# STUDY OF ADVANCED AUTOMATIC DIAGNOSTIC/ PROGNOSTIC TEST EQUIPMENT FOR MAINTENANCE OF MILITARY AUTOMOTIVE VEHICLES

(Report No. A-4712, Task 53)

by

F. A. Creswick and E. N. Wyler

TACTEC

Battelle
Columbus Laboratories

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FINAL REPORT

on

# STUDY OF ADVANCED AUTOMATIC DIAGNOSTIC/PROGNOSTIC TEST EQUIPMENT FOR MAINTENANCE OF MILITARY AUTOMOTIVE VEHICLES

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F. A. Creswick and E. N. Wyler

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In this review of the current technology for automatic diagnostic/prognostic test equipment, it was found that advanced systems could be developed that would use fewer sensors and have prognostic capability by use of signature-analysis, trend-analysis, and/or failure-monitoring techniques. Developments in the electronics industry on microprocessors and in the automotive industry on sensors can be expected to make appreciable cost reductions possible in hardware for automatic test equipment. By 1980 manufacturing costs of test equipment might be half of present costs and further reductions would be possible.

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further reductions would be possible.

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# FOREWORD

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The consultation and cooperation of Major Covington; Donald Sarna and Joseph Sraj of the U. S. Army Tank-Automotive Research and Development Command; and Dr. William Whelan and Richard Salter of The RAND Corporation in the conduct of this study is acknowledged and appreciated.

## DISCLAIMER

# EXECUTIVE SUMMARY

This study consisted of a review of the current technology for automatic diagnostic test equipment for maintenance of automotive vehicles which could lead to new test-equipment concepts for reducing maintenance costs and improving the condition of the DoD vehicle fleet.

A first generation of such test equipment is now becoming available for both military and commercial use. These systems use limit tables, truth tables, and elementary forms of waveform analysis as the basis for their diagnostic capability. The functional and cost effectiveness of this equipment is as yet unproven. Shortcomings of present equipment are judged to be (1) an inconveniently large number of connections that must be made with the vehicle and (2) high equipment cost. There appears to be little incentive for ARPA to develop yet another fault-isolation-type system of the type currently being developed.

Advanced systems could be developed that would (1) use fewer sensors and (2) have a prognostic capability by the use of signature-analysis, trend-analysis, and/or failure-agent monitoring techniques. These techniques are not sufficiently well advanced at present to justify hardware development, and basic signature-analysis studies are called for. In addition, a failure-model data base is needed for the implementation of these techniques.

Special-purpose systems for abuse monitoring and health monitoring (quick check) using current technology can be envisioned which ARPA might consider as prospects for research projects, although the economic incentives for such systems have not been examined. ARPA might also investigate the possible use of automatic test equipment as a means of automating maintenance-record keeping and collection of failure-history data.

Developments in progress within the electronics industry on microprocessors and in the automotive industry on sensors can be expected to make appreciable reductions possible in the hardware costs of automatic test equipment. With high-volume production, labor costs can be reduced. By 1980, the manufacturing cost of automotive test equipment might be half of present costs, and further reductions would be possible.

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# STUDY OF ADVANCED AUTOMATIC DIAGNOSTIC/ PROGNOSTIC TEST EQUIPMENT FOR MAINTENANCE OF MILITARY AUTOMOTIVE VEHICLES

by

F. A. Creswick and E. N. Wyler

## INTRODUCTION

### Motivation

A combination of circumstances has led to ARPA's interest in the subject of automatic diagnostic/prognostic test equipment for maintenance of military automotive vehicles. One factor is the recent advance in the technology of large-scale integration (LSI) electronic semiconductor devices which has led to dramatic reduction in the size and cost of microprocessors. These developments appear to offer the technological opportunity to develop new generations of low-cost automatic test equipment, either on-board or off-board, which can monitor vehicle condition more effectively than human vehicle operators or maintenance crews. Indeed, the automobile industry appears to be responding quickly to this opportunity, not only for diagnostic equipment but also to convert a variety of control functions from their present mechanical or electromechanical form to a central, electronic microprocessor control system.

A second circumstance is the apparent high present cost of maintaining the DoD automotive vehicle fleet (including combat and tactical vehicles). The annual maintenance bill is estimated to be on the order of $1 billion. Where comparisons can be made between military vehicles and privately or commercially owned vehicles, military-vehicle maintenance costs appear high. Thirdly, there is a prevalent belief that DoD vehicles are generally in poor mechanical condition, despite the high maintenance costs.

Thus, the possibility of effecting a major maintenance cost saving and at the same time improving the general condition of the DoD automotive vehicle fleet by means of advanced test equipment has been considered by ARPA to justify close scrutiny.

In addition to these present incentives, automatic test equipment is likely to become necessary in the future as new kinds of equipment and more complex equipment are developed and fielded.

There is little in the way of hard data to support the contention that vehicle maintenance costs are unnecessarily high at present or that vehicle condition is generally poor. However, the belief that these contentions are correct is widespread, and support is prevalent in the form of "horror stories" or other types of folklore. Generally speaking, the problem is attributed to unnecessary vehicle abuse and improper or inadequate maintenance. Abuse and, in some instances, lack of maintenance would account for a high incidence of mechanical problems or failures, and inadequate or improper maintenance would account for high repair costs and many vehicles in less than serviceable condition. The folklore includes items such as:

- Vehicle operators purposely disabling diesel-engine speed governors by downshifting at high speeds
- Maintenance crews filling the radiator with lube oil and the crankcase with coolant
- A repairman unnecessarily replacing three serviceable turbochargers in trying to solve a performance problem that was in fact the result of a plugged crankcase vent.

Repair by trial-and-error part replacement ather than by a logical diagnostic procedure appears to be a definite factor in high maintenance costs.

There is a widely held viewpoint that the inherent durability and serviceability of the vehicles themselves are adequate, and that the problem described here would disappear if only the vehicles received proper use and proper maintenance.

Obviously, this problem has many facets which include operator training and motivation, maintenance technician training and motivation, maintenance procedures, and procedural incentives and disincentives. It is unlikely that advanced automatic test equipment can impact these phases of the problem, but it can impact the problem by reducing maintenance time, reducing spare parts consumption, and by rapid identification and correction of vehicle faults in the field. It is also possible that advanced automatic test equipment can compensate in some instances for inadequate maintenance personnel training.

## Objectives

Initially, the objective of this study was to assist ARPA in defining one or more advanced-test-equipment systems that could effect a major impact on DoD vehicle maintenance costs. As the investigation progressed, it became apparent that no reasonable basis could be established for evaluating the economic impact of advanced test equipment in a short-term study, principally because of the paucity of firm, detailed data on present maintenance costs and information on how and why vehicles fail at present. Accordingly, emphasis in this study was modified, and the final objectives were to define the technological approaches available for the development of advanced diagnostic/prognostic test equipment for automotive vehicle maintenance, and to define basic technological studies that would enhance the current state of the art.

## Scope

Of concern in this study were all systems that affect the ability of the vehicle to move: principally engine, drivetrain, and suspension. However, emphasis was placed on the engine in this study because diagnosis of drivetrain- and suspension-component faults tends to be simpler (with the exception of automatic transmissions) than diagnosis of engine faults. While it is recognized that diagnosis of the armament systems of combat vehicles may well be an integral part of future vehicle diagnostic systems, it was not included in this study.

Four organizations participated in this study: ARPA, U. S. Army Tank-Automotive Research and Development Command, The RAND Corporation, and Battelle's Columbus Laboratories. Battelle's role was to study the technology, while the economic analysis and characterization of the present maintenance system was the responsibility of The RAND Corporation. Accordingly, this report addresses only the technological aspects of the problem.

## Methodology

The procedure followed in this study included: (1) a survey and evaluation of existing vehicle test systems, (2) compilation of present and future automatic diagnostic/prognostic techniques, (3) conceptualization of possible system functional options, (4) assessment of sensor technology gaps and research needs, (5) a survey of electronic component developments, (6) definition of promising candidate systems, and (7) definition of basic research needs. Activities consisted primarily of review of the open and Government literature, contacts with system developers and individuals having expertise in related technologies, analysis of information, and conceptual studies.

## CONCLUSIONS

On the basis of this investigation the following conclusions have been drawn:

(1) A first generation of automatic diagnostic test equipment for maintenance of automotive vehicles is presently becoming available for both military and commercial applications. The characteristics of the more advanced of these systems are the following:

- Multiple connections with sensors either temporarily or permanently mounted on the vehicle
- A central electronic microprocessor control with electronic memory
- Computer automated test sequencing
- Automatic pass/fail testing principally by limit-table comparison supplemented by some elementary forms of waveform analysis
- Automated diagnostic logic using truth tables
- Automatic display and recording of test results.

In general, these systems are not prognostic, i.e., they can diagnose certain existing failures but not impending failures. As yet, experience with these systems is limited and their functional effectiveness and cost effectiveness has not been proven.

(2) The principal deficiencies of this first generation of equipment are judged to be (a) an inconveniently large number of required connections to the vehicle and (b) high equipment cost. While such systems may prove to be cost effective, the large investment required is expected to be a deterrent to their deployment.

(3) There is little apparent incentive to develop another fault-isolation type diagnostic system using present technology, although it may be desirable to investigate extending the capability of present systems to include automation of maintenance-record keeping.

(4) Technological possibilities for future, advanced automated diagnostic test systems include (a) obtaining more diagnostic information from fewer sensors by signature-analysis techniques, and (b) introducing prognostic capabilities by the use of trend analysis, failure-agent monitoring, or signature analysis. These technologies are not sufficiently advanced at present to justify hardware development. Lacking are (a) practical signal-processing techniques and (b) failure models based on failure-history data.

(5) Failure-history data cannot presently be used as a basis for the design of diagnostic test equipment for military vehicles principally because a recent, organized body of such data is not available. In lieu of failure data, serviceability criteria appear to be a reasonable basis for formulating system design concepts. The following list of serviceability criteria is suggested:

- Kinematic integrity
- Compression
- Ignition
- Cranking power
- Fuel supply and metering
- Cooling
- Lubrication

- Clean air
- Steering
- Braking.

(6) A vehicle operation monitor could be developed that would be useful in collecting failure-history data and the relationship of vehicle operation and maintenance action to failure. (ARPA initiated a Phase I design study of a Vehicle Monitor System (VMS) in FY 1976.)

(7) It is technically feasible to develop a small, simple abuse monitor that would be useful in determining the relationship between vehicle abuse and vehicle failure. Such a system might monitor the following five parameters and record a count of abuse incidents:

- Overtemperature
- Low oil pressure
- Overspeed
- Reverse voltage polarity
- Excessive suspension shock.

Sensors for all but the last parameter would already be available in military vehicles. However, it is not clear that ARPA should undertake such a development, partly because the potential human-factors problems associated with an abuse monitor have not been resolved, and partly because the VMS will have an abuse-monitoring capability.

(8) A vehicle health monitoring system could be developed with present technology that would give a quick assessment of vehicle serviceability with few connections. An automatic system can be envisioned that uses only three sensors to check out compression, cranking system, charging system, ignition and fuel systems, and air cleaning. This could be supplemented by a quick manual/visual inspection of lubrication and cooling systems.

A cost-effectiveness study of such a system would be appropriate before a design study is initiated.

(9) A gas-turbine diagnostic system may be needed in the future if the XM-1 battle tank is designed with a

turbine powerplant. If so, techniques presently used for condition monitoring of aircraft turbine engines would be applicable, principally gas-path analysis and vibration-level monitoring.

(10) Basic technical studies of the following types are needed:

- Conception and demonstration of practical signature-analysis techniques for the diagnosis and prognosis of powertrain faults
- Accumulation of a failure-model data base for application to diagnosis/prognosis by trend-analysis, signature-analysis, and failure-agent monitoring
- Conception and demonstration of automated oil-analysis methods
- Conceptual studies on the use of diagnostic test equipment for the automation of maintenance record keeping and compilation of failure-history data.

(11) It does not appear to be necessary or appropriate for ARPA to undertake research on advanced sensors for automatic diagnostic test equipment. While it will be important in future developments to reduce sensor costs, it appears that developments currently in progress within the automotive industry will produce this result. Sensor costs in the range of $1 to $10 can be expected by 1980.

(12) As a consequence of current developments in electronic-component technology it can be expected that, in the future, more complex automatic diagnostic test equipment can be developed, and that equipment will be more compact, faster, and lower in cost. While cost reductions are difficult to predict, a 50 percent reduction in system manufacturing cost by 1980 appears possible, and further reductions would be made over the next decade.

## PAST AND PRESENT DIAGNOSTIC SYSTEM DEVELOPMENTS

At present there is no automatic test equipment in the field for maintenance of Army automotive vehicles at the organization or DS/GS levels. Present automotive TMDE includes items such as the volt ohmmeter, tachometer, dwell meter, vacuum gauge, compression tester, and timing light--the usual array of automotive garage test equipment. However, the U. S. Army Tank-Automotive Research and Development Command (TARADCOM, formerly TACOM) has developed several types of diagnostic systems, and presently has plans for fielding the first of these systems in CY 1979. In addition, several commercial automatic diagnostic systems have been developed, both for gasoline and diesel engines, some of which are now on the market. Collectively, these systems comprise a first generation of automatic test equipment for automotive use. Experience with these systems so far is limited, and their effectiveness (particularly cost effectiveness) has not been evaluated. Their common characteristics are that they acquire data from the engine by way of various sensors and either make automated decisions based on these data or aid the operator in making a decision so that faults or conditions needing correction can be identified.

There are also current diagnostic-system developments for marine and aeronautical applications that employ technology that is potentially useful in automotive applications.

The following paragraphs describe the past and current diagnostic systems of principal interest.

### Built-In Go/No Go

Go/No Go is a system that was developed by RCA(1)* under contract to the U. S. Army TACOM in CY 1971-72 for initial application to the M151A2 1/4-ton truck (spark-ignition engine) and the M35A2 2-1/2-ton (diesel engine) truck. These vehicles were selected because of their high density in the Army fleet.

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* References are given at the end of the report.

Development of this system was discontinued after demonstration because of the apparent unfavorable economics.

Go/No Go consisted of four component groups: a set of transducers permanently located at various points on the vehicle, an electronics box installed on the vehicle, an operator's display mounted on the instrument panel, and a mechanic's display which connected to the instrument panel when used. The electronics box was 10 x 10 x 3-1/2 in. and could have been smaller, perhaps 3 x 8 x 3 in.

The operator's display presented two groups of three lights each. The first was a vehicle-condition group with a green "READY" light, a yellow "REPAIR" light, and a red "STOP" light. There was also a warning buzzer that came on with the red "STOP" light, which would be switched off by the operator. The second group of lights gave separate red indications for low oil, water, and brake fluid. The intended interpretation by the operator was that a green light meant the vehicle is ready, yellow meant maintenance is needed, and red meant failure is likely.

The mehcanic's display box used a thumbwheel selector switch and a green (Go) and a red (No Go) light by which the operator could check the condition of each component or system monitored by the system. The mechanic's display box also contained a POWER TEST feature for spark-ignition engines (by ignition interrupt). The mechanic is to depress the "POWER TEST" button and run the engine at wide-open throttle; the engine is assumed to have sufficient power if the yellow "LOW POWER" light does not come on.

The test capability of the Go/No Go system is described in Table 1. There are 15 or 16 tests in all that comprise a comprehensive check on vehicle condition. Most of the automated decisions made by the system are pass/fail tests of a single parameter under specific conditions. In addition, there is waveform analysis of starter current and ignition primary voltage. Twenty-one sensors or sensing points are used: eight pressures, four electrical voltage or current, three temperature, three fluid level, one speed, one ignition timing, and one linear motion.

The Go/No Go system was installed and demonstrated on the M151 and M35 vehicles, and was judged to be technically feasible by its developers.

TABLE 1. GO/NO GO SYSTEM TEST CAPABILITY

| Test Indication | M151A2 | M35A2 |
|---|---|---|
| Starter-system failure | X | X |
| Insufficient fuel delivery | X | X |
| Fuel-nozzle malfunction | | X |
| Clogged fuel filters | | X |
| Restricted air intake | X | X |
| Low engine power | X | |
| Insufficient compression | | X |
| Excessive engine binding | X | X |
| Loss of secondary voltage or improper spark timing | X | |
| General deterioration of ignition system | X | |
| Low oil level in crankcase | X | X |
| Low oil pressure | X | X |
| Clogged oil filter | X | X |
| Low coolant level | X | X |
| Engine overheating | X | X |
| Charging system fail | X | X |
| Low brake fluid | X | X |
| Brake pedal travel | X | X |
| Air-supply pressure | | X |

## Maintenance Indicator System

The Maintenance Indicator System (MIS, also sometimes called MIP, Maintenance Indicator Panel) was developed by Teledyne Continental Motors(2) under contract to the U. S. Army Tank-Automotive Command. It is a built-in system designed to monitor critical engine and drivetrain operating parameters by means of a visual light display located on the vehicle instrument panel. The system operates by means of 14 sensing switches permanently located at various points in the vehicle. When any parameter is out of limits, the sensing switch turns on the appropriate light on the panel, and the light remains on until the condition is corrected. Thus, all the decision making logic is imbedded in the sensing switches. When the vehicle master switch is turned on, all panel lights are illuminated for a few seconds as a self-test.

Table 2 lists the functions that the MIS is designed to monitor. The associated panel light is either red or amber depending upon the seriousness assigned to the out-of-limit condition.

The MIS was installed in two M54A2 cargo vehicles and operated for 5,000 miles of durability testing in 1972 at Aberdeen Proving Ground, and in 1973 two M35A2 2-1/2-ton trucks equipped with MIS went through 20,000-mile durability tests. An MIS system has also been designed for the M60 tank. The developers project about a 40 percent increase in mean miles between failures if applied to the M60 with associated reduced life-cycle costs. To date, the Army has not decided to field the MIS in any of its vehicles.

There are two points worth discussing in regard to the MIS approach. Operating experience has shown that on-board displays must not give false indications of trouble with any frequency if they are to be trusted. This implies that high system reliability plus judicious setting of limits are important with such systems. Secondly, there is the opportunity to revise maintenance procedures with the use of such a system, that is, a number of service operations can be performed only when needed instead of periodically.

TABLE 2. MAINTENANCE INDICATOR SYSTEM TESTS
(As Applied to M60 Tank)

| |
|---|
| Engine oil pressure low |
| Engine oil temperature high |
| Engine oil level low |
| Engine oil filter restricted |
| Transmission oil level low |
| Transmission oil temperature high |
| Engine fuel filter restricted |
| Engine fuel filter water drain required |
| Generator output high, low |
| Generator blower motor nonoperational |
| Engine hydrostatic lock warning |
| Brake fluid low |
| Air-cleaner element missing or restricted |
| Engine manifold heater operating |

## STE/ICE System

The Simplified Test Equipment/Internal Combustion Engine (STE/ICE)(3-5) system was developed by RCA for maintenance of Army vehicles under contract with TACOM. The basic piece of equipment in the STE/ICE system is a Vehicle Test Meter (VTM) which is a portable militarized electronics box measuring 11.5 x 8.5 x 7 in. Associated with the VTM is a diagnostic connector assembly consisting of various permanently installed sensors wired to a connector mounted on the vehicle instrument panel. Alternatively, the VTM can be used with temporarily installed transducers supplied in a transducer kit. The STE/ICE VTM is shown in Figure 1.

The STE/ICE unit is basically a sophisticated, versatile, multifunction test meter. There is no automatic sequencing of tests and no internal diagnostic logic performed. There are 21 basic test functions as listed in Table 3 which the operator may call for by selecting the appropriate 3-digit code-number thumbwheels on the test meter. Test readout is by a 4-character light display, and the operator generally must compare the test

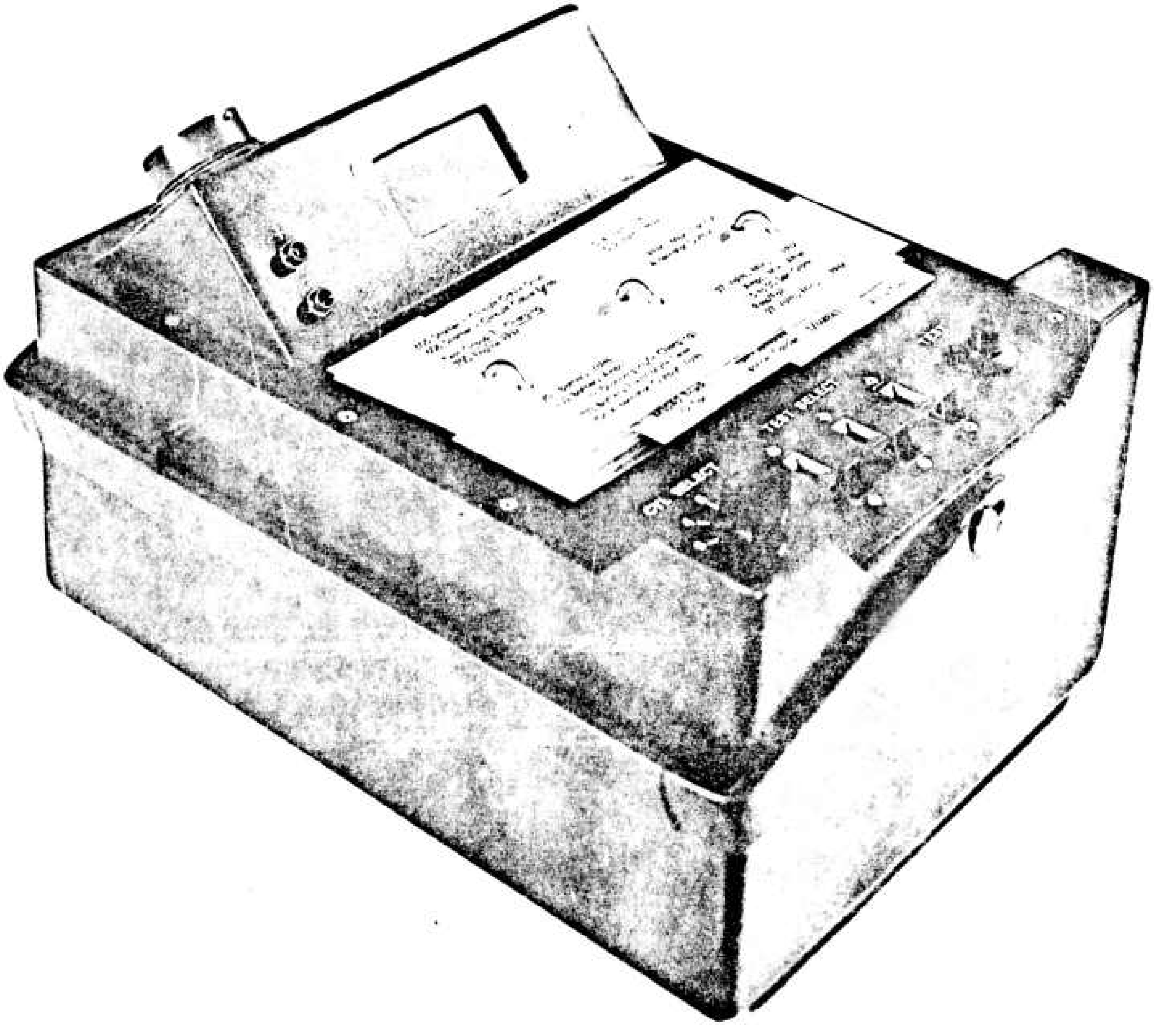

FIGURE 1. STE/ICE VEHICLE TEST METER

TABLE 3. STE/ICE TEST FUNCTIONS

| Test No. | Test Function |
|---|---|
| 200,300,400,500, 600,700 | Engine speed |
| 201 | Spark-ignition power test |
| 202 | Compression-ignition power test |
| 203 | Compression balance |
| 301 | Fuel-supply pressure |
| 302 | Fuel-supply return pressure |
| 303 | Fuel-filter pressure drop |
| 304,305 | Air-cleaner pressure drop |
| 306,307 | Turbocharger outlet pressure |
| 308 | Airbox pressure |
| 309,310 | Intake-manifold vacuum test |
| 401 | Oil pressure |
| 402,403 | Coolant temperature |
| 501 | Dwell angle |
| 503,606,710 | Points voltage/negative battery cable voltage drop |
| 504 | Ignition-coil primary voltage |
| 505 | Ignition-coil primary resistance |
| 601,701,704,707 | Battery voltage/alternator/ generator output voltage |
| 602 | Starter voltage |
| 603,604,702,705, 708 | Starter current and alternator/ generator current |
| 703 | Battery electrolyte level |

value with the acceptable range given on a set of plastic instruction cards attached to the test set and make pass/fail decisions. Fault isolation is accomplished by following diagnostic sequences given in the operator's instruction manual. These sequences are listed in Table 4. Eight of the sequences are for engines that will start; there are also 13 test sequences for diagnosis of engines that will not start. STE/ICE also has a self-test sequence.

There are up to 25 connections with the vehicle (either permanent or temporary): 13 electrical current or voltage, 9 pressure, 1 speed, 1 temperature, and 1 fluid level.

The STE/ICE electronics makes only a few pass/fail decisions; thus most of the logic must be performed by the test system operator. Waveform analysis is performed by STE/ICE in the compression-balance test and the compression-ignition power test. This power test is based on an engine snap acceleration and deceleration under no load.

A Rockwell PPS-4 microprocessor is used in the system. The system includes 512 x 4 words of scratch pad memory, 1536 x 8 words of programmable read-only memory (PROM) for constants, and a 4K x 8 PROM program memory.

So far, STE/ICE has been applied to the M151A2, M35A2, M113A1, and M48/M60 vehicles. The system has passed performance tests, and the Army plans call for initial fielding in CY 1979.

## ATE/ICE System

Automatic Test Equipment/Internal Combustion Engine (ATE/ICE) (6,7) is an experimental system developed by the U. S. Army TACOM for use in maintenance of military vehicles. The initial concept was generated by Dynasciences Corporation; other contractors have been TRW Systems and Energy Group, and RCA/Government and Commercial Systems. The hardware is similar in concept to the STE/ICE but ATE/ICE employs automatic test sequencing, has a higher degree of internally programmed diagnostic logic, and is programmable. (STE/ICE can be reprogrammed only by replacing a PROM circuit board.) Thus, while ATE/ICE was developed for use with military

# TABLE 4. STE/ICE TEST SEQUENCES[a,b]

| Sequence No. | Description |
|---|---|
| G01 | Engine start |
| G02 | Set high idle |
| G03 | Cooling system |
| G04 | Oil pressure |
| G05 | Idle-speed adjustment |
| G06 | Governor circuit |
| G07 | Power |
| G09 | Battery voltage |
| NG20 | No crank - no start |
| NG30 | Crank - no start |
| NG40 | Engine will not idle |
| NG50 | Ignition system |
| NG60 | Ignition, crank - no speed measurement |
| NG70 | Battery circuit |
| NG80 | Starter circuit |
| NG90 | Engine - cranking |
| NG100 | Fuel system |
| NG110 | Ignition timing |
| NG120 | Charging circuit |
| NG130 | Cooling system |
| NG140 | NO GO power |

(a) Sequences are not automated; operator must follow flow diagram.

(b) With diagnostic connector assembly (permanently installed sensors wired to connector mounted on vehicle instrument panel).

vehicles, it is a highly versatile system that could be used for a range of applications including medical use.

The main component of the ATE/ICE system is a portable electronics box called the Programmable Diagnostic Unit (PDU) which measures 19.3 x 14.1 x 14.1 in. (cover on) and weighs 64 lb including a 4-lb hand-held set communicator. The system may be used either with permanently installed (diagnostic connector) sensors in the vehicle or temporarily connected sensors supplied in a kit. The PDU is shown in Figure 2.

The set communicator incorporates a 10-digit keyboard for entering instructions and an output display consisting of three six-digit alphanumeric words. There is provision for an optional printer.

ATE/ICE uses fewer sensors than STE/ICE: seven electrical current or voltage, two pressure, one temperature, and one flow.

The system employs a 16-bit CDC 469 Mil-Spec computing system with 8K words of memory. Programming is accomplished by cassette tape.

The operator initiates testing by entering one of the sequence numbers shown in Table 5, after which the system automatically leads the operator through the test sequence.

TABLE 5. ATE/ICE TEST SEQUENCES

| Sequence No. | Program |
|---|---|
| 3 | Confidence |
| 4 | Automated inspection |
| 5 | No start |
| 6 | Performance test |
| 7 | Tune up |

The Confidence sequence is a system self-test and there are 19 possible diagnostic messages that can be displayed if an internal fault is found. The Automated Inspection List leads the system operator through a

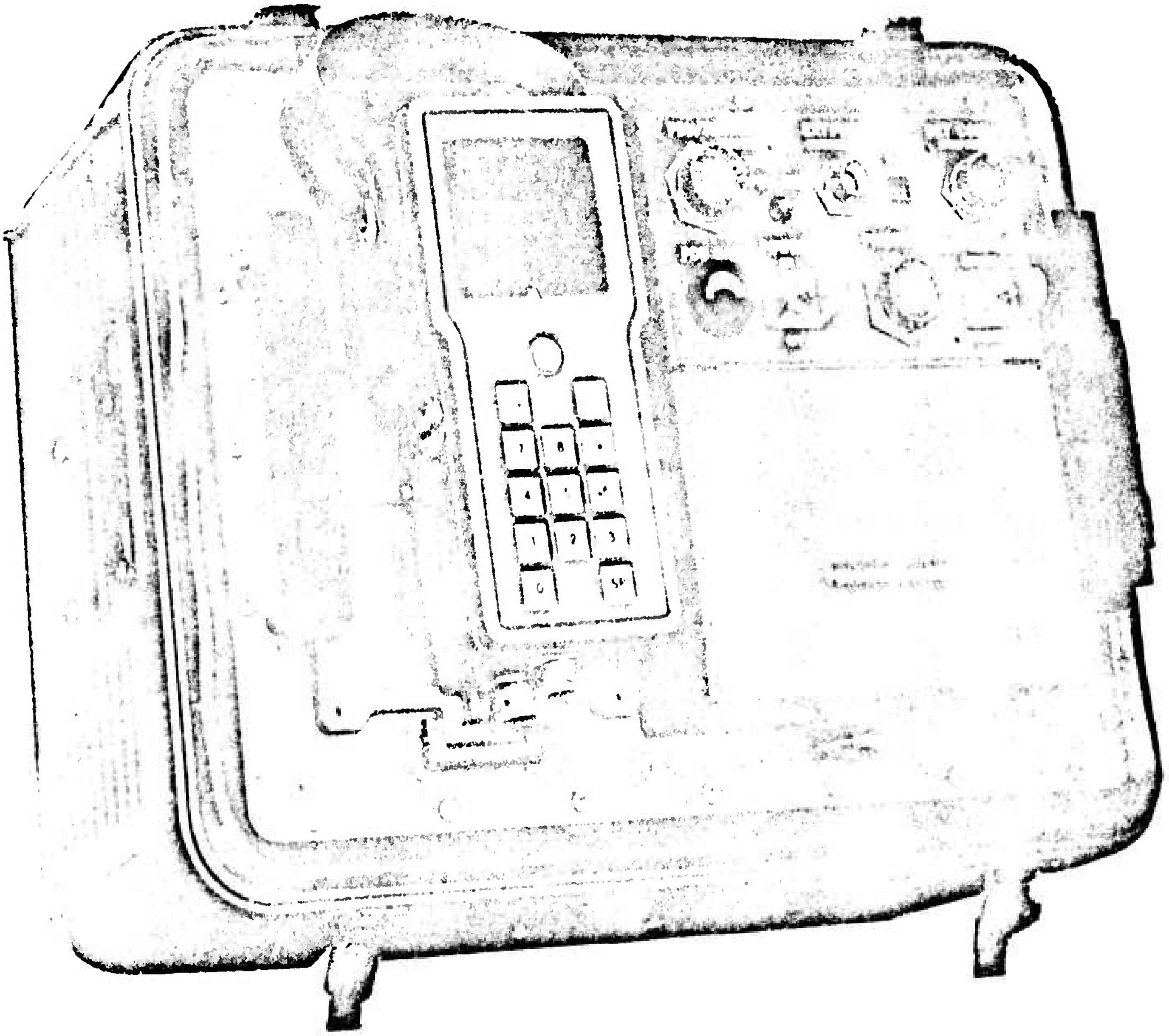

FIGURE 2. ATE/ICE PROGRAMMABLE DIAGNOSTIC UNIT

sequence of 17 visual checks of vehicle condition. If the No Start sequence is selected, the system assumes that the engine will not start and proceeds to check out the engine to isolate the fault. If the fault is isolated, the operator receives one or more of 31 available diagnostic messages--English-language abbreviation.

The Performance test sequence evaluates the engine performance based on several criteria, and fault-isolation procedures are entered only if associated performance criteria are not met. In the Tuneup test sequence, the system functions as a test meter and the operator can measure speed, dwell, voltage, current, vacuum, crankcase blowby pressure, and ambient pressure.

The ATE/ICE program is presently unfunded, but there are plans to reactivate development work in FY 1978.

## Hamilton Test Systems' Autosense

The Autosense(8) system was developed by Hamilton Test Systems Division of United Technologies Corporation for use in maintenance of spark-ignition engines by commercial automotive service organizations and by fleet owners. The hardware consists of a floor-mounted console, a hand-held control, and hookup harness.

The console, shown in Figure 3, contains the electronics which include a microcomputer with a random-access memory (RAM), an optional nondispersive infrared HC/CO exhaust-gas analyzer, and an output printer.

The hand-held control has a keyboard with 10 numerical digits and seven function buttons for making inputs to the system, eight status indicator lights, and an output display of three 5-digit numbers.

The hookups consist of 15 electrical connectors, all temporary, plus intake-manifold vacuum, and an optional exhaust-gas probe. Thus, there are no permanently installed sensors used with the Autosense system. Autosense has the capability of adapting to built-in diagnostic connectors as they begin to appear on new vehicles. The hookup harness is mounted on a boom attached to the console which can swing out over the vehicle for convenience.

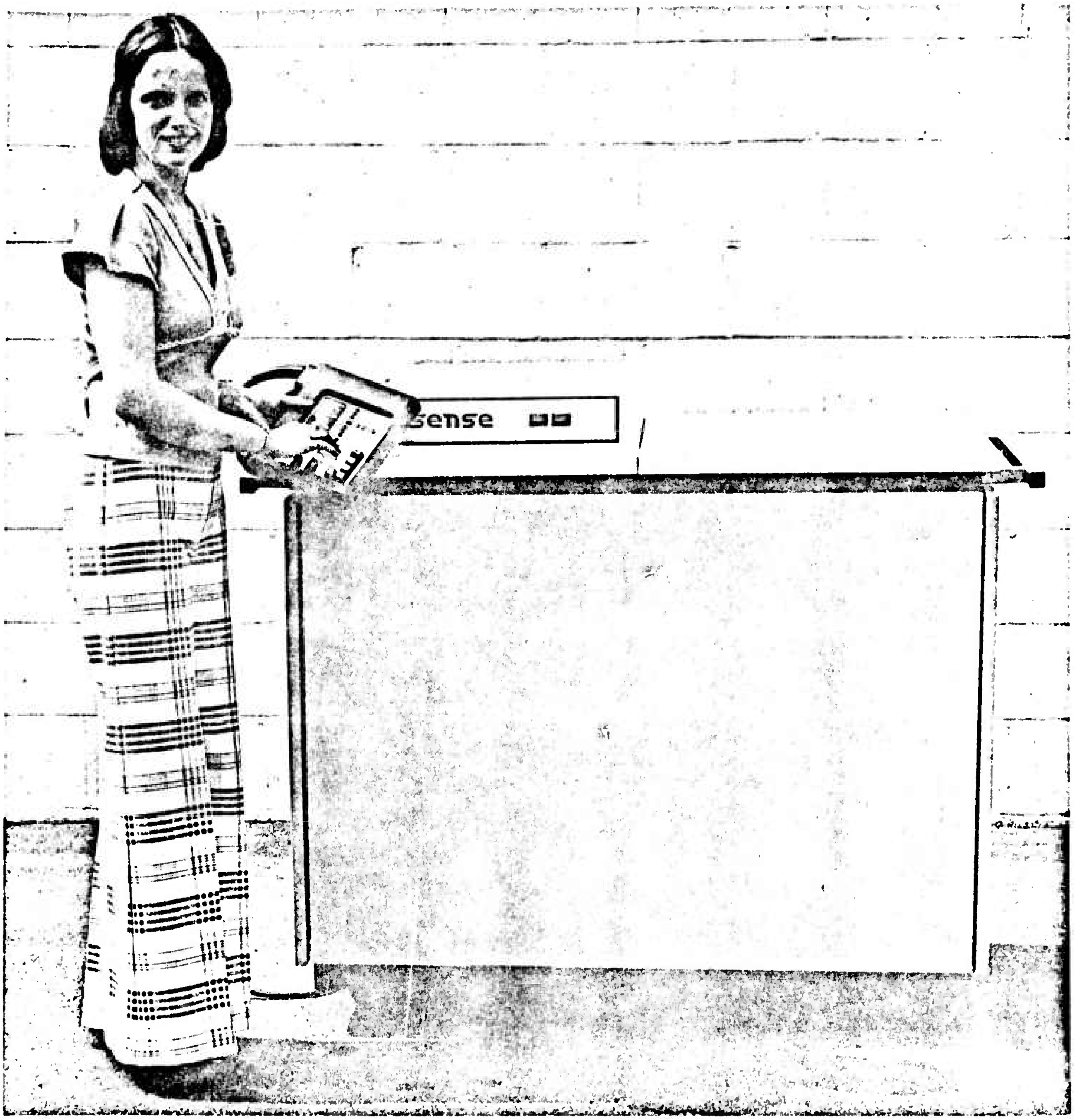

FIGURE 3. AUTOSENSE DIAGNOSTIC SYSTEM CONSOLE AND HAND-HELD CONTROL BOX

Table 6 lists the basic test functions of the autosense system which comprise checks on ignition system, starting system, compression, and individual-cylinder power contribution and charging system.

The operator initiates the test sequence by depressing the start button and identifying the vehicle. The operator then selects one of 31 available test sequences, which are listed in Table 7. Once the sequence is initiated, the system leads the operator through the test by numerical-code instructions which require an operator's manual for interpretation (an experienced operator would probably not need to refer to the manual). The operator receives a visual display of results via the control box; in addition, the printer on the console automatically puts out a hard copy of the results. The printed test values that are outside of limits are marked with an asterisk, and, at the conclusion of the test, diagnostic repair-code numbers are printed out. These specify repair actions to be taken and, again, the operator's manual is needed to interpret the repair-code number. There are approximately 180 types of diagnostic messages available in the Autosense system.

The Autosense systems employ limit tables for making pass/fail decisions, truth tables for diagnostic logic, and waveform analysis of starter current to determine relative cylinder compression. Autosense systems are presently available for purchase.

## Autosense Diesel

Hamilton Test Systems has also developed a diesel version of the Autosense system which is currently undergoing field trials(10). "Dieselsense" (or whatever its trade name will be) uses the same console and hand-held control as Autosense but with different sensors and different basic test functions.

Basic test functions of one version of Dieselsense are listed in Table 8. With this version, there are 21 connections to the vehicle: 11 electrical, 7 pressure, 2 temperature, and 1 speed. All connections are temporary but the permanent installation of several adapters is required.

TABLE 6. AUTOSENSE BASIC TEST FUNCTIONS

| |
|---|
| Engine speed |
| Cylinder power contribution |
| Compression balance |
| Intake manifold pressure |
| Primary ignition current |
| Primary ignition voltage |
| Distributor point voltage |
| Battery-to-coil voltage drop |
| Coil condition |
| Capacitor condition |
| Spark-plug firing voltage |
| Spark-plug load test |
| Distributor rotor-gap voltage |
| Dwell |
| Basic timing |
| Total timing |
| Starter solenoid/relay current |
| Starter current |
| Battery voltage |
| Starter solenoid/relay voltage |
| Battery to relay voltage |
| Starter positive-cable voltage drop |
| Cranking speed |
| Battery voltage |
| Battery current |
| Regulator battery voltage |
| Alternator/generator output voltage |
| Exhaust hydrocarbon content |
| Exhaust carbon monoxide content |

TABLE 7. AUTOSENSE DIAGNOSTIC SEQUENCES

| Sequence No. | Description |
|---|---|
| 900 | Total health check, standard-ignition vehicle |
| 905 | Total health check, standard-ignition vehicle, less emissions |
| 907 | Total health check, electronic-ignition vehicle |
| 910 | Total health check, electronic ignition vehicle, less emissions |
| 901 | Tuneup/running, standard-ignition vehicle |
| 908 | Tuneup/running, electronic-ignition vehicle |
| 904 | General health check, with emissions check |
| 906 | General health check, without emissions check |
| 902 | Tuneup/no start, standard-ignition vehicle |
| 909 | Tuneup/no start, electronic-ignition vehicle |
| 903 | No crank |
| 920 | Primary ignition, standard-ignition vehicle |
| 921 | Secondary ignition |
| 922 | Timing, standard-ignition vehicle |
| 923 | Coil output, engine running |
| 930 | Charging system, engine running |
| 931 | Cylinder performance, engine running |
| 933 | Emissions check, engine running |
| 934 | Carburetor adjustment, engine running |
| 935 | Starter system, engine running |
| 936 | Timing, electronic-ignition vehicle, engine running |
| 939 | Secondary ignition, electronic ignition, engine running |
| 924 | Coil output, no start |
| 927 | Primary ignition, standard-ignition vehicle, no start |
| 928 | Secondary ignition, no start |
| 929 | Timing, standard-ignition vehicle, no start |
| 932 | Compression check, no start |
| 937 | Timing, electronic-ignition vehicle, no start |
| 938 | Primary ignition, electronic ignition, no start |
| 925 | Battery condition, no crank |
| 926 | Starter feed system, no crank |

TABLE 8. AUTOSENSE DIESEL TEST FUNCTIONS

| Test No. | Test |
|---|---|
| 1 | Engine oil level |
| 2 | Engine coolant level |
| 3 | Drive-belt condition |
| 4 | Fuel and air-line condition |
| 5 | Throttle-linkage travel |
| 6 | Cylinder ID location |
| 11 | Atmospheric pressure |
| 12 | Battery voltage |
| 13 | Cranking |
| 14 | Battery cranking current |
| 15 | Battery cranking voltage |
| 17 | Battery cable ΔV |
| 18 | Starter-switch voltage |
| 21/32 | Relative cylinder compression |
| 33 | Cranking fuel pressure |
| 34 | Cranking speed |
| 35 | Cranking attempt battery voltage |
| 36 | Battery current |
| 37 | Battery to starter ΔV |
| 38 | Battery cable ΔV |
| 39 | Starter-switch voltage |
| 40 | Fuel and oil bleed |
| 41 | High idle water pressure |
| 42 | Water Δ pressure |
| 43 | Pressure cap |
| 44 | Thermostat setting |
| 48 | Average horsepower |
| 49 | Air in fuel |
| 56 | Deceleration rate |
| 57 | Blowby |
| 58 | Air-filter restriction |
| 59 | Air-tank charge time |
| 60 | Compressor cut-out |
| 61 | Compressor cut-in |
| 62 | Idle RPM |
| 63 | Idle fuel pressure |
| 64 | Cab tachometer accuracy |
| 65 | Cab water-temperature accuracy |
| 66 | Cab oil-pressure gauge accuracy |
| 67 | Fuel-pump check point No. 2 |
| 68 | Fuel-pump check point No. 1 |
| 69 | Fuel-pump rated pressure |
| 70 | Governor cut-off |
| 71/82 | Relative power contribution |
| 83 | Oil-pressure regulator cut-in |
| 84 | Oil-pressure regulator cut-in speed |
| 85 | Oil temperature |
| 86 | Idle oil pressure |
| 87 | High idle oil pressure |
| 89 | Minimum intake manifold pressure |
| 90 | Turbocharger condition |
| 91 | Voltage-regulator voltage |
| 92 | Alternator voltage |
| 93 | Battery voltage |
| 98 | Fuel solenoid voltage |
| 99 | Fuel solenoid current |

## PRD IDEA

The Integrated Diesel Engine Analyzer (IDEA)$^{(11)}$ was developed by PRD Electronics Division of the Harris Corporation for commercial use in maintenance of diesel engines of any size and application. This system is presently undergoing field tests.

The system hardware consists of the mobile cabinet shown in Figure 4 and associated sensors and wiring harness. The system employs a 16-bit microprocessor with 4K of ROM (read-only memory) and 1K of RAM.

To operate the system, the mechanic first reads in the test program from cassette tape and sets the engine identification number on a 2-digit thumbwheel. After initiating the test with a pushbutton, a 2-line, 64-digit alphanumeric display leads the mechanic through the test sequence, and a printer on the cabinet puts out a hardcopy of the results. The system then automatically goes through a diagnostic sequence and prints out diagnostic information. The basic test parameters are listed in Table 9.

TABLE 9. PRD INTEGRATED DIESEL ENGINE ANALYZER TEST PARAMETERS

| |
|---|
| Engine speed |
| Torque |
| Power |
| Exhaust manifold temperature |
| Coolant outlet temperature |
| Coolant temperature rise |
| Fuel inlet temperature |
| Fuel temperature rise |
| Lube-oil temperature |
| Lube-oil pressure |
| Blower pressure rise |
| Turbocharger boost pressure |
| Fuel-supply-pump discharge pressure |
| Fuel-pump suction pressure |
| Air-cleaner pressure drop |
| Crankcase pressure |
| Air-box pressure |

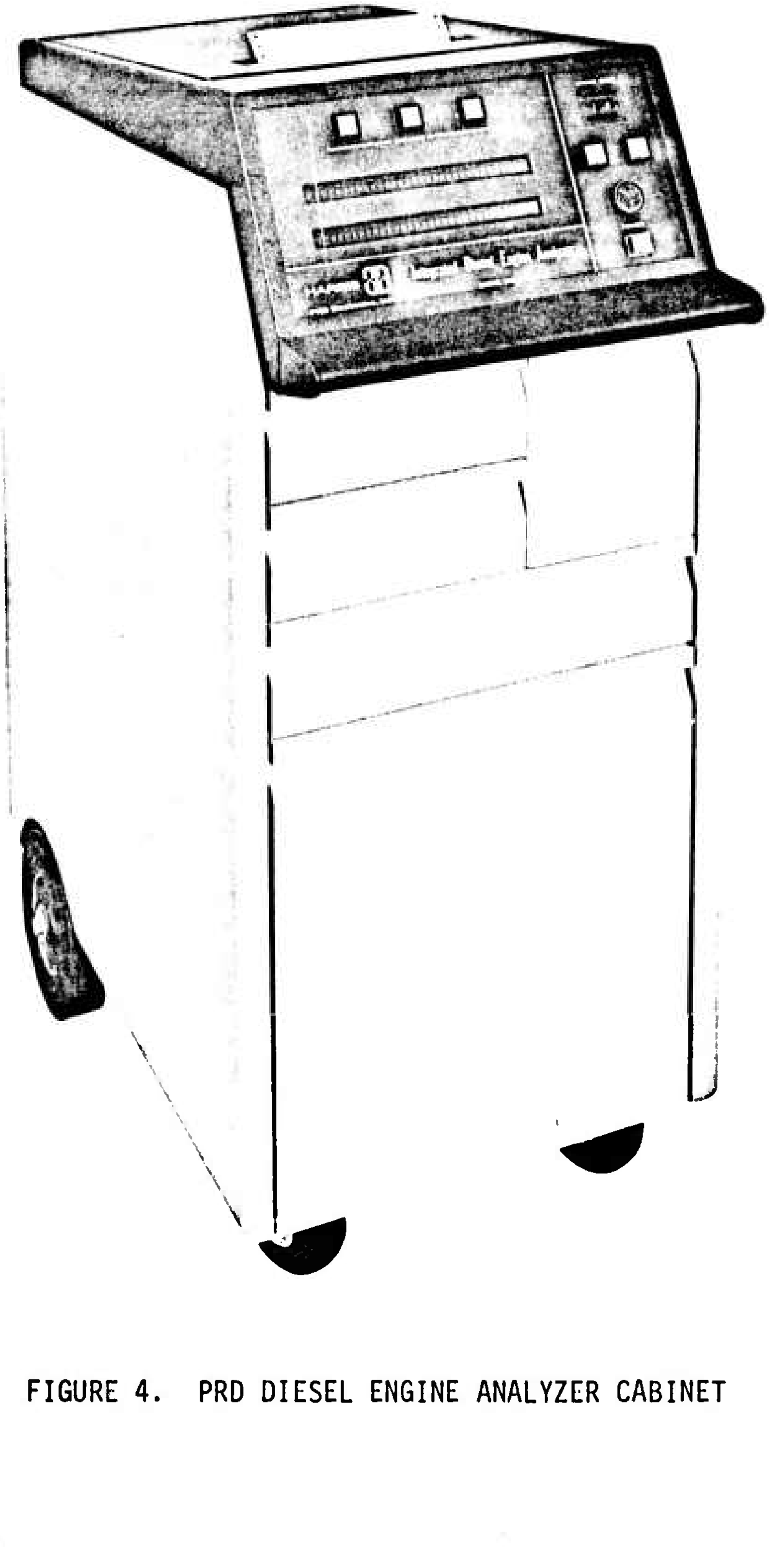

FIGURE 4. PRD DIESEL ENGINE ANALYZER CABINET

There is an alarm function built into the system which indicates low oil pressure, high coolant temperature, and engine overspeed.

Using the same hardware, PRD has also introduced a BMS 1000 Bus Maintenance System(12) which is programmed for fault isolation in air-conditioning and electrical systems as well as in the engine.

## PRD "Mini"

PRD Electronics has also developed a "Mini" version of their diesel engine analyzer(13). A sketch of the portable console is shown as Figure 5.

The Mini uses only two sensors: a speed pulse pickup from the flywheel and a crank position reference signal. With these two inputs, the system has the capability to determine relative cylinder compression during cranking tests and relative cylinder power contribution during a snap acceleration test. This capability is included in the larger PRD IDEA system.

## Sun 2001

The Sun 2001 Diagnostic Computer(14), developed by the Sun Electric Corporation, is an extension of the familiar service-station type of engine performance tester and the only one of the automotive systems investigated that uses a CRT display as the principal output means. One of the CRTs displays ignition waveforms while the other presents digital instructions and both digital and graphical displays of the test results. A printer is available.

The mechanic can select one of several "area" test sequences or 12 individual "pinpoint" tests listed in Table 10 by way of the appropriate setting of an array of 41 switches or pushbuttons. The switches and buttons are labeled, and the system computer displays instructions for control setting and operation.

There are no pass/fail tests made by the system and there is no programmed diagnostic logic; thus, the mechanic makes all interpretations of the test results.

FIGURE 5. PRD "MINI" DIESEL ENGINE ANALYZER

The Sun 2001 employs 10 connections: 8 electrical, 1 pressure, and 1 HC/CO exhaust probe. A microprocessor with a 4K-word memory is used in the system.

TABLE 10. SUN 2001 TEST SEQUENCES

| Sequence No. | Description |
|---|---|
| 1 | Cranking |
| 2 | Alternator output |
| 3 | Idle |
| 4 | Low cruise |
| 5 | Automatic power balance |
| 6 | Snap acceleration |
| 7 | High cruise |
| "Pinpoint" Test | RPM tests |
| "Pinpoint" Test | Infrared tests |
| "Pinpoint" Test | Voltage tests |
| "Pinpoint" Test | Ignition tests |
| "Pinpoint" Test | Ohm tests |
| "Pinpoint" Test | Condenser tests |
| "Pinpoint" Test | Amperage tests |
| "Pinpoint" Test | Ignition-coil tests |
| "Pinpoint" Test | Cylinder power balance |
| "Pinpoint" Test | Dwell tests |
| "Pinpoint" Test | Engine-speed tests |
| "Pinpoint" Test | Cylinder-leakage tests |

## Depot MAIDS

Depot MAIDS(15) is an automatic diagnostic engine test system developed by Hamilton Standard Division of United Technologies for the U. S. Army Frankford Arsenal. The system is presently installed in a complex of engine test cells at the Letterkenny Army Depot in Chambersburg, Pennsylvania. It is used to diagnose malfunctions in operable engines returned to Letterkenny for rebuilding, which permits repair as necessary instead of complete rebuilding.

MAIDS is used for five engines: Cummins 300, Teledyne Continental 1790-7B (gasoline, carbureted), -8 (gasoline, fuel injected), -2A (diesel), and the General Motors 8V71T and 6V53 diesels. However, the system can be used on any engine for which software has been developed.

There are presently four dynamometer cells on MAIDS (two 1790 and two 6V-8V) but the theoretical limit is 16 cells. Additional core memory is needed for each new cell added. All cells can operate concurrently on a time-sharing basis. Each cell has some of its own signal conditioning equipment.

MAIDS is built around a 32K Honeywell 516 computer with 2 disc units of 3.6-million word capacity. Master software is on 500-600 punched tapes which are read onto disc as required for normal operation. FORTRAN IV is used as the source language for software.

Instructions and test results are by teletype, one in each cell and one at the master console, and a single digital display of any selected parameter is available. The master console also has a two-beam oscilloscope for viewing waveforms. There is also an intercom system between control rooms, test cells, and the computer room. In the computer room there is a simulator used for checkout and calibration of the computer and system. The system also has a confidence test (self-test) for checkout.

The truth and limit tables used for acceptance criteria and diagnosis are part of the software. These can be changed readily.

Engine test sequencing is automatic unless the operator opts for manual control. The computer continuously performs a safety monitor check and will shut down the test and print out the cause of shutdown if a problem occurs.

The system will conduct both quality-assurance and diagnostic tests, the former employing about 50 readings and the latter about 250. It also sequences a run-in test for remanufactured engines.

Table 11 lists the malfunctions that can be identified by the MAIDS system. To accomplish this, a fully instrumented engine will employ 25 temperature sensors, 9 pressure sensors, 18 vibration sensors, 7 fluid-flow sensors, and 3 speed sensors in addition to inputs for starter current, crankshaft position, torque, throttle position, and magneto voltage.

It requires about 2 man-hours to instrument an engine for the MAIDS diagnostic test, 1/2 hour to install the engine, and 1/2 hour to run the test including a 5-minute warmup period. Diagnosis is generally accurate. In part, the effectiveness of the system is related to the tightness of the limit tables. The diagnostic test can find faults in remanufactured engines that pass the QA test if the specs are too tight.

## MO/MARS

The Mobility Measurement and Recording System (MO/MARS)(16) was developed by General American Research Division (GARD) for U. S. Army TACOM. It is not a diagnostic test system, but rather a recording system for monitoring engine and vehicle parameters under field operating conditions. It is of interest here because its purpose was to provide baseline operating data on "acceptable" vehicles and on vehicles with seeded faults for potential use in diagnostic maintenance systems. TACOM was also after information on the acceptability of idle tests for assessing vehicle status.

The central hardware component was a cabinet (bigger than a bread box) which contained a tape recording unit and signal-conditioning and data-processing electronics. In the first phase of the study, an M151 vehicle was instrumented for the following parameters:

- Test time
- Cab shock and vibration
- Brake application
- Panic stops

## TABLE 11. DEPOT MAIDS DIAGNOSTIC CAPABILITY

### Starter Current Analysis

- Low compression in each of 12 cylinders
- Defective starter

### Ignition Analysis

- Plugs not firing (each of 24 plugs)
- Plug or harness shorted (each of 24 harnesses)
- Plug or harness open (each of 24 harnesses)
- Magneto timing (each of 4 magnetos)
- Magneto synchronization
- Magneto mechanical condition
- Magneto capacitor open
- Magneto unacceptable
- Magneto short life remaining

### Injection Analysis

- Replace fuel injector (each of 12)
- Replace injector pump (2)
- Adjust timing (2 RB and 2 LB)

### Intake and Exhaust Valve Analysis

- Negative valve clearance or broken rocker arm
- Low valve clearance
- High valve clearance
- Worn cam drive/timing late
- Cam timing early

### Steady-State Analysis

- Worn piston rings
- Defective injector nozzle
- Defective turbocharger
- Oil cooler air restriction
- Defective cooling fans (2)
- Defective fuel pump
- Defective oil-pressure regulator
- Defective main oil pump
- Defective piston squirt pump
- Oil cooler internal restriction
- Injection timing
- [illegible] advance unit
- Manifold [illegible]ance
- Injector pump rich or lean
- Defective valve train
- Valve timing
- Defective oil-temperature bypass
- Bent connecting rod
- Main or connecting rod bearing worn
- Defective fuel bleeder valve

- Front- and rear-wheel speed
- Front- and rear-axle shock
- Engine speed
- Temperatures: ambient, coolant, differential, and transmission
- Vehicle pitch.

The system is set up to record only in response to certain triggers, not continuously.

More recently, the system was installed in an M35 2-1/2-ton truck and operated for 20,000 miles over various types of terrain, with and without seeded defects. The following parameters were measured:

- Date, time of day
- Clutch slippage
- Battery voltage
- Air, fuel, oil pressure
- Vehicle odometer, speed
- Temperatures: transmission, transfer case, engine oil, coolant, ambient
- Engine speed, power, compression.

This program is presently inactive.

## Navy Diesel-Engine Condition Monitoring System

A study(17) was conducted to determine the feasibility of installing a diagnostic test system in LST 1179 class ships as a means of improving readiness and decreasing propulsion-system maintenance costs. The study, requested by the U. S. Naval Ship Engineering Center, was conducted by the

Mechanical Failures Prevention Group which is sponsored by the National Bureau of Standards. The work was carried out cooperatively by four contractors: Mechanical Technology, Inc., Latham, N.Y.; Shaker Research Corporation, Ballston Lake, N.Y.; General American Research Division, Niles, Ill.; and Wear Sciences, Inc., Scotia, N.Y. This group studied propulsion-system failure data and present maintenance practices, defined a proposed diagnostic test system, and performed a cost-effectiveness analysis of the proposed system. They concluded that $30,000 to $70,000 per ship of the present maintenance costs of $740,000 per ship per year could be saved with the use of the diangostic system, depending upon whether possible manpower reductions were allowed.

It was concluded that a development of a fully automatic diagnostic system utilizing software logic for fault isolation would be too costly considering that there were only 20 ships in this class. Instead, a "data system" approach was recommended, in which operating data are to be displayed in a format that would allow proper identification of malfunctions by maintenance personnel. The system was to perform continuous limit checks on sensed parameters and to store data for periodic trend analysis. A listing of the recommended parameters is given in Table 12.

The powertrain in this ship consists of six 2750-hp Alco diesels and associated drivetrain components.

## Tractor-Transmission Diagnostic System

An investigation was conducted(18) by Shaker Research Corporation, Ballston Lake, N.Y., to investigate the feasibility of a technique for using ultrasonic vibrations generated by the powertrain components of off-road vehicles to diagnose the mechanical condition of these components. The study was conducted under contract to the U. S. Army Mobility Equipment Research and Development Command, Fort Belvoir, Virginia.

Specifically, the study was to investigate the validity of the hypothesis that the high-frequency vibration generated by the impacts and high loading associated with the shift transients are indicative of the type of vibration generated by degraded components during steady-state operation.

TABLE 12. PROPOSED PARAMETERS FOR NAVY DIESEL ENGINE CONDITION MONITORING SYSTEM

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**Reference**

- Ambient pressure
- Ambient temperature

**Power Train**

- Engine speed
- Cylinder exhaust temperature
- Firing pressure
- Cylinder pressure
- Crankcase pressure
- Free-end torsional vibration
- Vibration analysis

**Fuel System**

- Pump pressure
- Header pressure
- Fuel-rack position
- Fuel analysis (water)
- Fuel consumption

**Air Inlet and Exhaust System**

- Manifold temperature
- Manifold pressure
- Turbocharger exhaust temperature
- Turbocharger vibration
- Turbocharger lube-oil pressure
- Exhaust smoke meter

**Cooling System**

- Water out temperature
- Water in temperature

**Lube Oil to Engine**

- Pump pressure
- Header pressure
- Level gage
- Inline oil analysis

**Shaft and Coupling**

- Runout
- Holset coupling relative angular displacement
- Dental coupling relative angular displacement
- Pedestal bearing temperature
- Clutch temperature

**Gear Box**

- Bearing temperature
- Lube-oil pressure
- Lube-oil temperature
- Thrust-bearing axial position
- Chip detector

**Governor and Controls**

- Load-control position
- Propeller pitch

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The drivetrains of three Caterpillar D8H Crawler tractors with powershift transmissions were instrumented with accelerometers at several points in this program. Based on an analysis of the resulting data, a simple automatic diagnostic system was formulated that would allow fault isolation of major drivetrain components such as the transmission.

## Related Development Efforts

### AIDAPS

The Automatic Inspection, Diagnostic and Prognostic System (AIDAPS)(19) is being developed by the U. S. Army Aviation Systems Command (AVSCOM) to monitor engine, driveline, avionics, and armament for Army aircraft. Initial contractors were Northrup Corporation and Hamilton Standard Division of United Technologies; the present contractor is the Garrett Corporation, and the applications are the UH-1H and AH-1G helicopters.

Two aspects of the AIDAPS system are potentially applicable to land vehicles: gas-path analysis and vibration signature analysis.

In the gas-path analysis technique (as applied to the turbine engine, in this case), engine temperatures, pressures, shaft speeds, power output, and fuel flow are sensed, and various engine performance parameters are computed on the basis of these inputs. Diagnostic logic is performed on these parameters to determine whether the engine mode is normal and the probable cause of an abnormal mode. Faults such as worn seals, excess clearances, plugging or fouling, and damaged blading are detectable. Gas-path analysis will be potentially useful provided a turbine engine is selected for the XM-1 main battle tank. References 20 and 21 give additional information on gas-path analysis.

Vibration analysis is conducted on the drivetrain gearboxes in the helicopter. Vibration data are processed by the AIDAPS system such that the signature of a fault as a cracked or pitted bearing race can be detected and identified. This approach is in an early stage of development;

however, the technique is versatile and potentially applicable to internal-combustion engines. Vibration signature analysis is discussed in more detail in a subsequent section of this report.

## TRENDS Engine-Condition Monitoring System

The TRend analysis and ENgine Diagnostic System (TRENDS) was developed by Hamilton Standard as a maintenance tool for stationary gas-turbine engines.(22)

A single central computer provides the core of the system. There is a Central Unit (CU) (capable of handling 50 engines) for each total system, a Data Collection Unit (DCU) for each grouping of up to two engines, and a set of sensors on each engine.

The sensed parameters include pressure, flow rates, temperature, oil quantity, speed and vibration. Other electrical measurement signals are taken directly from existing instruments.

The CU accepts the data from the DCU's and utilizes it to perform the following functions:

- Engine-condition monitoring
- Automatic data logging
- Automatic data reduction
- Trend detection and analysis
- Maintenance action requests
- Routine maintenance flagging

The CU utilizes a number of different techniques such as gas-path analysis and comparisons against limit tables to evaluate constantly the health of the engine. A method of regression analysis is used to detect any trends in the systems toward the development of specific defects or the exceedance of any limits. The specific problems which may be diagnosed are:

- Anti-icing valve operation
- Oil-filter blockage
- Blocked/streaky nozzles or damaged combustor
- Excessive oil consumption
- Bearing-seal deterioration
- Compressor-blade problems
- Turbine-blade problems
- Bearing problems
- Fouled compressors
- Bowed first-stage nozzles
- Fouled turbines or worn seals
- Generator bearings, coupling and exciter ends, over overheating
- Generator overheating
- Exciter overheating
- Compressor and compressor-station equipment malfunction.

The approaching needs for routine maintenance or the development of engine malfunctions such as "dirty compressor" are recognized by TRENDS and maintenance messages are printed out in English language.

## Comparison of Current Automotive-Vehicle Diagnostic Test Systems

From the preceding discussion, it is apparent that a variety of approaches have been taken in the development of automatic test equipment for automotive-vehicle powertrain maintenance. For purposes of this report, the similarities in these systems are more important than their differences, in that the similarities in the more advanced systems serve to define the current state of the art, i.e., the characteristics of the first generation of automatic diagnostic test equipment.

In terms of hardware, these systems have the following common elements:

- Sensors
- Signal conditioning
- Data storage and processing (mini or microcomputer)
- Display or output.

In fact, it is probable that a versatile hardware system could be developed that could perform the functions of any of the diagnostic systems described in the preceding paragraphs (not that there is necessarily any incentive to do this). The point is that the hardware that has been put together for these systems is extremely versatile.

The differences among these systems are principally in the software, i.e., the computer program containing the following elements:

- Automatic test sequencing and operator instruction
- Automatic data acquisition and management
- Limit tables
- Truth tables for diagnostic logic
- Algorithms for waveform analysis
- Algorithms for trend analysis (not currently used in automotive systems but used in related systems).

Although the specific approaches are different, each of the more sophisticated systems contains most of these elements.

## TECHNICAL BASES FOR FUTURE SYSTEMS

From the preceding discussion, it is clear that substantial effort has been expended previously in the development of automatic test equipment for maintenance of automotive vehicles, and that this effort has resulted in a first generation of equipment that is now in an early stage of utilization. Under these circumstances, it is pertinent to consider the technical directions that might be taken in a next generation. The purpose of this section is to describe the technology that is available as a basis for the development of advanced systems.

## Diagnostic/Prognostic Techniques

### Definitions

In this context, prognosis is taken to mean the prediction in time of the occurrence of a future fault, while diagnosis is taken to mean the identification of an existing fault. All prognosis is a form of diagnosis, but diagnosis is not necessarily prognostic.

Prognosis is sometimes elementary and sometimes very difficult. For example, brake shoes wear continuously and eventually wear to the point where they are no longer serviceable (failure). The process is predictable, and the time to one mode of failure can be estimated easily. On the other hand, a fatigue failure of a connecting rod gives little evidence until shortly before complete fracture occurs. The prognostic clues in this case are much more difficult to sense.

In this application, the prognosis concept is important when it can identify that some condition or impending fault not presently out of acceptable limits will move out of limit before the next inspection/maintenance period.

Present automotive automatic diagnostic test equipment is primarily nonprognostic, and a logical step is the development of a prognostic capability for certain types of equipment.

### Built-In Warnings

The built-in warning is an elementary but useful diagnostic tool. One example of this technique is the breakable link designed to fracture when brake linings are worn to a maximum acceptable limit, giving a red warning light to the driver on the vehicle instrument panel. This feature is used in some passenger cars. Another example is the system required in all current U. S. passenger cars to signal failure of one brake circuit. In this case, a transducer senses an unbalance in pressure between the two brake master cylinders and closes a switch to give the warning. Oil-pressure, coolant-temperature, and battery-discharge lights are other forms of built-in warnings. Further, all of the functions of the Teledyne Continental Motors Maintenance Indicator System (MIS), described previously in this report, are built-in warnings.

Clearly, it would be impractical to instrument every major component or system of a vehicle to give an automatic malfunction warning; however, a few such warnings are obviously appropriate.

In some cases, a visual indication or auditory warning may be appropriate. Visual indications could not be made an integral part of automatic test equipment, but could complement an automatic system. That is, if the status of a component could be determined readily by a visual inspection, there would be no need to incorporate a feature to diagnose that component in an automatic system. An example of this type of feature is the wear indicator used by General Motors Corporation on front-suspension ball joints. By looking at the relative position of two scribed lines, the mechanic (or owner) can determine whether ball-joint wear is excessive. This feature was incorporated at virtually no additional manufacturing cost.

Another example of visual indication is a sight glass on a carburetor float bowl--used in the past on some Russian vehicles. With this feature, the mechanic can tell at a glance (1) whether the float is properly adjusted and (2) whether the fuel pump is operative. This feature would add manufacturing cost and possibly create a potential leak point, but it could possibly reduce the life-cycle cost of the vehicle. An example of an auditory warning is a "squealer" on brake shoes that will contact the brake drum or disk at the maximum acceptable wear point.

Simple mechanical fault or wear indicators, where they can be incorporated into a design at little or no additional manufacturing cost, make a lot of sense. Built-in warnings are generally not prognostic if they are on/off devices, but can be prognostic if there is an analog output.

## Parameter Limit Comparisons

Single-parameter limit comparison is perhaps the simplest type of diagnostic logic available, but the simplicity is deceptive in that establishing the limits can be difficult. With this technique, the value of the monitored parameter is compared to stored values of acceptable limits. If the value is within limits, the test is passed; if not, the test is failed. In cases where wear is a normal, gradual process, it becomes necessary to select a point at which wear is unacceptable--ideally the point at which the vehicle is either no longer serviceable* or can be expected to be unserviceable within a short time. Establishing limits not only requires judgment but also generally requires a good data base. For example, to determine low limits of acceptability for cylinder compression, it may be necessary to run tests in which the compression is progressively reduced (perhaps by negative valve lash), and both compression and vehicle performance are tested, until performance is judged unsatisfactory. If the limit is set too tight, vehicles will be taken out of service unnecessarily; if the limit is too loose, failure incidence will be raised.

Multiple-parameter limit comparison is also a useful approach. For example, in a two-shaft turbine engine, there will be a predictable normal relationship between fuel flow and engine speed. If the test system determines that this normal relationship fails to exist, it will give a fault indication. In this case, the logic is a little more involved but not difficult. The problem of setting limits remains the same. Gas-path analysis can be considered a form of multiple-parameter limit comparison--in this case, a more involved form requiring considerable effort in development. However, to a large extent, the data base for gas-path analysis can be derived analytically.

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* In Army jargon, serviceable is taken to mean that the vehicle can perform its intended function.

Limit comparison can identify the existence of a fault, but cannot always isolate the specific fault. A single set of limit-comparison tests (i.e., taken in one test session) will generally not produce prognostic information.

## Truth-Table Diagnostic Logic

We can assert the following:

> If (a) the power output of a particular SI-engine cylinder is low, (b) the compression of that cylinder is normal, and (c) the ignition-coil voltage is normal, then (d) the spark plug or lead wire is defective.

Presuming this statement is true, and if we have a test system that makes pass/fail tests on cylinder compression, cylinder power, and coil voltage, we can then program the diagnostic system to test this statement. This is a powerful diagnostic technique, and one that can be automated readily. A complete diagnostic routine would operate on a sequence of such statements, i.e., a truth table. Most of the diagnostic logic used in current systems is of this type.

The truth-table technique is not generally prognostic.

## Trend Analysis

Trend analysis is accomplished by storing test-parameter values over a period of time (i.e., a number of tests at time intervals), extrapolating the parameters over some time period and making pass/fail judgments on the extrapolated value. The test-data storage can be accomplished by retaining prior test values either in the test system memory or by magnetic tape, for example. This technique is diagnostic in the sense that a sudden shift in the value of a test parameter is a signal of the possible occurrence of a fault. It is obviously prognostic in that it can indicate the possible future occurrence of a fault.

Trend analysis is a powerful technique that is well adapted to automated systems; however, it has some potential pitfalls.

To be accurate, trend analysis requires failure model, that is, the knowledge of how a parameter will change in time, typically, in moving from within to outside acceptable limits. If the rate of change is constant, then extrapolation by means of a linear regression analysis is probably appropriate. Some parameters will remain essentially constant for an extended period, but change rapidly once an incipient fault is present. In this case, a different form of extrapolation is obviously necessary.

In general, a data base from which failure models can be formulated is necessary if trend analysis is to be used effectively. A variety of time-series forecasting methods is available, and it is probable that one can either be selected or devised that will fit any given failure model.

Another problem with trend analysis is that it becomes difficult to use in a changing environment. Assume, for example, that a vehicle is used in a very dusty environment and that some loss of compression progressively occurs as the result of abrasive cylinder wear. Trend analysis might predict "failure" in a relatively short time. If, however, the vehicle is moved to a different environment, the progressive compression loss may cease or revert to a much lower rate of change. In such a case, human judgment might be used to ignore such an impending failure warning.

In spite of these potential difficulties, trend analysis is judged to be a valuable diagnostic/prognostic technique.

## Dynamic Signature Analysis

Signature analysis as a means of diagnosis is the equivalent of "listening" for a fault, although the signature of a fault can be in forms other than sound. The following are some types of possible signatures emitted by faults in a vehicle powertrain:

- Sound
- Pressure
- Vibration

- Exhaust composition
- Gas flow rate
- Wear debris
- Temperature patterns
- Speed variation
- Electrical waveforms
- Electrostatic charge
- Electromagnetic radiation.

Many faults (principally mechanical) will have an acoustic or vibration signature that can be "heard"--this is the technique by which the experienced mechanic, according to popular folklore, puts a screwdriver to his temple and the other end to the engine and isolates engine faults on the basis of what he hears. The sound or vibration is generally assumed to be periodic, but it may be aperiodic or have aperiodic components. The general problem with this type of signature analysis is that the pertinent acoustic information is "buried" in extraneous sound (or vibration). The human ear/brain combination has an amazing power to extract this type of information. For example, we can identify the sound of a single (solo) instrument playing in a symphony orchestra, identify individuals by their voice in a crowded room, or hear the sound of a bad water-pump bearing over the roar of an engine.

To date, this signature-analysis capability has been difficult to automate for engine diagnosis. There have been two basic approaches to this problem. One is to examine signals in the time domain, in which case frequency components of the signal are not identified. The other is to convert a signature to the frequency domain, as by a Fourier transform, in which case the syntax of the signal is lost. Of course, some combination of these approaches can be used.

One approach to developing an automated signature-analysis capability is to "seed" the engine with a selected fault and then to devise a pattern-recognition scheme by which the abnormal signature can be discriminated from the normal signature.

Pavlidis and Fang(23) of Princeton University, with support from Frankford Arsenal, experimented with signature analysis on four 12-cylinder tank engines before and after repair. The data sources were digitized taped signals from accelerometers mounted on the engines--about 1,200 points per record at 16,000 points per sec, all with the engine at 1,600 rpm. Faults in the engines were intake manifold, connecting rod, valves, and rings. Pavlidis' basic scheme was to compute average power (amplitude) in a sequence of time zones or "windows" over one engine cycle, and by locations of peak amplitudes within time windows discriminate between the faulty engines and repaired engines, with no prior consideration of the type of fault existing within the engine. Of course, this in itself is not equivalent to a diagnostic capability--it showed that one could discriminate between a faulcy and normal engine, but not that one could identify a fault on the basis of the difference. However, it did show that this method of signal processing could possibly be used as diagnostic signature-analysis technique.

In general, purely empirical signature analysis techniques have proven to be difficult to develop, for two reasons. One is that, because of typically high signal-to-noise ratios, it is often necessary to look for small differences. Secondly, a large data base must be developed on which to base the diagnostic routine. If a prognostic capability is desired, another dimension is added to the needed data base.

At present, chances for success are greater for signature-analysis techniques in which there is an analytical basis for detecting fault signatures. One such technique has been defined by Burchill, Frarey, and Wilson(24) of Shaker Research Corporation. If a component such as a ball bearing has a fault, such as a pit on one of the bearing races, there will be an impact caused at predictable (ball passing rate) frequency. This impact will in turn cause a shock-excited vibration in that region of the structure at some resonant frequency. By tuning into that (resonant) frequency component of the output of an accelerometer mounted on the structure and demodulating the signal, the signature of such a fault (pitted bearing race) can be detected. This technique can be automated.

RCA(25) has developed a signature-analysis technique that will detect certain engine faults on the basis of the signal from a microphone placed at the vehicle tailpipe exit. The system hardware tracks the cylinder firing frequency and computes the ratio of the exhaust-pressure amplitude at the third subharmonic to the amplitude of the fundamental. If there are combustion faults, as due to a valve leak or defective fuel injector, this ratio will be high; if combustion is normal, this ratio will be low.

This technique has a good analytical basis: if all combustion-pressure pulses are alike, there will ideally be no subharmonics; if they are different, subharmonics will be generated. Accordingly, a large data base should not be needed for implementation of this approach.

Present equipment employs a limited amount of signature analysis as a means of fault diagnosis. Dynamic starter-current variations and engine-speed variations have been used to determine parameters such as individual cylinder compression and power contribution, starter-circuit condition, and overall engine power. Table 13 lists a variety of possible diagnostic signature-analysis techniques for engine maintenance, some of which are proven and some of which are not.

Dynamic signature-analysis techniques have two distinct and powerful advantages. One is that many fault signatures are accessible by this approach that are not detectable by limit-comparison, truth-table, or trend-analysis techniques. Second is the ability to extract large amounts of useful information by a single input channel. For example, a single accelerometer mounted on the engine block has, ideally, the capability to diagnose any internal engine fault generating an auditory signal. Considering the present early stage of development of signature-analysis techniques and the potential power of the technique, a substantial basic research effort in this area appears justified.

## Exhaust-Emissions Analysis

Exhaust emissions are a form of engine signature, and because of the typically slow time response of gas-analysis instruments, a quasisteady-state approach to emission analysis must be taken. The effect of engine

TABLE 13. SIGNATURE-ANALYSIS TECHNIQUES APPLICABLE TO AUTOMOTIVE-ENGINE DIAGNOSTIC/PROGNOSTIC TEST EQUIPMENT

| Sensor | Fault Application | Technique | Present Status |
|---|---|---|---|
| 1. Speed pickup (flywheel housing or tach drive) | a. Cylinder compression | Speed variation during cranking | Proven |
| | b. Cylinder power contribution | Speed variation during snap acceleration | Proven |
| | c. Cylinder power contribution | Speed variation with engine under load (on-board system) | No information |
| | d. Engine power | Time of snap acceleration and deceleration | Proven |
| 2. Accelerometer pickup on cylinder head | a. Combustion intensity (misfire) | HF signal analysis: intensity at acoustic resonant frequency of combustion chamber | Proven |
| | b. Valve timing and adjustment | Timing and amplitude of vibration signal | |
| 3. Accelerometer pickup on cylinder block | a. Wrist pin, connecting-rod bearings, main bearings, bent connecting rod, ring/cylinder-wall damage | Various | Experimental |
| 4. Accelerometer on transmission | Impeller, gears, bearings, clutches | Various | Experimental |
| 5. Accelerometer on gear box housing | Bearings gears | Various | Experimental |
| 6. Pressure transducer at tailpipe | Combustion intensity (misfire) exhaust valve condition and adjustment | Amplitude of subharmonics | Experimental |
| 7. Pressure transducer in intake manifold | Intake valve adjustment | No information | No information |

TABLE 13. (Continued)

| Sensor | Fault Application | Technique | Present Status |
|---|---|---|---|
| 8. Pressure transducer in crankcase | Blowby | No information | No information |
| 9. Pressure transducer in fuel-injection pump (diesel) | Nozzle defects pump defects, leaks, injection timing | Various | Proven |
| 10. Pressure transducer in engine oil system | Bearings, filters | No information | No information |
| 11. Pressure transducer in automatic transmission high-pressure line | Various | No information | Experimental |
| 12. Pressure transducer in engine cylinder | Combustion intensity, valves, compression | No information | No information |
| 13. Primary ignition current, secondary voltage | SI ignition-system components | Peak comparisons, miss counting | Proven |
| 14. Starter current probe | a. Starting circuit resistance | Amplitude of initial spike | Proven |
|  | b. Cylinder compression | Current peak comparison | Proven |
| 15. Battery current and voltage probes | a. Battery condition | Voltage change during initial discharge period | Proven |
|  |  | Voltage during cranking | Proven |
|  | b. Charging circuit | Initial current after battery discharge period | Proven |
| 16. Exhaust emissions: HC, CO, $NO_x$ | Carburetion, ignition timing, injection timing, injectors, exhaust valves | Various | Experimental |
| 17. Electrostatic probe in engine exhaust | Uncertain | Not established | Experimental |
| 18. RF pickup | Ignition system | No information | Experimental |

faults on emissions has been of interest from the standpoint of air-quality control, and the resulting data base is potentially useful for the development of diagnostic systems based on exhaust emissions analysis. Some relationships between engine faults and emissions are shown in Table 14. The faults amenable to detection by emissions analysis are related to ignition and fuel systems and exhaust valves. To our knowledge, no one has developed an automated system of this type. Chances for technical success in diagnosing a limited number of faults appear reasonable. Such a system would probably not have a prognostic capability.

In addition to the exhaust-gas constituents listed in Table 14, electrostatic properties of exhaust gas could possibly yield diagnostic information. Wright-Patterson AFB has conducted a study(26) of this phenomenon with some positive results.

## Wear-Debris Analysis (Oil Monitoring)

Wear debris is another fault signature; it yields both diagnostic and prognostic information. Oil analysis has been used for some time in many applications including aircraft turbine engines and diesel highway truck engines. In general, the technique has been found to be effective. To our knowledge, oil monitoring has not been automated to the point where it could be used as a feature of automatic test equipment. Considering the potential usefulness of automated oil monitoring, this area probably deserves some research effort.

Oil analysis is carried out by examining the chemical composition and/or the physical nature of particulate mattter in an oil sample, and comparing the results with previous results. As such, it is a form of trend analysis as well as signature analysis. As such, it requires failure models for accurate interpretation of results. Any change is a warning signal; a large increase in debris is a trouble signal. In many cases, the chemical or physical properties of the particles can be used to suggest the particular faults involved. However, distinguishing between a benign change and a change indicating a serious problem can sometimes be difficult. Long experience, i.e., a good data base, appears to be important in this regard.

## TABLE 14. EFFECT OF ENGINE FAULTS ON EXHAUST EMISSIONS

| Fault | HC | CO | $NO_x$ | Smoke | Temperature |
|---|---|---|---|---|---|
| Spark Ignition | | | | | |
| Missing plug | + | 0 | - | 0 | - |
| Advanced timing | + | + | + | 0 | ± |
| Retarded timing | - | - | - | 0 | ± |
| Rich mixture | + | + | - | + | - |
| Moderately lean mixture | - | - | ± | 0 | ± |
| Very lean mixture | + | 0 | - | 0 | - |
| Burned exhaust valve | + | + | 0 | + | + |
| Diesel | | | | | |
| Fouled injector | + | + | - | + | - |
| Burned exhaust valve | + | + | - | + | + |
| Overfueling | + | + | + | + | + |

Note:

+ = increase

- = decrease

0 = no significant change

± = may increase or decrease.

## Failure-Agent Monitoring

Failure-agent monitoring is a basic technique for failure prognosis. It involves monitoring in some manner a failure-inducing agent and relating the sensed parameter(s) to damage or amount of component lifetime. Thus, it is not the physical damage that is sensed, but rather the presence of the agent inducing the damage. Possible agents are mechanical strain, temperature, dirt, corrosive environment, or vibration.

One such technique that has been studied extensively is relating cyclic strain measurements to cumulative fatigue damage. Computational procedures have been worked out so that this approach can be automated(27).

Another example is a "salt sniffer" developed by Baird-Atomic(28) which continuously monitors sodium levels in the fuel and intake air of gas-turbine engines. Sodium is a corrosive agent to high-temperature turbine components.

A possible technique is continuously monitoring entrained particulate matter in the engine air intake and relating it to cylinder wear (reciprocating engine) or blade erosion (turbine engine). With this approach, or any other failure-agent monitoring technique, a failure model is necessary that relates the agent to the damage. It is probable that a battery life model could be developed that would relate state of charge and charge/discharge cycles to battery life expectancy and which could be automated readily.

Basic research studies in this area appear to be needed.

## Machine Intelligence

In this context, an intelligent machine can be thought of as one which has the capability to develop and improve its function according to its successes and failures in making relevant and correct diagnostic/prognostic fault identifications. A machine which is programmed to devise algorithms for fault detection, and which receives accurate feedback from the failure and/or repair process, could possibly have this capability.

With present hardware technology, and assuming such a program could be devised, it would probably require a large main-frame computer for execution. Accordingly, it would not appear to be a possibility for an on-board or maintenance-shop equipment item. Nevertheless, the concept deserves some consideration.

A system can be envisioned consisting of (1) data acquisition systems on-board each vehicle, (2) a diagnostic test set at each maintenance facility, and (3) a central intelligent computer to which all test sets are connected. During vehicle inspection/maintenance periods, the on-board information stored by the data systems is read out to the diagnostic test set which processes the information, prints out maintenance instructions, and also sends the data to the central system.

The central computer would have the job of periodically reprogramming the test-set terminals to (1) improve diagnostic techniques on the basis of increased failure-history data, and (2) tailor the diagnostic functions of the test set to the prevailing important failure modes.

Such a system would automatically alleviate our present problem of insufficient data on how vehicles fail.

An intelligent system is probably impractical to consider for first or second generations of automatic diagnostic test equipment, but it might be contemplated for a third generation--whenever that might be. Some blue-sky thinking on how this might be accomplished is possibly justified at present.

## Functional Options

As an aid to both system concept definition and evaluation of potential cost saving and improvement in vehicle operational readiness, it is instructive to consider the various functions that automatic test equipment could perform in or on a vehicle. Various options are described in the following paragraphs. The functions defined may be somewhat arbitrary, but they seem logical and workable. It may be possible to define other functions, but these seem to be the important ones.

## Operation Monitor

A general system concept for an operation monitor has already been defined at ARPA in the course of this study with the assistance of The RAND Corporation and Battelle. This concept has been called the Vehicle Monitor System (VMS) and two study contracts were awarded (RCA(29) and Rockwell International(30)) to define such a system. It is envisioned that this system will record and store on the vehicle three types of information for an extended period of time: vehicle and powertrain operating variables, parameters indicating engine condition, and maintenance actions. The first two categories of information will be collected automatically by sensors installed in the vehicle, while the third category must be input manually by maintenance personnel. Data capacity for a month's normal operation is considered a design objective.

As presently envisioned, the system need not have either a diagnostic capability or an on-board warning capability. Rather, its purpose is to collect engineering data which can be used to aid the design of both future vehicles and future maintenance systems. With a large data base collected by the VMS installed in selected fleets, it would be possible to formulate better duty-cycle data and qualification tests for powertrain and chassis design and testing. It would also be theoretically possible to relate both operating variables and maintenance history to engine condition, and to develop failure models for use in designing diagnostic/prognostic test equipment.

As such, the present VMS concept is primarily a research tool rather than a piece of maintenance equipment. However, such a system could well become a part of future maintenance systems.

## Abuse Warning

The idea of an abuse-warning system is to give an indication that the vehicle is or was being operated in a damaging mode, presumably one that exceeds certain design limits or represents an improper operating mode. The indication could be given to the driver at the time of the occurrence or later to maintenance personnel. The human-factors considerations connected with such a system concept appear to present some difficulties.

An abuse warning could be useful to a conscientious operator, possibly even compensating for lack of adequate operator training if such were the case. However, it can be imagined that irresponsible drivers could even have contests to see who can get the most red lights turned on in a given time.

Maintenance personnel could possibly use an abuse indication to help in the diagnosis of an engine appearing to be in poor condition. A record might also serve as a deterrent to abuse; this would also invite destruction of the system. Accordingly, it is not clear that an effective abuse-warning system can be defined.

## Service Requirement Indication

An example of this kind of system is the Teledyne Continental Motors Maintenance Indicator System (MIS) which was described earlier in this report. The function of this type of system is to indicate when service operations (nonrepair) should be performed. The potential benefits of this type of unit are twofold: (1) catastrophic failures due to lack of service can be avoided if the warnings are heeded, and (2) service checks need be made only on warning (probably requiring changes in maintenance policies and procedures). However, the validity of the service-only-on-warning concept is questionable because it would not serve to prevent situations in which immediate service would be required.

Such systems, by themselves, would not be expected to possess any diagnostic capability other than the one-to-one correspondence between indicator (light) and the indicated service requirements.

To be effective, a service requirement indicator system should, as a minimum, monitor those service requirements which, if not met, would lead to rapid or catastrophic failure such as engine cooling, lubrication, and air filtration. Beyond that, it would probably be important to keep the system simple and reliable. Frequent false indications would lead to mistrust of the system.

## Malfunction Warning

The purpose of a malfunction warning system would be to give an indication to the vehicle operator that a fault has occurred which jeopardizes the operational status of the vehicle in the future. As envisioned, the system need not identify that fault, but would serve as an indication that a repair is necessary in the immediate future. Go/No Go, described earlier in this report, incorporates a malfunction warning feature. The principal difference between the malfunction warning system and the health-monitoring system described in the following section is that the former serves the vehicle operator and gives automatic indication, while the latter serves the maintenance personnel and would probably give outputs only when interrogated.

Malfunctions to be searched for should probably be limited to those types that would lead to an inoperative vehicle in a time interval less than scheduled time between inspections. Of course, the utility of the malfunction warning is trivial in the case of those failures that immediately render the vehicle inoperative or which are otherwise immediately obvious to the vehicle operator.

## Health Monitoring

The functional options described above would logically be on-board systems; a health monitoring system could be located either on-board or off-board the vehicle.

The purpose of the health-monitoring system would be to determine whether the vehicle under test is in good operating condition or, alternatively, whether repair is necessary or advisable. Such systems need not be diagnostic to the extent that they isolate the existing fault; rather, the intent is to make a quick check with minimum effort. However, it would be highly desirable to have a prognostic capability that could detect the existence of impending faults as well as existing faults.

If a health-monitoring check gave an indication that a particular vehicle was in poor condition, the next step would be to submit the vehicle to a check by a fault-isolation system.

## Fault Isolation

The function of a fault-isolation system is obvious: if a vehicle is inoperative or suspected of having a fault, the system determines the needed repair actions. Thus, a diagnostic capability is essential.

Systems such as the Depot MAIDS, HTS Autosense, PRD IDEA, and ATE/ICE do provide fault isolation in the sense that they perform diagnostic logic on the basis of a number of measurements and identify a needed repair action.

## Repair Verification

The functions of a repair verification system are to (1) ascertain that the fault was properly diagnosed and indeed corrected, and (2) ascertain that no associated maintenance-induced faults have appeared.

Either a health-monitoring system or a fault-isolation system would have this capability.

## Damage Assessment

The function of a damage-assessment system would be, in the event of being disabled partially or fully by enemy action in a combat situation, to advise the vehicle operator of the repair action needed to restore the operational capability of the vehicle. Thus, a damage-assessment system would be an on-board fault-isolation system tailored to those powertrain faults likely to occur as a consequence of combat damage.

## Combined Systems

Obviously, it is possible to conceive systems that combine two or more of the functions discussed above. For example, an off-board system designed for fault isolation might also incorporate a health-monitoring capability. It is also possible to conceive of a system combining all the above functions--perhaps with part of the system on-board and part off-board.

## Significant Failure Modes

Unfortunately, there is no organized, current body of data on how automotive vehicles fail in the DoD fleet. Such information would be valuable for two purposes: (1) assessing the cost effectiveness of proposed automatic diagnostic test equipment, and (2) tailoring test equipment to the significant failure modes. The first of these purposes is the more important, in fact, test equipment tailored too closely to a particular powerplant's problems might lack versatility and be susceptible to rapid obsolescence unless the tailoring was all done in the software.

It is probable that DoD-vehicle powertrains fail in every way imaginable, and that it is more important to have the capability to detect critical faults than prevalent faults. One possible means to select the significant failure modes is to consider the factors which are essential to the capability of the vehicle to move. The following list is suggested:

- Kinematic integrity (ability of the engine and driveline to rotate and perform the intended mechanical motions)
- Compression
- Ignition (SI only)
- Cranking power
- Fuel supply and metering
- Cooling
- Lubrication
- Clean air
- Electric power generation
- Steering
- Braking.

A vehicle completely lacking any one of these factors either will not start, will not continue to run for long, or will not be usable. Accordingly, it would seem appropriate for automatic diagnostic test equipment to address those items on the list that are not readily diagnosed by other means.

If the engine or other powertrain components cannot be rotated, that condition becomes apparent quickly, although the cause may not be obvious, and perhaps cannot be determined without opening up the system. Steering problems are also readily apparent, and the faults may yield quickly to a visual inspection. The remaining items in the list appear to be good candidates for automatic diagnostic test. For the present, serviceability criteria appear to be a reasonable basis for the design of automatic diagnostic test equipment.

Consideration of prevalent abuse modes may also be instructive. Following is a list of the more serious types of abuses compiled at TARADCOM.

- Engine overspeed
- Reverse battery polarity
- Operation with low fluid levels
- Operation at overtemperature condition
- Operation with clogged or missing filters
- Contaminated fuel (water)
- Overloaded vehicle
- Driving too fast over rough terrain
- Hotrodding
- Operation with parking brake on
- Overfueling
- Improper adjustments
- Engine lugging
- Shifting without clutch.

These are not necessarily in order of importance, although the first four can lead to catastrophic secondary failures. Test equipment that performs a monitoring function as part of its diagnostic function could be designed to detect some of these abuses.

## Impact of Developments in Electronic-Component Technology

Development of high-density microprocessor chips and their use in microcomputers has vastly increased the flexibility, speed, accuracy, and the economy of instrumentation and control systems. Although a minimum workable microcomputer requires only a microprocessor and some form of input/output device, a wide variety of peripheral equipment has been and is being developed to increase microcomputer versatility. This equipment includes both magnetic and solid-state memories, A/D and D/A converters, multiplexers, modems, keyboards, card and tape readers, displays, and printers. Particular emphasis is being placed on reduction of size, cost, and power consumption of peripheral equipment.

The circuit-board sizes of available complete microcomputers (without input/output equipment) range from about 2 x 2 to 15 x 21 in., with some computer systems being comprised of as many as 10 boards. Terminals are available with a keyboard and an LED display that are small enough to be hand-held. Miniature tape cassettes measuring about 2 x 1.3 x 0.3 in. to be used with small drive units are available as an input for microcomputers. Also desktop CRT terminals and small printers are available. Both floppy disc and hard disc memories are commercially available in small sizes to provide high-density memory at a reasonable cost.

### Microprocessors

The microprocessor was developed as a solution to a problem of standardization of electronics for calculators. It is a general-purpose, large-scale integrated (LSI) circuit whose function is determined by programming. Since the function of the microprocessor is programmable from memory, it is a versatile, complex, integrated logic circuit that can perform a multitude of electronic functions.

With the addition of some form of input/output device the microprocessor becomes a workable microcomputer. In essence, then, the microcomputer is a system comprised of one to about four LSI chips which can be used together with some memory and interface circuitry to form a stand-alone controller or which can be combined with more memory, a power supply, and other miscellaneous circuitry to form a complete general-purpose computer known as a microcomputer. In contrast, the minicomputer is comprised of several integrated circuits and discrete components to form hard wired logic circuits. The minicomputer normally has a larger memory capacity than the microcomputer and is of larger overall physical size and higher cost.

The driving force behind the development of the microprocessor was the need to develop a broadly useful type of complex integrated circuit whose particular function could be determined after fabrication by programs which the logic block could execute. This concept eliminates the need for the design of custom circuits for specific applications and permits a high enough volume of production of the general-purpose microprocessor to make it cost effective. Development of the microprocessor was based on improvements of existing technology to permit a higher density of logic gates on the semiconductor chip. Microprocessor chip density has been increased by a factor of 8 in less than 10 years and improvement at a similar rate is expected until 1980. It is expected that a density of 100,000 gates/chip ultimately will be achieved.

Microprocessors can be classified by both the technology they use and by their word lengths. Most microprocessors use MOS technology to achieve minimum size and power consumption while a few are bipolar where speed is more important than size and power requirements. The first microprocessors used 4-bit words, but now most are 8-bit machines with a few 12-bit designs and a growing list of 16-bit architectures. At present, there is only one bipolar microprocessor with a word length longer than 4 bits. The Scientific Micro Systems 300 is an 8-bit processor. With this one exception, bipolar microprocessors are implemented with bit-slice architectures, either 2- or 4-bit. To build, for example, a 16-bit computer one could use four 4-bit slices, a slice being a set of chips to handle operation on only part of a data word. A microprogram stored in a read-only memory (ROM) controls the movement of information between slices and thus defines the architecture of the machine. Minicomputers are now being implemented using bipolar bit-slice chip sets and so the distinction between microcomputers and minicomputers is becoming fuzzy. Another example of the blurring of the line between these two classes of computer is the Data General mN601 16-bit NMOS one-chip microprocessor. This device has the same architecture and uses the same instruction set as the company's NOVA minicomputers. It can be used as a powerful programmable controller or the heart of a one-board microcomputer or a multiboard minicomputer.

The semiconductor technologies for digital electronics fall into four basic types: (1) bipolar, (2) NMOS (N-Channel Metal Oxide Semiconductor), (3) CMOS (Complementary Metal Oxide Semiconductor), and (4) PMOS (P-Channel Metal Oxide Semiconductor). Devices built around the bipolar technology operate at higher speeds but cost more and consume more power than those of other technologies. NMOS technology provides devices that function more reliably and compare favorably in price with PMOS. CMOS is still a relatively new technology and is used by only two suppliers of microprocessors at the present time.

Recent advancements in semiconductor technology and circuit configuration have resulted in techniques that are permitting increased density in bipolar devices and higher speed operation of MOS devices. In the case of the bipolar devices, technology has been developed to decrease the area required by a transistor through use of insulators instead of P-N junctions in the isolation structure. Also, a circuit approach, $I^2L$ (integrated injection logic), aims toward the complete elimination of the necessity of device isolation and permits bipolar circuit densities comparable to those achieved in MOS devices. However, the advantages in density have been gained at the expense of reduced speed, elimination of series gating and the use of transmission gates, and increased production cost. In the case of MOS devices, techniques have been developed to minimize capacitances and reduce source-drain spacings that result in higher switching speeds. It should be noted that the approaches used to increase the MOS device switching speed have resulted in a reduction of achievable density and in some cases the versatility of the device.

At the present time it appears that neither the MOS or bipolar approach has any major advantage for use in microprocessors. Each new technological feature added to either device type will result in some tradeoff so that it is unlikely that either MOS or bipolar devices will be improved to the point where either will offer a dramatic advantage over the other in microprocessors in the foreseeable future.

Since the first integrated circuits became available in the early 1960's, and the subsequent acceptance by electronic designers of standard integrated-circuit families, there has been a continuing trend toward more complex integrated functions and lower cost devices. In most cases, because the functions that could be performed by the complex circuits were limited, the market for the existing circuits was also limited so that the cost advantage that might be gained by higher volume production was not realized. Now with the microprocessor on the scene, the possibility exists for producing fewer standard logic blocks with a resulting increased market and reduced cost because of the high volume production. In the past few years the maximum practically achievable number of gates per single chip has increased dramatically while the price of maximum complexity integrated circuits has remained roughly constant. Improvements in technology have resulted in increased speed and capacity of large-scale integrated circuits with a cost of $10 or less at the factory. Although gate propagation delays near the fundamental limits (a few tenths of a nanosecond) of silicon technology have been achieved, it is unlikely that such speeds can be achieved in microprocessor chips because heat removal is difficult. Gate densities, propagation delays, and the speed-power products for the technologies used in current microprocessors are shown in Table 15.

TABLE 15. DENSITY, SPEED, AND POWER CHARACTERISTICS OF MICROPROCESSOR TECHNOLOGIES

| Technology | Density, gates/mm$^2$ | Gate Propagation Delay, ns | Speed-Power Product, pJ |
|---|---|---|---|
| CMOS | 30 to 40 | 10.0 | 5 |
| CMOS/SOS | 80 to 120 | 3.0 | 3 |
| NMOS | 80 to 120 | 20.0 | 5 |
| PMOS | 50 to 90 | 50.0 | 145 |
| Schottky bipolar | 30 to 40 | 2.0 | 5 |
| ECL bipolar | 30 to 40 | 0.5 | 5 |
| $I^2L$ bipolar | 100 to 200 | 10.0 | 5 |

It is expected that future LSI circuits may have a minimum power-speed product as low as 1 pJ with a gate propagation speed of 1 ns which will result in single-gate power dissipation of 1 mW. Since a maximum of about 3W can be dissipated into air by an IC package, a maximum of about 3000 logic gates could be incorporated into a single circuit without special design for cooling. This level of complexity was about three times the state of the art at the end of 1975 and would be adequate for a 16-bit central processing unit (CPU) capable of executing about 10 million instructions per second. Lower speed devices could be produced with even greater capacity.

The prime motivation for increased LSI circuit complexity is the achievement of lower cost per function and improved reliability. The reliability of LSI circuits depends upon the design, process, interconnections and packaging. Mean time between failures of about 10 million hours per packaged chip can be obtained without undue difficulty, and 100 million hours is said to be possible by exercising special precautions. If adequate screening and burn-in procedures are followed, failure rates of between 0.001 and 0.01 percent per 1000 hours are expected in a laboratory or computer environment while failure rates ranging between 0.010 to 0.10 percent per 1000 hours may be expected in severe environments.

## Electronic and Electromechanical Memories

There have been dramatic advances in memory and storage technology suitable for microcomputer use over the past 10 years. The rapid rise of the popularity of mini and microcomputers has opened new market areas for memories which has resulted in further acceleration of memory development. Since most microprocessors are utilized in dedicated applications, a majority of the memory used is ROM (Read-Only-Memory) or PROM (Programmable Read-only Memory). In microcomputer applications there has been a decided broadening of memory markets to include floppy discs, tape cartridges, cassette storage elements, along with solid-state RAM (Random Access Memory), and core memory.

Semiconductor RAM memory costs have declined steadily over the past 10 years to the point where the OEM (Original Equipment Manufacturer) cost per bit in a 16K-bit chip with a 500 ns cycle time is about 0.12 cent in 1976. It is expected that by 1979, devices with a 64K-bit capacity will be available in 18-pin in-line packages (1.0 x 2.5 cm) at an OEM price of about 0.04 cent per bit. It is predicted that read-only memory chips will be developed with about twice the density of the read/write chips. The MTBF of these devices is expected to be $10^7$ to $10^8$ hours. If the cycle time of these types of memories is reduced by a factor of 10 (to 50 ns), their cost is likely to increase by a factor of 2 to 5, and their operating power will be increased substantially over the slower devices.

Although core memories are still used in a few microcomputers, it is likely that their use will be abandoned as semiconductor technology advances, primarily because of the cost advantage of the semiconductor memory (less than one-half the per bit cost). The major, if not the only, advantage core memories offer over semiconductor memories is their nonvolatility. Core memories typically have access times of between 500 and 1000 ns with a great cost penalty being paid for access times less than 500 ns.

New storage devices such as the floppy disc, tape cassette, and small tape cartridge can provide a mechanism for low-cost storage where fast access and cycle times are not required. The average access time for a floppy disc system is about 200 ns with a price per bit ranging between 0.01 and 0.08 cent. The tape cassette system provides a compact storage mechanism where its average access time of about 120 s can be tolerated. The price per bit for tape cassette storage systems is comparable to that of the floppy disc system. The tape cartridge system has an average access time of about 15 s with a price per bit for storage of about 0.0035 cent. It is likely that these types of storage systems will be improved in the future if high-volume usage develops. The major problem with these electromechanical storage systems will likely be reliability.

Two relatively new technologies are evolving that will fill the access time gap between the electromechanical and semiconductor and core storage systems and provide nonvolatile memories. These are the magnetic bubble and charge-coupled device (CCD) memories. Both of these systems are electronic serial memories. Although no bubble chips are offered for sale, availability of 64K-bit chips have been projected at 0.05 cent per bit in the near future. CCD chips are available in 9- and 16K-bit configurations. The average access time to any bit for a 16-bit chip is less than 100 μs at the maximum serial data rate of 2 megabits per second. Chip price for these devices, in large quantities, is under 0.1 cent per bit. Overall densities for the CCD device are quite likely to exceed those of the RAM by a factor of 3 to 10. Both the bubble and CCD systems may become competitive with the floppy disc and also may find use where low cost is mandatory and comparatively low performance characteristics are adequate.

It appears unlikely that either the bubble or CCD memory will become competitive on a cost basis with MOS RAM but they may be developed to a point where their speed and reliability will result in their use in special applications or as a substitute for tape or disc systems. Their small size makes both of these memory systems attractive for use as peripheral memory for microcomputers.

There are many factors that are considered in choosing a memory for a computer. These factors include price, access time, power requirement, memory density, nonvolatility, volume, and possibly others. A comparison of some of these factors for various memory systems that will be used in microcomputers is shown in Table 16.

It may be noted from Table 16 that the semiconductor RAM's are volatile memory systems while the magnetic core and serial access systems are not. The volatility of the semiconductor RAM's is a problem, but it has been solved through the use of battery back-up power to supply refresh power to the memories. In fact, such an emergency power back-up system is less costly for semiconductor systems than for core systems because of the lower power requirements of the semiconductor devices.

In looking at the changes occurring in memory technologies, it appears that evolutionary improvements are possible in almost all of them. These improvements are likely to result in higher densities and speeds and lower costs. The technologies least likely to exhibit any dramatic improvement are tape cassettes and cartridges because the technologies are relatively mature.

TABLE 16. MEMORY SYSTEM CHARACTERISTICS

| Memory Type | Cost, cents/bit | Approximate Access Time, µs | Speed-Power Product, pJ | Memory Density, bits/in.$^2$ | Volatility | MTBF, hr |
|---|---|---|---|---|---|---|
| Core | 0.063 | 1.0 | 370 | $6.5 \times 10^3$ | Nonvolatile | 10,000[(a)] |
| Bipolar | 2.5 | 0.1 | 5 | $1.24 \times 10^5$ | Volatile | 180,000[(a)] |
| MOS | 0.25 | 1.0 | 5 | $7.5 \times 10^4$ | Volatile | 180,000[(a)] |
| CCD | 0.126 | <100 | 10 | $1.25 \times 10^5$ | Nonvolatile | -- |
| Magnetic bubble | 0.25 | 2500 | -- | $10^6$ | Nonvolatile | -- |
| Floppy disc | 0.1 | 0.5 s | -- | $2 \times 10^6$ | Nonvolatile | 5,000 |
| Tape cassette | 0.04 | 120 s | -- | $1.0 \times 10^4$ | Nonvolatile | 2,000 - 4,000 |
| Tape cartridge | 0.0035 | 14 s | -- | $1.3 \times 10^4$ | Nonvolatile | -- |

(a) MTBF for 16K-word x 16-bit array.

It is expected that MOS RAM memory devices with a 64K-bit capacity will be available by 1985 at a component manufacturing cost of about 0.01 cent per bit and a complete memory system price of about 0.04 cent per bit for devices with cycle times on the order of 500 ns. Higher speed semiconductor devices will be available but at a cost 2 to 5 times per bit higher than that of the 500 ns devices.

Predictions indicate that CCD memories in 128K-bit chips with 5-MHz shift rates and a 1000-bit length register will be available by 1980. It is likely that the average access time for such devices will be about 0.1 ms, and the per bit OEM price will be about 0.05 cent.

Bubble memories should be available in 128K-bit PBF (Permalloy Bar File) by 1980. The chip size for such a memory will be about 3 mils square. The per bit OEM price for the bubble memory is expected to be about 0.05 cent per bit. Access times approaching 2 ms appear achievable.

Another memory technology under development that is worthy of consideration is the EBAM (Electron-Beam-Accessed Memory). This memory is comprised of an MOS chip memory plane which is the target for an electron beam. The developmental device is in the form of a CRT measuring about 17 in. long by 4 in. in diameter. It stores 32M-bits with an access time of about 30 μs. Data may be transferred by this device at a rate of 10M bits per second. It is expected that the EBAM will be commercially available by 1980 with a per bit OEM price of about 0.02 cent per bit. Projections indicate that this storage device shows promise of reaching a capacity of $10^9$ bits with an OEM price of a few millicents per bit.

It is possible that floppy disc memory systems may be improved to the point where their price per bit may reach the 0.01 cent per level if high-volume usage develops. Access times of about 0.1 s are achievable in the near future.

It is unlikely that any major advances will be made with small magnetic-tape storage mechanisms in the near future. Some improvement may be made in tape materials and head spacings to permit some increase in storage capacity. Also, some price reduction in the better tape materials could result in a small decrease in the per bit storage costs.

It is unlikely that the physical sizes of the various memory devices will decrease by any great amount in the near future. Semiconductor memories will be packaged in much the same manner as they are now. The drive mechanisms used with electromechanical storage systems have just about reached their minimum size limit for the available storage media so that further significant size reductions of these types of memory systems are unlikely. The most likely physical size reduction of memory in a total microcomputer system will occur with the substitution of CCD or magnetic bubble systems for tape cassette and floppy disc systems.

## Input/Output and Data Conversion

The decreasing cost of micro- and minicomputers is motivating manufacturers of peripheral equipment to continue to lower their prices too. There is a wide variety of small, relatively inexpensive printers, CRT terminals, keyboards, displays, paper tape, and care I/O equipment available in addition to the full-scale equipment used with larger computers. Advances in semiconductor technology are providing signal processing and control equipment of smaller size and lower cost that are useful with microprocessor-based automatic test equipment. This equipment includes modems, multiplexers, analog-to-digital converters, digital-to-analog converters, and voltage-to-frequency converters.

## Input/Output Equipment

Although various microcomputers provide I/O interfaces for CRT and TTY terminals they are not discussed in this report because it is felt that their characteristics are common knowledge. It should suffice to say that these types of terminals have been and will continue to undergo constant improvement with some comparatively low cost units becoming available for use with microcomputers.

There is a wide variety of printers available for use with microcomputers. The trend in their development has been toward smaller and lower cost units. The lowest cost small printers are the 6 to 80-column matrix and 7-segment printers. Such a printer is available at a cost of about $140 and offers a speed of 138 lines per minute with 18 columns of full alphanumerics. Another type of printer that appears to be ideal for use with microcomputers is a unit that mounts like a panel meter and uses a 7-segment thermal print head. At the present time this printer sells for $475 and can print 6 columns of numerics with a few letters available but will be available soon with about 20 columns of printout. Some printers are incorporating microprocessors and memories to provide input buffering to store characters. One such printer prints 80 columns on 5-in.-wide paper at a rate of 2 lines per second. This printer is available at a cost of about $500.

Where hard copy is not required, the output unit can be in the form of any one of a number of visual displays such as LED (light emitting diodes), gas discharge, fluorescent, liquid crystals, or incandescent. These types of displays are available in a wide range of sizes and configurations and could be produced in almost any configuration desired. These displays most commonly use an array of 7 illuminated segments for numerics and a 5 x 7 or 7 x 9 dot matrix for more complex character displays such as alphanumerics and special symbols. Other display technologies that will likely find future application are light emitting film, electrophoretics, and electrochromics.

There is a wide variety of keyboards available that can be used as inputs for microcomputers. These boards are available in standard configurations or can be specified in custom designs at low cost. Because of their simplicity, it is unlikely that major advances will occur in keyboards in the near future.

In addition to the separate display and keyboard units, at least one hand-held small computer terminal is on the market currently. This terminal provides a full keyboard and two lines of 10 characters LED readout. It can display the full set of ASCII (American Standard Code for Information Interchange) characters in both upper and lower case. It is likely that additional similar small terminals will be developed with improvements in the future. Such terminals should be available at a cost of well under $1000 in the future.

Signal conversion for the microcomputer in engine test equipment will require the use of multiplexers, analog-to-digital converters, and possibly digital-to-analog converters. Several of these types of devices are commercially available in integrated-circuit packages.

Multiplexers are available in integrated circuits for both analog and digital applications. Digital multiplexers are readily available that will switch 16 lines input to 1 line output. Analog multiplexers are available to handle 8 channels of data. Either the analog or digital multiplexers can be used in combinations to provide switching for as many data channels as desired. The price of the 16-line to 1-line digital data multiplexer is about $10 and an 8-channel analog multiplexer sells for about $3. It is likely that these prices will decrease some in the future as semiconductor technology advances and if sufficient market develops for them.

During the past few years several high-performance analog/digital (ADC) and digital/analog converters (DAC) have been developed for use with computerized instrument systems. Within the past year monolithic devices for use with microcomputers have appeared on the market. Some of these devices incorporate multiplexing and sample and hold amplifiers. The multiplexing circuits permit either random or sequential data sampling. Eight-bit ADC's and DAC's are available in dual in-line packages at a price of from $15 to $20. It is likely that these devices will decrease in price with advancement in semiconductor technology and increased market demand. Also, it is reasonable to assume that the devices will become more complex and offer the designer more options in their application.

## Probable Impact of Microcomputers on Test Sets

The current price for microcomputers (less peripherals) ranges between about $295 for the simplest of systems to about $5000 for more complex units. Printed circuit board sizes for single board computers range from about 2 x 2 to 15 x 21 in. Multiple board units incorporate from 2 to 10 boards and their board sizes range from 3 x 4 to 15 x 21 in. The performance and capacities of the available microcomputer systems are as varied as their physical configurations. Data word sizes vary from 4 bits to 16 bits with instruction word sizes from 8 to 48 bits. Address capacities range from 1000 to 1 million words. Register add times range between 0.2 and 20 µs per data word. Remote access memory capacity normally ranges from 0 to 256K bits (with a maximum of 2M bits possible) with access times ranging between 81 and 1500 ns. Read-only memories normally range from 0 to 32K bits with some special optional units available with up to 1 million bits with access times ranging from 50 to 1800 ns. Programmable read-only memory capacities normally range from 0 to 16K bits with the maximum capacity going to 1 million with optional equipment. Access times for the PROM's range from 50 to 2300 ns. There is a wide range in the number of input and output ports with bit per port capacities ranging between 8 and 16 bits. Input/output rates vary between 110 and 256K bauds in the asynchronous mode and 2400 and 1M bauds in the synchronous mode.

This diversity in size, performance, and cost of microcomputers makes prognosis of changes for the future extremely difficult except for very general consideration of trends. It is expected that the general trend for increased complexity of large-scale integrated circuits will result in microcomputers with more functions incorporated within the microprocessor chip so that fewer IC packages will be required for a computer with given performance characteristics and capacity. The reduction in the number of IC packages will result in a corresponding reduction in physical size and a reduction in cost since the trend has been for the cost of complex IC's to remain constant while the complexity increases. Limiting factors on speed and capacity of the computers will be power dissipation and off-chip connection density that is limited by state of the art on maximum pin count for the LSI packages. With the advances that seem likely over the next few years it may be possible that a complete minicomputer including a 16-bit central processing unit, 32 K bits of ROM and/or read/write memory with simple I/O interfaces could be commercially available. The speed of such a device with serialized I/O could be in the range of 100,000 to 1M instructions per second and be produced at a manufacturing cost of $10 or less.

## Sensors

Diagnostic-system developers have found a variety of sensors available for detecting parameters such as pressure, temperature, speed, and vibration. In general, they have been able to find sensors that satisfy accuracy and durability requirements. However, these have been laboratory-instrumentation type devices which are produced in low quantities and sell at high cost. In fact, the cost of the sensors has been a significant part of the overall manufacturing cost of some automatic test equipment systems.

In the future, the cost of sensors for diagnostic equipment may be reduced dramatically as the consequence of present R&D efforts in the automobile industry. The automobile manufacturers are doing internal development work and are working with vendors on low-cost sensors for use in future on-board electronic systems for various functions, notably ignition-timing and fuel-metering control. It is likely that, by 1979-80, new low-cost sensors will be available for pressure, temperature, position, air flow, and oxygen. While cost objectives are considered proprietary information by developers, it is reasonable to expect that the sensors will have OEM prices in the range of $1 to $10.

Under these circumstances it would not be appropriate for ARPA to conduct sensor research for this application. Even in the absence of the current activity on sensor development in the automobile industry, it would probably not be reasonable for ARPA to conduct sensor research for this limited application because there are no really critical sensor needs that are inhibiting diagnostic-system development at present.

The fluid-flow sensor is a possible exception to the above statement. Air flow and fuel flow are seldom used at present in diagnostic systems because of the apparent lack of low-cost accurate sensors.

## Overall Impact

It seems clear that current developments in electronic-component and sensor technology will have the following impacts on future automatic test equipment:

- Greater complexity
- Reduced size
- Higher speed
- Greater reliability
- Lower cost.

The availability of larger, more complex computing devices will enable system capabilities to be expanded readily, and reduced size of electronic components will allow the size of electronics boxes to be shrunk somewhat, although further reductions in size may not be important. Higher speed will facilitate more elaborate diagnostic computation and possibly the sharing of microprocessors with other on-board control functions. Reliability will, of course, be important as complexity increases.

Possible cost impacts are difficult to quantify. Following is a possible cost scenario, based on the assumptions that by 1980, (1) sensor OEM costs are reduced by an order of magnitude, (2) microprocessor and memory OEM costs are halved, (3) the cost of A/D converters, multiplexers, amplifiers, and clocks are reduced by 25 percent, and (4) the cost of printers, keyboards, LED displays, tape readers, cables, and cabinet hardware remain unchanged (all assumptions based on constant dollars, of course). If it is further assumed that each of the above component groups comprises one-quarter of the cost of the system, we can compute that a given system hardware might cost in 1980 about 60 percent of the present cost. If we include a learning curve and some volume-production benefits, a 1980 hardware cost of about half of today's cost does not appear unreasonable.

However, the manufacturing cost of present automatic test equipment is perhaps two-thirds to three-quarters labor and about half of that is for quality control; accordingly, reduced hardware costs will not by themselves have a large impact on manufacturing costs. The more significant cost reductions are likely to result from design for reduced assembly labor content and the use of automated testing in high-volume production. While there is no firm basis for estimating how these costs will evolve, a 50 percent reduction in overall manufacturing costs by 1980 might be possible, and further reductions in the following years could be expected.

# RESEARCH OPPORTUNITIES

## Fault-Isolation Systems

There appears to be no incentive for ARPA to develop another first-generation version of a fault-isolation type of automatic diagnostic test system, which presumably would employ multiple sensors, automatic test sequencing and display of results, limit-comparison types of pass/fail tests, and waveform analysis or truth-table logic for fault isolation. Such an effort might only prove that there is a slightly better way to configure such a system.

First-generation systems have the undesirable characteristics of high equipment cost and requiring a large number of connections to be made with the vehicle. A second-generation system might avoid these characteristics and also incorporate a prognostic capability by employing signature-analysis, trend-analysis, and/or failure-agent monitoring techniques. However, this technology is not sufficiently advanced at present to justify system development. Fundamental research studies to develop and prove out signature-analysis techniques, and to collect a data base for the formulation of mathematical failure models are called for.

Conceptual studies could be conducted to explore the possibility of using automatic test equipment to automate maintenance record keeping, both at the organizational level and at some central repository.

## Operation Monitoring Systems

A vehicle operation monitor is potentially useful at present as a research tool for collecting data on vehicle operating modes and maintenance actions and their relationship to failure modes. This is the basis on which the ARPA Vehicle Monitor System (VMS) study is presently being conducted.

An on-board monitoring or data-taking system is also potentially useful as part of an automatic diagnostic test system, that is, it could record historical data which would provide useful information to a diagnostic/prognostic system during inspection/maintenance periods. For the present, it would appear that this technology is being explored adequately by the VMS study.

## Abuse Warning Systems

The VMS being developed will have the capability to monitor certain modes of abuse. To that extent, the technology for and feasibility of abuse monitoring systems is being studied.

It would also be possible to develop a small, unobtrusive abuse monitor that would involve only a few parameters. Following is a possible parameter list:

- Overtemperature
- Low oil pressure
- Overspeed
- Excessive or reverse-polarity voltage
- Excessive suspension shock.

Sensors are already in the vehicles for the first four parameters; only suspension shock would require an additional sensor: an accelerometer. The system could simply record incident counts; thus, a rudimentary recording system could be used. The stored data could be read out during inspection/maintenance periods, and the indication of an abusive incident could serve as justification for a health check or fault-isolation routine. It could also become a part of the maintenance record for possible use in a failure-model data base.

Of course, such a system could probably not be kept secret, and its presence might be objected to by some vehicle operators.

## Health-Monitoring Systems

An automatic health-monitoring system can be envisioned that would provide a rapid check of vehicle serviceability. The use of such a system might be substituted for periodic inspections; thus, there would be the possibility of cost saving, less vehicle time in the maintenance shop, and fewer maintenance-induced failures while at the same time maintaining a high level of vehicle serviceability. Vehicles identified as having some problem would be taken out of service and subjected to fault-isolation tests before repair action.

Some of the features of a possible system of this type are listed in Table 17. The system would automatically conduct health checks on compression, charging, ignition and/or fuel system, and the air filter with only three sensors: a speed pickup, a current sensor and a pressure sensor. To supplement the automatic features, the lubrication and cooling systems would be checked out by a quick visual/manual inspection. The hardware could be mounted on a wheeled stand, and a hard copy of the results would be desirable to provide a permanent inspection record.

If the vehicle had an abuse monitor, as described in the previous section, stored information could be read out automatically by the health monitoring system.

State-of-the-art technology is adequate to develop such a system; however, it may not be different enough from most existing types of systems to warrant demonstration by ARPA.

## Damage Assessment System

As previously discussed, a damage assessment system may be desirable for combat vehicles to provide information to the vehicle commander on the status of the vehicle in the event of damage. The following is a list of parameters that such a system might monitor and display:

- Oil level
- Coolant level (except air-cooled)
- Fuel pressure
- Transmission pressure
- Air supply (air-box pressure)
- Battery voltage.

TABLE 17. FEATURES OF PROPOSED HEALTH MONITORING TEST SYSTEM

| Functional Area | Type of Test | Sensor | Diagnostic Technique |
|---|---|---|---|
| Compression | Cranking, ignition or fuel defeated | Speed | Cranking speed peak-to-peak variation |
| Cranking | Cranking, ignition or fuel defeated | Starter current | Initial current peak |
| Charging | Steady speed | Alternator current | Charging rate after cranking |
| Ignition and/or fuel system | Snap acceleration | Speed | Individual cylinder power contribution by speed variation |
| Air filter | Steady speed or snap acceleration | Pressure | Limit comparison on $\Delta p$ across air filter |
| Lubrication | Steady speed | Vehicle oil pressure gauge | Visual |
| Cooling | Engine stopped | None | Manual fan belt tension and integrity check |
|  | Idle | None | Visual inspection for leaks, blockage |

This set of parameters addresses most of the serviceability criteria in a rudimentary way. If the vehicle is inoperative, it may or may not be useful to understand the problem. If the vehicle is operative, it would be useful to know whether there has been damage to the pwoertrain and whether trouble is impending. A basic problem with a damage assessment system would be the susceptibility of the system itself to damage, and the possibility of a resulting false indication.

## Other Functions

Service requirement warning systems and malfunction warning systems have been developed in the past, namely MIS and Go/No Go (described previously). No obvious opportunities for improving on these systems are apparent.

Repair verification is a potentially useful function for automatic diagnostic test equipment, but special equipment for this purpose does not appear to be needed in that health-monitoring or fault-isolation systems can perform this function.

## Gas-Turbine Diagnostic Systems

While most of this report is directed toward reciprocating-engine powerplants, there exists at the time of this writing a good possibility that the XM-1 tank will have a turbine engine. If this proves to be the case, the Army's automatic diagnostic test equipment would have to accommodate this new engine type. This can probably be done with a software change, provided the hardware can accommodate a different sensor complement.

The diagnostic techniques developed for aircraft turbine-engine monitoring would be useful in this case: principally gas-path analysis and vibration analysis. By monitoring parameters such as the following, a comprehensive check can be made on the thermodynamic performance and mechanical condition of the principal engine components:

- Compressor and turbine inlet and outlet temperatures
- Compressor and turbine inlet and outlet pressures
- Combustor outlet temperature profile
- Engine speed
- Fuel flow.

In addition, vibration level at the fundamental rotative frequency provides a good check on possible damage to rotary-component blading.

Since this technology is available for use with the turbine-powered tank, there appears to be no incentive for ARPA to conduct research in this area.

## Integrated Systems

It is worth noting that electronic microprocessors may in the future be used on automotive vehicles for functions other than diagnostic test. As this occurs, it may be possible to incorporate diagnostic functions into these systems. Of course, the converse could also happen, that is, diagnostic test systems could be programmed to take on other functions as well. If either happens, it will be a marriage of convenience, and it is not obvious that this possibility has any impact on the technology that must be developed for future test systems. It would probably effect a cost saving; otherwise, there would be little incentive to integrate these functions.

Surveillance of future developments in the field of automotive electronics by ARPA is probably justified; on the other hand, it can hardly be avoided by any group working on automatic diagnostic test equipment for automotive vehicles.

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# APPENDIX

## ORGANIZATIONS AND INDIVIDUALS CONTACTED

## APPENDIX

## ORGANIZATIONS AND INDIVIDUALS CONTACTED

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