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BOOZ, ALLEN & HAMILTON INC.
TRANSPORTATION CONSULTING DIVISION

JUNE 1983

PREPARED FOR
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
LEWIS RESEARCH CENTER
UNDER CONTRACT DEN3 – 142

FOR
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16. Abstract

The Gas Turbine Transit Bus Demonstration Program was designed to demonstrate and evaluate the operation of gas turbine engines in transit coaches in revenue service compared with diesel-powered coaches. The main objective of the program was to accelerate development and commercialization of automotive gas turbines. The benefits from the installation of this engine in a transit coach were expected to be reduced weight, cleaner exhaust emissions, lower noise levels, reduced engine vibration and maintenance requirements, improved reliability and vehicle performance, greater engine braking capability, and superior cold weather starting. Originally planned as a three phase, eight year program applying improving gas turbine propulsion technology, the program was terminated at the conclusion of Phase I.

Four RTS-II advanced design transit coaches, borrowed from the Mass Transit Administration of Maryland, were converted to gas turbine power using engines and transmissions supplied by the Detroit Diesel Allison Division of General Motors. Development, acceptance, performance and systems tests were performed on the coaches prior to the revenue service demonstration in Baltimore, Maryland.

The program was terminated by a resource allocation decision made by the program sponsors, the United States Departments of Energy and Transportation. However, this report was prepared to facilitate the transfer of technological information to groups and individuals interested in gas turbine engine applications to transit coaches.

17. Key Words demonstration, diesel-powered, gas turbine engines, test, transit coaches

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EXECUTIVE SUMMARY

The Gas Turbine Transit Bus Program was originally planned as a three phase, eight year program applying continuously improving gas turbine propulsion technology to transit coaches. Each phase was to have included the installation of the latest gas turbine technology, followed by proving grounds testing, and then public demonstrations in revenue service. During Phase I of the program a number of changes were made to accelerate the introduction of ceramic components and technologies originally planned for later phases. Consequently, Phase I coach conversion and testing periods were extended. Proving grounds testing at the Transportation Research Center (TRC) of Ohio indicated that vehicle performance, fuel consumption and noise objectives had been met, but engine braking/brake life, vehicle weight and vibration objectives had not been met. Since the program was terminated after only a brief period (three months) of revenue service demonstrations in Baltimore, Maryland, data are insufficient to fully assess program objectives in the areas of reduced maintenance requirements, improved reliability, and superior cold weather starting. Proving grounds testing indicated some reliability problems with ceramic components, which had been retrofitted into the Phase I engines (prototype Detroit Diesel Allison GT4-404). The manufacturer reported substantial reductions were observed in controlled turbine engine emissions compared to diesel engines in its proprietary emissions testing program.

The program was not in the opinion of Booz, Allen & Hamilton a technical failure, indeed excellent turbine engine coach development information was obtained and is documented in this report. Termination of the program was a resouce allocation decision made by the program sponsors, the United States Departments of Energy and Transportation. This report was prepared to facilitate the transfer of technological information to groups and individuals interested in gas turbine engine applications to transit coaches.

I. INTRODUCTION AND OVERVIEW

I. INTRODUCTION AND OVERVIEW

This chapter provides an overview of the Gas Turbine Transit Bus Demonstration Program. This chapter is organized into the following sections:

- Program Background
- The Planned Program
- The Actual Program.

PROGRAM BACKGROUND

For over a decade the Federal Government has been actively engaged in efforts to develop and accelerate improvements in transportation vehicle propulsion systems. The main thrust of these efforts has been directed toward reducing exhaust emission pollutants and reducing energy consumption. In addition to continuing activities focused on near-term efficiency improvements in presently available propulsion systems, a major pursuit has been the development of advanced propulsion systems for intermediate and long-term improvements.

One of the most promising advanced propulsion systems is the gas turbine engine. The gas turbine not only offers potential for reductions in noxious emissions and fuel consumption, but also provides operators with potential improvements in vehicle performance and maintenance costs.

Development of the gas turbine engine as a potential power source for automotive vehicles began in the early 1950s. In 1976, when this program was being planned, only three manufacturers in the United States were actively engaged in the development of gas turbines in the range of 150 HP to 650 HP, a range that could realistically be considered for application to automobiles, trucks and transit coaches. Of these advanced propulsion systems only the GT-404 engine shown in Figure I-1, manufactured by Detroit Diesel Allison (DDA) a division of General Motors Corporation, was planned for early commercialization.

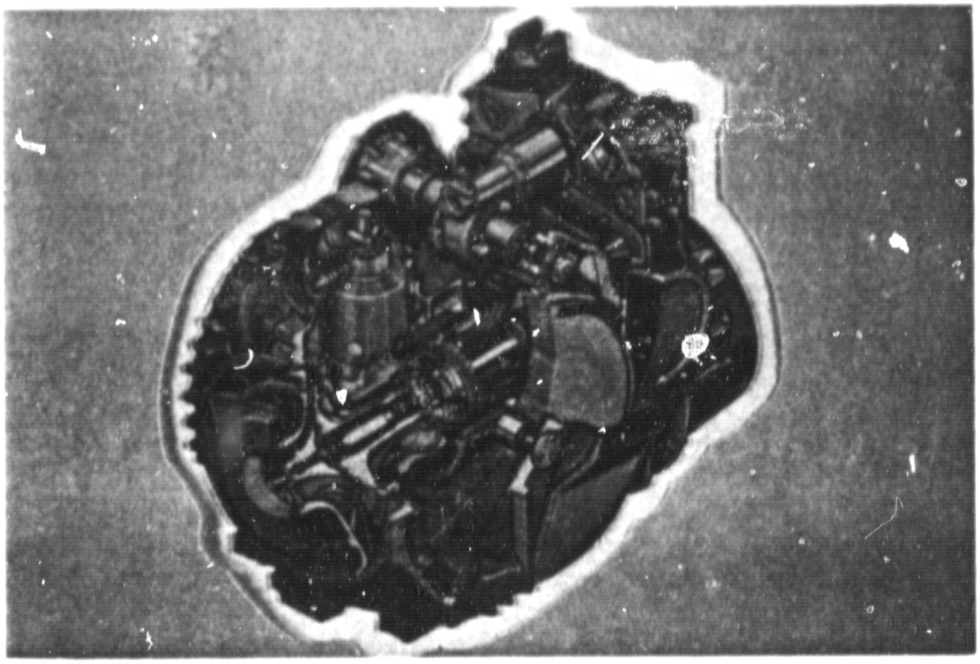

FIGURE I-1
DDA GT-404 Gas Turbine Engine

By 1976 nearly 100 DDA gas turbines had been field-tested in trucks, transit coaches, intercity coaches, marine craft, and industrial/electrical generator sets and air compressors. Between 1972 and 1976 test engines operated in 24 trucks of ten different makes in widely divergent service and eight gas turbine engines operated in Greyhound intercity coaches throughout the country. In the most recent of these applications, the turbine engine demonstrated greatly improved reliability and fuel consumption rates compared with earlier turbines. In fact, the fuel consumption in the intercity coaches was nearly competitive with that of the diesel engine.

In the early 1970s, under the Urban Mass Transportation Administration (UMTA) Transbus program, three DDA gas turbine engines were installed in the Transbus prototype coaches, shown in Figure I-2, manufactured by the Truck and Coach Divison of General Motors. This engine was selected for testing in Transbus because of the gas turbine's apparent advantages and demonstrated potential in heavy trucks. During this program the turbine engine demonstrated its potential as a viable transit coach

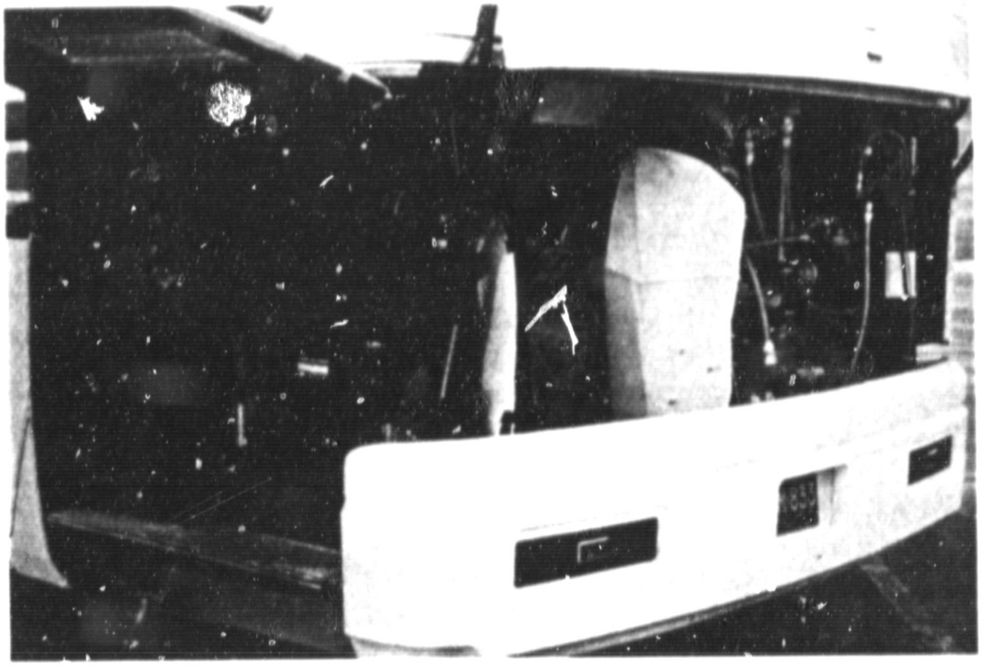

FIGURE I-2
Gas Turbine Engine Installed in
Transbus Prototype Coach

power plant by exhibiting advantages over the conventional diesel engine in transit coach applications. However, fuel consumption demonstrated in the program was higher than contemporary diesel engines.

THE PLANNED PROGRAM

Although the gas turbine was long recognized as a promising candidate propulsion system, there was a lack of actual operating experience with gas turbines in the transit industry that would lead to a demand for commercialization of the automotive gas turbine. Thus the Gas Turbine Transit Bus Demonstration Program was planned to provide this missing experience.

The design of the demonstration program included three phases as shown in Figure I-3. Phase I called for a demonstration of prototype all-metal gas turbine engines in Advanced Design Bus (ADB) transit coaches. Phase II called for the demonstration of pre-production engines with ceramic components in Transbus coaches in two cities. Phase III called for the demonstration of full production gas turbine engines in Transbus coaches in two other cities. All of this work was planned to be conducted over a period of eight years.

PHASE I - PROTOTYPE ENGINES

Subcontractors

Detroit Diesel Allison
Coach Manufacturers
Proving Grounds
Demonstration City Operating Property #1

Vehicle Summary

Proving Grounds:	1 Diesel Advanced Design Bus
	1 Turbine Advanced Design Bus
Demonstration City #1:	5 Turbine Advanced Design Buses

PHASE II - PRE-PRODUCTION ENGINES

Subcontractors

Detroit Diesel Allison
Coach Manufacturers
Proving Grounds
Demonstration City Operating Properties #2 and #3

Vehicle Summary

Proving Grounds:	1 Diesel Transbus
	1 Turbine Transbus
Demonstration Cities #2 and #3:	5 Turbine Transbuses each

PHASE III - PRODUCTION ENGINES

Subcontractors

Detroit Diesel Allison
Coach Manufacturers
Proving Grounds
Demonstration City Operating Properties #4 and #5

Vehicle Summary

Proving Grounds:	1 Turbine Transbus
Demonstration Cities #4 and #5:	5 Turbine Transbuses each

FIGURE I-3
Planned Program Phases

In Phase I, which began in April of 1978, a fleet of five gas turbine-powered coaches was to be operated in revenue service while one other gas turbine-powered coach was durability tested at a proving grounds along with a diesel-powered coach to provide a comparative data base for performance and durability.

The six gas turbine engines and modified V-730 transmissions were to be procured directly from DDA by the U.S. Department of Energy, one of the program sponsors, because their long lead times required immediate procurement to meet the planned schedule for Phase I.

The in-city demonstration coaches were to be borrowed from the demonstration site and returned to their fleet after the program. The proving grounds turbine coach was to be borrowed either from the coach manufacturer who performed the coach/engine integrations or from the demonstration city. The diesel baseline was to be procured from the coach manufacturer under an exclusive contract for the proving grounds tests.

The coach/engine integrations were to be performed by the manufacturer of the coach models that were selected by the sponsor for demonstration.

The demonstration site selection was to be made by the sponsor based on information gathered by Booz, Allen from interested transit properties and measured against a set of selection criteria. The selection was to be made on the basis of capability, environment and cost.

Proving grounds tests were planned for a gas turbine and a diesel coach. The objectives were to identify installation errors, to determine improvements to be incorporated in Phases II and III, and to determine availability, maintainability and operating cost comparisons. To accomplish this both coaches were to be tested for a year--25,000 miles in durability testing with the gas turbine undergoing additional performance, noise and emissions testing.

THE ACTUAL PROGRAM

Circumstances changed the program significantly. First, the extremely high cost ($250,000 each) of the GT-404 prototype engines and transmissions made it necessary to cut some program costs. It was decided that since these were hand-built engines (no off-the-shelf spares), all six engines would be purchased but only five installed. The sixth engine would be used as a spare. Later in another effort to cut costs, the sponsors decided to install only four engines.

Five coaches were borrowed from the demonstration property, the Mass Transit Adminstration (MTA) of Baltimore, Maryland, which saved the program the cost of the diesel baseline coach. The coaches were all 1979 RTS-II models manufactured by the Truck and Coach Division of General Motors Corporation and were taken from a fleet of 60 RTS-IIs delivered new to the MTA in January 1979. Four of the transit coaches were retrofitted with the gas turbine engine, acceptance tested, and then placed in revenue service along with other diesel-powered coaches from the same RTS order. Thus, the coaches with the gas turbine engines represented the same design (expect for installation changes), service history, and mileage as the diesel powered coaches. At the begining of the demonstration, the RTS-II, an advanced design coach introduced to the transit market in 1977, had little transit experience. Since that time, adjustments and improvements in the coach have been introduced which have improved the coach's performance.

Neither one of the two ADB coach manufacturers were interested in performing the coach/engine integrations. Therefore, an invitation for bid had to be prepared, issued to independent coach fabrication shops, and responses evaluated prior to a selection. Although the shop selected was not as familiar with the new RTS design as the manufacturer and some of the wiring and plumbing schematics had not been updated by the manufacturer, the shop engineered all of the changes using a dummy engine provided by DDA and a coach provided by MTA.

Since the sponsors were thinking about adding a six-month demonstration of alcohol fuel at the end of the Phase I demonstration, a decision was made to install two 125-gallon nylon fuel tanks during the coach/engine integration to save time and cost later in the program. This new tank capacity would also ensure that the coaches had sufficient diesel fuel to meet any schedule they were asked to run.

Coach heat usually supplied by the diesel engine cooling water was not available with the gas turbine engine. Therefore, an oil-fired water heater was installed in the coaches using the existing coach heat exchanger, circulating pump and surge tank. The heater used an additional 20-gallon fuel tank placed next to one of two standard size (125-gallon) nylon engine fuel tanks. It made use of the same filler access door and burned #1 diesel fuel. This heating system was an expedient design adaptation and was not expected to be the long-term design appraoch. A light weight integral heating system using waste exhaust gas heat was to be designed in Phase II.

The proving grounds testing was shortened to six months with one of the four demonstration coaches acting as th previously dedicated turbine test coach. Most of this time was spent correcting installation problems, repairing, engine deficiencies and assisting DDA in improving the engine/transmission coach interface.

The gas turbine demonstration experienced unexpected engine problems because of the ceramic components incorporated into the Phase I engines. These problems directly impacted the schedule, and necessitated unbudgeted mechanic labor. The repairs also required additional engineering and spares support by DDA.

The ceramic components required more development work, which was outside the scope of the program. Because of the unacceptable disruptions and additional costs they caused, and a change in Federal policy to withdraw from automotive hardware development, the decision was made to terminate the program at the end of the third month of public demonstration.

The next four chapters discuss program results and the detail of the three principal activities:

- Conversion of the coaches from diesel to gas turbine power

- Testing of the converted coaches

- Demonstration of the coaches in transit revenue service.

The final chapter, Program Participants, discusses the roles an responsibilities of the demonstration program participants.

II. RESULTS AND CONCLUSIONS

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The Gas Turbine Transit Bus Demonstration Program was designed to demonstrate and evaluate the operation of gas turbine engines in transit coaches in revenue service compared with diesel-powered coaches. The main objective of the program was to accelerate development and commercialization of automotive gas turbines. The benefits from the installation of this engine in a transit coach were expected to be:

- Reduced weight
- Cleaner exhaust emissions
- Lower noise levels
- Reduced engine vibration
- Reduced maintenance requirements
- Improved reliability
- Improved vehicle performance
- Greater engine braking capability
- Superior cold weather starting
- Fuel consumption penalty less than fifty percent.

The results of the demonstration program in the achievement of these expected benefits are summarized in Table II-1 and discussed and shown in detail in the following paragraphs and Table II-2.

Since, the program was terminated after only three months of revenue service demonstration, the data, therefore, are insufficient in some cases to make conclusive statements regarding achievement of the expected benefits.

WEIGHT

The gas turbine-powered coach did not achieve the expected weight savings of approximately 1,000 pounds. In fact, it was only 50 pounds lighter than the diesel-powered coach. To factors account for this result.

TABLE II-1
Summary of Expected Benefits

Objective		Met Objective
1.	Reduced weight	No, but has potential
2.	Cleaner exhaust emissions	Yes (manufacturer's detailed test results proprietary)
3.	Lower noise levels compared to diesel	Yes
4.	Reduced transmissed engine vibration compared to diesel	No measurable difference
5.	Reduced maintenance requirements	Insufficient data
6.	Improved reliability	No, ceramic components need further development
7.	Improved vehicle performance	Yes
8.	Greater engine braking capability	No
9.	Superior cold weather starting	No
10.	Fuel consumption penalty less than fifty percent	Yes

TABLE II-2
Expected Benefits Versus Actual Test Results

EXPECTED BENEFITS (Program Plan Page No.)	ACTUAL TEST RESULTS	CONCLUSIONS DRAWN
Reduced Installed Weight - Savings 1,000 pounds (p. 15)	Bus Curb Weights: Diesel 27,230 lbs; Gas Turbine 27,180 lbs; ADB Spec. 26,000	Without extra fuel tank and auxiliary heater system, gas turbine coach would have weighed 26,200.
Cleaner Exhaust emissions (p. 15, para. 3)	Emission figures for the gas turbine are proprietary, but manufacturer tests show that is cleaner than the diesel by an order of magnitude	Gas turbine has cleaner exhaust emissions -- virtually no odor or smoke.
Lower Noise Levels (P. 16, para. 2)	Exterior: Diesel / Gas Turbine / ADB SPEC Curb idle: 68dB(A) / 67dB(A) / 65dB(A) Pull away: 80dB(A) / 78dB(A) / 80dB(A) Pass-By: 81dB(A) / 81dB(A) / 83dB(A) Interior: Rear Seats: 81dB(A) / 80dB(A) / 83dB(A) Driver Seats: 73dB(A) / 70dB(A) / 75dB(A)	Gas turbine has lower noise levels except at Pass-by where it was the same.
Reduced or low-vibration Operation (p. 16, para. 6)	No measureable difference in vibration level at firewall	Motor mounts successfully in eliminating transfer of engine induced vibrations to body.
Eliminated cooling radiator, fan and plumbing (p. 16, para. 5, 6)	No radiator, fan or plumbing	Reduced maintenance.
Reduced lubricating oil consumption (p. 16, para. 1)	Diesel 236 qts.; Gas Turbine 0; ADP Spec ----	Reduced maintenance, labor and material.

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TABLE II-2

Continued

EXPECTED BENEFITS	ACTUAL TEST RESULTS	CONCLUSIONS DRAWN
Good Reliability (p. 14, para 5, 6)	5 Turbine engine failures 26,471 mi/5 or 5,294/failure 1 Diesel engine failure 38, 835 mi./2 or 19,417 mi./failure	Experimental ceramic components, responsible for 4 of the 5 engine failures, were not ready for an in-service demonstration.
Improved Vehicle Performance for Power Rating (p. 15, para. 2)	Top Speed: Diesel 68mph; Gas Turbine 60mph; ADB SPEC 60mph Acceleration To 10mph: Diesel 6.0 sec; Gas Turbine 5.5 sec; ADB SPEC 4.5 sec To 30mph: Diesel 18 sec.; Gas Turbine 15 sec.; ADB SPEC 19 sec. Speed on Slope 2 % Grade: Diesel 50mph; Gas Turbine 52mph; ADB SPEC 45mph 16% Grade: Diesel 12mph; Gas Turbine 20mph; ADB SPEC 7mph	The turb..e engines offer improved acceleration and hill climbing performance.
	Accessories Diesel: Passed; Gas Turbine: Passed at high idle; ADB SPEC: Adequate at extended idle operation	The gas turbine requires testing to determine optimum gear ratios for driving accessories.
Greater Engine Braking Capability (p. 15, para. 2)	Brake Life Extropolated: Diesel 21,095 mi.; Gas Turbine 9,767 mi.; ADB Spec. 15,000 mi.	No engine braking from gas turbine on low speed transit duty cycle because stop is completed in less than 6 seconds.
Equal to rated power at max. output shaft speed/effective in each trans. gear range	Manufacturer tests show that the turbine engine continues to produce power for 6 seconds after throttle closing.	
Superior Cold Weather Starting (p. 16, para. 4)	Diesel: Ether assist at 2 F Gas Turbine: Starter jumped at 4 F ambient ADB Spec: Start at 0 to 10 F with aids; Start at +30 F without aids Both passed ADB Spec.	The gas turbines cold weather starting was equivalent to the diesel's. It did not demonstrate improved cold starting ability.
	Fuel Consumption ADB cycle: Diesel 3.99 mpg; Gas Turbine 2.03 mpg; Diff. 48% Balt. Revenue Service: Diesel 3.30 mpg; Gas Turbine 2.31 mpg; Diff. 30%	The gas turbine as expected consumed 30 to 40% more fuel than the diesel engine.

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The turbine coach, in this first phase of what was planned to be a three-phase program with heater development in Phase II, had to be equipped with a temporary auxiliary heater system arrangement to heat the passenger compartment during the revenue service demonstration. This system, incuding fuel, weighted 280 pounds. Another 700 pounds was added by the weight of the fuel in an extra engine fuel tank that had been coupled with the regular tank during engine installation in an attempt to save installation costs and time at the end of Phase I when a short alternate fuels demonstration was planned to occur.

Without the auxiliary heater system and the additional fuel tank, we believe the coach could have net or even exceeded the 1,000 pound weight savings.

EXHAUST EMISSIONS

The gas turbine engine appeared to meet all present and proposed Federal and state emission standards to 1984. This conclusion is based on statements from Detroit Diesel Allison that, although the specific test results on the GT404-4 engine are proprietary, the engine was an order of magnitude clearner than the 8V-7IN diesel for all controlled emissions tested in the 13-mode Federal test Procedures for heavy-duty engine emissions. Additionally, the gas turbine engine, unlike the diesel, was virtually smoke and odor free.

NOISE LEVEL

The gas turbine-powered coach exhibited equal or lower noise levels, in tests for both exterior and interior noise although the high pitch whine-type noise typical of turbine engines is perceived as a louder noise. Test results were obtained without any special attention to noise reduction. It is possible, therefore, that noise levels could be significantly reduced with the development of additional treatments for the engine air intake and exhaust and the engine compartment insultation.

ENGINE VIBRATION

There was no measureable difference in engine-induced structural vibration levels between the gas turbine- and diesel-powered coaches. It was expected that since all the components within the gas turbine engine are rotating, generating significantly lower vibration levels than the reciprocating diesel engine, that the number and severity of coach structural failures would be reduced. However, the engine-to-cradle and cradle-to-frame isolation mounts of the RTS coach proved to be effective in eliminating engine-induced vibration into the coach structure with both the diesel and turbine engines.

MAINTENANCE REQUIREMENTS

The gas turbine-powered coaches were not operated for sufficient time or mileage either at the test track or in revenue service to verify any reductions in maintenance requirements because of the lack of a water-based cooling system or the lower oil consumption.

RELIABILITY

The gas turbine engine did not demonstrate the improved engine reliability that had been expected. In fact the turbine engine experienced one engine failure per 5,294 miles of operation compared with one failure per 19,417 miles for the diesel engine.

However, four out of the five turbine engine failures were caused by the failure of ceramic components, which were originally not scheduled to be installed in the Phase I engines. The decision by program sponsors to accelerate the ceramic technology evaluation was implemented by retrofitting ceramic regenerators and seals into the Phase I engines. These components may have been ready for controlled testing in a vehicle at a test track but they were not sufficienctly developed for public demonstration in a revenue service environment.

VEHICLE PERFORMANCE

The gas turbine-powered coach achieved more rapid acceleration and improved gradability compared to the diesel coach. However, because of the throttle delay on acceleration, the gas turbine's time to complete the entire ADB duty cycle was more than the diesel's time.

The gas turbine's rapid acceleration and improved gradability were achieved with only two weeks of development testing at the proving grounds, where the engine idle speed, differential gear ratio and transmission shift points were selected. Further development testing should allow refinement of these parameters and improve the overall performance of the gas turbine on the ADB duty cycle.

ENGINE BRAKING CAPABILITY

The gas turbine-powered coach did not demonstrate increased brake life as a result of increased engine braking. It experienced instead a reduction in brake life--9,800 miles operating on the ADB duty cycle compared to 21,000 miles for the diesel.

Because of the engine's high-temperature, high-volume gas flow, the gas turbine continued to produce power for approximately 6 seconds after throttle closing. The low-speed portion of the ADB duty cycle has stopping times of less than 6 seconds, which means that engine braking was not available before the coach had already stopped.

COLD WEATHER STARTING

The cold weather starting capability of the gas turbine-powered coach was equivalent to the diesel coach when the coach was equipped with batteries in good condition. With increased battery power, the turbine should start in substantially colder ambient temperature than the diesel.

FUEL CONSUMPTION PENALTY LESS THAN FIFTY PERCENT

As expected, the gas turbine engine had a fuel consumption penalty compared to the diesel engine. During the systems testing at the proving grounds running the ADB duty cycle, the turbine consumed 48 percent more fuel than the diesel. In the revenue service demonstration at Baltimore, the turbine's fuel penalty was only 30 percent because of the higher speeds and fewer stops of the Annapolis route compared to the ADB cycle.

Continuing engine development work is necessary, as originally planned in the total program plan, Department of Energy/Department of Transportation Gas Turbine Transit Bus Demonstration Program Plan, April 1978, to improve the gas turbine engine's fuel economy and make it competitive with the diesel engine in transit operation.

III. COACH CONVERSION

III. COACH CONVERSION

This chapter describes the steps in the conversion of four diesel-powered coaches to gas turbine power by Modern Engineering Services Company of Detroit, Michigan. There were three main tasks in this process:

- Design. Although the gas turbine engines and transmissions were designed and provided by the Detroit Diesel Allison Division (DDA) of General Motors, further engineering design and analysis was necessary to provide engine support systems including:

  - Air intake and filtration
  - Exhaust
  - Oil cooling
  - Electrical and control circuits
  - Fuel tanks

  In addition, special designs were required for the turbine coach heating and cooling system and for engine compartment cooling. The repowered coaches were designed to conform to Part II: Technical Specifications of the "Baseline Advanced Design Transit Coach Specification" with addenda, except for items not applicable to gas turbine-powered coaches.

- Development. The first coach to be converted was used as a mock-up of the engine compartment to assist in and verify the engine installation. A empty gas turbine engine block and other mock-ups and fixtures were used to verify adequate engine compartment design. Newly designed systems and components were checked and tested to assure adequate operation of all coach systems affected by the gas turbine engine installation.

- Conversion. Four advanced design transit coaches were converted to turbine power. All required components for the conversion were fabricated or purchased by the conversion subcontractor, Modern Engineering Service Company. Each of the repowered coaches was functionally tested to verify that all systems performed as anticipated.

Major efforts in the gas turbine coach design, development and conversion are discussed below including:

- Engine compartment configuration
- Special design requirements.

ENGINE COMPARTMENT CONFIGURATION

The engine compartment space on the standard RTS-II coach, while adequate for the original DDA 6V-71 and 8V-71 diesel engines, as shown in Figure III-1, proved to be marginal for the gas turbine engine. Although the gas turbine engine is smaller, necessary associated equipment and components required more space. Increased demands on space were caused by:

- The necessity for large turbine exhaust ducting
- Increased need for insulation to isolate engine compartment components from elevated turbine engine temperatures
- The need for a large intake air system with provisions for noise reduction
- The need to locate coolers for the engine and transmission oil, which are not needed with a diesel engine
- The need to locate a heater for the coach interior, since hot water from an engine radiator is not available for heating as it is with a diesel engine.

The turbine engine did not require a water cooling system and the elimination of the radiator used to cool water in a diesel engine saved considerable space. However, the net effect of the conversion modifications was a need for greater space for system components than in the diesel engine configuration.

Figure III-2 shows the basic solution arrived at for installing the DDA GT-404-4 gas turbine engine. It was mounted transversely in the engine compartment with the front of the engine (compressor inlet) facing the left* side of the coach. Therefore, the air inlet for the turbine engine induction system has to be from the left side of the coach.

* All directions assume standing at the rear of the bus looking forward.

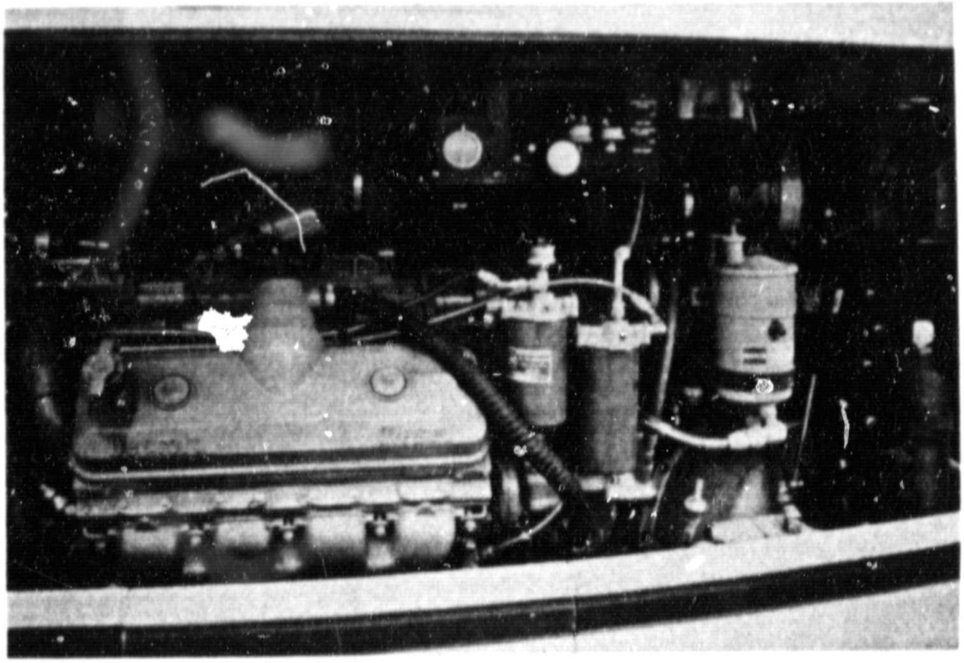

FIGURE III-1
Engine Compartment with Original Diesel Engine Installation

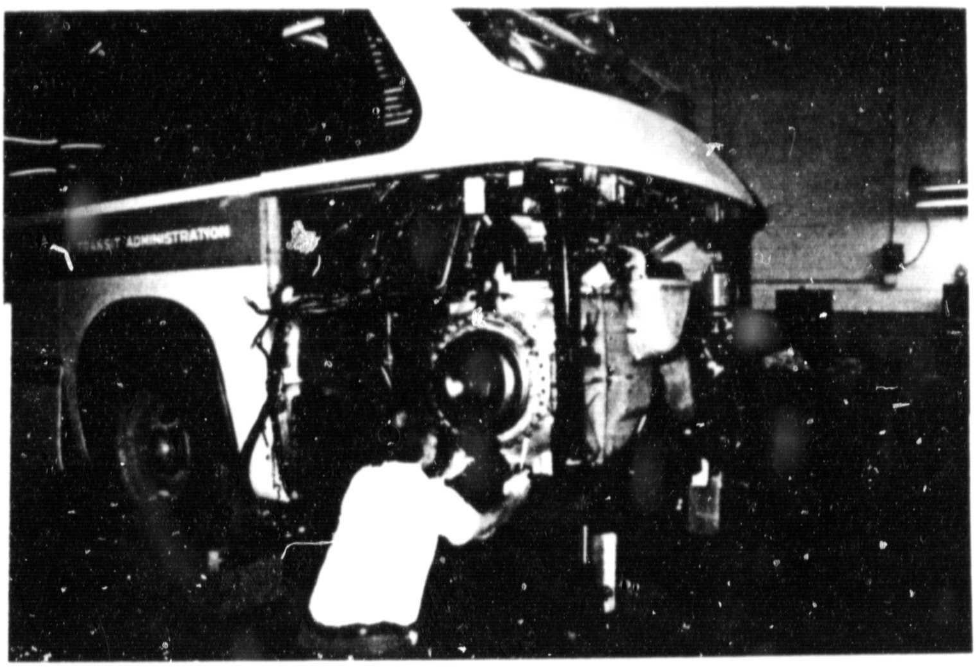

FIGURE III-2
Engine Compartment with Gas Turbine Engine Installation

The diesel version radiator and air conditioning condenser were removed from the left side of the engine compartment and the vacated space was used for the air inlet to the turbine. The coach compartment heater, shown in Figure III-3, was located in the lower level of the engine compartment on the left side engine frame rail.

The cooling system for the engine oil was installed on the right hand side of the engine compartment. A separate cooling system for the transmission oil was mounted under the passenger compartment on the right side of bay three in front of the rear door.

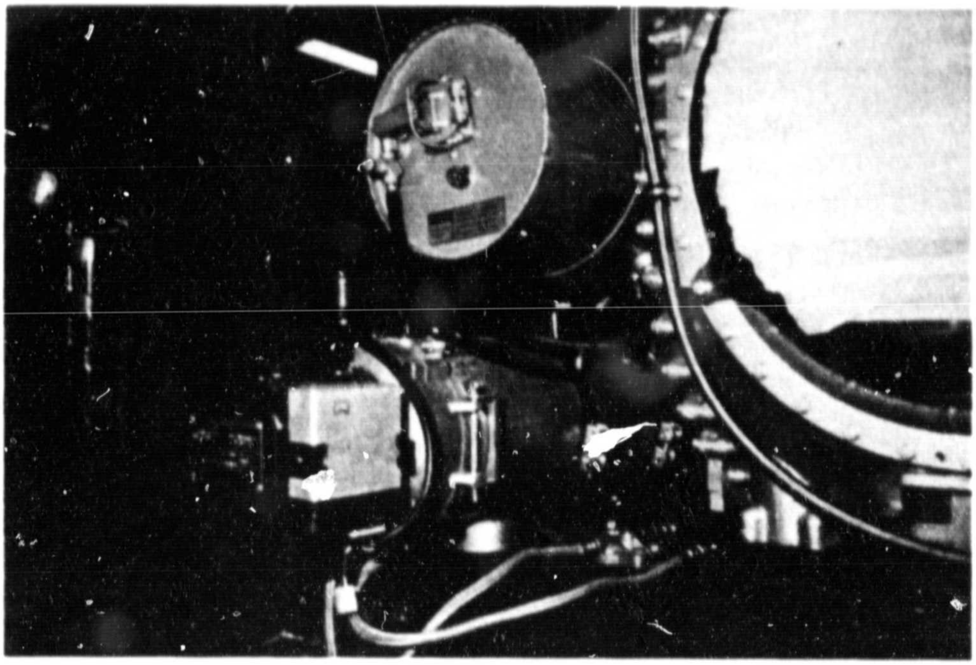

FIGURE III-3
Coach Compartment Heater

The normal location of the air conditioning condenser on the diesel engine coach is outboard of the engine cooling radiator on the left side of the engine compartment. Since the radiator was not required with a turbine engine and the space was needed for the turbine air inlet, the air conditioning condenser was located in the upper rear area of the coach outside of the engine compartment as shown in Figure III-4. This is the same location used on the "New Look" coaches manufactured prior to the Advanced Design Bus. It was determined that the "New Look" condenser, which was still available from GM of Canada, would fit between the structural members on the RTS coaches and could be covered by an enclosure that would not exceed the length and height limitations of the original RTS. The enclosure for the condenser was designed by Booz, Allen and Modern Engineering. Modern built the enclosure for each of the coaches.

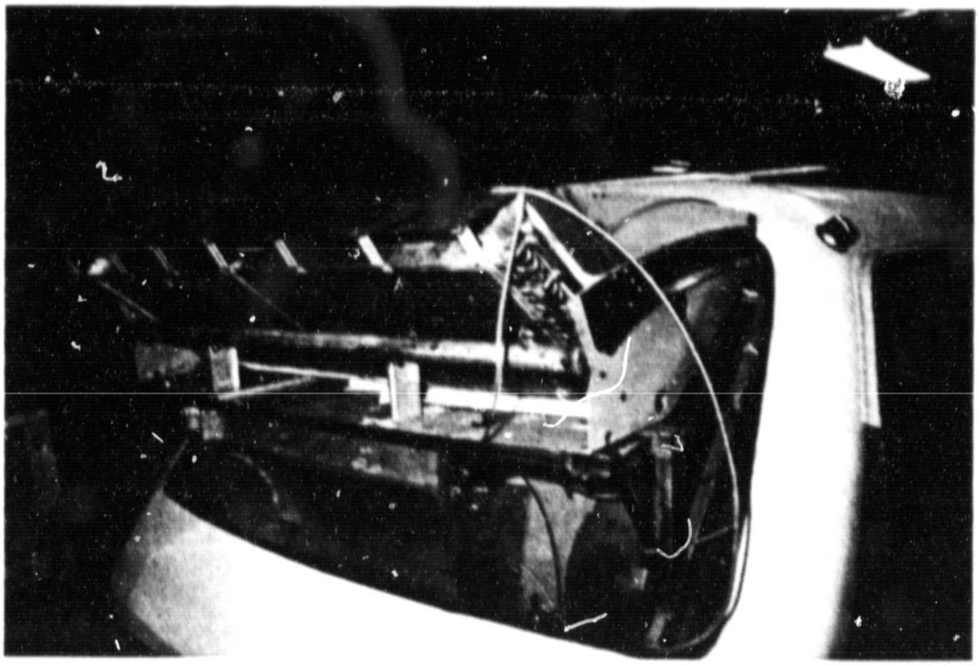

FIGURE III-4
Air Conditioning Condenser Location

The GT-404-4 turbine has exhaust ports on both sides when viewed from the rear, and when mounted transversely these ports appear on the forward and rear sides of the engine. In a study made prior to the start of the gas turbine program it was determined that a normal exhaust routing for the forwardmost port would interfere with the rear cross seat support. Thus the forward exhaust elbow was headed downward under and to the rear of the engine, emerging at the right side of the rear (short) exhaust duct. Although this resulted in a very complicated twisting duct, as shown in Figures III-5 and III-6, it eliminated any need for structural redesign of the coach or the loss of seating capacity.

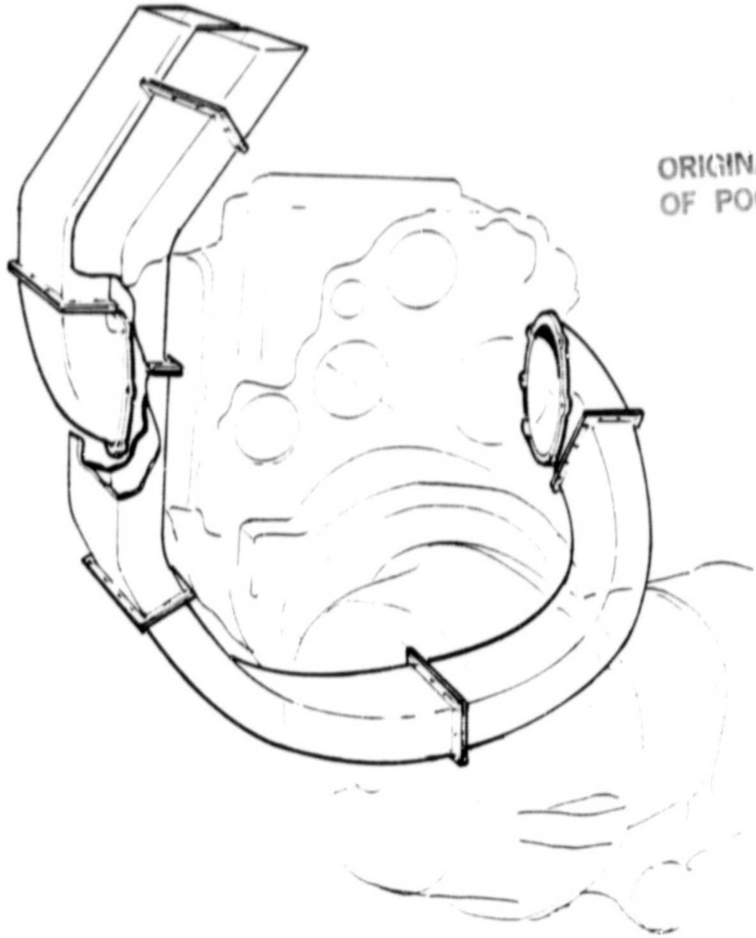

FIGURE III-5
Engine Exhaust Schematic Drawing

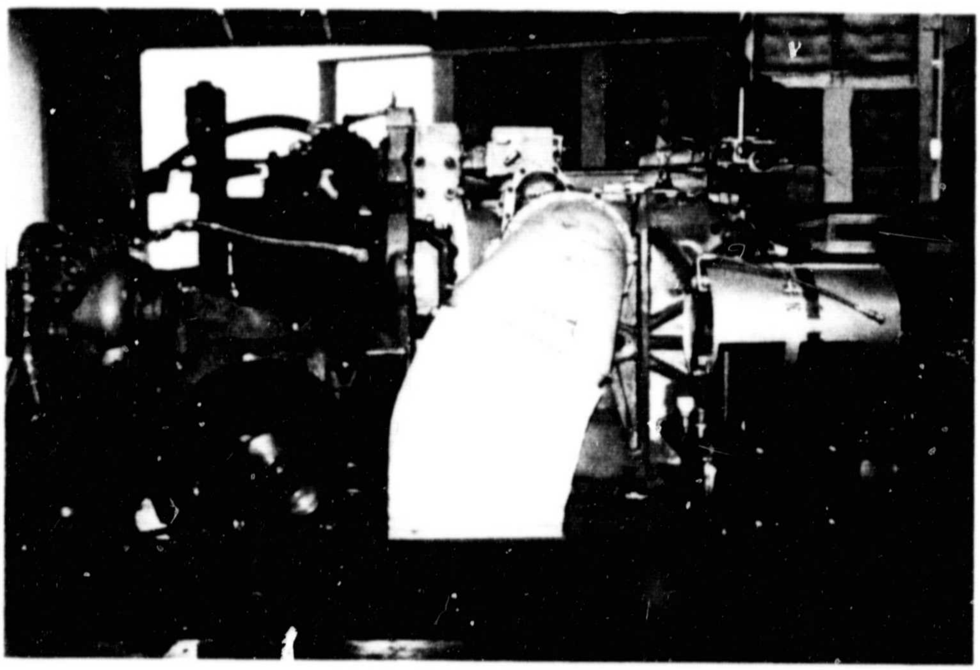

FIGURE III-6
Engine Exhaust Duct Installation

SPECIAL DESIGN REQUIREMENTS

As mentioned earlier, special engineering design and analysis was required for several of the turbine coach support systems. Discussed below are the design analyses associated with:

- Air intake
- Exhaust
- Oil cooling
- Electrical and control circuits
- Heating, ventilating and air conditioning
- Fuel tanks
- Engine compartment cooling.

Air Inlet

The turbine air inlet had to be capable of handling a large volume of air and also had to reduce the noise generated by this large air flow to acceptable levels. Original plans were made for use of the PALL Corp., Centrisep inlet air cleaner and silencer package used on the Greyhound turbine coach installation. However, preliminary layouts made for the RTS II turbine coach indicated packaging problems that made it necessary to explore alternatives. The Detriot Diesel Allison engineering staff recommended the elimination of the silencer portion of the installation, the narrowing of the air cleaner and the use of insulation materials in the ducting to bring the noise down to acceptable levels. Several sound absorbing materials were considered including Conaflex F-100 and Scott 30900 compressed reticulated foam. The Scott material was finally selected and the intake plenum lined with 1-inch-thick material, as shown in Figure III-7. Noise tests indicated there was adequate noise suppression.

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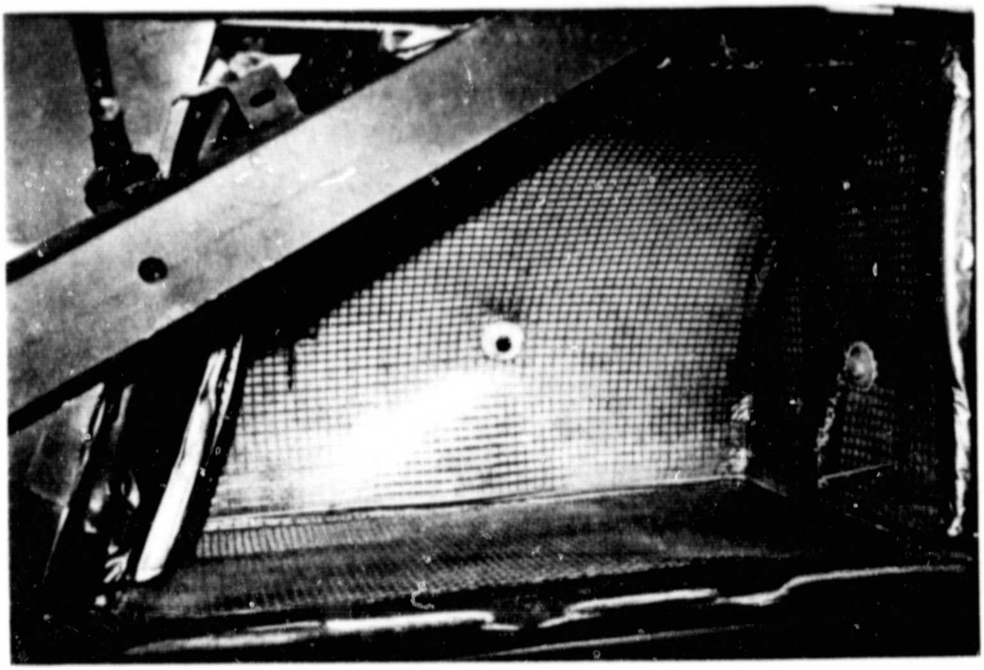

FIGURE III-7
Intake Plenum Insulation

Exhaust

After the appropriate exhaust duct configuration was determined, as discussed earlier, the ducts were fabricated out of stainless steel and covered with 1/2-inch Temp-Mat insulation, which in turn was covered with a moldable high temperature epoxy material called Fiberfrax LDS to provide a hard exterior surface that was impervious to damage. Although the ducts were originally covered all around, it was later determined that it was only necessary to cover the surface adjacent to the engine where the heat was most critical. A later improvement was made by sealing the duct joints to prevent the escape of gases into the engine compartment. The exhaust gases were expelled through an opening above the engine access door as shown in Figure III-8.

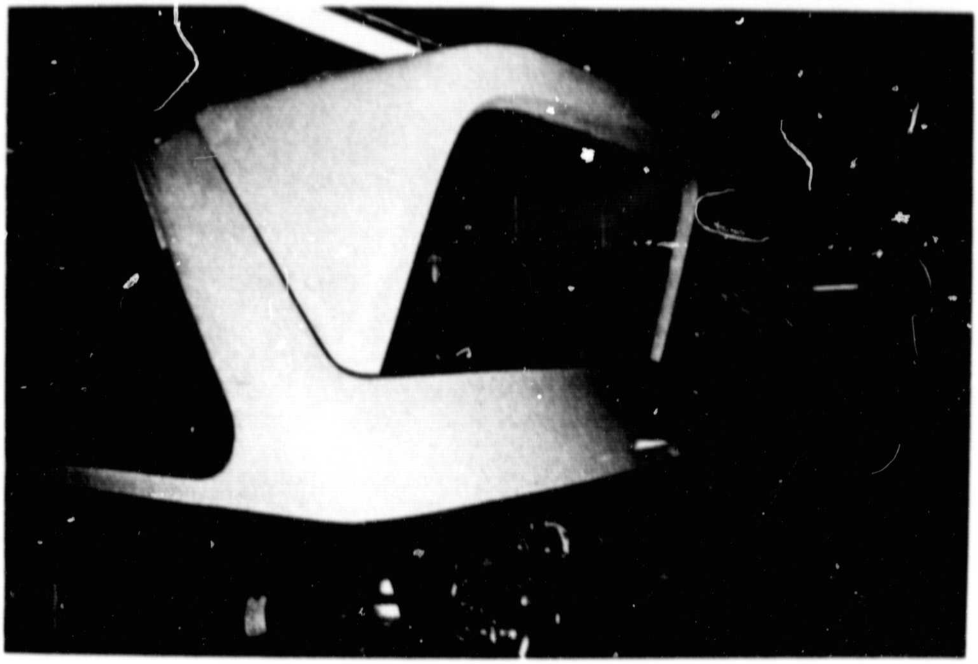

FIGURE III-8
Engine Exhaust Duct Opening

Booz, Allen & Hamilton suggested that some protection be given to the exhaust openings to prevent objects from being thrown into the ducts and the entry of rain into the regenerator particularly when the engine was not running. Different designs were tried and finally the exhaust outlet was covered with an expanded metal grating.

High frequency noise from the engine exhaust can be a problem with turbine engines. To prevent this problem, the exhaust ducts were made with double wall construction. As shown in Figure III-9, the inside wall is perforated stainless steel sheet, the outside regular stainless steel sheet with 1/2-inch Temp-Mat insulation between the walls for noise abatement.

Noise measurements indicated the double wall construction with 1/2-inch Temp-Mat insulation was a worthwhile noise silencer. Sound levels at the exhaust ducts were found to be lower than the turbine-powered Greyhound coach which did not have double wall exhaust ducts.

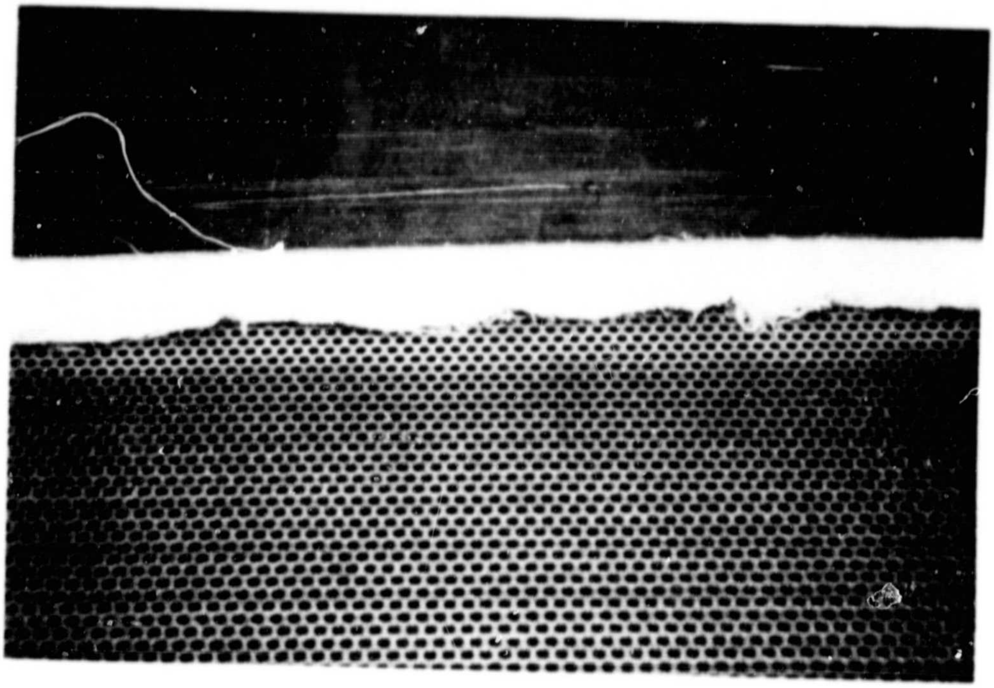

FIGURE III-9
Engine Exhaust Duct Insulation

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Oil Cooling

The original packaging concept for oil cooling called for a dual oil cooling unit for both the engine oil and the transmission oil on the right side of the engine compartment. The front unit of the cooler made by Young Radiator Company was designed to cool the transmission oil and the rear unit was designed to cool the engine oil.

Road tests on Coach #3319 showed that the oil temperatures for both engine and transmission were excessively high, indicating that the colling unit was not functioning properly. The malfunction was caused by two factors. First, a vital structural member mounted diagonally crossed the two cores shown in Figure III-10 and blocked off some of the fins. Secondly, a low pressure area adjacent to the core and created outside the coach while it was underway, effectively reduced the ability of the fan to draw outside air through the radiator core.

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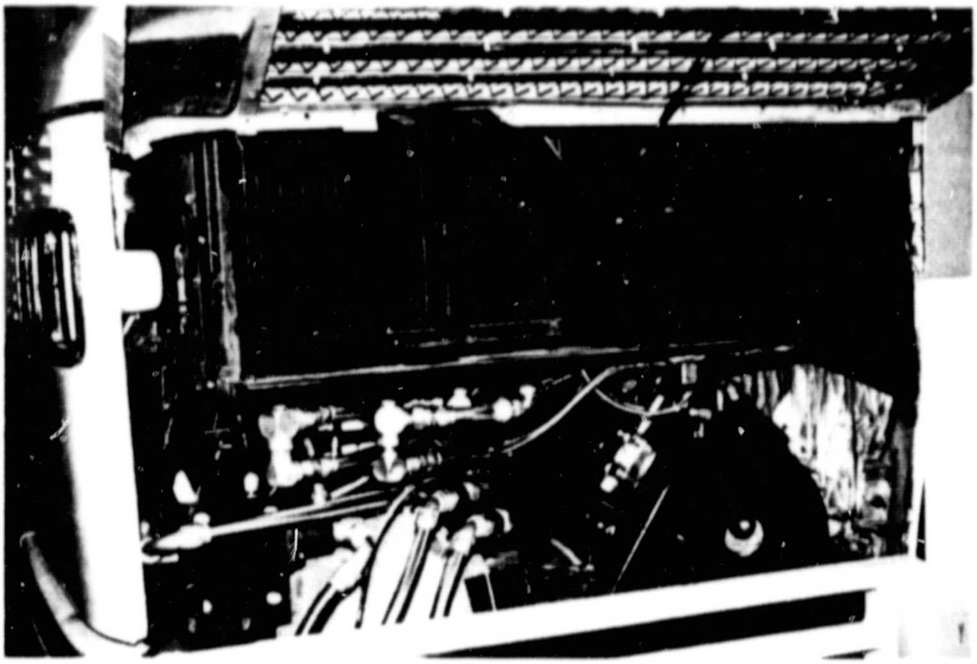

FIGURE III-10
Original Oil Cooler Installation

It was decided to use both halves of the core for engine oil only, and to plumb them in parallel. This added core capacity provided enough cooling to get the engine oil temperatures down to acceptable limits.

The original cooler concept called for a shaft and belt to drive the cooling suction fan. This installation was not satisfactory since the motor and fan mounted on a cantilevered bracket presented a vibration problem. It was decided to replace this fan with an electric motor drive. No 24-volt motors were found small enough to fit in the available space, so a smaller 38-volt fan motor was used and was driven by a 38-volt alternator.*

A new self-contained unit was acquired to handle the transmission oil cooling and was mounted under the passenger compartment on the right side of bay three in front of the rear door. This completely integrated cooler, shown in Figure III-11, proved to be extremely efficient and provided a dramatic lowering of the transmission oil temperatures under all operating conditions.

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* See electrical circuit section.

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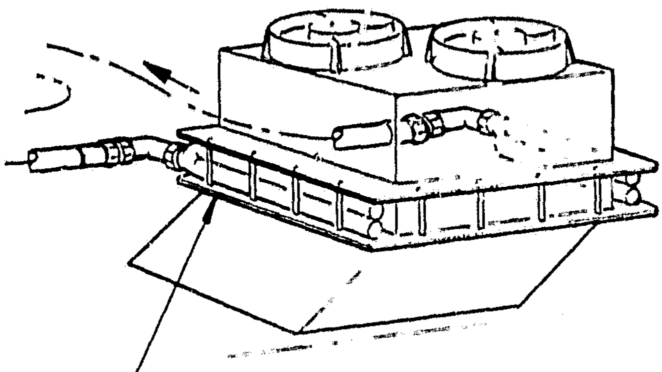

FIGURE III-11
New Transmission Oil Cooler Design

Electrical and Control Circuits

Electrical calculations made as part of the RTS conversion feasibility studies showed that the existing 24-volt alternator supplied with the diesel coach was capable of handling all of the turbine coach electrical load with the exception of the air conditioning condenser fan, which would require a separate 38-volt alternator. Thus a separate 38-volt alternator was added to the engine compartment. In the course of configuring the components on the coach it was later found more convenient to use the 38-volt alternator to power the engine oil fan motor and the 24-volt alternator to power the air conditioner condenser fan motors.*

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* See sections on oil cooling and heating, ventilation and air conditioning.

In the course of converting the coaches to turbine power several major changes in wiring were encountered:

- There were inherent differences in the approach to wiring the two types of power sources
- The air conditioning condenser located on the roof required wiring changes caused both by the location and the different type of air conditioning system used
- The direct-fired hot water heater on the turbine coach required its own circuitry.

The original purpose of this program was to test the viability of the gas turbine power source in revenue service. However, the possibility existed that the coaches would be reconverted to diesel power if the turbine did not perform satisfactorily during the testing phase of the program. Therefore, as much of the diesel wiring as practical remained intact to reduce the wiring complexity. This resulted in excess wires or excessively long wires being used. During the development of the program, this decision to save as much wiring as possible created certain problems. There were electrical malfunctions caused by ground loops and voltage spikes, and some confusion in the wiring and identification of connections caused by this excess wiring.

The rear apparatus relay box location in the diesel coach (under the rear seat support) interfered with the turbine engine when it was installed in the coach mockup. A new box was designed, fabricated and installed on the firewall of the engine compartment. On the initial trip to Baltimore with Coach #3319, failures occurred with this box because of high temperatures in the engine compartment, principally fusing of relay contacts and melting of plastic parts. It was necessary to find a cooler location to prevent these failures, and a more accessible spot for servicing the box in the field. Booz, Allen & Hamilton suggested a location inside the passenger compartment, over the rear seat, as shown in Figure III-12. It was also decided to relocate the engine control box from its location in the radio box in bay three to the same area. Both boxes were enclosed with a vacuum-formed cover that blended into the existing inside rear trim panels.

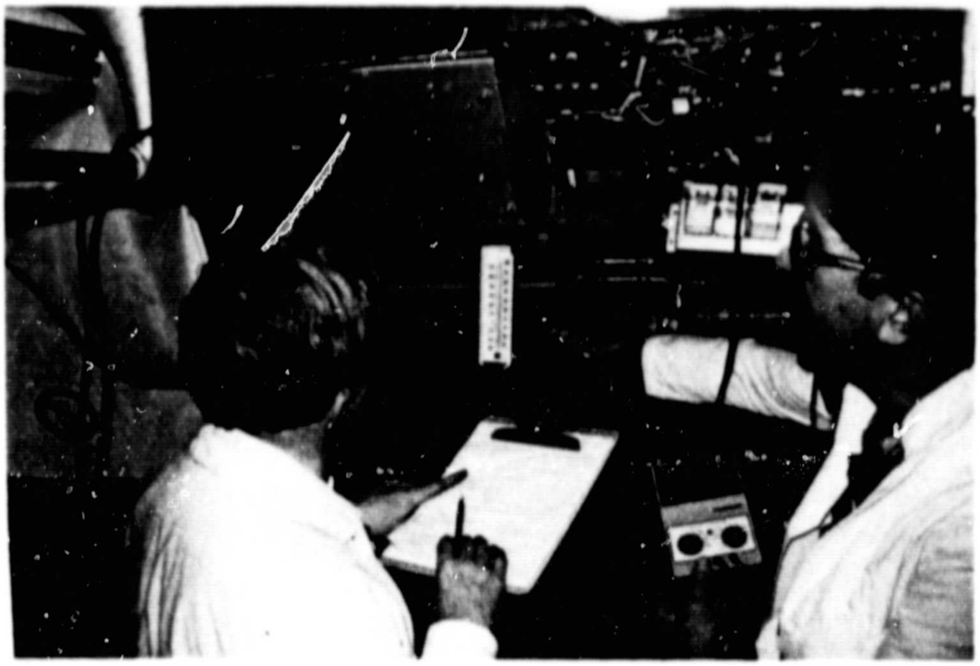

FIGURE III-12
Rear Apparatus Relay Box and
Engine Control Box Location

Heating, Ventilating and Air Conditioning

The only readily available heater of sufficient size to carry the coach load was one made in Germany by Webasto, and marketed in the United States by Webasto North America, Inc. It proved to be an efficient, oil-fired unit of relatively small size (8 inch diameter x 26 inches long) and space was made available for it at the lower level of the engine compartment on the left side engine frame rail (see Figure III-3), accessible through the engine compartment access door opening.

The heater was equipped with an individual 20-gallon fuel tank in order to separate the usage of heating fuel from that used for motive power, and to prevent damage to the heater in the event that alternate fuels were later specified for the turbines or in the event of coach breakdown and/or out of fuel in the main tanks.

As mentioned earlier, the turbine coach air conditioning system was modified to use a "New Look" condenser on the roof area of the coach. In the original air conditioner installation mounted on the roof on the

"New Look" coaches, the condenser cooling fan pulled air from the outside through an opening in the top of the enclosure and exhausted it into a sealed compartment and through the condenser. This system was discarded in favor of a pair of cooling fans driven by 24-volt motors blowing directly on the condenser. There was insufficient room to mount 24-volt motors vertically as on the "New Look" coaches, so by slanting the condenser to the rear at the top and mounting the motors in an angular position, it was possible to keep the motors below the roof line. The direct cooling system also eliminated the need for a perfect seal between the enclosure and the coach body, simplifying the assembly and fit problems. The two fans were wired in such a way that only one fan would run under normal conditions. The second fan would operate automatically as a booster when ambient temperatures or compressor head pressures required additional cooling capacity.

The Maryland Mass Transit Authority and Booz, Allen & Hamilton decided to replace the Trane air conditioning compressor on the turbine coaches with one made by Carrier to evaluate this component. Carrier was contacted regarding their interest in this program and Carrier agreed to supply the experimental compressors at no charge.

The standard diesel coaches as supplied utilized Honeywell temperature controls. GMC had experienced some problems with this line of controls on their production coaches, and had been working with Vapor Company to develop more reliable controls. Booz, Allen & Hamilton decided to incorporate this product improvement in the turbine coaches as well to provide a more dependable system for both heating and air conditioning. Representatives from Vapor Company provided assistance in the development of the controls used to amalgamate the Webasto direct fired heater and the relocated air conditioning system.

Fuel Tanks

Since alternate fuels were being considered as part of the gas turbine demonstration program, an investigation was made of means of increasing the fuel capacity of the turbine coaches. Alcohol-type fuels normally have a lower BTU content per given volume and require additional fuel tank capacity to obtain the same daily mileage.

After reviewing suggestions by Modern Engineering, Booz, Allen & Hamilton authorized Modern to add another fuel tank to increase the capacity of the coach. Various configurations were investigated, including the use of combinations of terne plate and nylon tanks, all nylon tanks, or all nylon on some coaches and all terne plate on others. The program sponsor decided to replace all terne plate tanks with nylon tanks, and to install an additional nylon tank in-series, and interconnected, to allow them to be filled at the same time through one opening and to act in service as though they were a single tank.

Suitable nylon tanks were located at a supplier to the Truck and Coach Division of General Motors Corp., and permission was obtained from GMC to purchase the necessary number of tanks, since they owned the tooling. The locations of the filler necks on the GMC tanks were not in the right place for our use but the tank manufacturer was able to relocate them to new specifications without difficulty. One tank was mounted in the normal location in bay two with the additional tank mounted in bay one with a balance line joining the two. This arrangement, shown in Figure III-13, gave the coach a total fuel capacity of 250 gallons.

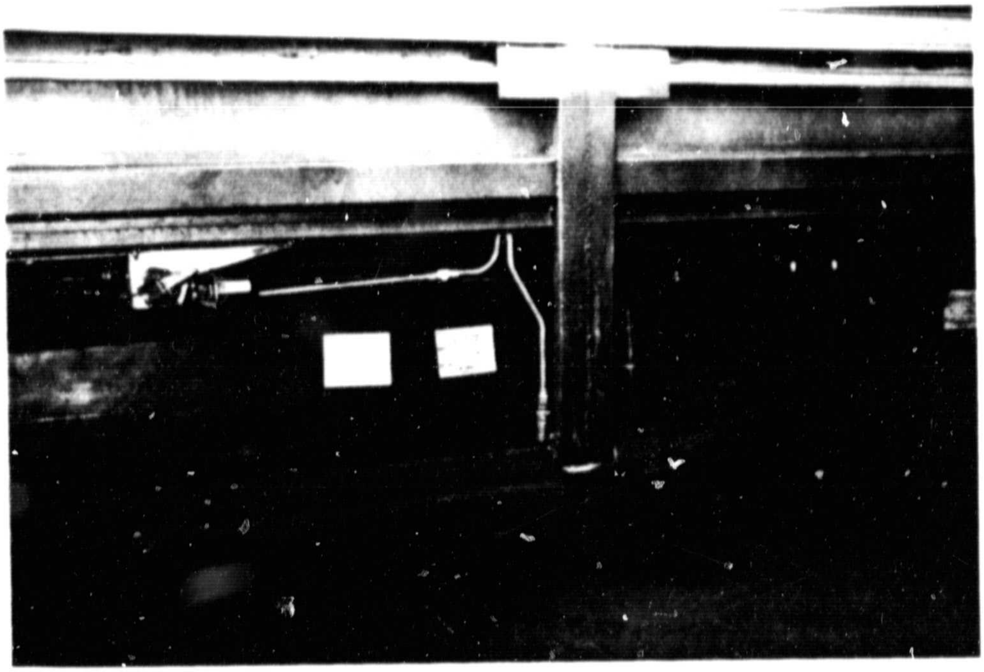

FIGURE III-13
Fuel Tank Location

Engine Compartment Cooling

No initial plans were made for special cooling of the engine compartment. Normally the warm engine compartment air would rise, be blown out of the compartment by the oil cooler fan, and escape through the 1-inch clearance around the exhaust ducts and the ledge plate opening.

Early tests, of only short mileage duration, did not indicate an excessively high engine compartment temperature. However, on the initial trip of Coach #3319 to Baltimore, the engine compartment overheated. The coach was returned to Modern Engineering and changes were made including the installation of a revised exhaust system with sealed duct joints. Coach #3319 was returned to Baltimore and again it encountered an engine compartment temperature problem, which was caused by exhaust gas recirculation. The coach was again returned to Modern and the exhaust recirculation problem was corrected by increasing the upper duct insertion into the exhaust outlet.

Further tests were made under various conditions. Thermocouples were installed in the area of four temperature sensitive components on the engine: the fuel metering valve, the clutch control valve, solenoid valves and the relay panel. Test readings were taken under various conditions as Coach #3319 was being driven on the highway and on transit coach type runs. The following readings were taken:

- Normal test readings with engine compartment closed up
- Readings with rear engine compartment door left ajar creating an approximate 2.5-inch opening across the top of the door
- Readings with lower side engine access door covers removed
- Readings with the rear engine compartment door completely open.

The test readings showed a vast improvement (25-30°F) with the rear door ajar and also with the lower side door covers removed. The readings with the rear door completely open showed that the temperature could be reduced further if more openings and a faster air flow from the oil cooler fan could be provided. Stainless steel louvers were incorporated into the rear engine access door, as shown in Figure III-14, for increased air flow through the engine compartment.

The use of blower fans and ducting cool air to the temperature sensitive areas were also tested. Two small commercially available fans providing 100 cubic feet per minute (CFM) each were tried, ducting air from the condenser area above the ledge plate into the engine compartment. This showed only a slight improvement of 2-6°F.

FIGURE III-14
Rear Engine Access Door Design

Later, two larger fans of 300 CFM (like the driver's blower fan) were obtained to replace the smaller units. These fans showed a much greater improvement (8-12°F) in the heat sensitive areas where the air was being directed.

The original six-bladed oil cooler fan was replaced by a seven-bladed model which reduced the engine compartment temperature level by an additional 10°F.

IV. PRE-DEMONSTRATION TESTING

COACH TESTING

Testing was conducted at the Transportation Research Center (TRC) of Ohio automotive proving grounds. The proving grounds staff conducted the tests and performed required maintenance and repairs under the direction of a test engineer from Booz, Allen & Hamilton. The categories of tests which were performed on the vehicles included development, acceptance, performance and systems tests. The scope of the test, the test results, and potential impacts on the demonstration are described below.

DEVELOPMENT TESTS

Although engineering tests related to product development were not within the original scope of this program, certain development tests were made upon request by Detroit Diesel Allison. Track tests, measuring acceleration and deceleration rates, as shown in Figure IV-1, were made on gas turbine Coach #3319 to evaluate the optimum rear axle ratio to use on the coaches converted to turbine power. The rear axle ratios were evaluated in terms of their effect on vehicle performance. An evaluation was also made of the optimum transmission shift points to use with each of the rear axles tested. The best rear axle ratio and shift points identified as a result of these tests were then used on all of the converted coaches for the revenue demonstration.

ACCEPTANCE TESTS

Acceptance tests were conducted on all of the converted coaches to verify the proper functioning of the unique conversion components, to check the quality of the conversion work, and to verify that the converted coaches were in compliance with the applicable ADB specifications. The acceptance testing procedures included verifying proper operation of the engine, doors, windshield wipers and washers, lights, vehicle instrumentation, air conditioning system, and other major operating systems. The checks were performed by visual inspection and 500 miles of road testing, followed by a thorough examination of the hoses, pipes, connections, fittings, engine, transmission, air conditioning, compressor, heater and fuel tanks.

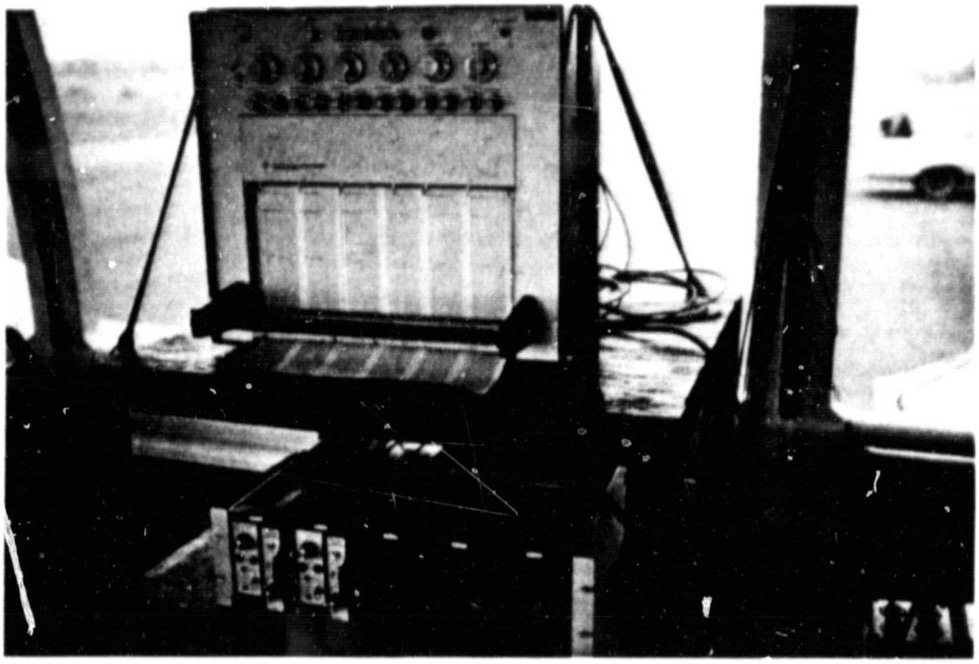

FIGURE IV-1
Acceleration and Deceleration Rate Measurements

PERFORMANCE TESTS

One converted coach, #3319, and one unmodified diesel-powered coach identical to the gas turbine coach before conversion, were subjected to the performance tests during August and September, 1980 for compliance with the appropriate requirements of the November 1978 issue of the "Baseline Advanced Design Transit Coach Specifications." Performance tests were conducted to:

- Measure specific parameters on converted coaches related to passenger comfort, vehicle performance and impact on the urban environment.

- Generate precise data on the coach systems unique to the gas turbine engine that could be useful for product improvements.

The tests on the diesel engine coach were used to provide a controlled data base.

A total of 15 tests were conducted to verify and quantify the operating parameters and characteristics of both diesel and gas turbine transit coaches. Tests were:

- Operating Environment, the capability of each coach to achieve normal operation in temperatures between -10°F and +115°F:

  - Gas turbine cold start was conducted with an ambient temperature of +2°F. The engine started normally. However, the ECA control box had to be bypassed and manually controlled until the engine was at idle

  - Diesel cold start at +2°F required ether for starting. At +27°F, coach started normally after cranking for 10 seconds.

  Tests indicated that gas turbine vehicle starting was no more complex than diesel vehicle starting and could be readily accomplished in revenue service.

- Air Systems, the amount of coach air system pressure reduction (leak-down) after eight hours of non-operation:

  - After eight hours of sitting, gas turbine coach air pressure decreased 9-10 psi, which was within the allowable range

  - After eight hours, diesel coach air pressure descreased 23-25 psi, which was not within the allowable range.

  The air system of the turbine was intact and did not exhibit leaks detrimental to operation. The diesel air system leakage failed to meet the ADB specification but was not sufficient to disrupt normal operation of the coach.

- Exterior Noise, the noise level outside the coach at full power and at idle (Figure IV-2):

  - Gas turbine coach curb idle noise was 71.3 to 72.5 dBA, exceeding the ADB specification of 65 dBA

  - Diesel coach curb idle noise was 67.7 to 72.5 dBA, which also exceeded the ADB specification.

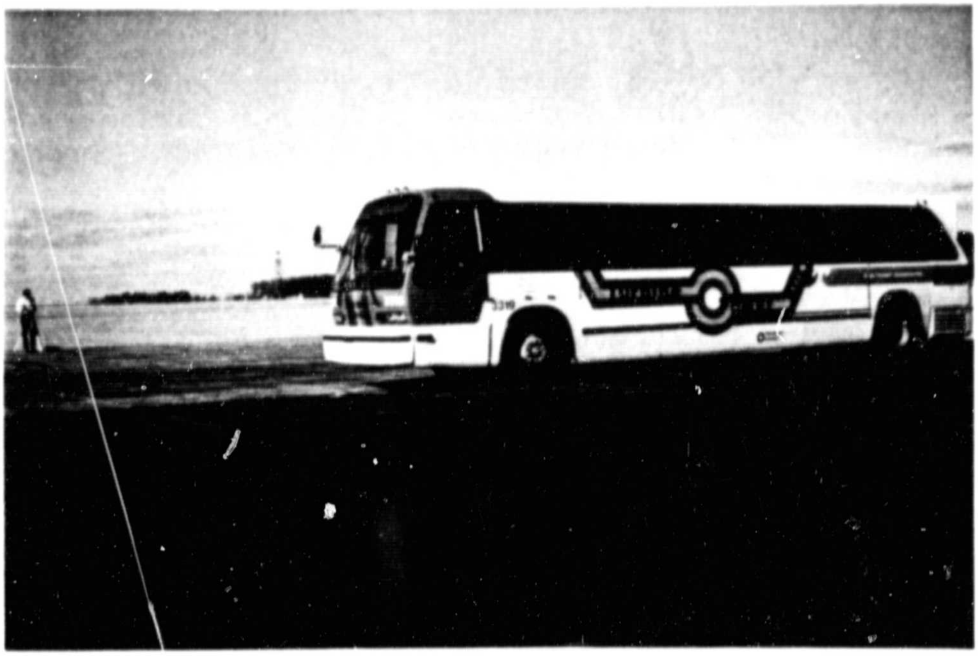

FIGURE IV-2
Exterior Noise Test

While both coaches failed to meet the ADB noise specification for curb idle, the turbine coach did not exhibit higher noise and, therefore, should not be any more objectional to pedestrians than the diesel coach.

- <u>Interior Noise</u>, coach-generated noise levels experienced by passengers and the driver (Figure IV-3 and IV-4):

  - Gas turbine noise level was 80.0 dBA at the rear of the coach, gradually reducing to 70.2 dBA at the driver's seat. Running the HVAC raised the noise levels 3 to 5 dBA.

  - Diesel noise level was 81. dBA at the rear of the coach and 73. dBA at the driver's seat.

  The gas turbine averaged a 1 dBA lower noise level than the diesel. This decreased noise should reduce driver and passenger fatigue.

- <u>Top Speed</u>, the vehicle's top speed on a level grade (Figure IV-5):

  - The gas turbine achieved a maximum top speed of 58.5 mph (with a 6 mph head wind) on the

FIGURE IV-3
Interior Noise Level at Driver's Seat

FIGURE IV-4
Interior Noise Level at Rear Passenger Seats

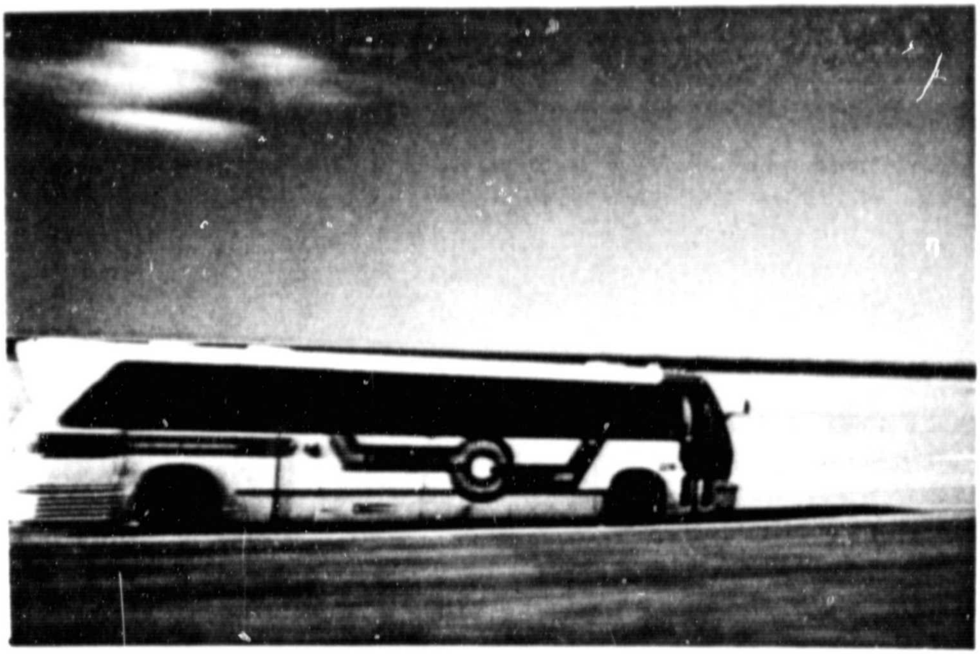

FIGURE IV-5
Top Speed Test

front straightaway of the test track and 60 mph (with a 6 mph tail wind) on the back straightaway. Wind speed was 6 mph, 90°East.

- The diesel coach achieved a maximum speed of 68 mph on the front straightaway and 68 mph on the back straightaway (both with a cross wind). Wind speed was 4 mph, 29°West.

Top speed of the gas turbine coach was less than the diesel coach but still exceeded the current speed limit (55 mph) and, therefore, was suitable for revenue service.

. Speed on Slopes, the ability of the coaches to maintain a speed of 45 mph on a 2-1/2 percent grade and 7 mph on a 16 percent grade:

  - The turbine coach maintained a speed of 52 mph on a 2-1/2 percent grade and 20 mph on a 16 percent grade

  - The diesel coach maintained a speed of 50 mph on a 2-1/2 percent grade and 12 mph on a 16 percent grade.

The gas turbine coach maintained higher speeds on slopes than the diesel coach. This should be beneficial to the speed of revenue service in hilly terrain.

- Acceleration, vehicle acceleration, at wide open throttle, from a stand still until each vehicle reached top speed:

  - The gas turbine coach accelerated from 0 to 50 mph in 33-36 second

  - The diesel-powered coach accelerated from 0 to 50 mph in 42-50 seconds.

  The gas turbine coach exhibited more rapid acceleration from 0 to 50 mph. However, because transit service rarely accelerates beyond 20 to 30 mph, this relatively rapid acceleration for the turbine should be of only marginal benefit.

- Jerk, the maximum rate of change of acceleration (jerk) for each coach:

  - The turbine coach's maximum rate of change of acceleration (jerk) recorded was .03g/second

  - The diesel coach's maximum rate of change of acceleration (jerk) recorded was .03g/second.

  The maximum jerk (rate of change of acceleration) recorded for the turbine coach was the same as that recorded for the diesel coach, indicating that passengers would not experience any unusual discomfort or notice any increase in smoothness with the turbine coach.

- Operating Range, the operating range of the coach with a full tank of fuel on the design operating profile course:

  - The gas turbine coach operated for 431.4 miles before fuel exhaustion with a fuel consumption of 2.03 miles per gallon

  - The diesel coach operated 379.8 miles before fuel exhaustion with a fuel consumption of 3.88 miles per gallon.

  Both coaches met the ADB operating range specification with the gas turbine coach range exceeding that of the diesel coach by about 14 percent.* Both coaches also operated to specification on slopes with low fuel.

- <u>Performance of Engine-Driven Accessories</u>, the performance of engine-driven accessories at low vehicle speeds and during extended periods of idle operation:

  - For the gas turbine coach, all accessories operated satisfactorily at normal engine idle speed for one hour. However battery system charging level was not acceptable.

  - All diesel coach accessories operated satisfactorily at idle for one hour.

  Extended operation of the turbine coach at idle with lights and A/C operating could result in a low battery charge.

- <u>Service Brake Friction Material Durability</u>, the average brake life expectancy:

  - The average brake life expectancy for the turbine coach running the design operating profile was 9,766.6 miles. This was less than the required durability.

  - The brake life expectancy for the diesel coach was calculated to be 21,095 miles.

  The projected brake life expectancy of the turbine coach was less than half that of the diesel coach. This is the only serious deficiency identified in the turbine coach design that was not correctable during the testing program.

- <u>Fuel Tank Slope Operation</u>, the ability of the fuel tank design to assure adequate fuel supply on a 6 percent slope:

  - The gas turbine coach operated for the specified 15 minutes under load on the 6 percent upgrade with 25 gallons of fuel, and 30 minutes at idle on the 6 percent downgrade with 10 gallons of fuel

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* The turbine coach was equipped with two 125-gallon tanks versus the one 125-gallon tank on the diesel coach.

- The diesel coach operated for the specified 15 minutes under load on the 6 percent upgrade with 25 gallons of fuel, and 30 minutes at idle on the 6 percent downgrade with 10 gallons of fuel.

Operation in hilly terrain, such as in some places in Baltimore, should not present a problem to the coaches even with low fuel.

- <u>Fire Detector Effectiveness</u>, the correct operation of temperature sensors in the engine compartment:

  - All three of the fire detectors on the gas turbine coach activated between 235°F and 265°F (General Motors service manual specification)

  - All three of the fire detectors on the diesel coach activated in the proper temperature range (235°F-265°F).

An engine compartment fire in either coach should be detected quickly to allow shut downs and evacuation of the coach without injury to passengers.

- <u>Interior Climate Control</u>, correct operation of vehicle heating, ventilating and air conditioning systems:

  - During cold weather, the Webasto heater satisfactorily heated the turbine coach interior to a comfortable level. However, the air conditioning system did not operate properly. HVAC problems identified were later corrected on all four turbine coaches

  - Interior temperatures in the diesel coach were comfortable throughout the test period.

Initially, the air conditioning system on the test turbine coach failed to operate properly due to compressor control logic and wiring problems. The air conditioning system problems experienced on the test coach were corrected by Modern Engineering on all four turbine coaches and its operation was monitored during acceptance testing on each coach. The interior temperature was maintained at a comfortable level and the system operated satisfactorily on all four coaches.

- Engine Induced Structural Vibration, the level of engine vibration-induced strain in the structure of the vehicles:

  - The gas turbine engine in Coach #3319 caused no structural strain or vibration in the engine mount area of the coach chassis

  - The diesel engine in Coach #3316 caused no structural strain or vibration in the engine mount area of the coach chassis.

  The reduced vibration level of the gas turbine engine should not results in any measurable increase in coach fatigue life. Also, passengers should not experience any increase or decrease in comfort.

SYSTEMS TESTS

Systems tests were conducted on the same converted coach and unmodified coach used in the performance testing. The two coaches were to be operated continuously on a 24-hour-per-day basis between September 1980 and February 1981 to gain information on how the turbine coaches would perform with extended vehicle operation under simulated transit-type service. Specific system test objectives were to:

- Identify fleet defects in the converted coaches.

- Verify corrections developed for fleet defects.

- Eliminate infant mortality failure on the converted coaches from the revenue service demonstration.

- Generate comparative operating data on the diesel and gas turbine coaches under controlled and repeatable conditions.

- Measure the time required to perform scheduled inspections, maintenance, and repairs on the gas turbine coaches compared to the diesel coaches under controlled and repeatable conditions.

- Develop data on operating costs in controlled and repeatable conditions for the diesel and gas turbine coaches.

- Assess the overall reliability of the converted coaches.

The tests were conducted at TRC between September 1980 and February 1981, and consisted of running the "Design Operating Profile" (as defined in the November 1978 "Baseline Advanced Design Transit Coach Specification"). This profile, which simulates city, arterial, and commuter bus routes was set-up on the high speed test track at TRC with appropriate markings for city, arterial, and commuter bus stops.

The following instrumentation, as shown in Figures IV-6 and IV-7, was installed in both coaches prior to starting the systems tests:

- Argo electronic tachograph to record speed and time
- Brake lining termocouples hooked to a digital readout to monitor brake temperatures
- Lighted electric door timers to indicate door closing time at each stop
- Brake pressure application gauges.

In addition, both coaches were ballasted to Seated Load Weight (SLW) and the speedometers and tachographs were calibrated. The brake linings on both coaches were also measured and recorded.

During the systems tests, TRC drivers recorded the following information:

- Time
- Ambient temperature
- Ambient humidity
- Brake temperatures.

<u>Gas Turbine Coach #3319 System Test Results</u>

Gas turbine Coach #3319 was tested for 35 days from September 23, 1980 to February 18, 1981. During this time the coach accumulated 7,252.2 miles.

The problems that developed during the systems testing on the gas turbine-powered coach indicated that further engineering development work was required. However, the program sponsors believed that the data gathered from even a non-perfect demonstration would have value and decided to proceed with the demonstration at that time.

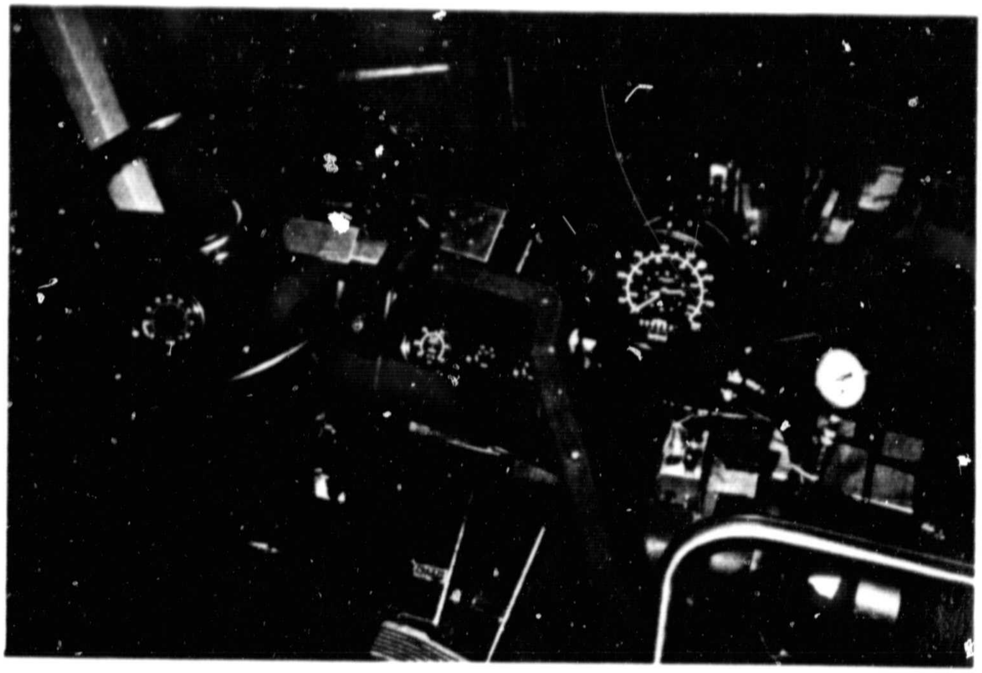

FIGURE IV-6
Argo Electronic Tachograph and
Brake Application Pressure Gauges

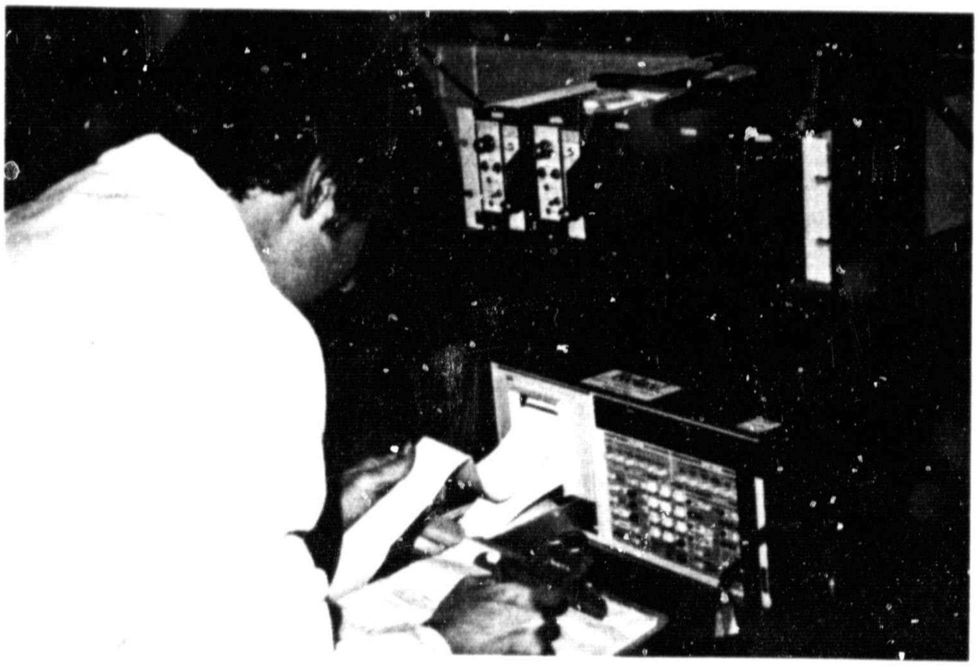

FIGURE IV-7
Digital Readout for Monitoring
Brake Temperatures

The coach was out of service 73 percent of the testing days available. The main reasons for the downtime were:

- Engine--The coach was out of service approximately 49 days for engine work. The left ceramic regenerator was damaged due to the failure of the hot-cold seal and the T-6 area shrouding, Figures IV-8 and IV-9. This problem caused extensive downtime because the engine had to be removed and sent to DDA for repair and then returned to TRC for re-installation. The coach was also out of service for the replacement of engine fuel valves and engine control boxes (ECA). System testing on the coach was stopped on February 18, 1981 because of a combustion chamber failure.

- Transmission--The coach was out of service approximately 11 days for transmission problems. The fluid coupling was replaced twice and the transmission was replaced once because of excessive clutch material and metal in the oil and oil pan. In addition, systems testing was delayed because of various fluid coupling back-up pressure adjustments made by DDA.

- Heating, Ventilating, and Air Conditioning (HVAC) System--The coach was out of service for HVAC changes approximately 20 days. The air conditioning portion of the HVAC system was inoperative which required the coach windows to be blocked open for ventilation on hot days. During the cold weather operation of the systems tests the coach was out of service twice because of the failure of the Webasto heater. The first failure, which accounted for the loss of 17 days, was caused by lack of parts availability from the factory.

- Tires--The coach was out of service approximately one day (24 hours) for the replacement of tires. Because of the rough surface of the high speed test track, the average tire tread mileage during testing was approximately 2,800 miles. The coach required two sets of tires while performing systems tests. High tire wear is normal for track testing and is not indicative of a problem with the turbine coach.

- Brakes--The coach was out of service approximately 9 days for brake replacement. During the first week of the systems tests the brake temperatures would not stabilize and the brake temperatures increased daily. On the sixth day

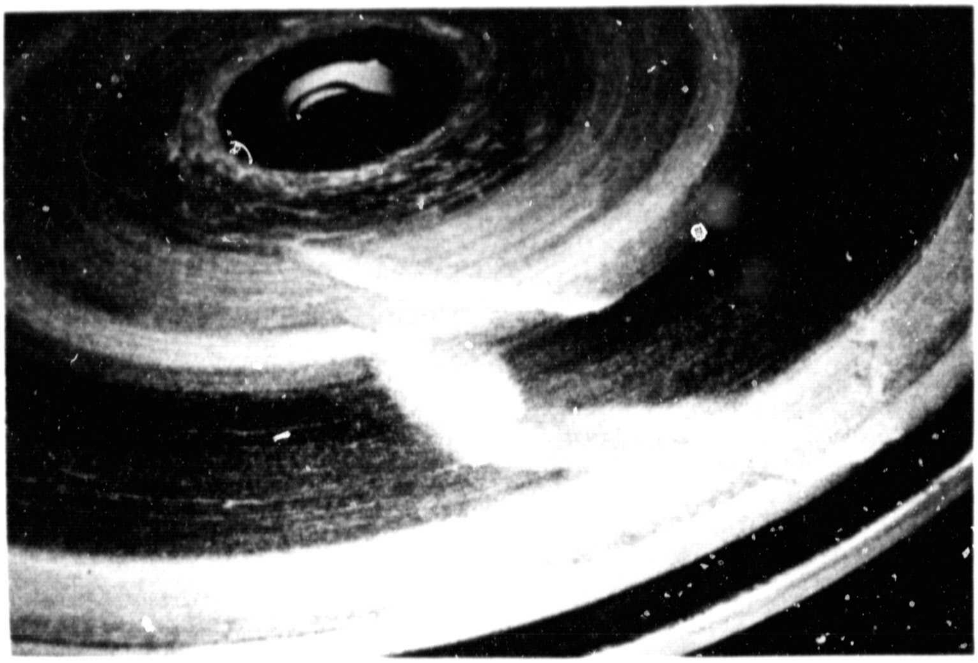

FIGURE IV-8
Damaged Left Ceramic Regenerator
(Close-up of Damaged Area)

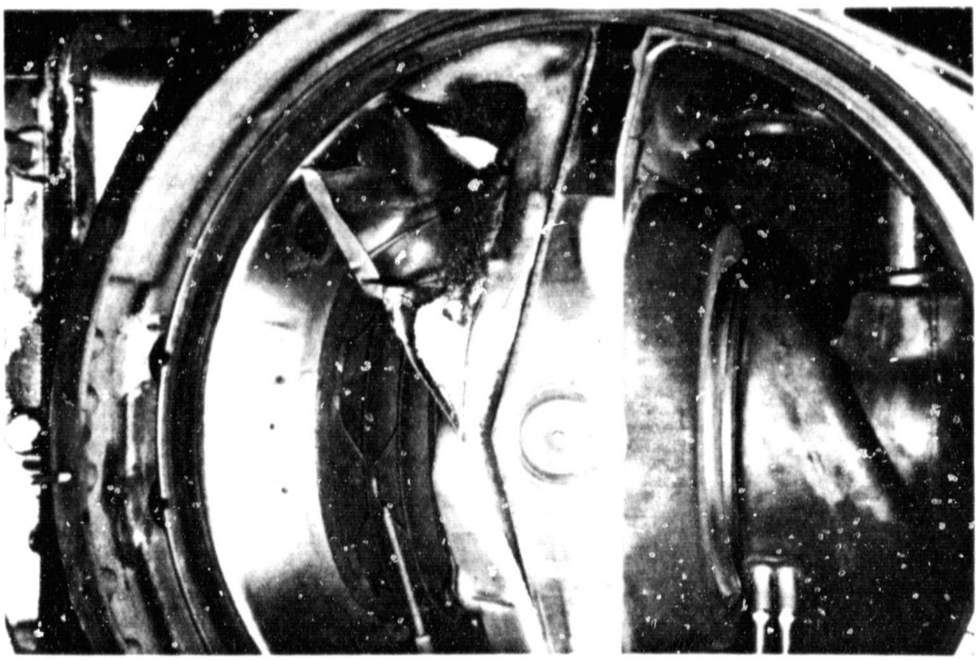

FIGURE IV-9
Damaged Left Ceramic Regenerator
(Showing Failed Hot-Cold Seal and T-6 Area)

the brake temperatures reach 985°F, at which time the brakes were checked and found to be glazed, Figure IV-10. The brake drums were turned and the linings replaced. The brake temperature monitoring instrumentation was very erratic and troublesome during the tests and caused some delays in the systems testing schedule.

The high brake temperatures experienced during the first week of testing was caused by the test procedure, which allows shutdown only for coach refueling. The test procedure was thereafter modified to include one hour of shutdown during every 8 hours of operation. This schedule is more indicative of actual revenue service operation.

- <u>Other Downtime</u>--The coach was out of service approximately 7 days for generator, regulator and 38-volt alternator problems. The generator was replaced because of the failure of the front bearing and required removal of the engine exhaust system to check the engine magnetic oil drain plug for the missing generator bearing retainer. The 38-volt alternator failed because of broken drive belts. Problems were also encountered with the transmission temperature switches and the transmission cooling fan relays.

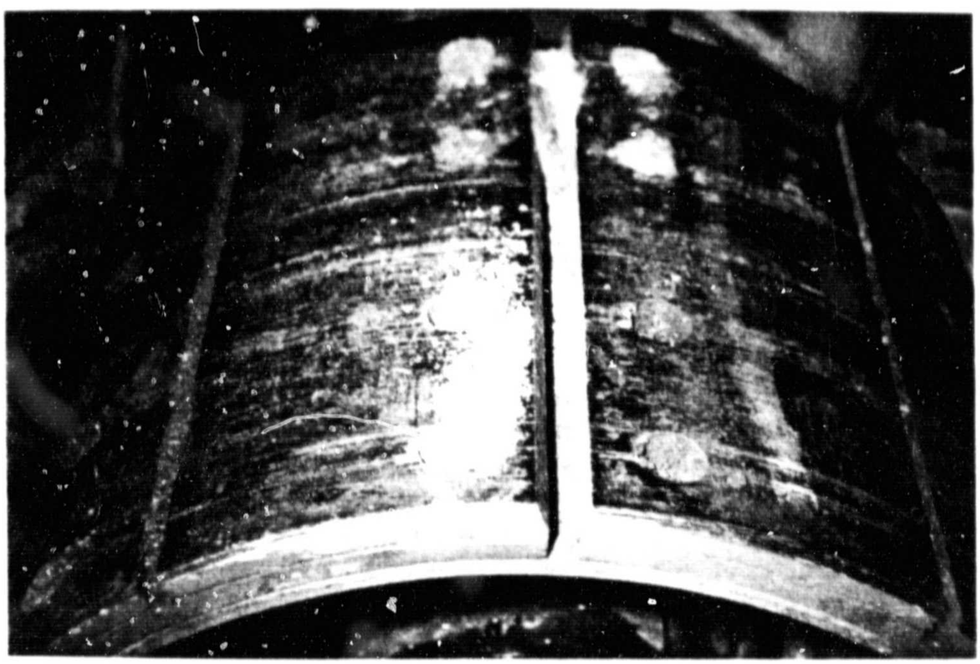

FIGURE IV-10
Glazed Brake Drums

- Adverse Weather Conditions--The coach was out of service for 130 hours from January 19, 1981 to February 18, 1981 because of adverse weather conditions at the high speed test track at TRC. These adverse weather conditions were due to either ice, snow of fog conditons that did not allow safe operation of the vehicle or that caused unsafe conditions affecting other test vehicles on the track.

Diesel Coach #3316 Systems Tests Results

Diesel coach #3316 began systems testing on January 16, 1981 and completed systems testing on February 24, 1981. The coach accumulated 8,495.3 miles during the 30 days of systems test operation.

The diesel coach was very reliable, operating on the systems test with a minimum of downtime.

During this time the coach was out of service for 10 days. It experienced three mechanical problems that were quickly resolved:

- Engine Throttle Slave Cylinder--The coach was out of service for 3 days when it developed an air leak, which required the installation of a new air throttle slave cylinder. The actual repair took 3 hours. The remainder of the time was spent awaiting delivery of the parts.

- Kneeling Controll Diversion Valve--A needed kneel check valve was installed while the track was closed for adverse weather so no test time was lost.

- Driver's Heater Fan Motor--The driver's heater fan motor was removed, while the track was closed for adverse weather, to investigate a complaint of a lack of heat. The front bearing was bad and was replaced.

The remaining downtime was due to tire changes, brake instrumentation difficulties, and adverse weather conditions. Closing of the track for adverse weather, as for the turbine coach, accounted for about 130 hours of downtime on the diesel coach.

V. PUBLIC DEMONSTRATION

V. PUBLIC DEMONSTRATION

A one-year revenue service demonstration was planned to provide operational and performance data from a "real world" environment. Past experience had shown this step to be necessary to verify proving grounds data and to acquire transit industry and public support for government-sponsored projects.

Selection of the best possible demonstration site is fundamental to a successful demonstration program. The following site selection criteria were developed to ensure such a selection:

- Adequate ADB fleet size
- Commitment to furnish coaches for repowering and in-city demonstration and willingness to provide additional proving grounds coaches
- Willingness to participate in the management of the demonstration and to dedicate personnel required
- Good public exposure under a variety of transit conditions
- Commitment to perform the demonstration within constraints of allocated program budget.

These selection criteria were applied to an initial list of 29 interested properties. Application of the criteria narrowed the list of potential site operators to three and the management of these properties were personally interviewed prior to the final selection of a demonstration site.

The DOE/DOT program sponsors selected the Mass Transportation Administration of Maryland to conduct the demonstration in Baltimore, Maryland. Ken Hussong, the Maintenance Director at Baltimore MTA, gave the following reasons for his interest in participating in the gas turbine transit bus program:

> "Mass transit properties' budgets overrun in maintenance, which is already a large share of operating costs. The Federal government may not

always be willing or able to bail them out. Properties have a responsibility to investigate every possibility of cutting costs, including new technology such as the gas turbine engine.

Since labor is such a big maintenance cost, anything that will reduce labor such as fewer wearing parts, elimination of water cooling system, or extended brake life is attractive."

The MTA and Booz, Allen, which was the technical director of the demonstration, developed a formal plan for conducting the demonstration program. The plan detailed the objectives, roles and responsibilities, facilities and logistics support, public awareness thrust, vehicle activities, data collection requirements, and reporting techniques. This document was to be the tool for controlling the public demonstration.

It was planned that the turbine coaches operate only on the weekdays and that the assigned routes be limited to the Annapolis-Baltimore run until the coaches had demonstrated a certain degree of reliability. This plan would allow MTA to limit comprehensive mechanic training to a specific, limited number of mechanics and to confine the driver training to a reasonable number of drivers. The plan would also ensure that program management would be available to solve problems as they arose.

The demonstration was divided into a number of activities:

- Driver/mechanic training
- Revenue service
- Non-revenue demonstration.

DRIVER/MECHANIC TRAINING

Training began before the first turbine coach was delivered to Baltimore for the demonstration. A two-week mechanics school on the gas turbine engine was conducted by DDA in April of 1980, and in February of 1981 Modern conducted training on the installation package.

Training of drivers began with the delivery of the first coach and continued intermittently throughout the demonstration as other drivers who select their own routes in this Division, selected the Baltimore-Annapolis route.

REVENUE SERVICE

Gas turbine coaches #3318, #3320, and #3321 were placed in revenue service early in April of 1981, Figure V-1. Gas turbine coach #3319, the proving grounds test coach, was delayed at the test track and began public demonstration the middle of May. During April, the coaches were available to operate in revenue service 69 percent of the scheduled coach days* and were operated on a revenue route 37 percent of the coach days. The three coaches accumulated 5,038 miles of revenue operation. Downtime was evenly divided between engine- and coach-related problems but the number of separate, specific coach-related problems outnumbered the engine-related problems by over two to one. This may be attributed to several reasons. For the most part, mechanics were familiar with coach-related problems and the repairs were generally easy to accomplish. Engine problems on the other hand were usually more complicated to diagnose and to repair, especially on the prototype gas turbine engines with which they had had minimum exposure and experience.

FIGURE V-1
Gas Turbine Coach #3321 in Revenue Service
(April 1981)

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* Number of weekdays in the month multiplied by the number of gas turbine coaches delivered to MTA.

Coach #3319 was delivered to Baltimore on May 5 and placed in revenue service on May 12. The four gas turbine coaches continued to operate in weekday revenue service and accumulated 4,997 miles of service. The coaches were available fo⁻ service 54 percent of the coach days and operated 38 p⁻rcent of the coach days. Approximately 63 percent of the downtime this month was engine-related, however the number of coach-related problems reported continued to outnumber engine problems by two to one.

The four coaches continued to operate throughout June, accumulating 9,184 miles of service, Figure V-2. They were available 73 percent of the coach days and operated 72 percent of the coach days, which accounts for the higher accumulated mileage. Sixty-seven percent of the downtime was because of engine-related problems, but the ratio of coach-related to engine-related problems remained a little over two to one.

The gas turbine coaches were planned to operate in tandem with a like number of diesel-powered coaches on the same schedules and routes. Because of the logistics and costs involved with this plan however, the control concept

FIGURE V-2
Gas Turbine Coach #3321 in Revenue Service
(June 1981)

was modified so that MTA simply collected like data on specified diesel coaches during the demonstration time period. This modification makes direct comparison of the data impossible, but it is valuable to compare the two sets of data for general operational results and trends.

Figure V-3 graphically displays the availability for service, and usage of the gas turbine coaches and the diesel baseline against their respective number of coach days. Because the demonstration was terminated early (at the end of the third month) any conclusions or comparisons need to be made with care. One observation may be that MTA's need for coaches to operate in revenue service did not exceed the availability of coaches, either diesel or turbine, during the three months as indicated by the "available, not used" spaces on the chart. Another observation may be that it took the MTA several months before they began to maximize the revenue service operations of the gas turbine coaches. One last observation may be that the program coaches, both turbine and diesel, did not receive especially preferential maintenance treatment as indicated by the large blocks of "not available" time. This may be because, in MTA's desire to keep the most coaches possible operational at all times, they sometimes made the program coaches wait in turn for service and repair. Diesel control coach #3303 was sidelined for 36 days in May and June for a hole in the engine block. Diesel control coach #3305 was sidelined most of June because of water in the crankcase.

Figure V-4 categorizes the types of problems reported for both the diesel coaches and the gas turbine coaches on an incidences per coach day basis. This method of comparison was selected so that some correlation could be made even though each group had different numbers of vehicles and operated different number of days. Since the gas turbine coaches experienced more engine/transmission problems on a per coach day basis, the related systems such as batteries and electrical are proportionately larger. Air conditioning problems were about the same for each group but coach-related problems such as brakes, door mirror and miscellaneous were smaller for the turbine coaches. This may have been due to the turbine coaches being brought up to new condition just prior to the demonstration while the diesels simply continued to operate as fleet vehicles without a pre-demonstration inspection and tune-up.

The revenue service demonstration in Baltimore was stopped by MTA at the end of June when two of the four gas turbine coaches were down for major engine problems. MTA stated that they believed the turbine coaches were

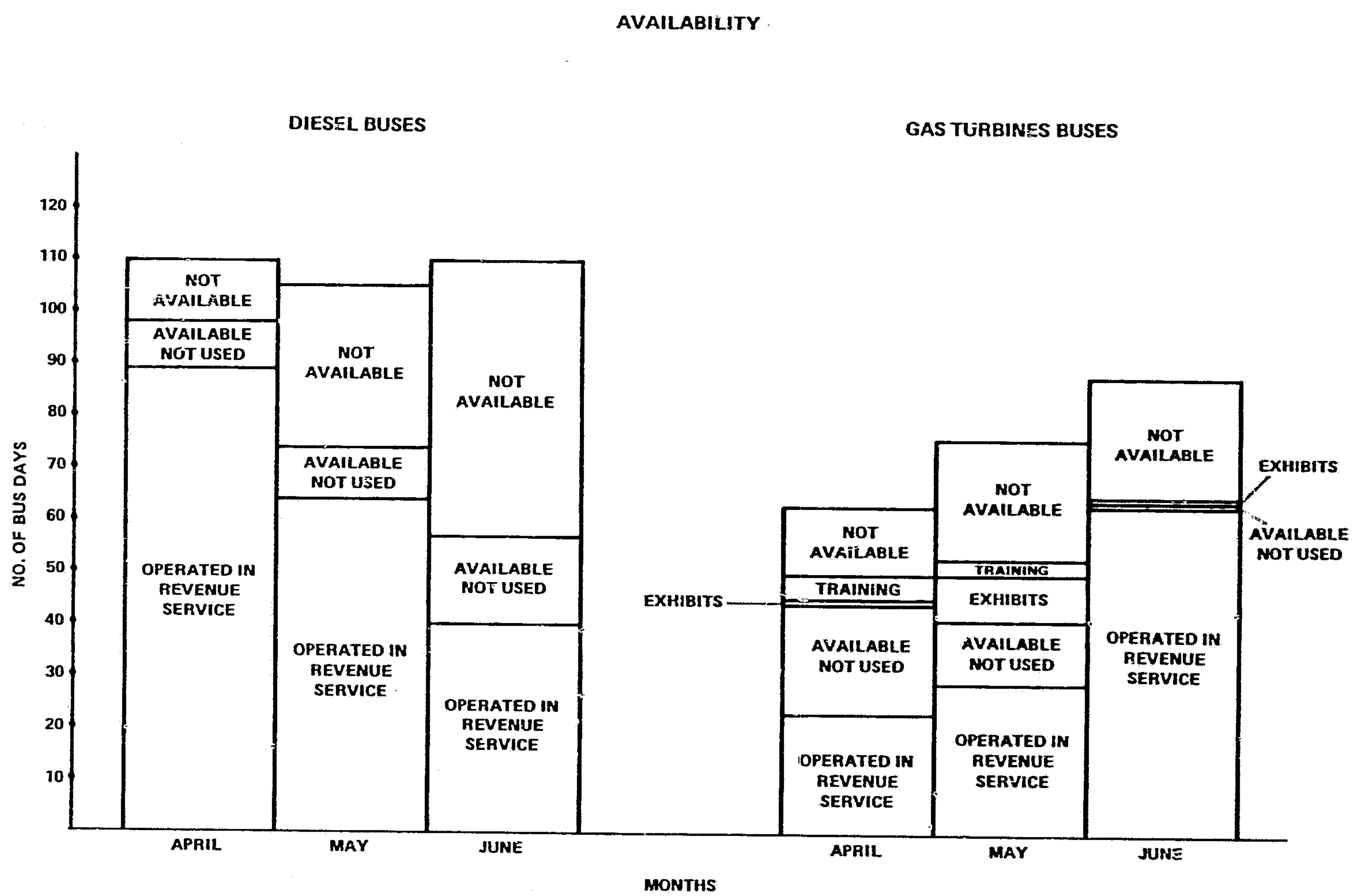

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FIGURE V-3
Gas Turbine Coaches Availability for Service

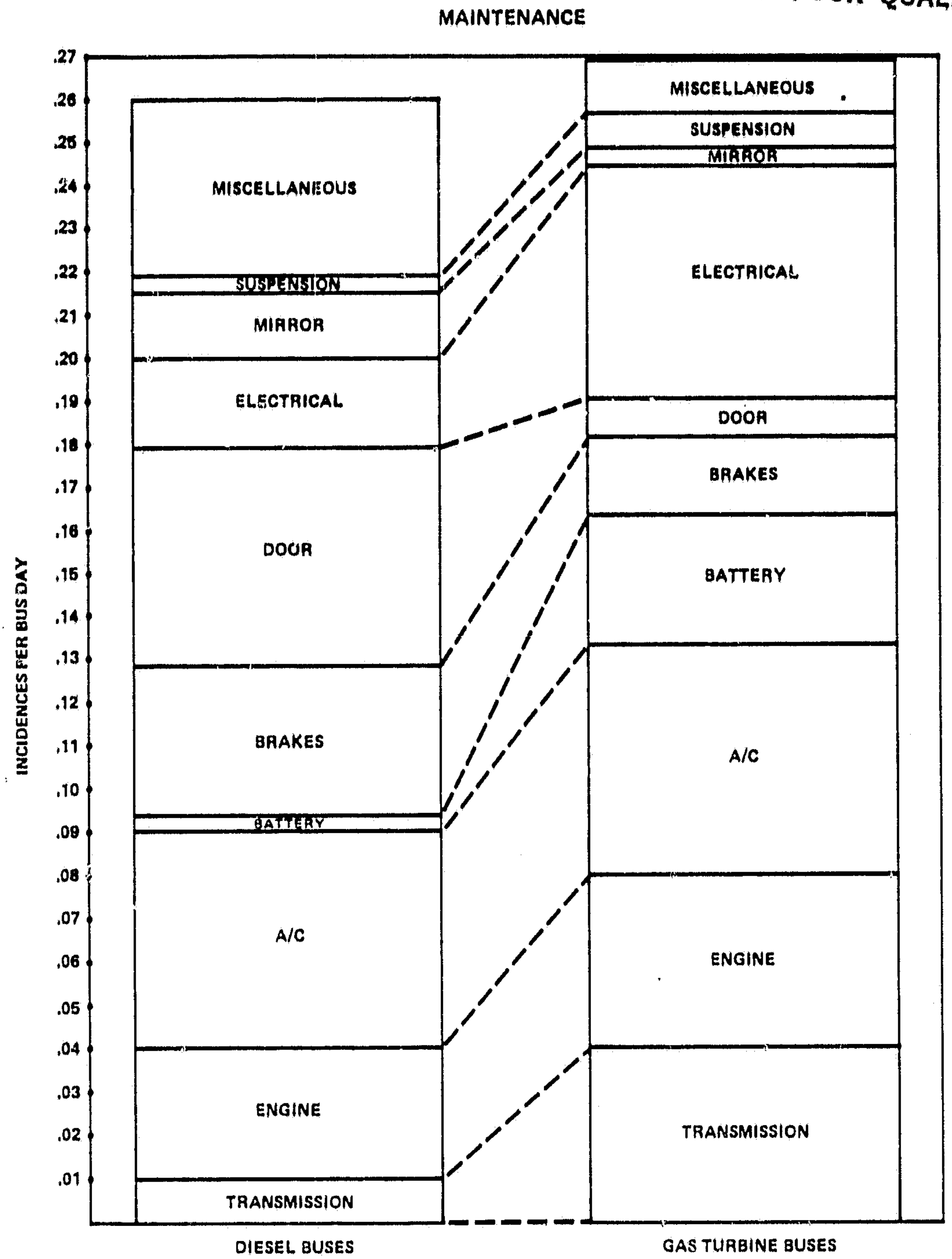

FIGURE V-4
Types of Maintenance Problems for
Diesel and Gas Turbine Coaches

requiring an inordinate, and unplanned for, amount of maintenance time and expense. They were also unable to obtain formal commitment from UMTA to extend their financial grant to conduct the demonstration and perform these extra repairs.

The termination of the demonstration is in part related to the engine reliability problems encountered. Thus it is appropriate to discuss here the number and types of engine failures that occurred during the demonstration:

- Coach #3318
  - On April 23, the left hand inboard and outboard seals and left hand ceramic regenerator disc failed and had to be replaced
  - On May 6, the engine oil pump drive gear and shaft had to be replaced
  - On June 15, the ceramic regenerators failed again.
- Coach #3319
  - On May 19, the transmission failed and had to be replaced
  - On June 26, the left hand ceramic regenerator disc failed.
- Coach #3320
  - On May 25, regenerator on this coach was pulled for an investigative inspection into the causes of failures on the other coaches.
- Coach #3321
  - On May 13, the left hand ceramic regenerator seal failed and had to be replaced.

Four other engine failures occurred during the program--three at the proving grounds and one during a non-revenue demonstration in Baltimore. These problems are discussed under the activity headings.

NON-REVENUE DEMONSTRATIONS

Non-revenue demonstrations of the gas turbine coaches occurred throughout the program. The first unveiling of the gas turbine coach took place in Dearborn, Michigan on April 14, 1980 when Coach #3319 was exhibited at the Fifth International Automotive Symposium for five days, Figure V-5. Symposium attendees were invited to examine the engine installation and were given rides on the coach to evaluate its performance. Local television and radio stations covering the symposium featured the coach on several evening news programs.

From Dearborn, the coach was driven to Baltimore, Maryland for an official ribbon cutting ceremony held in connection with MTA's 10th anniversay, Figure V-6. Dignitaries at the ribbon cutting ceremony, as shown in Figure V-6, were (from left to right):

- Frederick Dewberry, Deputy Secretary of Maryland DOT
- L. A. Kimball, Administrator of Maryland MTA
- Theodore Lutz, Administrator of the Urban Mass Transportation Administration (UMTA) of DOT
- Henry Stadler, Director of Office of Vehicle and Engine R&D of DOE.

FIGURE V-5
Gas Turbine Coach #3319 on Display
at Dearborn, Michigan

FIGURE V-6
MTA Ribbon Cutting Ceremony

One September 3, 1980, Senator Charles Mathias of Maryland was given a special demonstration and ride on Coach #3321 prior to its exhibition on September 9 and 10 to attendees at the Southesastern Coach Maintenance Forum being held in Towson, Maryland. Between these two exhibitions the coach developed a power dimnishment, which was caused by defective left hand ceramic regenerator seals. DDA sent two engineers to Baltimore and replaceed the seals.

On April 15 UMTA regional officials from Philadelphia were given a special exhibition of gas turbine coach #3318. The coach performed well except for rough shifting of the transmission.

From May 5 through May 14 Coach #3320 was on static display in the Baltimore Convention Center for the Maryland AFL-CIO Convention where over 3,000 people viewed the coach and the engine installation.

Public/driver reaction surveys were conducted by the MTA Marketing Department. However, the Marketing Director reported the theft of this data during a break-in at the MTA and it was not available to Booz, Allen for analysis.

The next chapter in this report recaps the program participants and their expected role in the program.

VI. PROGRAM PARTICIPANTS

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The "Gas Turbine Transit Bus Demonstration Program" was a cooperative effort by the Division of Transportation Energy Conservation (TEC) of the U.S. Department of Energy (DOE) and the Urban Mass Transportation Administration (UMTA) of the U.S. Department of Transportation (DOT) to test and evaluate the use of gas turbine engines in transit coaches.

The program participants are shown in Figure VI-1. In addition to DOE and DOT, they included:

- Jet Propulsion Laboratory (JPL)
- NASA-Lewis Research Center
- Booz, Allen & Hamilton, Transportation Consulting Division
- Detroit Diesel Allison Division (DDA) of General Motors Corporation
- Modern Engineering Service Company
- Transportation Research Center (TRC) of Ohio
- Mass Transit Administration (MTA) of Maryland
- Midwest Bus Rebuilders.

The roles and responsibilities of each participant are described below.

U.S. DEPARTMENT OF ENERGY (DOE)

DOE was responsible for the overall program direction. DOE provided overall program strategy and controls consistent with meeting joint DOE and DOT goals and objectives supplied funds for the planning and implementation and issued reports on program results. Because of the program's time constraints, DOE directly procured the gas turbine engines for Phase I. DOE also interfaced directly with various government agencies and continually assessed technical output for transfusion into the advanced automotive heat engine developments program.

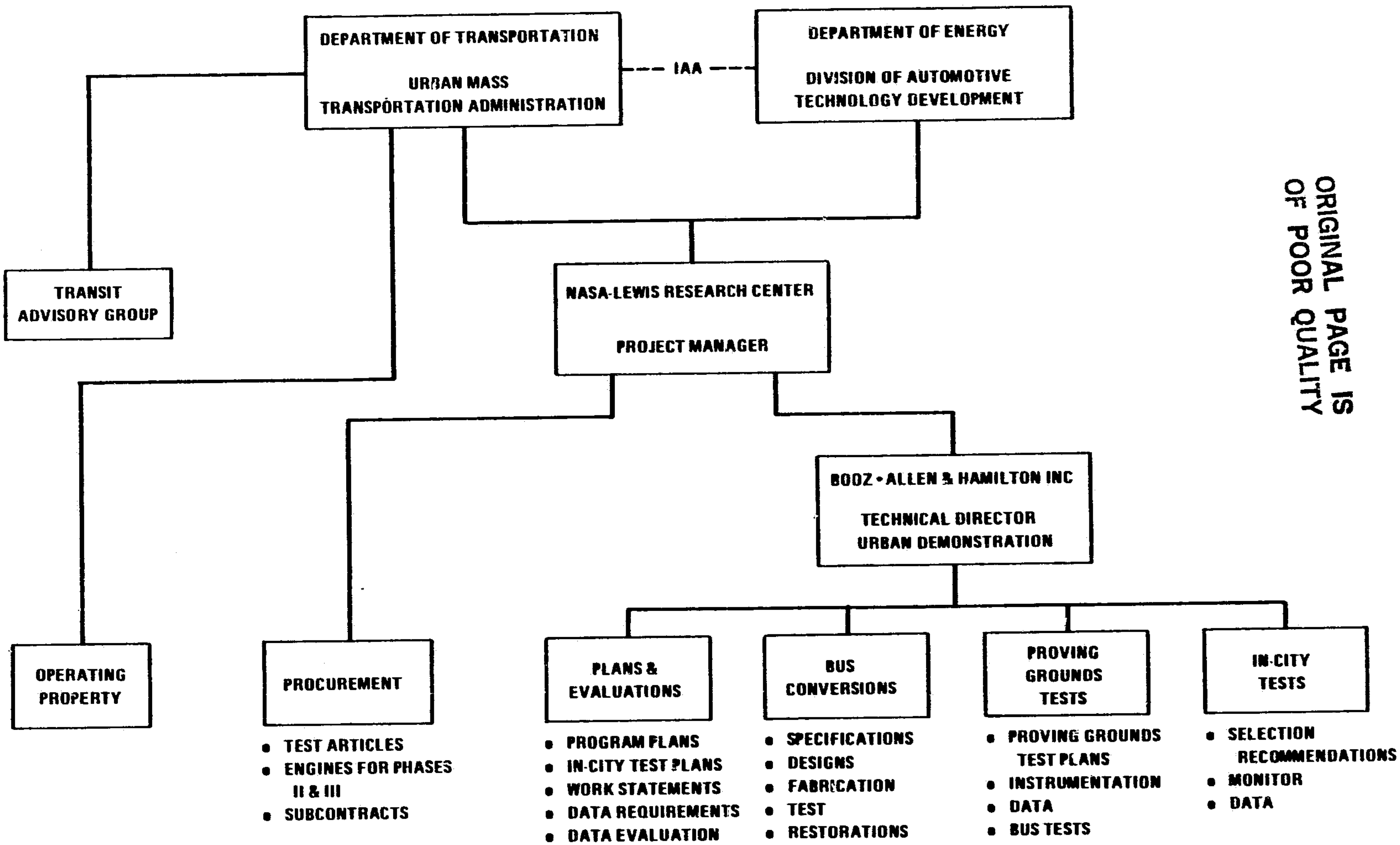

FIGURE VI-1

Program Participants

U.S. DEPARTMENT OF TRANSPORTATION (DOT)

DOT was responsible for the overall technical direction of the in-city demonstration. DOT's Urban Mass Transit Administration (UMTA) provided guidance for and coordination of the site selection activities for the demonstration and made formal announcements of demonstration activities. UMTA provided engineering and management support as required, and assisted in special presentations and demonstrations as required, and also provided coordination, liaison, and principal interface with other parts of DOT and the transit industry.

JET PROPULSION LABORATORY (JPL) AND NASA-LEWIS RESEARCH CENTER

JPL initially served as the project manager, responsible for the procurement and monitoring of services required for program implementation. The NASA-Lewis Research Center later replaced JPL in this function.

The project manager was the single point of contact with regard to programmatic elements involving the project. The project manager was responsible for the quality, timeliness, reasonableness of cost, and performance of all services. They provided for schedule control, management reporting, and monitoring of technical results through the use of a reporting structure to ensure that technical, cost, manpower, and schedule data were compatible and could be analyzed on an integrated basis.

BOOZ, ALLEN AND HAMILTON INC. (BA&H)

Booz, Allen & Hamilton (BA&H) was the technical director for the in-city demonstration project responsible for planning and implementing the project. BA&H developed detailed plans, procedures, specifications, and the data systems to be used in the testing program. BA&H subcontracted the coach/engine conversion and integration activities as well as the restoration activities at the end of the demonstration and provided technical direction and guidance for conversions. BA&H monitored the subcontractor work and provided support as required. BA&H conducted acceptance tests on the coaches before delivery for further program testing, directed the performance and systems testing at the proving grounds, and provided for the collection and evaluation of the in-city test data.

DETROIT DIESEL ALLISON (DDA)

DDA was responsible for provision of the gas turbine engines and the transmissions that were installed in the transit coaches for proving grounds and in-city testing.

DDA was under contract to provide six all-metal prototype engines for Phase I but later retrofitted them with ceramic components. They provided an engine buck for initial coach installation modeling, and engineering support to the conversion shop for integration of the coaches/engines and for the auxiliary heating system. They also provided specific spares and engineering support, as necessary, during the proving grounds tests and the in-city demonstrations. Prior to the testing and demonstrations, they provided training for the gas turbine-powered coach drivers and mechanics. They also provided technical assistance, as requested, to identify or correct any engine installation or operating problems.

MODERN ENGINEERING SERVICE COMPANY (MODERN)

Modern provided manpower, facilities, equipment, and materials for the conversion activities under subcontract to Booz, Allen. Under Booz, Allen's technical direction, they developed the engine installation design and engineering drawings, and designed the heating system installation in the gas turbine-powered test coaches. Modern also performed the coach conversions at the beginning of Phase I.

TRANSPORTATION RESEARCH CENTER (TRC) OF OHIO PROVING GROUNDS

TRC was contracted to provide manpower, facilities, and certain instrumentation for testing. TRC conducted the engineering and development testing of the first retrofitted coach. TRC conducted the performance and systems testing on both the turbine and diesel proving grounds test coaches, performed routine service and maintenance on the proving grounds coaches, and kept accurate daily records of all proving grounds activities.

MASS TRANSIT ADMINISTRATION (MTA) OF MARYLAND

The MTA was responsible for providing the advanced design production coaches as required for conversion to gas turbine engine power and acceptance testing before being returned for the in-city demonstrations. MTA supplied drivers and mechanics for the coaches during the revenue service demonstration. These employees attended training by DDA in the proper care, maintenance and techniques for operating the gas turbine coaches. The MTA was also responsible for conducting the demonstration testing in accordance with the demonstration plan developed cooperatively with Booz, Allen. MTA provided routine coach maintenance and repair, special demonstrations/displays, and technical data collection.

MIDWEST BUS REBUILDERS INC.

Midwest provided the manpower, facilities, equipment and materials for the reconversion activities at the close of Phase I. Using the specifications and drawings, they restored the gas turbine coaches to their pre-test condition except for the dual fuel tanks and the modified air conditioning which MTA requested be retained.