Instrumentation of a Reconditioned Robbins Tunnel Boring Machine

J. Lach, D. Fashimpaur, R. Florian, M. Kucera, C. Laughton, P. Lucas,
M. Shea,
Fermilab
Batavia, IL 60510

T. Budd, J. Johnson
Kenny Construction Co.
Wheeling, IL 60090

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Future accelerator projects at Fermilab may require the construction of tunnels in the northern Illinois bedrock. To understand how tunnel costs might be reduced we investigate the details of conventional tunnel boring machine (TBM) operations in an on going tunnel project. This may allow us to gain insights as to how we might increase the reliability and productivity of current TBM operations. Ultimately this should lead to lower tunneling costs. We describe instrumentation that was used to measure the parameters of this TBM operation.

Project Overview
The Tunnel and Reservoir Plan (TARP) is a large complex of tunnels (about 100 miles in length) located in the Chicago area bedrock. It is used for pollution and flood control. It is the excavation of one of the tunnels in this continuing project that we will instrument.

Tunnel
The most recent addition to this system is the Torrence Avenue project, which is nearing completion. It is in Silurian Dolomite which has unconfined compressive strength which varies between 14,000 and 18,000 psi. This project consists of a single 34,150 ft long, 27 ft, 4 in diameter mainline tunnel and two smaller feeder tunnels. Each of these feeder tunnels is 17 ft, 2 in diameter and 4000 ft in length. The three tunnels are approximately 350 ft below grade level. A reconditioned Robbins TBM was used to excavate one of these two

smaller feeder tunnels that we have chosen to instrument. Figure 1 shows the penetration of the TBM from the instrumented feeder tunnel into the mainline tunnel on January 20, 2000. This dramatic entry signaled the end of the first pass of our data taking. The construction of these tunnels is a joint venture of Kenny Construction (sponsor)/Kiewit Construction/J. F. Shea.
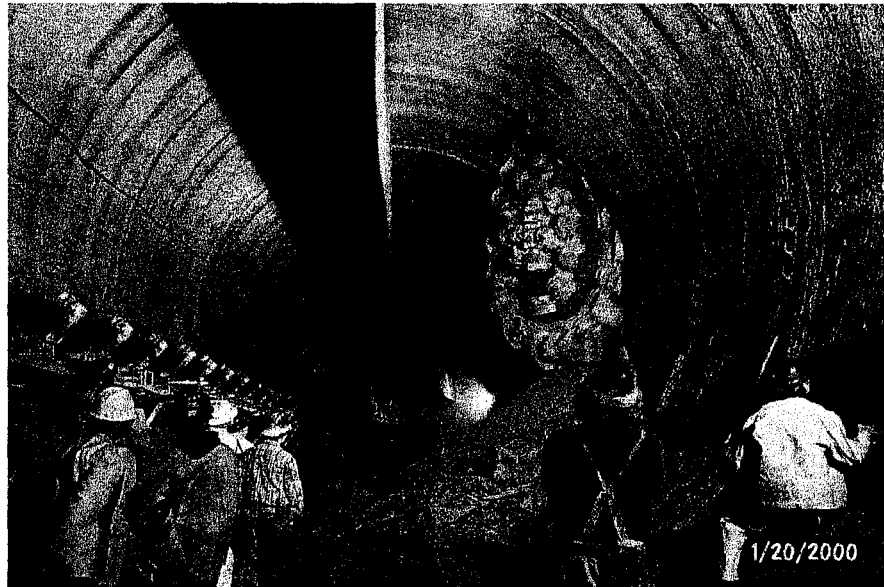

Figure 1

TBM entering the main line tunnel

TBM

The TBM was built by the Robbins Company in 1980 with a diameter of 18 ft, 6 in and rebuilt by Kenny for the present job. It has a boring stroke of 5 ft with a thrust of 840 tons distributed on 38 cutters of 17in diameter. Six 250-hp motors power the cutter head. The machine configuration utilizes two horizontal grippers capable of a maximum gripper force of 2827 tons. The TBM weighs about 284 tons. Figure 2 is a diagram of the TBM showing the instrumentation. A horizontal conveyor belt from the cutter head to muck rail cars transports the excavated rock. At the tunnel head the muck cars are emptied into a hopper which is lifted to the surface by crane.

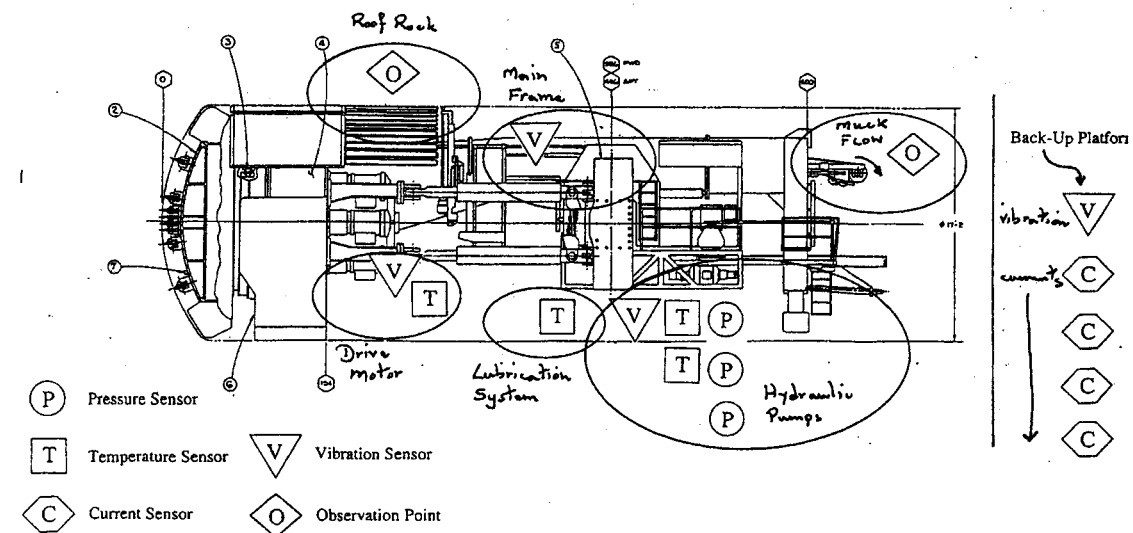Kenny-Fermilab Collaboration
Plans for TBM-Systems' Monitoring

Figure 2

TBM and monitoring system

Instrumentation

The instrumentation installed on this "vintage" TBM included temperature sensors, vibration sensors (accelerometers), hydraulic pressure sensors, electrical current sensors, and a device that measures the extension of the cutter head. Some of these devices are pictured in Figure 3. Two TV cameras (not shown) were also part of the instrumentation package. We would like to emphasize that this instrumentation involved only minor modification to the TBM and it could be rapidly removed if it malfunctioned or interfered with the mining operation.
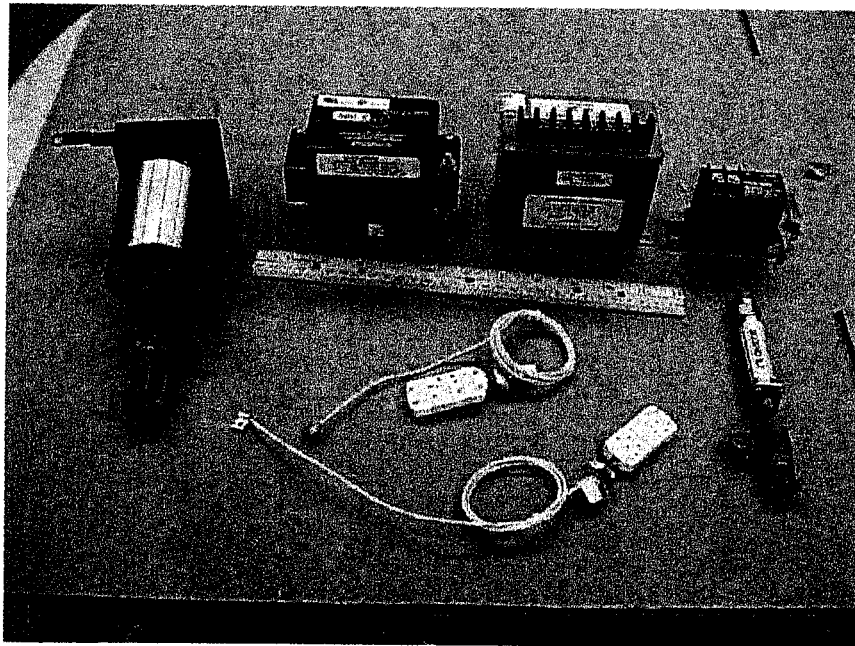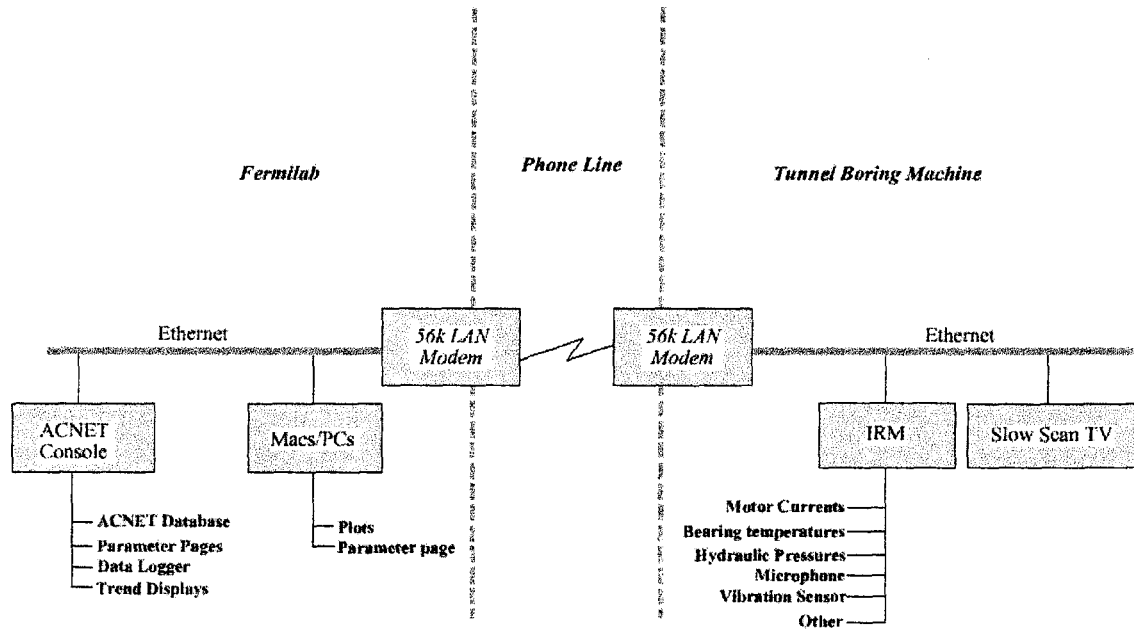
Figure 3

Sensors mounted on the TBM
Pictured (clockwise from left) are the extension sensor, current sensors,
pressure indicator, and temperature sensors. Accelerometers are now shown

Data Acquisition System
The data acquisition system is shown schematically in Figure 4.

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Fermilab   **Phone Line**   **Tunnel Boring Machine**

Data Acquisition from TBM

Figure 4

Data Acquisition System

The data acquisition system is housed in an aluminum
environmentally protected box at the TBM heading shown in Figure 5.
This box is mounted on the TBM trailing gear which follows the TBM
advance. Inside this box is a standard Fermilab accelerator controls
system Internet Rack Monitor (IRM) module. The IRM contains a
Motorola 6820 processor (the same processor that powers the
Macintosh II computer). It is configured as an Internet node, and
accepts and processes Ethernet signals from the detectors. The two
TV cameras are controlled by the slow scan TV module that is also
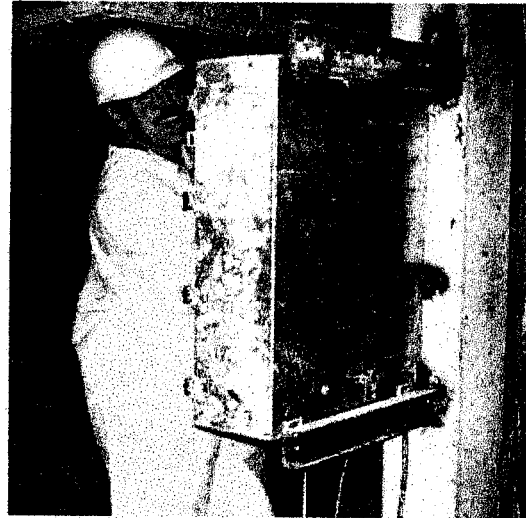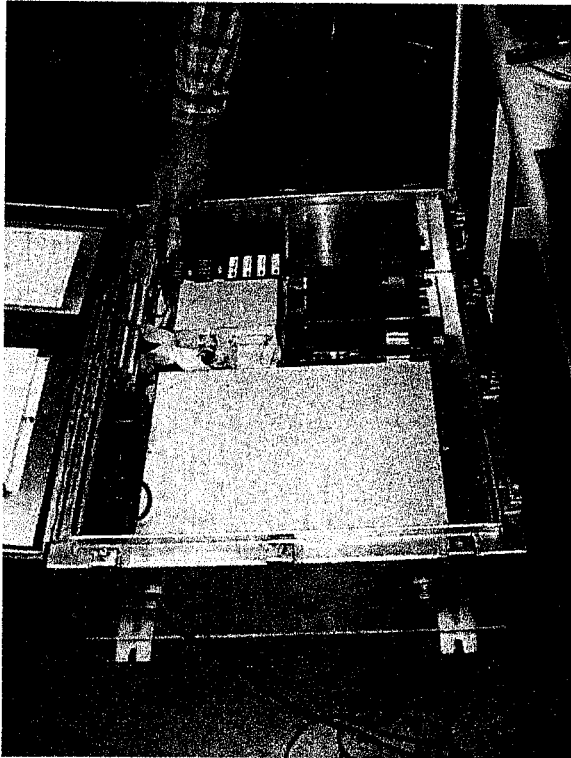housed in the aluminum box.

Figure 5

Photograph of the Data Acquisition System Box

The data acquisition system box (Figures 4 and 5) contains a 56K LAN modem. This allows us to transmit data over a conventional dedicated telephone line to another 56K LAN modem at Fermilab. From here one has a choice of viewing the data with the standard Fermilab accelerator control system (ACNET) or a separate Macintosh based system. Both were used.

This combination of hardware and software allows us to treat the TBM data in the same way as we would treat any other data from the Fermilab accelerator system.

All data is recorded with a time stamp (hour, minutes, seconds, date and year). Most measurements consist of a single value (temperature, current, pressure or extension) and the time stamp. This process is more complicated for the vibration sensors. Here each measurement

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is a matrix consisting of 1024 values of the accelerometer (each value separated by one millisecond) for each of the four accelerometers. This data is discussed in a separate section.

Figure 6 is the ACNET TBM data parameter page.

```
W95   TUNNEL  BORING MACHINE          SET    D/A    A/D   Com-U *COPIES*
-<FTP>+ *SA   X-A/D  X=TIME        Y=T:BAPI30,T IBEAM ,            ,
COMMAND ----  Eng-U  I= 0          I= 0        , 0         ,-5          ,-2
-< 1>+  One+  AUTO   F= 3600       F= 50       , 9         , 4          , 2
  Z:TBMHPV       Hyd. Pump Vibration                -.029    G
  Z:TBMCMV       Cutter Drv Mtr Vibration           -.02     G
  Z:TBMMPV       Main Frame Vibration               -.015    G
  Z:TBMBPV       Back-up Pltfrm Vibration           -.021    G

  Z:TBMTHP       Thrust Hyd Pressure                31.33    PSI
  Z:TBMGHP       Grip Hyd Pressure                 -193.7    PSI
  Z:TBMAHP       Lube Oil Pressure                 -160.9    PSI

  Z:TBMDI0       Drive Motor Current 0              -.119    AMPS
  Z:TBMDI1       Drive Motor Current 1              -.119    AMPS
  Z:TBMTPI       Thrust Pump Current                -.181    AMPS
  Z:TBMGPI       Gripper Pump Current               -.048    AMPS

  Z:TBMTPT       Thrust Hyd Pump Temp               14.23    C
  Z:TBMGPT       Grip Hyd Pump Temp                 11.83    C
  Z:TBMLST       Lubrication System Temp            17.62    C
  Z:TBMCMT       Cutter Drive Motor Temp            28.01    C
  Z:TBMCHE       Cutter Head Extension              2.078    IN
```

Figure 6

The TBM ACNET data parameter page

This page lists the items that are being monitored and gives the current value of the detectors. This page can also be accessed through the WEB page. Below the four rows of page description lines, one finds four columns. The first column gives the computer name for each detector, followed by a description of the detector, then its value including units.

The first four detector lines are the vibration sensors (accelerometers). The data indicated is not relevant since it is only the first value of the above matrix. The second set of three lines are the hydraulic pressure readings for each of the three systems (thrust, gripper, and lubricating oil). The next set of four are currents in the first two drive motors (only 2 of the 6 were instrumented) and the current in the thrust and gripper hydraulic

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pump motors. The last group of five lines contains the temperatures for indicated motors and the extension of the thrust hydraulic cylinder.

Data Recording and Display

Data was recorded and archived to disk drives using ACNET. We recorded the signals from the detectors at 5-minute intervals. This data could be displayed using PC or Macintosh computers at Fermilab connected to the Fermilab internal network. The flexible display system in ACNET allowed one to choose a time window and display the output of up to eight devices in a single plot. Displays could also be put on Fermilab web pages, which could be viewed by anyone with password access.

Mining Cycle

We illustrate the TBM mining cycle by displaying a series of plots over a two-hour period. In Figure 7a we plot time on the horizontal axis and the vertical axis shows the thrust cylinder extension (TBMCHE) and the three (???) hydraulic pressure measurements (see figure 6 for the definitions). Note that the vertical scales differ for each of the plotted measurements. Measurements were made at 5-minute intervals. The data points are connected with a straight line in this figure. Probably the most useful direct indicator of TBM performance is the thrust cylinder extension (TBMCHE) plotted as a function of time. From this one plot one can easily see the motion of the TBM and compute the rate of rock penetration. For each foot of penetration, we mine about 20 tons of rock.
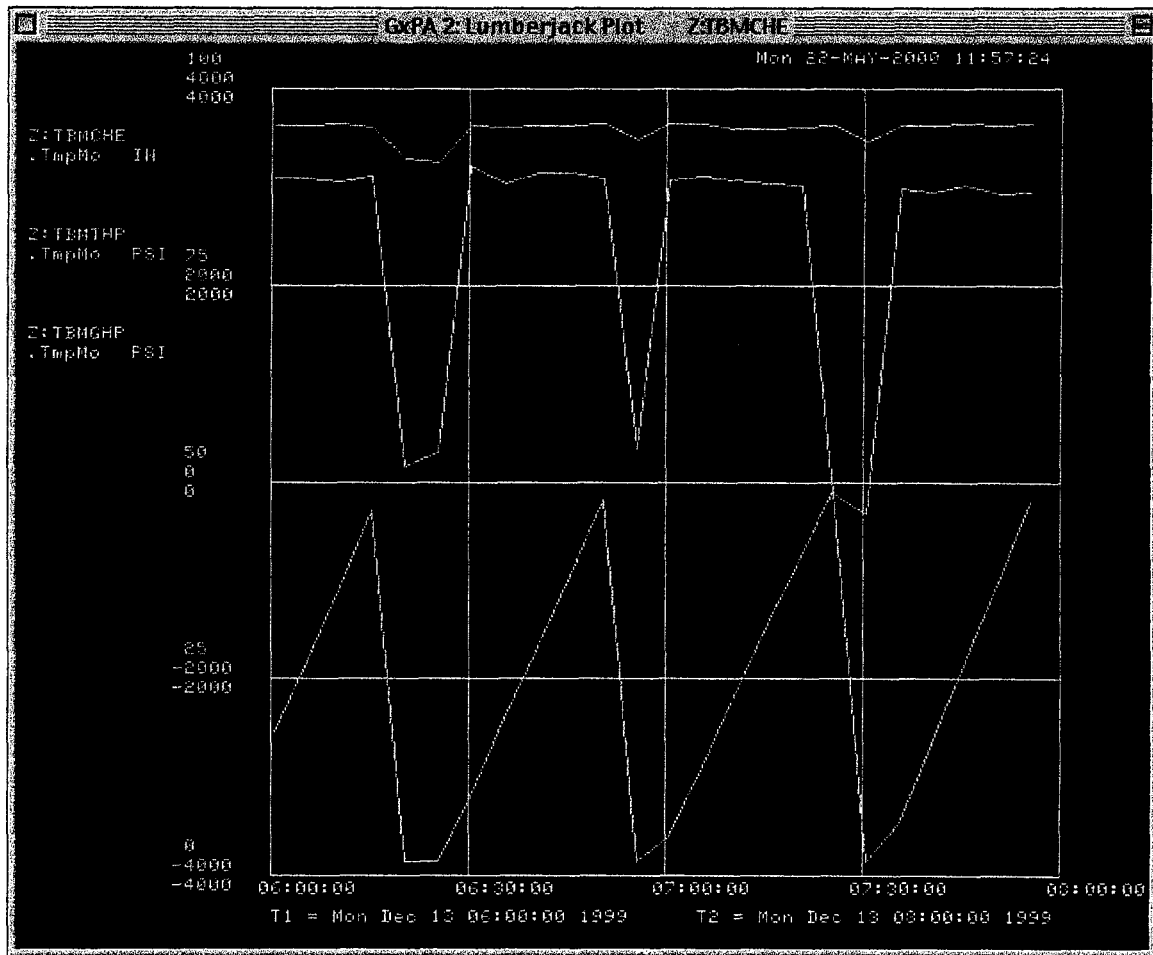
Figure 7a

The TBM mining cycle showing pressures and thrust cylinder extension.

In Figure 7b we plot, for the same time period, the electrical
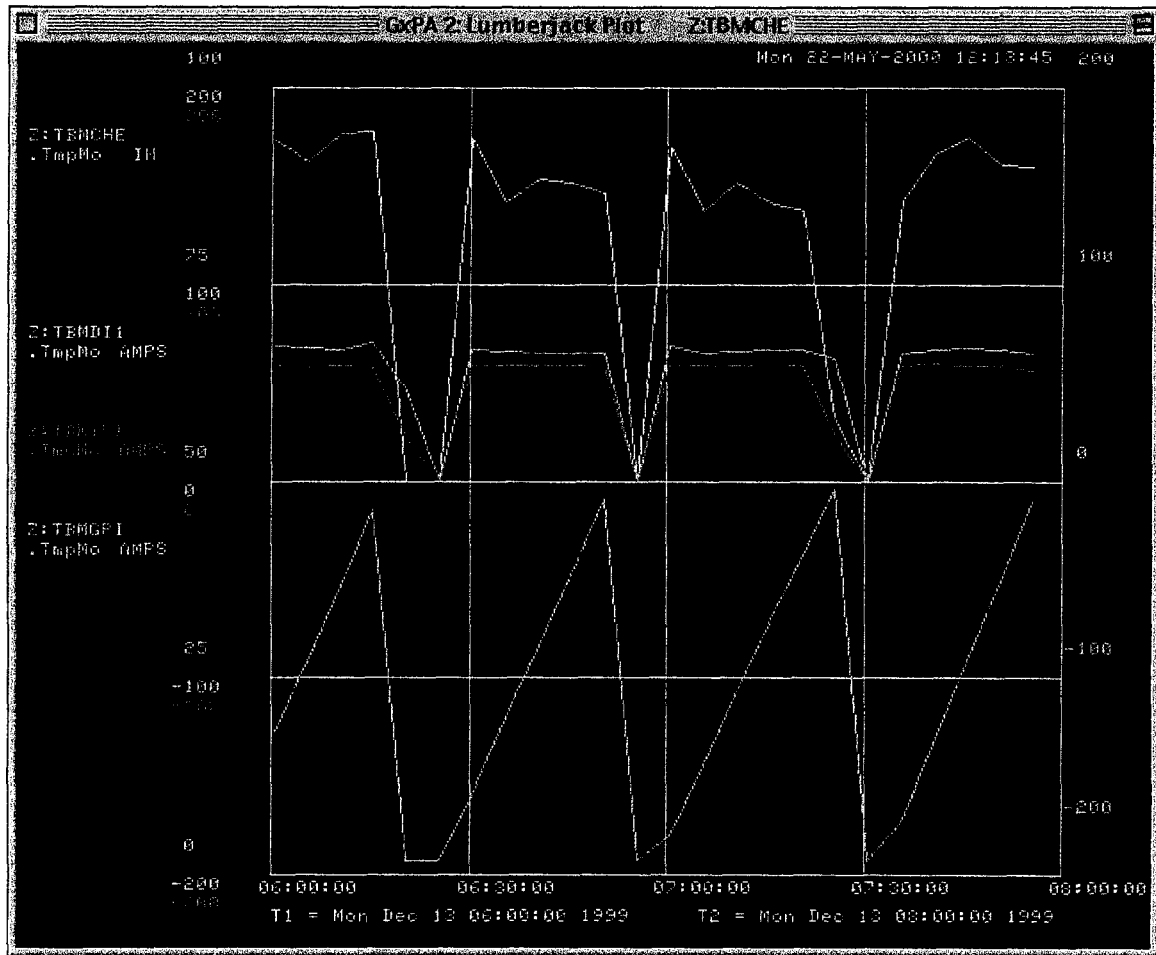currents. Again see Figure 6 for the definitions.

Figure 7b

The TBM mining cycle showing currents and thrust cylinder extension.

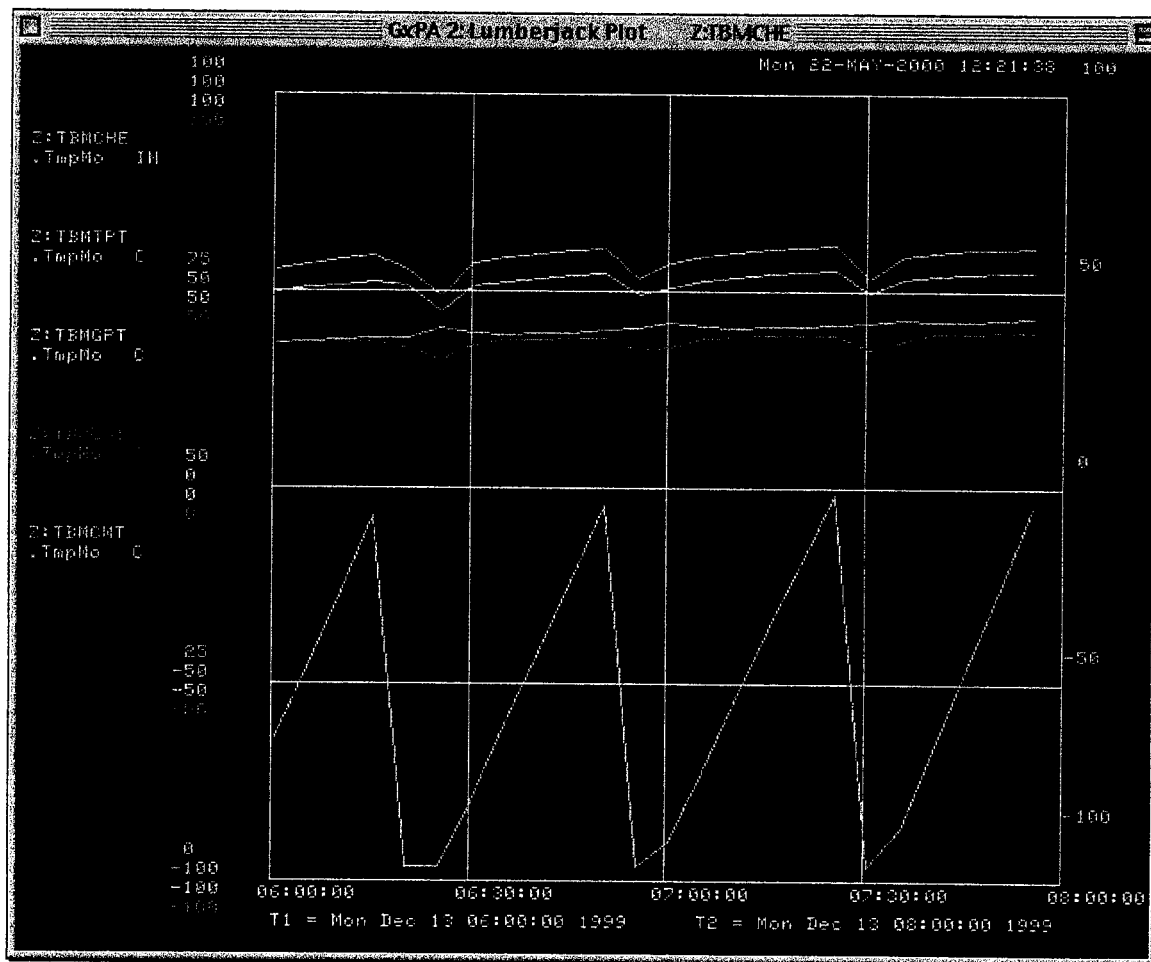Figure 7c shows the measured temperatures for the same period.

Figure 7c

The TBM mining cycle showing temperatures and thrust cylinder extension.

Data Collection Period

Mining of the 4000-foot tunnel started about October ?????? and continued until completion on January 20, 2000 (Figure 1). Instrumentation was installed and debugged simultaneously with mining. Figure 8 shows the measurements of TBMCHE and TBMTPT from the period of December 6, 1999 to January 24, 2000. It is within this period that we feel the most reliable data was recorded.

Let us look more closely at this plot (Figure 8). Starting from the left we see when the last instrumental modification was made (December 9, 1999 at about 14:00). Since the temperature measurements were not working before this modification, the appearance of temperature data (TBMTPT) on Figure 8 give us a time

marker for this modification. A few hours later we see the halting of operation because of a personal injury. At this time the temperature reaches an equilibrium point of about 12 degrees C. The next major interruption occurs just before Christmas for a planned (?) shutdown. This is followed by a loss of data from 0:45 on December 28,1999 to January 7, 2000 at 11:00. This corresponds to a period when the TBM power cable (and our phone cable) was being extended. The fact that there was a faulty connection to our phone line was not noticed because Fermilab was closed for this holiday period. Data taking ended with the TBM break through to the larger tunnel (Figure 1) on January 20, 2000 at 9:00. Reploting the data utilizing the much better time resolution (recall data was recorded every 5 minutes) allows one to localize these actions to a few minutes.
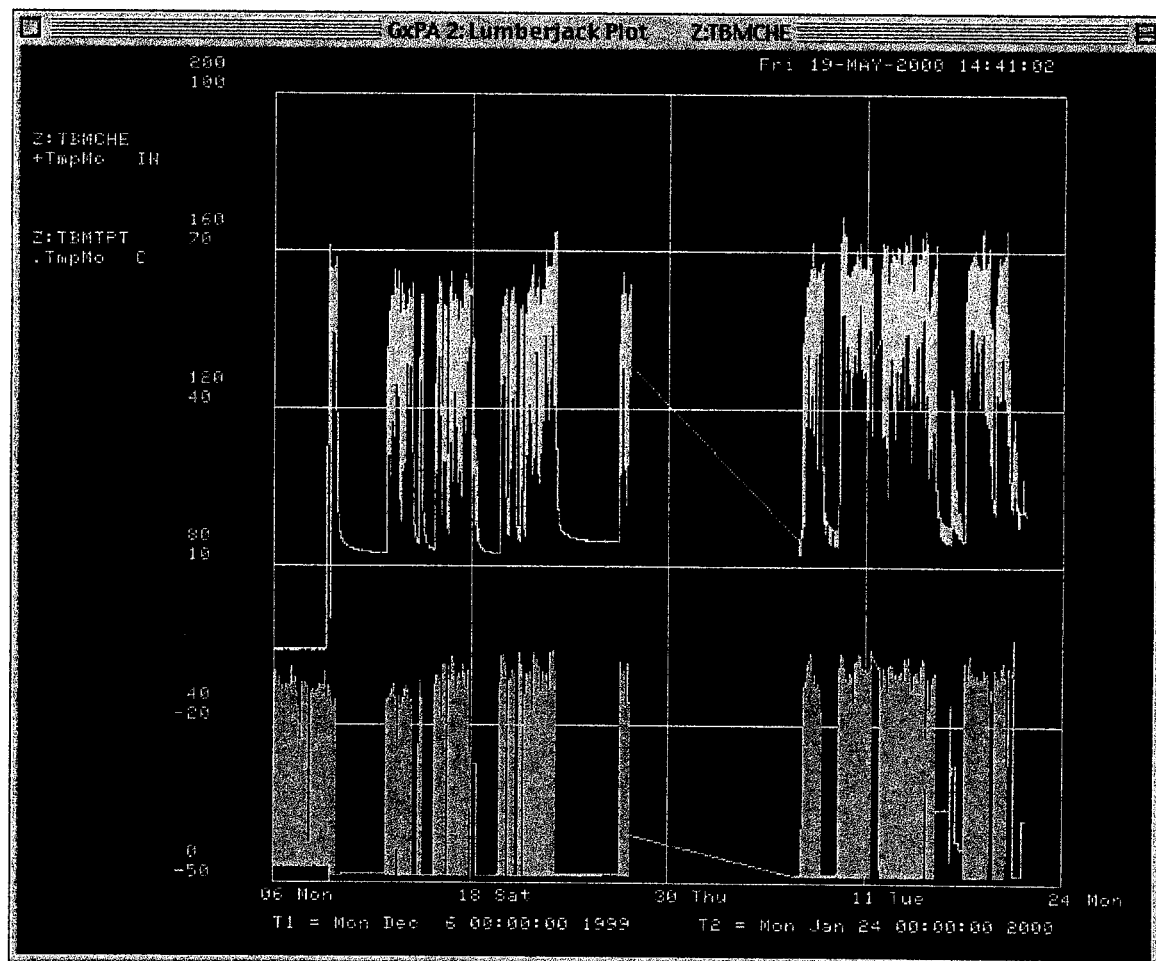

Figure 8

The TBM mining cycle covering the data collection period.

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Penetration and Advance Rate Computations

The recorded data can be examined and used for computations by a spread sheet program (like EXCEL) to yield information about the performance of the TBM. We illustrate this in Figure 9 where the plots represent the data collected in a full day (January 13, 2000). Here we plot the thrust cylinder extension (now in feet and in blue) as in the previous figures. However we can also compute the instantaneous cutter head velocity, or instantaneous penetration rate (with sign), by reference to the thrust cylinder (in ft/h and red).
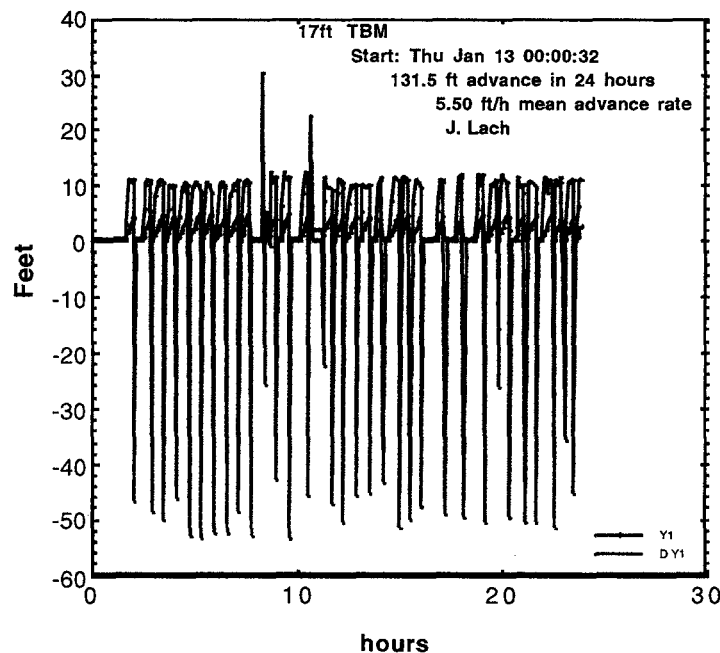

Figure 9

One day of TBM mining.

We see (Figure 9) that when the TBM is mining rock (positive sign) it is advancing at somewhat more that 10 ft/h. The regrip cycle can proceed about 5 times faster than that. With the help of the spread sheet code, we can compute the total amount of penetration in the 24 hour period (131.5 ft) and thus compute the mean advance rate (5.5 ft/h) on this day. Note that it is only about one half of the best instantaneous rate corresponding to a utilization of about 50% (3x8 hour mining) on January 13, 2000.

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Let us look at the full period from the time the data acquisition system was working till the tunnel completion. Figure 8 shows us that this is the period from December 9, 1999 (14:00) to January 20, 2000 (9:00). If we exclude from this period the time of the faulty telephone connection (December 28,1999 (0:45) to January 7, 2000 11:00) we find that 1971 ft of tunnel were mined in 704 hours or a mean tunneling rate of 2.81 ft/h. Correction is not made for the time tunneling operations were suspended for the holidays (Can we get this number????).

INTERNET Plots

As the run progressed the on-line plots became available. They could be accessed on the INTERNET through a Fermilab web page:

http://www-linac.fnal.gov/cgi-bin/tbm.pl

At that point you will be asked for the user name and password:

kfjointproject
17ftTBM106St

The first page is shown in Figure 10. It shows two television cameras that were mounted on the TBM trailing gear. The first camera was directed at the conveyor belt and could be used for monitoring the quality (size and shape) of the excavated rock. The second camera was directed at the tunnel ceiling and could be used to monitor the tunnel rock for cracks, etc. For each camera a frame was recorded every minute and 30 frames spooled. This allowed a 30 frame movie to be replayed under user command for each camera. Lighting conditions were not always optimal (as in Figure 10) but this should not be an intrinsic problem.
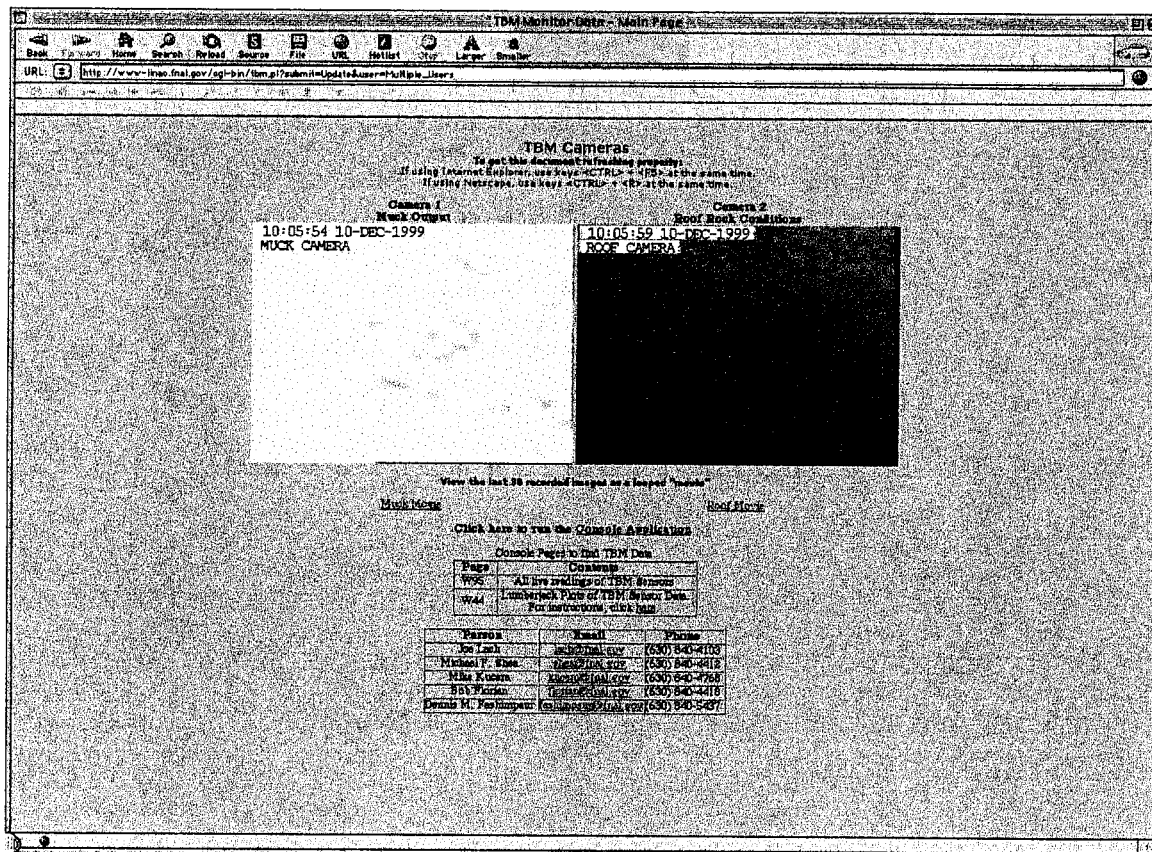
Figure 10

First On-line page

Two plots were also available on line. Tunneling progress for the last day (24 hours) shown as Figure 11. Here was plotted as a function of time the thrust cylinder extension and the thrust pump temperature. From these one could get the status of the mining operation. Another plot (similar to Figure 8) was available with data from the last week. These plots were remade every hour and put on the Internet page. Thus an hourly report was available to anyone who had the interest (and password). The one-hour update could certainly be made shorter. Anyone who had direct access to the Fermilab system could make any displays they wished as soon as the data was taken.
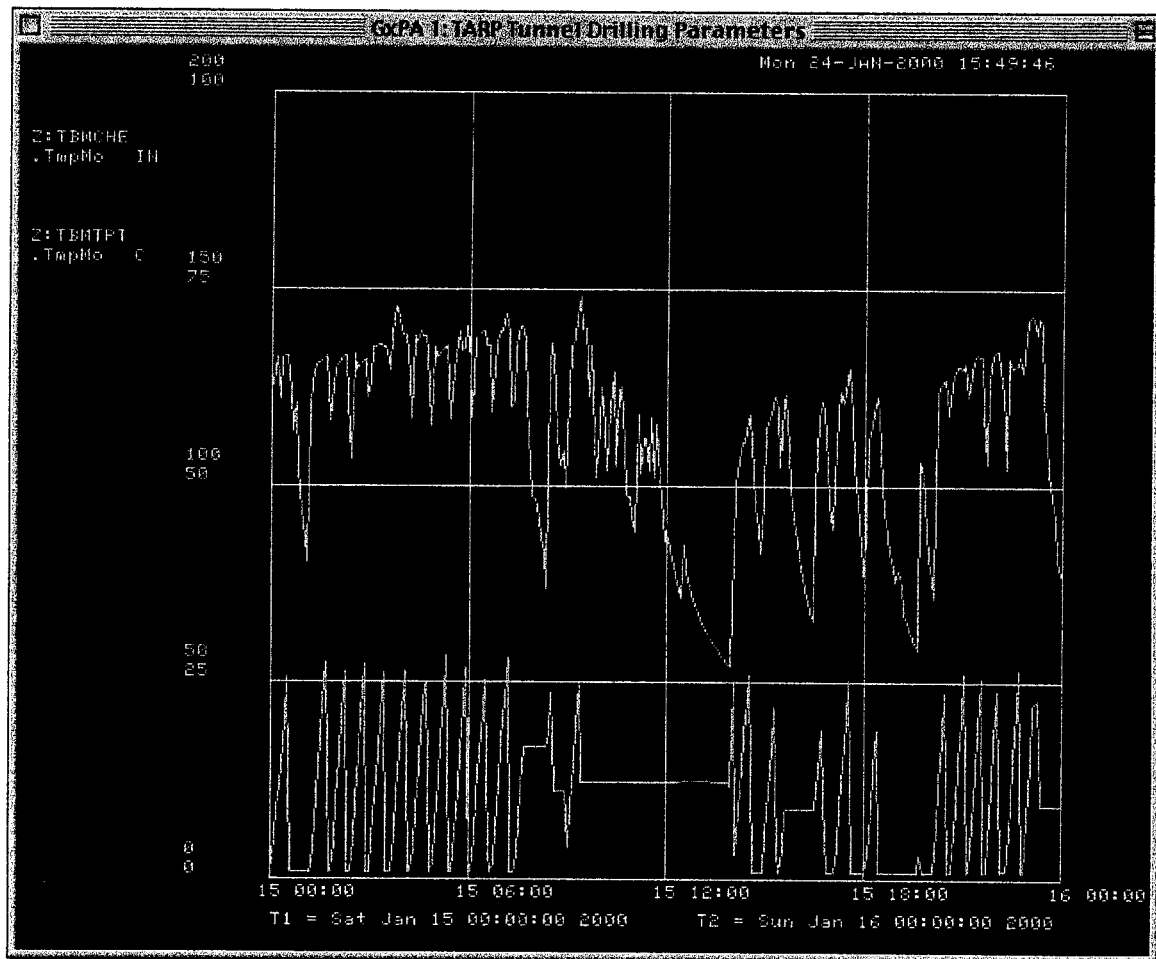
Figure 11

24 hour On-line page

Vibration   Sensors

Data collection is more complicated for the vibration sensors. Here each measurement is a matrix consisting of1024 values of the accelerometer (each value separated by one millisecond) for each of the four accelerometers (Figure 6).

The data from each of these accelerometers is 1024 measured values of the force (proportional to the acceleration) on the sensor and this is plotted in Figure 12. This "time domain" plot displays the amplitude of the displacement as a function of time.
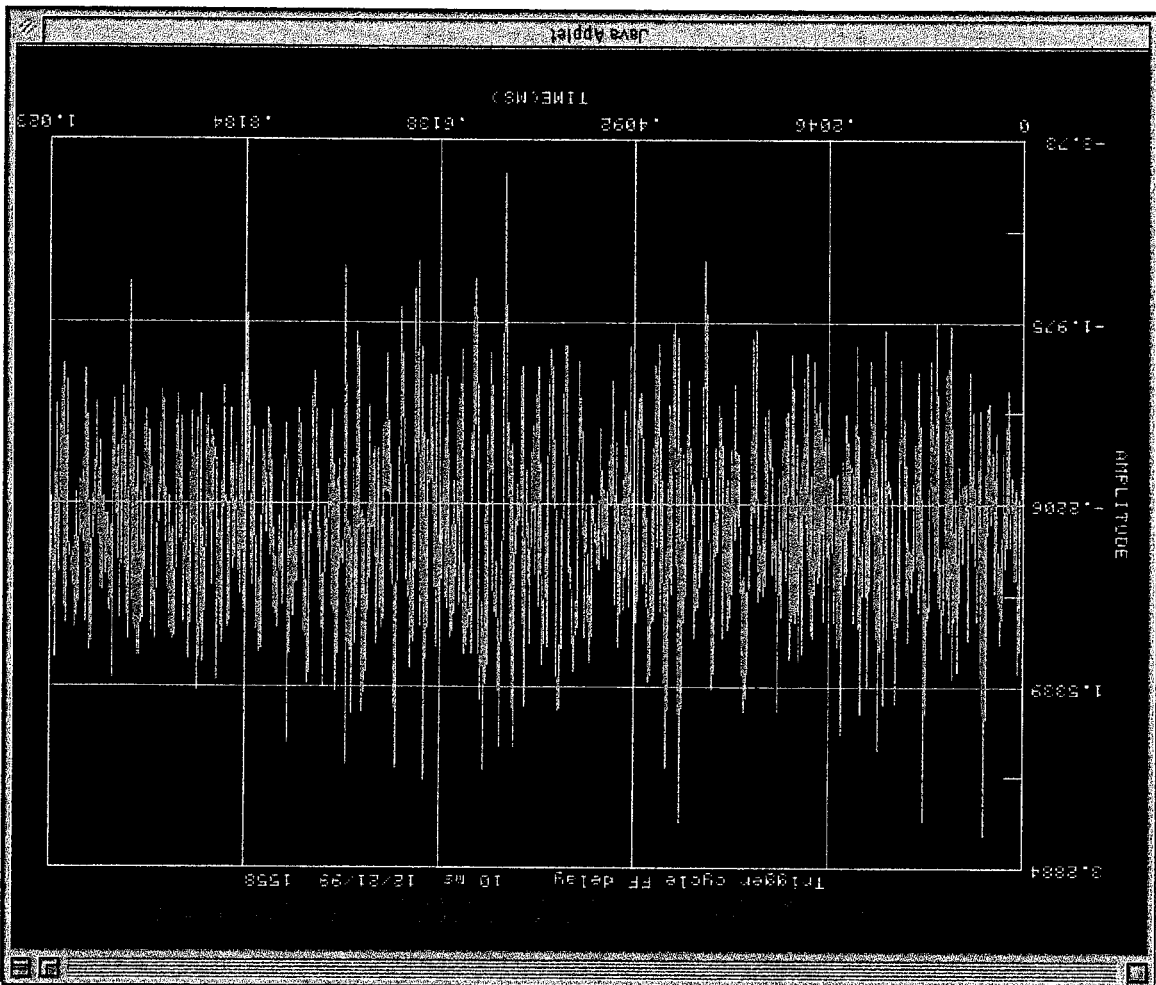
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the 60 Hz line voltage.
Using a Fourier transformation, the time domain information can be converted to the "frequency domain". Figure 12 shows the data of Figure 11 after the transformation. In it we display the frequency spectra, the amplitude as a function of frequency. Note the peak at
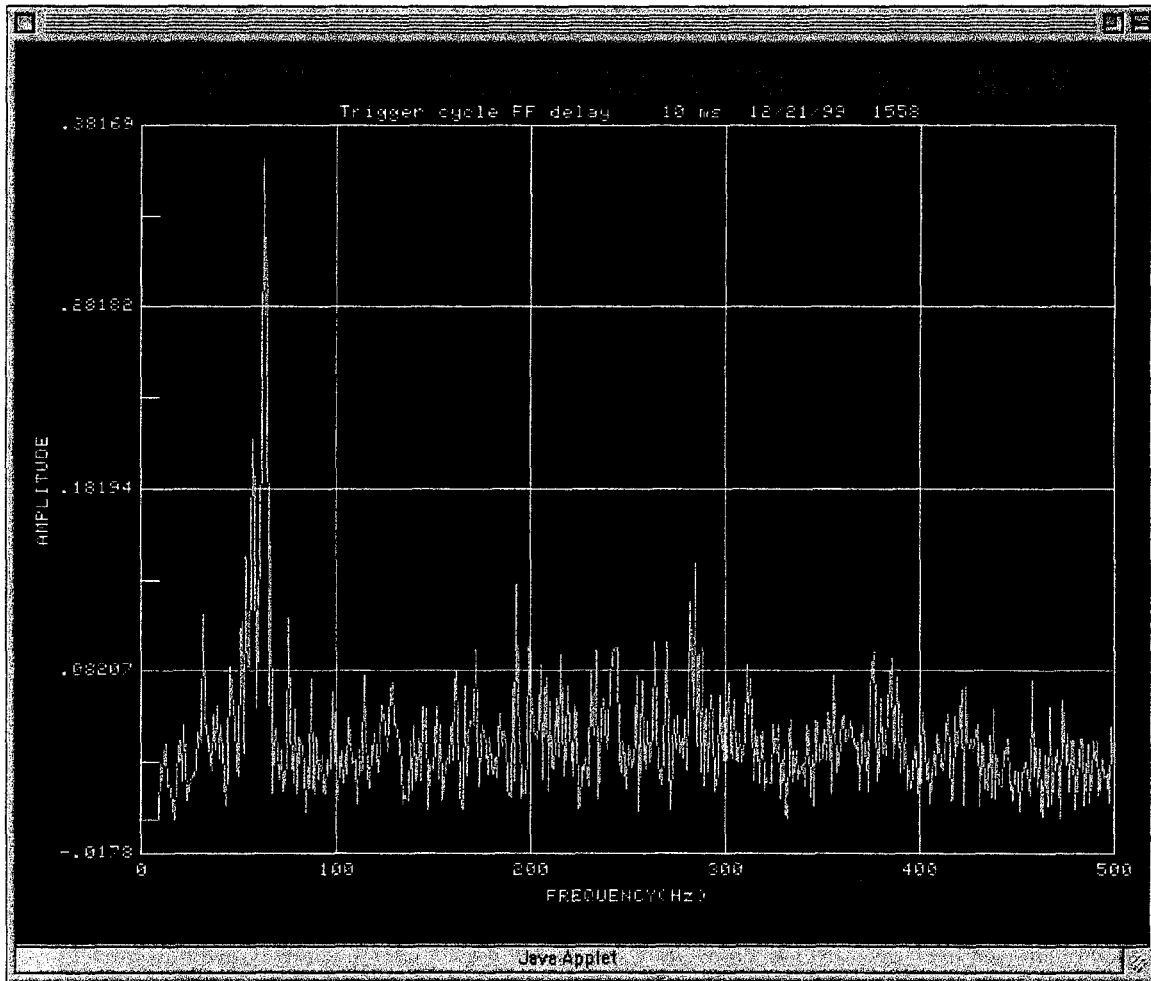
Time Domain Spectra

Figure 12

Figure 13

Frequency Domain Spectra

Although the ability to make these measurements was clearly
demonstrated, software was not readily available to record them so
that the effects could be systematically studied. What is the
important frequency range? How does one use this to predict
failures? These are the important questions which need to be
studied.

What have we learned?

1. Monitoring the operation of a reconditioned TBM can be done
   relatively easily. Instrumentation can be attached to the TBM
   using few "hard" connections and without interfering with

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production. The logged data provides all the information needed to assess the progress and status of a TBM system.

2. The status of the tunneling operation can be posted in real time on the Web where it is available (underpass word control).

3. Provides for data to make rapid decisions (time = $).

4. How do we use all of the information?

5. How can we identify potential failure points?

6. How would we use the accelerometer data?

7. Preventative replacement/maintenance?

8. Identify causes for reoccurring downtime in real time.

9. Comprehensive review without going underground.

10. This was a bi-directional data system. It was used only to monitor the TBM performance. Control functions could also be initiated.