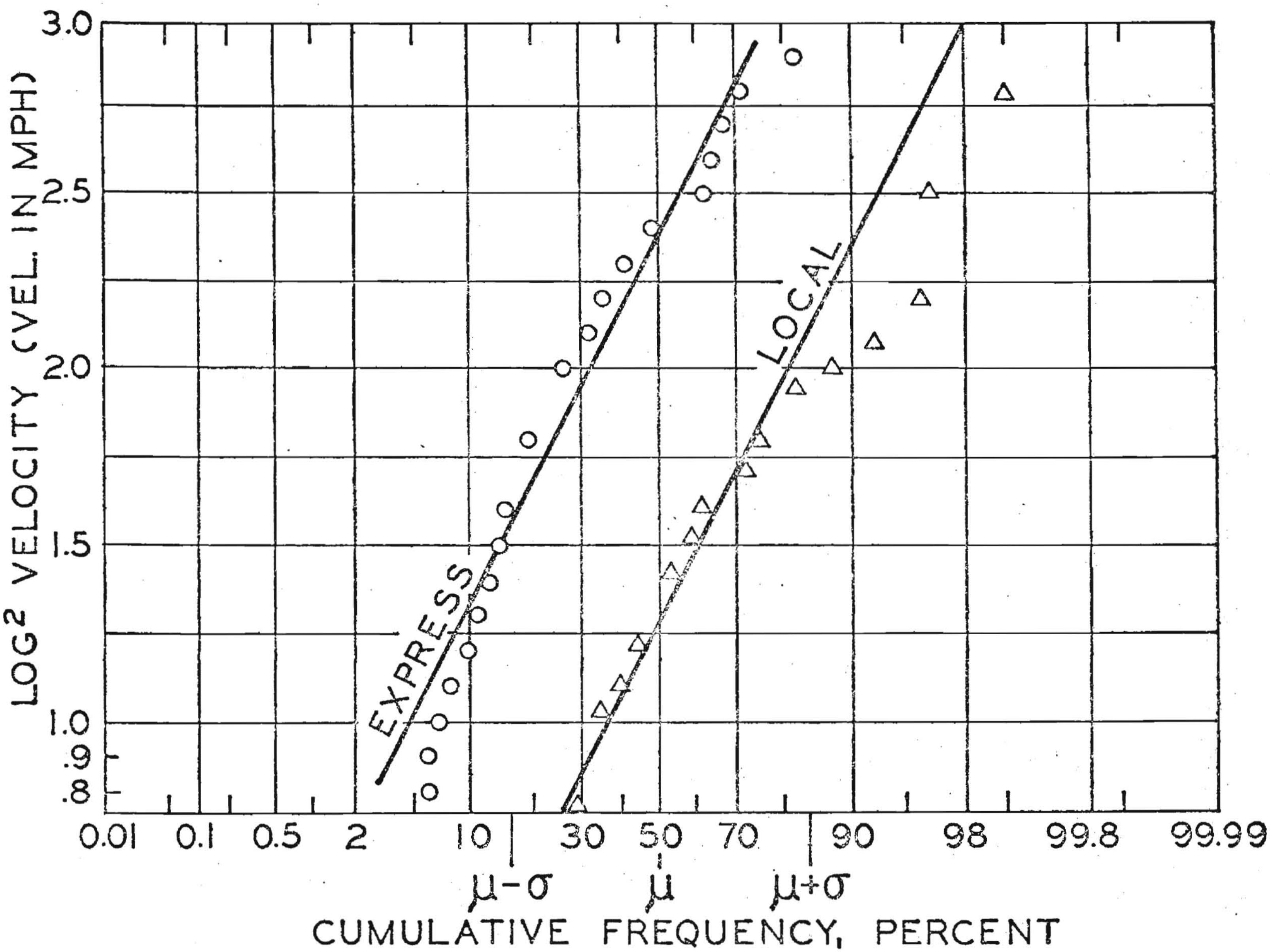

Fig. 19 - Examples of statistical distribution of vehicular velocity (plotted as $\log^2 V$)

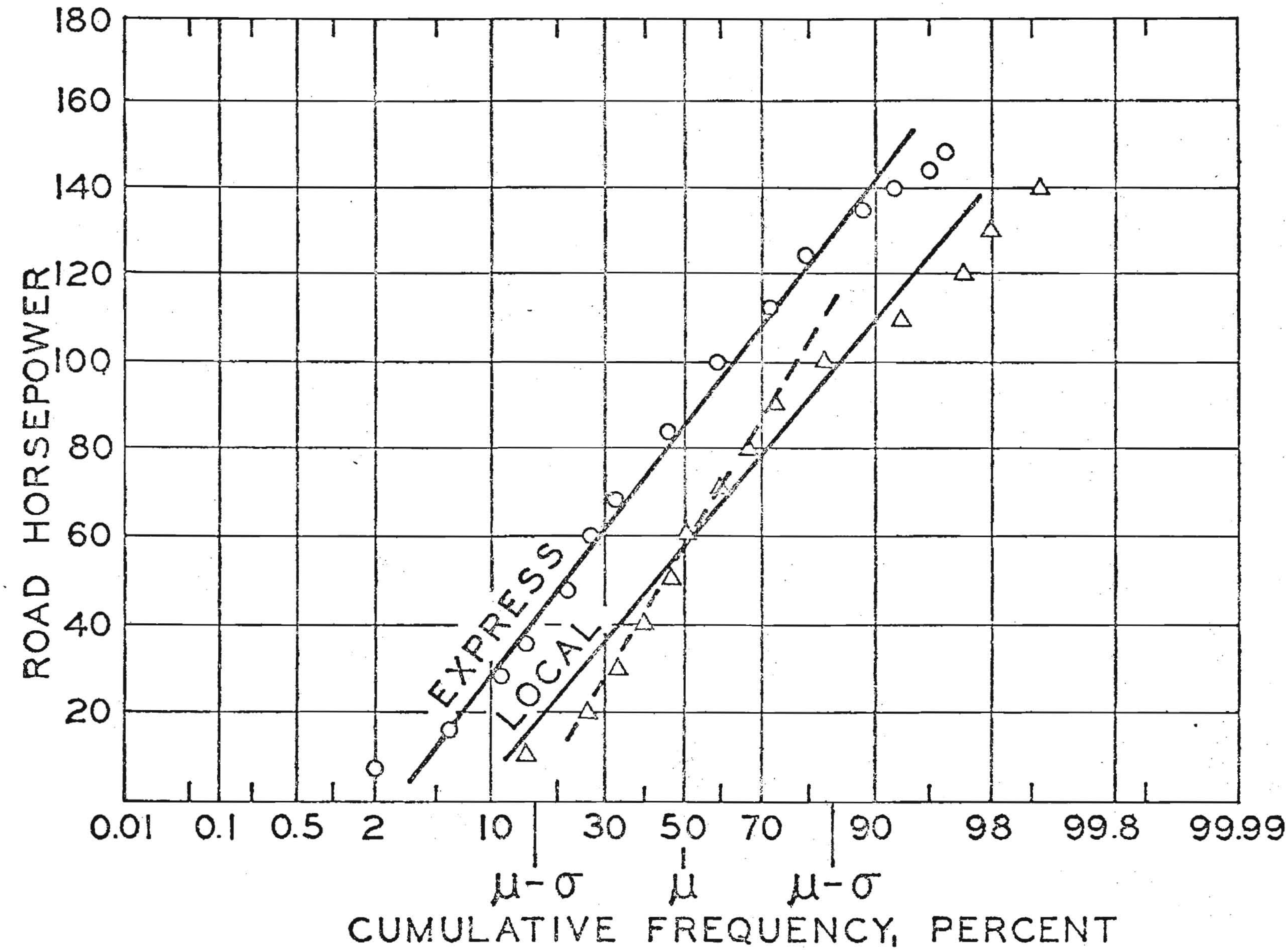

Fig. 20 - Examples of statistical distribution of road horsepower. Dashed line is an optional fit over mid-range of local route data

Statistical mean values and standard deviations for all of the route cycle tests are given in Table III. These were all derived from graphical plots similar to Figures 17-20, being taken from straight-line fits. Such arbitrary characterizations should not be extrapolated much beyond the central portion of the distribution. It may be noted that two of the positive-horsepower entries were described by standard deviations which exceeded the mean values; the extremes of the actual distributions were, of course, not gaussian.

Of the variables given in Table III, the road gradient would be expected to be the most nearly reproducible if more than one test were made over the same route. The fact that mean gradients for tests of the same route disagreed by a fraction of a percent is partly due to instrument error. Discrepancies are also introduced if velocities along given gradients are not duplicated, since the time rate of sampling during a test remains constant.

TABLE III

STATISTICAL MEAN VALUES AND STANDARD DEVIATIONS OF DRIVING CYCLE DATA [a]

Route		Acceleration mph/sec	Gradient Percent	Log^2 Velocity	Velocity mph	Power hp
A-C 58 Diesel	Mean	-0.58	0.25	1.27	13.3	58
	Std.Dev.	1.5	2.2	0.85	--	40
Steam	Mean	-0.25	-0.3	1.25	13.1	48
	Std.Dev.	1.2	2.25	0.53	--	26
A-C 41-A Diesel	Mean	0.25	0.0	1.35	14.5	72
	Std.Dev.	1.45	1.1	0.58	--	33
Steam	Mean	0.15	-0.1	1.20	12.4	64
	Std.Dev.	1.45	1.05	0.65	--	25
A-C R-F Diesel	Mean	0.7	0.0	2.38	35.0	84
	Std.Dev.	0.8	1.9	0.82	--	44
Steam	Mean	-0.25	0.5	2.10	28.0	75
	Std.Dev.	0.6	1.5	0.60	--	28
MUNI 32 Diesel[b]	Mean	-0.3	-0.35	1.4	15.3	24
	Std.Dev.	0.5	0.5	0.35	--	22
Steam	Mean	-0.2	-0.45	1.2	12.4	27.5
	Std.Dev.	0.5	0.55	0.45	--	22.5
MUNI 55 Diesel[c]	Mean	0.25	0.4	1.2	12.4	102
	Std.Dev.	2.55	3.4	0.50	--	103
Steam[c]	Mean	0.1	-0.2	0.88	8.7	40
	Std.Dev.	1.65	3.4	0.47	--	15
SCRTD 83 Diesel	Mean	0.35	0.2	1.15	11.8	62
	Std.Dev.	1.85	1.3	0.59	--	67
Steam	Mean		Incomplete Test			
	Std.Dev.					
SCRTD 60-E	Mean	-0.3	-0.2	2.78	46.4	150[d]
	Std.Dev.	0.5	1.3	(b)	--	110

(a) Basis: Data sampled only when in motion; power sampled only when values were positive.
(b) Data not a good fit to normal distribution.
(c) Diesel and steam routes differed, invalidating comparison.
(d) Computed values for power were later found to be somewhat higher than actual for this run. Mean value for positive hp was probably in the range 115-130 hp.

RESULTS OF TECHNICAL EVALUATION

Scope of Investigation

The technical results of this program are interesting because they represent a documented point of departure (state-of-art) upon which future improvements may be based. Testing and evaluation included the subjects of road performance, exhaust emissions, sound levels, fuel consumption, safety, and general operating characteristics. The Phase I portion of the program (design, development, installation, and pre-delivery trials) involved bench testing for development and to determine the fitness of the powerplants. Phase I also involved road testing by the contractors. Phase II included testing and evaluation by IR&T with the cooperation of the fleet operators and contractors, the measurement of emissions by the California Air Resources Board (ARB) and sound levels by the California Highway Patrol (CHP), and public service demonstrations. Phase II.5 overlapped Phases I and II, and was a period devoted to short-term engineering improvements.

Non-technical evaluation work (such as public and patron reaction surveys, surveys of transit management and personnel opinions, and a documentary motion picture) (25) were supervised by the Scientific Analysis Corporation of San Francisco. The results of this work are recorded in separate reports (26-29).

In reviewing these results, one should bear in mind that this project was not a competition to see who could build the "best steam bus." What should emerge, rather, is a composite picture of how the present state-of-the-art in vehicular steam powerplants compares with that of the highly-evolved diesel engine.

Bench Tests

Bench tests of the powerplants by the contractors were conducted primarily for experimental development and for proving fitness prior to installation. There was insufficient time for detailed mapping of performance and efficiency in the laboratory, but a few of the more important data points were determined. All expanders were tested at full load on a dynamometer for maximum gross power and steam consumption. Then, complete systems were tested for net power output. Some of the more important characteristics have already been given in Table I.

The Brobeck and SPS systems were subjected to endurance testing prior to installation. Before installation was permitted, each system was required to survive a total of sixteen hours at a net power output of 160 hp or more. At least one continuous hour at this level was required. As an alternative, Lear Motors Corporation was permitted to fulfill the intent of this requirement by thirty-two hours of road testing.

The best brake specific fuel consumption (bsfc), based on net system output, was in the range 0.985 to 1.18 lb per bhp for the three powerplants. This corresponds to an overall thermal efficiency of 11.7 to 14%, based on a lower heating value of 18,500 BTU/lb of fuel. Values of bsfc at part load were higher. Examples are given in Table III, from Brobeck test data.

Accessory and auxiliary loads can be very high. Steam Power Systems, Inc. (SPS) listed the following breakdown at full load:

Powerplant Auxiliaries	Power Required
Condenser fans	30 hp
Boiler fan	12
Feedwater pump	8
Fuel and Lubricant pumps	1
TOTAL	51 hp
Vehicle Accessories	
Alternator	5 hp
Air compressor	4
Air conditioning	25
	34 hp

Combined auxiliary and accessory load, 85 hp

Thus, the SPS System, with a 275 gross hp expander, would deliver a 224 hp net shaft output. However, with all vehicular accessories operating, the power available as input into the transmission would be reduced to 190 hp.

TABLE III

BENCH TEST RESULTS, BROBECK POWERPLANT

Speed, rpm	Net Torque, lb-ft	Net Power, bhp	Steam Inlet Temperature, °F	Steam Inlet Pressure, psig	Specific Water Rate, lb/net bhp-hr	Specific Fuel Cons., lb/net bhp hp
1200	139	32	718	260	20.0	1.96
1177	280	63	789	400	13.7	1.36
1155	378	83	818	440	16.7	1.23
1250	350	83	830	420	10.3	1.03 (a)
1173	540	120	835	600	12.8	1.13
1581	168	51	754	270	18.9	1.73
1609	300	92	774	400	15.5	1.32
1621	432	133	799	500	12.9	1.14
1573	640	192 (b)	877	660	11.2	1.03 (a)
1991	63	24	758	220	37.1	3.64
2025	289	112	769	440	17.2	1.52
2013	435	167	785	560	14.9	1.22
2013	476	182	852	620	12.9	1.16

NOTES: (a) Net horsepower figures are after all powerplant auxiliary loads have been deducted. During these tests, the air brake compressor and the bus alternator were also being driven. Without these two vehicular accessories, the value for best bsfc would be about 0.985 lb/bhp-hr.

(b) The maximum bhp shown in this table is 192. A run not listed yielded 200 net bhp.

Lear Motors was the only one of the contractors equipped for emissions measurement during the Phase I development period. From June, 1971 to February, 1972, they performed a total of 68 fully-instrumented bus boiler tests. Emphasis was on low emissions and the development of high boiler efficiencies. Boiler efficiencies as high as 96% have been measured in the laboratory at 1/3 output (10 gal/hr fuel rate) and 89% at a maximum fuel rate of 35 gal/hr.

Approximately 200 hours of turbine tests were conducted at Lear Motors. The maximum gross turbine output obtained was 249 hp with a turbine efficiency of 65.5%. The turbine with its gearbox was de-rated to 220 gross hp for use in the bus system, in the interest of high operating reliability.

Bus Operation and Public Service

The Brobeck bus was first moved under its own power September 9, 1971. It traveled 3,465 miles during the program. The Lear bus, operational January 27, 1972, traveled 3,900 miles. The SPS bus, finished March 17, 1972, went 1,007 miles. Thus, the total miles accumulated under steam power was 8,372 miles. The longest trip taken was with the Lear bus, 230 miles from San Francisco to Reno over the Sierra Nevada Mountains without major problems.

All three buses were used in public demonstrations. Notable occasions were in November, 1971 when the Brobeck bus carried 500 passengers in Washington, D.C. over a four-day period, and April 1972 when the three buses were demonstrated to the California Legislature and to the public in Sacramento.

The steam buses were operated in revenue passenger service in the cities of Oakland, Berkeley, San Leandro, Hayward, San Francisco, and Los Angeles. The Brobeck bus was operated by A-C Transit for 18 days, on the 41-A (East Oakland to Berkeley), 80, and 82 lines (Hayward to Oakland). Numerous operating problems were encountered, including a broken engine crosshead; failures of the burner blower, motor, the feed water pump, and cylinder relief valves; and early in the period, low water mileage. After improvements to the powerplant, however, this bus operated the last nine days with no operational problems whatever.

The San Francisco MUNI operated the Lear bus for 11 days of revenue service over the 32 (Embarcadero) and 17 (Park Merced Express) lines. On two demonstration occasions, the bus was operated over the 19.3% grade on the 55 (Sacramento Street) line. Once, on a regular run on the 32 line, 98 passengers were aboard the coach. Major problems were encountered on only two occasions; one a boiler leak (three days were required to replace the boiler) and the other a broken fan belt on the burner blower.

The SPS bus was slated for operation on the 83 line (Wilshire Blvd.) in Los Angeles. However, it served only two days because of numerous mechanical difficulties. After the first one-way run was completed on September 7, 1972, a pulley driving the burner fan failed.
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 leak deteriorated to the point where the loss of power and water became serious. The powerplant was repaired in San Diego. The final day of service (September 29) was flawless except for the failure of a battery terminal, which was corrected at curbside. Service was discontinued when powerplant and fleet operator contracts expired September 30.

Tables IV, V, and VI summarize the operation of the three steam buses from the time the installation was completed through the end of the project.

Road Performance

The road performance of the steam powered buses was similar to buses powered by six-cylinder 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 vs. diesel buses are summarized in Table VII.

The steam-powered vehicles, being highly experimental, were variable in performance. Steam inlet temperatures to the expander had a very noticeable effect upon power delivered to the rear wheels. This effect prevented the obtaining of best results from the SPS bus during tests of full-throttle acceleration from a standing start; the same bus was capable of higher accelerations had the test method allowed a running start. With

TABLE IV
OPERATION OF STEAM BUS, BROBECK/A-C TRANSIT

DATES	EVENTS
September 9, 1971	Bus first moved under own power.
September 13-30	Road tests and demonstrations.
October 1	Vehicle transferred to A-C Transit.
October 4-5	Emissions tested in San Francisco (boiler was leaking).
October 12	Sound levels tested in Oakland.
October 13-November 1	Boiler repairs and road tests.
November 2	Bus shipped by rail to Washington, D.C.
November 12-19	Bus operated for 75 miles in Washington, D.C. traffic. Demonstrated during UMTA Steam Bus Symposium November 17. Cumulative 320 miles since September 9.
December 6, 1971-January 14, 1972	Repairs and improvements. Additional boiler leaks found and repaired.
January 17-22	Free rides in several East Bay cities to inaugurate service.
January 24	First day of revenue service, Route 41-A. Three round trips totaling 74 miles. Nearing completion of last trip, engine crosshead failed.
January 26-February 24	Repairs and improvements.
February 25-April 23	Road tests and engineering evaluation.
April 26	Bus demonstrated to California Legislature in Sacramento.
April 27-May 1	Emissions and sound levels tested in Sacramento.
May 2	Bus driven from Sacramento to Oakland, 80 miles with one precautionary stop for water in Vallejo.
May 5-24	Engineering road tests and maintenance. Four small boiler leaks repaired.

Table IV con't

DATES	EVENTS
May 25-June 9	511 miles of revenue service, Routes 41-A and 82-X. 19 one-way trips completed out of 22 trips scheduled. Burner control problems and high water consumption experienced.
June 12-August 18	Phase II.5 engineering improvements. Bus displayed to Society of Automotive Engineers in San Francisco.
August 29	Sound level tests in San Francisco.
September 19-29	Final period of revenue service. 440 miles traveled, 82-X line, including check-out runs. Excellent and flawless service, except exhaust odor noted on some of the runs. Water recovery much improved.
September 30	Contract concluded. 3,465 miles under steam power.

TABLE V

OPERATION OF STEAM BUS, LEAR/S.F. MUNI

DATES	EVENTS
January 27, 1972	Powerplant installation completed; bus driven 13 miles, with loads up to 58 passengers.
February 11	"Open house" at Lear Motors in Reno. Several bus demonstration rides given. Cumulative miles, 250. (Boiler had failed February 10 from overheated tube, but repaired that evening.)
February 14-April 24	Road tests and engineering evaluation in Reno. Many revisions and repairs. Weaknesses in turbine housing, gearbox, and auxiliaries corrected. Controls improved. Cumulative miles on April 10, 1,100.
April 26	Bus demonstrated to California Legislature in Sacramento.
April 27	Sound levels tested in Sacramento. Emissions tests begun, but boiler leak developed and bus was shipped back to Reno.
April 28-July 19	Phase II.5 improvements to power system made in Reno. Road tests and engineering evaluation. July 4, 1750 miles.
July 20	Bus delivered to San Francisco.
July 29-August 1	Engineering evaluation tests.
August 4	Official turn-over ceremonies to S.F. MUNI.
August 7-25	Bus used in revenue service in San Francisco over 32 and 17 lines. Operation was reliable except for three days out to replace boiler, and broken auxiliary-drive belt which interrupted service on August 25.
August 28-30	Engineering evaluation tests, in San Francisco. Sound level tests, August 29. Miles driven in San Francisco, 582.
August 31-September 1	Bus driven 230 miles from San Francisco to Reno, over Sierra Nevada Mountains.
September 13-15	Emissions tested in North Hollywood.
September 16	Bus driven half-way back from North Hollywood toward Reno. Gearbox failure halted the trip.
September 30	Contract concluded. 3,900 miles under steam power.

TABLE VI

OPERATION OF STEAM BUS, SPS/SCRTD

DATES	EVENTS
March 17, 1972	Bus operated for first time.
March 17-April 20	Road tests in San Diego and engineering improvements. 125 miles on bus by April 10.
April 26	Bus demonstrated to California Legislature in Sacramento.
April 27-May 2	Sound levels and emissions tested in Sacramento.
May 5-August 6	Phase II.5 engineering improvements. Road testing and engineering evaluation. 491 miles by July 20.
August 7	Bus delivered to Los Angeles.
August 14-29	Engineering tests in Los Angeles. A failure of the burner fan occured.
August 23-25	Emissions tested at North Hollywood.
August 30	Bus officially turned over to SCRTD.
September 1	Sound levels tested in Los Angeles.
September 5-6	Revenue service was scheduled, but burner fan failure and problems with oil pump drive caused postponement.
September 7	First day of revenue service. One-way run of 7.3 miles on 83 line was completed satisfactorily. After turning around for return trip, a drive pulley for the burner fan failed.
September 8	Bus withdrawn from service when a boiler leak was discovered.
September 11	Road tests performed, over 86 miles, in spite of worsening boiler leak. At end of day, leak got so bad that further tests had to be postponed.
September 13-25	Powerplant repaired in San Diego. Bus later towed to San Diego for system installation.
September 26-27	Road tests in San Diego. Condenser fan belt failed. Feed water pump failed because an oil line had been left disconnected. 968 miles accumulated.
September 28	Route cycle test over 83 line was satisfactory.
September 29	Second day of revenue service. A successful 15 mile round trip on the 83 line was made with air conditioning operational. A battery terminal failure, not attributed to the steam system, caused a 27 minute delay until corrected.
September 30	Contract concluded. 1,007 miles under steam power.

TABLE VII

URBAN BUS ROAD PERFORMANCE

	Diesel GM 6V-71 (a)	Diesel GM 8V-71 (b)	Diesel Cummins 903 V-8 (c)	Steam Brobeck	Steam Lear	Steam SPS (d)
GVW as tested, lb	25,320	26,860	28,000	30,580	28,470	30,900
Top speed, mph	52	65(e)	70 plus(e)	56	54	58(e)
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(f)	16% at 8 mph	18% at 2 mph	20% at 2 mph	N.A.

NOTES:
(a) N-55 injectors
(b) N-60 injectors
(c) Derated engine
(d) Steam temperatures were too low for best power output.
(e) Overdrive transmission used.
(f) 35,000 lb GVW overload test.

the SPS bus, steam temperatures at engine idle would drop. Recovery of the temperature after accelerating from rest came too late for best road horsepower. To illustrate the latent capability of SPS bus, 130-140 hp were observed on a chassis dynamometer during emissions testing, while a comparable bus powered by a Cummins 903 V-8 diesel engine showed a maximum of 120 hp on the same dynamometer.*

All steam buses were handicapped by the use of transmissions not well-matched to the expanders. The Lear turbine, for example, was often forced to operate at speeds too low for good efficiency, and hence both performance and fuel economy suffered unduly. The highest road horsepower observed with the Lear bus were in the range 125-138 hp, calculated from performance on two highway grades near Reno. This corresponds well with 135 road hp inferred from chassis dynamometer tests. And yet, a maximum of less than 90 hp was developed under the highly non-ideal conditions of route-cycle testing on the MUNI 55 line.

The maximum road hp delivered by the Brobeck bus was 153 hp on the R-F line driving cycle test. Calculating from the maximum powerplant net output (200 bhp) and an assumed power transmission efficiency of 0.85 in direct gear, 170 road hp should be achievable.

Exhaust Emissions

Several tests were made of the exhaust emissions of diesel vs. steam buses by the California Air Resources Board. Table VIII 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, while none of the diesel buses did so. These standards limit carbon monoxide emissions to 25 grams per engine bhp-hr and combined hydrocarbons and nitrogen oxides to 5 grams per bhp-hr. It should be emphasized that the diesel emission test results are based on a random sampling from well-maintained fleets, and are not necessarily

*Power readings on a chassis dynamometer having small-diameter rollers can be much less than actual power delivered to the rear wheels, because of the very abnormal rolling resistance. This is especially true with buses, since the unladen weight on the rear axle is much higher than with trucks. The same Cummins-powered bus developed over 210 road horsepower in route-cycle tests in this program.

TABLE VIII

EXHAUST EMISSIONS OF STEAM AND DIESEL BUSES (a)
(Figures in grams per engine bhp-hr)

	CO	HC	NO_2 (b)	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) (c)	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
Ave. steam	4.0	0.9	1.8	2.7
Diesel buses: (d)				
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
Ave. diesel	4.3	1.4	10.4	11.8
California Heavy Duty Standards				
1973	40	-	-	16
1975	25	-	-	5

Notes:

(a) All tests were performed by the California Air Resources Board.

(b) NO_x was measured as nitric oxide (NO) and expressed as equivalent NO_2.

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

(d) 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.

"typical" of diesel engines generally. Of special interest is the fact that the cleanest steam system emitted only 6% the oxides of nitrogen as the cleanest diesel tested.

While the diesel engine is already regarded as a relatively "clean" engine in terms of carbon monoxide (CO) and hydrocarbons (HC), nevertheless, the cleanest steam bus emitted only 62% the CO as the cleanest diesel. The lowest value of HC for a steam bus was 40% of the lowest value observed for diesels.

On the basis of averages, the steam buses had 91% of the CO, 64% of the HC, and 17% of the NO_2 of the averages of the diesels tested.

All emissions tests were made with No. 1 diesel fuel.

During the Lear emission tests, water injection into the combustion chamber was employed.

Both diesel and steam bus operation was virtually smokeless (opacity 1% to 4% for most runs) when the steam systems were operating properly. However, all steam buses emitted puffs of visible exhaust smoke if the controls called for a sudden change in firing rate. Controls could no doubt be designed to eliminate this.

Light odors, reminiscent of a gas turbine or jet engine exhaust, were sometimes noted around the steam vehicles.

Sound Levels

Sound level tests were conducted by the California Highway Patrol. The test results are summarized in Tables IX and X.

The quietest steam bus was 2.5 to 10 decibels quieter than diesel buses during the 50' drive-by tests. Moreover, the quietest steam bus in the 15' tests (simulating curb-side) was 6 to 14 dB quieter than the quietest diesel tested. On the other hand, interior sound levels of steam buses were similar to or higher than diesel in most cases. It would appear that interior sound levels may be influenced as much by the construction of the bus as by the character of the powerplant, and much needs to be done in terms of soundproofing vehicles generally.

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 proven successful in gas turbine practice.

TABLE IX

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	A-C #678 GM6V-71	STA #408 GM6V-71	MUNI #3309 GM8V-71	SCRTD #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:

(a) All measurements by California Highway Patrol

(b) Microphone was placed alongside the roadway, with distances measured from the center-line of path of travel.

TABLE X

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	A-C #678 GM6V-71	STA #408 GM6V-71	MUNI #3309 GM8V-71	SCRTD #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	71	72	72	68	72	69

Notes:

(a) All measurements by California Highway Patrol

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

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 30 mph. Under the same test conditions, a diesel bus can do at least 8 to 10 mpg. Under actual stop-and-go route conditions, steam at 0.52 to 1.1 mpg was noted against the diesel at 2.3 to 3.7 mpg. The idle fuel consumption was 3.2 to 4.7 gal/hr for steam vs. 0.5 to 0.7 gal/hr diesel.

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

These three steam systems did not achieve specific fuel consumption as high as demonstrated possible during the Doble-Besler era. In the present project, bench tests yielded specific fuel consumptions exceeding 1.0 lb per net bhp-hr. One reference (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 prospects for considerable future improvement, will be given in a later section.

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 control were applied during the program:

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 non-explosive designs.
3. All steam generators were hydrostatically proof-tested.
4. 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.
5. Limiting governors were applied to prevent accidental expander overspeed.

TABLE XI

FUEL CONSUMPTION OF STEAM AND DIESEL BUSES
(GVW 25,000 to 30,000 lb)

	Brobeck	Lear	SPS	GM 6V-71	GM 8V-71	Cummins 903 V-8
Cruise fuel mileage, mpg:						
20 mph	2.4	1.8	2.2	-	4.7	7.7
30 "	3.5	2.2	2.3	10.2	7.1	11.8
40 "	3.0	2.3	2.9	-	8.1	10.3
45 "	-	-	-	8.9	-	-
50 "	2.5	2.1	2.5	-	7.1	8.8
60 "	-	-	-	-	-	7.5
Idle fuel consumption, gal/hr:	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 "	-	0.7	-	-	3.68	-
SCRTD #83"	-	-	0.6	-	-	3.02

NOTE: See Table II for more examples of route fuel mileages.

6. Flame sensors were installed to stop fuel flow in the event of ignition failure.
7. 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 (Figure 21). On a number of occasions, tube failures did occur on the experimental steam generators. These occurences proved to be inconveniences, rather than presenting a hazard. Because of the large exhaust ducts, steam from tube failures vented 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."

No accidents of any kind occurred in connection with the testing or demonstration of any of the steam buses.

Operating Characteristics

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

Approximately 25 different transit drivers and driver instructors drove the steam buses. All were able to handle the buses acceptably well with minimal instruction. A different "throttle feel" and, in the case of the Brobeck bus, more steering effort required because of the altered weight distribution, were the main comments. While overall performance of the steam buses was similar to that with six-cylinder diesel power, response to the throttle differred somewhat. The response of a

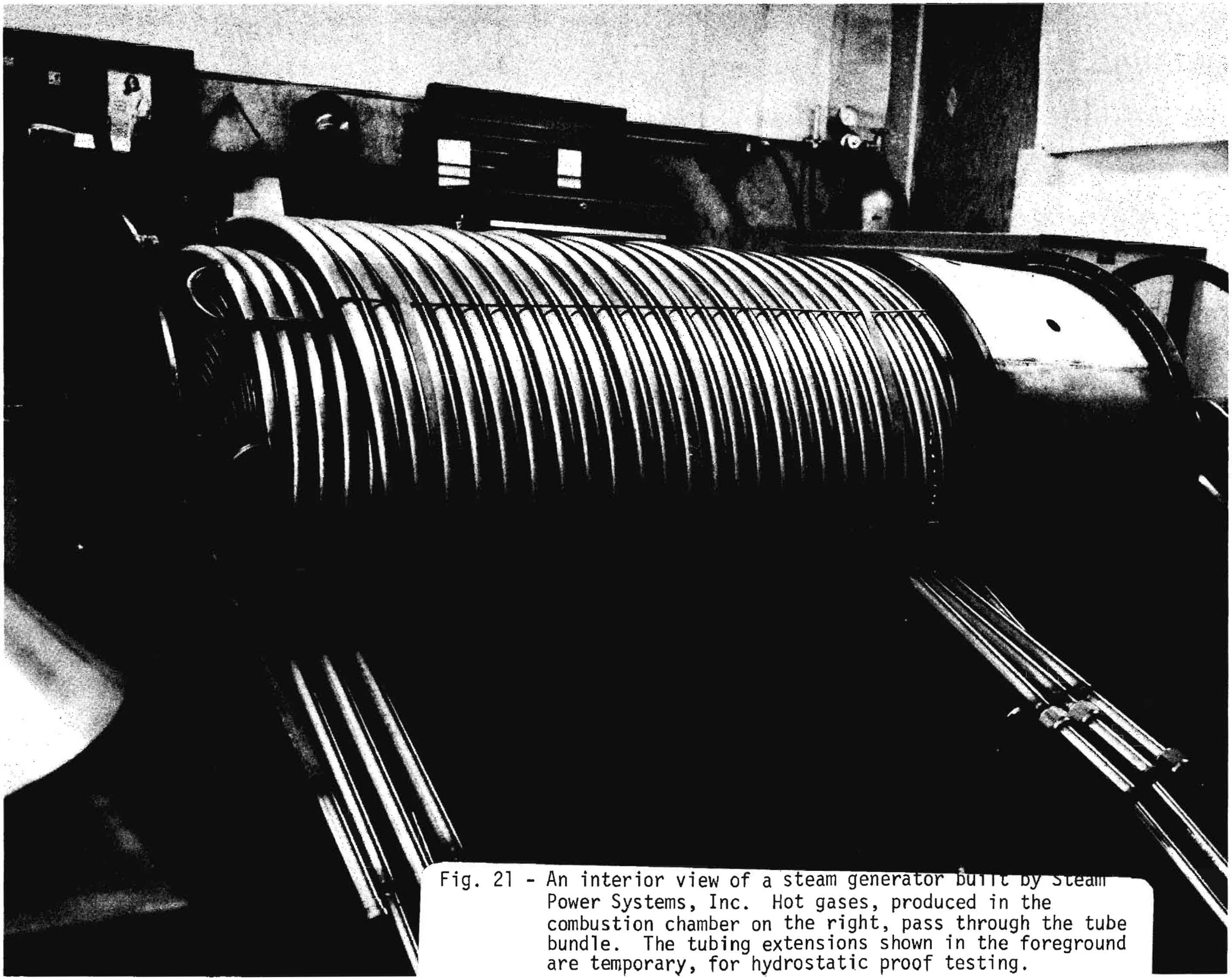

Fig. 21 - An interior view of a steam generator built by Steam Power Systems, Inc. Hot gases, produced in the combustion chamber on the right, pass through the tube bundle. The tubing extensions shown in the foreground are temporary, for hydrostatic proof testing.

diesel engine to throttle movement is sharp and virtually instantaneous, while that of the steam systems seemed less abrupt.

Several of the drivers were interviewed to obtain their reaction to steam buses. Most drivers interviewed felt the public was interested in steam buses, because people asked a lot of questions during public service. One driver said that passengers "would let the diesel buses go by and wait for the steam bus. They enjoyed it."

All drivers were eager to share their experiences, and most felt it was an "honor" to have been selected to drive the steam bus and that they had played a "special role in history." Some even expressed resentment against passengers who were "unjustly" impatient with the state of steam bus development. One driver expressed this feeling when he said, "I don't think these people have had enough time to get all the bugs out of their engine. I don't think that General Motors built their engines in 18 months and perfected them."

A driver who operated the AC Transit steam bus before and after it underwent an improvement program remarked that when he was driving on the freeway, "I completely forgot that I was driving a steam bus, we were moving along that smoothly."

All start-up procedures were controlled from the driver's seat. Sufficient steam to start the expander could be raised within a minute from a cold switch-on. Careful warm-up of the expander was then needed in the case of the reciprocating designs, and this required an additional two to five minutes. Such care was needed lest water be trapped in the cylinders and cause damage. The Lear turbine could be started just as soon as steam was available. All three systems had to be driven several blocks before the entire system was up to temperature and maximum power became available. Once the powerplant was hot, it could be restarted within a matter of seconds, even after a lapse of up to half an hour.

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 or on a hot day. The buses had adequately sized condensers and sufficient fan horsepower, which normally should have provided a touring range at least equal to a day's operation. In practice, however, all the steam buses sometimes fell short of this goal. In the case of the Brobeck and SPS buses, the location of condensers beneath the floor restricted the availability of fresh cooling air. There also was trouble when the condensers picked up dirt and debris from the street, impeding heat transfer effectiveness. The location of the condensers on the Lear bus was better. The two condenser cores were mounted on the sides of the bus (at opposite ends of the rear engine compartment) and with the fans drawing outside air inward. While this arrangement provided good access to cooling air, it led to engine compartment temperatures which were higher than desired. Even though the Lear arrangement was better, condenser overloading sometimes occurred when the turbine speed was loaded downward under full-throttle conditions, causing large drops in turbine expansion efficiency.

The waste heat release from the steam powerplants was appreciably greater than that of diesel engines. Therefore, much consideration had to be given to directing the heat flow away from the passenger compartment and from by-standers. In the future, much thought will no doubt be given to placing condensers on the rooftop of the vehicle, with both comfort and unimpeded air flow in mind.

Problems Encountered

Because these were early experimental systems, and also because of the limitations on the time available, many problems were encountered in keeping the powerplants running properly. This certainly does not imply that steam systems are inherently unreliable, but rather reflects a commomplace experience when any complex system is exercised at an early date. Quite often, trouble resulted from simple human error, such as forgetting to connect up an oil line or installing a control valve backwards.*

Problems tended to fit into one of four categories:

1. Failures of boiler tubing
2. Failures of the combustion or ignition system
3. Mechanical breakdowns
4. Electrical circuit or control problems

---

*Engineers and technicians literally worked day and night in preparing the buses for scheduled tests and demonstrations. Working under a dripping steam bus at 2:00 a.m. is sometimes not good for one's disposition.

Boiler tubing failures were usually traced to very definite causes, and thus could be virtually eliminated by proper design. All three contractors experienced such failures. A common cause was overheating or tube "burnout," due to control irregularities or insufficient feed water. A second type of failure was identified in the Brobeck boiler, in which tack welds were used to structurally position adjacent coils of tubing. Stresses imposed by vibration or thermal expansion sometimes caused such external welds to fail, breaking out a small piece of the tubing. In a third type of mishap, experienced by SPS, vibration caused adjacent coils to rub against one another and wear a hole through at the point of contact. On yet another occasion, a manufacturing defect was discovered in the tubing used. It is significant to note, however, that no pressurized weld (such as were used to splice lengths of tubing into continuous coils) ever failed in this program.

Combustor problems were usually traced to plugged nozzles, warped or heat-damaged combustor cans, or electrical ignition failtures.

Mechanical breakdowns were the most exasperating, especially since commonplace gears, bearings, pulleys, and belts were so often involved.

Purchased components, such as solenoid-actuated valves, often caused trouble because they had originally been designed for some other class of service. A particular valve seat designed for some industrial application might have been designed to last for thousands of hours. On the steam bus, it might lastonly fifty hours, because of peculiarities of the temperature, flow pulsations, or duty cycle.

The lack of suitable cylinder lubricants not only resulted in unusually high wear rates, but prevented the attainment of high thermal efficiencies by limiting the steam inlet temperatures that could be used. Little or no research had been done on steam cylinder oils since the days of the Stanley steamer.

A large share of problems were caused by electrical faults, mostly associated with control circuits. The overheating of electronic components in the engine compartment, spurious signals causing "noise" in logic circuits, and overloaded fuses and circuit breakers all were encountered.

Phase II.5 Improvements

The purpose of the Phase II.5 project extension was to make selected engineering improvements to the existing bus power system. This work was begun during the spring of 1972 and overlapped in time with Phase II tasks. The accomplishments vs. objectives for Phase II.5 are listed below:

Objectives	Accomplishments
Brobeck:	
1. Reduce emissions	Several alternate burners tested. While overall levels of emissions changed but little, dependence upon critical tuning adjustments has been reduced.
2. Reduce noise	Sound levels from burners and auxiliaries reduced, particularly at curbside idle (reduced from 74 dB to 68 1/2 dB) and interior (reductions of 1 to 7 dB).
3. Improve condenser efficiency	Water mileage went from less than one mpg previously, to an average of 5.4 mpg now.
4. Improve automatic controls	An automatic start-up sequence was installed but not fully tested.
5. Other improvements	A section of mild steel boiler tubing was replaced with stainless steel, eliminating boiler leaks. The expander was overhauled. General operating reliability was improved.

The Brobeck condensers initially suffered from tight packaging beneath the bus, and consequent restriction of cooling air flow. During earlier bench testing, 28 ft^2 of condenser frontal area was sufficient to condense all of the exhaust steam at full load. However, as mounted in the bus, the condensers were of inadequate capacity. During Phase II.5, the frontal area of the condensers was increased to 35 ft^2, and some of the condenser cores were re-mounted to provide improved cooling air flow.

Objectives	Accomplishments
Lear:	
1. Upgrade automatic controls	Automatic boiler controls miniaturized. Manual adjustments no longer needed while running. Stable steam conditions maintained under change of load.
2. Improve system reliability	Over 2,000 miles of shakedown testing in Nevada led to best reliability of the three buses.
3. Improve fuel economy via improved component efficiencies	Condenser and burner fan loads decreased. Idle fuel consumption reduced from 7.2 3.2 gal/hour. Route fuel economy remained poor because turbine redesign was beyond scope of Phase II.5.
4. Generally improve the system	a) A much improved transmission eliminated jerks. b) Sound levels reduced by about 4 dB outside, 5 dB inside.

Throughout the bus project, the Lear designs and then the installed system were constantly changed. This pragmatic, experimental (but costly) approach was innovative and yet the "final" result left much growth potential remaining to be exploited. True to Lear Motors' aircraft background, the components are lean without much "fat" or excess metal.

Objectives	Accomplishments
SPS:	
1. Improve expander	After improvements, expander was much tighter and free from steam and oil leaks. Basic engine block reliability is good (though auxiliary items remain very troublesome).
2. Improve steam generator	Boiler coils reworked to give better temperature balance between initial superheat and reheat sections. Burner reliability improved.
3. Improve operational characteristics	Automatic controls functioned well, except slow to regain superheat after idle periods.

Objectives	Accomplishments
SPS (con't):	
4. Reduce noise	Outside levels remain about the same. Interior noise at idle reduced by 5 dB.
5. Evaluate variable cut-off with hydraulically-driven valves	Assembly of two-cylinder test expanders was several months late, leaving little time for exploratory tests. During final week of program, expander ran well and was showing low indicated steam rates.

The variable cut-off experiments were conducted with a small bench-test expander. In spite of its small size (which normally tends to penalize thermal efficiency), results were very encouraging as a route to decreased fuel consumption. Even with inlet steam and reheat temperatures at 700°F and below, expander indicated thermal efficiencies*reached 27%.

---

*Indicated thermal efficiency is based upon indicated work done upon the pistons, before mechanical friction losses are deducted.

FUTURE POSSIBILITIES

General Outlook

The California Steam Bus Project can be viewed as a learning process, an accumulation of data that clearly indicates what was achieved and what remains to be achieved. While the state-of-art in steam propelled vehicles is not advanced enough to warrant immediate introduction into fleet service, the ECE now has been identified as one of the more promising candidates for the "clean engine of the future." What now can be said about the potential for Rankine cycle systems in the future?

The ECE approaches the problem of air pollution control by attacking that problem at its roots, namely the physics and chemistry of the combustion process. Fuel burning engines of the future, if they approach the theoretical limits of cleanliness, are likely to be ECE's. The Rankine cycle, with possibilities for a smooth, quiet application of high-torque propelling energy, 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, persistent and coherent engineering work will be required before the ECE can be ready for general application and acceptance. Obvious areas for improvement are fuel economy, operating reliability, packaging, combustor technology, automatic controls and improved transmissions. Winterizing mobile steam powerplants is another important consideration, but this would not be as difficult a problem in fleet operations as it would be with privately owned automobiles. Concurrent with powerplant development, research would need to be advanced in supporting fields of lubrication, metallurgy, working fluids and control concepts.

If the history of the steam automobile teaches anything, it would be to impart an understanding of the need for patient endurance in technical developments. Quite a number of "steam car revivals" were spawned over the last 60 years. Many of these attempts resulted in rapid technical advancement. They all had one common characteristic, however. All of the projects were terminated when their sponsors became unwilling to continue the long-term financial support necessary to bring the steam engine to market. Perhaps the special qualities of the ECE were not as sorely needed then. However, if these qualities will be needed in the 1980's, serious development must begin immediately.

Much undeveloped potential remains for Rankine cycle propulsion systems. Some of the main areas for improvement will be discussed.

Fuel Economy

The heavy fuel consumption of the present steam buses has been singled out as the largest obstacle to general acceptance. The implications go beyond the impact on bus transit system costs, since fuel costs are only about three percent of the total costs of providing bus transportation in cities (30). One issue is the impending national energy crisis(31). It is also important to note how decreasing the fuel consumption would lead to other power system improvements. For example, if the system thermal efficiency were improved, the following benefits would result:

1. Specific emissions in grams per horsepower hour (while already acceptably low) would be reduced even further.
2. The size and weight of heat transfer apparatus, such as boilers and condensers, would be reduced.
3. With reduced condenser loads, condenser fan requirements would decrease. This reduction of parasitic power loss would in turn further improve the system efficiency.
4. An incidental benefit from reduced fan power would be decreased fan noise.
5. Environmental heat release would be diminished.

The key to improving fuel economy lies in improving the thermal efficiency of the entire vehicle under actual driving conditions. Many opportunities exist to do this, including:

1. Increase the efficiency of the ideal cycle.
2. Increase the fraction of ideal cycle efficiency available in an actual powerplant.
3. Increase the efficiency of transmitting power to the wheels.
4. Reduce fuel consumption at idle.
5. Recover some of the braking energy.
6. Productively use a portion of energy normally wasted, such as rejected heat.

Ideal Cycle Efficiency

As a first step in evaluating future improvements to the Rankine cycle engine, one might examine the thermal efficiency of the ideal cycle (E_i):

$$E_i = \frac{h_1 - h_2}{h_1 - h_3} \tag{1}$$

Where the values of enthalpy (h) are:

h_1 = Enthalpy of the supply steam.

h_2 = Enthalpy of the exhaust steam.

h_3 = Enthalpy of the condensed liquid returned to the boiler.

The numerator of Equation (1) represents the work done by an ideal expander; the denominator is the amount of heat added in the boiler. The work to drive the feed pump has been ignored to simplify the equation; this and other system auxiliary loads will be discussed later. Calculated values of E_i have been plotted as the upper curve in Figure 22. This calculation, as an example, assumes supply steam at 1,000 psi is fed to an expander having a volume expansion ratio of 20, and that the condensate is returned to the boiler at 200°F. The influence of the temperature of the feed steam upon E_i should be especially noted.

The present state of the art, with steam temperatures in the range 700-1,000°F, would correspond to values of E_i of 0.28 to 0.30 if the other parameters were as assumed for the example. However, since the expansion ratios of the present steam buses were less than 20, the calculated value of E_i would be approximately 0.25 for their powerplants.

With serious efforts in future development, values of E_i would be expected to rise, perhaps to 0.30 in the short term and to 0.35 eventually. Experience could be analogous to that with gas turbines over the past twenty years, during which time turbine inlet temperatures were increased from 1,500°F to close to 2,000°F (32, 33) with commensurate increases in thermal efficiency. The use of high expansion ratios would be required to take advantage of high working fluid temperatures. Expansion ratios of 20 or more could be utilized (compared to fixed ratios as low as 5 in the present systems).

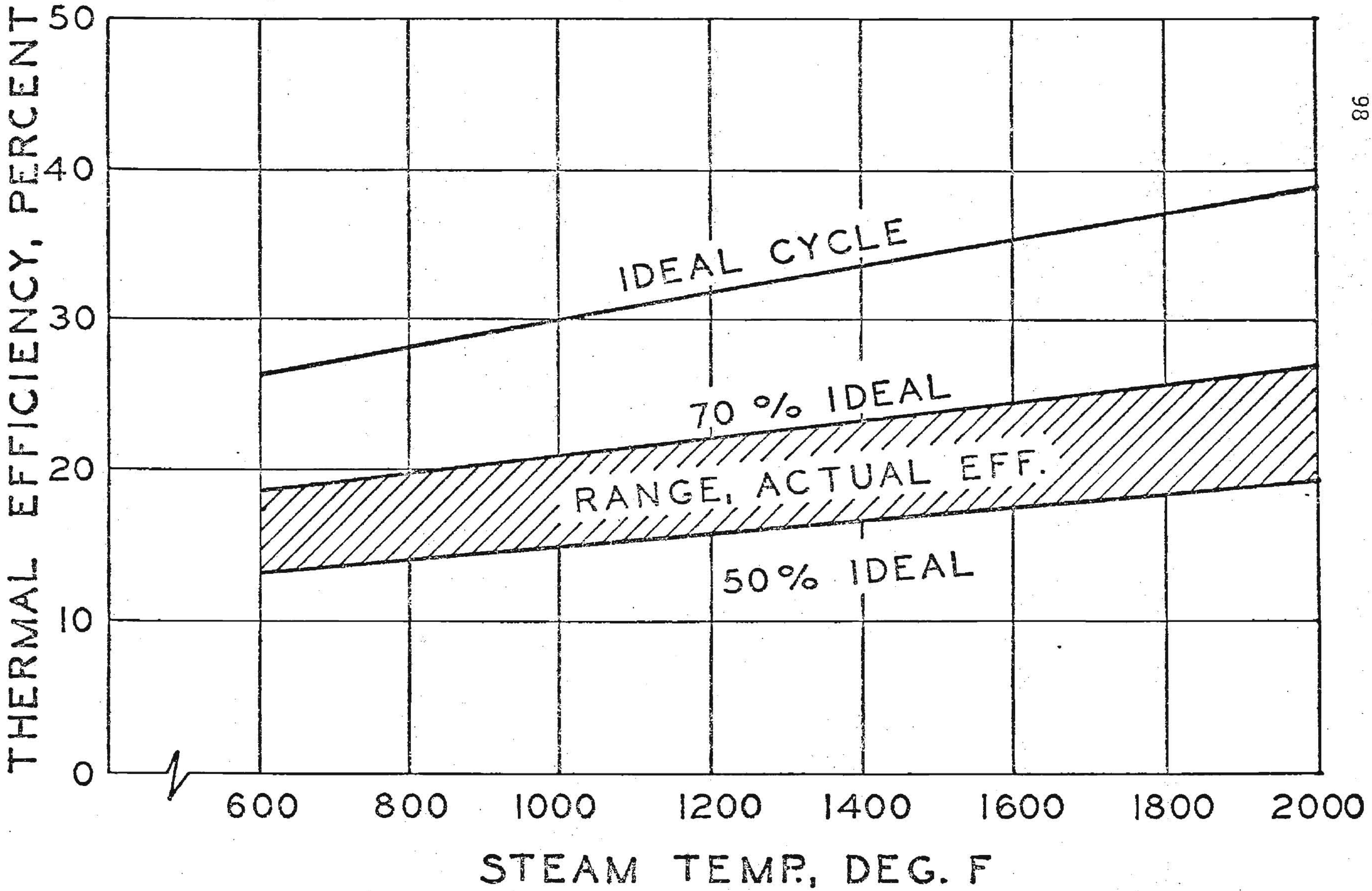

Fig. 22 - Influence of steam temperature on Rankine cycle thermal efficiency

Actual Thermal Efficiency

The actual overall thermal efficiency (E_{th}) of a power system is a ratio of net power output to the rate of fuel energy input:

$$E_{th} = \frac{\text{Net Power Output}}{\text{Rate of Fuel Energy Input}} \qquad (2)$$

The best values of E_{th} obtained from bench tests of the bus powerplants were in the range 0.117 - 0.140. Under the less favorable operating conditions as installed in buses, E_{th} was estimated to be on the order of 0.10. It will be noted that E_{th} was only about 40 percent of the ideal cycle efficiency, E_i.

The factors that influence E_{th} may be appreciated by examination of Equation (3):

$$E_{th} = E_i \, E_b \, E_e \, E_m \, E_a \qquad (3)$$

Terms not previously defined are:

E_b = The boiler efficiency.

E_e = The expansion efficiency, or the ratio of the actual heat extracted from the working fluid during the expansion process to the ideal isentropic enthalpy drop.

E_m = The mechanical efficiency of the expander.

E_a = The ratio of net system power output after deducting powerplant auxiliary loads to the gross power output of the expander.

As an illustrative example, if the ideal cycle efficiency (E_i) were 0.30 and if E_b = 0.85, E_e = 0.80, E_m = 0.90, and E_a = 0.85, the overall thermal efficiency would be 0.156 or 15.6 percent. This is 52 percent of the ideal efficiency (E_i).

A suitable goal would be to reach 60 percent of the ideal Rankine cycle efficiency. Assuming that E_i = 0.35 is possible, E_{th} would then be 0.21. Seventy percent of E_i would be 0.245, which might be attainable under laboratory conditions and perhaps under field conditions in the more distant future.

Figure 22 also gives a range of actual thermal efficiencies that may be expected in times to come. Present steam bus values lie below this region, because of lower ideal cycle efficiency, incomplete expansion, and high auxiliary loads.

Major gains over the present systems can be obtained by:

1. Increase expansion efficiency -- whether reciprocating or turbine. (Much of the present operation involved losses by throttling, condensation in the expander, and incomplete expansion.)
2. Reducing parasitic auxiliary loads. Just one example is the improvement of condenser fans, which in the present systems consume about 30 horsepower. This could be reduced to 10 or 15 horsepower or less with more efficient fans and fan drives. One suggestion is to power these fans with turbines driven by exhaust steam. Not only would this conserve premium shaft power, but it could permit the extraction of additional expansive work from the steam.

Lesser gains are also worthwhile, by:

1. Reducing boiler heat losses.
2. Reducing mechanical friction.
   (Boiler and mechanical efficiencies were reasonably high in this program already.)

Vehicular Thermal Efficiency

What really matters, of course, is the overall thermal efficiency of the entire vehicle. Vehicular thermal efficiency (E_v) may be defined as the work actually delivered to the rear wheels, divided by the heating value of the fuel burned during a particular vehicular mission. E_v may also be defined as:

$$E_v = E_{th} E_t \qquad (4)$$

Where

E_{th} = The actual powerplant thermal efficiency, as defined by Equations (2) and (3).

E_t = The power transmission efficiency.

Values for E_t can vary from zero (a hydraulic torque converter at stall) to numbers approaching 0.90 (losses would be in gears, bearings, universal joints, etc., in the transmission p oper, drive shaft, and drive axle).

If (as an estimate which was borne out by route cycle tests) the mean transmission efficiency in a stop-and-go mission were 0.60, and if the powerplant E_{th} were 0.10, then the overall E_v would only be 0.06, or 6 percent. This s in contrast with diesel power, in which E_{th} is around 0.30; even with E_t as low as 0.60, E_v is still a respectable 18 percent.

Much can be done to improve the efficiencies of power transmission when a Rankine power system is used. In the case of reciprocating expanders, a multi-ratio transmission can be dispensed with entirely, since these engines can be made reversible and can produce very high stall torques. Actually, most historical steam vehicles were "direct drive," meaning the steam engines were geared directly to the rear axle. Figure 23 is instructive, indicating the torque available at the rear axle of a German steam bus (circa 1935). It will be noted that this direct-drive steam bus could exert higher tractive efforts at all road speeds than a comparable bus with a gasoline engine and four-speed transmission.

When direct drive is used, the expander should have variable cut-off and would need to be reversible in rotation. With variable cut-off (the point at which the steam inlet valves are closed during the stroke of the piston), the expansion ratio can be high during cruising or light loads. The same expander can then also exert extremely high efforts for starting and hill climbing (at late cut-off or low expansion ratio) with some temporary increase in fuel consumption.

Trade-off studies must be done to see whether direct drive or some simplified version of variable-ratio geared transmission would be of higher overall efficiency for a given application.

Improved transmissions are also needed for turbine expanders. It is especially necessary, for the maintenance of high turbine efficiencies, that rotational speeds be kept very close to optimum values. This suggests the need for a large number of closely spaced geared ratios, perhaps eight or more rather than the four speeds used with the Lear bus. Infinitely variable transmissions (34) would be best, provided they could be made available with high transmission efficiencies.

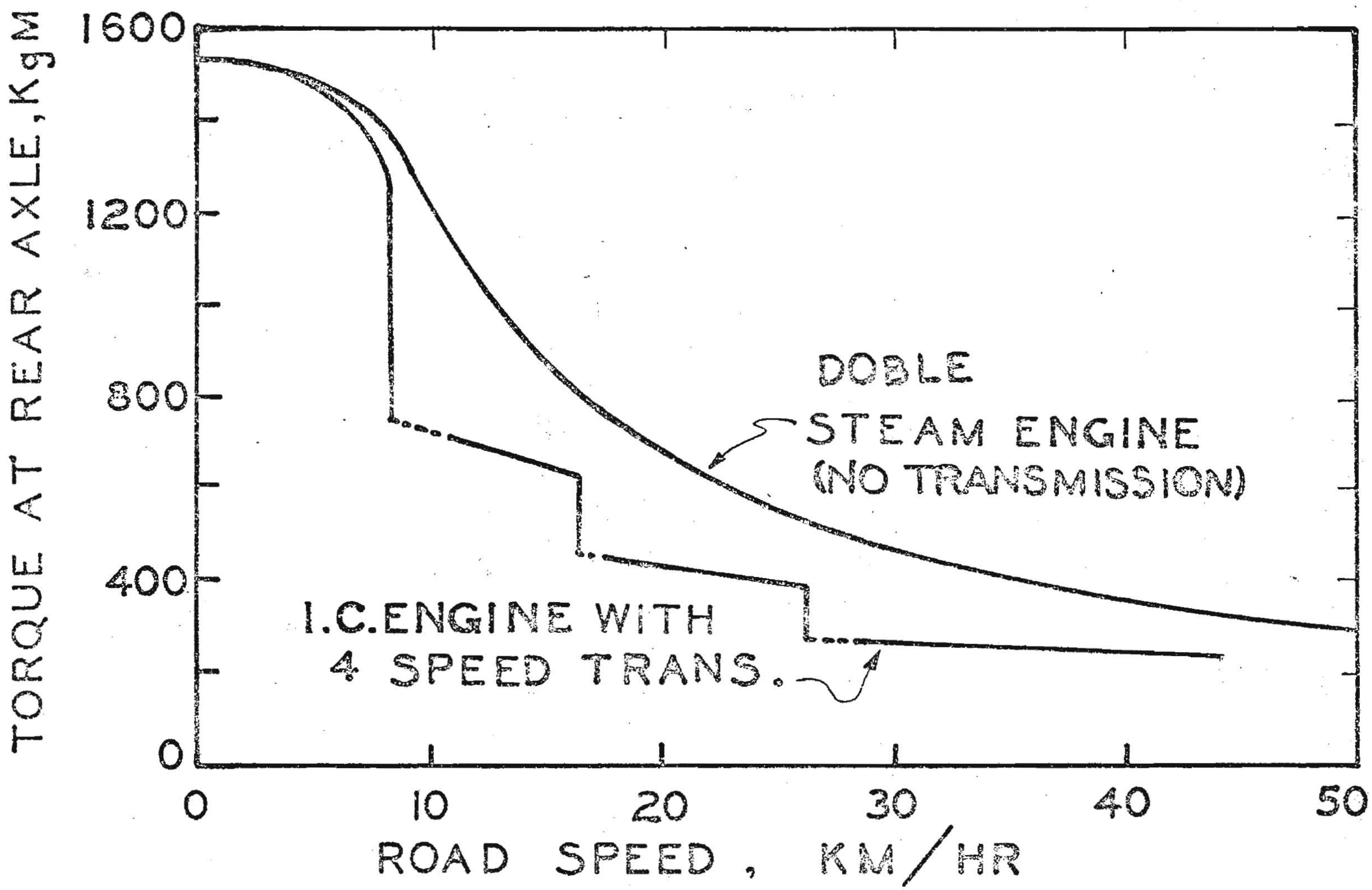

Fig. 23 - Historical. Performance potential of two German buses, circa 1935 (Ref. 5)

Vehicular Fuel Economy

A primary factor influencing a vehicle's fuel economy is the vehicular thermal efficiency discussed above. Another influence is the idling fuel consumption, particularly in a class of service where up to 40 percent of the mission time may be at idle. The idle fuel consumption of the present steam buses was very high. If only the essential loads had been maintained at idle (say with a small auxiliary expander), idle fuel consumption could be cut by two-thirds.

Table XIII summarizes some of the future possibilities in improving the fuel economy of ECE-powered buses, and compares these projections with the present state of affairs in steam and diesel power. It will be noted that it probably will be possible to reduce ECE fuel consumption to the point where it can compete with diesel in stop-and-go service. In an example given in the table, a projected future steam bus might consume only 6 percent more fuel than a diesel.

On the other hand, it is doubtful that the Rankine cycle can compete with the diesel for fuel economy in long-haul, over-the-road service. This will at least be true for a long time to come, since both the transmission and the ICE can have very high efficiencies under cruise conditions.

Possible Trends in Reducing Emissions

Even though the emissions demonstrated in this program were acceptably low, further reductions can be obtained by:

- o Reducing the amount of pollutants generated per pound of fuel burned (cleaner combustion).
- o Reducing, in turn, the amount of fuel burned per hp-hr 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 (13). One of the contractors (Aerojet General Corporation) has, in steady-state burner tests, demonstrated 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

TABLE XIII

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 (b)	0.10	0.15(a)	0.21(a)	0.30
System bsfc, lb/bhp-hr (b)	1.38	0.92	0.66	0.46
Transmission Efficiency (example)	0.60 (c)	0.85(d)	0.85(d)	0.60(c)
Vehicular Thermal Efficiency	0.06	0.13	0.18	0.18
Idle Fuel Rate, gal/hr	4.50	1.50(e)	1.00(e)	0.50
Calculated Fuel Mileage, mpg, Hypothetical Local Bus Route (f)	1.00	2.30	3.30	3.50

NOTES:

(a) Sixty to 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 cut-off or turbine expanders. Therefore, the values of these modifiers have been reduced to an assumed mean of 50 percent and 60 percent, respectively.

(b) As-installed operating conditions.

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

(d) Direct geared drive assumed, or high efficiency transmission developed for turbine.

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

(f) One local route tested required 2.4 hp-hr of propulsive energy per mile, and had two minutes of idle time per mile.

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 XIII, the projected engine brake specific fuel consumption (bsfc) can probably be reduced to 67 percent of present levels with near-term development and to 48 percent eventually. Combining the effects of cleaner combustion and reduced fuel consumption, then, we may expect future reductions as depicted in Figure 24.

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.

The present California steam buses require about 1 ft^3 for each net horsepower (200 ft^3 for 200 net hp), with the Lear system requiring less space. This includes the transmission, condensers, and working fluid reservoirs but not the fuel tank. About 150 ft^3 is available in present diesel engine compartments (including under-floor space behind rear axle), but not all of the space is actually occupied by the present diesel systems. A suitable goal would be to reduce the volume required for the ECE to 0.75 ft^3 per hp.

The dry weight of the present steam powerplants varied from 17 to 24 lb per net hp, compared to around 19 for the diesel (transmissions, radiators, condensers, auxiliaries included). A short-term goal for the ECE should be 15 lb per net hp, with 10 to 12 lb per net hp believed possible eventually.

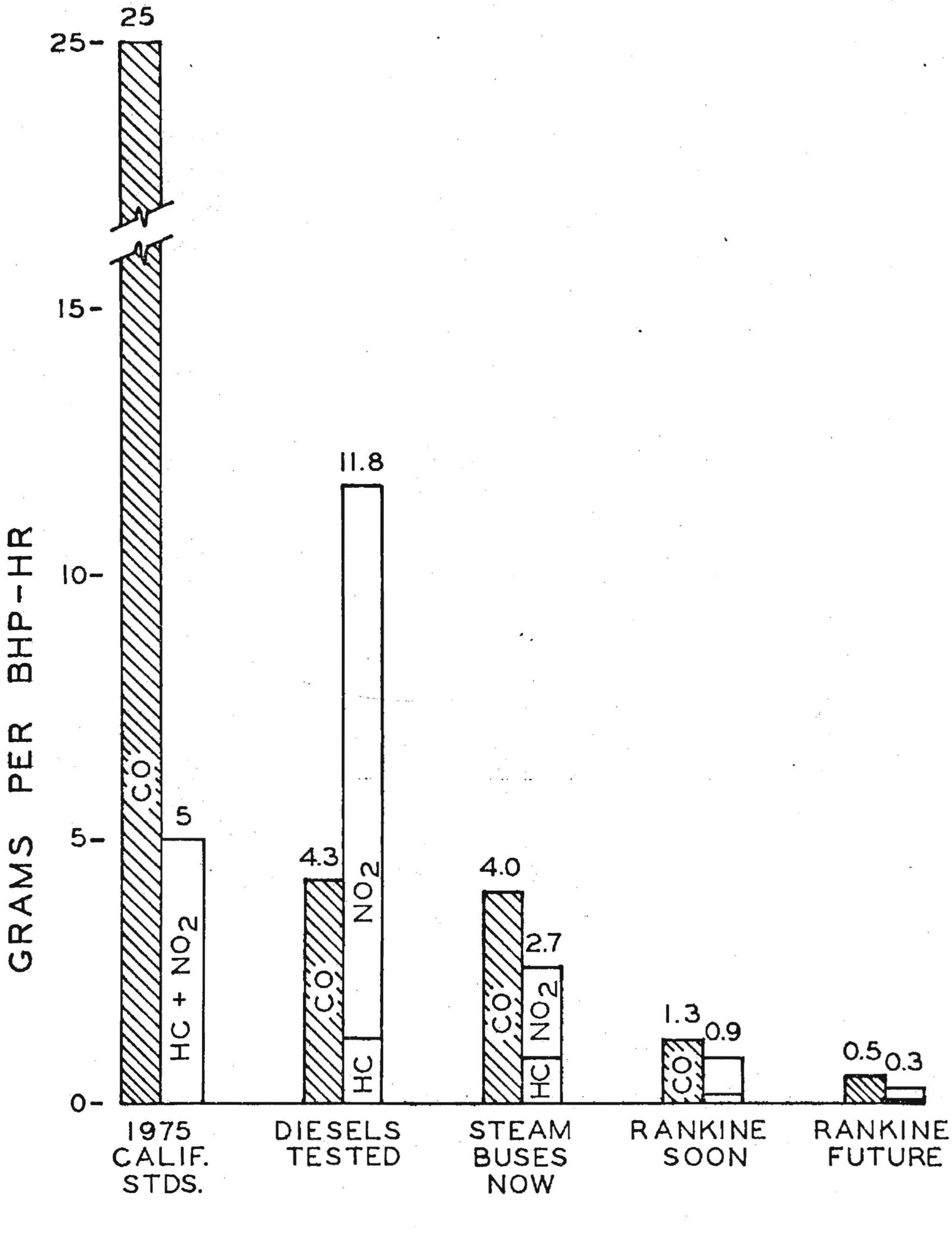

Fig. 24 - Exhaust emissions compared, together with projections into the future

Figure 25 shows that progress is already being made in the increase of specific output of Rankine power systems. Such trends, coupled with size reductions possible with future increases in thermal efficiency, are indeed encouraging to these concerned with packaging.

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.

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 non-standard materials or fabrication techniques required. (35) Steam systems are likely to cost somewhat more per pound than diesels, but may be lighter in weight.

The initial cost of a Rankine cycle (RCE) system may be estimated by the formula,

$$C_R = C_D \, (1-f+Rf) \, \frac{W_R}{W_D} \qquad (5)$$

Where: C_R = the purchase price of an RCE system.

C_D = the purchase price of a diesel system.

f = that fraction of the power system weight representing non-standard materials or fabrication techniques.

R - the ratio of non-standard to basic costs applying to the fraction (f).

W_R= the weight of the RCE.

W_D= the weight of the diesel system.

for the sake of illustration, assume f=0.3 and R=2.5 times the cost of "iron engine " technology. If W_R is 80% of the weight of a diesel system (W_D), and if a diesel system at a wholesale cost of $2.00 per lb and weighing 3,800 lb costs $7,600, the cost of a Rankine cycle

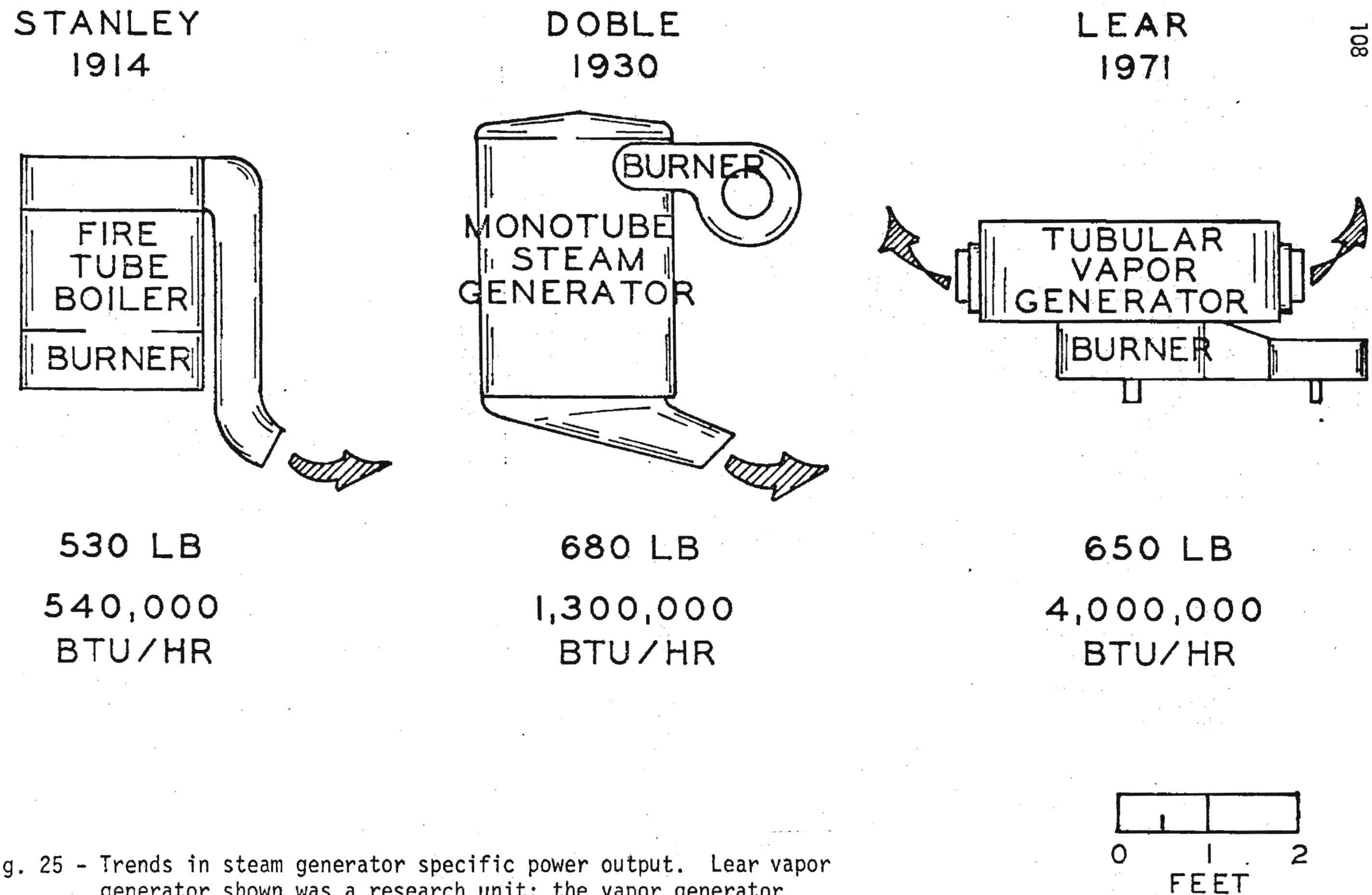

Fig. 25 - Trends in steam generator specific power output. Lear vapor generator shown was a research unit; the vapor generator installed in the bus was similar in size but heavier in construction.

system would be approximately $8,800. This assumes, of course, equal production quantities -- which would be unlikely at the outset. The weight of the RCE can be reduced, through technical evolution, to less than 65% of W_D. However, this would probably be offset to some extent by the use of a higher fraction of costly materials. Some overall cost reduction may still result, however.

What about the amortization of development and tooling costs? If, (as an initial estimate) these costs were $25 million <u>more</u> than diesel for the first 25,000 units produced, such costs would be $1,000 per unit. Thus, the RCE would be around $9,800 vs. $7,600 for present diesels -- around 30% higher than diesel.

But the above comparison is still not on a fair basis, because diesels themselves will no doubt become considerably more expensive if emissions from them are to be substantially reduced.

Unit costs are, of course, sensitive to the production quantities involved. Clearly, since 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 will be needed for the costs to be reasonable.

Eventual maintenance costs also remain a matter of speculation. When the whole vehicle is considered, as it should be, possible effects might include reduced costs to service brakes and transmissions when steam engines are used. However, attention would have to be devoted to elements that weren't there before, such as vapor generators and associated controls. Piston expander maintenance would be similar to present diesel engine blocks, but it would be much less if turbines were used.

Maintenance costs for a diesel, by comparison, may rise sharply if pollution control devices are added, particularly if sophisticated chemical treatment is needed to reduce oxides of nitrogen.

From previous discussion, it appeared that fuel costs for the ECE in stop-and-go service could become almost as low as for present diesels. This again would require considerable evolutionary improvement from the present state of the steam engine art. As in other cost elements, fuel costs for diesel engines may rise if emission improvements were enforced.

In summing up, it is not obvious that any cost advantage would result from the use of the ECE when compared with present diesel equipment. However, the benefits possible with the ECE in terms of cleanliness and quietness will almost certainly exceed those available with future diesels. In addition, diesels are likely to become more complex, costly, and bulky in the attempt to meet tighter standards. This points up the importance, in the future, of carefully quantifying the cost benefit ratios for alternate systems. The cheapest engine may no longer be the least costly to society.

SUMMARY AND CONCLUSIONS

Purpose

The purpose of the California Steam Bus Project was to demonstrate and evaluate the feasibility of external combustion engines (ECE) as a low-emission and quiet source of power for vehicles. City buses were chosen as host vehicles because of their availability from publically-owned fleets, and because the ECE appeared to have characteristics well suited to heavy-duty, stop-and-go vehicles. The findings, however, were envisioned to have implications for other types of urban vehicles, as well.

Sponsorship

This project was sponsored by the California State Assembly and partly financed through a $2,294,525 grant of funds by the Urban Mass Transportation Administration of the U.S. Department of Transportation. At the conclusion of the project, it was found that the local contribution to the project was in excess of $5.6 million. This local contribution was in the form of services, equipment, and research/development provided by the State, the participating transit districts, and by the contractors who developed the power systems. The contributions to the project by the engineering contractors alone exceeded $5.3 million. Thus, the total cost of the project was almost eight million dollars.

Project Beginnings

Even before any technical work was begun, studies revealed that the magnitude of the task was much larger than initially visualized. ECE power systems were not simply available "off-the-shelf" for the conversion of buses. Much engineering development would have to be included in the scope of work before any vehicle tests and demonstrations could take place. Thus, approximately two years elapsed (1968-1970) between the time the State of California first began to formulate plans, and the time work began on actual system development.

During June, 1970, three engineering contractors began the task of designing and developing the power systems. Each contractor was paired with a California fleet operator:

1. William M. Brobeck and Associates with the Alameda-Contra Costa Transit District (Oakland).
2. Lear Motors Corporation with the San Francisco Municipal Railway.
3. Steam Power Systems, Inc. with the Southern California Rapid Transit District of Los Angeles.

Many technical compromises had to be accepted in order to complete the work within a reasonable length of time. These limited objectives precluded optimization or a high degree of design sophistication.

Powerplant Designs

The three contractors were encouraged to develop their own individual design approaches. The Brobeck and SPS powerplants used compound-expansion engines, the former with three double-acting cylinders and the latter with six. The Lear System differed greatly from the others in the use of a turbine as the expander -- apparently the first motor vehicle in history to do so successfully. All three ECE systems operated by the Rankine cycle, and all used water (steam) as the working fluid. Steam was generated in forced-circulation, once-through tubular steam generators, which are both safe to use and quick steaming. Fan-cooled condensers were used to recover the water for re-use, although none of the powerplants were sealed systems and some make-up water had to be added on a daily basis.

Even though most historical steam vehicles had reversible, self-starting engines geared directly to the rear axle, these three steam buses used commercially-available automatic transmissions. This was done to simplify the expander design.

The Outcome

Within a remarkably short period of time, and for relatively modest funding by the government, all three buses were completed and the results evaluated. The first installation (Brobeck) was finished in September, 1971--15 1/2 months after contract work was started. The Lear bus was operating in January, 1972 and the SPS bus in March, 1972. All three steam buses were demonstrated to the Legislature in Sacramento on April 26, 1972. By the time the project was ended September 30, 1972, all three buses had been extensively tested and had participated in actual revenue service. The three demonstration vehicles accumulated a total of 8,372 road miles, including about 800 miles while carrying passengers in revenue service.

Technical Findings

Performance - Steam bus acceleration, top speed, and hill climbing were shown to be approximately the same as for buses powered by six-cylinder diesel engines.

Exhaust Emissions - In tests by the California Air Resources Board, all steam buses were found to be well below the 1975 California emission standards for heavy duty vehicles. While diesel-powered buses tested met the standards for carbon monoxide (CO), none of the diesels met the standards for combined hydrocarbons (HC) and nitrogen oxides (NO_x). When the cleanest steam bus was compared to a composite of the cleanest diesel bus, the steam bus produced 30.5% less CO and 86% less HC plus NO_x. The cleanest steam bus registered a 94% 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, at a distance of 50 feet. The reductions were 6 to 14 decibels in curb-side tests. On the other hand, interior sound levels were similar and sometimes higher than diesels. (Decibel readings are comparative measures of sound levels using a logarithmic scale. A reduction of three decibels corresponds to a 50% reduction of sound levels.)

Fuel Consumption - In the present state of limited development, steam bus fuel consumption was very high when compared to diesel power. The steam buses generally consumed more than three times as much fuel as the diesel buses in similar service. The discrepancy would not seem as large, however, if the comparison were to be made with other fledgling power systems such as the gas turbine and the natural gas fueled ICE (36,37).

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

Safety - The use of an inert working fluid (water), non-explosive steam generators, and fuels of relatively low volatility (No. 1 diesel) contributed to the accident-free record and inherent safety of these vehicles.

Revenue Service - The steam buses were usually able to duplicate time schedules of diesel buses in actual revenue passenger service. One bus incorporated air conditioning. Riders interviewed on the steam buses indicated a high degree of user acceptance of these experimental vehicles.

Powerplant Size and Weight - The powerplants required approximately 25% more space than that available for diesel installations. One of the steam systems was several hundred pounds lighter than a diesel system, however. The other two steam systems were heavier.

Maintenance Problems - As with any experimental devices, a great deal of inspection, rework, and maintenance was necessary in the field demonstrations. These systems were not pre-production prototypes, and much engineering development would be required before such power systems could meet transit industry standards for layout, reliability, and operating economy.

Conclusions

Although not all installations showed every potential attribute of the ECE, a composite picture demonstrated that steam buses can equal the road performance of diesel buses, and with greatly reduced exhaust emissions. The largest reductions, significantly, were in the oxides of nitrogen - the most difficult to control in the ICE. One bus was considerably quieter than diesels. Another system was lighter in weight than diesels. While all three powerplants required more space than diesels do, one bus demonstrated that passenger space need not be diminished if the several components are located separately.

The two greatest problems with the present steam buses were high fuel consumption and high frequency of repair. Both can be improved considerably in even short-term subsequent development (two years of intensive work) and can be nearly competitive with diesel fuel economy in stop-and-go urban service with longer-term development. While the fuel consumption can be reduced to within 10% of that of the diesel in stop-and-go service, it is unlikely that the ECE could approach the economy of the diesel in long-haul, over-the-road services. (It is unlikely that any other alternate powerplant will either, for that matter.)

It was far too early, in this program, to evaluate the potential reliability and possible maintenance costs. There is no reason to believe, if properly designed and highly developed, that these factors would be greatly different for Rankine cycle systems vs. diesel systems.

While exhaust emissions demonstrated in this program were acceptably low, they were not optimized. Further reductions can be obtained by two actions: first, by reducing the amount of pollutants generated per pound of fuel burned through even cleaner combustion; and second, by reducing in turn, the amount of fuel burned per horsepower hour of work produced. Much improvement is possible along both avenues. An average of emissions from the present steam buses was 4.0 grams/hp-hr of CO and 2.7 g/hp-hr of combined HC and NO_x. With further improvements, values only one-eight these levels should be attainable.

The ECE is likely to have a higher purchase price than present diesel systems (perhaps 30% higher). This is largely because development and tooling costs must be amortized over production quantities that will represent (at least initially) but a fraction of the heavy-duty engine market. Other costs such as for maintenance and fuel may be similar to those for diesel operation when the ECE reaches a high state of technical evolution.

However, such comparisons may shift in favor of the ECE with the passing of time. All diesel costs -- purchase price, maintenance, and fuel -- can be expected to rise as these engines become modified to meet increasingly tighter emmision standards.

In any event, it is most important that projected costs be compared in relation to the value of benefits derived -- including the value of cleaner air and a quieter environment.

RECOMMENDATIONS

Approximately four years of intensive study, development, and evaluation of steam power for motor vehicles were involved in this program. Actual development work was compressed into two years, a time insufficient to address all of the technical problems. Much insight was gained into the nature of those problems, however, leading to the following recommendations:

1. The Federal government should continue the support of Rankine cycle engine (RCE) development for heavy duty vehicles and other applications in the 200-400 hp class. Whether or not the RCE eventually becomes the "engine of the future," visible and substantial support will stimulate competing solutions toward true low-emission power systems. The hardware results can also serve to reinforce tight standards of the future in both emissions and noise.
2. It should be recognized, however, that the task of developing viable alternatives to the ICE can be protracted, difficult, and expensive. This is precisely why the private sector in engine manufacturing needs stimulation and assistance in such an undertaking. Progressive engineering and persistent efforts will be required. It is recommended that no less than $20 million be committed to RCE development over the next four years.
3. The first two years of development should stress design engineering and extensive bench testing of improved interim power systems. Vehicle demonstrations, so valuable in launching the earlier work, should be set aside for the time being. At the end of the two-year period, however, a limited number of improved systems should be made available for testing in vehicles.
4. The second period of two years should be devoted to engineering

refinement toward pre-production prototypes. Testing in vehicles would be secondary but concurrent with intensive laboratory testing, redesign, and development. At the end of this second period, a limited number of pre-production prototypes could be made available for futher testing in vehicles.

5. During the above two phases, a frontal attack should be made on those technical problems identified by the California Steam Bus Project and other programs. Reductions in fuel consumption, development of high-efficiency transmissions (or direct-drive), and improvement of reliability are of the highest priority. Size, weight, emissions, and noise can be greatly reduced. Packaging for vehicles can be much improved.
6. Exploration should continue with both turbine and reciprocating expanders, because it is not yet clear which is superior for heavy duty, stop-and-go vehicles.
7. Maximum use should be made of the research work on RCE components and systems currently being sponsored by the Environmental Protection Agency. Since the EPA is concentrating on propulsion systems for automobiles, their work is of a complementary rather than competing nature.
8. After the work on pre-production prototypes, a transition should be made from public to private support for further evolution and production tooling. Incentives should then be in the form of government support of the initial markets and in tightly drawn restrictions on emissions and noise for urban applications.
9. Since buses alone constitute a market that may be too small to warrant the development of a specialized RCE, every effort should be made to identify other applications that could benefit from this technology. These would be applications where cleanliness, quietness, high stall torque, and the ability to burn a wide range of fuels are needed.

REFERENCES

1. "The Automobile and Air Pollution -- A Program for Progress, Part II." A study for the U.S. Department of Commerce, Richard S. Morse, Chairman. U.S. Government Printing Office, Washington, D.C. December, 1967.

2. "Automobile Steam Engine and Other External Combustion Engines." Hearings before Senate Committees on Commerce and Public Works, May 27-28, 1968. U.S. Government Printing Office, Washington, D.C., Serial No. 90-82, 1968.

3. "Death of a Steam Bus." *Old Motor*, Vol 5, No. 7, May, 1967, London.

4. "Steam and Transportation." Pamphlet by Detroit Motorbus Co. (Undated, probably mid 1920's).

5. K. Imfeld and R. Roosen,"New Steam Vehicles," *Journal of the Association of German Engineers*, 1934.

6. William B. McGorum, "Steam -- A Postwar Power Possibility." *Bus Transportation*, September, 1944.

7. A.E. Meier, "Steam-Powered Buses." *Motor Coach Age*, Vol. XXIV, No. 1, January, 1972.

8. J.N. Walton, *Doble Steam Cars, Buses, Lorries, and Railcars.* Light Steam Power, Isle of Man, G.B. 1965.

9. S.S. Miner, "Developments in Automotive Steam Powerplants." Society of Automotive Engineers Paper 690043, January, 1969.

10. W. Boyn, "The First Steam Plane" (Besler). *Plane and Pilot*, Vol. 7, No 8, August, 1971.

11. R.L. Harris, R.E. Hulbert, and Marcus Lothrop, "Steam Power Package for Military Vehicles." Report on study for the Department of the Army, Yuba Manufacturing Co., San Francisco, 1953.

12. James L. Dooley and A.F. Bell, "Description of a Modern Automotive Steam Power Plant." Society of Automotive Engineers, Los Angeles Section, Paper S-338, January, 1962.

13. J.J. Brogan and G.M. Thur, "Advanced Automotive Power Systems Development Program." Paper presented to Intersociety Energy Conversion Conference, San Diego, Ca. September, 1972.

14. "Request for Proposal for an External Combustion Engine Power Systems for Demonstration Buses in Alameda and San Francisco Counties." Issued by California State Assembly, Sacramento, CA. May 1, 1969 with Amendments July 14, 1969.

15. F.C. Younger, "Characteristics of the Brobeck Steam Bus Engine." Society of Automotive Engineers Paper 720684, August 1972.

16. R.D. Burtz and R.L. Burton, "The Demonstration of an External Combustion Engine in a City Bus." Society of Automotive Engineers Paper 720682, August, 1972.

17. "California Exhaust Emission Standards, Test and Approval Procedures for Diesel Engines in 1973 and Subsequent Model Year Vehicles Over 6,001 Pounds Gross Vehicle Weight." Adopted November 18, 1970, and Amended February 17, 1971 by the California Air Resources Board.

18. R.C. Bascom and G.C. Hass, "A Status Report on the Development of the 1973 California Diesel Emission Standards." Society of Automotive Engineers Paper 700671, August 1970.

19. *SAE Handbook*. Published by Society of Automotive Engineers, Inc., New York, New York. 1972.

20. K.M. Klein and J.A. Head, "The Effect of Surface Type, Alignment, and Traffic Congestion on Vehicular Fuel Consumption." Oregon State Highway Department Bulletin No. 17, April, 1944.

21. R.A. White and H.H. Korst, "The Determination of Vehicle Drag Contributions from Coast-Down Tests." Society of Automotive Engineers Paper 720099, January 1972.

22. "Control of Air Pollution from New Motor Vehicles and New Motor Vehicle Engines." (Federal Driving Cycle.) U.S. Department of Health, Education, and Welfare, *Federal Register*, Vol. 35, No. 219, November 10, 1970, pp. 17288-17313.

23. F.B. Smith, Jr., W.A.P. Meyer, and R.U. Ayers, "A Statistical Approach to Describing Vehicular Driving Cycles." Society of Automotive Engineers Paper 690212, January 1969.

24. R.A. Renner and R.D. Lawhorn, "Characteristics of Urban Bus Driving Cycles." Society of Automotive Engineers Paper 720239, January 1972.

25. "Steambus!" Documentary motion picture of California Steam Bus Project, produced by Bay Area Educational Television Association, San Francisco, CA., 1972.

26. "Steam Bus Symposium Proceedings." Symposium sponsored by Urban Mass Transportation Administration, U.S. Department of Transportation, Washington, D.C., November 17, 1971.

27. J. A. Lane, "California Steam Bus Project, Final Report." Prepared with assistance of K. Napuk and R. A. Renner. Assembly Office of Research, California Legislature, Sacramento, California, January 1973.

28. "California Steam Bus Project, Final Report--Surveys," Volumes I and II, Scientific Analysis Corporation, San Francisco, California, January 1973.

29. K. Napuk, "California Steam Bus Project: Final Report of the Project Manager, Scientific Analysis Corporation, to the Project Director, Office of Research, California State Assembly." September, 1972.

30. "Distribution of Expenses 1972/73 Fiscal Year." *Transit Times*, published by A-C Transit District, Oakland, California, Vol. 15, No. 3, September, 1972.

31. *Scientific American*, Vol. 224 No. 3, Sept. 1971: Assemblage of 11 articles on the sources, conversion, utilization, and conservation of energy in present and future societies.

32. W.A. Turunen and J.S. Collman, "The General Motors Research GT-309 Gas Turbine Engine." Society of Automotive Engineers Paper 650714, 1965.

33. G. Engel and W.S. Anderson, "Compactness of Ground Turbine Depends on Integral Recuperator," *Society of Automotive Engineers Journal*, Vol. 79 No. 8, August, 1971.

34. R.J. Dorgan, J.M. Nolan, and R.L. Rio, "Transmission Considerations for Gas Turbines." Society of Automotive Engineers Paper 720169, January, 1972.

35. R.U. Ayers and R.A. Renner, "Automotive Emissions Control: Alternatives to the Internal Combustion Engine." Paper presented to the Air Pollution Control Association, West Coast Section, San Francisco, CA. Oct. 8-9, 1970.

36. N.B. Chew, "Gas Turbine Powered Trucks on the Job." Society of Automotive Engineers Paper 710269, May 1970.

37. P.C. Malte and G.A. Wooldridge, "Low Pollution Characteristics of Urban Transit Buses Fueled with Liquified Natural Gas." Society of Automotive Engineers Paper 720685, August, 1972.