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Date 4/28/94

CONVERSION OF GASOLINE SATURN SL-1 TO DEDICATED COMPRESSED NATURAL GAS USE

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

Edward N. Luton

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ABSTRACT

This thesis project investigates the viability of creating a practical, low-cost conversion of a light-duty vehicle to dedicated natural gas service. The vehicle used in the study is a 1991 Saturn SL-1.

The paper focuses on three main aspects: installation of conversion hardware, use of an electronic controller to tailor engine performance, and measuring performance of the final vehicle.

The conversion hardware consists primarily of a single compressed natural gas tank with brackets; valves, tubing, a pressure regulator, fuel injectors, and other components to create a fuel delivery system. Engine conversion involves substitution of original pistons with "flat-top" pistons, raising the compression ratio to 11.0:1.

An aftermarket electronic engine controller with comprehensive software manages all basic engine functions using existing engine sensors and output devices. The OEM controller is left only non-engine tasks to perform.

Initial performance data reveal a 7% decrease in engine torque, but a vehicle highway range (at 3600 psig initial fill) of 250 miles. Further testing and evaluation of the conversion are recommended.

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LIST OF ABBREVIATIONS

AE	acceleration enrichments
ADV	spark advance
AFV	alternate fuel vehicle
AGA	American Gas Association
ASE	after start-up
BTO	battery terminal offset
CAFE	corporate avg. fuel economy
CH ENG	check engine light
CLT	coolant temperature sensor
CNG	compressed natural gas
DE	deceleration enrichment
DFU	direct fire unit
DOHC	double overhead cam
ECM	engine control module
EGO	exhaust gas oxygen sensor
EGR	exhaust gas recirculation
EK	Energy Kinetics
GPO	general purpose output
IAC	idle air control
INJ	fuel injector
IOT	idle offset time
ISM	idle speed motor
LNG	liquified natural gas
LPG	liquid petroleum gas
MAP	manifold absolute pressure
MAT	manifold temperature
MBT	maximum brake torque
MEF	monitor engine functions
NFPA	National Fire Protection Assoc.
NG	natural gas
NPT	national pipe thread
NGV	natural gas vehicle
OEM	original equipment manufacturer
PFI	port fuel injection
PW	pulse width
RHC	reactive hydrocarbons
RXD	receive bus for computer
SAE	Society of Automotive Engineers
SCF	standard cubic feet
SE	start-up enrichments
SOHC	single overhead cam
SwBAT	ignition switch connection

TACH	tachometer
TBI	throttle body injection
TCF	trillion cubic feet
TEC/TEC-2	total engine controller
THC	total hydrocarbons
TOG	time on gamma
TPS	throttle position sensor
TXD	transmit bus for computer
VE	volumetric efficiency
WE	warm-up enrichment
WOT	wide-open throttle

Chapter 1

Results, Conclusions, and Recommendations

Project Description

Introduction

As government mandates and incentives stimulate a growing alternative fueled vehicle market, compressed natural gas (CNG) vehicles are playing an increasing role. Traditionally, heavy-duty vehicles such as trucks and urban buses have been popular conversion choices, but in recent years conversions of passenger cars have become increasingly common. Midsize fleet-vehicle cars, such as Ford Taurus, Honda Accord, and others have undergone conversion to CNG.

This project's goals include:

- creating a vehicle with acceptable performance - engine output similar to that in the gasoline fueled SL-1 and a 200 mile driving range
- using a minimum number of components (such as tanks) for simplicity and lower costs
- use modern components - a lightweight, composite tank and a mature fuel metering system
- retain capabilities such as an enlarged trunk (rear seats folded) and access to the spare tire, if possible
- create a tank mounting system which is relatively simple in design, manufacturing, and assembly

- conform to NFPA52 *CNG Vehicular Fuel Systems* standards [1]

By meeting these aims, the CNG Saturn could be among these others as a feasible commuter or fleet vehicle.

Results

The project's major goals are met. Increasing the compression ratio from 9.3:1 to 11.0:1 offsets to some degree the power loss (9.5%-20%) inherent in using NG as a fuel. The increase is accomplished using flathead pistons provided by Saturn. Preliminary dynamometer testing reveals an average decrease in brake torque of only 7% in the 1600-2500 rpm range.

A single, high-volume, 3600 psi tank (with one of the manufacturer's standard diameters but a custom length) extends the driving range to 250 miles and contributes to keeping the conversion simple and inexpensive. The price per unit storage would increase with multiple tanks: also, the number of valves, fittings, brackets, and other tank related devices would increase. A full tank weighs about 150 lbs, only slightly greater (about 55 lbs) than a full gasoline tank.

The engine management system, TEC-2 by Electromotive, uses all standard GM sensors and output devices (except for high-flow Bosch fuel injectors). The system uses a "speed-density" approach, as does the Saturn ECM. By calibrating the system as recommended by Electromotive, mostly empirically and partially theoretically, the engine is brought to an acceptable "up and running" condition. There is one shortcoming, however. Although the TEC-2 should control the linear

EGR valve, the attempt was unsuccessful. By publication, the pulsewidth modulated EGR should be functioning, as the probable cause of failure has been identified.

The mounting system is comprised of four simple brackets which mount a 16"x 32" tank transversely in the trunk. The bracket is bolted through the floor sheetmetal to reinforcing backup plates, located on either side of a major vehicle structural element. The tank is elevated slightly above the floor, allowing the spare tire to be removed. By mounting the tank near the seatbacks, a large portion of the trunk remains usable: this location also provides for a large crush zone between the rear bumper and the tank. By positioning the tank between the wheelwells, some side impact protection is also offered.

Conclusions

The Saturn CNG SL-1 is a promising alternative fueled vehicle. Whether or not the CNG fueled vehicles market makes production feasible, from an engineering viewpoint conversion is viable. The cost of the CNG components, at under $1500 (retail), makes this conversion one of the less expensive performed. If produced, factory assembly would seem more reasonable than converting gasoline SL-1s later: replacing the intake manifold, throttle body, pistons, intake-air ducting, fuel rail, fuel filler pipe, etc. while adding the tank, regulator, new fuel filler bracket, tubing, gages, wiring, new engine management, etc. can prove a daunting conversion task.

Perhaps the challenge requiring the most attention is the need for accurate, steady fuel/air metering. This area, still undergoing development, needs to provide a mixture within 0.5%-1.0% of stoichiometric to maximize emission quality.

Recommendations

This project is continuing and expanding under another University of Tennessee student. Several areas of possible continuing study exist:

- refining the fuel metering system (to yield a truly optimized calibration)
- activation of the EGR valve
- further increasing of the compression ratio
- emission control and testing
- acceleration and further range testing

Chapter 2

Conversion

The conversion to natural gas requires both a new fuel delivery system and new electrical wiring for additional electronics. The design and installation of these systems follows the guidelines established by the National Fire Protection Association as published in NFPA52 [1]. In the absence of similar government guidelines, NFPA52 has become a standard for vehicle conversions.

An overview of the fuel delivery system is presented, beginning with the fuel source and continuing along the fuel flow path.

Fuel Delivery System

Piping

The piping system to be described is shown by figure 1. All piping is $^1/_4$" 316 stainless steel, .028" wall thickness, and manufactured according to ASTM A-269. This piping is pressure tested to 4,500 psi and has a burst pressure of 16,800 psi, well above the 3,600 psi system pressure. All high-pressure pipe fittings are Swagelok® or Cajon®, made of 316 stainless steel. The Swagelok® fittings give a torque-free seal on the tubing, avoiding any initial strain . Where $^1/_4$" NPT threaded connections are used, such as at the regulator or solenoid valve, a thread sealant is necessary. Prolock® pipe sealant by Fel-Pro is selected.

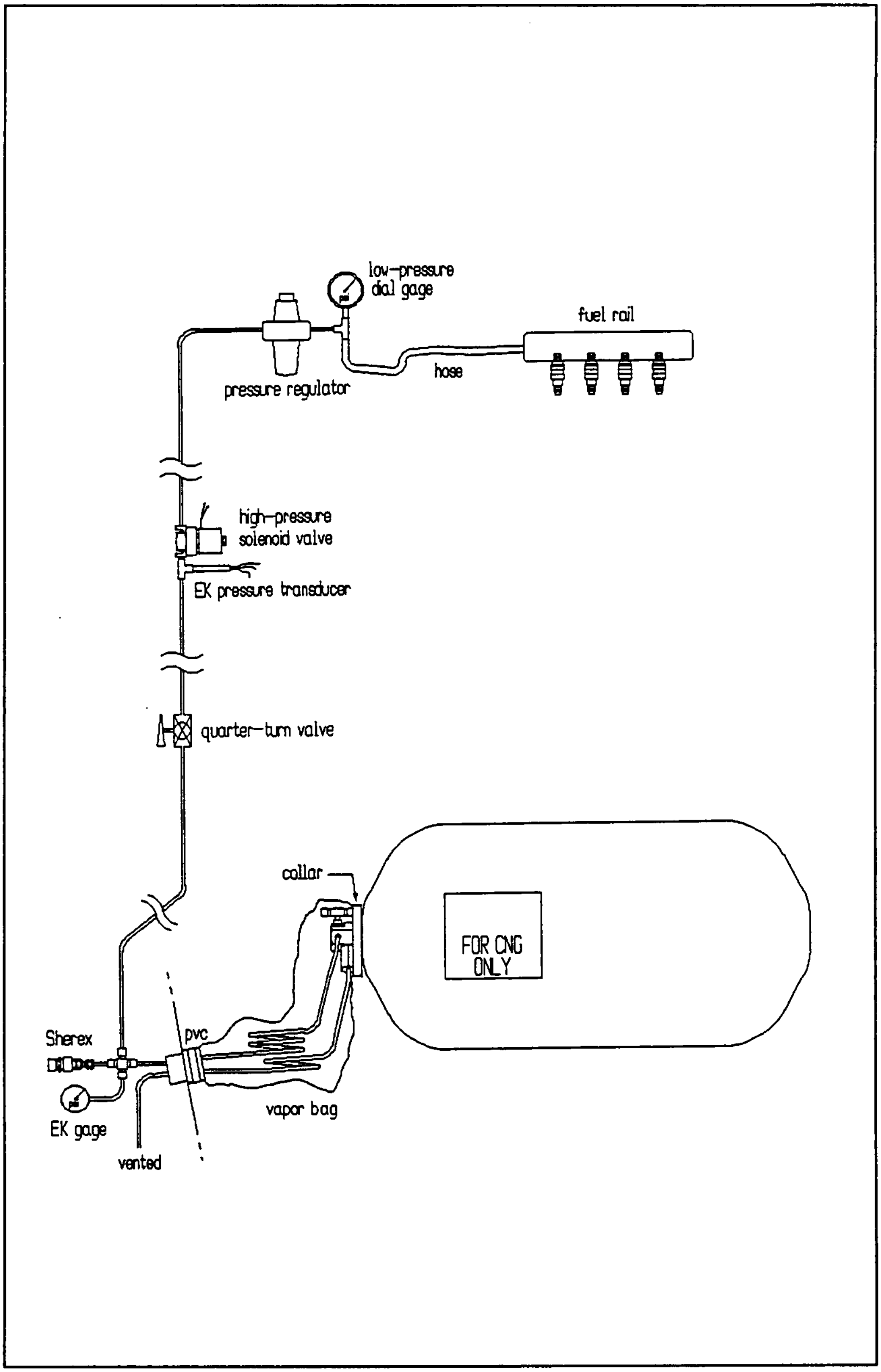


Figure 1: Fuel system

Piping Path and Support

From the tank valve, the tubing passes along the vehicle underside, generally following the path previously taken by gasoline lines. Support is provided approximately every two feet by aluminum bands riveted to the vehicle body, or by the plastic clips used originally for the gasoline lines. The circular aluminum bands are lined with rubber to prevent abrading the piping.

With the engine vibrating, the final piping connection from the pressure regulator to the fuel rail is provided by hosing. A $^1/_2$" OD synthetic rubber hose reinforced externally with steel braiding is used.

Refueling system

Various refueling hardware is offered; devices manufactured by Sherex were selected (Appendix D) Both nozzle and receptacle are constructed of sparkproof brass and have stainless steel internals. The receptacle is located behind the fuel door, supported by a steel plate (Photograph 3, Drawing A6).

There exists no universal standard for this hardware as yet; however the Sherex design is a major contender, as is a system offered by Impco. To refuel, the nozzle is attached to the receptacle by simply sliding back a collar, allowing the nozzle jaws to lock on firmly. A check valve prevents backflow when the nozzle is removed after fueling. For a virtually empty tank, complete refueling with a 2000 psi source requires 3-4 minutes. Of course, a several hour "overnight" filling is an alternative to this "fast-fill" method. In either case, the gas flows through a second check valve to reach the single CNG fuel storage tank.

A section of this refueling piping is curved into a 4"-diameter helix with 2 loops to insulate the upstream piping from the effects of tank vibration. A similar coil scheme is also used for the venting piping.

Tank

The single, 3600 psi storage vessel is a fiberglass overwrapped aluminum tank manufactured by Comdyne-1 (Figure 2). The diameter is a standard 16 inches; however, the length was shortened to 32 inches to accommodate the Saturn's trunk. Each end is threaded for valving, but by plugging one end and using a dual-port valve, only a single valve is necessary.

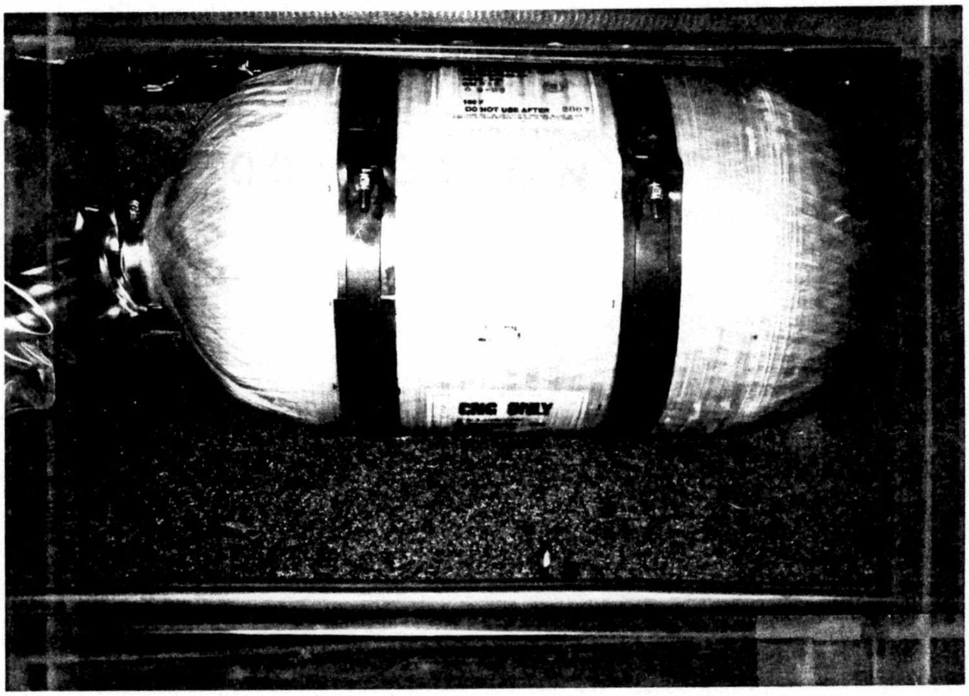


Figure 2: Tank and coiled tubing

Valve

Besides flow rate, the most important criteria for valve selection was compactness. An unnecessarily protrusive valve would force a shortening of the CNG tank, compromising vehicle driving range. A Mirada Controls Inc. solenoid valve (P/N B-51287) was identified as desirable; with its solenoid internal to the tank, the valve extends less than two inches. Regrettably, the valve was not yet available due to certification delays. Instead, a somewhat larger manual valve suffices (P/N B-51246) (Figure 3).

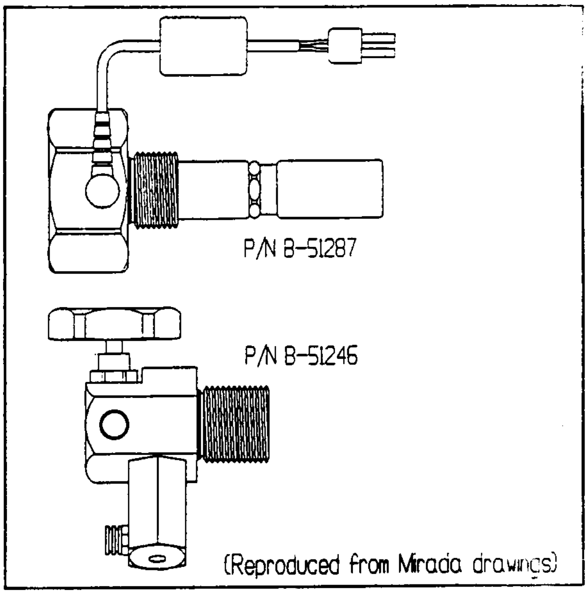


Figure 3: Tank valves

Attached to the valve is a temperature/pressure relief device: above 290 °F or 5400 psi, this safety relief vents CNG to the rear of the car.

Vapor Bag

Surrounding the valve body is a polyethylene "vapor bag", attached to the tank using a ring adapter (Figure 4). The opposite end is clamped to a 2" PVC tube exiting near the wheel well. Since the tank is located within the vehicle's interior, this safety device is mandated by NFPA 52 to direct any leaked gases to the exterior of the vehicle.

The ring adapter itself is secured to the tank using a silicon gel adhesive. A more standard valve protector, offered by the tank manufacturer, may perform the same function if a different tank valve is selected.

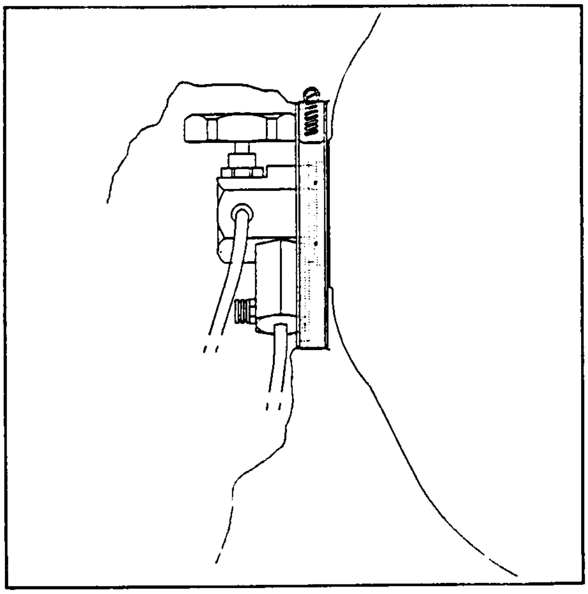


Figure 4: Vapor bag

Quarter-turn Valve

The next component encountered is a quarter-turn ball valve. This Parker valve (P/N 4Z-B6LJ-SST) is readily accessible and allows for the entire fuel system downstream (fuel injectors, pressure gages, regulator, etc.) to be isolated manually. It is installed as shown in Appendix B.

Transducer

Immediately next to a solenoid valve is a pressure transducer used to operate the OEM dashboard fuel gage. A system, offered by Energy Kinetics (EK), uses this high-pressure transducer in conjunction with an electronic-control center (model EK-110-DB-G-3600) which is mounted behind the dashboard. An adjusting screw inside the control center allows for calibration of the unit.

Solenoid

A high-pressure solenoid controlled valve is the next component downstream (Advanced Fuel Components model 211, Figure 5). Normally closed, it is actuated by the electronic controller when the ignition is turned to the ON position. The valve is mounted in the location previous occupied by the gasoline fuel filter.

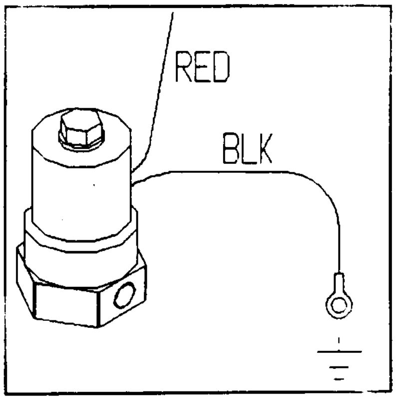


Figure 5: Solenoid

Regulator

A pressure regulator, mounted behind the battery, steps down the tank pressure to a nominal 90 psi. A Meco 8431 was used, although smaller and easier to mount regulators are available. A total of four ports are available; two inlet and two outlet. With piping occupying one inlet, the other is sealed with a plug. Of the two outlets, one is also plugged while the remainder runs to both a dial gage and the braided hose.

Fuel Rail

This two-foot hose leads to a fuel rail normally used on a Saturn PFI engine. The fuel rail was modified in two respects: it was shortened 4 $^1/_2$ cm and threaded to accept the hose fitting. Sawing off the rail's end provides a flat surface for the fitting to screw flush against. However, not enough material existed for threads to be cut into; the rail diameter was too large and walls too thin. Thus, a cylindrical plug of aluminum was welded into the end and tapped ($^7/_{16}$-20), solving the problem. Also, the rail originally contained an interior tube; it was removed.

The rail feeds four Bosh EV1.3A injectors, originally developed to provide a high flow rate required for racing engines. This injector flows 1149 g/min of n-Heptane at 2.7 bar. Using an empirical relationship provided by Bosch, the static flow (Q-stat) for CNG per injector is

$$(Q\text{-}stat\ N\text{-}Hept(g/\text{min}))(.0842) = Q\text{-}statCNG(g/\text{min})\ @\ 100psi$$

which yields

$$Q\text{-}stat\ CNG = 96.75\ g/\text{min}\ @\ 100psi$$
$$= 12.77\ lb/hr\ @\ 100psi$$

To arrive at an initial estimate of the Saturn engine natural gas fuel consumption, a rule of thumb is used: dividing the peak gasoline-engine horsepower in half gives the NG consumption in lb/hr. The stock SOHC engine output is rated at 85 hp, the NG consumption estimated at 42.5 lb/hr. With one injector providing only 12.77 lb/hr, four are required to meet the engine demands.

Engine Modifications

The engine receives only two major alterations: these regard the intake manifold and pistons.

Before conversion, a single throttle body injector could meet the fuel delivery needs of the engine. Now, with natural gas requiring four injectors, port fuel injection becomes a natural preference. To satisfy this option, an OEM intake manifold designed for PFI was delivered by Saturn and installed. As noted earlier, a stock fuel rail was adapted to feed these injectors.

A PFI manifold dictates the use of both a new throttle body and an air intake assembly (inlet duct, air cleaner housing, and cross-car duct). These standard components from a DOHC/PFI Saturn engine were substituted for the original SOHC/TBI assemblies.

The original pistons were replaced to raise the compression ratio, helping offset the performance drop that naturally results from using natural gas as a fuel. The new flathead pistons, provided by Saturn, raise the compression ratio from 9.3:1 to 11.0:1.

Figure 6: Flathead and stock pistons

Other conversions suggest higher ratios, approaching 14:1, may be desirable. However, to achieve a compression greater than 11:1 would require shaving the cylinder head. Although possible, this operation was rejected in favor of the simple exchanging of pistons.

An addition to the engine is a 58-tooth crankshaft pick-up wheel used by the new electronic controller. A gap in the series of teeth allows a magnetic pick-up to pulse the controller once per revolution. Installing the wheel with the gap 11 teeth from TDC on cylinder #1 permits the controller to know the crankshaft position as well as speed.

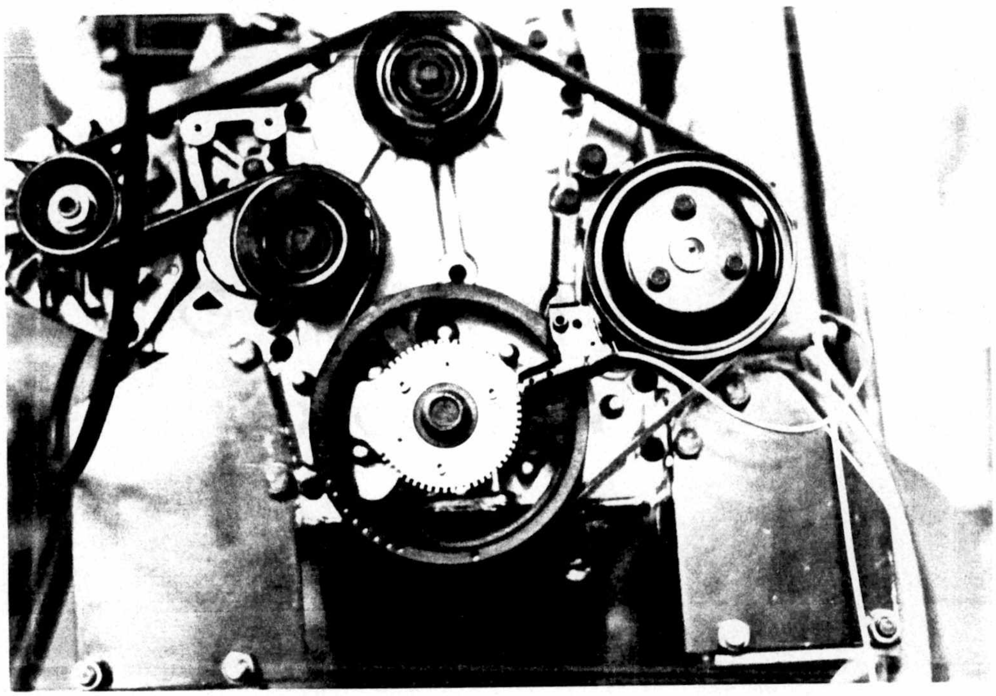


Figure 7: 3 1/2" pick-up wheel

Pressure Vessel

There were several concerns with the location and selection of a fuel tank(s). A location was chosen based on compromises between tank(s) size, number of tanks, interference with existing car abilities, and whether the tank(s) is interior or exterior. By existing car abilities is meant its spare tire capacity and its split fold-down rear-seat operation. The following five figures show basic possibilities for tank(s) configuration.

The option offered in Figure 8 is desirable because of its high total volume and external locations, but its drawbacks are the loss of the spare and the need for multiple tanks.

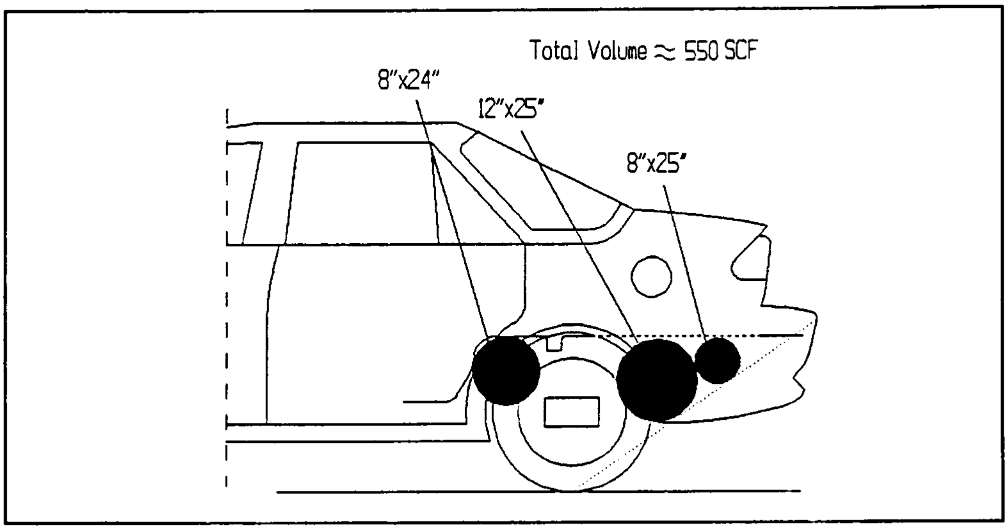


Figure 8: Option 1

Figure 9 shows an alternative which reduces the number of tanks to two, but places them within the car's interior. This arrangement prevents access to the spare and occupies the entire trunk; its redeeming advantage is the highest volume of any option.

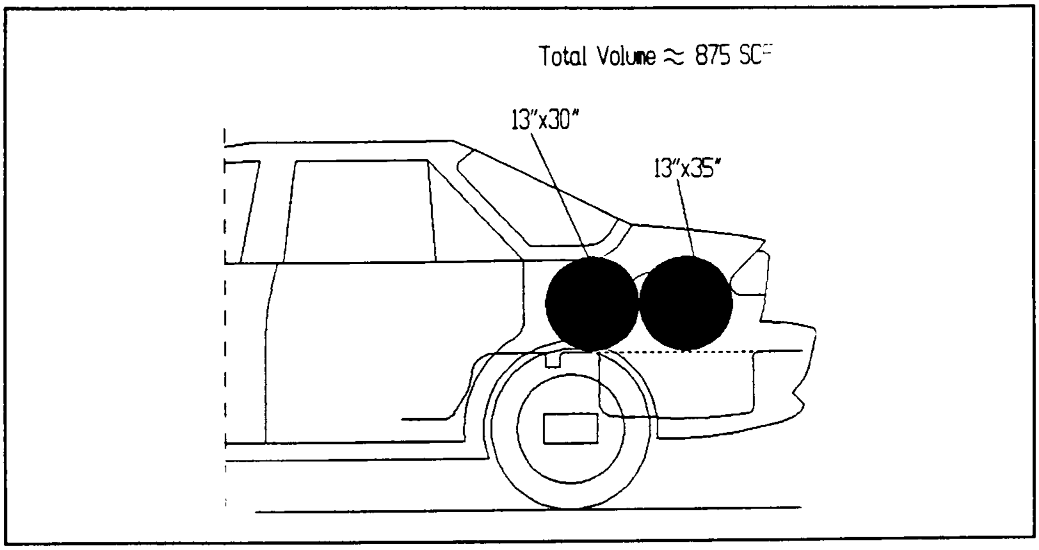


Figure 9: Option 2

Figure 10, by using a single tank, can fit a larger diameter in the trunk. Installing it near the rear avoids the protrusive wheel wells and allows a length of about 35 inches. External entrance to the trunk is blocked but some space remains behind the rear seatbacks. The spare is again blocked by this option.

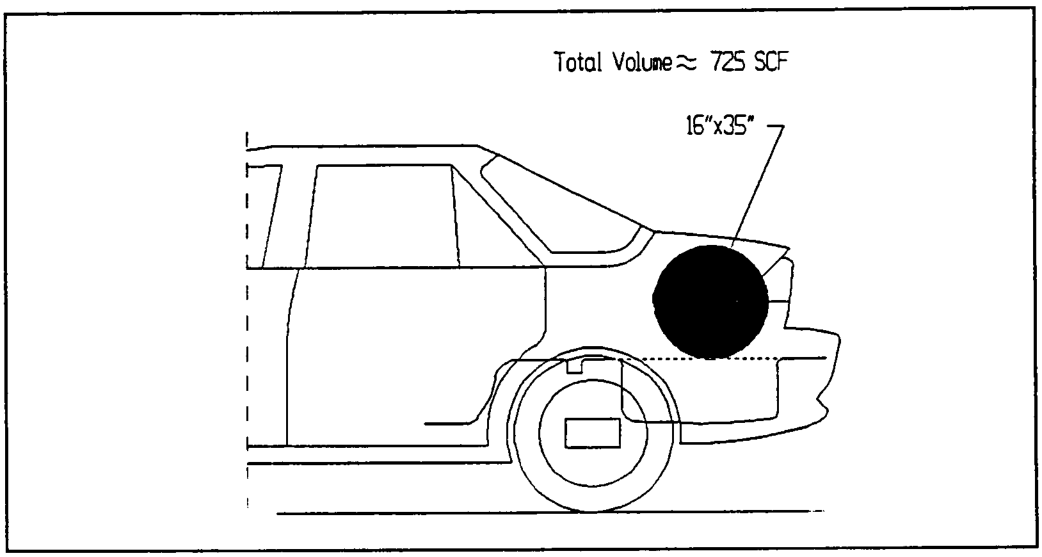


Figure 10: Option 3

Figure 11 also uses a single, large diameter tank. While its length is sacrificed by moving the tank forward, some trunk room is salvaged and the spare is accessible.

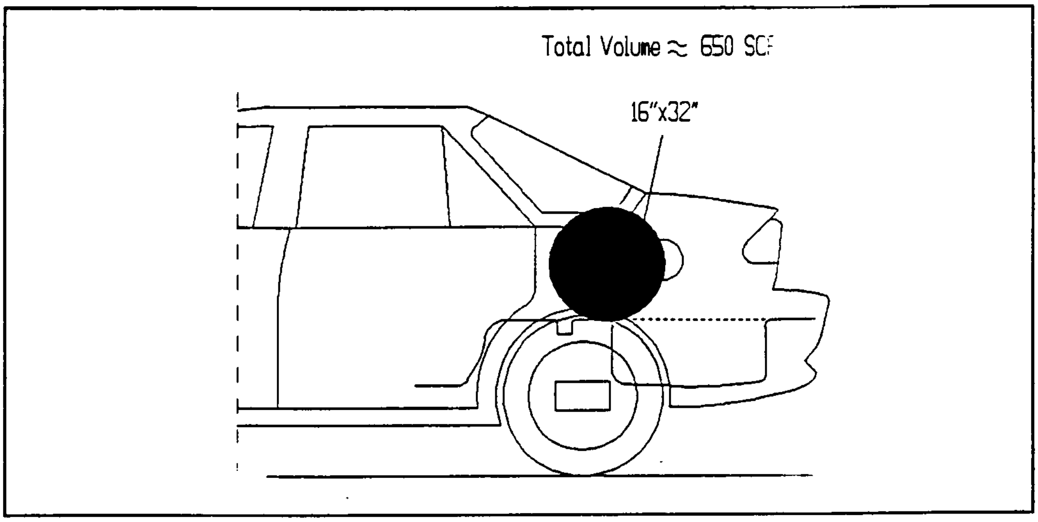


Figure 11: Option 4

The final basic option, shown in Figure 12, is the only interior tank option which allows trunk extension by folding down the rear seatback. However, the spare is obstructed and the tank weight is off-centered from the car's major axis.

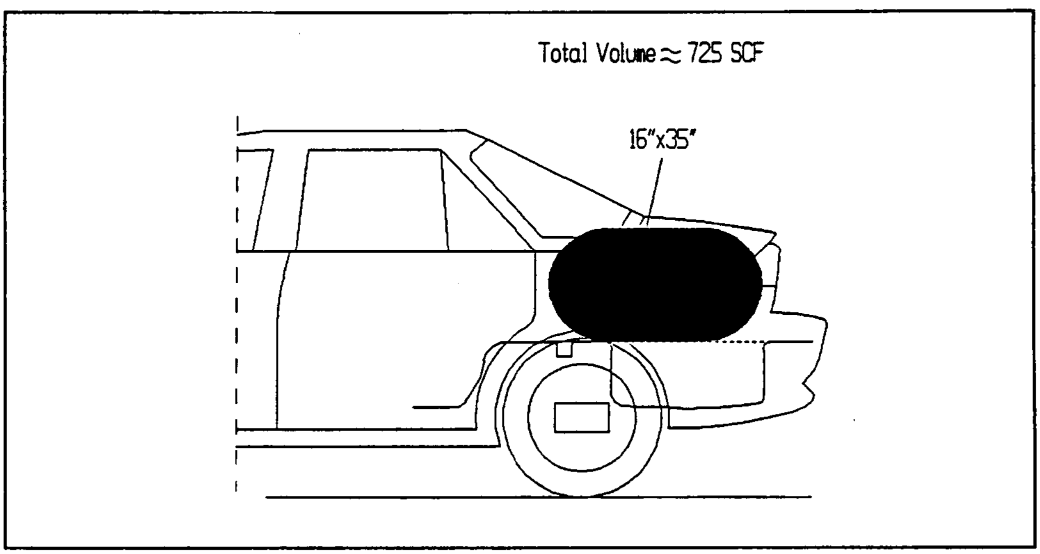


Figure 12: Option 5

Of these configurations, the fourth is selected for installation. Its volume should be sufficient for a 200+ mile range, a goal of the vehicle conversion. Although located internally, this option uses one third the tanks and associated hardware required by option 1. This choice also allows for access to the spare, deemed more important than retaining the trunk extension feature (by folding seatbacks). Lastly, this option places the vessel in perhaps the most crash-protected location, between the rear axles and leaving a 25 inch crush distance from the rear.

With external dimensions now decided, selection of the particular tank is made. The pressure vessel chosen is custom manufactured by Comdyne-1. The tank consists of a cold-drawn aluminum cylinder liner fully overwrapped with fiberglass. This type of tank is one of five available on the market: steel, hoop wrapped steel, hoop wrapped aluminum, full wrapped aluminum, and composite only. Only the final two options could seriously be considered for light-duty NGVs; the others are somewhat obsolete. Of the full wrapped aluminum and the composite tanks, only the full wrapped was commercially available at the time of tank selection.

The mounting of this tank is accomplished using the hardware shown in Figure 13 and in Appendix A. The four brackets elevate the tank an inch above the floor, allowing the spare tire cover to be removable. The fit is tight enough, however, that a slot cut in the spare cover is necessary to clear the trunk-lid clasp receiver. Also, the tank intrudes upon the rear speakers; shims are necessary to

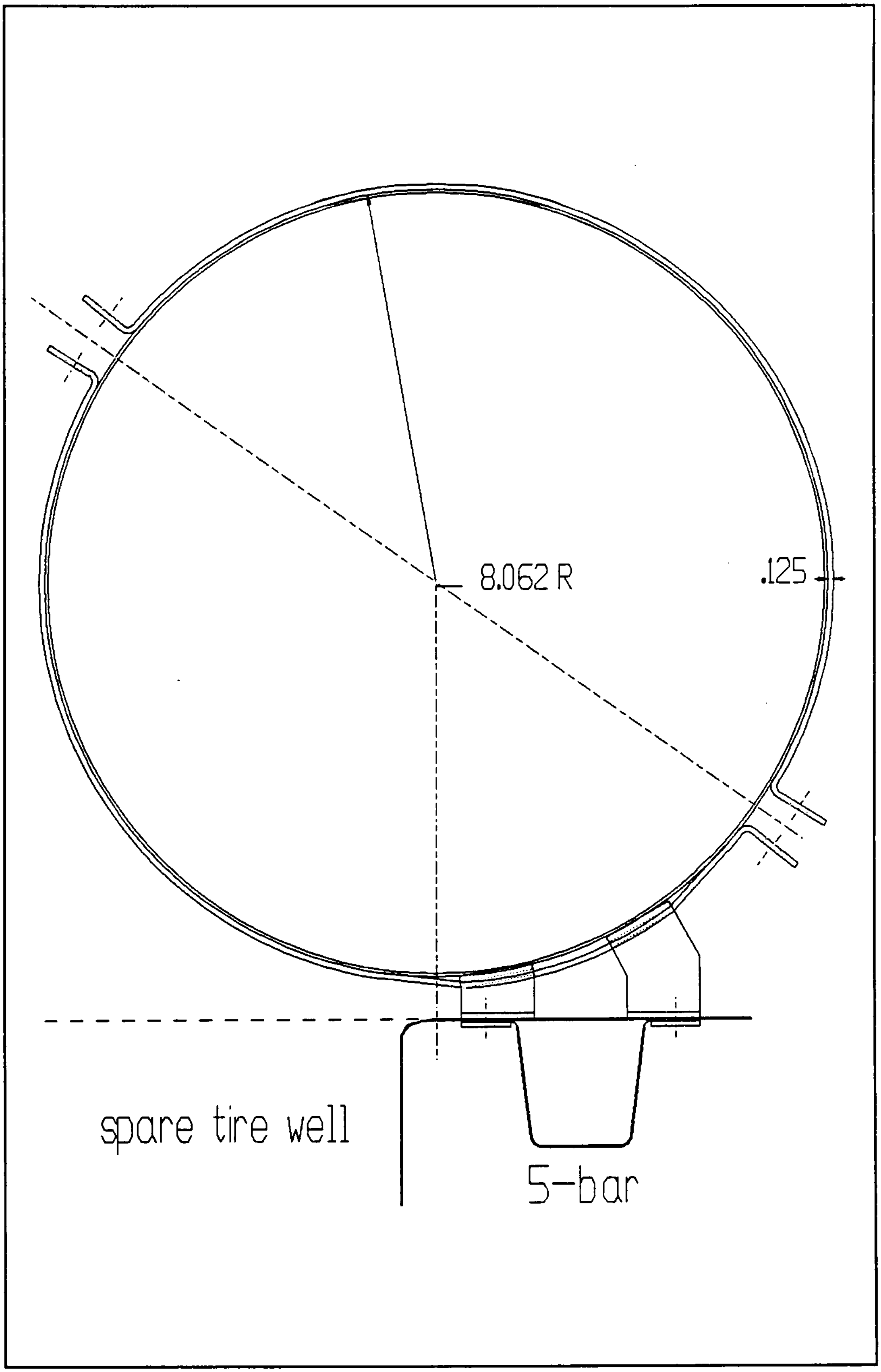


Figure 13: Tank mounting

raise both speakers $^1/_2$".

As noted earlier, to secure the plastic ring adapter to which the vapor bag clamps, silicon adhesive is used to affix it against the tank boss. The tank manufacturer also distributes tank valve shields which might have been suitable as well.

The tank itself is held in place by two hoops with bolted connections. Sandwiched between the tank and the hoops, the brackets hold the entire system in place. Without clamping, developed by tightening the hoop bolts, the hoops (and tank) would move freely. By avoiding any welded or bolted connections between the hoops and brackets, the hoops are easy to manufacture and install.

To prevent chaffing, a threat to any pressure vessel's integrity, a #20 neoprene band is placed between the hoops and brackets.

The front and rear brackets straddle the Saturn's "fifth-bar" member. Eight SAE grade 4 bolts ($^3/_8$") pass through the brackets and floor to backup plates, which reinforce the sheetmetal and distribute the loading to the fifth bar.

Free Body Diagram

A brief stress analysis is performed on the bracket bolts and on the regions of highest stress in the brackets.

The mounting system is first analyzed to determine bolt stresses. According to NFPA 52, the system should retain the pressure vessel under eight g's of acceleration. Free body diagrams (Figure 14) illustrate external horizontal forces and the resultant force components at the bolts (for front and rear collision scenarios).

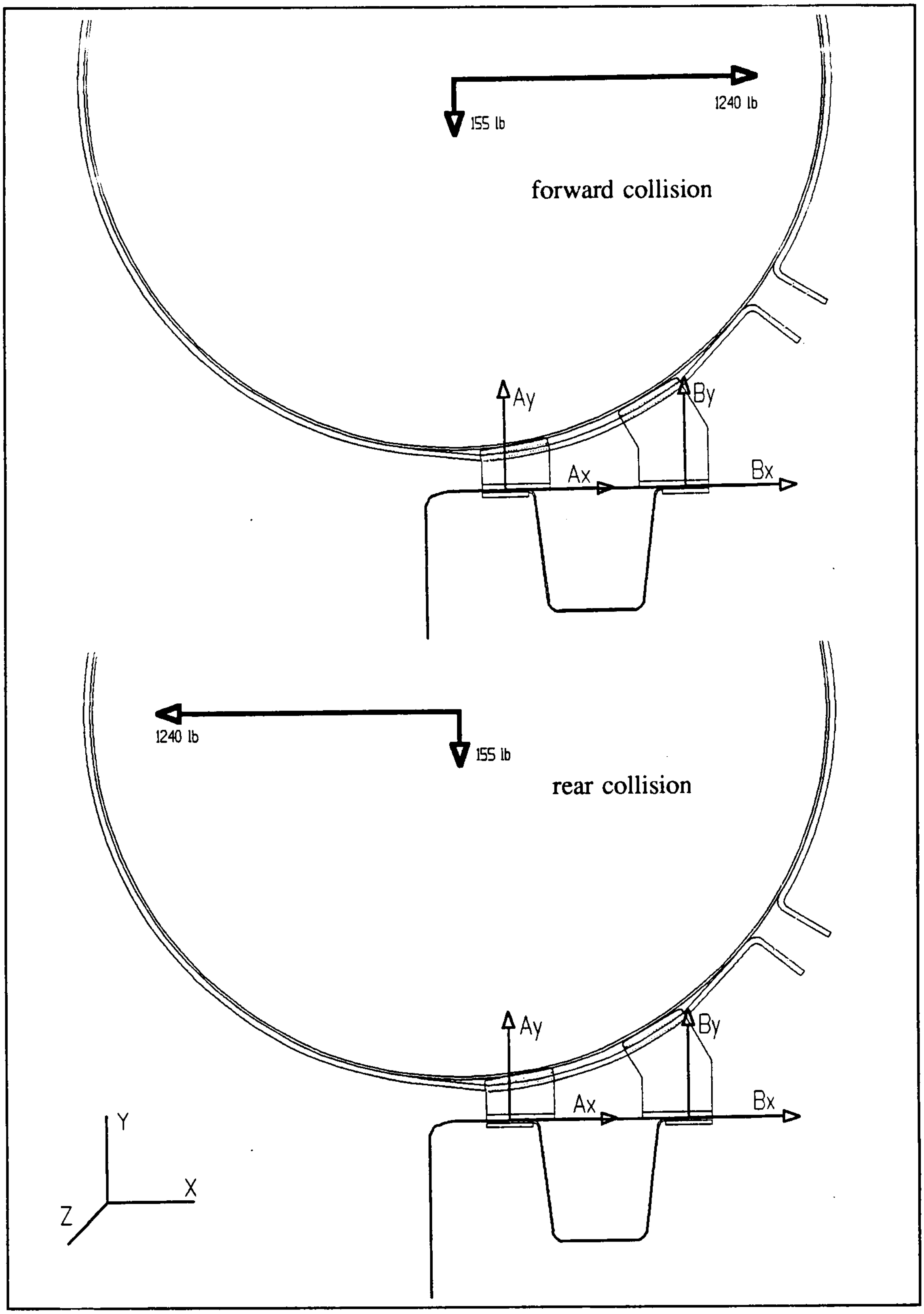


Figure 14: Tank/Brackets Free Body Diagrams

For calculations, the tank is taken to be 155 pounds. The tank alone weighs 125 pounds, 152 pounds filled to capacity. Including valve weight and neglecting the brackets yields the 155 pound total.

The first step is simply to sum the X-Y forces and moments; for the front-end collision they are:

$$\Sigma F_x = A_x + B_x + 1240 lbf = 0$$
$$\Sigma F_y = A_y + B_y - 155 lbf = 0$$

$$\Sigma M_A = (-155 lbf)(1.00 in) + (1240 lbf)(8.95 in) - B_y(3.93 in) = 0$$
$$\Sigma M_B = (-155 lbf)(4.93 in) + (1240 lbf)(8.95 in) + A_y(3.93 in) = 0$$

$$\therefore \; A_y = -2629.5 lbf \;\; and$$
$$B_y = 2784.5 lbf$$

$$A_x = B_x = -620 lbf$$

Thus the four bolts at "A" are put in tension, while the bracket at "B" is compressed. Selecting a $^3/_8$ inch diameter, the normal and shear stresses on a bolt element are:

$$\sigma_A = \frac{F}{A} = \frac{2629.5/4}{.1104} \quad , \quad \tau_A = \frac{620/4}{.1104}$$

$$= 5954 \frac{lbf}{in^2} \qquad\qquad = 1403 \frac{lbf}{in^2}$$

This tension and shear are shown below on an element, with the accompanying Mohr circle showing maximum shear stress (Figure 15).

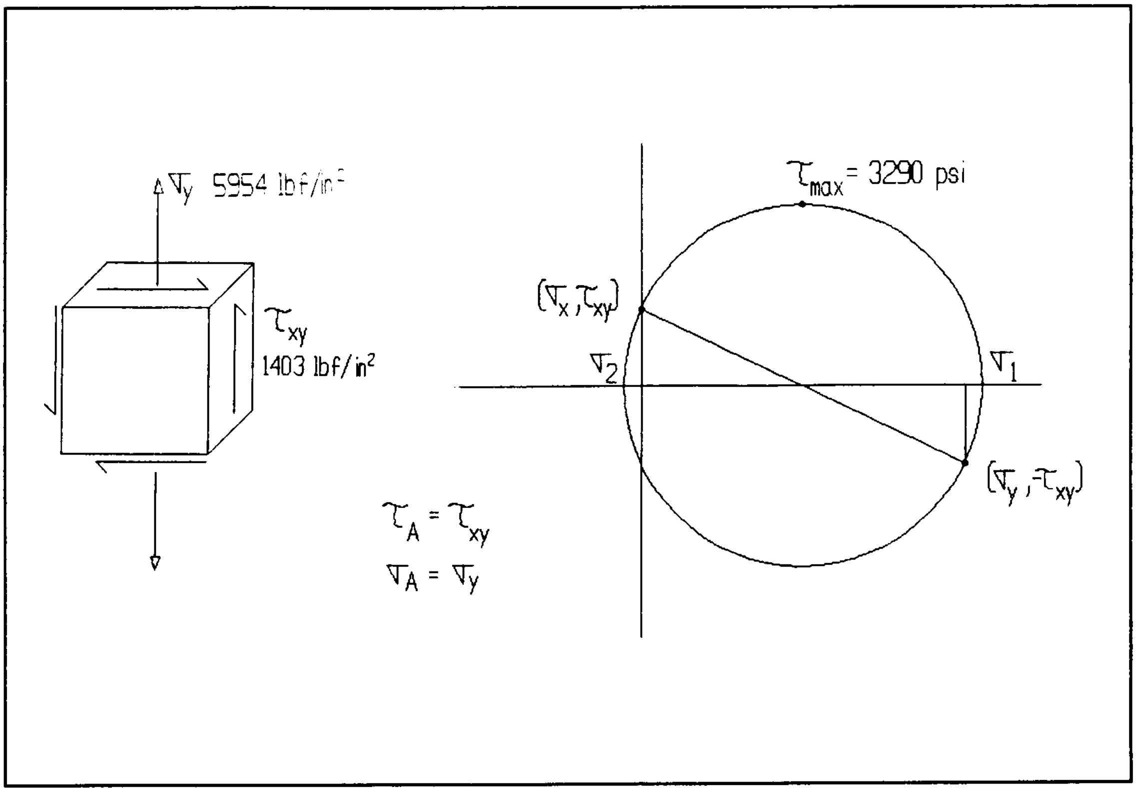


Figure 15: Element normal and shear stresses

Using the maximum shear stress theory, failure is predicted when the stress exceeds one-half the yield strength:

$$\tau_{max} \geq \frac{S_y}{2}$$

For a SAE grade 4 medium-carbon bolt, yield strength is 100 kpsi. In this application, the load is only about 3 kpsi, giving a safety factor of 50,000/3,290 = 15.2.

A similar force analysis can be performed for forces of a rear collision.

$$\Sigma F_x = A_x + B_x - 1240lbf = 0$$

$$\Sigma F_y = A_y + B_y - 155lbf \ = 0$$

$$\Sigma M_A = (-155lbf)(1.00in) + (-1240lbf)(8.95in) - B_y(3.93in) = 0$$

$$\Sigma M_B = (-155lbf)(4.93in) + (-1240lbf)(8.95in) + A_y(3.93in) = 0$$

$$\therefore \ A_y = 3018.4lbf \ \ and$$

$$B_y = \ -2863.4lbf$$

$$A_x = B_x = 620lbf$$

In this instance, the four "B" bolts are in tension while "A" experiences compression. The normal and shear stresses for "B" bolts are:

$$\sigma_B = \frac{F}{A} = \frac{2863.4/4}{.1104} \quad , \quad \tau_B = -1403\frac{lbf}{in^2}$$

$$\sigma_B = 6484\,\frac{lbf}{in^2}$$

while maximum shear stress is:

$$\tau_{max} = \left[\left(\frac{\sigma_x - \sigma_y}{2}\right)^2 + \tau_{xy}{}^2\right]^{1/2}$$

$$= \left[\left(\frac{0-6484}{2}\right)^2 + 1403^2\right]^{1/2}$$

$$\tau_{max} = 3533 \frac{lbf}{in^2}$$

and gives a safety factor of 14.2.

The bolt preload and corresponding torque are determined using equations provided by Shigley [2]. Of all the bolts, those at location "B" of the rear-end collision model experience the greatest tensile stresses. Therefore, the following calculations are taken using this magnitude of stress.

The preload is taken to be:

$$F_i = 0.75F_p \quad , \quad F_p = A_t S_p$$

$$F_i = (0.75)(.0775in^2)(65{,}000 \frac{lbf}{in^2})$$

$$F_i = 3778 lbf$$

To develop this preload, the bolt torque is

$$T = KF_i d$$

$$T = (0.2)(3778 lbf)(0.375 in)$$
$$T = 283\ in \cdot lbf$$

For the external loading, the portions taken by the bolt and by the clamped members are found from where the effective stiffness of the bolt and members are

$$B_y = P_b + P_m$$

$$P_b = P_m \frac{k_b}{k_m} \quad , \quad P_m = P_b \frac{k_m}{k_b}$$

$$k_b = \frac{A_d A_t E}{A_d l_t + A_t l_d} \quad , \quad k_m = \frac{0.577 \pi E d}{2 \ln\left(5 \dfrac{0.577 l + 0.5 d}{0.577 l + 2.5 d}\right)}$$

$$k_b = \frac{(0.1104 in^2)(0.0775 in^2)\left(30 \cdot 10^6 \dfrac{lbf}{in^2}\right)}{(0.1104 in^2)(0.1875 in) + (0.0775 in^2)(0.1875 in)}$$

$$k_m = \frac{(0.577)(\pi)\left(30 \cdot 10^6 \dfrac{lbf}{in^2}\right)(0.375 in)}{2 \ln\left(5 \dfrac{(0.577)(0.375) + (0.5)(0.375)}{(0.577)(0.375) + (2.5)(0.375)}\right)}$$

$$k_b = 5.024 \cdot 10^6 \frac{lbf}{in}$$

and

$$k_m = 18.219 \cdot 10^6 \frac{lbf}{in}$$

Substituting for P_m

$$B_y = P_b + P_b\left(\frac{k_m}{k_b}\right)$$

$$\frac{2862\ lbf}{4\ bolt} = P_b(4.63)$$

$$\therefore P_b = 154.6\ lbf$$

$$and$$

$$P_m = 561.3\ lbf$$

The total resultant maximum bolt load can now be found: it is the sum of the preload and the external load.

$$F_b = P_b + F_i$$

$$F_b = 154.6 + 3778 = 3932.6\ lbf$$

Electrical Systems

The electrical wiring is presented in appendix form: this discussion concerns only the physical mounting of electrical systems. The primary component is the TEC-2 controller. It bolts on the transmission housing, occupying the location the Saturn ignition module previously held: a steel bracket allows the TEC to use the same mounting holes as the module. Heat shielding is provided by a steel sheet metal shield which hides the #1 exhaust runner, the closest source of excessive heat. The Saturn module, minus coils, is relocated beneath the battery platform: the unit is still needed to supply a signal to the dashboard tachometer.

The Energy Kinetics control center is located behind the instrument panel on steering column supports. Two velcro tabs (2"x$^1/_2$") are more than sufficient to secure this light box in place.

With the transfer of sensors from the ECM to TEC, the ECM needs to be kept "happy" to prevent lighting the check engine light or interfering with other non-engine ECM functions. Therefore, resistors are placed in the ECM wiring, mimicking the sensors' resistances of the MAT and TPS, for instance. Another option, used with the MAP, is to wire the sensor to both controllers.

Chapter 3

Electronic Engine Control

Introduction

As Saturn's ECM content is proprietary, control of all major engine functions is shifted to an aftermarket unit. The "TEC-2" ECM, manufactured by Electromotive Inc., is selected. It houses two ignition coils and the controller electronics in a single, compact unit. The TEC-2 is sophisticated enough to receive all the relevant sensor inputs previously collected by the onboard ECM. The various power outputs (IAC, injectors, and solenoid) are provided for as well. In addition, the unit incorporates diagnostics capabilities, flashing fault codes in a manner similar to the Saturn ECM. The only remaining tasks reserved for the ECM involve controlling the tachometer and accessories such as climate control.

This unit was one of several on the market using a computer-controlled metering system. Companies such as Stewart & Stevenson, IMPCO, BKM, and SwRI also offer controllers, each of which uses injectors or high speed valves to meter natural gas.

Theory of Operation

The two most important functions of TEC-2 are fuel control and spark advance control. Both vary constantly: fuel control is governed by equations while spark advance relies on lookup tables.

TEC-2 controls fuel delivery by controlling the pulse width of fuel injectors according to equation 3.1.

$$\boldsymbol{PULSEWIDTH = (MAP \times \Gamma \times TOG) + IOT \pm BTO} \tag{3.1}$$

The manifold absolute pressure (MAP) is the main variable affecting pulse width. The manifold pressure, with air-temperature density correction, is used to calculate the mass air flow. This "speed/density" approach, where fuel delivery is based on air flow according to MAP, is the same method used by the original Saturn ECM.

The next equation term, gamma, acquires its value from an equation of its own.

$$\Gamma = \boldsymbol{SE + ASE + WE + AE + VETable + DE + EGO} + 1 \tag{3.2}$$

Gamma is a term reflecting fuel/air stoichiometry: $\Gamma=1$ is stoichiometric, $\Gamma=2$ is twice too rich, and $\Gamma={}^1/_2$ is twice too lean.

The equation sets gamma equal to one with enrichment variables increasing or decreasing this base value.

The first three terms are starting enrichments. SE (cold Start Enrichment) is a one-second long enrichment intended to compensate for gasoline condensation on cold cylinder walls; using NG, this term is not necessarily used. ASE (After Start Enrichment) has a 20-second duration; it helps the idle to stabilize and the EGO sensor to heat. WE (Warm up Enrichment) keeps the initial mixture slightly rich, leaning it back towards $\Gamma=1$ as engine temperature rises.

The fourth term, AE, is an acceleration enrichment. It counters the throttle response "flat spot" experienced when the fuel mixture is briefly leaned upon acceleration.

The engine volumetric efficiency is accounted for by accessing a MAP vs. engine-speed lookup table which allows the programmer to input VE compensation values.

DE (Density Enrichment) compensates for the change in air density as temperature varies. EGO (Exhaust Gas Oxygen) enrichment derives from feedback received from the EGO sensor. The A/F mixture is leaned or richened according to the presence of oxygen in the engine exhaust stream.

The third and fourth terms governing the pulse width in equation 3.1 are constants based on the characteristics of the particular fuel injectors selected. TOG (Time On Gamma) is chosen to define the pulse width of an injector at full throttle. IOT (Injector Offset Time) sets the pulse width at zero throttle. The raw fuel curve is thus defined by these two points on a MAP vs. PW graph (Fig. 16, based upon Electromotive drawing).

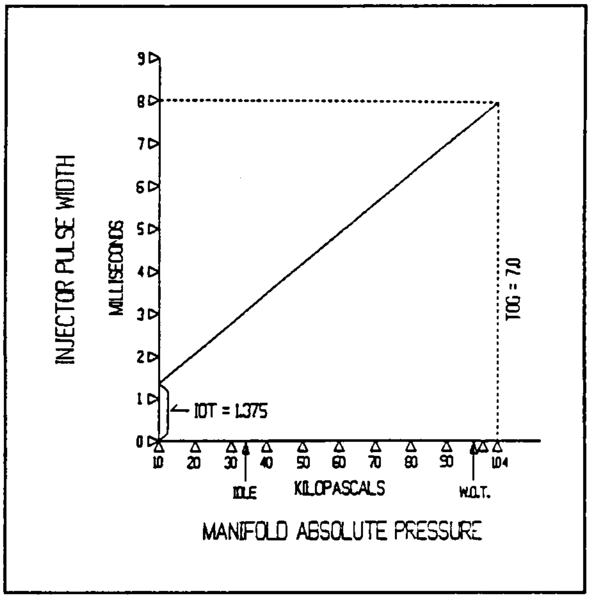


Figure 16: Raw Fuel Curve

The final term, BTO (Battery Time Offset), recognizes that the response of injectors varies slightly with voltage. Without compensation, the actual pulse width is shorter than defined for a sagging voltage source; likewise, above the nominal 12 volts, the actual pulse width is greater than defined. The BTO merely increases or decreases the PW linearly with the deviation from 12 volts.

These equation terms which govern the fuel control are determined by an iterative process where values are adjusted repeatedly (by the user) until the engine runs as desired. These final values then become part of the calibration file.

The second principal variable to be managed, spark advance, is a primarily a function of MAP and engine RPM. Deviation from these chosen values does at times occur: for regulating idle speed, spark advance is varied within certain set limits. Also, spark advance is offset by constant amounts based on engine temperature.

The rudimentary elements of TEC-2 engine control have been outlined; for a more comprehensive discussion of the capabilities of this controller and of the actual calibration of the system, the following section is provided.

Software and Calibration

The TEC-2 software, named "SUPER", is run on any personal computer with DOS, 512K minimum of RAM, and its serial port configured as COM1. Useful on this project, an IBM laptop provided freedom to edit calibration files and manipulate fuel delivery parameters, even with the car in motion.

The actual calibration used is presented in Appendix C. The parameters are listed in 15 main categories: raw fuel, enrichments, volumetric efficiency table, initial advance, advance table, coolant advance table, EGO, knock control, idle speed, rev. limiter, sensor failure, mat sensor enable, battery voltage compensation, GPO table, and GPO frequency.

With the final data compiled elsewhere, the following step-by-step explanation of calibration may prove laborious, unnecessary, or irrelevant to many readers.

MEF

SUPER is menu-driven software with two principal abilities: real-time monitoring of engine functions and the creation of calibration files. The "Monitor Engine Functions" (MEF) screen is used throughout the calibration process to display the latest effects of calibration changes; some parameter changes (spark advance, Γ, TOG, and IOT) can even be made directly from this screen with the engine running (Figure 17).

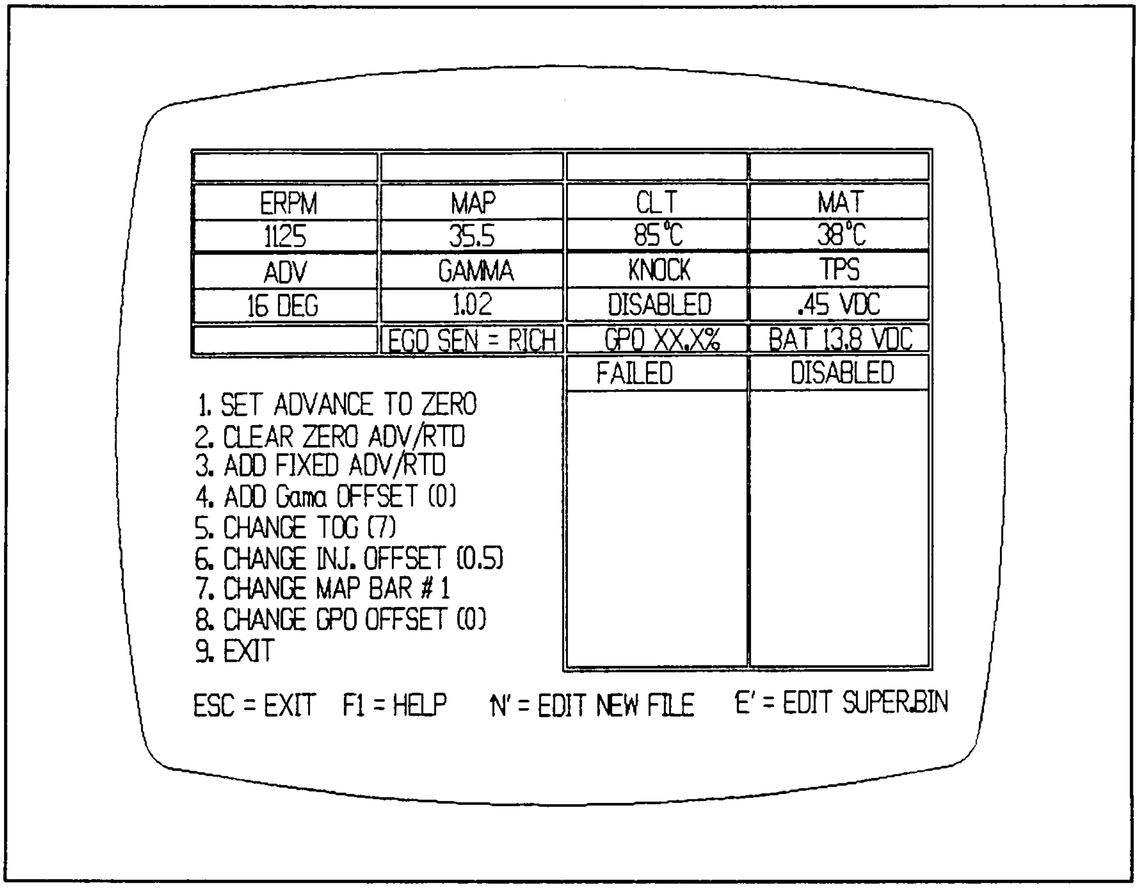


Figure 17: MEF screen display

The first step towards achieving proper engine control is to get the engine "up and running". Inspecting the MEF screen, the "failed" column (which indicates failed sensors) should be clear. If so, a trial starting calibration file can now be created.

Raw Fuel Parameters

The Raw Fuel Parameters are the most important to manipulate in preparing the engine for "up and running". TOG, IOT, minimum injector turn-on time, number to divide tachometer by, simultaneous or alternate injector firing, MAP offset, and TPS voltage at closed throttle are all given values.

Time On Gamma can be initially set using the following equation:

((120,000/max RPM)/no. of cylinders)*(no. to divide tach by)

Which becomes ((120,000/5000)/4)*(1) = 6.

Injector Offset Time is given a default value of 0.5 ms for now.

Minimum injector turn-on time merely sets a minimum pulse width. This constant, positive value provides a "floor" below which the software is forbidden to use any calculated pulse widths. Thus, this minimum allowable value prevents using zero or negative calculated values for pulse width.

The number to divide tachometer by sets the number of injector pulses per engine revolution. A value of 1 is chosen, firing the injectors every 180° of crankshaft rotation. If 2 was selected, the injectors would fire half as often.

The fuel injectors are set to fire simultaneously; alternate firing, where firing alternates between two groups of two injectors, is the other option.

The MAP offset is a constant to be added or subtracted from the sensed MAP value. It provides for vehicles calibrated at one altitude to operate at another. The offset is set at zero.

Lastly, the TPS voltage at closed throttle is noted from the MEF and inserted into the trial starting calibration.

After Raw Fuel Parameters are set, there still remain 14 lesser categories of parameters: for the trial calibration, these may be given values suggested by Electromotive if not otherwise known.

Idle Calibration

The engine may now be started and the idle speed set. Monitoring the warmed-up engine via the MEF screen, TOG and IOT are varied, if necessary, to produce a steady idle. These two values are now considered as fixed for the remainder of the trial calibration, and are expected to survive unchanged to the final calibration.

Maintaining the proper idle speed is accomplished using the software parameters listed in the appendix. As shown, the target idle speed at various temperatures is defined.

To meet the target, the software constantly chooses between two possible closed-loop schemes: coarse or fine idle speed control. If the true idle speed is far from the target speed, coarse idle speed control is used. For small deviations, fine idle speed control is selected. TEC-2 employs a user-provided number to define the boundary between coarse and fine control.

In the coarse control mode, the IAC motor may be quickly stepped to drive the true idle speed rapidly towards the target. When the true and target speeds are close (fine idle speed control), the IAC motor is stepped considerably slower. Thus the two modes provide for swift convergence on the target idle speed without overshoot.

The above idle speed control involves only the IAC motor; however, the spark timing can also be altered to influence idle speed. The timing is both retarded and advanced to respectively lower and raise the idle.

Choke Calibration

Choke enrichments may be fine-tuned after a stable warm idle is achieved. These gamma adjustments fall in two categories: temperature-based enrichment and time based enrichment.

The temperature-based warm-up enrichment allows for adding large enrichments at cold temperatures and lesser enrichments as the engine warms to and beyond 80 °C. Time-based alterations are offered in both 1 and 20 second durations. These are also empirically determined.

Advance and VE table

Dynamometer testing helps provide values for both these lookup tables. For spark timing, the advance producing the greatest engine output at various MAP vs. RPM values was explored. It soon became evident that the variation in engine torque with changing advances was slight and difficult to gage with the dynamometer's measurement resolution. Several degrees change in advance would not necessary be reflected by a corresponding change in display output torque.

Saturn's original spark timing fell within the range of advance suggested as acceptable by dynamometer testing and was used as a guide. To these base advances were added 2° to compensate for natural gas' slower flame speed. Jääskeläinen and Wallace [3] suggest an additional 2°-3° of advance while a paper by Genslak [4] reports testing of a General Motors 5.7-L NG engine revealed another 5° advance needed.

GPO table

A general purpose output table allows for an output device wired to the TEC GPO port to be controlled. This lookup table contains values dependent upon MAP and engine speed which govern the outputed pulse-width modulated signal. The EGR valve was attached to this port, with a two transistor circuit in-between (Figure 18). The GPO can not normally drive a solenoid of less than 45-50Ω resistance; the circuit provides for driving Saturn's 8-9Ω coil.

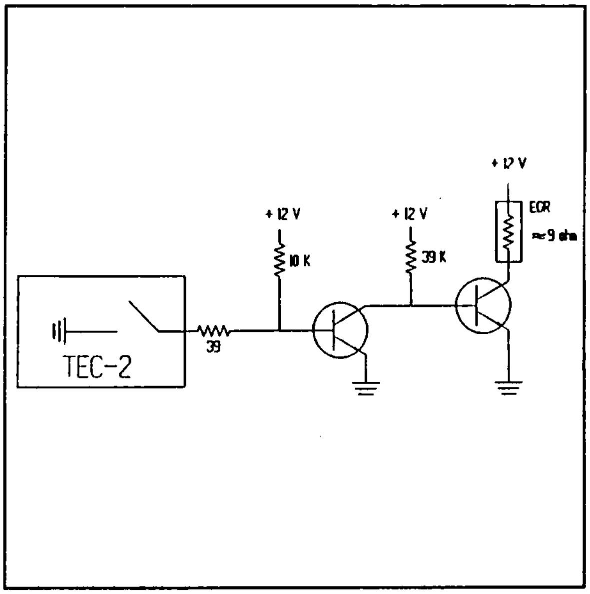


Figure 18: EGR circuit

The circuit proved to open and close the valve pintle properly when tested by manually grounding the COIL(-) wire; however, when the TEC-2 was wired to perform the same task in a pw modulated fashion, the valve failed to operate. This problem was unable to be corrected; the EGR was thus left in a fully closed, inactive state. Since the end of engine testing, a possible solution to this problem has surfaced. The EGR coil previously relied on a recirculation diode within the ECM: although the TEC-2 has a similar diode, the external transistor circuit isolates it from the EGR valve itself. The EGR coil, without a shorted path to de-energize rapidly, may not be able to respond as fast as the modulation requires. This supposition will no doubt be investigated by those continuing research on the SL-1.

Chapter 4

Performance

Power

A General Electric TLC-3544 DC dynamometer is used to measure engine output torques from 35% to 80% full throttle. A torque loss of about 7% compared with the standard SL-1 engine is experienced. The experimental points are shown on a plot of torque vs. rpm, superimposed on a normal SL-1 torque curve [5].

Since torque was not measured at WOT, a curve fitting of the data at the lower throttle openings allows for extrapolating a data point at WOT. Using a linear curve fit for all data, the average power loss in the 1600-2500 rpm range is calculated at 6.8%.

Normally, a power loss of at least 9.5% is expected simply by using NG as a fuel: the increase in engine compression helped offset this conversion loss. Assuming a 6.8% loss, maximum horsepower for the CNG engine drops from 85 hp to 79 hp. The raw dynamometer data and plots are shown in Appendix E.

Range

A single preliminary vehicle range test was performed; to expand upon this result, further range testing by this university is envisioned.

The results of the range test were promising: the driving range projected for the Saturn exceeds the expected 200 miles. The vehicle is expected to drive about 250 miles on a single, 3600 psi fill-up.

The test was performed on I-40 and I-75, west of Knoxville, TN on a clear day. The terrain varied from flat to gently rolling and traffic was light enough to avoid any congestion. The target vehicle speed was 55 mph, but actually varied between 55 to 60 mph according to the car's own speedometer. The road distance covered was based on both the odometer and interstate mile markers.

To begin the trial, the CNG tank was filled to 2000 psi, the greatest pressure locally available. The pressure was read off the vehicle's own pressure gage, located behind the fuel door. The resolution of this gage limits the accuracy of the test; for further testing another means of measuring fuel consumption would produce more certain results. The Saturn was driven until the engine died: the total distance covered was 140 miles, which would yield about (3600/2000)*(140 miles) ≈ 250 miles with a truly full (3600 psi) tank.

Emissions

A study of emissions on this particular vehicle is anticipated to be part of another thesis at the University of Tennessee. As of this writing, no emission testing has been performed. The following is a brief summary of emissions that can be expected, based on natural gas industry figures and testing of other vehicles over the years.

The overall NGV emissions picture is promising. The potential exists for reduction in CO, reactive hydrocarbons (RHC), NO_x, and CO_2. Sulphur dioxide and particulates are practically eliminated. Possibilities suggested by natural gas associations are enthusiastic: compared with gasoline emissions, decreases of 90%, 80%, 30%, and 30% for CO, RHC, NO_x, and CO_2, respectively, are conceivable . These numbers are perhaps optimistic for current NGVs; thus a comparison is made with emissions results from tests on an engine similar to Saturn's.

A paper by Jääskeläinen and Wallace [3] compared the performance and emissions of a 2.0L 4-cylinder Nissan engine when run on gasoline versus natural gas. At MBT and 2000 rpm., total hydrocarbons (THC) were reduced about 50% and NO_x decreased 700 ppm (down about 25% for moderate engine loading) over gasoline. A small drop in CO emissions was noted but attributed mostly to a difference in fuel/air mixtures: the engine ran slightly leaner on natural gas.

Spark timing and EGR both influenced emissions. Advancing spark timing increased both THC and NO_x in about the same linear fashion for both gasoline and natural gas: no gains in NG emissions over gasoline can be expected. Varying the EGR flow demonstrated tradeoffs between THC and NO_x production. As EGR increases, THC rises and NOx falls. The level of EGR chosen becomes a compromise between levels of two emissions.

The paper stressed that the ability of a controller to maintain a stoichiometric fuel/air mixture was paramount to emissions. Unfortunately, their closed-loop control was unable to keep the mixture as consistent as desired, damaging the emissions quality. The mixture ideally would not vary more than 0.5% - 1.0% from stoichiometric.

LIST OF REFERENCES

List of References

[1] National Fire Protection Association. NFPA52 Compressed Natural Gas (CNG) Vehicular Fuel Systems. 1992 ed.

[2] Shigley, Joseph. Mechanical Engineering Design. New York: McGraw-Hill Publishers, 1989.

[3] Jääskeläinen, Hannu, and James Wallace. (1993) "Performance and Emissions of a Natural Gas-Fueled 16 Valve DOHC Four-Cylinder Engine." SAE 930380

[4] Genslak, S.L. (1972). "Evaluation of Gaseous Fuels for Automobiles." SAE 720125

[5] Reilly, D.J., Andersen, R.P., Casparian, R.J., and P.H. Dugdale. (1991) "Saturn DOHC and SOHC Four Cylinder Engines." SAE 910676

[6] Energy Information Administration (DOE). Natural Gas Annual 1990 Volume 1 DE92007051

[7] American Gas Association. (1992) "Natural Gas Vehicle Safety Survey- an Update." Issue Brief 1992-3. March, 1992.

[8] Klausmeier, R. (1989). "Assessment of Environmental, Health, and Safety Issues Related to the Use of Alternative Transportation Fuels." Radian Corp., for Gas Research Institute. Final Report. October, 1989.

[9] Krupka, M.C., Peaslee, A.T., and H.L. Laquer (1983). "Gaseous Fuel Safety Assessment for Light-Duty Automotive Vehicles." Los Alamos National Laboratory. Technical Report. November 1983.

[10] 100th Congress. Public Law 100-494 "Alternative Motor Fuels Act of 1988." Y1.1/8:100-494.

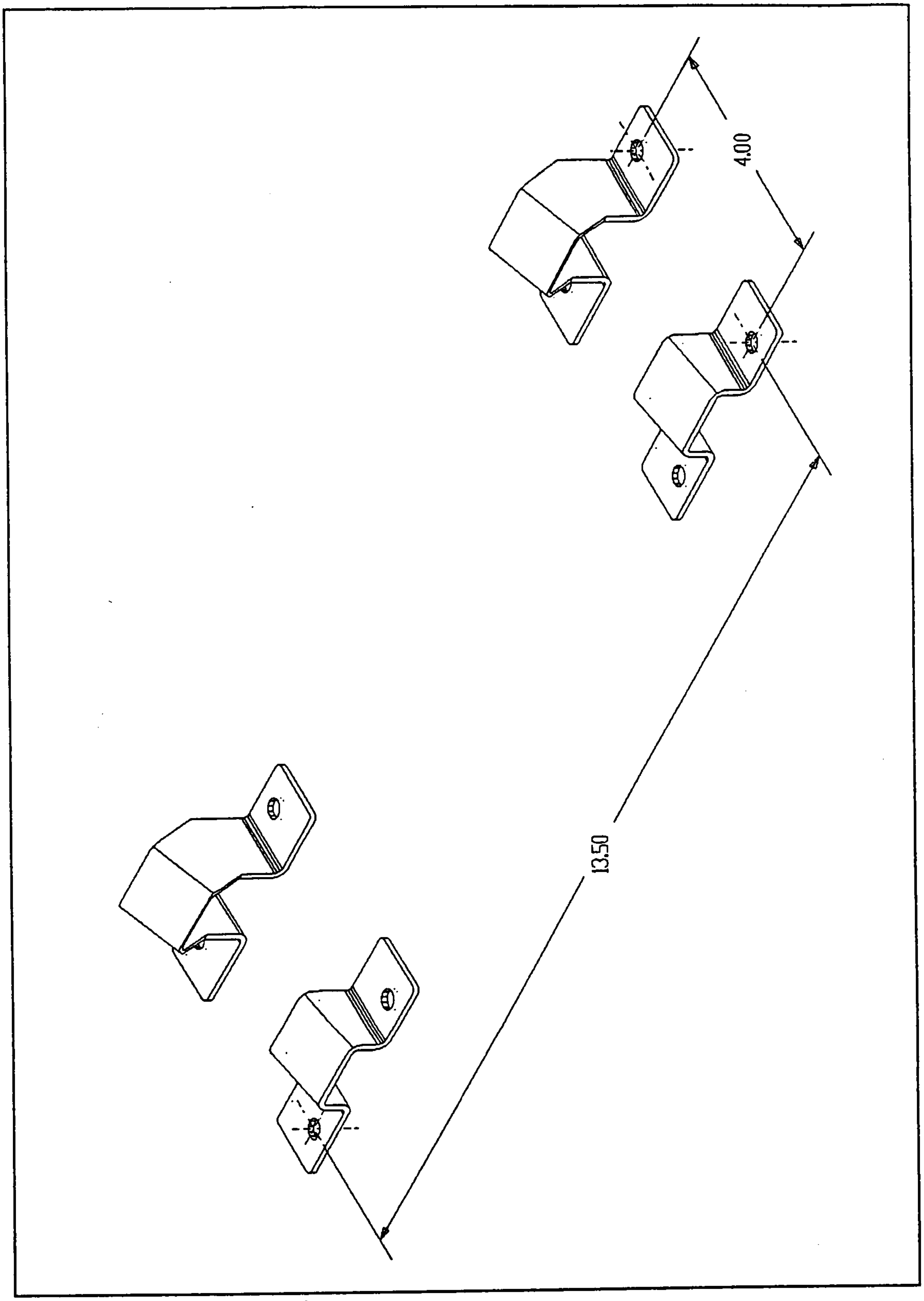
[11] 101st Congress. Report 101-490 "Clean Air Act Amendments of 1990." Y1.1/8:101-490.

[12] 102nd Congress. Report 102-1018 "Energy Policy Act of 1992." Y1.1/8:102-1018.

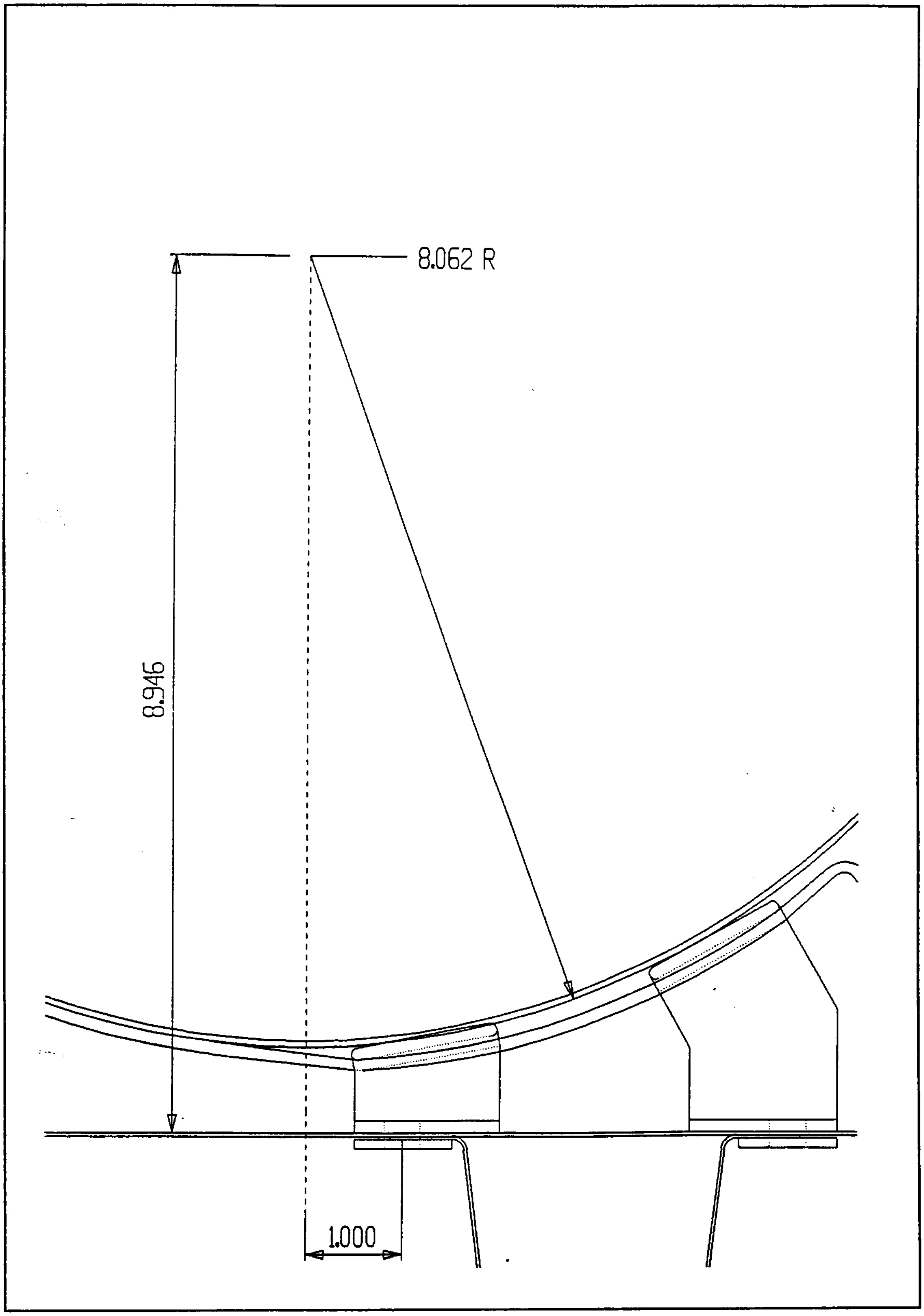
APPENDICES

APPENDIX A - DESIGN DRAWINGS:

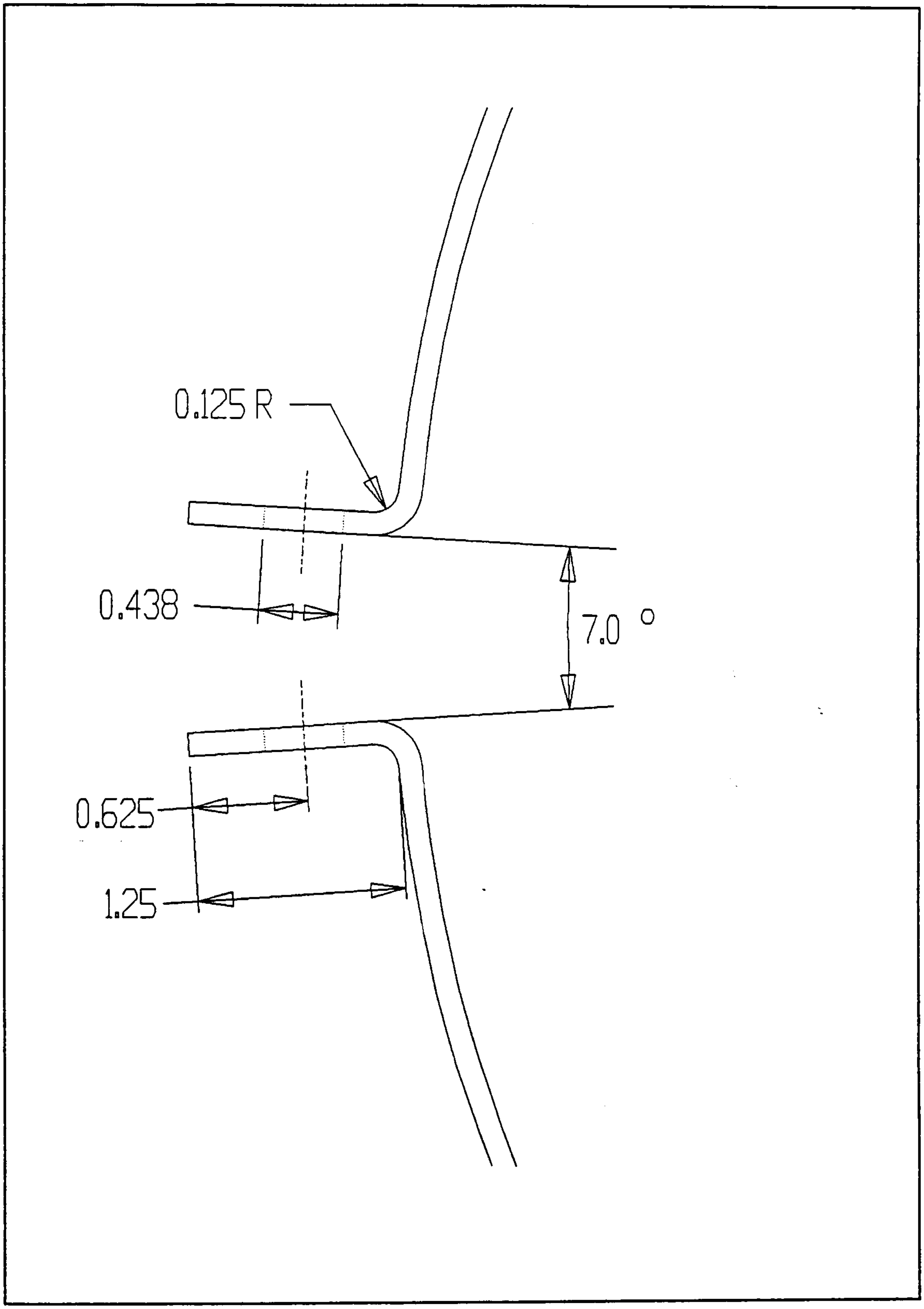
HARDWARE AND ELECTRICAL SYSTEMS



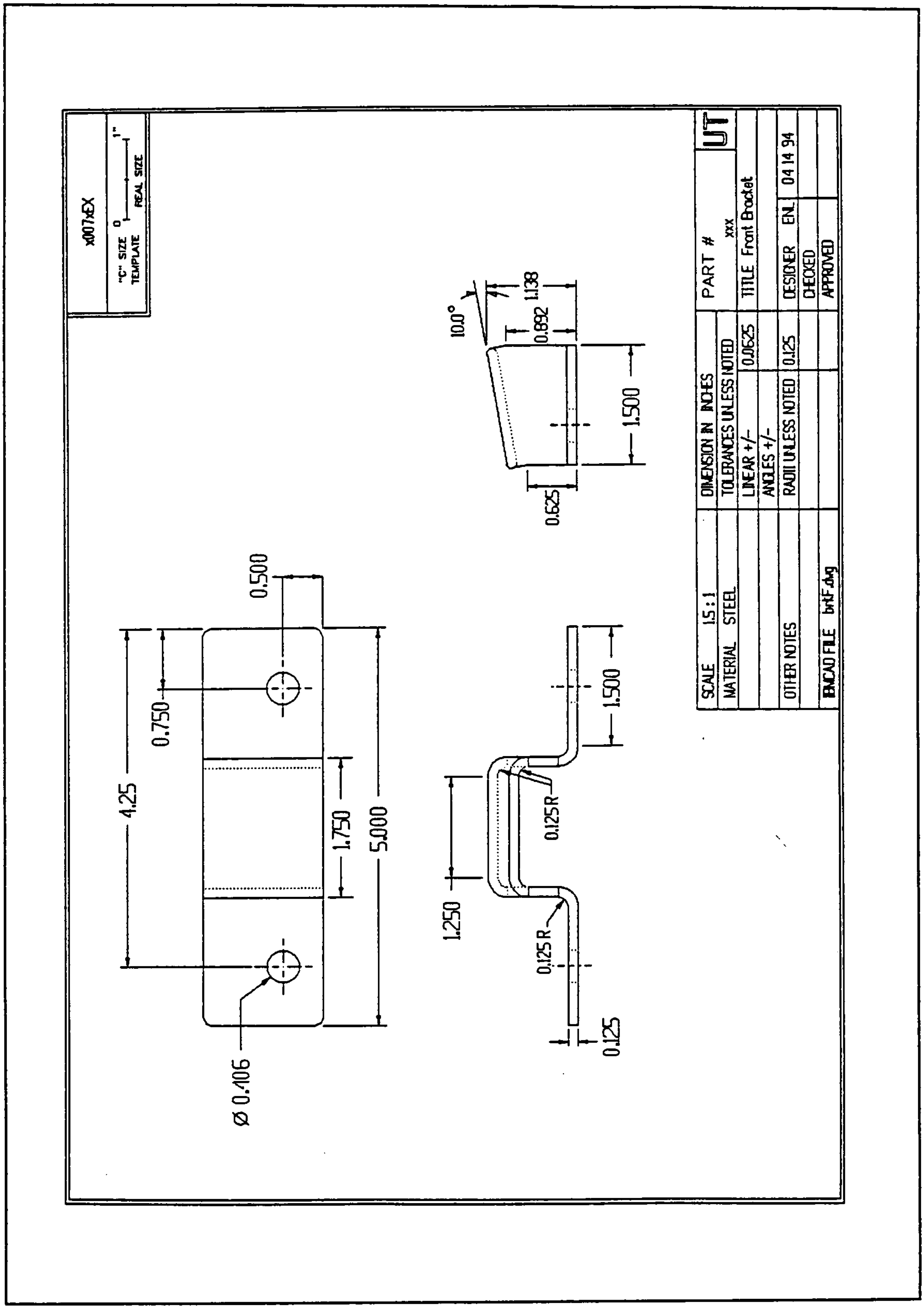
Drawing A1: Bracket spacing



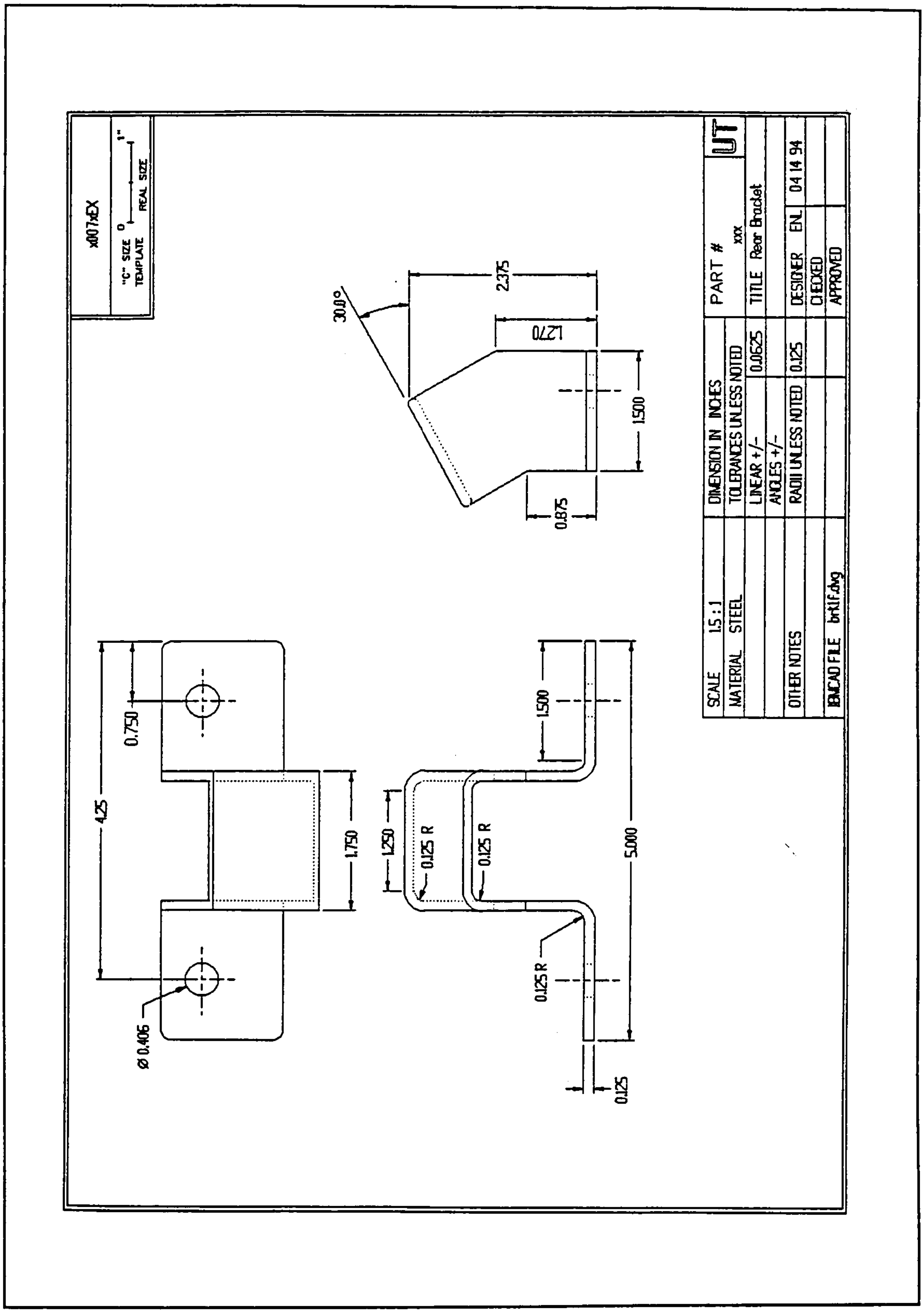
Drawing A2: Hoop/bracket assembly



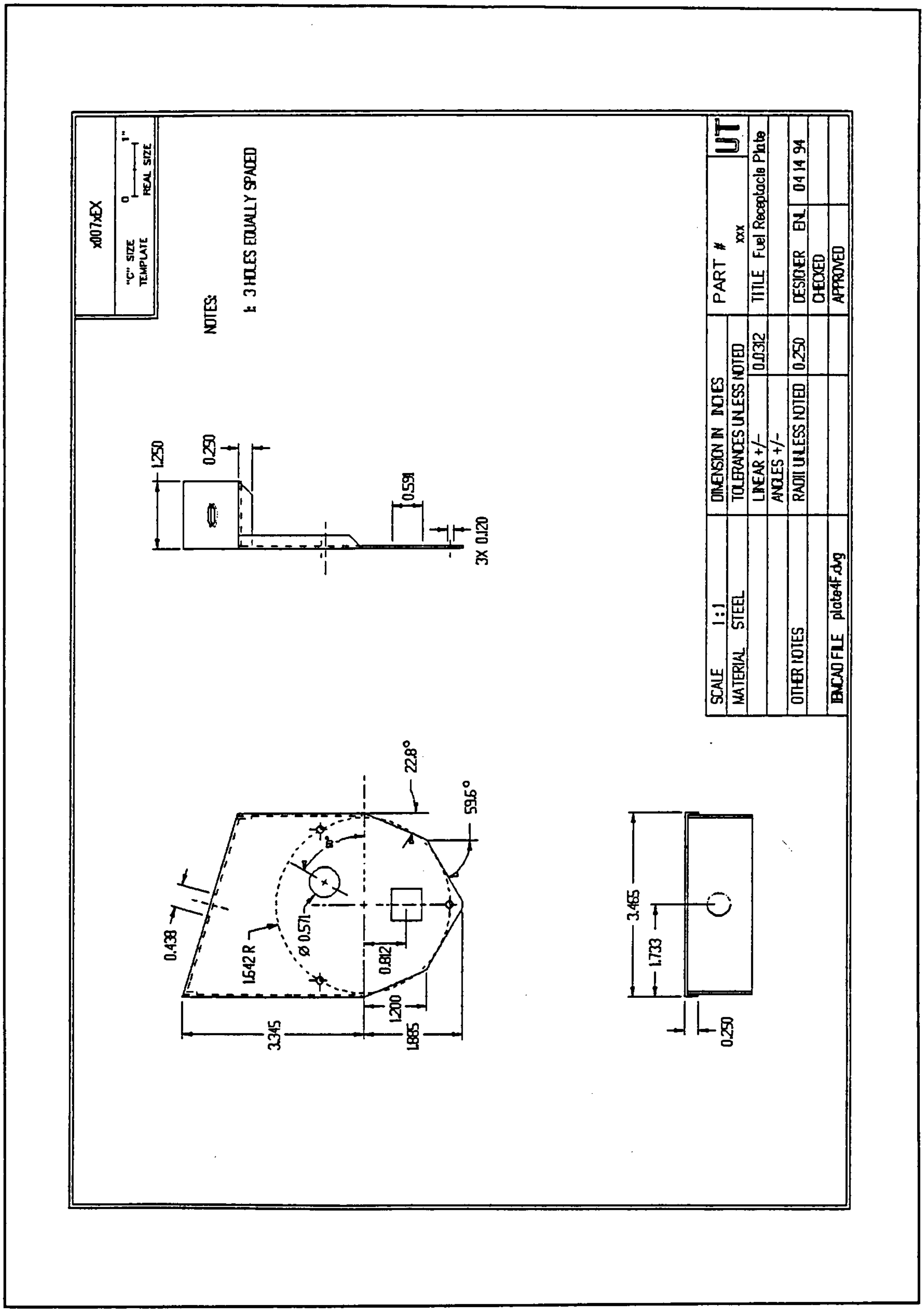
Drawing A3: Hoop bolted connection



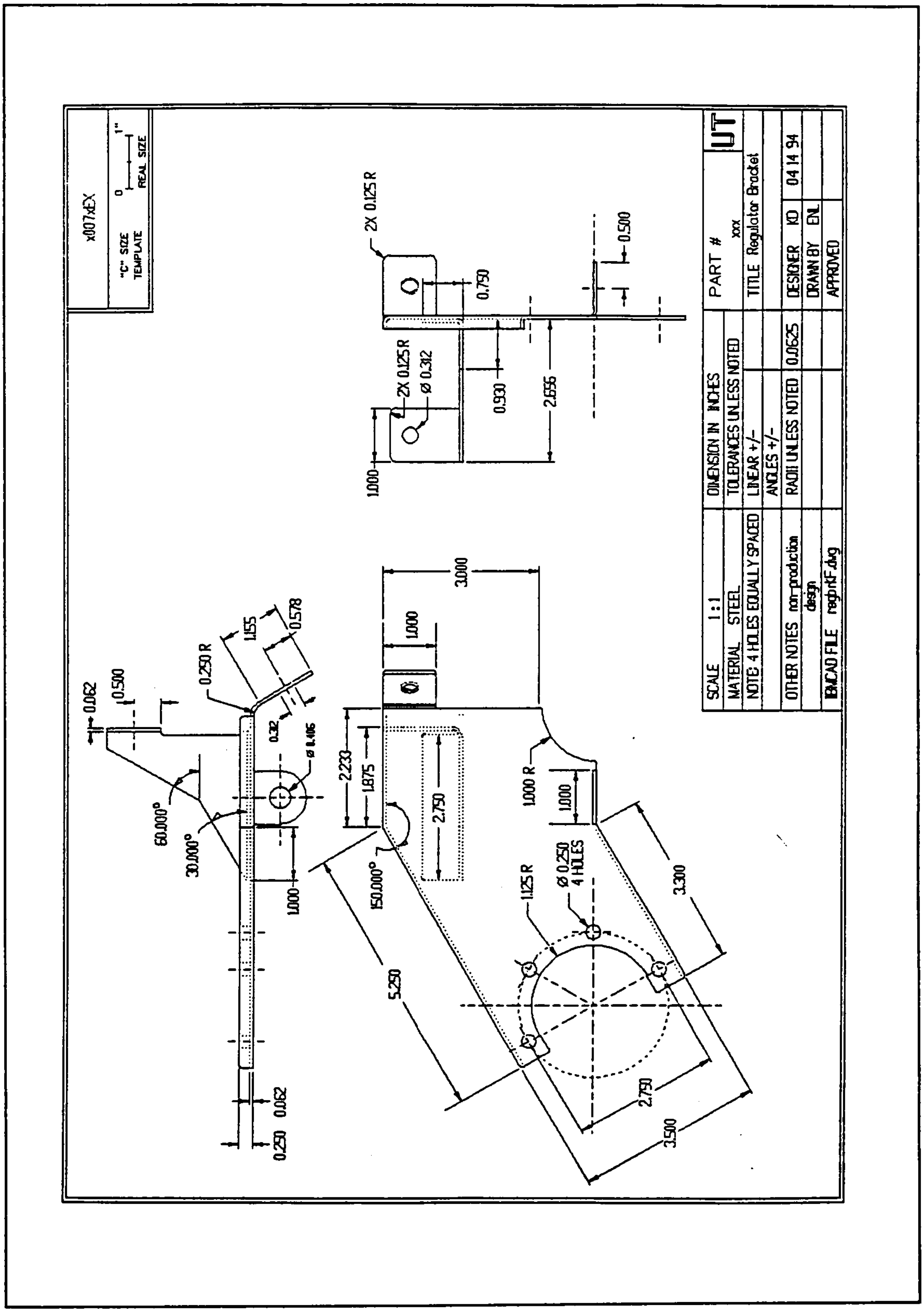
Drawing A4: Front bracket



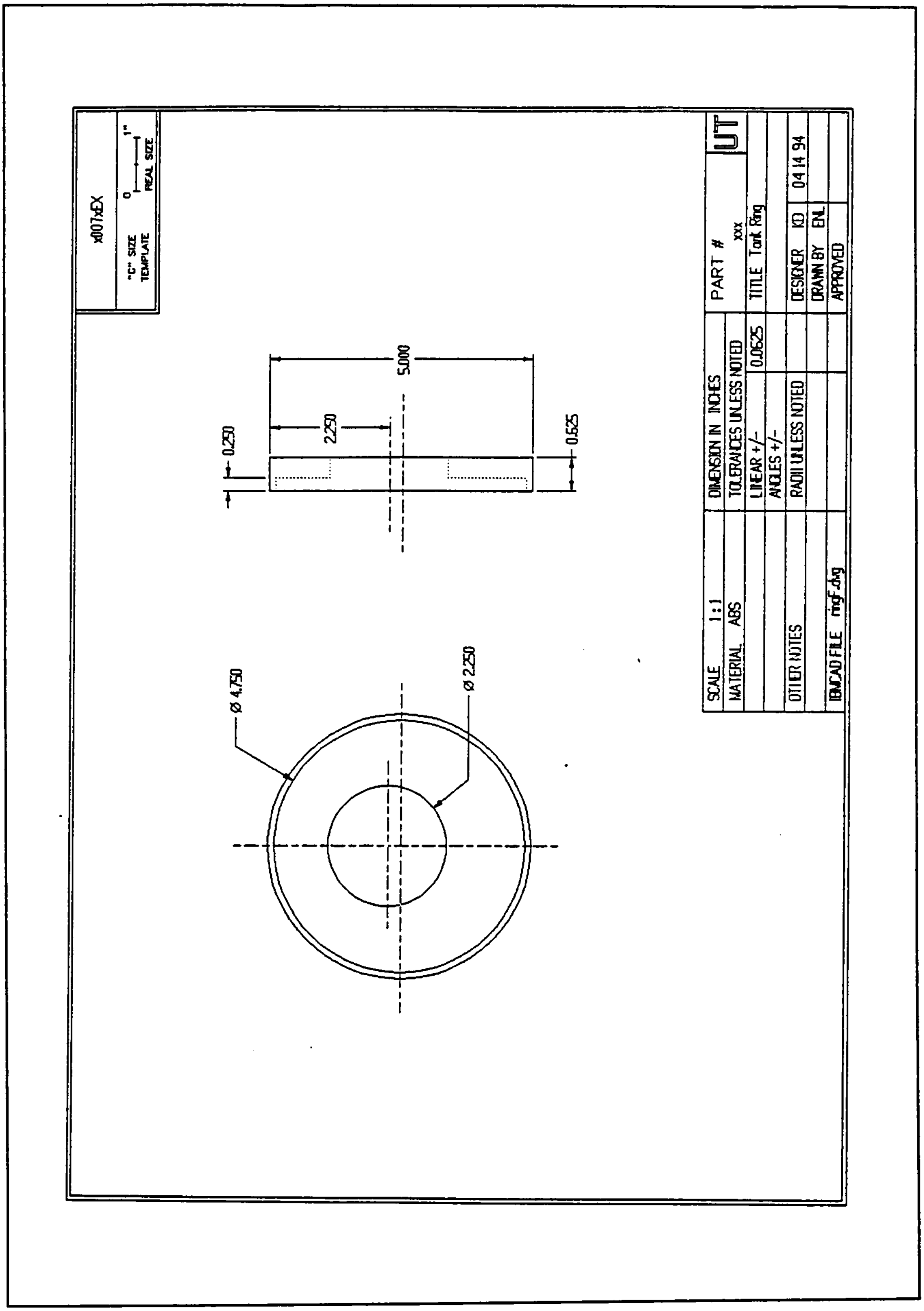
Drawing A5: Rear bracket



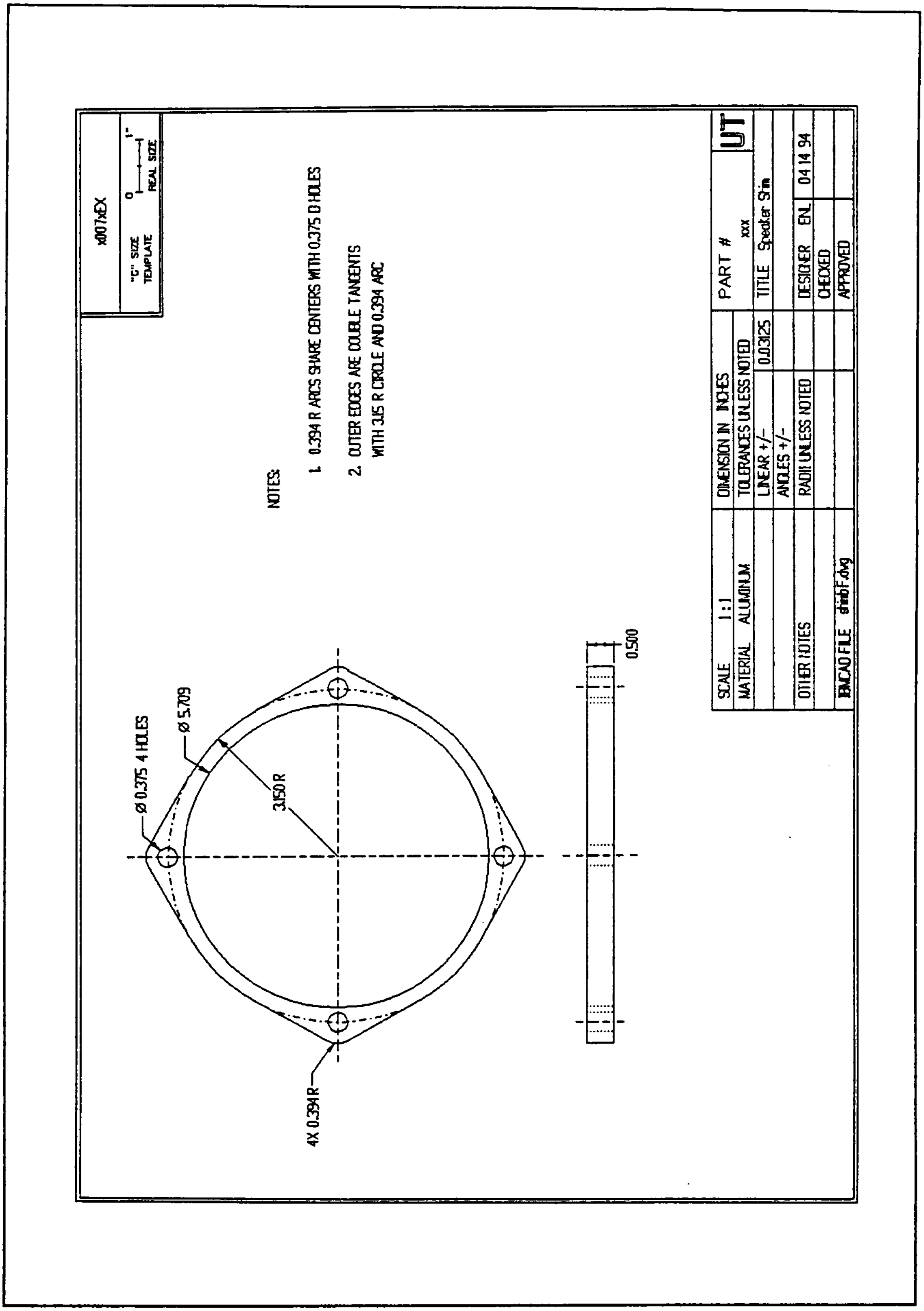
Drawing A6: Fuel receptacle plate



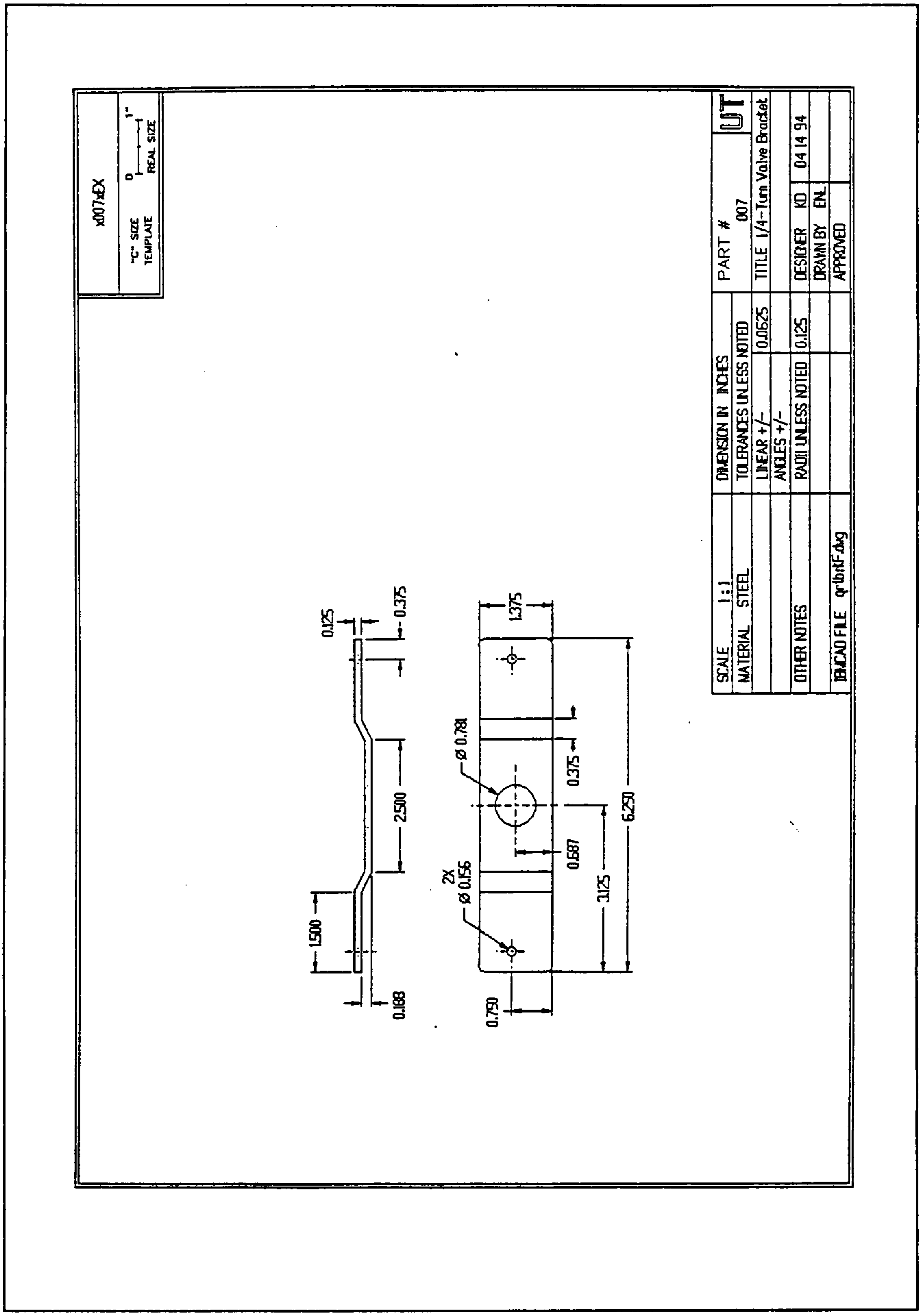
Drawing A7: Regulator bracket



Drawing A8: Tank ring



Drawing A9: Rear speaker shim



Drawing A10: 1/4 turn valve bracket

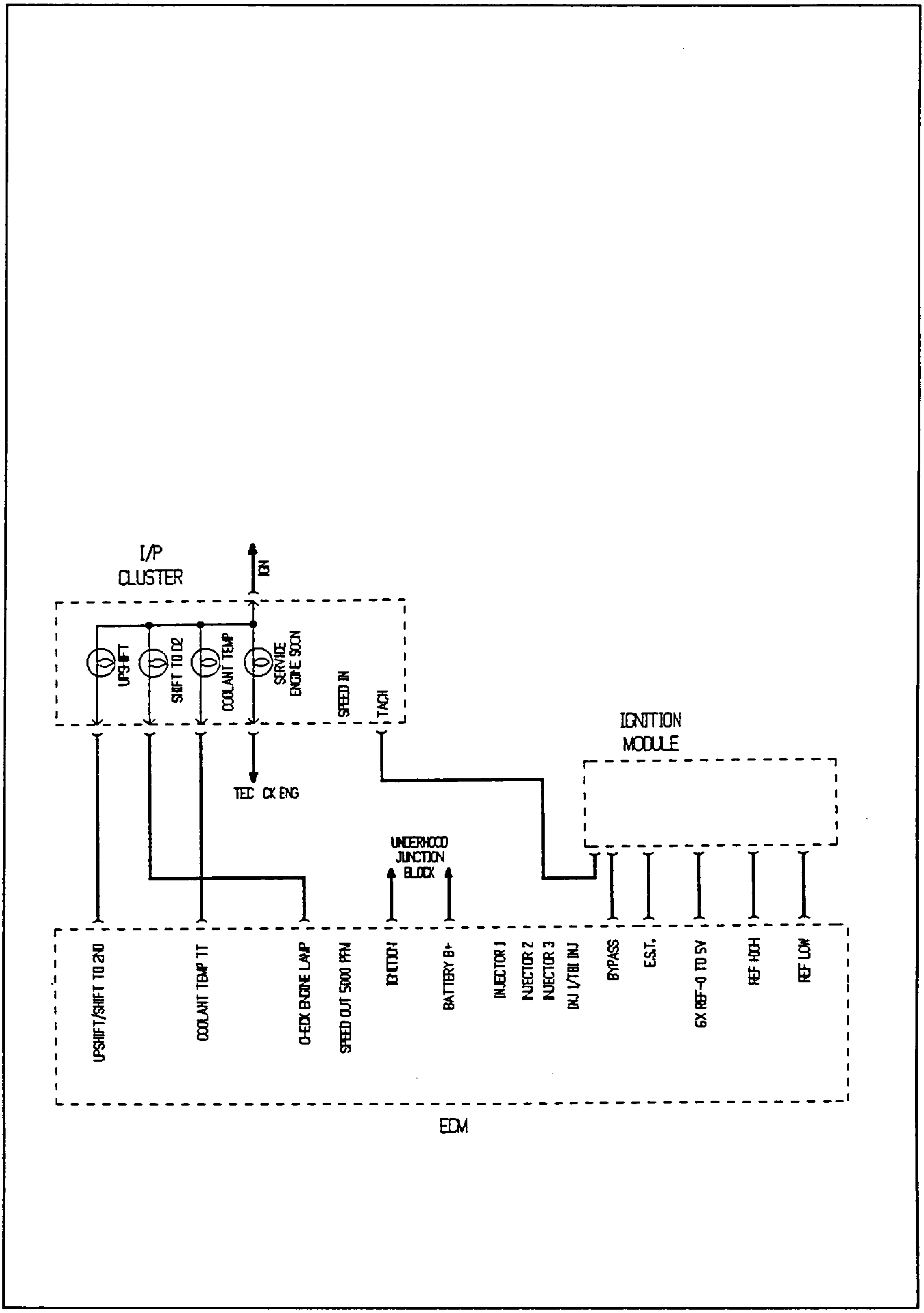


Figure A1: ECM wiring

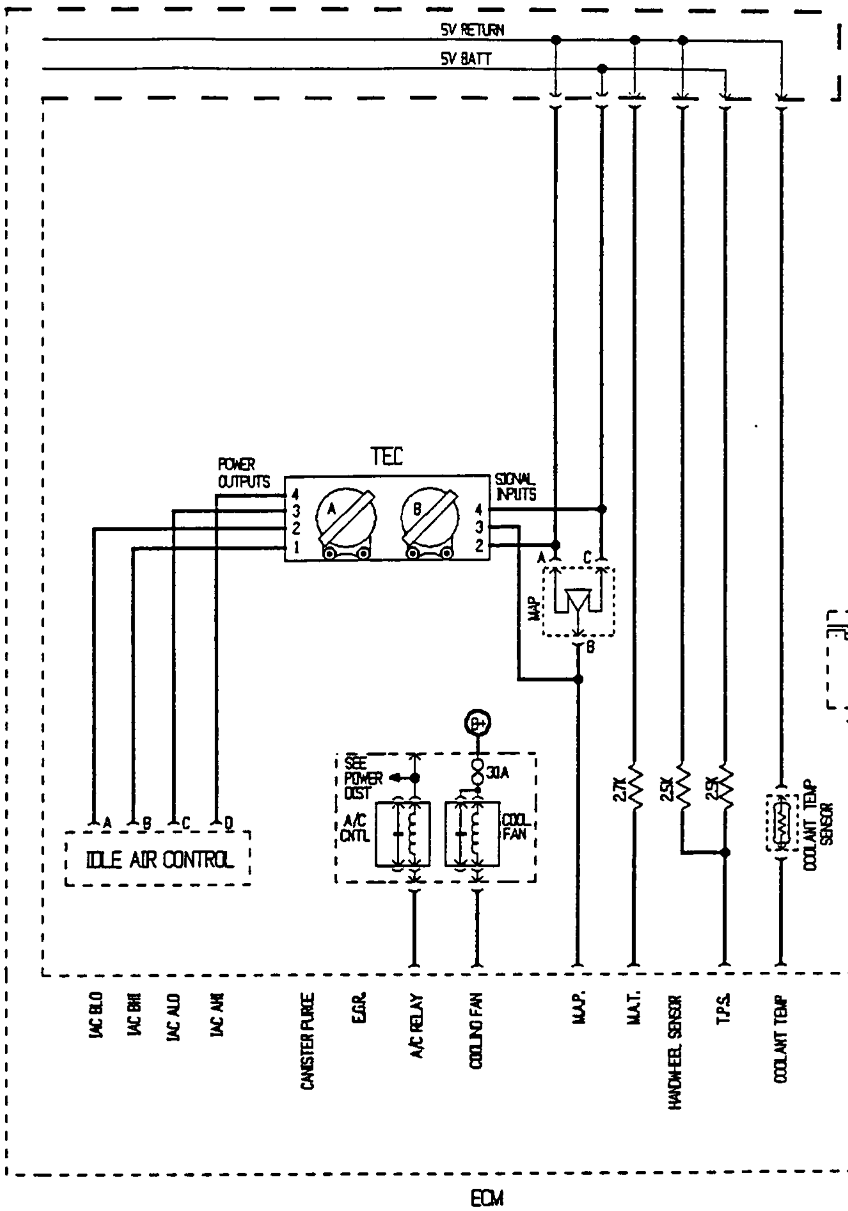


Figure A2: ECM (cont.)

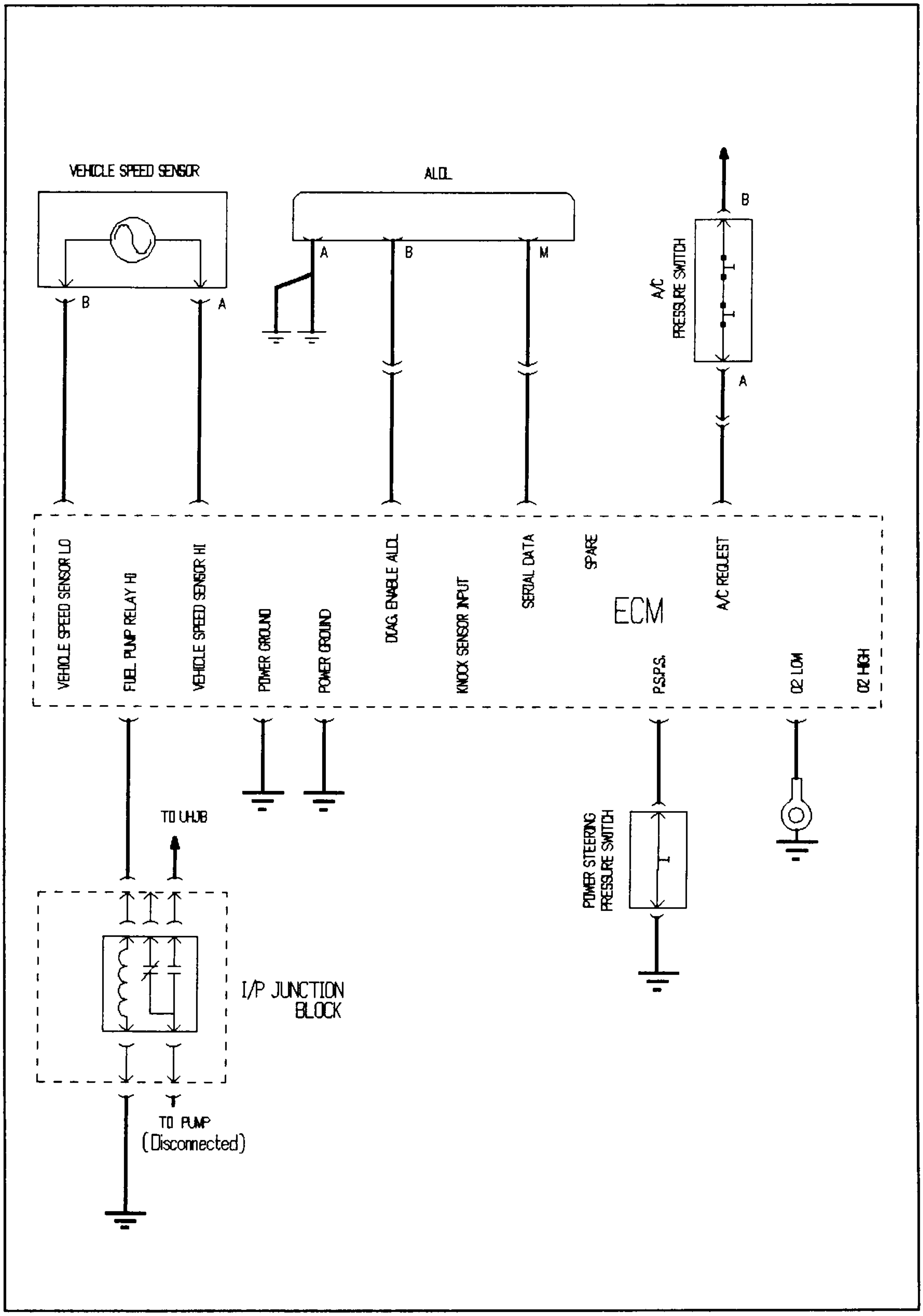


Figure A3: ECM (cont.)

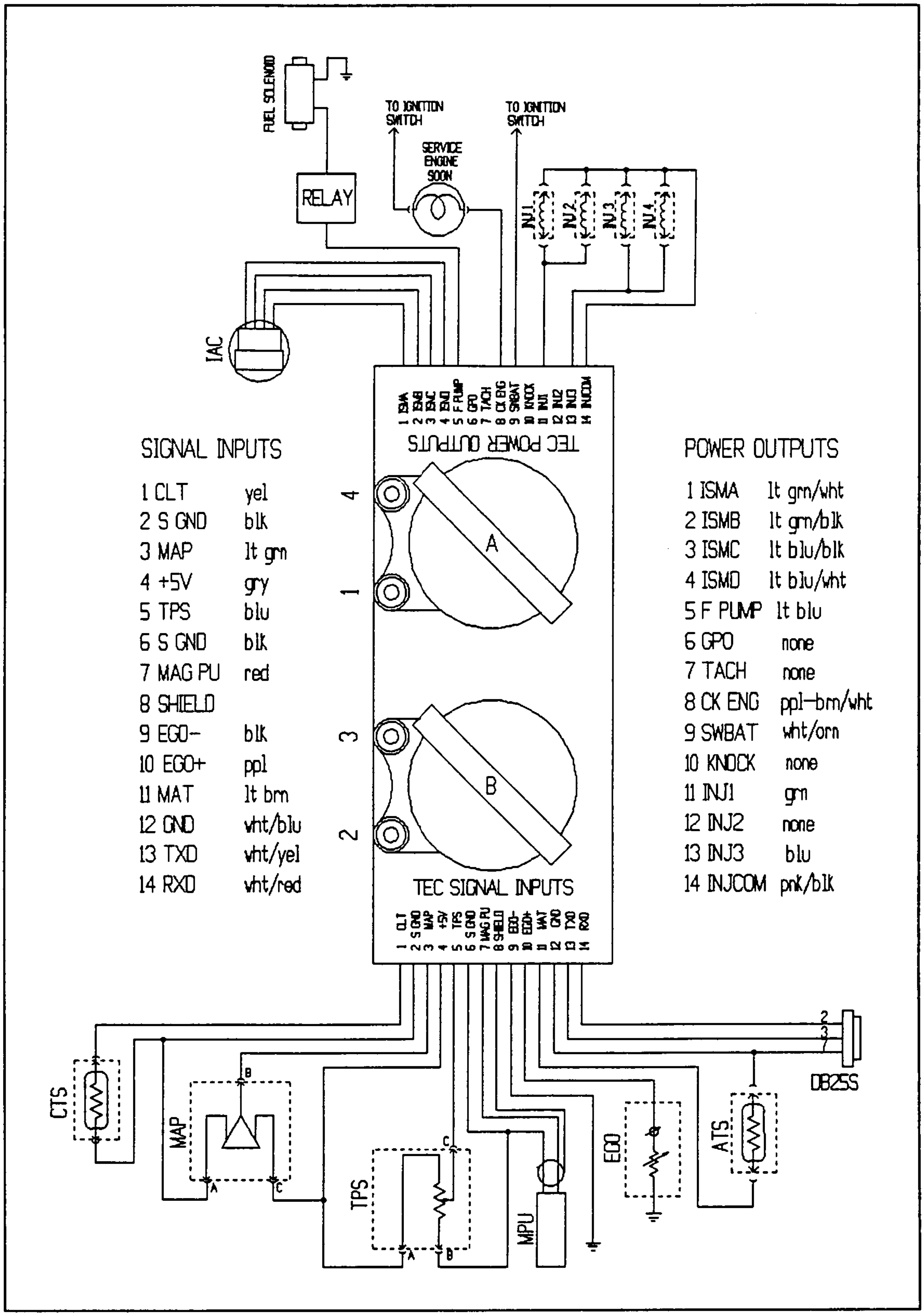


Figure A4: TEC-2 wiring

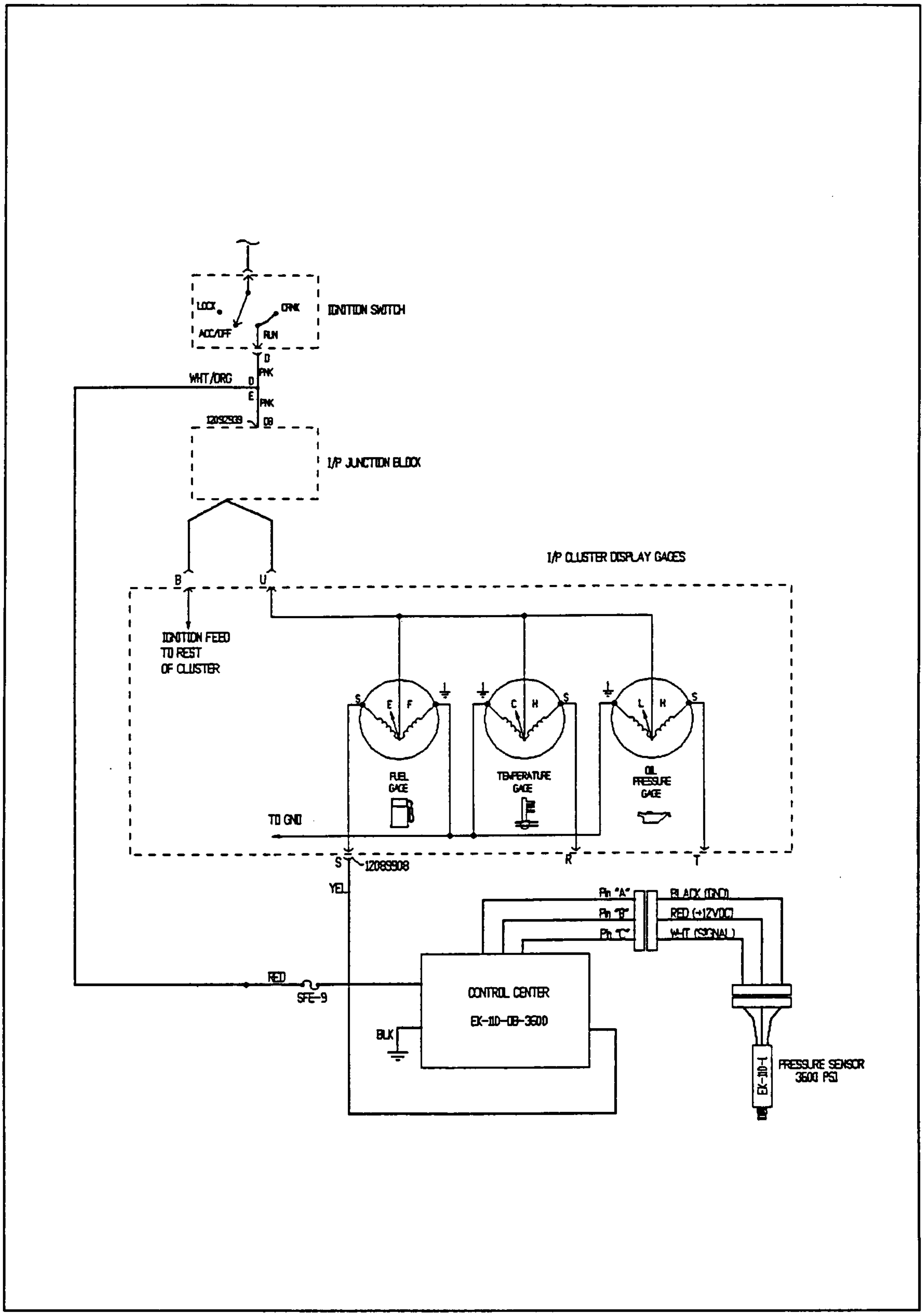


Figure A5: EK controller wiring

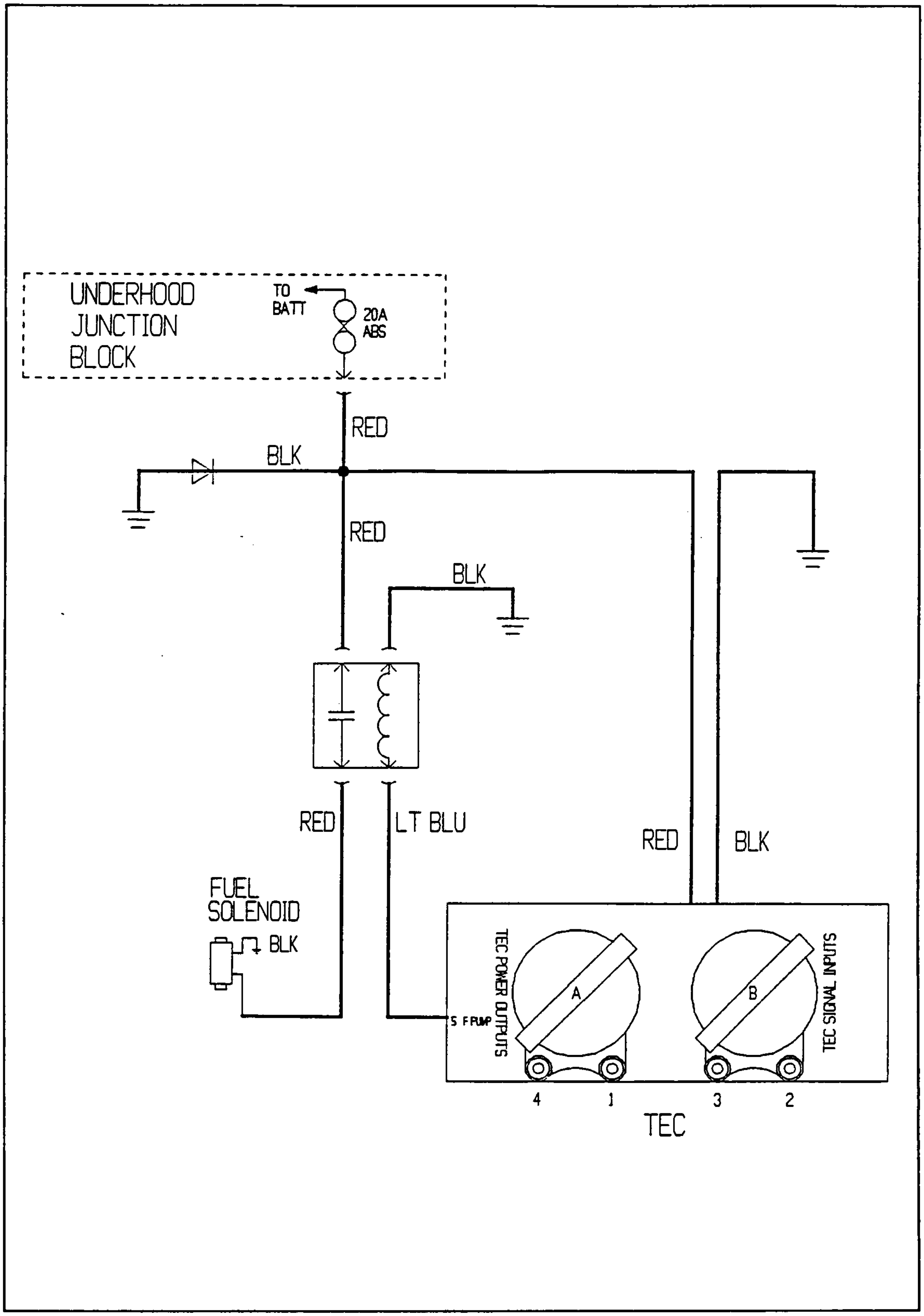


Figure A6: Solenoid relay wiring

APPENDIX B - PHOTOGRAPHS:

INSTALLATION

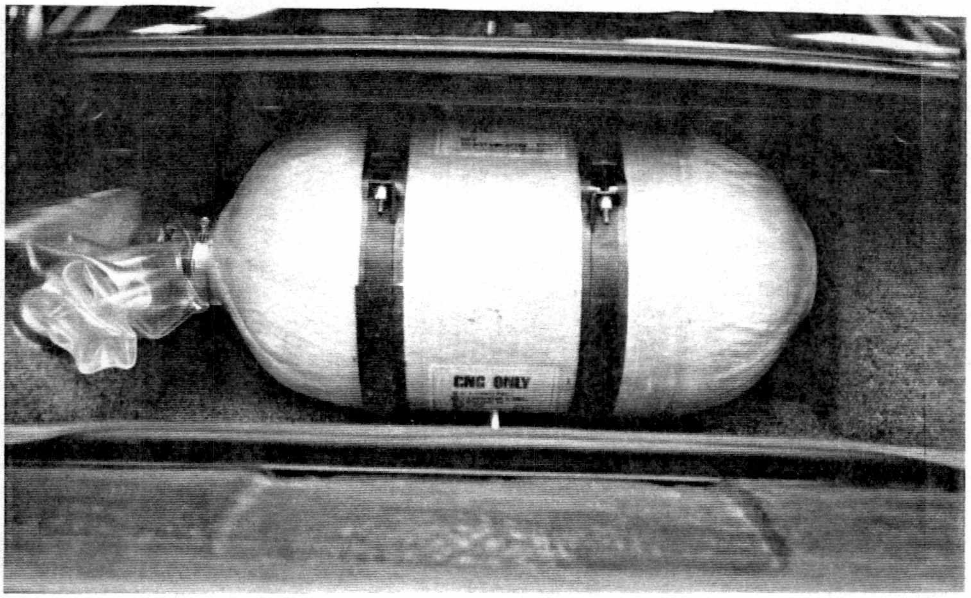


Photo 1: Transverse tank mount

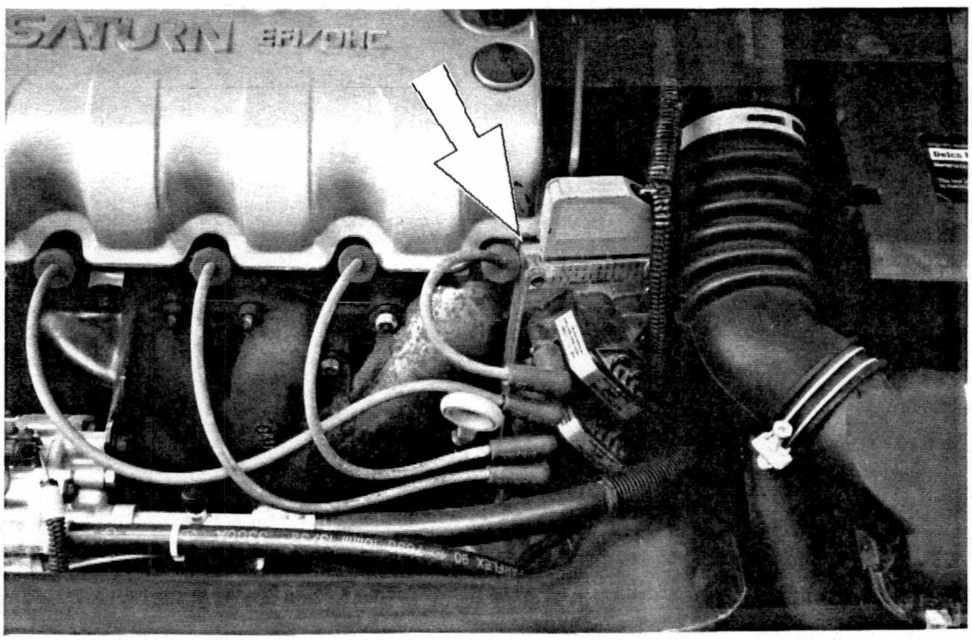


Photo 2: TEC-2

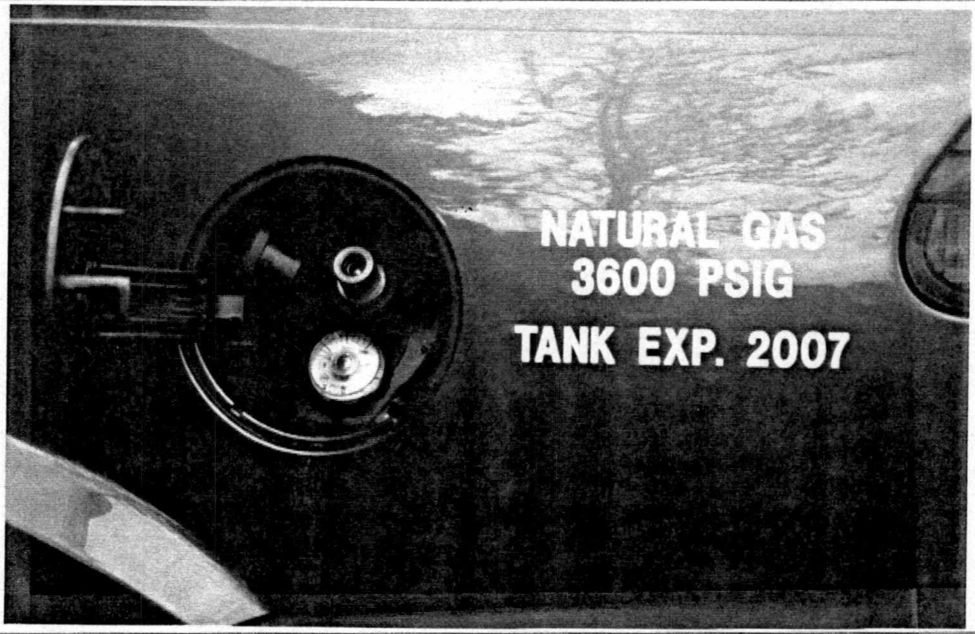


Photo 3: Sherex and EK gage

Photo 4: Quarter-turn valve

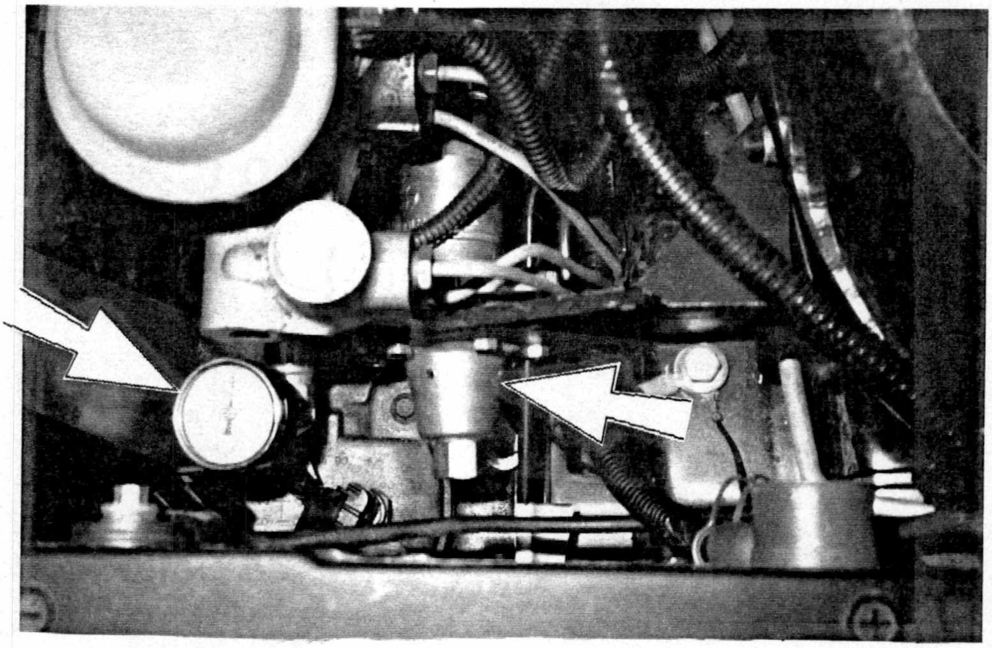


Photo 5: Pressure regulator and dial gage

APPENDIX C - CALIBRATION FILE

1. RAW FUEL PARAMETERS

Time on for one GAMA = 7 ms

Injector offset time = 1.375 ms

Minimum turn-on time for injectors = .1 ms

Number to divide tach by for injector output = 1

Injectors are set to fire on simultaneous events

MAP offset = 0

TPS voltage of closed throttle = .25 volts

2. ENRICHMENTS

Choke Enrichments

WARM-UP ENRICHMENTS VS. COOLANT TEMPERATURES

CLT TEMP	-30C	-20C	-10C	0C	10C	20C
GAMA PLUS	.3	.25	.2	.2	.15	.1

CLT TEMP	30C	40C	50C	60C	70C	80C
GAMA PLUS	.1	0	0	0	0	0

ONE-SECOND START-UP ENRICHMENTS

SE0 Temperature-based start-up enrichments = 1 GAMA

SE1 Fixed start-up enrichments = .2 GAMA

PW0 Fixed start-up injector pulse width = 4 ms

CLT0 Temperature below which to activate PW0 = 10 °C

TWENTY-SECOND START-UP ENRICHMENTS

ASE0 Temperature based 20-second enrichment = 0 GAMA

ASE1 Fixed 20-second enrichment = 0

ACCELERATION ENRICHMENTS

Sensitivity of Acceleration Mode

ACE0 Throttle position rate = 15 volts/sec

ACE1 Manifold pressure rate = 4 KPa/ms

One Second Gama Enrichments

ACE2 Coolant based acceleration enrichment = .2 GAMA

ACE3 Fixed acceleration enrichment = .1 GAMA

Variable Time and Amount Gama Enrichments

ACE4 Time period for enrichments = .25 s

ACE5 Throttle position rate of change enrichment= 1 GAMA

ACE6 Manifold pressure rate of change enrichment= 0 GAMA

ACE7 Fixed acceleration enrichment = .05 GAMA

Fixed Injector Pulse Width Enrichments

ACE8 Fixed pulse width amount= 2 ms

ACE9 Period to add fixed pulse= .2 s

DE-ACCELERATION ENRICHMENT

RPM Activation

DCCL0 Cold RPM above which DECEL may activate= 2500 RPM

DCCL1 Hot RPM above which DECEL may activate= 1600 RPM

Position Rate

DCCL2 Rate above which DECEL activates= 15 volts/s

Manifold Pressure Activation

DCCL3 Manifold pressure during DECEL= 25 KPa

Post De-Acceleration Cutoff

DCCL4 1-second enrichment after injector cutoff= 0 GAMA

MAT Density Enrichment/Enleanment

DE0= .05 GAMA

3. VOLUMETRIC EFFICIENCY TABLE

VOLUMETRIC EFFICIENCY (GAMA)								
100	1	1	1.04	1	1	1	1	1
85	1	1	1.05	1.04	1.1	1.1	1.1	1
75	1	1	1.06	1.05	1.12	1.1	1.1	1
65	1	1	1.07	1.06	1.13	1.1	1.1	1
55	1.1	1.1	1.1	1.08	1.16	1.2	1.2	1.1
45	1.1	1.1	1.16	1.14	1.22	1.2	1.2	1.1
35	1.1	1.2	1.27	1.2	1.25	1.25	1.25	1.2
25	1.1	1.3	1.39	1.3	1.3	1.3	1.3	1.3
KPa / RPM	400	800	1600	2000	3000	4000	5000	6000

4. INITIAL ADVANCE AND BAR

Initial advance =10°

BAR = 1

5. ADVANCE TABLE

ADVANCE (DEGREES)								
100	0	0	9	12	18	22	25	25
85	0	0	13	18	23	27	30	30
75	2	2	20	23	26	29	32	32
65	6	6	21	25	29	33	36	36
55	10	10	26	28	33	37	40	40
45	15	15	31	33	37	41	44	44
35	16	16	37	40	40	45	48	48
25	16	16	21	31	33	35	38	38
KPa / RPM	400	800	1600	2000	3000	4000	5000	6000

6. COOLANT ADVANCE TABLE

CLT TEMP	-30C	-20C	-10C	0C	10C	20C
ADV (DEG)	14	12	10	8	6	4
CLT TEMP	30C	40C	50C	60C	70C	80C
ADV (DEG)	4	3	3	2	1	0

7. EGO PARAMETERS

EGO is enabled

Coolant temp. above which EGO is enabled = 55° C

Throttle position above which EGO is disabled = 4 volts

Voltage above which EGO is rich and below

which EGO is lean = .5 volts

Rich to lean GAMA step size = .008 GAMA

Lean to rich GAMA step size = .008 GAMA

Number of engine events between updates = 8

Authority range for EGO = .2 GAMA

8. KNOCK CONTROL PARAMETERS

Knock is **disabled**

Knock threshold A = x

Retard rate B = x° /engine function

Max. retard C = x°

Advance rate D = x° /engine function

Knock control inhibited above E = xxx RPM

9. IDLE SPEED PARAMETERS

CLT TEMP	-10°	30°	70°
RPM	1000	900	900

Idle speed is enabled

Number of steps to reset ISM at power on = 150

Manifold pressure below which to disable ISM = 25 KPa

COARSE IDLE SPEED CONTROL

RPMs off target at which to switch to coarse = 100

Number of steps to decrease speed per wait period = 2

Decreasing speed wait period = 250 ms

Number of steps to increase speed per wait period = 2

Increasing speed wait period = 250 ms

FINE IDLE SPEED CONTROL

Number of steps per wait period = 1

SPARK ADVANCE IDLE SPEED CONTROL

Retard timing rate if RPM is too high = 1

Advance timing rate if RPM is too low = 1

10. REV LIMITER PARAMETERS

Rev limiter is enabled

Rev limiter is set to cut coils off on rev. limit

Rev limit speed = 5250 RPM

Rev limit hysteresis = 250 RPM

Auxiliary rev limit engine speed = 12000 RPM

11. SENSOR FAILURE PARAMETERS

A. CLT Sensor

voltage above which CLT sensor fails = 4.96 volts

voltage below which CLT sensor fails = .04 volts

default CLT sensor temperature = 70° C

B. MAT Sensor

voltage above which MAT sensor fails = 4.96 volts

voltage below which MAT sensor fails = .04 volts

default MAT sensor temperature = 25° C

C. TPS Sensor

voltage above which TPS sensor fails = 4.96 volts

voltage below which TPS sensor fails = .04 volts

default TPS sensor voltage = .5 volts

D. MAP Sensor

voltage above which MAP sensor fails = 5 volts

voltage below which MAP sensor fails = .04 volts

default MAP sensor pressure = 104 KPa

E. EGO Sensor

time required for EGO sensor to fail = 120 s

12. **MAT SENSOR ENABLE/DISABLE**

MAT sensor is enabled

13. **BATTERY VOLTAGE COMPENSATION**

Battery voltage compensation = 75 μs/volt

14. GENERAL PURPOSE OUTPUT TABLE

DUTY CYCLE (PERCENTAGE)								
100								
85								
75								
65								
55								
45								
35								
25								
KPa RPM	400	800	1600	2000	3000	4000	5000	6000

15. GENERAL PURPOSE OUTPUT FREQUENCY

The frequency of the general purpose output is 31 hz

16. SOFTWARE VERSIONS

This file is for use with calibration software 27.1 and TEC PROM version 33

APPENDIX D - SUPPLIED COMPONENTS DRAWINGS

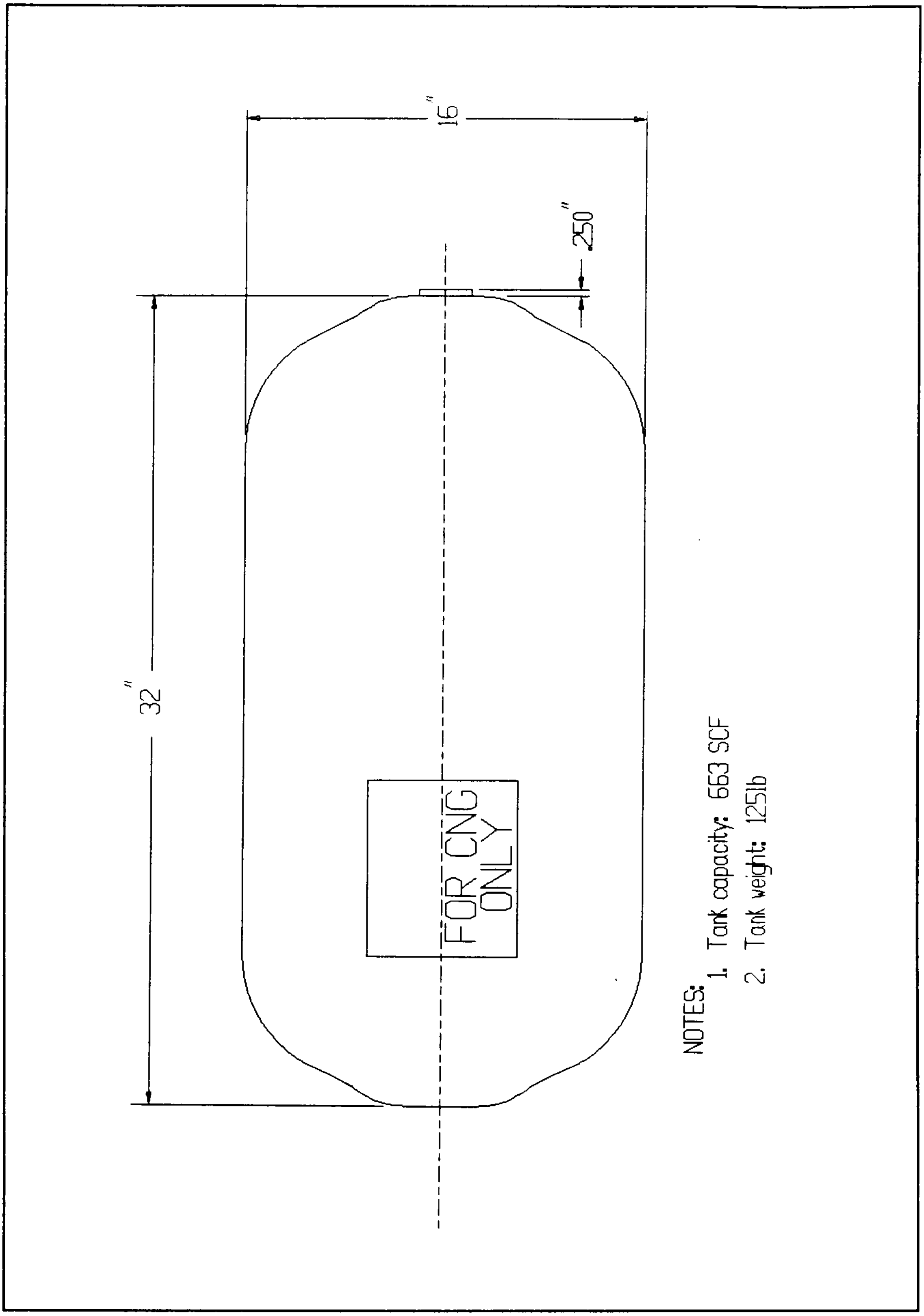


Figure D1: Comdyne-1 tank

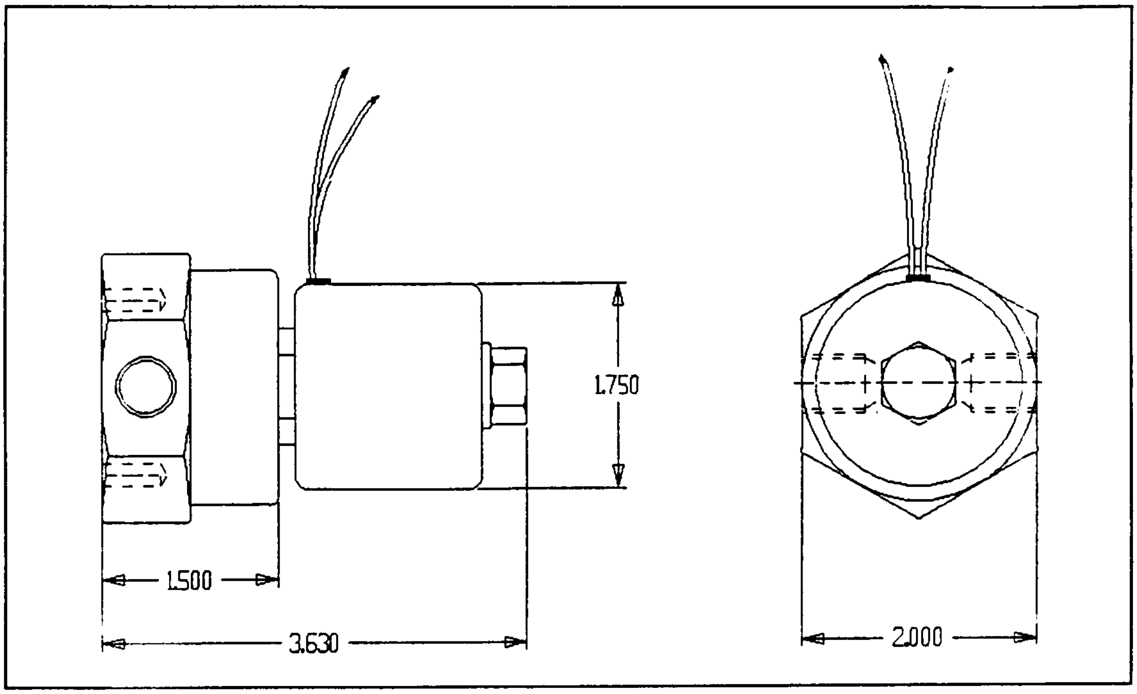


Figure D2: Solenoid valve (reproduced from AFC drawings)

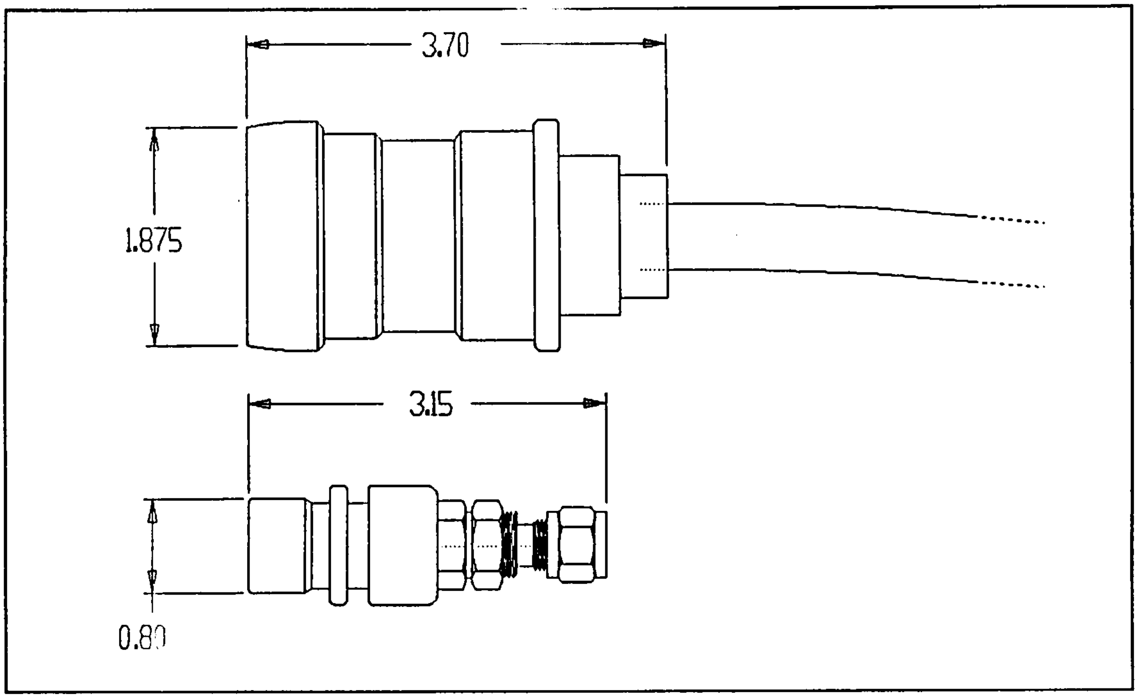


Figure D3: Sherex fueler and receptacle

APPENDIX E - ENGINE OUTPUT

Graph E1: CNG vs. Gasoline torque (reproduced from SAE 910676)

Table E1: CNG torque at selected rpm

RPM	MAP	ENGINE TORQUE (NM)
1600	35	23
1600	40	27
1600	51	46
1600	62	64
1600	70	76
1600	80	96
1600	**100**	**127***
2000	51	45
2000	60	60
2000	70	75
2000	80	92
2000	**100**	**124***
2500	41	33
2500	51	49
2500	60	65
2500	71	83
2500	73	87
2500	**100**	**132***

(* extrapolated pt., linear fit)

APPENDIX F - PARTS PRICING

Major Components Price List

Comdyne-1 pressure vessel (with valve)	700
tank brackets	30
tubing	26
vapor bag kit	49
Sherex receptacle	46
EK dial pressure gage	14
quarter-turn valve	57
high-pressure solenoid valve	85
Meco pressure regulator	135
reinforced fuel hose	15
Sherex receptacle, regulator, and solenoid brackets	20
tube fittings.	90
gasoline fuel tank, pump, straps (removed)	subtract x amount
evaporative canister and valve (removed)	subtract x amount
TOTAL	≤ \$1267

Bill of Materials

Part	Manufacturer	P/N	#	Price each
CNG tank	Comdyne-1	-----	1	700
Tank valve	Mirada Controls	B-51246	1	incl. w/tank
$^1/_4$" tubing	American Stainless & Supply	-----	20'	1.30
Vapor bag	Stewart & Stevenson Power	N201001	1	48.75
Receptacle	Sherex Industries	SR1040H	1	46.00
Dial gage (high pressure)	Energy Kinetics	EK-4500	1	14.00
Dial gage (low pressure)	Engineered Specialty Products	102D15,$^1/_8$CBM	1	5.00
$^1/_4$ turn valve	Parker	4Z-B6LJ-SST	1	56.61
Fuel gage controller	Energy Kinetics	EK-110-DB-G-3600	1	130.00
Solenoid	Advanced Fuel Components	model 211	1	85.00
Regulator	Modern Engineering Co.	stock# 8431	1	135.00
Fuel hose	Everflex	S-10, ($^1/_2$" O.D.)	2'	1.44
Fuel injectors	Bosch	B 280 412 912	4	80.60

FUEL LINE FITTINGS: (includes 25% volume discount where applicable)

45° SAE/MS Positionable Male Elbow	Swagelok	400-5-4ST (SS)	1	11.70
SAE/MS Male Connector	Swagelok	400-1-4ST (SS)	1	4.65

Part	Manufacturer	P/N	#	Price each
Union Cross	Swagelok	400-4 (SS)	1	21.98
Male Connector	Swagelok	400-1-4 (SS)	2	3.83
Street Tee	Cajon	4-ST (SS)	1	13.65
Female Connector	Swagelok	400-7-2 (SS)	1	4.95
Pipe Plug	Cajon	4-P (B)	2	1.35
Elbow	Cajon	4-E (B)	1	4.58
Enlarging Bushing	Weatherford	322x4x2 (B)	1	.77
Street Tee	Cajon	4-ST (B)	1	6.45
Hex Nipple	Cajon	4-HN (B)	1	1.88
Swivel Hose Connector	Dana	4-4FPX	1	3.06
Fixed Hose Connector	Dana	4-4MP	1	3.06
Male Elbow	Dana	4MB-2MP90	1	3.97

APPENDIX G - INTRODUCTION TO NATURAL GAS INDUSTRY

The following is an overview of some basic aspects and trends of the natural gas industry; included are natural gas supply, production and consumption, transmission, price, the NGV outlook, and federal laws regulating the industry. The intent is to provide a basic understanding of the current and future role of natural gas in the nation's energy strategy and the prospects of natural gas vehicles as a part of this vision.

Supply

Natural gas is an abundant natural resource promising supplies well into the next century. According to the Department of Energy [6], the ultimate domestic production of natural gas is estimated to be about 2,000 trillion cubic feet (TCF). Of this total volume, 40% has been depleted over the past century. The remaining resource base (1,200 TCF) is projected to extend perhaps another 100 years (Fig. F1).

Recovery from unconventional sources such as tight sandstone and Coalbed methane continues to increase, due in part to government incentives. In 1987, 26 billion cubic feet of coalbed methane were recovered; by 1990 196 billion cubic feet were produced. These alternative sources of natural gas are expected to become increasingly important to supplying future demand.

Production and Consumption

Natural gas currently accounts for about a quarter of the nation's energy consumption. Although production and consumption drifted downward from 1973

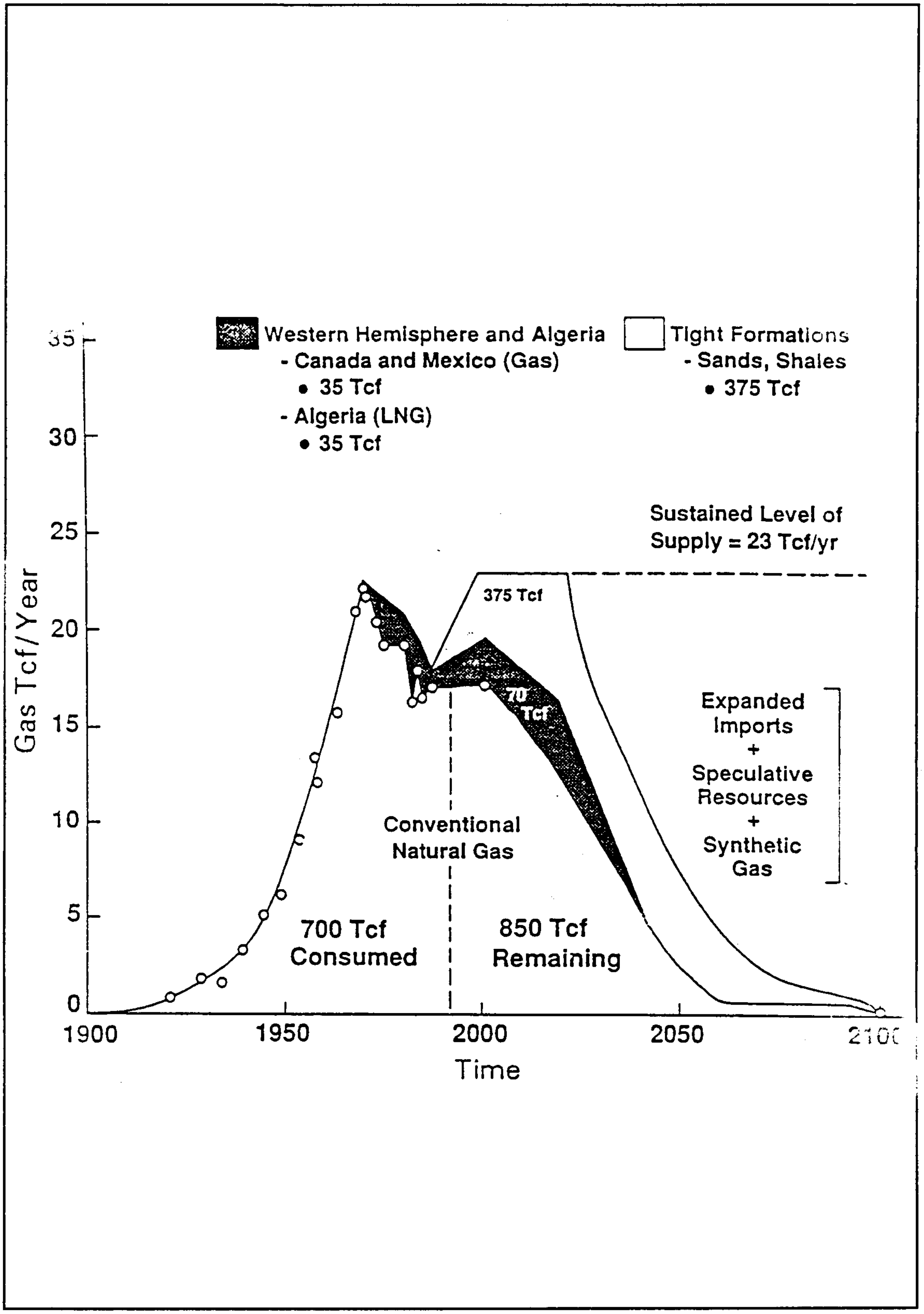


Figure F1: NG resource base (DE92007051) through 1986, current trends have been upward since and are forecast to continue until 2002 before leveling.

For 1990, the volumes of production and consumption are diagramed in figure F2. As shown, 21.5 TCF was withdrawn: after repressurizing, removal of nonhydrocarbons, extraction losses, and venting and flaring, 17.8 TCF remained. Including imports (8% of consumption) and storage, the volume rises to 18.7 TCF. After consumption for pipeline and plant fuel, 16.9 TCF remained available to customers, divided as shown.

The bulk of production is from a handful of mid-west and southern states (Fig. F3). In 1990, Texas, Louisiana, and Oklahoma produced about 14 TCF while the rest of the nation contributed only 4.5 TCF. About 28% of the total production (5 TCF) came from the Gulf of Mexico. Of the 1.5 TCF imported, virtually all is piped from Canada. The remaining imports, 0.08 TCF, was shipped from Algeria as LNG.

Transmission

Over a million miles of pipeline link 47 of the lower 48 states in a transmission network flowing natural gas generally northeastward mainly from the Gulf of Mexico and bordering states (Fig. F4). New pipeline construction is expected to advance, driven in part from demand created by government legislation.

Price

The price of natural gas, influenced by government regulations and incentives as well as demand, rose throughout the 1970s and peaked in the early 1980s. The price has since fallen and stabilized as shown by Figure F5. The large slump in the mid-1980s can be explained in part by the dramatic drop in oil prices that occurred in 1985.

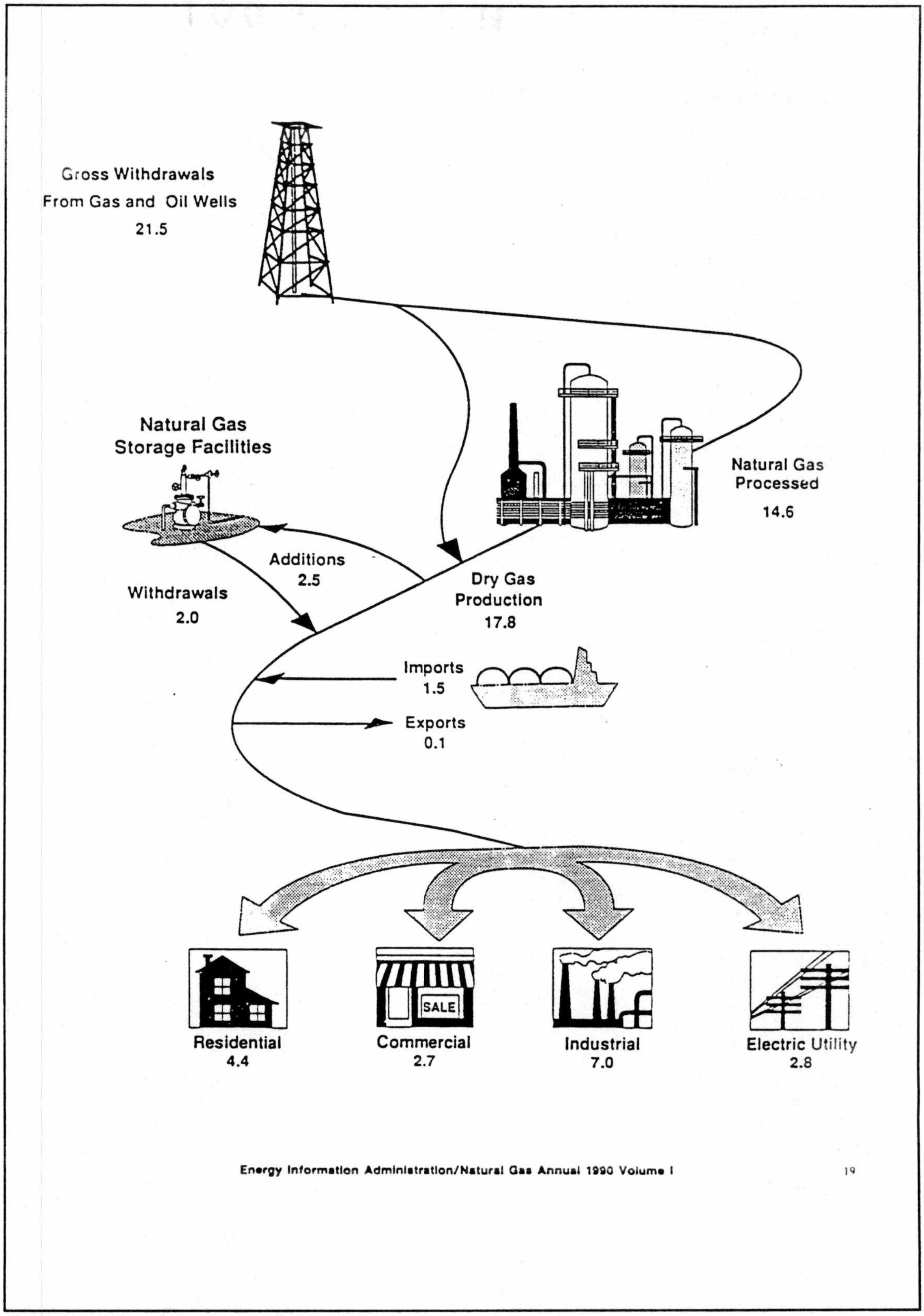


Figure F2: Production and consumption (DE92007051)

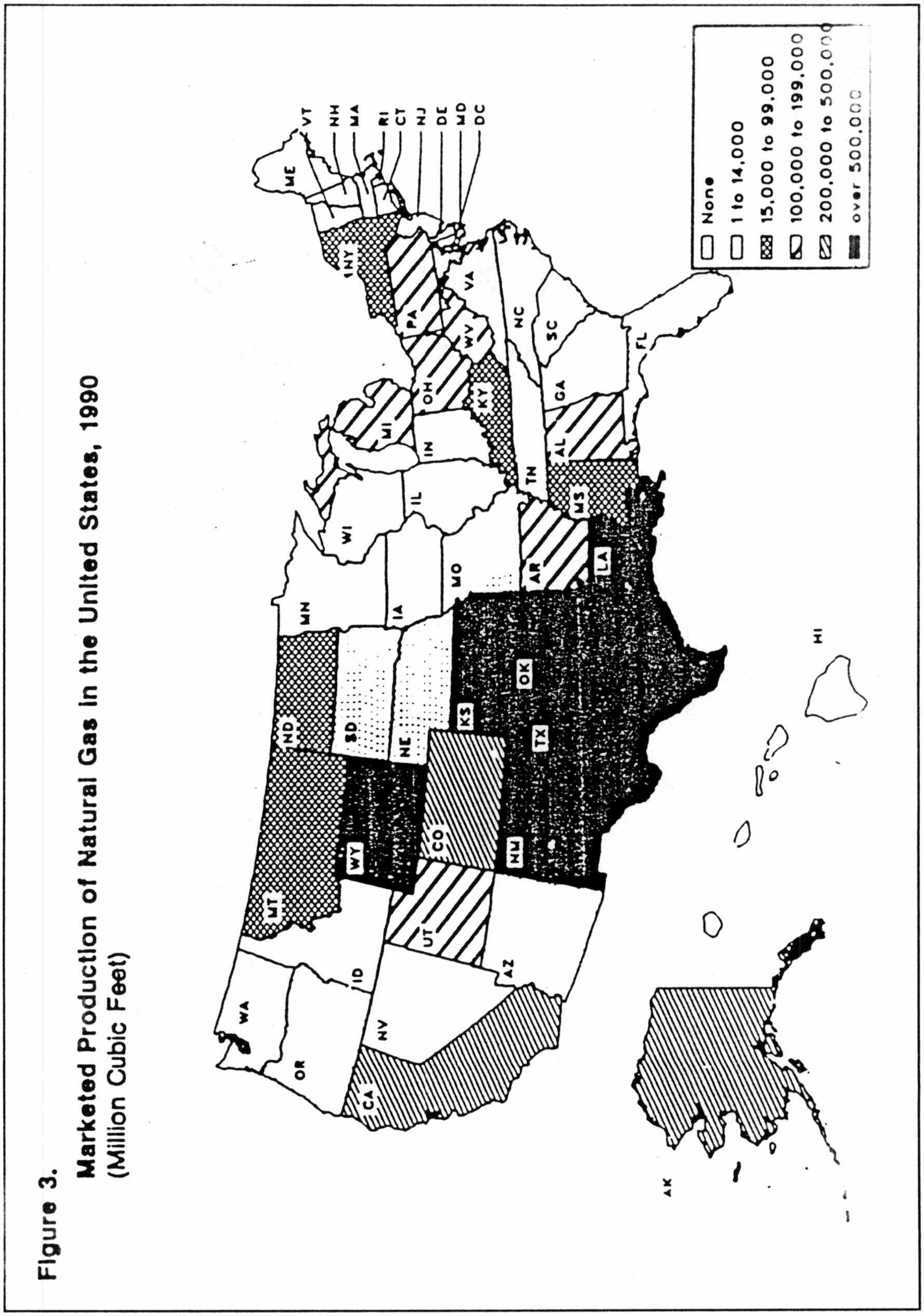


Figure F3: Production by region (DE92007051)

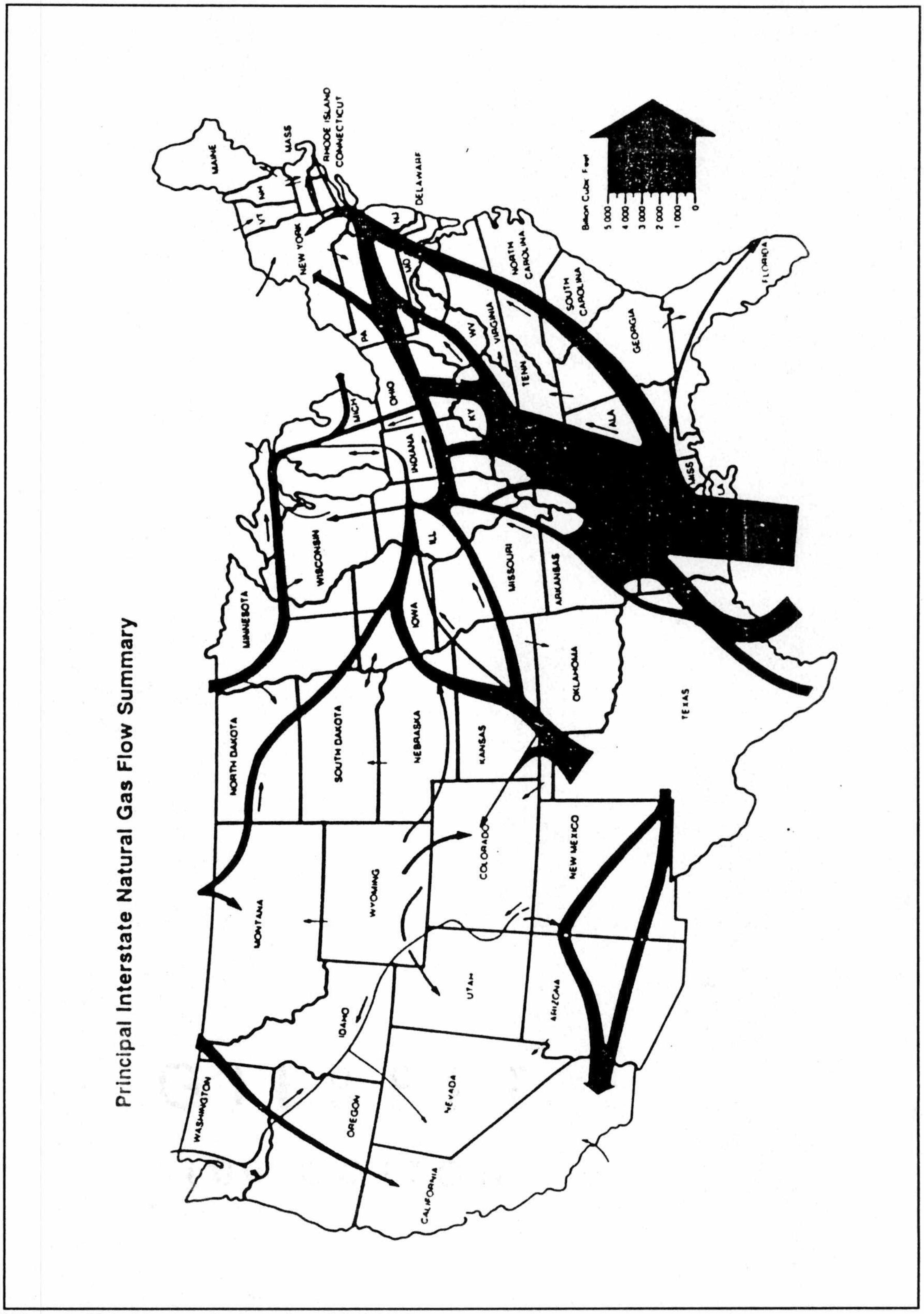


Figure F4: Transmission (DE92007051)

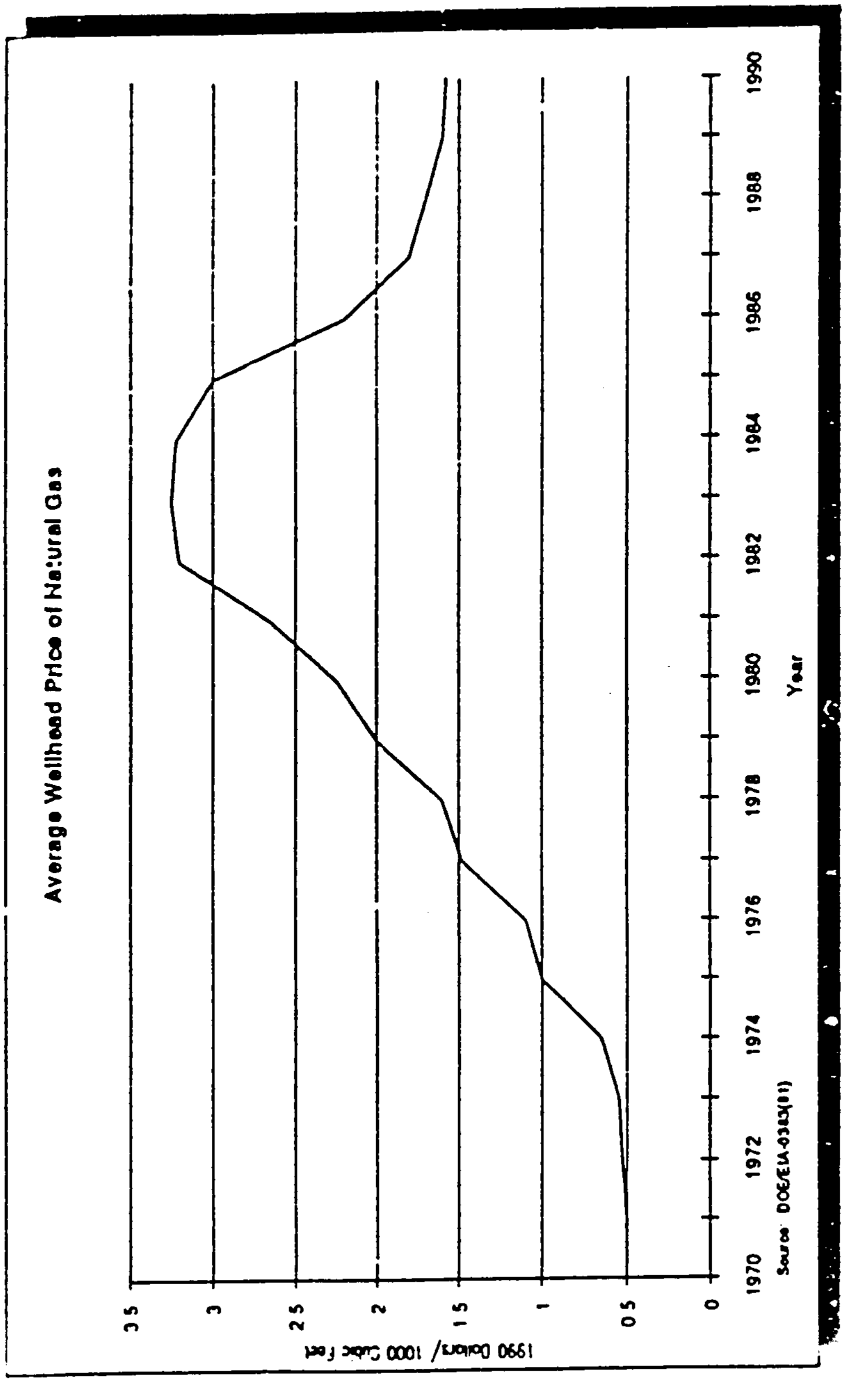


Figure F5: Price trend

Whereas Figure F5 shows wellhead prices, Figure F6 charts prices seen by consumers. Although the prices are higher and vary with the customer, the trend follows that of wellhead prices.

To forecast costs of natural gas (and other fuels) to 2010, the Energy Information Administration (EIA) bureau of the DOE used the Intermediate Future Forecasting System (IFFS) model. The IFFS arrives at a price for a particular year based primarily on supply versus demand considerations. Government policies and regulations are also considered in the model.

The resulting price projections trend upward in an ever increasing fashion, but only mildly in the near future. These projections are best used as merely "working figures" for setting long-range policy; the actual price forecasts are historically quite inaccurate. Currently, natural gas costs about $0.75 per gallon equivalent of gasoline.

NGV

The outlook is increasingly promising for NGVs playing a role in transportation. Worldwide there exist over 700,000 NGVs, most in Italy and New Zealand. The United States is responsible for about 40,000 of these and yearly additions are growing rapidly.

There currently exists a thin structure of refueling stations nationwide. As of April 1993 there were just over 700 refueling stations across the country with about 400 available for public access. Until more stations are constructed, NGVs will be constrained chiefly to regional rather than interstate travel.

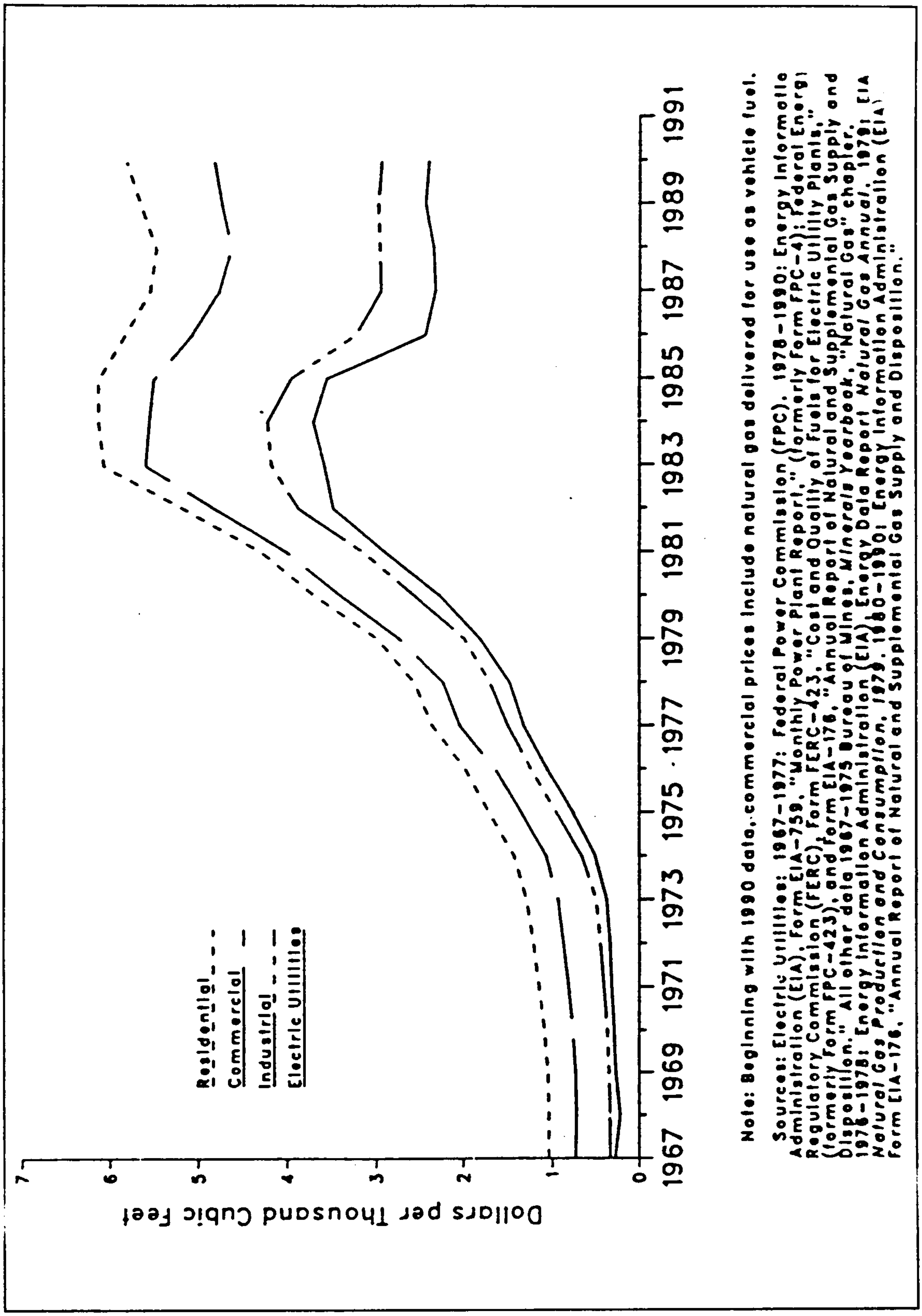


Figure F6: Price trend (consumer)

Safety is always a concern. According to a study by the AGA [7] of 8,000 fleet vehicles, no deaths were reported for over a quarter-billion miles traveled and 651 resulting collisions . The integrity of modern CNG tanks was one of two reasons quoted. A second was the properties of natural gas itself.

One favorable property of natural gas is its density; any leakage would rise rather than pool on the ground around the vehicle. It also has a higher ignition temperature than gasoline (1200 °F vs. 600°F). The flammability limits (5% - 15% by volume) are desirably narrow.

Safety studies by both Klausmeier [8] and the Los Alamos National Laboratory [9] were favorable to compressed natural gas vehicles. Klausmeier ranked dedicated NGVs safer than gasoline, LPG, and methanol vehicles. At Los Alamos, CNG was rated second (behind diesel) for safety in collisions; the other fuels studied were LNG, LPG, and gasoline.

The emissions of NGVs vary widely; however many produce lower levels of CO, CO_2, THC, and particulates than gasoline. NO_x can be reduced as well but is actually higher in some cases.

Performance of an engine deteriorates a theoretical 9.4% just by using NG. Data from conversions show power losses ranging up to 20%.

Regulations

The federal government, using mandates, regulations, and incentives, has promoted the adoption of alternative-fueled vehicles (AFVs) in both public and private sectors.

Three of the more recent and important of these initiatives are the Alternate Motor Fuels Act of 1988 [10], Clean Air Act Amendments of 1990 [11], and the Energy Policy Act of 1992 [12]. The main features of each are briefly outlined.

The Alternate Motor Fuels Act

"is to encourage the...use of methanol, ethanol, and natural gas as transportation fuels...and the production of methanol, ethanol, and natural gas powered motor vehicles"(102 STAT. 2442).

To this end, the secretary of the DOE is instructed to secure for the Federal Government vehicle fleet the "maximum number practicable" of alcohol and natural gas powered vehicles each year. Both dedicated and dual energy vehicles are to be acquired using $12 million in funds for 1990-1993. Access to this fleet of demonstration vehicles is available upon request to any federal department, and is studied to determine performance, fuel economy, safety, emissions, and maintenance costs.

Two other AFV testing programs are also established; a $4 million study of commercial heavy duty trucks and a $2 million testing of urban buses.

A manufacturing incentive is also provided in the act. For both alcohol and natural gas vehicles, a gallon equivalent is considered for fuel economy purposes to be only 0.15 gallons. Thus the vehicle is considered to have a fuel economy rating $6\ ^2/_3$ times the actual amount, aiding manufactures in meeting federal CAFE standards.

The Clean Air Act Amendments of 1990 are divided into eight sections, one of which addresses mobile source emissions in particular. Most vehicles are impacted, whether public or private, fleet or non-fleet.

For private, non-fleet vehicles, stricter requirements for emissions will be introduced in 1994 and tightened in following years. Equipment to control emissions (such as catalytic converters) will be required to last 10 years/100,000 miles rather than the current 5 years/50,000 miles. AFVs are not required to meet these standards.

Fleet vehicles, both public and private, are targeted for AFV acquisition. Those with fleets of 10 or more centrally refueled vehicles in a metropolitan "non-attainment" area are required by law to purchase AFVs. The phase-in begins in 1998 with 30% of new light-vehicle purchases being AFVs. By the year 2000 and afterward, the quota is set at 70%.

For urban buses, a timetable sets new purchases to be 10, 25, 60, and 100 percent AFVs in 1992, '93, '94, and 1995, respectively.

To refuel these vehicles, the law requires local officials in the non-attainment areas to offer the alternate fuel for sale at one or more retail gasoline stations.

An innovative feature of the law much heralded by the Bush administration was the "emission reduction credits" approach. Basically, this provides for companies not meeting the mandated AFV purchasing levels to buy "credits" from companies which exceeded nominal purchasing quantities. Obviously this was intended to be an incentive to profit from surpassing the mandated levels.

The Energy Policy Act of 1992 also uses mandated purchases of AFVs. For 1993, '94, and 1995, federal fleets must purchase a total of 5,000, 7,500, and 10,000 light-duty AFVs. For the years 1996-1999, AFVs must be 25, 33, 50, and 75 percent of new purchases, respectively.

To aid AFV purchases, financial incentives are included in the law. For dedicated AFVs, deductions up to $2000 may be taken for light-duty vehicles. Dual-fuel AFV purchasers may deduct the difference in price between the AFV and the unconverted vehicle.

Incentives of up to $100,000 are also provided for companies to construct fleet refueling facilities.

VITA

Edward N. Luton was born on May 20, 1968 in Oak Ridge. He attended Oak Ridge High School, graduating in 1986. Edward then enrolled at Tennessee Technological University, obtaining a bachelors degree in mechanical engineering in May of 1991.

A second degree in mechanical engineering was pursued at the University of Tennessee. Edward graduated with his masters on May 13, 1994.