SCALE MODEL PENETRATOR INSTRUMENTATION AND TESTING

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ABSTRACT

Sandia National Laboratories Telemetry Technology Development Division has designed and fielded earth and ice penetrator instrumentation recorders for many years. Recently we developed a miniature, reusable, transient-event recorder for use in scale model penetration tests. The miniature size of the recorder permits testing of penetrators as small as 4 inches in outside diameter by 20 inches in length. The recorder can survive and record shock environments exceeding 4,000 times the acceleration of gravity (gs). Typical applications are rock, soil, and ice penetration tests launched from a gas gun developed by Advanced Projects Division III. Typical impact velocities range from 600 to 1,000 feet per second.

SYSTEM DESCRIPTION

The recorder is battery powered, capable of recording six analog data channels, and uses semiconductor memory for data storage. A portable computer is used to read out and reduce the data, which can be done in the field after penetrator recovery. The power control circuitry in the recorder conserves battery life by removing operating power from all non-essential circuitry in the unit after the test event. A dedicated keep-alive battery supplies the ultra-low power memory circuitry. This provides the capability of quick turnaround testing and greatly reduces the cost of testing since a single battery module has enough capacity for ten or more tests. Figure 1. is a block diagram of the MP86 recorder as applied to penetration testing.

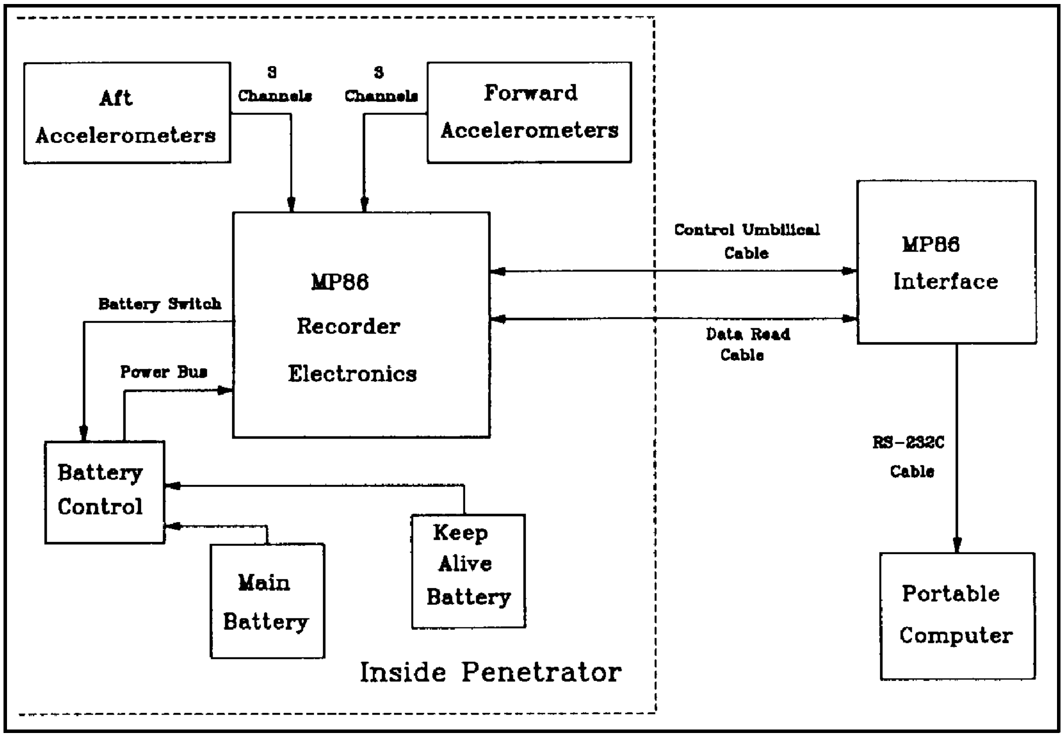

Figure 1. MP86 Gas Gun Test Configuration

MP86 RECORDER DESIGN

The Miniature Penetrator 1986, (MP86), instrumentation recorder consists of a high-speed digitizing circuit with eight analog inputs, which records a transient event into 32,768 bytes of static random access memory (SRAM). Six accelerometers and input signal conditioning, a battery power switching circuit, and batteries are also included in the recorder package. The data can be recovered after the event using a small interface box and a portable computer. Stringent power requirements in penetration testing have resulted in an ultra-low power design using Complementary Metal Oxide Semiconductor (CMOS) devices for digital logic and memory circuits. Using these low power devices and careful design consideration of the power-down sequence of the circuitry, the MP86 recorder can retain data for up to one year on a small keep-alive battery. Another power conserving feature of MP86 is an automatic power down circuit which switches power off of the analog and digitizing circuits immediately after data is loaded into memory. This feature allows the completion of up to 10 gas gun tests on a single battery pack. A block diagram of the recorder is shown in Figure 2 and specifications are provided in Table 1. Note, the “~” symbol on Figure 2 and elsewhere in the report indicates negative-true logic signals.

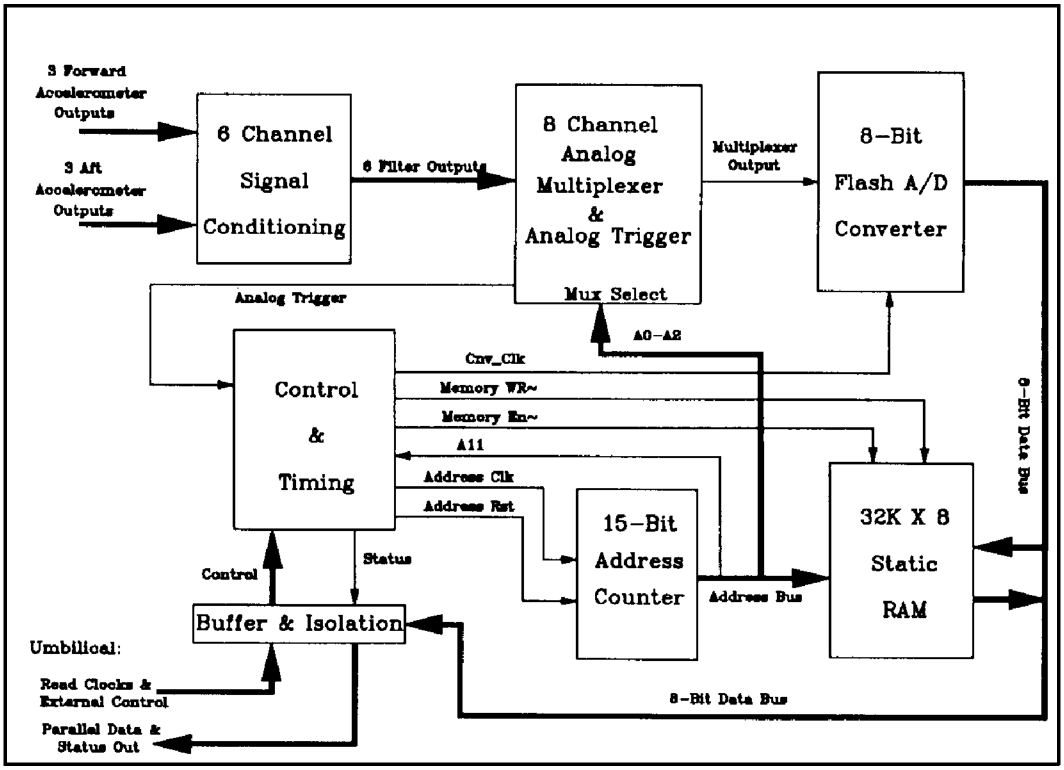

Figure 2. Block Diagram of the MP86 Data Recorder

DIGITIZER CONTROL & TIMING

The MP86 digitizer control and timing functions are generated by a simple state machine implemented in random logic. The state machine includes a sequencing circuit which generates memory, multiplexer, and conversion timing signals in response to four control inputs.

The Arm command starts the recorder into a free-running state, converting data and writing into memory, while waiting for a trigger event. The data conversion rate is typically set at its maximum rate of 200,000 samples per second providing a full memory data window of 164 milliseconds. The memory is loaded in a circular buffer fashion until a trigger occurs.

The trigger can be generated manually by the Cycle input or can be sensed from the signal conditioning output of an axial accelerometer in the Analog Trigger input. After the trigger, a time-out counter is enabled and the sequencer shuts down after a partial memory load is complete. This “early” shutoff leaves some of the pre-trigger data in the memory intact. After the sequencer shutoff occurs, the circuit is left in its low current state. All of the analog and conversion circuitry is powered down by the battery power control circuit. The digital control circuitry and memory are maintained on the keep-alive battery. This circuitry draws about 1 microampere current in this state. Data can be retained in the recorder for up to one year after the test.

Then, the data can be strobed out of the data package into the interface box with the application of `Out_Command`. The read-out timing signals, which are generated in the interface box, are used to strobe the data out of memory. The interface box also formats the data into the RS-232C serial format for transfer to the portable computer.

Table 1. MP86 Recorder Specifications

Data Conversion Rate	200 ksamples/sec
Channel Sample Rate	25 ksamples/sec/chan (8 channels)
Data Resolution	8 bits/sample
Memory Capacity	32,768 samples
Record Time	Pre-trigger = 10 msec. (typical) Post-trigger = 154 msec. (typical) Total = 164 msec.
Signal Conditioning	6 channels, Full Bridge Input
Analog Filters	4-pole low-pass, 5 kHz (typical)
Voltage Monitors	2 inputs
Power Requirements	10 Volts @ 120 ma (inc. transducers) -7 Volts @ 10 ma 3 Volts @ 1 μa (Keep Alive)
Battery Cells	Eagle-Picher LTC-7PST
Battery Configuration	Main = 4 series by 2 parallel Negative = 2 series Keep-alive = single cell
Battery Life	Main = 5 hours Keep-alive = one year
Shock Survivability	5,000 gs for 1 msec., all axes 1,000 gs for 10 msec., all axes
Operating Temperature	0°C to 70°C
Recorder Size Penetrator Size	2.0" diameter by 15" length 4.2" diameter by 20" length

ANALOG DATA CONVERSION

The MP86 analog multiplexer has eight inputs which are clocked with the least significant memory address lines A0 through A2. Thus, each of the eight inputs are sampled and digitized in sequence at a constant rate of 1/8 of the data conversion rate. The maximum data conversion rate of 200,000 samples/second is limited by the analog-to-digital (A/D) conversion time and analog multiplexer switching. The specifications in Table 1 assume this maximum setting. The data conversion rate can be adjusted to provide total recording times ranging from 164 milliseconds (at the highest data rate) to several seconds for longer duration events at lower data rates. Since the memory capacity is fixed, the record time is inversely proportional to the data conversion rate.

Note from Figure 2 that there are eight multiplexer inputs and only six channels of signal conditioning. Signal conditioning requires considerable space and power, and this is one of the reasons that there are not eight channels available. The remaining two multiplexer inputs are normally used for internal voltage monitors which do not require conditioning. Signals typically monitored are battery and gauge excitation voltages. These monitors have been of considerable diagnostic value in penetration testing with MP86.

ACCELEROMETERS AND SIGNAL CONDITIONING

The MP86 instrumentation recorder includes six accelerometers mounted in two triaxial stations. The Endevco 7270A series piezoresistive accelerometers are used for several reasons. First, DC response is very important in recording the long duration pulses typical of penetration events. Thus, a piezoresistive device is required. The 7270A accelerometer is a very small, rugged device with very high frequency response. Also, the 7270A is available in 60, 20, 6, and 2 kg ranges providing a wide selection of sensitivity.

There are six channels of full bridge signal conditioning in the MP86 instrumentation recorder. Each signal conditioning circuit provides a balanced, differential input designed for full bridge operation with DC response. Gain and offset are resistor adjustable. There is a four-pole, anti-aliasing, low-pass filter for each channel. Common filter realizations used are Bessel and Butterworth with a wide range of cut-off frequencies available. All of the signal conditioning outputs are over- and under-voltage protected. Also, voltage regulators are provided for accelerometer excitation.

BATTERIES

MP86 requires three battery sources for penetration testing: a main operational battery, a negative supply battery and a keep-alive battery for data retention. The battery cells used in the MP86 recorder are Eagle-Picher LTC-7PST lithium thionyl-chloride. These cells were chosen for high energy density and shock ruggedness. The main operational battery consists of two parallel stacks of four series cells, capable of providing 120 milliamperes of current for about five hours. This parallel arrangement also offers redundancy for reliability in field tests. The keep-alive battery consists of a single battery cell. The capacity of this battery far exceeds the one year data retention requirement. The negative supply battery is a single stack of two series cells and is required by the analog circuitry for negative voltage bias.

BATTERY CONTROL

The main battery and negative supply can be switched on and off with an external control input using a Silicon Controlled Rectifier (SCR) circuit in the battery control module (Figure 1.). This electronic switching circuit has been designed to reject voltage transients on inputs or outputs allowing high reliability in adverse conditions.

There is no need to have the main battery or negative supply turned on after the recorder has completed data acquisition. Therefore in order to conserve batteries, the SCR circuit is controlled internally as well. A circuit, which monitors the end of the recording event, automatically switches the SCR circuit off after the package has recorded an entire event. This prevents the operational batteries from supplying current any longer than is required. This is important since the recovery of the penetrator can take anywhere from an hour to several days. The automatic shutoff dramatically increases the number of tests that can be performed without unit disassembly for battery servicing. Without automatic shutoff, the majority of battery life would be consumed during the recovery period. Since the automatic shutoff feature returns the circuitry to its quiescent state, recovery time is not critical. Since the batteries are not rechargable, the entire battery module is discarded when it no longer has sufficient capacity. Therefore, time and money are saved since the frequency at which batteries need to be changed is reduced significantly.

HIGH-G ELECTRONICS ASSEMBLY

The selection of integrated circuit (IC) packages is dominated by the requirement of shock ruggedness. Plastic “gull wing” style small-outline packages are used, where available, to conserve space. Transistors are also specified in plastic packages. The advantage of plastic packages is that they are solid, molded devices with no voids inside. Ceramic and hermetic can devices are not molded and have internal leads free to move in cavities inside the device. Since these internal leads are unsupported, they are more apt to break or short in a shock environment. Because of the limited availability of plastic, small-outline packages at the time of this design, limited use of ceramic flat packs was required. These ceramic devices seem to do well but have been dropped from later designs. All of the capacitors are ceramic and the diodes and resistor packages are molded styles.

Having selected appropriate components for the assembly, the next important considerations come in fabrication. DIPs should be soldered onto the board with 1/8" plastic spacers underneath to provide support below the devices. Resistors and capacitors should be spaced off the board slightly to permit potting to flow under them. “Gull wing” style SO packages should be soldered in so that the body of the device touches the printed circuit, (PC), board surface. After the PC boards are assembled and inspected, a thin layer (1/32") of polysulfide rubber compound is coated over all of the components and wire connections. This coating protects the components from damage or stress associated with the curing of the hard potting.

Once the PC boards are assembled, they are interconnected in a stack with berrylium-copper slide wires inserted through electrical spring sockets which are soldered into the boards. The battery module is assembled and wired using the same technique. This stacked and wired assembly can now be placed into a mold and potted in micro-balloon filled epoxy. A vacuum should be drawn on the components during each step of the potting process to eliminate voids in the potting. Once the potting is cured, the electronics modules can be removed from the molds and installed in the package.

PACKAGING & HARDWARE

The penetrator design requires that the entire package fit into a volume that is 2 inches in diameter and 15.5 inches long. It is also required that the two triaxial accelerometer stations be as far from each other as possible. These requirements are satisfied with the package design illustrated in Figure 3. The electronics and batteries are packaged in three separate modules with an accelerometer station located at each end. Each module is uniquely keyed to its adjacent modules by pins and the connectors which provide electrical connection between the modules. The modules are solidly potted for reasons already discussed in the HIGH-G ELECTRONICS ASSEMBLY section.

The main electronics module contains the digitizer, memory and three signal conditioning channels. The battery module contains the the battery packs and the battery control circuitry. The forward amplifier consists of the other three signal conditioning channels needed for the accelerometers in the forward housing.

A steel tube slides over the electronics and is held in place by a flange on the aft accelerometer housing and locking rings on the forward accelerometer housing. The tube provides the package with lateral support and stiffness allowing it to be preloaded into the penetrator. A preload is required so that the modules do not move when subjected to the high shock loads. The location of the package in the penetrator is illustrated in Figure 4.

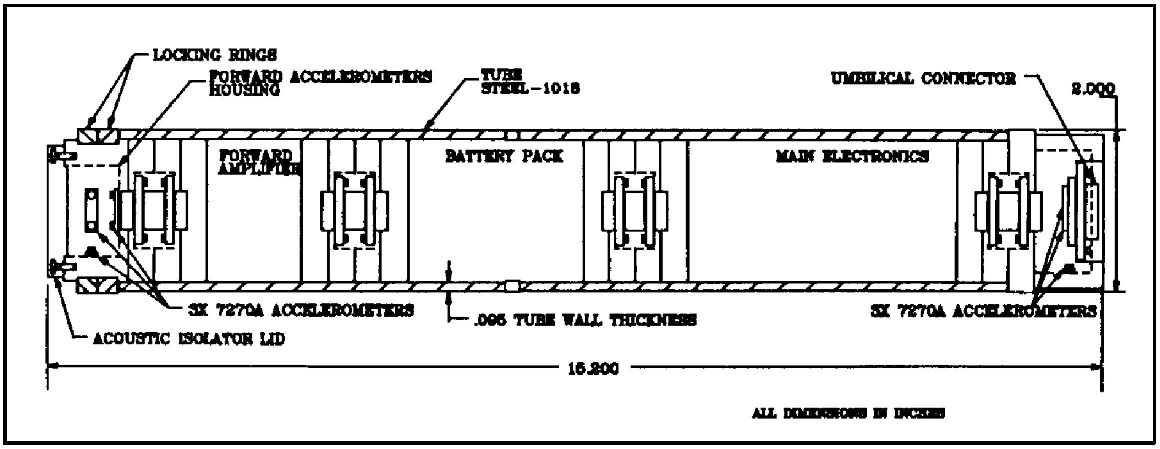

Figure 3. MP86 Mechanical Design for Package

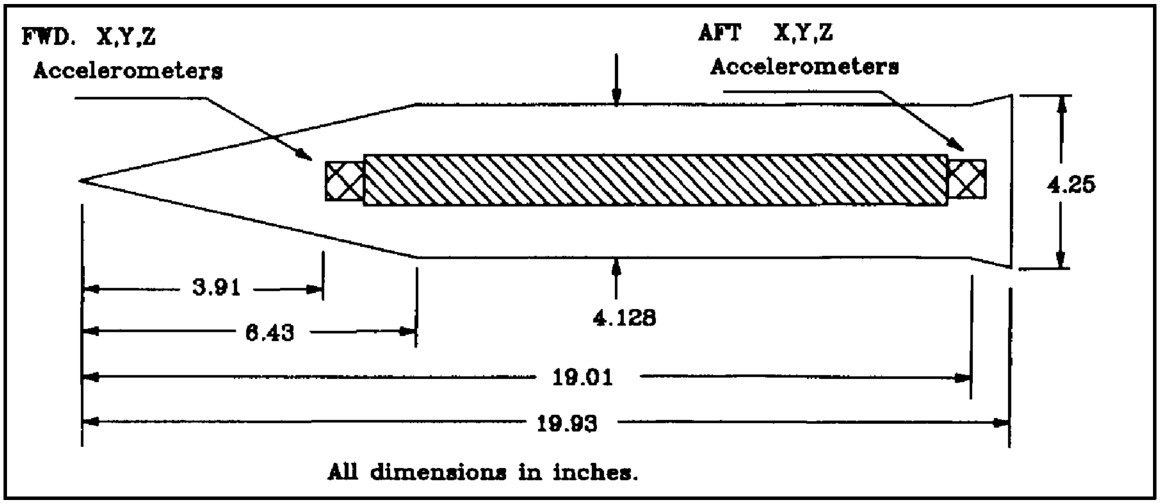

Figure 4. MP86 Recorder in Penetrator

FIELD TEST SETUP

The basic test setup is shown in Figure 5. The data recorder is remotely controlled and monitored while in the barrel of the gun. The package battery power can be switched on and off from the remote trailer. The package can also be armed remotely. The fire control for the gun is done from the same trailer. This is a convenient situation since the arming and powering of the data package can be conveniently coordinated with the countdown sequence and gas gun operator.

GAS GUN TEST SEQUENCE

Before the penetrator is loaded into the gun, several preliminary checks are performed to ensure a safe and successful field test. First, is an on site check of the data package installed in the penetrator. This involves basic functionality tests and reading bias data out

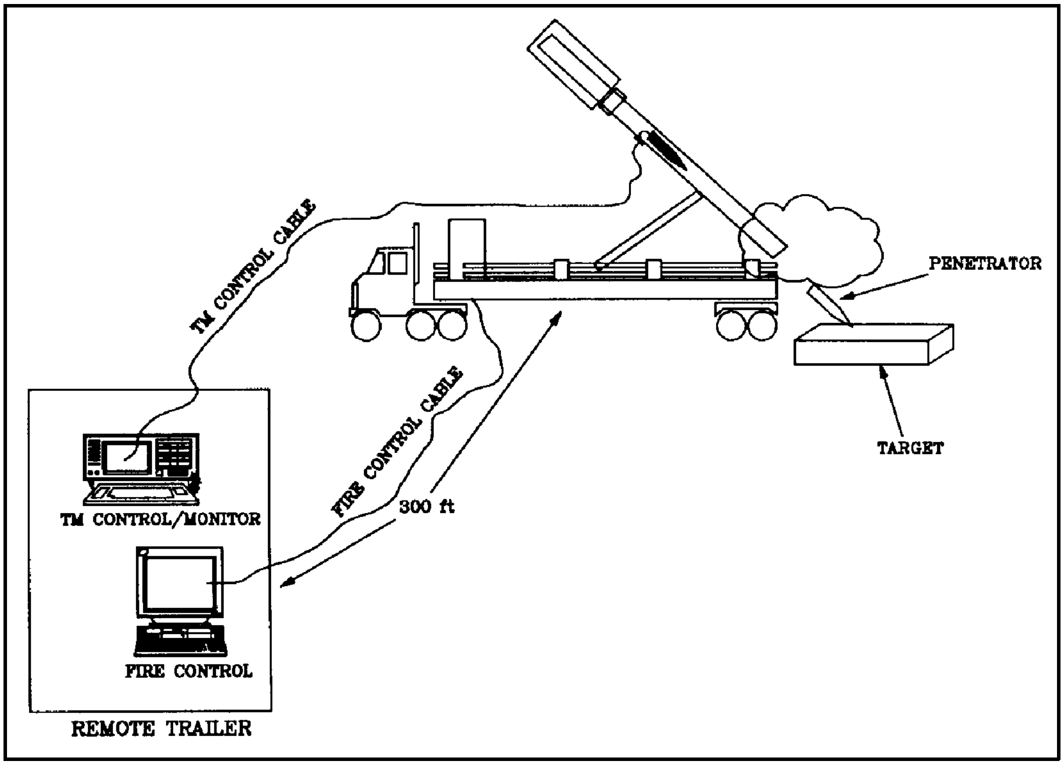

Figure 5. MP86 Gas Gun Field Test Setup

with a personal computer. This flags any problems that may have transpired since the last checkout. Next, the 300 foot cable used for remote control is checked with the control box. Finally, a remote control check is performed with the control box and the penetrator through the long cable. Satisfied with the results of the preliminary checks, the penetrator can then be loaded into the gun.

Once the penetrator is loaded into the gun and the barrel is sealed, the gun site is cleared of all test personnel. Control and monitor checks are performed one last time before gas gun personnel begin filling the gun's air tank. When the desired pressure is achieved in the gun, a one minute countdown is started. The data package is not turned on until the last 30 seconds of the countdown. With 10 seconds remaining in the countdown, an ARM is issued and the TEST_EN monitor is checked to confirm the arming. All status on the package is immediately lost once the unit is fired. Once the gun site is deemed safe, recovery of the penetrator may begin. After the penetrator is recovered, the test data is read out on site. The data can then reduced and displayed for quick-look analyses at the test site.

FIELD DATA ANALYSIS

The computer interface and field data reduction software developed for MP86 make field data analysis and plotting possible with very little support equipment (Figure 1). The software package is implemented on several portable, IBM compatible computers. The plotting routines provide auto-zeroed and auto-scaled plots of the data calibrated in engineering units. The software also provides integration and digital filter routines for field data reduction. Figure 6 is a typical field data plot. Note, the data from Figure 6 can be keyed to Table 2 with the “Ana Ch: ?” entry in the title of each plot. The top plot of Figure 6 is analog channel 1. Table 2 indicates that this is “AFT Axial Accel.”

PENETRATION DATA RESULTS

The test data provided was recorded in a penetrator fired from the gas gun into an ice target. Table 2 is the data list for this test and is fairly typical of scale model penetration tests. Figures 6, 7 and 8 are the axial acceleration, velocity, and displacement respectively. The axial acceleration is measured and the velocity and displacement are calculated by integrating and double integrating the acceleration data. The calculated velocity and displacement are compared to independent measurements of those same metrics to verify the integrity of the recorded data. An independent velocity measurement is obtained with high speed cameras, which capture the penetrator exiting the barrel of the gun. The distance traveled by the penetrator, after target impact, can be physically measured when it is recovered. Comparisons of these independent velocity and displacement measurements typically agree to within ±3.0 percent. A full set of these plots is generated for each test using data reduction algorithms developed by Division 5144 and implemented on IBM and compatible personal computers. Integration, digital filtering, and spectral analysis are all available in this software package.

Table 2. Data List

Measurement	Chan No.	Calibration Range	Channel Sens. (units/cnt)	Sample Rate (ksps)	Analog Cutoff (kHz)
AFT Axial	1	-6,000/+3,000 g	35.035 g	25.20	5.0
AFT Lateral Y	2	-8,000/+8,000 g	62.234 g	25.20	5.0
AFT Lateral Z	3	-8,000/+8,000 g	61.546 g	25.20	5.0
FWD Axial	4	-6,000/+3,000 g	35.547 g	25.20	5.0
FWD Lateral Y	5	-8,000/+8,000 g	62.009 g	25.20	5.0
FWD Lateral Z	6	-8,000/+8,000 g	61.115 g	25.20	5.0
8 Volt Reg.	7	0.0 / 17.0 V	0.0496 V	25.20	N/A
Main Battery Monitor	8	0.0 / 23,0 V	0.0876 V	25.20	N/A

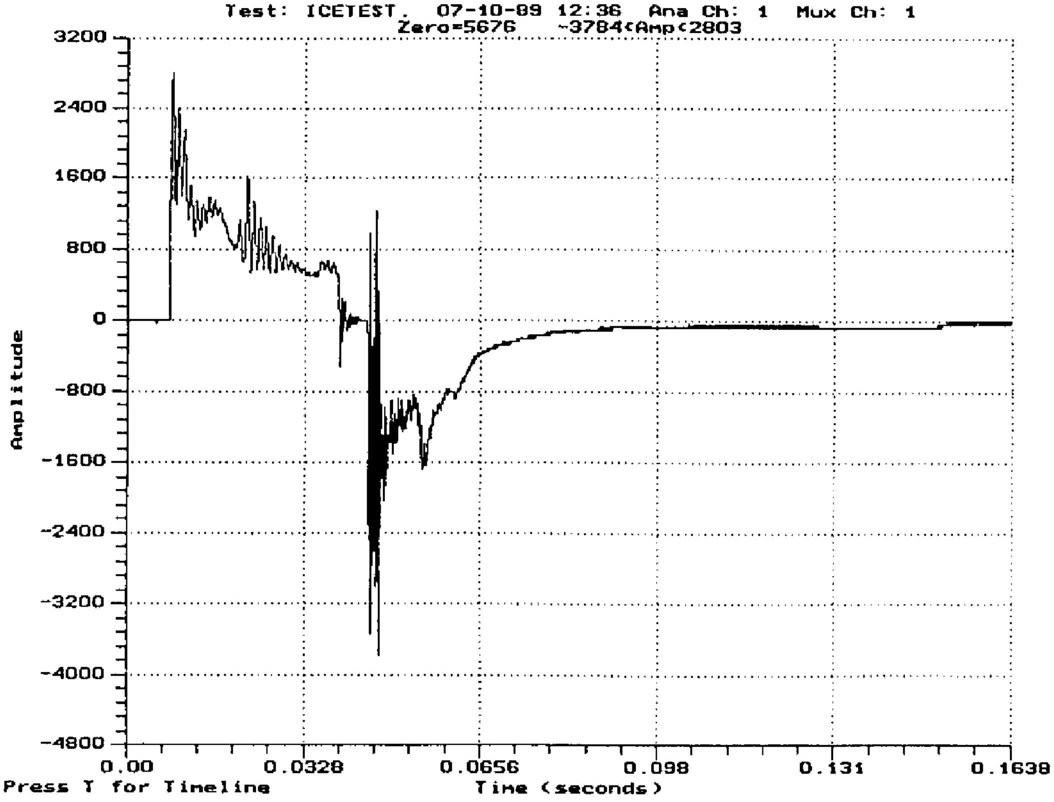

Figure 6. Typical Acceleration Data from Penetration Test

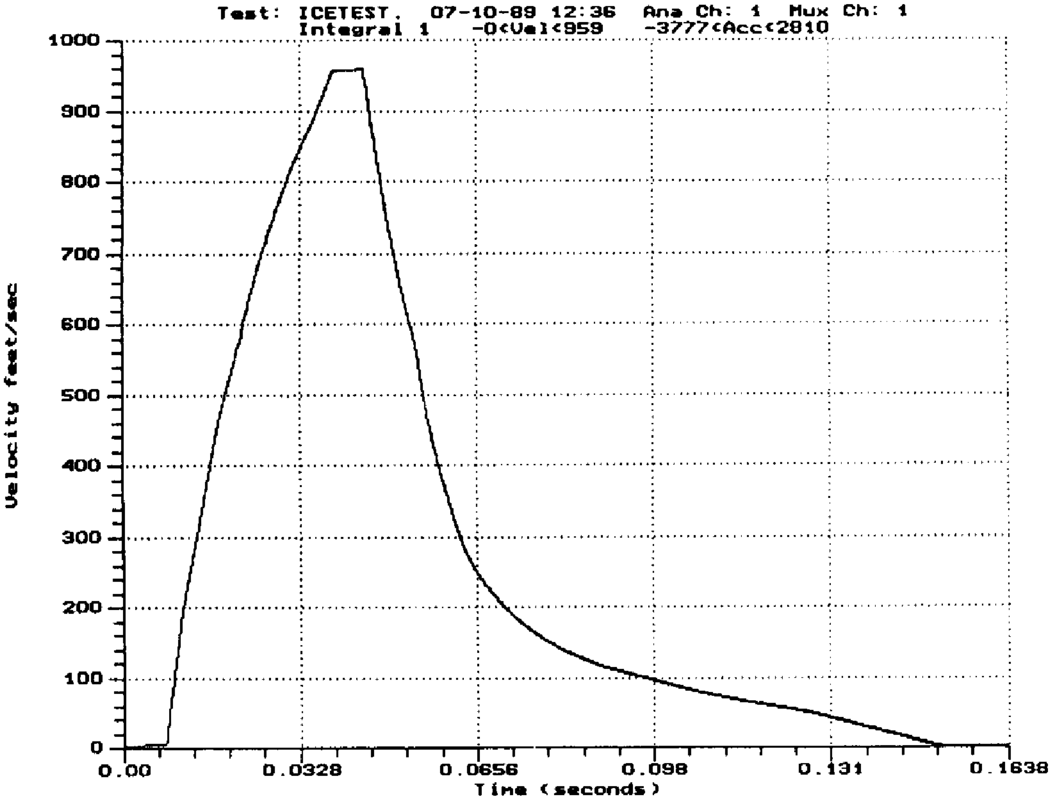

Figure 7. Computed Velocity derived from Acceleration

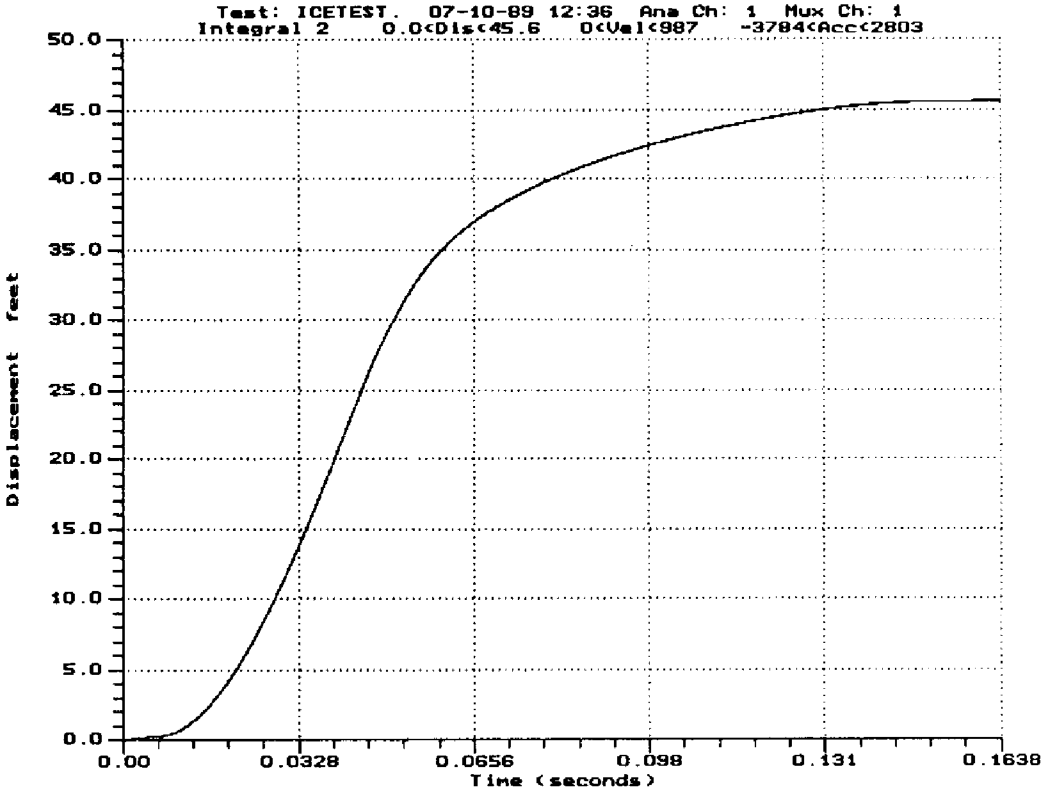

Figure 8. Computed Displacement derived from Acceleration

CONCLUSIONS

The MP86 high-g data recorder is a reliable tool for instrumented penetration testing. It provides high quality data in extremely harsh environments. Its miniature size makes it ideal for scale model penetrator tests. It is capable of supporting multiple tests with quick turnaround requirements. The miniature data recorder used in conjunction with the new gas gun has proven to be a valuable resource for penetrator testing. This scale model penetration test system has optimized the time required for Penetrator tests, resulting in an increase in the quantity of data produced. Also, the tests provide an inexpensive alternative to evaluate penetrator designs before proceeding with expensive, full scale tests.

The computer interface allows data reduction at the test site with minimal support equipment. Since the support equipment is all battery operated, testing can be done in remote areas with no AC power required. The field data reduction software (see Figures 7, 8, 9) provides data verification and hard copy in tile field.