FINAL PROJECT REPORT

Development of a Hydrogen Fueled Transit Vehicle

Submitted by

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Submitted to

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1. INCENTIVES FOR INVESTIGATION OF HYDROGEN AS A TRANSIT BUS FUEL

The urban environment creates a unique set of requirements for public transportation. A city bus system or similar urban transit system will only be fully utilized if (1) it effectively serves a sufficient user population, and (2) alternatives to its use, specifically the use of private automobiles, become less attractive. With the possibility of hydrocarbon fuel shortages becoming more imminent, and costs following a sharply rising trend, increased demand for public transit may be anticipated. Meeting the needs of the expanded user population will require the expansion and upgrading of existing systems. But other requirements exist: clean air quality and independence of the public transit system from the same oil price/availability situation that would increase public transit demand.

The continued or expanded use of diesel powered buses meets neither of these requirements. The need for the use of a synthetic fuel, or electrification of the transportation circuit is obvious. The capital costs involved in electrification are unnecessarily prohibitive. Among the few synthetic fuels that may realistically be considered, hydrogen is a choice worthy of consideration as it effectively meets both requirements, and integrates well with other urban needs, such as electric power peak-shaving or refuse disposal.

2. SUMMARY

On June 1, 1980, the City and County of Denver contracted with the Lundin Center for Hydrogen Energy Technology of the Denver Research Institute, University of Denver, for modification of a Regional Transit District (RTD) bus to operate on hydrogen. The intended use of this bus was for demonstration of a non-polluting transit vehicle on the Denver Sixteenth Street Transitway Mall.

The vehicle modifications were to include the installation of high pressure tanks for hydrogen fuel storage, and the conversion of the engine to hydrogen as its operational fuel.

Many administrative and scheduling changes have occurred during the course of the contract period. Due to delays in the acquisition of mall buses by the RTD, the intended mall vehicle, a new Vetters airport apron type bus, was not available for conversion to hydrogen as originally planned.

A modified project work schedule was drawn up which would allow the latest possible delivery date of the bus from the RTD. This is shown in Appendix 1. This schedule anticipated that a minimum of eight months would be required following the delivery date of the bus to complete the proposed conversion work.

Two contract time extentions were granted extending the contract period to December 31, 1981, due to the unavailability of the bus. Realizing that the intended bus would not be available until early 1982, the RTD provided a substitute bus for the hydrogen conversion in August of 1981. This was a 1975 FMC circulator bus; one of several which had been withdrawn from service by RTD and was scheduled for replacement. Redesign of both the hydrogen storage system and the engine modifications was required to accomodate this vehicle. Considerable effort was also required to refurbish this bus to an acceptable condition for use as a demonstration vehicle. In May, 1982, the conversion work was completed and preliminary tests indicated that all original design specifications had been met or exceeded.

This report provides a description of the work done under this contract, technical details of the vehicle modification, disclosure of preliminary test data and observations, and a description of vehicle operating procedures. It is important to note that this is an experimental vehicle employing many technical approaches which have not previously been implemented or tested. It is therefore imperative that this vehicle only be operated or refueled by personnel with sufficient experience in hydrogen engine technology and hydrogen fuel handling. Operation or refueling by insufficiently qualified personnel is hazardous and could result in a potentially catastrophic situation.

3. ADVANTAGES AND LIMITATIONS OF HYDROGEN AS A VEHICLE FUEL

The most compelling incentive for use of hydrogen as a vehicle fuel is the low pollution nature of its combustion. For fuel-air mixtures leaner than 0.65 of the stoichiometric (chemically correct) fuel-air ratio, the combustion of hydrogen in air results in essentially no harmful emissions. The primary exhaust product is water. For mixtures between 0.65 and 0.95 of stoichiometric, certain levels of NO_x (oxides of nitrogen) are produced as a result of the combination of nitrogen and oxygen from air at the high combustion temperatures. Lower NO_x levels are encountered with precisely stoichiometric fuel-air mixture, although difficulties in achieving a perfectly homogeneous stoichiometric fuel-air charge prevent the use of such mixtures without deterioration of efficiency.

The unique zero-pollution nature of lean-burn hydrogen engine operation makes hydrogen particularly attractive in vehicle applications which require the performance of an internal combustion engine, but the zero-pollution features previously only achievable with electric vehicles.

In addition, engines operated on hydrogen are noted for their high thermal efficiency. A hydrogen fueled vehicle can be expected to achieve higher miles per BTU ratings than equivalent vehicles operated on gasoline or diesel fuel.

Several disadvantages of hydrogen must be pointed out. Hydrogen possesses substantially different combustion properties than most common fuels. These are summarized in Table 1. A hydrogen-air mixture can be ignited much more easily than mixtures of other common fuels with air. This is fundamentally due to the very wide flammability limits, and the very low minimum ignition energy of hydrogen in air. One important ramification of these properties is that special fuel handling procedures must be observed to assure safe refueling and operation of a hydrogen vehicle. An additional ramification of hydrogen's ignitability is the tendency of hydrogen engines to backfire in the intake manifold when conventional gaseous fuel carburetion equipment is used for the conversion of the engine. One of the key technical tasks of this project was elimination of this backfire problem. This was accomplished through the use of an experimental fuel injection system, which will be described later in this report.

Another major difficulty is the lack of an adequate means for storage of sufficient hydrogen on-board a vehicle. Several means for on-board hydrogen storage have been suggested or demonstrated. These are summarized in Table 2.

It was originally proposed that a metal hydride fuel storage system be used for fuel storage on the bus. Due to budgetary limitations, this phase of the project was not funded. Therefore, the least expensive means for on-board hydrogen storage was selected. This was compressed storage in high pressure cylinders. This method suffers from a poor hydrogen density per system weight and per system volume. This imposes a range limitation on the vehicle since an inadequate amount of fuel can be stored on board. For the bus, nine pressure cylinders are used to provide approximately one hour of operation in typical service. Details of this system are provided later in this report.

4. HYDROGEN PRODUCTION AND SUPPLY

Since the practicality of operation of a bus on hydrogen depends heavily upon the availability and economics of a hydrogen supply, some discussion will be presented on this topic. For a more detailed assessment of hydrogen as an urban transit fuel, the reader is directed to reference 1.

Hydrogen is, at present, produced only in small scale, often as a by-product of industrial operations such as chlorine production and hydrocarbon reformation. The generation process in widest use is steam reformation of methane, in which natural gas is used as the energy feedstock. This method would be neither practical or economical for large scale hydrogen production to support hydrogen use as a fuel.

A well known means for hydrogen production is electrolysis of water. Electric power is required, which must be produced using fossil fuels, nuclear, hydroelectric, solar or wind energy. Hydrogen may be produced directly from heat inputs using one of many available thermochemical water splitting cycles, such as the sulphur-iodine cycle (2). Hydrogen may also be produced by coal gasification (3). It is possible to decompose water in a one step process at high temperature in the presence of a catalyst. Very high temperatures are required and conversion efficiency is poor, but the simplicity of such a process might be an attractive means for utilizing the very high temperatures available at the focal point of a concentrating solar collector, or in possible future application of a fusion reactor (4). Processes are presently under study for direct photoelectrolytic decomposition of water via solar energy (5).

Certainly the most proven existing technology hydrogen generation process is electrolysis. A unique opportunity exists for utilization of off-peak electric power in conjunction with hydrogen fueled city buses and fleet vehicles. Refueling of fleet vehicles normally takes place at night--a period of low demand on the electric power grid. Electrolytic production of hydrogen for use as a vehicle fuel may be a good means for off-peak power utilization, improving the cost effectiveness of in-place power generation facilities.

Studies have been done on the use of electrolytically produced hydrogen stored in metal hydride tanks, and later used in gas turbine powered generators or fuel cells for utility peak shaving (6, 7). An integrated peak power storage-vehicle fueling system might solve two key urban problems simultaneously.

5. TECHNICAL DESCRIPTION

5.1 Summary

Modifications to the bus to enable it to operate on hydrogen included the conversion of the engine by use of a specially designed hydrogen fuel injection system, the installation of a turbocharger and its accessories, the installation of high pressure cylinders for hydrogen fuel storage, the installation of hydrogen regulation and delivery components, and the installation of an electronic safety control system and appropriate instrumentation.

5.2 Fuel Injection Development

The development of a means for elimination of backfiring in hydrogen engines was a problem that required a solution in order to achieve acceptable operational characteristics for the bus. Considerable effort was made to better understand the reasons behind backfiring and then to implement a means for preventing backfiring and achieving adequate engine power output levels.

Although the problem of induction ignition is not unique to hydrogen, it is certainly more pronounced with hydrogen than with other gaseous or liquid fuels. This is fundamentally due to the exceptionally low minimum ignition energy (0.02mJ at $\emptyset=1$) and the wide flammability limits ($0.21 < \emptyset < 7.34$) of a hydrogen air mixture. The equivalence ratio $\emptyset$ is defined as the actual fuel-air molar ratio divided by the stoichiometric or chemically correct ratio. Several mechanisms by which a backfire may be initiated have been identified or suggested. The surfaces of the exhaust valve, piston or spark plug can ignite a fuel-air charge if their temperatures are sufficiently high. Combustion chamber hot spots can also be conducive to backfiring, due to their high local temperatures. This situation may be accentuated by the very small (0.6 mm for $\emptyset$=1) surface quenching distance of the hydrogen-air mixture. The catalytic effects of some materials contacted by the fuel-air charge in the combustion chamber have also been identified as mechanisms by which ignition can occur at decreased temperatures (8).

The presence of deposits caused by the pyrolysis of lubricating oil have been shown to cause ignition, even while average surface temperatures are acceptably low (9, 10). The temperatures of small particles attached to combustion chamber surfaces or suspended in residual exhaust gas at the end of the exhaust stroke can be significantly higher than the average surface temperatures, due to the small thermal mass and poor heat transfer of these particles. At the beginning of the intake stroke, these particles may be of sufficient temperature to serve as ignition sites for the incoming fuel-air charge.

Watson and Milkins (11) have investigated the possibility of residual gas ignition. They suggest that as the incoming hydrogen-air mixture is combined with unscavenged residual exhaust gases, its temperature increases and its composition is diluted; but the temperature of the first introduced hydrogen-air mixture increases more rapidly than the mixing process can dilute the composition below its flammability point. As a result, ignition of the intake charge may occur. This hypothesis might be extended to account for the situation in which valve overlap allows the backflow of exhaust products into the intake manifold, which occurs especially under high load, low RPM conditions.

Ignition of the intake fuel-air charge has also been attributed to undesired firing of the spark plug due to electromagnetic cross-induction between spark plug leads, or individual ignition coils if used.

In the previous work of this investigator and others at UCLA (12), several geometries of electronically controlled hydrogen fuel injection were evaluated as possible means for avoiding the backfire problem.

The essential features of both direct and port injection systems are that: 1) no combustible fuel-air charge is present in the intake manifold, and 2) fuel delivery may be delayed somewhat after the intake of air has begun.

The delayed fuel delivery feature allows for quench cooling of residual exhaust gases and potential ignition sites having low thermal masses. These include deposits and suspended particles from oil pyrolysis, and sufficiently small combustion chamber hot spots. The absence of fuel in the intake manifold ensures that should induction ignition occur, it will only involve the charge of a single cylinder rather than the entire contents of the intake manifold. The resulting backfire is better described in the same context as ignition "miss," much less consequential than the backfire of a carbureted hydrogen engine.

For the bus application, a port injection approach was selected. Direct cylinder injection is limited in practical applications due to the possibility of incomplete fuel-air charge mixing in the cylinder resulting in incomplete combustion, which can be responsible for poor thermal efficiency and high NO_x emissions (12). This is especially true as equivalence ratios approaching stoichiometric are used, since complete combustion of a stoichiometric mixture required perfectly homogeneous mixing of the fuel and air. This is extremely difficult to accomplish entirely during the compression stroke since turbulent mixing effects from the intake stroke are largely diminished. Other limitations of direct injection are the requirement for a hydrogen supply pressure higher than might normally be available from a metal hydride or liquid hydrogen vehicular storage system, and the need for a high flow injection valve capable of withstanding combustion chamber temperatures and pressures.

Several design approaches to realizing timed port injection on a multi-cylinder engine were investigated. The test engine selected for system development was a 2.6 liter, 4 cylinder, 4-cycle, Mitsubishi engine normally used in several Chrysler automobiles and light trucks. A feature of this engine is the "MCA-Jet" third valve which is normally used to improve the combustion efficiency of a lean fuel-air mixture with substantial EGR. The cylinder head is aluminum alloy and the engine block is cast iron. No special provisions were made to reduce lube oil entry into the combustion chamber. In fact, the rapid accumulation of greasy carbon deposits on the spark plugs indicated that significant oil was entering the upper cylinder, either past the piston rings or through the valve guides. Surface gap spark plugs and a capacitive discharge ignition system were used for all tests. The ambient air pressure during all tests was approximately 82 kPa (620 mm Hg) because of Denver's 1610 m (5300 ft) altitude. Fuel-air equivalence ratio data were determined by analysis of exhaust oxygen content.

The initial injection configuration tested involved the timed injection of fuel through the third valves under electronic control. A single electronic fuel injector of the type previously described was used to supply all four cylinders by manifolding of all third valve inlets to the common fuel injector. In this manner, the third valves acted as selector valves since only one of these valves is open at any time. The engine coolant temperature was maintained at 71°C (160°F). The ignition timing was fixed at 20°BTDC. Using this setup, a minimum injection delay period of 30°ATDC was found to be adequate for eliminating induction ignition. Advancement of injection timing prior to TDC resulted in immediate backfiring at high power output conditions.

A fuel metering device as described in Figure 1 was constructed as a means of mechanically metering hydrogen mass flow so as to be proportional to intake air mass flow. This metering unit incorporates the throttle body and vacuum controlled slide of a standard SU carburetor. The position of the slide follows air mass flowrate in a non-linear, but one-to-one relationship. A tapered pin coupled to the slide is used to meter hydrogen flow in the lower hydrogen metering valve assembly. A differential pressure across the metering valve orifice of 221 kPa (32 psi) or greater is maintained in order to ensure sonic flow conditions in the orifice, which makes flowrate in the valve independent of the downstream intake manifold pressure. By selectively cutting an appropriate (experimentally determined) taper on the metering pin, a relationship between hydrogen and air flow rate is established which can be either held constant, or varied with air flow. In our engine tests using this metering unit, a constant fuel-air ratio was maintained over the entire range, except at low flowrates and idle condition where a leaner fuel-air ratio was used.

This metering unit was employed to supply hydrogen to the third valve manifold. This configuration allows the separate delivery of fuel, but since the third valve opens simultaneously with the main intake valve, independent timing of fuel delivery was not possible. Tests of the engine using this setup provided similar results to those obtained for electronic injection timing at TDC. Backfiring occurred for engine loads greater than 345 kPa (50 psi) BMEP (Brake Mean Effective Pressure) at engine speeds above 2500 RPM.

A means by which hydrogen flow from the fuel metering unit may be timed was devised using a rotary valve as depicted in Figure 2. Hydrogen enters the rotary valve through the central inlet port, and is distributed to the appropriate cylinder by the rotation of the valve shaft, which is driven through a 2 to 1 reduction timing belt drive from the crankshaft. The total duration that each of the outlets is open is 163 degrees of crankshaft rotation, although the majority of flow occurs within the central 81° of this period. Timing of fuel delivery is adjusted by rotation of the valve assembly in its mounting bracket. Hydrogen flows from each of the outlet ports to nozzles located just upstream of each intake valve in the intake ports.

Tests were conducted using the metering unit - rotary valve combination. For these tests, the third valve manifold was connected to the main intake manifold so that only air was inducted through the third valves. Hydrogen fuel pressure to the metering unit was maintained at 276 kPa (40 psi), which results in a fuel-air ratio of $\emptyset = .55 \pm .05$ over the upper operating range, with a gradual reduction to $\emptyset = .45$ at light load and idle conditions. Use of this lean fuel-air ratio ensures against the formation of any significant NO_x emissions, which typically are encountered for $\emptyset > .65$. A diagram of this injection configuration is shown in Figure 3.

With the injection period located between 15°ATDC and 178°ATDC, backfiring was not observed at any speed or load setting. It was observed that with coolant temperatures higher than 71°C (160°F), specifically 82°C (180°F), backfiring would occur after approximately 30 seconds of continuous operation at the maximum power condition. Conversely, even with coolant temperatures as low as 54°C (130°F), backfiring would occur immediately during full throttle runs if the injection initiation position was advanced to prior to TDC or retarded to later than 60°ATDC. For injection timing later than approximately 60°ATDC, injection flow continues after the point of closure of the intake valve leaving some hydrogen entrained just upstream of the intake valve, which is inducted at the beginning of the next intake stroke. Only with decreased coolant temperatures and injection initiation between 10° and 20°ATDC was backfiring eliminated under all conditions. The results of full-throttle variable RPM tests of this configuration are shown in the lower data of Figure 4. For these runs, a fixed ignition timing position of 19°BTDC was used. No backfiring was observed during these tests.

In an effort to investigate improved power output of the engine, a turbocharger and charge air cooler were fitted. The turbocharger was an IHI RH05 unit with internal adjustable wastegate. This would normally be considered too small a turbocharger for this engine displacement if the engine were operated on gasoline, but was selected because the lower exhaust heat content of a lean operated hydrogen engine dictates the use of a smaller turbine in the turbocharger. Engine tests showed that positive boost pressure was available at 2000 RPM with full 10 psi boost available at 2500 RPM (limit set by the wastegate). However, the compressor efficiency drops off rapidly for engine speeds greater than 3500 RPM such that only 4 psi boost is available at 4000 RPM. A somewhat larger turbocharger would be optimum for this engine.

A different metering pin was used in the fuel metering unit, and the hydrogen supply pressure was increased to 414 kPa (60 psi) to provide a richer fuel-air ratio of $\emptyset = 0.7 \pm .05$. The liquid-to-air charge air cooler maintained the intake air temperature between 60 and 80°C (140 and 176°F) during these runs. An electronic ignition timing control system was used to permit optimization of ignition timing. Ignition timing for these runs was optimized for best torque at each engine speed. The resulting timing curve was timing at TDC for 1500 RPM and less, linearly increasing to 12°BTDC at 3000 RPM, and constant at 12° above 3000 RPM.

Full-throttle, variable RPM test results of the turbocharged, injected engine are shown in the upper data of Figure 4. The roll-off in power above 3500 RPM shown in Figure 4 was due to the decrease in turbocharge boost above this speed. As before, the engine coolant temperature was limited to 71°C (160°F). Each data point represents a 120 second continuous run at full throttle. No backfiring was observed during these tests. It was observed that if the ignition timing was abnormally advanced to the point of audible knock, backfiring would result within approximately 15 seconds of operation at the 3500 RPM maximum power point. This is presumed to be due to excessive average temperatures of combustion chamber surfaces induced by the knock condition.

From the data and observations of these tests, certain conclusions were drawn. Induction ignition can be caused by excessive temperatures of large thermal mass combustion chamber surfaces such as the cylinder walls, valves, piston or spark plug, or by low thermal mass sites with cyclically varying temperatures such as surface deposits, suspended pyrolysis products or hot residual exhaust gases. Avoidance of induction ignition required both the maintenance of acceptably low average temperatures of the large thermal mass surfaces, and the provision for convective cooling of the small thermal mass sites prior to the delivery of fuel to the cylinder. Improved cooling of the cylinder head, piston and valves, and the use of very cold spark plugs is indicated to achieve the lower average temperatures. Timed fuel injection provides a means of delayed fuel delivery in order to pre-cool the small thermal mass sites and residual exhaust gases.

A more comprehensive report of this experimental work appears in reference 13.

The fuel injection system developed for the 2.6L. Chrysler-Mitsubishi engine was up-scaled for use on the eight cylinder engine of the bus. The engine supplied in the FMC bus was a Chrysler 440 $in.^3$ displacement V-8 industrial engine. The condition of the engine as delivered from the RTD was extremely poor, so that a complete rebuild was required. Preliminary design effort had been directed toward the use of a Ford 351 $in.^3$ V-8 industrial engine which would have replaced the diesel engine in the originally proposed Vetters mall transit bus. This design work was modified to accomodate the larger Chrysler engine.

The Chrysler engine was a poor candidate for hydrogen conversion. Its wedge configuration combustion chamber generates low turbulence, so that poor combustion efficiency and excessively high engine operation temperatures are problems. The high combustion chamber temperatures could become an uncontrollable cause of backfiring during hydrogen operation.

A draft of the final design of the injection rotary valve appears in Appendix 2. The upscaled metering unit required the use of a two-inch throat SU carburetor body, which is the largest available. A draft of the metering valve, which is the lower assembly of the metering unit (the SU carburetor is the upper assembly) appears in Appendix 3.

A photograph of the completed installation of the fuel injection equipment on the engine appears in Figure 5.

5.3 Turbocharger and Other Engine Modifications

As in the case of the test engine, a turbocharger was added to improve the engine power output. A Rotomaster TO-4 series unit was used, appropriately sized for this larger engine. The right side exhaust manifold was modified to mount the turbocharger, and the left and right exhaust manifolds were connected via a cross-under exhaust pipe. A Rotomaster BPR wastegate was used, and its setting was determined during actual vehicle testing later.

There was insufficient room in the engine compartment for a charge air cooler, but some provision for stabilization of the intake manifold temperature was provided. The internal exhaust heating passages in the intake manifold were blocked off, and water was circulated through these passages via an electric water pump and an external heat exchanger which is mounted in the previous location of the air conditioning heat exchanger in the engine compartment. This probably has only a small effect on charge air temperature rise during high boost operation.

Surface gap spark plugs in conjunction with a capacitive discharge ignition system were used.

A dual idler pulley was installed to reroute the fan and waterpump drive pulleys in order to provide room for the rotary valve, which is driven via a timing belt from the crankshaft. A throttle linkage was fabricated to interface the hydrogen metering unit. The existing air cleaner was retained, and adaptors were made to connect it to the metering unit through a four-inch diameter flex hose. Numerous other modifications to the engine and drivetrain were required during the course of this work.

5.4 Hydrogen Fuel Storage System and Regulation Components

Nine K type high pressure cylinders were used for on-board hydrogen storage. Each has a storage capability of approximately 0.45 Kg. (1.0 lb.) of hydrogen at 13.8 MPa (2000 psig), STP conditions. The total hydrogen storage capability is therefore 4.1 Kg. (9.0 lbs.) The hydrogen consumption rate during typical bus service was estimated to be approximately 3.6 Kg. (8 lbs.) per hour, so that this capacity would probably provide a one hour operational range for the bus under most circustances.

No exterior areas were available for mounting the cylinders, so that it was necessary to mount them in the interior of the bus, under a false floor in the midsection of the chassis. A semi-hermetic enclosure was constructed of 1" plywood around the cylinders. The cylinders were rigidly mounted in two braces of 2" angle iron. Vents were provided on both sides of the enclosure, connected to outside air. All wood surfaces of both the enclosure and the original plywood bus floor were treated with a fire retardant and sealed with a latex based paint. The top of the enclosure forms a false floor on which the original floor linoleum and bus seats are mounted.

The nine cylinders are connected to a common manifold fabricated of 2.5 cm (1.0 in.) diameter thickwall steel tube. Each cylinder is connected via a braided stainless steel reinforced, teflon cored high pressure flex line. Individual shutoff valves at each tank are provided. Access to these valves is provided by a swing-up type door at the rear section of the cylinder enclosure.

Hydrogen at cylinder pressure flows from the manifold to a high pressure two-way ball valve. This is intended to be the main manual shut-off valve for the system. When the valve is open, hydrogen cylinder pressure is connected with a high flow rate primary pressure regulator. It is also connected with a pressure gauge and a refueling quick-connect fitting through a check valve. The regulator reduces the hydrogen pressure to 345 KPa (50 psig), which is the operating pressure of the fuel injection system. All of the above mentioned components are located within the cylinder enclosure, and are accessible through the left-hand side vent, which swings open for access to the refueling quick connect fitting and the manual shutoff valve.

At 345 KPa (50 psi.) pressure, hydrogen leaves the cylinder enclosure through a 0.95 cm. (3/8") copper tube which terminated in the engine compartment. All contact surfaces of the copper tube are isolated from abrasion by lengths of neoprene hose used as grommets.

The main system solenoid valve is located on the firewall of the engine compartment attached to a shock isolated aluminum plate on which the system control electronics are also mounted. When the solenoid valve is open, hydrogen flows through a reinforced neoprene (2.8 MPa rated) hose to the fuel metering unit on the engine.

Substantial safety factors have been applied in the selection of all the hydrogen pressure carrying components of the system. Particular attention was paid to the avoidance of deleterious vibration effects on system components and pressure lines. Component selection was often based upon previous personal experience with a given component in vehicular hydrogen service.

5.5 Electronic Safety Control System and Instrumentation

Both the ignition system of the engine and the hydrogen solenoid valve are actuated only upon the command of an electronic control unit which responds to several engine and control inputs. This unit and its associated control relays are mounted on the aluminum plate with the solenoid valve, located on the left firewall in the engine compartment.

A flammable gas detector is located inside the hydrogen tank enclosure. It is sensitive to very minute levels of hydrogen, well below the flammability limit of hydrogen in air. It provides an audible warning of hydrogen leakage which can be heard from outside the bus through the enclosure vents. Because the enclosure is sealed to the bus interior, its warning tone is barely audible inside the bus. A yellow pilot light is located on the dashboard of the bus which indicates the warning of the gas detector in a manner visible to the operator. It is felt that this warning method is less likely to cause a possible panic reaction by bus passengers in the event of a fuel system leak.

The operation of the electronic safety control system can now be described. It is the primary function of this system to allow hydrogen to flow to the fuel injection system only when it is absolutely safe to do so. A toggle switch is located on the dashboard above the ignition key switch. When this toggle switch is on, the control system is enabled.

To start the engine, it is necessary to first turn on the toggle switch, and then start the engine with the ignition key.

A blue pilot light on the dashboard indicates whenever the hydrogen solenoid valve is open. The valve will not open (and therefore the blue light will not activate) until the engine starter has been engaged and the engine is cranking. Once the engine has started, the blue light will remain on. If any problem should occur which would cause the engine to stall, the hydrogen solenoid valve will automatically shut off. If a hydrogen leak is detected by the gas detector, the hydrogen solenoid valve will also shut off immediately. (The blue light will go out, the yellow light will turn on.)

The shut down of a hydrogen engine requires a specific procedure to avoid the accumulation of unburned hydrogen in the exhaust system of the vehicle. (This hydrogen is ignited when the engine is started again resulting in a loud exhaust afterfire.) The electronic control system accomplishes this sequence automatically regardless of whether the ignition key or the toggle swith is turned off first. When either is turned off, the hydrogen solenoid valve is immediately shut off. The ignition system remains on until the engine rotation has completely stopped. It then is turned off automatically. This sequence assures that any hydrogen delivered to the engine is combusted rather than passed through it unburned, which could occur if the ignition is turned off prior to hydrogen shutoff in hydrogen engines not using this electronic safety system.

The control system is failsafe in the sense that an electric power failure also causes the closure of the hydrogen solenoid valve. A diagram of the entire hydrogen fuel system and electronic safety control system appears in Figure 6.

Instrumentation is provided on the dashboard to monitor intake manifold pressure, and exhaust pressure and temperature. These are labeled accordingly.

An electronic bargraph type readout is installed in the lower left dash area. This provides an indication of hydrogen fuel pressure in the tanks whenever the manual shutoff valve is open. The gauge is activated whenever the system is enabled (toggle switch on). The transducer for this remote pressure sensing system is mounted in a high pressure port of the regulator, located within the cylinder enclosure.

It is important that at no time is the exhaust pressure allowed to exceed 138 KPa (20 psig). Pressures in excess of this could be destructive to the engine and turbocharger, or could lead to engine overheating to the point of backfiring. The vehicle operator should constantly observe the exhaust pressure gauge to avoid this condition.

6. OPERATIONAL TEST RESULTS

Approximately two hours of vehicle operation have been completed in order to debug, adjust and test the injection system, fuel system, and all vehicle components. In addition, preliminary tests were performed on the engine prior to installation in the bus, and on the fuel storage system to assure against any leakage.

The fuel injection system and ignition timing were set up on the engine prior to installation in the bus. The fuel metering unit is set to deliver a fairly lean misture at idle and low load ($\emptyset$=0.5) but becomes increasingly rich as air intake flowrates become greater (maximum $\emptyset$=0.9). With this calibration of the injection system, the fuel-air mixture remains fairly lean during light engine loads representative of typical city driving. Under these conditions, virtually no NO_x emissions are produced and the exhaust is essentially pollution free (except for lube oil pyrolysis). When maximum power is demanded, the richer mixtures are available, with a sacrifice in emissions. Detectable NO_x emissions are usually encounted for $\emptyset > 0.7$.

Ignition timing was set static at 20°BTC. This is considered a compromise dictated by budgetary constraints which prohibited further engine optimization. The actual timing range requirement and control function for this injection-engine combination could be quite broad and complex.

Under high load, high RPM conditions, the wastegate exhibited a oscillatory characteristic in which it would sequentially open and close at an approximate one cycle per second rate. This occurred regardless of the wastegate pressure setting. The only resolution to this problem was the disablement of the wastegate by restriction of the manifold pressure connection line. In its present configuration, the turbocharger is working in a non-wastegated mode. A maximum of 83 KPa (12 psi) boost pressure is generated at approximately 2700 RPM. This is an ideal boost schedule for this vehicle since the automatic transmission rarely allows the engine to exceed 3000 RPM in city driving. However, as previously mentioned, the operator must pay careful attention to the exhaust pressure to avoid dangerously high levels (above 138 KPa or 20 psi).

The bus was found to exhibit acceleration capability similar to, and possibly exceeding that of a standard gasoline operated FMC bus, although this evaluation is purely a qualitative one. The bus tends to move slowly from a dead stop due to the lean idle injection setting and lack of turbocharge boost. Once the road speed has exceeded approximately 15 mph, the fuel-air ratio becomes richer and boost becomes available. A dramatic increase in acceleration ability is noticed.

Fuel consumption rate and vehicle range were found to match initial design predictions very closely. Approximately 6.4 Kg (14 lbs.) of hydrogen were used in the two hours of vehicle testing. This is within the 3.6 Kg/hr (8 lb/hr) predicted usage rate, although the test service schedule was probably less strenuous than actual fully loaded passenger service. It is tentatively concluded that a one-hour vehicle operational range is realizable.

It was observed that under very high engine vacuum conditions, oil smoke appears in the exhaust. A brief burst of smoke is sometimes observed during rapid engine decelleration transients. The source of this smoke is believed to be either oil leakage through the turbocharger compressor seal, or oil suction past the piston rings since the engine was just rebuilt and the rings are not yet seated.

An accumulation of dirt particles in the metering orifice of the regulator caused a leak-through condition in the regulator which caused a release of hydrogen into the cylinder enclosure through the regulator safety relief valve. The engine had just been shut off prior to this occurrence. The hydrogen detector responded immediately, and the main shut-off valve was turned off to stop the flow. Cleaning of the regulator orifice rectified the problem. It is believed that the grit entered the system during a refueling operation. The refueling quick-connect fitting had accumulated road dirt which was inducted into the fuel system during refueling. Since this occurrence, the opening of the quick connect fitting has been sealed with tape to prevent dirt intrusion. The incident has not occurred again.

In its present configuration, the fuel system does not contain a filter since only clean, tanked hydrogen was to be used. It is recommended that a high pressure, fine mesh filter be inserted between the refueling fitting and the check valve to further assure against this occurrence. A further improvement recommended is the insertion of a high pressure solenoid valve in series with the manual shut off valve. This should be actuated by parallel electrical connection with the hydrogen solenoid valve in the engine compartment, although an electrical override switch should be provided since this valve would have to be open to permit refueling. This valve would provide additional protection in the event of catastrophic failure of the regulator, check valve, pressure transducer or pressure gauge.

It is felt that the most important observation was that under no conditions was intake backfiring observed. This represents a significant step in hydrogen engine technology since all previous hydrogen fueled vehicles (buses or otherwise) have been plagued with this problem despite such methods as water injection, exhaust gas recirculation, improved carburetors and other techniques. The successful backfire-free operation of this bus has provided verification of the effectiveness of timed fuel injection in eliminating hydrogen engine backfiring.

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	H_2	CH_4	C_3H_8	Gasoline
Minimum Ignition Energy (mJ)	0.02	0.28	0.25	(0.25)[a]
Ignition Temperature (°K)[b]	858	810	783	530
Adiabatic Flame Temperature (°K)[b]	2384	2227	2268	(2270)
Flammability Limits (% in air)	4.0-75	5.3-15	2.2-9.5	1.5-7.6
Laminar Flame Velocity (cm/sec)[b]	190	38	40	($\leq$30)
Diffusivity (cm^2/sec)	0.63	0.20	—	(0.08)
Minimum Quenching Distance (cm)	0.06	0.25	0.19	—
Normalized Flame Emissivity[b]	1.00	1.7	1.7	1.7

[a]Quantities in parentheses are estimates.

[b]Data for stoichiometric air-fuel mixtures.

Table 1. HYDROGEN COMBUSTION CHARACTERISTICS COMPARED WITH OTHER COMMON FUELS

HYDROGEN SOURCE	DENSITY OF STORAGE* lbs. H_2/ft.^{3}	CONSIDERATIONS AND LIMITATIONS
Compressed hydrogen gas (2,000 psig)	0.650	Requires gas compression for storage
Liquid hydrogen (20°K)	4.48	Requires gas liquefaction for storage
Fe-Ti hydride	3.30 (0.9 wt.%)	Mass of system
Mg-Al hydride	3.36 (6.0 wt.%)	Insufficient engine waste heat for use of this hydride alone
Partial decomposition of hydrocarbons	Varies	On-board hydrogen generation equipment required
$NaBH_4$	7.84**	Chemical Expense
B_5H_9	15.59**	Dangerous to handle

*Volume of containment vessel not included
**Water not included

Table 2. COMPARISON OF AVAILABLE ON-BOARD HYDROGEN STORAGE TECHNIQUES

FUEL METERING UNIT
(Component 1 for)

GASEOUS FUEL INJECTION TECHNIQUE INCORPORATING AIR FLOW CONTROLLED FUEL METERING.

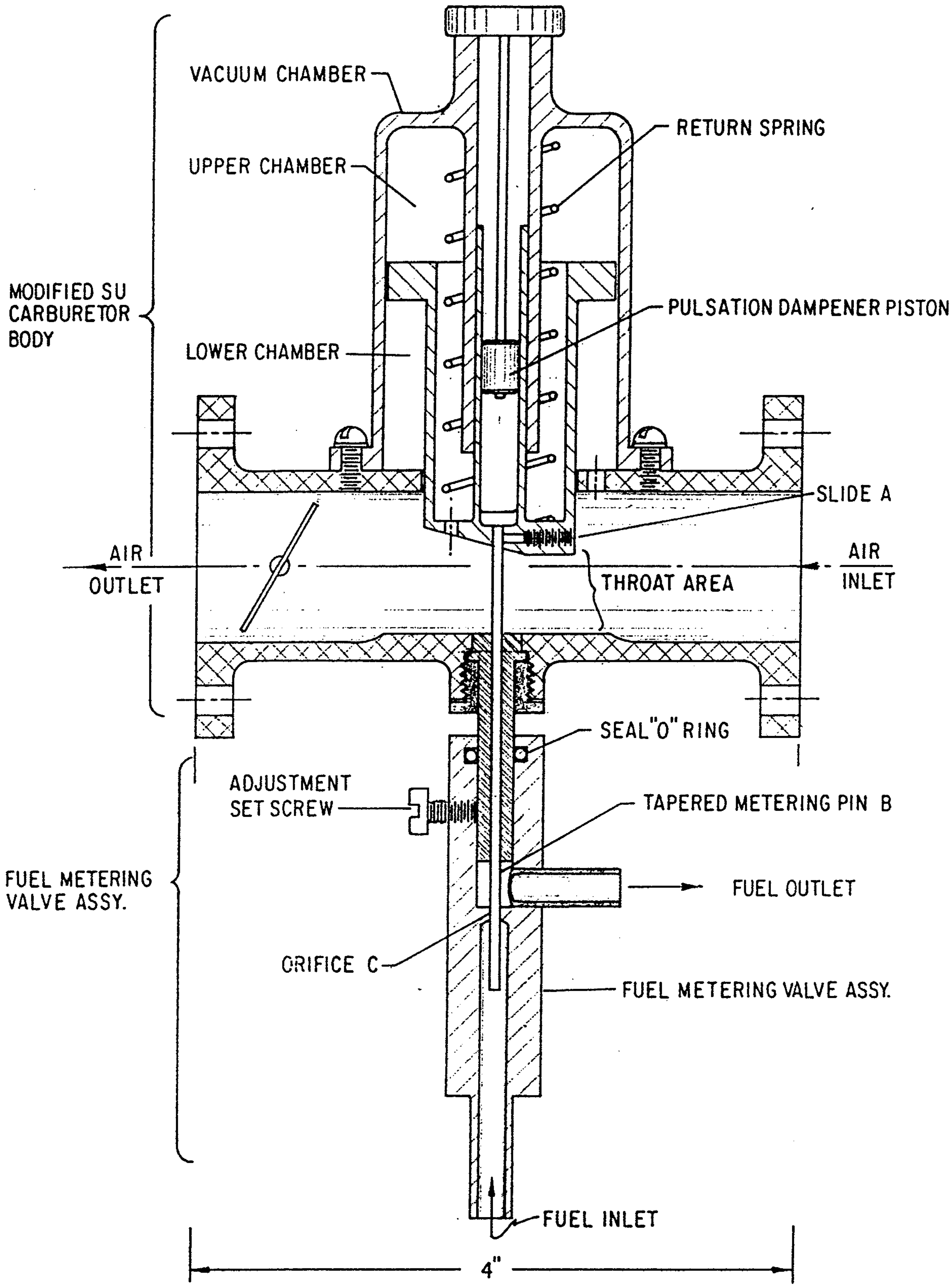


FIGURE 1

ROTARY VALVE INJECTION DISTRIBUTOR
(Component 2 for)
GASEOUS FUEL INJECTION TECHNIQUE INCORPORATING AIR FLOW CONTROLLED FUEL METERING

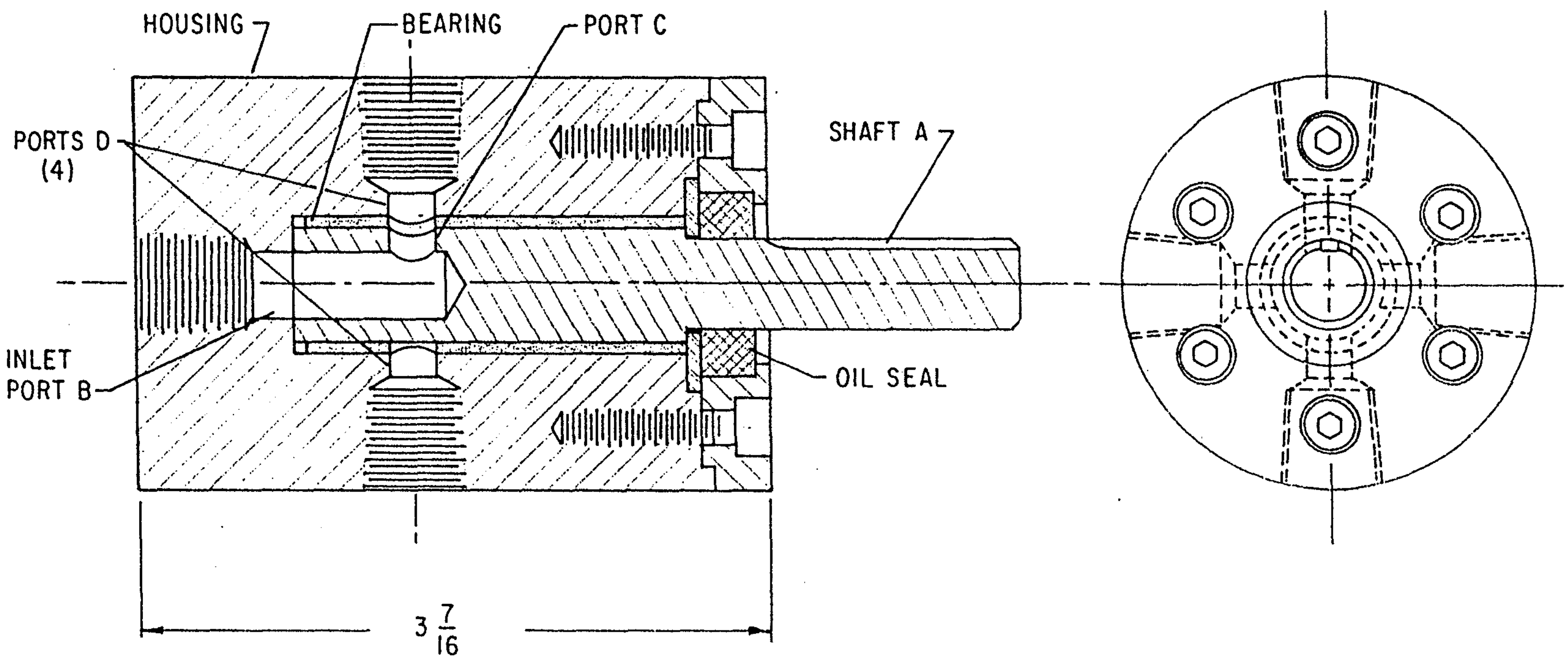


FIGURE 2

PHANTOM PLAN VIEW OF TYPICAL SYSTEM INSTALLATION OF GASEOUS FUEL INJECTION TECHNIQUE INCORPORATING AIR FLOW CONTROLLED FUEL METERING.

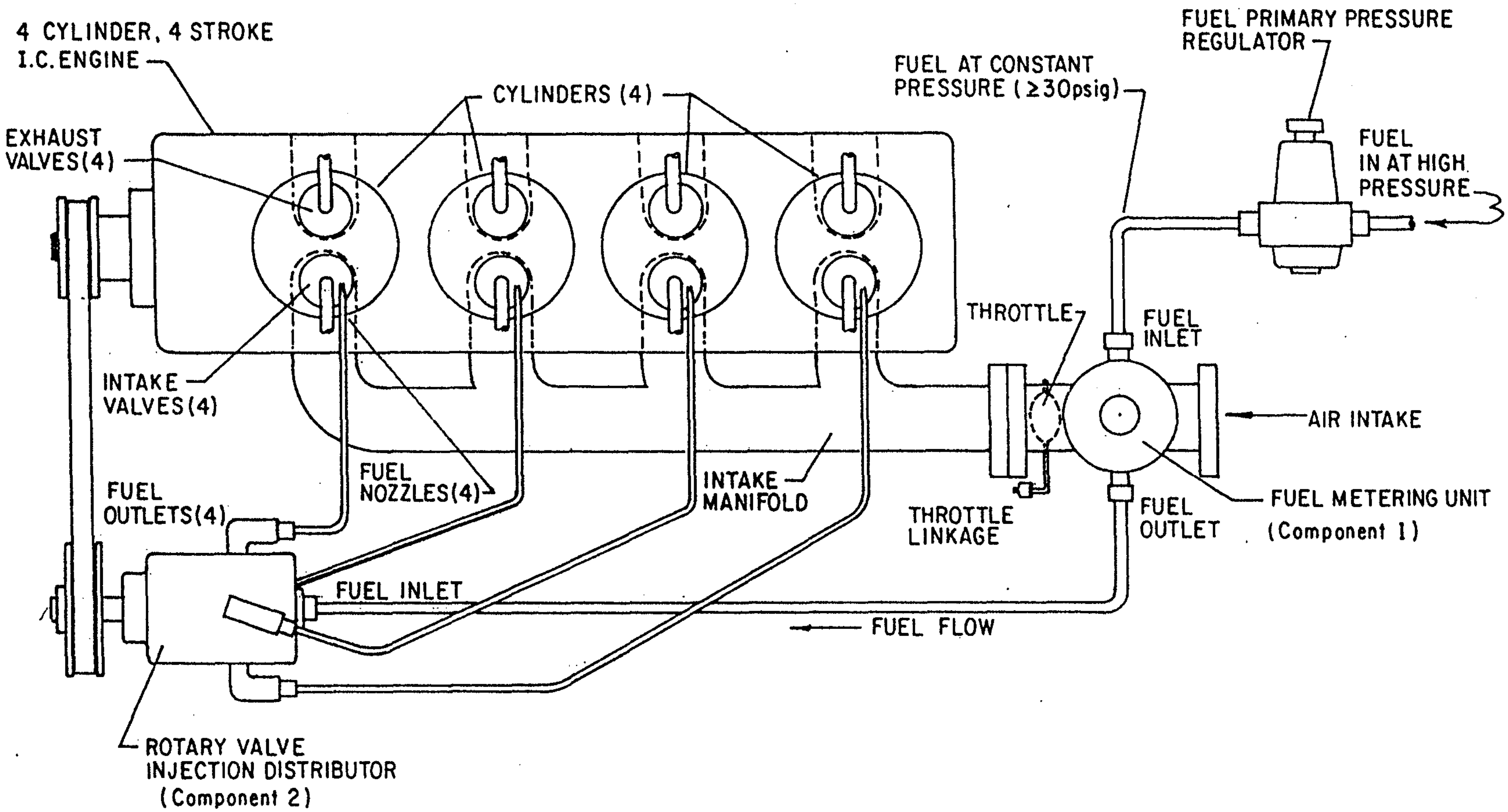
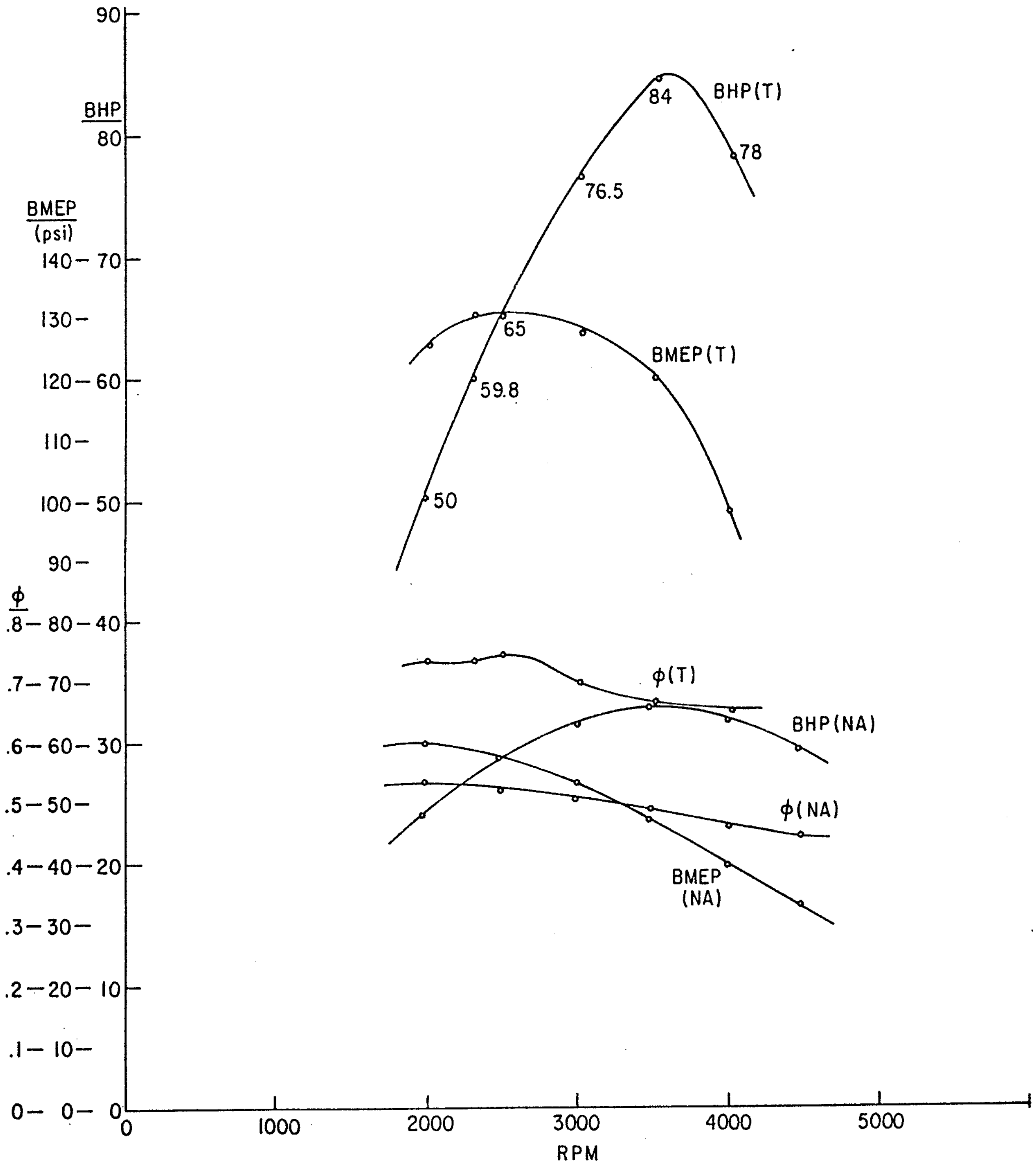


FIGURE 3



FULL THROTTLE - VARIABLE RPM TEST

FIGURE 4. T: HYDROGEN FUELED 2600 cm^3, 4 cyl, ENGINE USING TIMED PORT INJECTION, TURBOCHARGER, INNER-CHARGE COOLER, ELECTRONIC IGNITION TIMING CONTROL (0-30° BTDC)

NA: HYDROGEN FUELED 2600 cm^3, 4 cyl, ENGINE USING TIMED PORT INJECTION, NATURALLY ASPIRATED, STATIC TIMING (19° BTDC)

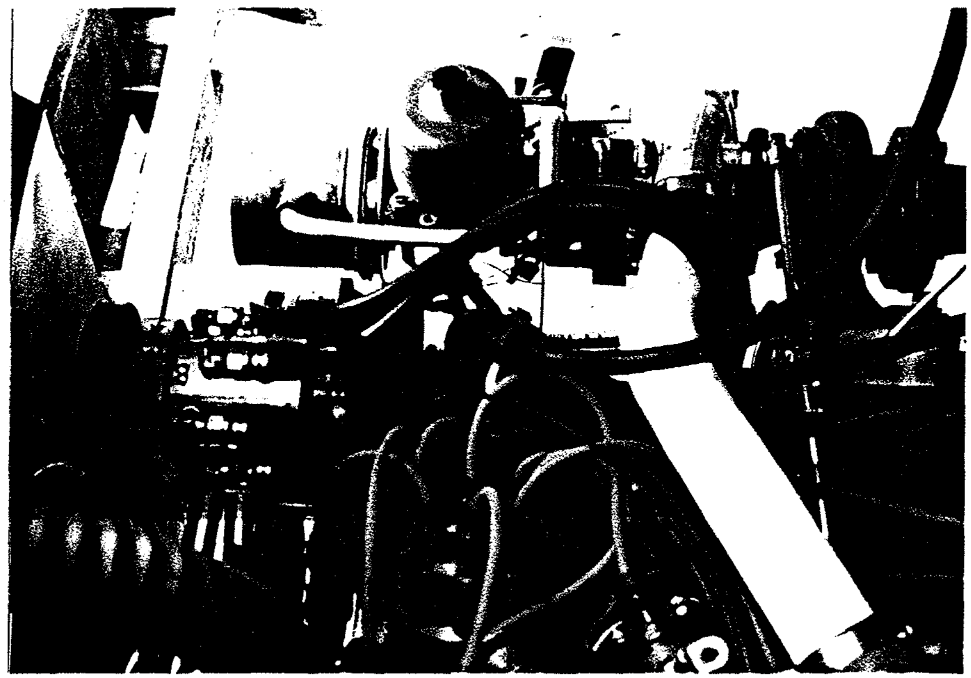


Figure 5

Hydrogen Fuel Injection System
on Chrysler 440 Engine in FMC
Transit Bus.

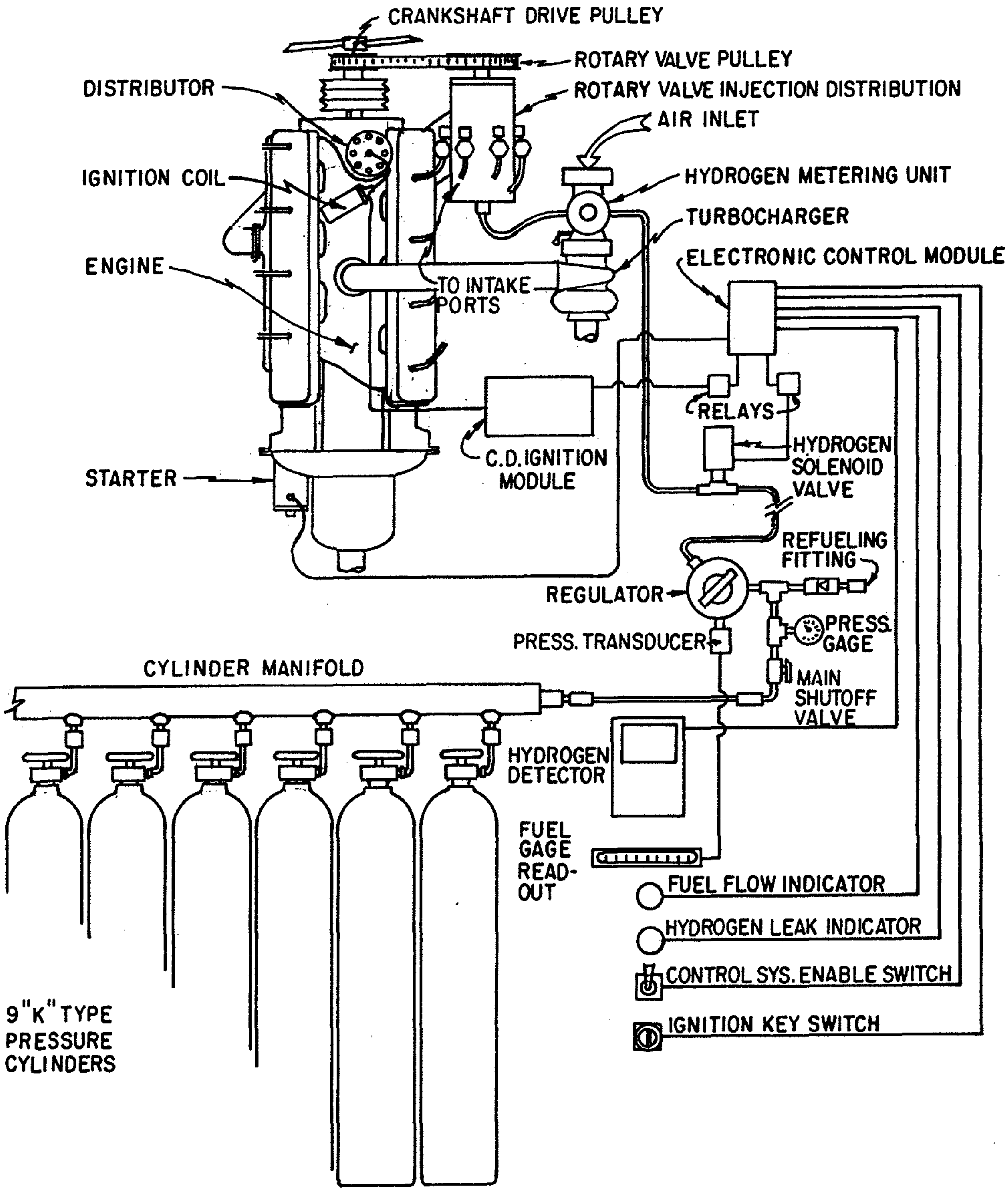


FIGURE 6. HYDROGEN FUEL SYSTEM DIAGRAM FOR TRANSIT BUS

Appendix 1

WORK SCHEDULE

RTD H_2 Bus Program
Tasks to be Completed by Month End

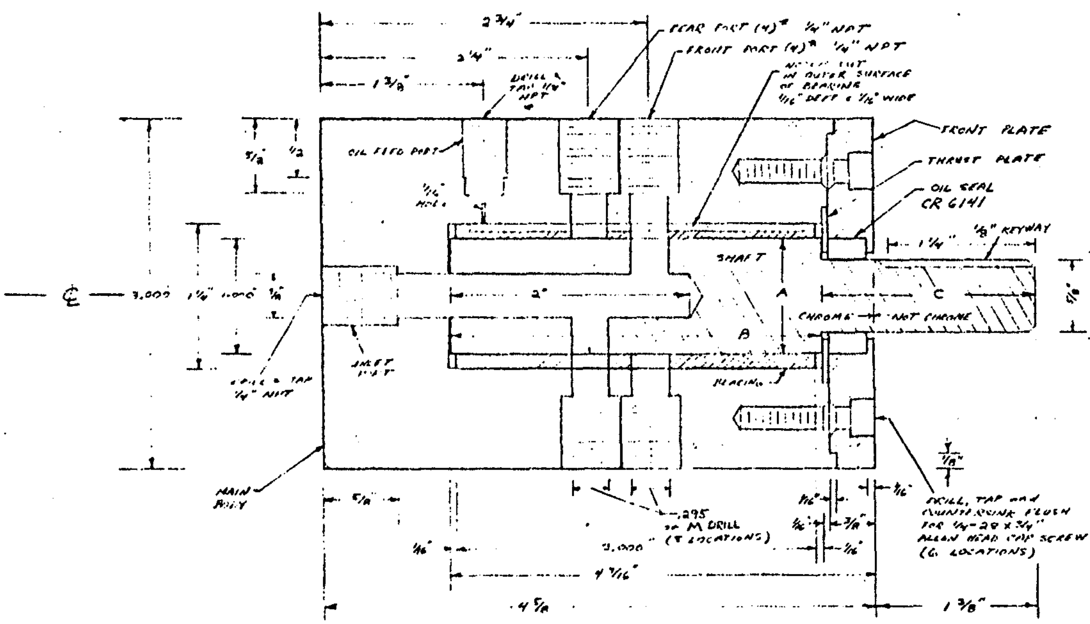
July 1980	Injected engine first operated
Aug.	Refinement and tests of engine Installation of 4 injectors
Sept.	Vehicle-Engine identified. Planning of actual vehicle and layout. Preliminary draft of vehicle.
Oct.	Decision on aspiration technique for bus engine. Decision on engine to be used.
Nov.	Procurement of engine
Dec.	Dyno setup to be completed of non-converted engine
Jan. 1981	Fabrication of aspiration apparatus for engine
Feb.	Preliminary data generated on engine-aspiration system performance
Mar.	Refinement and further tests of engine
Apr.	Redesign of aspiration hardware for high reliability
May	Probable vehicle delivery. Engine R&R Chasis stripped.
June	Installation of engine in bus chasis
July	Installation of H_2 fuel system and instrumentation
Aug.	Bus modification completed
Sept.	First road tests completed
Oct.	Repair-Remods where needed
Nov.	Comprehensive road tests completed
Dec.	Report written. Manuals written. Vehicle delivered

Appendix 2

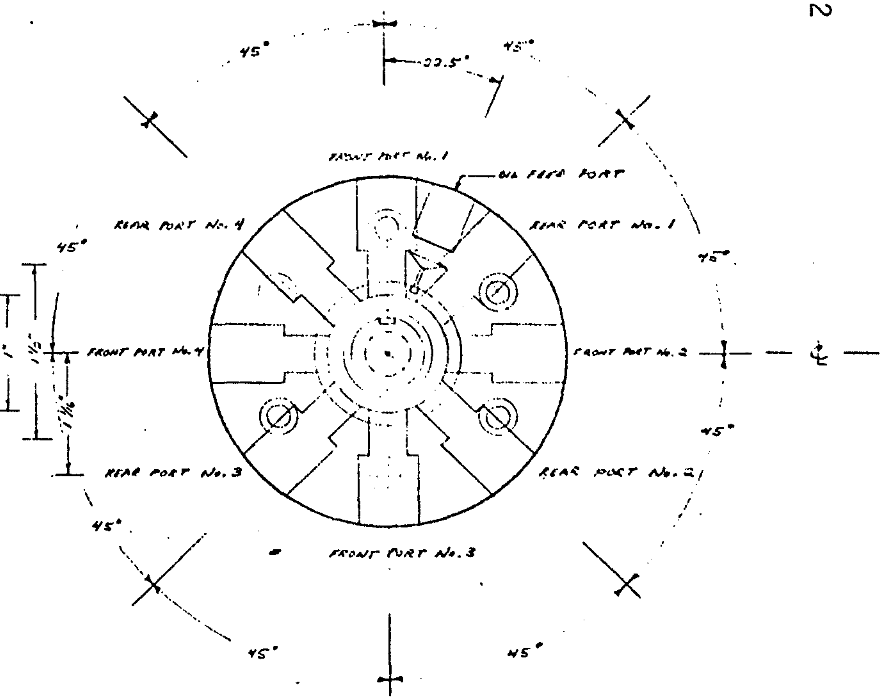
C.A. MacCarley 11/10/81

ROTARY VALVE ASSEMBLY FOR GASEOUS FUEL INJECTION
SERIES II FOR 8-CYLINDER ENGINE APPLICATIONS
SCALE: 1:1
DESIGNED AND DRAWN BY C. A. MACCARLEY
DENVER RESEARCH INSTITUTE, UNIVERSITY OF DENVER
NOVEMBER 10, 1981

SIDE CUTAWAY VIEW



FRONT PHANTOM VIEW



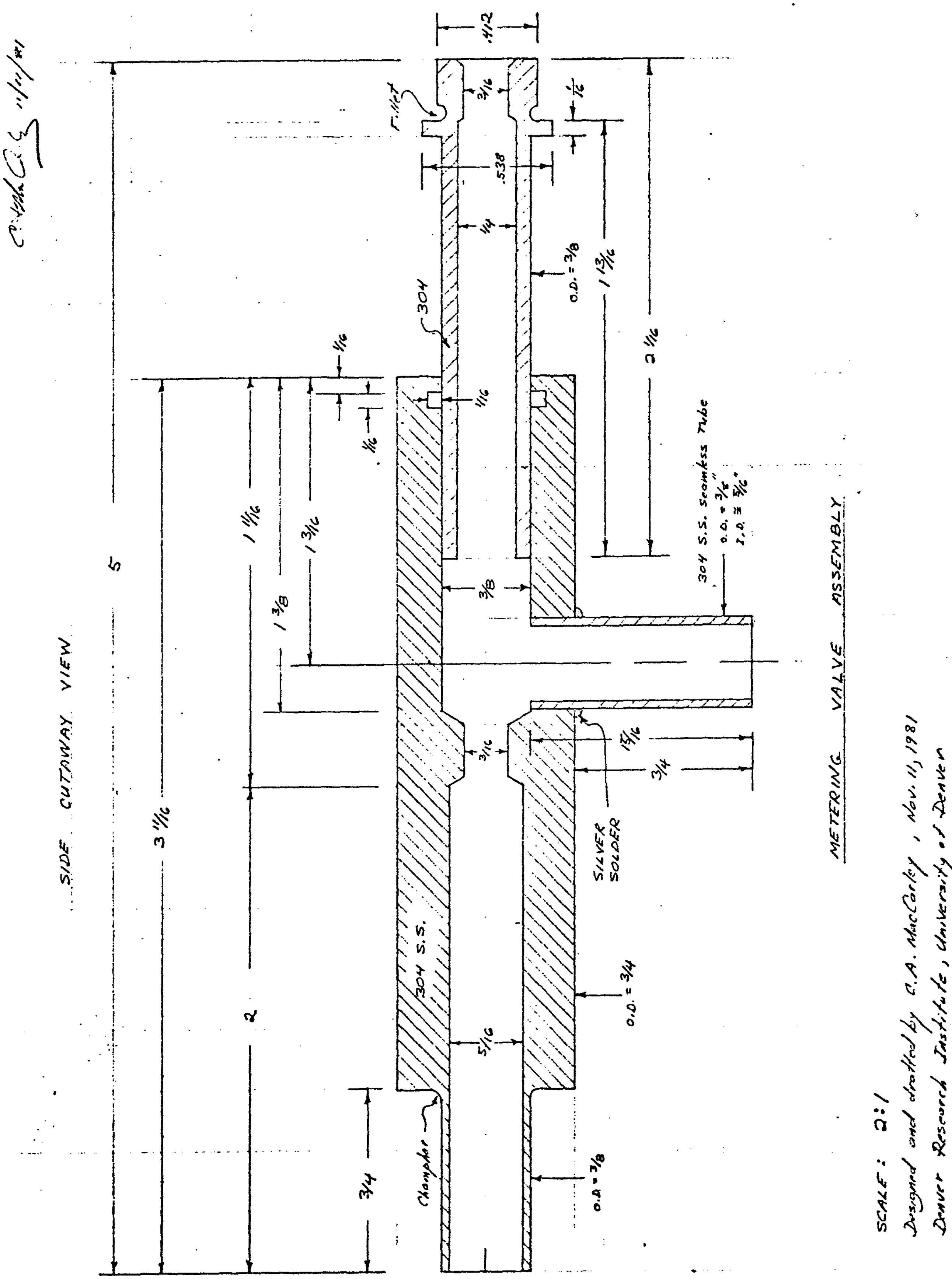
DIMENSION DETAILS: A = .998" AFTER CHROME PLATING AND FINAL GRINDING. PRELIMINARY DIMENSION FOR A IS .988". B = 3.120" AFTER CHROME PLATING AND GRINDING. PRELIMINARY B = 3.110". C = 1¹³⁄₁₆ AFTER CHROME PLATING AND GRINDING. C DIMENSION IS NOT CRITICAL. TOLERANCES: TO BE DISCUSSED VERBALLY.

MATERIALS: MAIN BODY AND FRONT PLATE: ALUMINUM
SHAFT: 1018 STEEL, GROUND ON CENTERS ; HARD CHROME PLATED .010", THEN GROUND TO FINAL DIMENSION. SURFACE FINISH: 10 μin.
THRUST PLATE: KETOSE, HEAT TREAT TO ROCKWELL C45. FINAL GRIND IF NECESSARY.

NOTES: * SIDE CUTAWAY VIEW IS FOR REFERENCE ONLY. PORT LOCATIONS ARE INCORRECT. REFER TO FRONT PHANTOM VIEW FOR CORRECT PORT LOCATIONS. FRONT PORTS ARE LOCATED AT 90° ANGLES AROUND THE PERIPHERY OF THE MAIN BODY. REAR PORTS ARE LOCATED AT 90° ANGLES AROUND THE PERIPHERY ALSO, BUT INTERSPACED BETWEEN THE FRONT PORTS. THE OIL FEED PORT IS LOCATED AT A 22.5° ANGLE FROM FRONT PORT No. 1. THE NOTCH CUT IN THE BEAR. MUST CLEAR ALL PORT PASSAGES.

BEARING IS BUNTING #1620-24 (BRONZE); PRESS FIT IN MAIN BODY.

Appendix 3


SIDE CUTAWAY VIEW
METERING VALVE ASSEMBLY
SCALE: 2:1
Designed and drafted by C.A. MacCarley, Nov. 11, 1981
Denver Research Institute, University of Denver
304 S.S.
SILVER SOLDER
Chamfer