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Development of an Ultra-Safe, Ultra-Low Emissions Natural Gas-Fueled Bus

Phase I: Systems Design

Final Report

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Preface

The National Renewable Energy Laboratory (NREL) contracted with Southwest Research Institute (SwRI) to develop an ultra-safe, ultra-low emissions natural gas-fueled school bus. The project team consists of SwRI, Blue Bird Corporation, Deere Power Systems Group, and CNG Cylinder Company. Design of the component systems, i.e. vehicle, engine, and fuel storage systems, was the primary focus of work for Phase I.

The author would like to acknowledge the contributions made by the following people for providing the material used in compiling this report: Don McCaw, Deere Power Systems Group, John Drawe, Blue Bird Corporation, and Bart Hayes and Dan Arcese, both of CNG Cylinder Company.

Executive Summary

The National Renewable Energy Laboratory (NREL) contracted with Southwest Research Institute (SwRI) to develop an ultra-safe, ultra-low emissions natural gas-fueled school bus. To develop the bus, SwRI teamed with Blue Bird, Incorporated, a school bus manufacturer, Deere Power Systems Group, an engine manufacturer, and CNG Cylinder Company, a supplier of compressed natural gas storage and handling systems. The primary focus of work for Phase I was the design of the component systems, i.e. vehicle, engine, and fuel storage systems.

The Deere 6081 natural gas engine is the base engine for the proposed school bus. Several modifications are required to optimize its performance and emissions potential, since the current engine design underwent a rapid development process. Additional engine design will involve redesign and reevaluation of several of the power cylinder components. These modifications are required for several reasons: reduced oil consumption, increased efficiency, and increased durability. Modifications which lower oil consumption are intended to reduce particulate emissions.

Blue Bird has initiated work on design and construction of the prototype bus. The new bus design will offer increased driver visibility, a wider body and a new roof structure. A child restraint system which utilizes seat belts will also be incorporated into the new design. Design has been completed on the new chassis. The new chassis allows simplified removal of the CNG fuel tanks and provides increased side impact protection and lower weight. The chassis has been designed to accommodate the Deere 6081 engine, control system, and exhaust system, and the intake air and engine coolant cooling systems. A new four-wheel disc brake system has also been developed for the bus.

CNG Cylinder Company has made a design change on the compressed natural gas fuel tanks which it will be delivering for the bus. Fiberglass-wrapped aluminum tanks will be substituted for the all-composite tanks originally proposed. This change has several reasons: safety concerns, production scheduling, and some technical issues.

The bus chassis prototype is expected to be completed by the middle of July, 1995. A complete prototype vehicle body and chassis should be delivered to SwRI by the beginning of December, 1995. This prototype vehicle will include the new compressed natural gas cylinders and associated fuel storage system hardware which has been designed by CNG Cylinder Company.

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Technical Discussion

Design of Component Systems

Phase I of this project, System Design, concentrated on design of each of the component subsystems. These subsystems included the engine and control system, bus body and chassis, and compressed natural gas fuel storage system. The major features of the design work for each of these systems is outlined below.

Engine Design

The Deere 6081 natural gas engine will be the base engine for the proposed school bus. A photograph of the 6081 engine is shown in Figure 1. This engine, in its present form, will require several modifications to optimize its performance and emissions potential. Figure 2 is summary of the emissions obtained by the engine in its current configuration. The current emissions levels out of the engine nearly meet the California Air Resources Board (CARB) Ultra-Low Emissions Vehicle (ULEV) limits for oxides of nitrogen plus nonmethane hydrocarbons (NO_x + NMHC) and particulate matter (PM) but greatly exceed those for formaldehyde (HCHO). To meet the CARB standards, therefore, an oxidation catalyst is required. As Figure 2 indicates, this catalyst removes nearly all of the carbon monoxide and formaldehyde. It also removes a significant amount of the unburned hydrocarbons and particulates.

Figure 3 shows a comparison between the current levels and the desired goals for this project. The current engine design underwent a rapid development process, and additional efforts will lead to a more optimum design, which should be able to provide the same or lower emissions with increased efficiency. The main focus of the project will be to lower the engine-out NO_x emissions to the 1.0 g/bhp-hr level without a significant increase in hydrocarbon emissions. Further reductions in particulates are also desired. While emissions reductions are important, additional emphasis will be placed on maintaining or improving engine efficiency. The maximum efficiency level of the current engine is approximately 38 percent. A goal of the project will be to reach the 40 percent efficiency level at the lower emissions levels. This level of accomplishment has been attained in a recent engine development project, details of which were found in a literature search.

Base Engine Changes

Most of the additional engine design will involve the power cylinder components. At the beginning of Phase I, the engine had unacceptable engine-out particulate emissions, and this problem was due to high oil consumption. The power cylinder components have a large effect on oil consumption, and modifications which lower oil consumption should have a positive effect on particulate emissions. Two piston/piston ring/valve guide seal configurations were identified as potential low particulate emission components during the original development work on the Deere 6081 engine. Complete sets of these prototype components are currently being procured from various suppliers. Prototype cylinder liners designed to lower oil consumption will also be obtained.

The piston design will change in several ways. The compression ratio will be raised to 11:1 or possibly 12:1 from the current 10:1 level in order to increase efficiency. Figure 4 shows the effect of increasing compression ratio on the thermal efficiency of a typical Otto-cycle engine. The piston-head clearance will be reduced from approximately 0.080 inches to 0.031 inches. This reduction in clearance should increase the squish velocity level as shown in Figure 5. Higher squish velocity levels promote increased in-

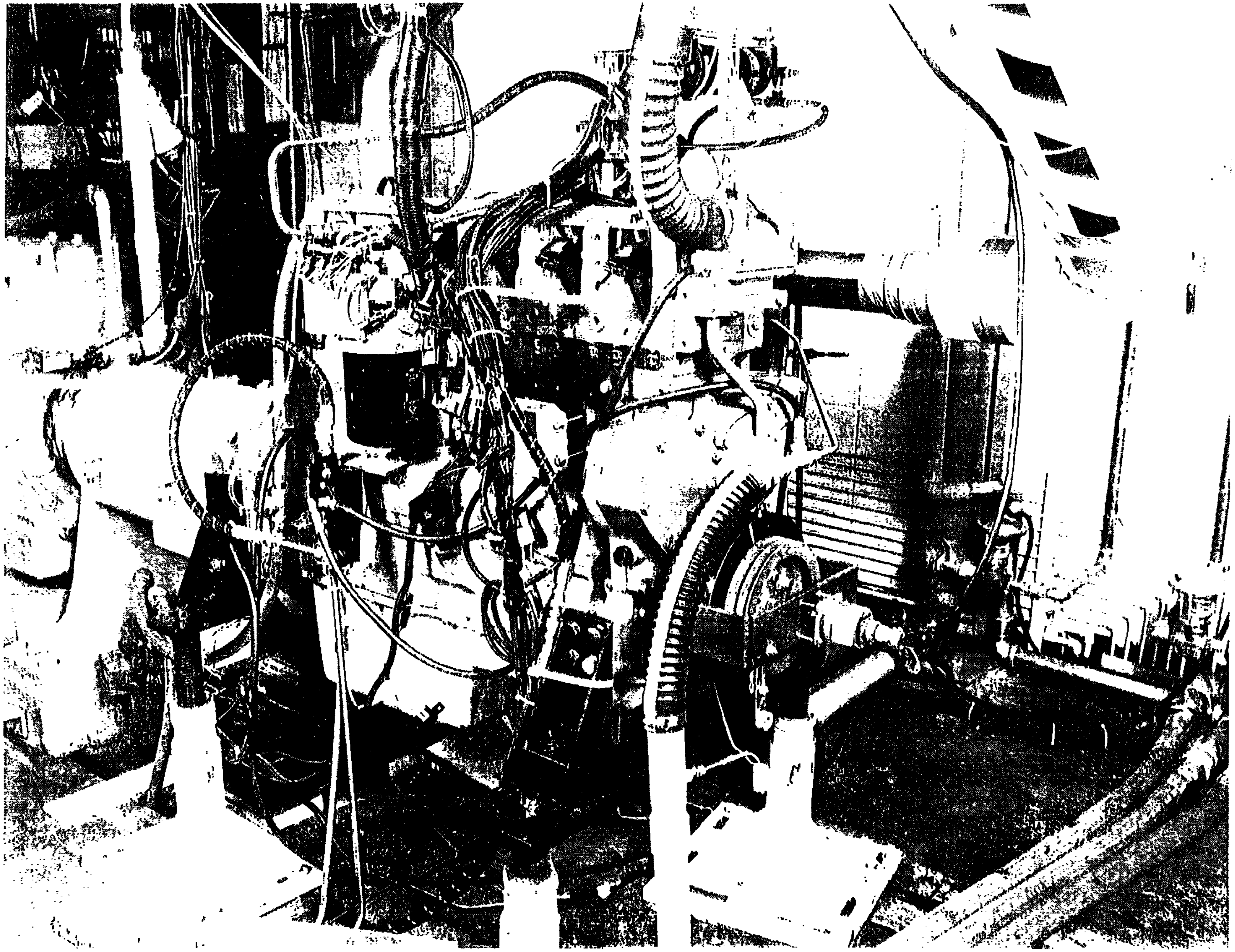


Figure 1. Photograph of Deere 6081 engine

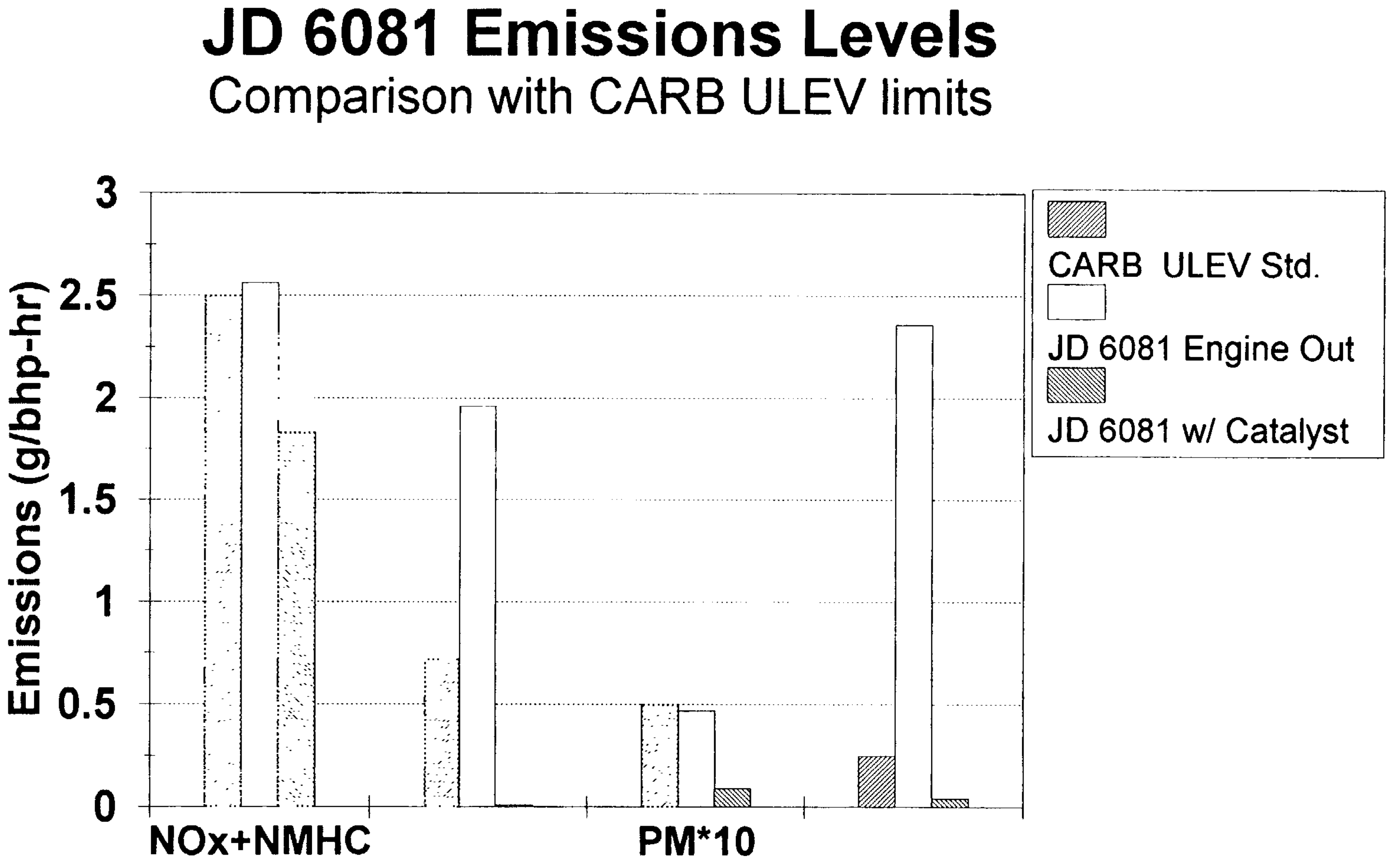
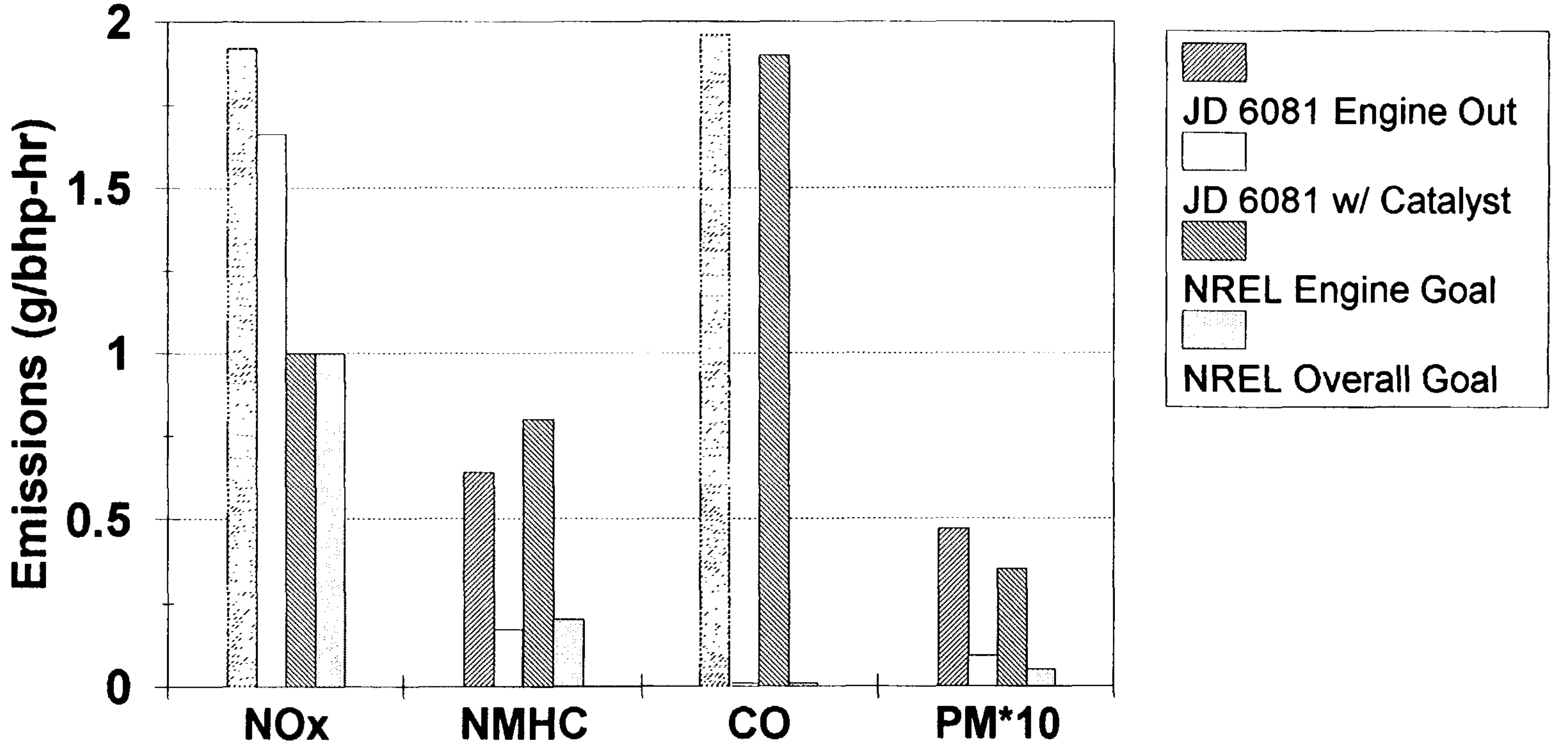


Figure 2. Emissions levels for current engine configuration

Emissions Comparison

Current JD 6081 Levels vs. NREL Goals



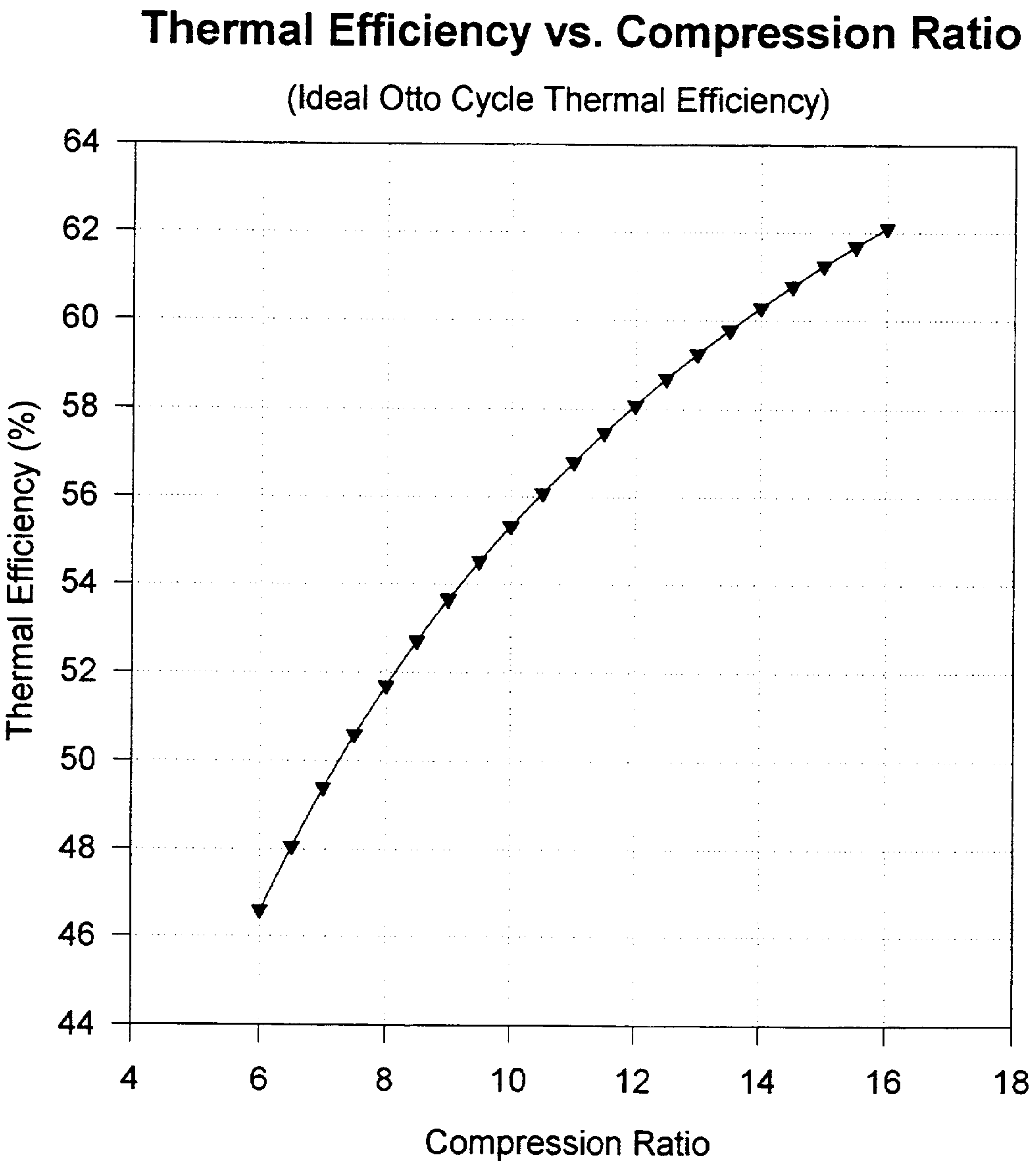


Figure 4. Effect of compression ratio on thermal efficiency

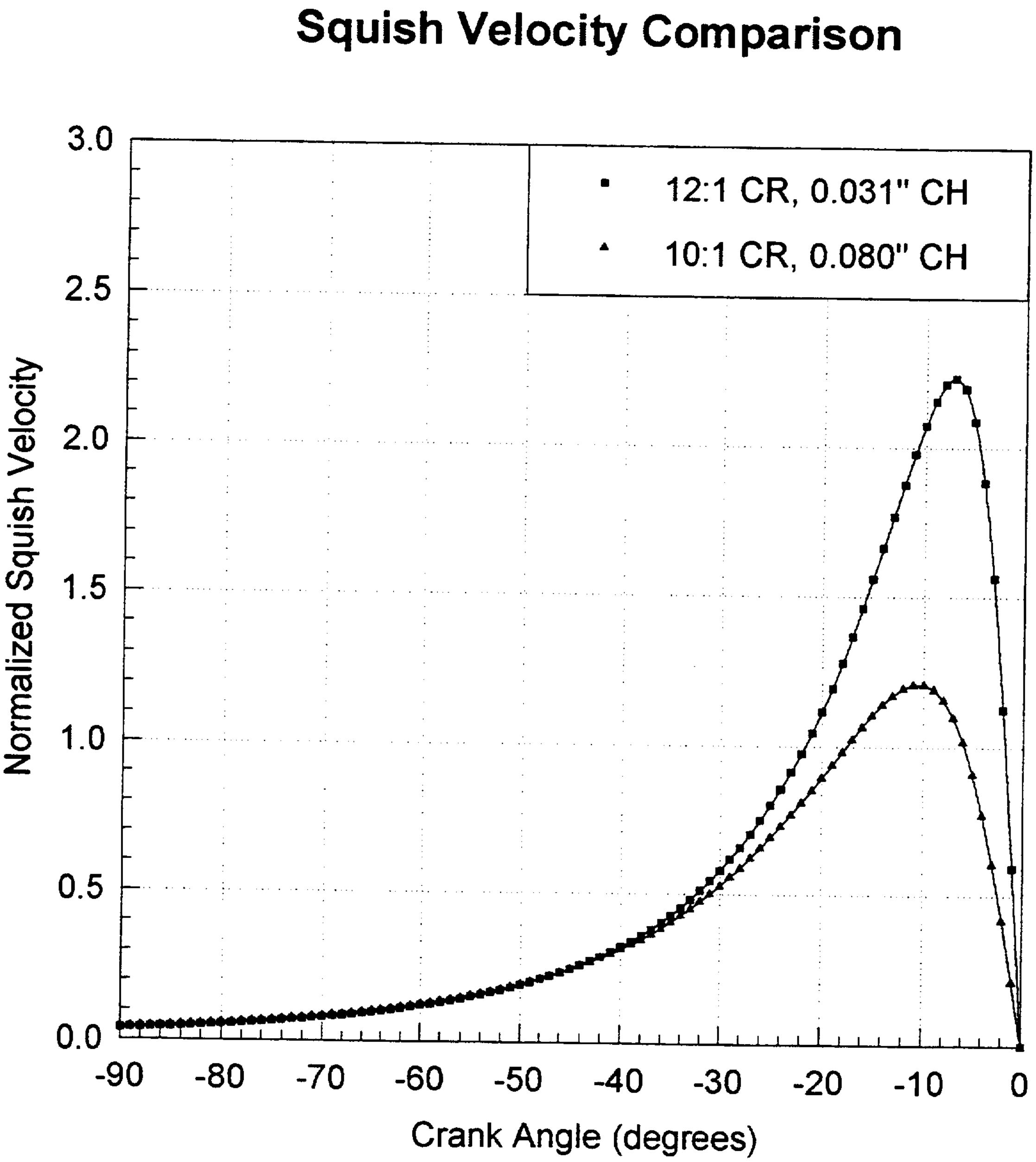


Figure 5. Comparison of squish velocity for two piston designs

cylinder turbulence levels which provide more efficient lean combustion and increased knock tolerance. Another change will be to modify the piston bowl geometry. A directed squish piston will be tested to see if any performance advantage over a simple bowl geometry can be found.

The valve and valve seat angles will be changed to 30 degrees, since this angle has been shown to increase the flow capacity of the valve seat, while maintaining good durability. Powdered metal or ceramic valve guides will be tested in an attempt to reduce wear of these components. Use of ceramic valve guides will also allow use of zero-leakage valve guide seals which should lower the oil consumption of the engine and the resulting particulate emissions. The intake ports in the head will be modified to uniformly lower the swirl number at each port to reduce pressure losses and provide equal filling of each cylinder. The schematic shown in Figure 6 summarizes the changes being made to the power cylinder components and the effect each change will have on the performance or emissions of the engine.

A larger turbocharger turbine housing and a less restrictive exhaust manifold will be tested for reduced exhaust back pressure on the engine. Reductions in back pressure on the engine are expected to produce more efficient operation and extension of the lean misfire limit.

Emissions Control System

Control Strategies

Several strategies for controlling the air/fuel ratio will be studied to determine their advantages and disadvantages in terms of transient response and emissions control. The current speed-density system will be compared to a modified speed-density system based on a model of the air induction system. This "observer-based" technique should provide a better estimate of intake air flow during transient conditions and allow better fuel control. These systems will also be compared to a mass air flow system which utilizes a direct measurement using a mass air flow sensor.

Various methods for fuel introduction and metering will also be studied. The current engine uses pulse-width modulated (PWM) fuel injectors, very similar to those used in gasoline engines. Two types of proportional metering valves, which provide a steady flow of fuel, will be tested. One of these valves is a low pressure metering valve developed at SwRI. The systems will be compared to determine if any control or emissions benefits can be attained by changing to the new fueling equipment.

Catalyst manufacturers will be consulted to obtain the optimum oxidation catalyst for lean-burn, natural gas operation. The catalyst will be required to readily oxidize nonmethane hydrocarbons. In addition, the catalyst should also oxidize a significant fraction of the methane emissions.

Engine Diagnostics

Increasing the compression ratio of the engine will increase the likelihood of knocking combustion, which could potentially damage the engine. Available knock sensor technology will be evaluated to determine how well knocking conditions can be detected. Signal conditioning and control algorithms for determining the presence of knock and enabling corrective action will also be investigated. In a parallel effort, Gas Research Institute (GRI) will be funding the development of a magnetostrictive knock sensor. This sensor functions on an entirely different principle compared to typical piezoelectric knock sensors. The magnetostrictive sensor consists of a magnet and a pickup coil. The magnet induces a magnetic field in the engine structure, and as the engine structure undergoes an elastic wave due to vibrations caused by knocking, the magnetic field changes and this change is detected by the pickup coil. This sensor has been shown to be sensitive to both knocking and misfire conditions, and it is possible that one sensor could be

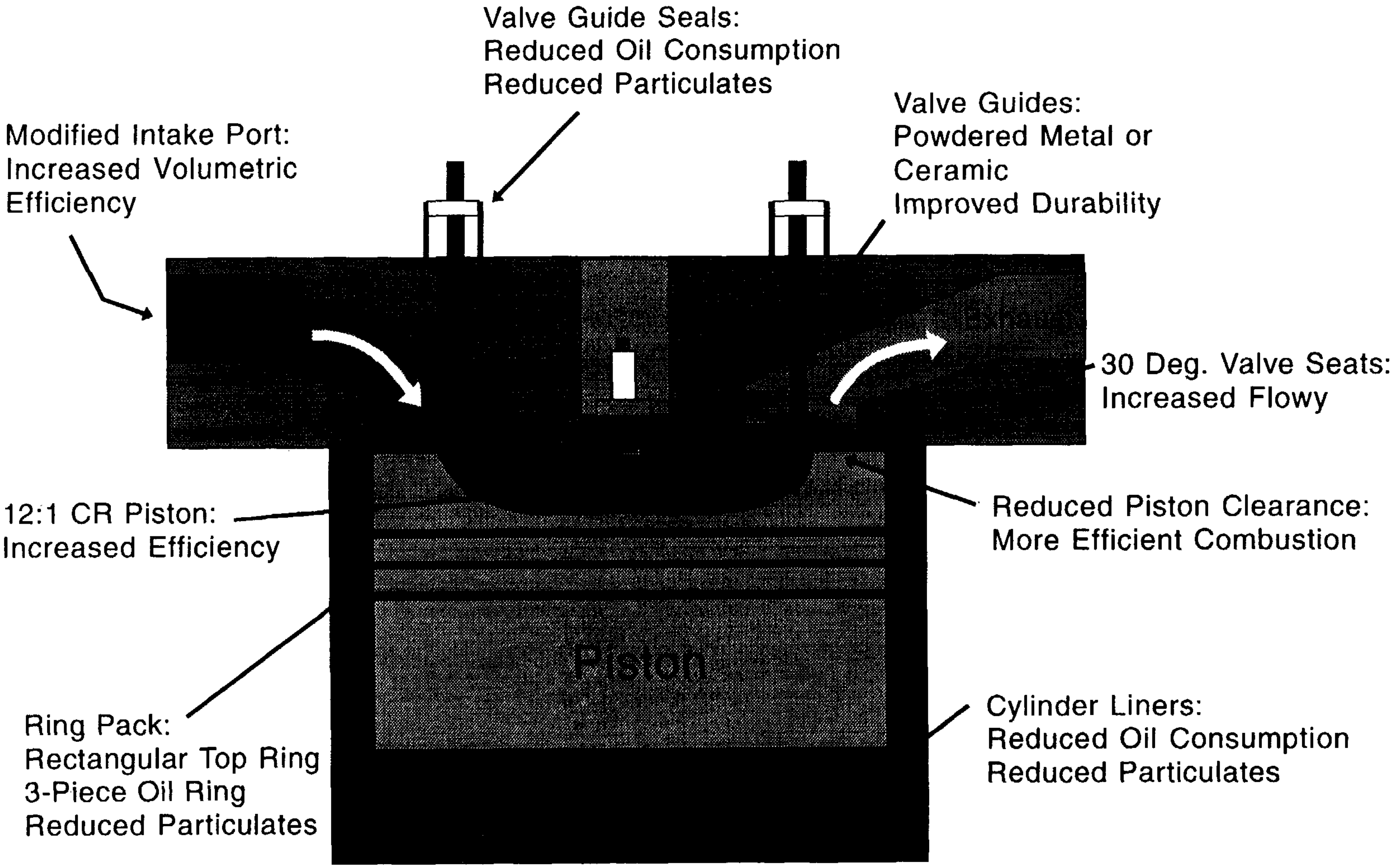


Figure 6. Schematic of proposed engine changes

used for both purposes. GRI will use the Deere engine as a test bed for development of the sensor, since a typical lean-burn, turbocharged natural gas engine is required. If this sensor development is successful, this technology will be incorporated into the Deere control system.

Meeting the CARB ULEV goals will require an oxidation catalyst which maintains a high conversion efficiency. Monitoring the effectiveness of the catalyst with dual UEGO sensors will be investigated. A UEGO sensor will be placed before and after the catalyst. The output of the two UEGO sensors will be compared to determine the catalyst efficiency. If the catalyst is working properly, the concentration of oxygen after the catalyst should be lower than before the catalyst, due to utilization of the excess oxygen by the catalyst to oxidize carbon monoxide, unburned hydrocarbons, and particulates.

Detection of misfire will also be investigated using instantaneous crank angle velocity (ICAV) measurements. Lean Power, Inc. offers a digital signal processing chip which provides a misfire indication based on ICAV measurements using a magnetic pickup on the flywheel. An evaluation board which uses this chip will be purchased from Lean Power. A series of misfire tests will be conducted to see if the board can reliably detect misfire. If so, this technology will also be integrated into the Deere control system.

Vehicle Design

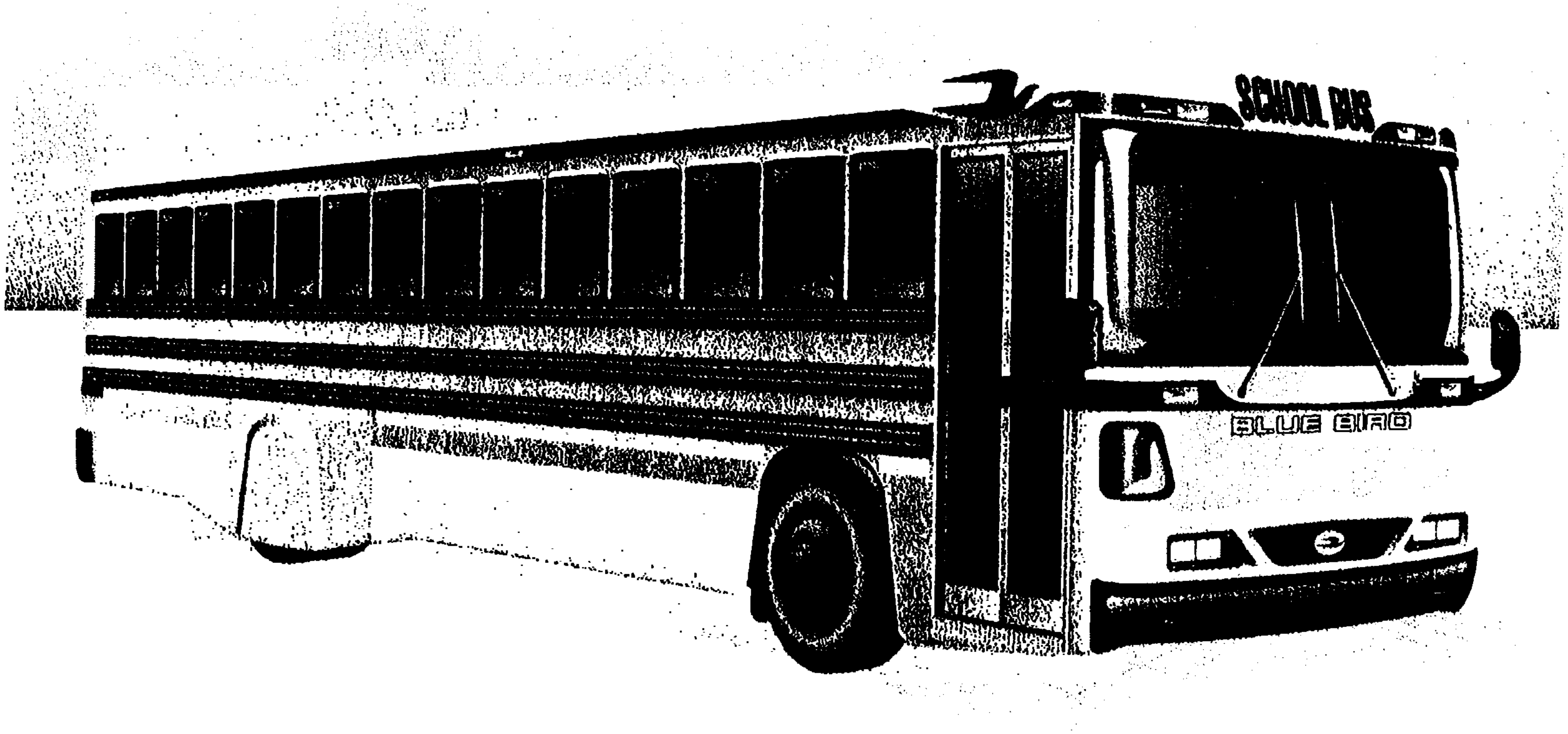
Blue Bird has initiated work on design and construction of the prototype bus. Figure 7 is an illustration of the conceptual design of the bus. During Phase I, the bus design has moved from the concept stage to the final design and prototype stage. Body and chassis designs were drafted and reviewed by Blue Bird personnel for compliance with the project goals. The new bus design will offer increased driver visibility, as well as a wider chassis and a new roof structure. Additional features include a microwave detection system around the perimeter of the bus and wheel well skirts for the protection of pedestrians near the bus. In addition, a fire detection and suppression system will be installed in the bus. To provide additional visibility of the rear of the bus, a closed circuit video camera will be mounted to obtain a view behind the bus. Seat belts will also be added to the seat design to provide a child-restraint system.

Alternative methods for attachment of the lower and the upper frame rail to make CNG tank removal possible was considered during this phase. Blue Bird has contacted several fastener manufacturers concerning this application, and both welded and staked fasteners will be evaluated. Modifying the chassis by turning the lower frame rail flange outboard to facilitate tank removal is also being evaluated. Figure 8 shows the proposed layout of the tanks inside the chassis rails.

The new chassis and body design will utilize additional body crossmembers to also serve as chassis crossmembers. This is required, since the CNG tank installation displaces the area normally used for chassis crossmembers. However, use of the additional body crossmembers will both reduce vehicle weight and add additional side impact protection.

Chassis design work aimed at the installation of the John Deere turbocharged-aftercooled CNG-fueled engine has also been accomplished. Work is complete on sizing the intake air aftercooler and engine coolant heat exchanger. Also completed is design work for installation of the electronic fuel management system, electronic foot throttle, and exhaust system. One prototype bus has been built with these components and is presently undergoing performance development.

Blue Bird has also completed development of a four-wheel hydraulic disc brake system. They have built and tested a prototype diesel-fueled bus with a gross vehicle weight rating (GVWR) of 33,000 lbs using this brake system. Testing of the braking system has demonstrated shorter stopping distances than other



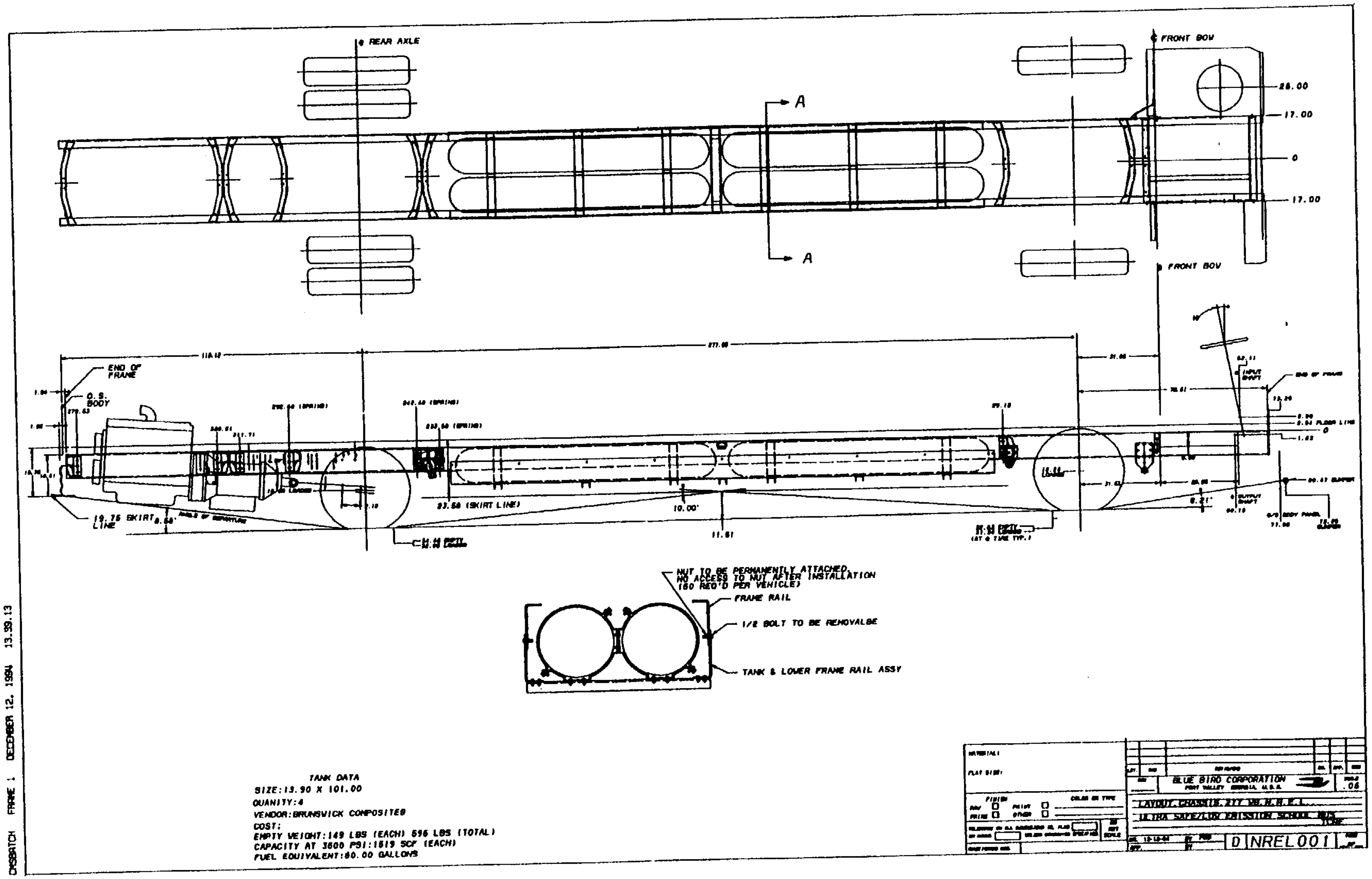
NREL CONCEPT

ULTRA SAFE AND LOW EMISSION
DEDICATED ALTERNATIVE FUEL SCHOOL BUS

RFP NO. RAW-4-13519

BLUE BIRD

Figure 7. Illustration of bus design concept



TANK DATA
SIZE:13.90 X 101.00
QUANITY:4
VENDOR:BRUNSWICK COMPOSITES
COST:
EMPTY WEIGHT:149 LBS (EACH) 596 LBS (TOTAL)
CAPACITY AT 3600 PSI:1519 SCF (EACH)
FUEL EQUIVALENT:60.00 GALLONS

Figure 8. Schematic of CNG tank installation

hydraulic or air-operated brakes, longer brake lining life, less rolling resistance when the brakes are released, and more responsive pedal feel for the driver. Testing has also shown that less energy is required to power the vehicle when this new brake system is used in combination with low rolling resistance tires.

The body design focused on three areas: the body structure, flexible skirting in the wheel areas, and lighting. Blue Bird has conducted simulated roof-load tests to confirm that the new roof bow design has a higher yield load than that of the conventional roof bow. The new design also provides more headroom at the outboard sides of the bus.

Blue Bird is currently working with two vendors for the flexible side skirts and wheel covers. The design goal is to utilize "soft" tooling for the molding of these parts so that lead-times will be reduced. Blue Bird is also working with the Hella Corporation to develop low profile overhead warning light systems as well as new headlights for improved styling.

Fuel System Design

CNG Cylinder Company has made a design change on the compressed natural gas fuel tanks which it will be delivering for the bus. Fiberglass-wrapped aluminum tanks will be substituted for the all-composite tanks originally proposed. This change has several reasons: safety concerns, production scheduling, and some technical issues.

The production schedule would not meet the deadline for tank delivery for this project. Also, it was felt that since safety is paramount for this project, the use of the aluminum tanks, which can withstand the working gas pressure even without the fiberglass wrap, was more appropriate. Previous experience with all-composite tanks has shown that the plastic liner can develop leaks. The all-composite tanks also exhibit a unique behavior as they are pressurized: the tanks both elongate and twist. The twisting effect is more pronounced on long tanks, and complex brackets would be required to support the tanks and manage this twist without adding undue stress to the tank. To overcome this, six shorter tanks would have been required to hold the desired amount of fuel.

Use of the fiberglass-aluminum tanks will allow the use of four 15" diameter by 84" long tanks which should provide enough fuel storage for a range of over 400 miles. These tanks can also become the standard production fuel tank for all CNG-fueled Blue Bird school buses.

To address concerns regarding environmental weathering of the fiberglass wrapping, a new type of resin will be used instead of an epoxy resin for bonding the fiberglass. This type of resin repels liquids which will prevent liquids such as water and sulfuric acid (battery electrolyte) from absorbing into the fibers and weakening the composite material. CNG Cylinder Company is also investigating various coatings for the cylinders for additional protection.

Project Schedule

An overall schedule for the project was developed at a meeting between all of the subcontractors and the NREL technical monitor. This schedule is shown in Figure 9. A complete prototype vehicle body and chassis should be delivered to SwRI by the beginning of December, 1995. This prototype vehicle will include the new compressed natural gas cylinders and associated fuel storage system hardware which has been designed by CNG Cylinder Company.

DEVELOPMENT SCHEDULE FOR ULTRA SAFE, ULTRA LOW EMISSIONS ALTERNATIVE FUEL SCHOOL BUS

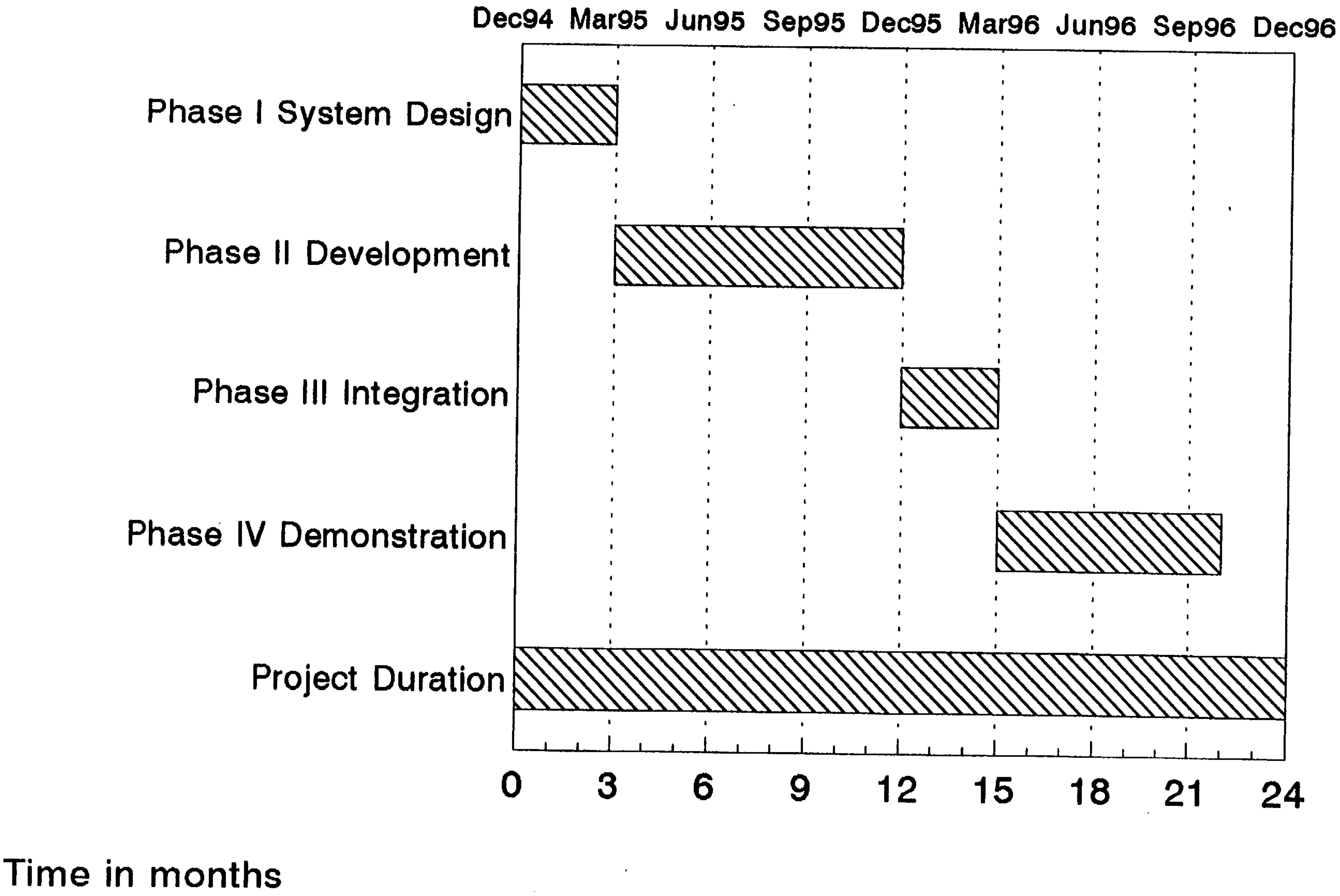


Figure 9. Project schedule

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Phase I of this project focused on the design of the component systems for an ultra-safe, ultra-low emissions school bus. SwRI teamed with Blue Bird, Incorporated, Deere Power Systems Group, and CNG Cylinder Company to design the engine and fuel storage systems for the vehicle. Based on this work, design and construction on the prototype bus have begun. The prototype bus should be completed by the end of calendar year 1995.

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