The Operator Interface for the Mirror Fusion Test Facility

Neil C. Lang
Lawrence Livermore National Laboratory
Livermore, Calif., 94550

UCRL--95588
DE87 002755

Introduction

The Mirror Fusion Test Facility (MFTF) is the most recent in a series of experimental facilities at the Lawrence Livermore National Laboratory built to study the tandem mirror concept for magnetic fusion. The primary objective of MFTF is the demonstration of improved plasma confinement by scaling to larger size and higher energy. However MFTF has many other physics and engineering goals. Many technologies such as high-field superconducting magnets, high-current continuous neutral beam sources, and large vacuum and cryogenic systems will have to be developed for a mirror fusion reactor, and MFTF's engineering objectives include the design and construction of these systems.

The uncertain and most likely changing nature of a large experimental facility like MFTF, as well as its large number of control and monitor points, ruled against the traditional hardware approach involving walls of knobs, dials, oscilloscopes, and strip chart recorders. Rather, from the beginning, project management specified computer control of all systems, and operation of the complete MFTF under an integrated computer control system became a major engineering goal. The Integrated Controls and Diagnostics (ICADS) group was charged with the design and implementation of this control system. We designed a control system with an extremely flexible operator interface which uses computer generated CRT displays for output and pointing devices such as touch sensitive CRT overlays, mice, and joysticks for input.

Construction of MFTF was completed at the end of 1985 within the project budget of $241.6M and was followed immediately by a 5 month long acceptance test. During this period (known as PACE test) operators, engineers, and physicists successfully used our computer control system daily to test MFTF. Much of their willingness to forsake the traditional hands-on hardware approach to testing was a result of the powerful and flexible operator interface to the MFTF control system. In this paper, we describe the operator interface with emphasis on the displays, the touch screens, and the mouse. We also report the experiences of users and, in particular, stress those aspects of the user interface they strongly liked and disliked.

Description of the Mirror Fusion Test Facility

In Figure 1 we show an artist's representation of MFTF. The most visible component is the 215 foot long, 35 foot diameter vacuum vessel. Located inside the vessel are the 42 liquid helium cooled superconducting magnets that provide the intense magnetic fields required for confinement of plasma. The vessel, its external pumping systems, and the internal network of large cryopanels provide a vacuum in the vicinity of 10^{-10} atmosphere required to conduct magnetic fusion experiments. Further description of the MFTF facility can be found in LLNL 1986.

Plasma is created by bombarding injected hydrogen gas with high-energy, high-current neutral hydrogen beams. In full operation MFTF will use 22 injection source modules which are powered by 22 outdoor-mounted 90 kilovolt, 90 ampere power supplies. A variety of ion and electron cyclotron resonance heating systems (ECRH) will be used to heat the plasma at appropriate locations within the vessel. The vessel is housed in a 2 meter thick concrete vault to absorb the neutrons produced by fusion events. The area immediately adjacent to the vessel will also experience high magnetic fields whenever the magnet system is operating.

Since this is an experimental facility, MFTF is also heavily instrumented to allow engineers and physicists to better understand its operation. We estimate that in full operation there will be approximately 25000 individual sensors to monitor, as well as 10000 individual devices to control. In addition we expect to collect 8 megabytes of plasma diagnostic data on every physics shot. MFTF is designed to support a maximum physics shot rate of one every 5 minutes.

MFTF is controlled from our centralized control room located a few hundred feet away from the vessel and outside the hostile environment immediately surrounding the vessel. The control room contains seven operator stations or consoles; five of these have three 19 inch and two 13 inch color CRTs while the 2 remaining "super" consoles each have three additional 19 inch CRTs (see figure 2). The consoles use low resolution (640x256) 8-color bit-mapped graphics displays. A detailed description of the prototype console can be found in SPECKERT 1979.

Operators monitor MFTF by calling up the appropriate display panel, and control the facility by manipulating objects on the panels using the mouse or the touch sensitive screens overlaying the 13 inch CRTs. There are no physical keyboards associated with the consoles. Instead a "soft" keyboard is provided on control panels wherever alphanumeric input is required.

The MFTF Integrated Control System

We designed a two-level hierarchical control system (shown in figure 3) to operate MFTF. At the top level is the Supervisory Control and Diagnostics Systems (SCDS) which acts as the interface between the operator and the machine by displaying information on the CRT screens and accepting operator input as described above. SCDS functions as a setpoint controller and performs no real-time closed-loop control. It is the responsibility of the lower level in this hierarchy to perform the actual closed-loop control if required. Furthermore SCDS is capable of responding to exceptional conditions on a human response time of a second or two, and hence all critical parts of the physical hardware on MFTF must be protected by local hardware or software.

In addition to functioning as the operator interface, SCDS provides the central storage facility used to record the current state of the machine as well as to archive selected machine and diagnostic data. SCDS also coordinates activity among the independent systems; in particular SCDS is responsible for checking that all systems participating in a plasma shot are ready before it issues the "ok-to-shoot" permissive.

At the lower level in our control system, we find the Local Control and Instrumentation System (LCIS) consisting of some 60-70 independent LSI11/73 microprocessors which are interfaced through a variety of control and diagnostic equipment to the physical hardware on MFTF. Their main functions are to control the hardware and to perform regular polling of hardware devices and report significant changes to the supervisory system.

The division of the control system along these lines has a number of significant benefits. It allows the use of a common interface between the SCDS and LCIS computers for all subsystems. By requiring that the LCIS computers report only changes we can in many cases reduce the amount of data handling required at the supervisory level. Furthermore, an engineer or technician can control the hardware directly through the LCIS microprocessor for development or checkout purposes.

The SCDS Computer System

SCDS consists of a network of seven Perkin Elmer 3230 and and two 3250 minicomputers connected together by 1 megabyte of shared memory (see figure 4). The 3250 computers each have 8 megabytes of local memory, while the 3230 computers are configured with 2 or 4 megabytes each. Attached to seven of the SCDS computers through high speed serial links are a variable number of functionally related LCIS microcomputers. Each 3230 processor also has a Ramtek controller which drives the CRTs on a control console. The 3250s will be used for controlling diagnostics instruments and processing diagnostic data during physics experiments.

Our network architecture allows for rapid reconfiguration of the system in the event of failure of any single component in which case SCDS must be down for no more than 5 minutes. A second block of shared memory is available in case there is a failure in the primary block. If a SCDS computer fails, its LCIS microprocessors are switched to a designated backup computer. The requisite processes along with any associated machine state data will be started on the backup computer, and machine control will be reestablished within the allotted 5 minutes.

The SCDS control software consists of a number of modules (see figure 5). These include the console system (CS) which manages the displays and operator interactions, the Execute-Action (EA) system which implements operator commands, the LCC manager which handles communication between the SCDS system and the LCIS system, and a data base management system (DBMS) which not only stores and retrieves machine data but can also notify interested tasks whenever entries in the data base have been updated. The Inter Process Communication System (IPCS) handles the message passing between all SCDS components and is the glue that holds the SCDS software together.

A high degree of software modularity and independence results from the message-oriented nature of the SCDS software architecture. Messages are created and sent through standard calls to the IPCS. The initiating task need not know the details of the communication or the location of the destination task (since most messages are passed through shared memory, the destination task can be on any SCDS computer). On the other hand the structure and content of the message is known only by the initiating and terminating task. Hence additions or modifications of SCDS components (especially in the Execute-Action system) are much easier because of the separation of message passing and message content.

Another feature of SCDS software involves machine transparency. For example processes executing on a given SCDS node can communicate with any process on any node and can access data stored on any node without knowing the exact location of the process or the data, since the IPCS automatically routes the messages to the appropriate node. Processes can also be easily relocated in the event of a machine failure with no effect on other processes in the network.

Note that this architecture allows an operator at any console to view data and initiate Execute-Action modules that reside on any node in the SCDS network independent of the console at which he chooses to work. In order to prevent simultaneous control of a device by multiple operators, we implemented a resource control system based on both operator access rights and resource ownership. Every MFTF operator is given a set of access rights corresponding to the devices or systems he is authorized to control. An operator desiring to control a device must first log-in to SCDS using the badge reader on the console. He then takes over the resource he wishes to control. Since a resource can be owned by only one console at any given time, this procedure eliminates the possibility of simultaneous control of any given device or system.

To illustrate the message-oriented event-driven nature of SCDS, consider the activity that results when an operator pushes a button to open a roughing valve in the roughing vacuum system (see figure 6). When the operator pushes a button a message is sent to the Console System (1) which performs a syntactic check on the operation, and updates the control panel accordingly (2). The CS also forwards the message to the appropriate Execute-Action module for a semantic check (4) which involves checking for access rights and resource ownership as well as whether the requested action is allowed at this time. The CS also informs the DBMS to notify it when the valve opens so that appropriate displays can be updated (3). Meanwhile the EA module will send a message to the LCC manager responsible for the LCIS microprocessor connected to the valve in question to start the valve in motion (5-8). When the valve has fully opened, the microprocessor senses that a limit switch on the valve itself has closed (9-10) and reports the valve opening to the to the LCC manager (11), which will update the DBMS to this effect (12). Next the DBMS notifies the CS that the valve status has been updated (13) and finally the CS will query the DBMS to get the new valve status and to update the display accordingly (14).

The SCDS Operator Interface

In the remainder of this paper we discuss in detail the operator interface to the MFTF control system. First we describe typical display and control panels and how to use them. Next we describe the organization of the 227 panels that comprise the SCDS operator interface, and how operators navigate through this collection of panels. We recently modified the console to accept a mouse as input which permitted major changes in the design and use of panels. The operator interface to the Fusion Chamber System was redesigned completely to use the mouse extensively, and we describe this significant modification to the interface. Finally we conclude with operator reaction to the SCDS interface.

Display Panels

Display panels are used to show the operator the current state of both individual devices and complete systems; they typically are brought up on the 19 inch CRTs. An associated software display module (part of the Console System) is initiated whenever a new display is brought up, and it is responsible for updating the dynamic part of the display whenever the corresponding data in the DBMS are modified.

Standard color conventions are followed. We use green to indicate the "asserted" or "on" state; hence a green valve signifies a valve that is open while a green pump signifies a pump that is on. Green is also used to indicate values that have reached setpoint. Red is used to indicate exceptional or dangerous conditions, as well as the off or shut-down state, while yellow is used to indicate a warning state. Data without any particular state associated with it is typically displayed in cyan.

Operators are warned whenever the system determines that a displayed value may no longer be valid. We highlight data whose reliability is suspect by either appending a yellow question mark, or by displaying the data in black characters on a yellow background. This occurs whenever a LCIS computer has determined that a device it is monitoring is no longer functioning, or whenever SCDS notices that the LCIS computer itself has shut down. A more serious, but less common, situation occurs when the display module itself either hangs or crashes and the entire display ceases updating. In this case the console system superimposes a banner on the display warning the operator that the display is no longer active.

Control Panels

Operators issue commands to control MFTF by touching buttons on control panels. Before the introduction of the mouse these panels were always displayed on the 13 inch CRTs since only these monitors were overlaid with a touch sensitive transparent screen. Buttons represent objects and actions that can be performed on those objects, as well as other display and control panels the operator may wish to bring up. Figure 7 shows a typical control panel with buttons representing objects (valves and pumps) and actions (open/close and on/off). The row of 11 buttons at the bottom of the control panel are used by the operator to quickly bring up other related control panels.

A command corresponds to a series of button touches. However only certain sequences of button touches result in acceptable (or legal) commands and operators generally must touch the buttons in a specific order to issue a command to SCDS. To guide the operator, we dash the outline of buttons that cannot be legally selected at that particular time. The legitimate button pushes for each control panel are specified by an LR (left recursive) grammar. This approach is quite general and permits the specification of rather complex button sequences.

Most of our control panels require that the objects be touched first followed by the desired actions. To help the operator, we typically color object buttons green and action buttons blue. When the panel in figure 7 is first brought up only the buttons around the valves and pumps are solid. Suppose the operator chooses a valve. The system acknowledges the button touch by latching the button (indicated by a double border) and issuing a low volume beep. Then the 'open' and 'close' buttons become solid since it now legal to touch these buttons. However the 'on' and 'off' buttons remain dashed because turning a valve on and off does not make sense. In cases involving critical operations an extra confirm or execute button must be touched as part of the command. This reduces the chance that a legal but undesired command will be accidentally issued to SCDS. At any time during a command sequence the operator can terminate that incomplete command by touching the CLEAR CP button. This removes all the latched buttons and allows him to restart.

The elimination of invalid button hits by making buttons unavailable increases operator confidence and reduces the time required to construct a command. This feature is very popular with both novice and experienced operators.

Organization of Panels

We had to organize control panels into some understandable structure so that operators can quickly access the display and control panels of interest to them. We chose to arrange the panels into a hierarchical or tree structure. At the top of the hierarchy we find a source or global view panel which has a button for each major

MFTF system. The operator touches the button for the system of interest and a new panel with a set of buttons corresponding to components of that system is brought up. The operator continues bringing up new control panels by touching buttons until he reaches the control panel with the set of operations he wants to execute. If he wishes to go back up this tree of panels he need only touch the WIDER VIEW button at the bottom of the panel, and if he wishes to jump back to the global view he touches the GLOBAL VIEW button.

Operators also use control panels to bring up display panels on the 19 inch CRTs. We created two distinct sets of control panels. One set is used to bring up display panels only, while the other set brings up control panels for machine control. We explicitly separated these two classes of control panels into a separate display mode hierarchy and control mode hierarchy each rooted in its own separate global view panel. In this way a casual observer in the control room is free to examine any and all displays using the display mode hierarchy of control panels without ever accessing a panel from which he could attempt to exercise machine control. On the other hand an authorized operator can quickly access the control panels he needs to do his assigned work by navigating through the control mode hierarchy of control panels.

We used colored borders to differentiate these two hierarchies of control panels. White borders indicate control mode while purple borders indicates display mode. We extended these conventions for panel borders to include red for exception system panels and orange for access rights and resource control panels.

The DISPLAY MODE and CONTROL MODE buttons at the bottom of a control panel allow for rapid movement between control panels in the two hierarchies. They are designed to permit an operator to quickly bring up display panels and then return to control mode.

The SAVE CP and GET CP buttons allow operators to store and recall a control panel while the LAST CP button allows operators to toggle between the two most recently used control panels. In practice operators took moderate advantage of the LAST CP button, but rarely elected to store control panels for fast recall. This reflected the fact that related control panels were usually very close in the panel hierarchy and hence operators could get from one panel to the other using other buttons on the panel.

The ACCESS MODE button brings up the resource ownership panel which operators use to take over or relinquish control of the MFTF resources they are responsible for. As indicated above an operator must own the resource before the Execute-Action system will accept any commands involving that resource. It should be noted that SCDS allows any authorized operator with appropriate rights to 'steal' any currently owned resource. This counterintuitive feature allows rapid reassignment of resource ownership, and thus control, from one console to another in the event of an emergency; for example the test director might notice trouble in a given system and could take ownership of the resource to place the system in a safe state if the appropriate operator were not at his console at the time. This feature of course demands that operators in routine, non-emergency situations check very carefully that a resource is not already owned before trying to acquire ownership. This was not a problem in the small MFTF control room where operators could easily talk to one another.

The SCDS Exception Handling System

An exception in SCDS is defined as any unusual or unexpected event. A command that failed to be executed in the hardware, and a monitored value that exceeds a critical limit are two examples of exceptions. When an exception is recognized SCDS automatically records the exceptions in a permanent machine journal, and immediately attempts to notify the operator who owns the resource by displaying an exception message at the bottom of the center 19 inch CRT on his console (NOWELL 1979). Each exception has a priority associated with it reflecting the severity of the event. Exception messages are color coded on the screen to aid the operator in evaluating their significance. Low priority exceptions appear in cyan while the highest priority messages appear with a flashing red background. If more than one exception arrives at the console the most recent exception of highest priority is displayed and the others are stacked up behind it. To view outstanding exceptions, the operator touches the EXCEP DISP bottom row button to list the 10 most recent exceptions. Operators are expected to examine this list of exceptions with care as they will disappear when the EXCEP DISP button is touched again.

Operators expressed considerable dissatisfaction with the incomplete implementation of the exception handling system. Operators could not view exceptions by priority or subsystem nor could they acknowledge exceptions individually. Furthermore in order to restore the bottom part of the center display which had been overwritten with the exception message, operators were forced to acknowledge all outstanding exceptions.

As we indicated above, the exception system tries to notify the operator most likely to be interested in the exception. In most cases that is the operator who owns the resource. However if that operator is logged out at the time or that resource is no longer owned, then the exception system tries to find another operator who ought to be informed. During the PACE test it was quite common to have only the test director for that shift logged in. Operators in charge of individual systems very often logged out whenever they left the control room. The single remaining logged-in operator would then receive every exception generated by all systems. The volume of messages was compounded by the tendency of application programmers to use the exception system to report any event of more than passing interest. Another major source of messages were inappropriate alarm limits on devices; noisy devices could cross the boundary between the alarm and non-alarm state quite frequently and would generate an exception message every time. It is very difficult for operators, under these conditions of message inundation, to properly examine and interpret the messages, and in some cases significant exceptions were lost. A good exception handling system must filter and sort the exceptions so that operators are presented only with the most significant information.

Initial Testing of SCDS during Technology Demonstration

During the first quarter of 1982 the project met a major milestone (called Technology Demonstration) by successfully pumping down one end-dome of the MFTF vessel, cooling two superconducting magnets to liquid helium temperature, and operating the magnets at their design current of 5775 amperes. Operators used SCDS to control and monitor the MFTF system during much of this period, thus verifying that SCDS in fact did work. However this testing did reveal some significant deficiencies in SCDS. The most significant one involved an unacceptably large degradation in SCDS response time during periods of high activity (WYMAN 1983).

We analysed this degradation and identified a number of major contributors. The most significant factor was inadequate memory in the SCDS computers which prevented all necessary code modules from being resident simultaneously. This sometimes could prevent both Execute-Action and display modules from being loaded immediately upon operator request. We upgraded the computers shortly after Technology Demonstration, and added sufficient additional memory to ensure that all code modules in use at any given time would remain memory resident. We also allocated more memory to the DBMS to keep data base table memory resident, redesigned the DBMS notification facility to reduce execution time (LANG 1983), redesigned the application level interface to simplify user calls to the DBMS, as well as optimized critical sections of the DBMS to increase execution speed. Application programmers in many cases redesigned their data base tables to minimize the number of data base accesses required to process monitor reports from the LCIS computers. We also enhanced the software in the LCIS computers to eliminate unnecessary monitor reports and thus reduce the number of reports to be processed by SCDS. These software changes were implemented in the two years following the 1982 Technology Demonstration. During our 1985 PACE acceptance test operators found the response time to be highly acceptable and we rarely observed any degradation in response time.

Technology Demonstration also revealed a problem with the organization of operator panels for the Fusion Chamber System (FCS). The separation of control and display panels into separate hierarchies worked best for systems typically involving a small number of control points, and hence a small number of control panels, and a much larger number of values to be displayed. While most MFTF systems satisfied this pattern, the Fusion Chamber System consisted of approximately the same number of display and control panels. FCS operators experienced some trouble switching between the panels in the separate hierarchies, and requested that corresponding display and control information be displayed on a single panel. They also requested that the amount of control function per panel be increased to allow control of a FCS subsystem from a single panel. Since implementation of the full FCS system for PACE involved a three-fold expansion in the number of controls, we decided to redesign the FCS interface. In the next section we describe the changes we made to the FCS control system to satisfy the operators' requests.

Enhancement of the Operator Interface for PACE Test

Addition of a Mouse

In mid 1985 we added a mouse to each of the seven consoles. By moving the mouse, operators moved a cursor that appeared on the face of a CRT screen. Depressing the mouse button selects or "picks" the object under the cursor and is equivalent to touching an object using the touch screen. The cursor can be moved easily from one screen to another allowing operators to select objects on any screen at the console. However we did not attempt to provide other mouse related functions such as dragging (i.e. moving the mouse with a mouse button depressed). Although the mouse basically replicated the pointing and selecting functions already provided by the touch screens, buttons and other selectable objects no longer had to be confined to the two 13 inch monitors.

Use of the mouse allowed significant changes in the design of panels. On touch screens, buttons had to be at least as large as the imprint of a fingertip. With a mouse, buttons can be shrunk to the size of the cursor allowing more selectable objects to placed on a control panel. Furthermore the mouse eliminated any errors associated with parallax and touch screen miscalibration which had significantly limited how close buttons could be located on control panels.

Another way in which we took advantage of the mouse involved adding a LAST SCREEN button to each display to allow operators to toggle back and forth between two different displays on a single CRT. This effectively doubled the amount of display screens without adding more CRTs.

Redesign of the Fusion Chamber System Operator Interface

The addition of the mouse allowed us to completely redesign the fusion chamber system panels to better implement the three-fold expansion of that system. First we eliminated the concept of separate control and display panels. Most FCS panels show both selectable objects as well as status displays, and the panels can be displayed interchangeably on the 13 and 19 inch monitors. The bottom row buttons on older control panels have been replaced with a narrow band of buttons with similar function at the top of the panel increasing somewhat the amount of space available for machine control and display.

Figure 8 shows a typical new FCS system panel. These panels are based on a schematic representation of the system, in which components are identified by symbol shapes and color instead of descriptive text strings. To further reduce the number of panels we pack the displays rather densely with both selectable objects and monitored values. We also removed the button outlines that identified selectable devices on the screen, although the invisible button became visible and latched whenever the object was selected. Note that the action buttons such as "OPEN" or "ON" normally associated with valves and pumps cannot be found directly on these new panels. When an object is selected the corresponding actions appear in a new menu which temporarily overwrites the top menu bar. These changes allowed us to meet our goal of a single panel for each FCS subsystem. In fact we were able to implement the expanded FCS control system using about the same number of panels that were used for Technology Demonstration. The FCS operators felt strongly that concentrating related control on a single dense panel was superior to splitting it over two or more panels.

We also organized the the FCS panels into a network connection. Any panel closely related to the current panel in use appeared as a button on that panel and could be reached directly with a single button touch. All other FCS panels could be reached indirectly through a system directory panel listing all FCS panels grouped by major subsystem. This panel was accessible by touching the MASTER button on any FCS panel. Hence any panel was at most two screen selections away. This network organization was very well received by the operators.

Enhanced Displays

Most SCDS displays map a set of entries in the DBMS to specific locations on a display screen. The value in the data base is displayed as a number, text string, special symbol, or even simply as a color at a specific location on the screen. That part of the screen will be updated whenever the value in the DBMS is changed. A small number of SCDS displays are somewhat different; they may display time variations in previously measured parameters or even large blocks of text stored in the DBMS. These special displays were enhanced considerably with the addition of the mouse.

An example of such an enhanced display is the waveform plotting facility used by operators running neutral beam injectors or the ECRH system to look at the many waveforms collected during a shot. Figure 9 shows a typical waveform display in which up to 8 different waveforms can be plotted (the waveforms are color coded for identification). The operator can "zoom" in on any part of the displayed data by using the mouse to pick the lower left and upper right corners of a rectangle he wishes to see in expanded format.

Although the machine control part of SCDS is required to keep only the current machine state, there are situations in which operators need to examine some time history of machine parameters. One example of this need arose during vessel pumpdown at the beginning of the PACE test. Here operators found the rate of pressure change in the vessel over a period of hours to be a helpful diagnostic. To provide this short-term archiving capability, we created a DBMS table that functioned as a circular buffer in which we recorded the most recent 30 hour history of approximately 200 parameters in the FCS system. Next we modified the waveform plotting routines described above to display an operator selected subset of these machine parameters as a function of time. We then added a real time parameter plotting capability in which we plot the next 10 minutes of values for selected parameters in real time. FCS operators were able to make better informed decisions about the performance of the pumping system using our new time history plotting capability (see fig 10 for an example of a vacuum system real time plot). The real-time "trending" facility was also used extensively by the magnet system operators to follow magnet charging curves during their phase of PACE test.

We also recognized several applications in which we needed to display a variable amount of text on a display screen. The list of currently tripped alarms in the magnet system is an example of an application in which the text could fill as little as a line or two on the screen or could require many screens. We developed a customized text display in which a portion of the complete text is shown in a window on the display screen. Users can then scroll forward or backward by picking the appropriate button in a scroll bar at the right of the display.

Figure 11 shows a text display of this type used to browse through the contents of the SCDS machine journals. This display was very handy during code checkout since the application programmer could see immediately all relevant messages that his code was logging to the journal. During regular PACE operations this display overcame some of the shortcomings of the exception handling system, as operators could now locate and review previously acknowledged exceptions. Operators select the "P" or "L" icon or button at the top or bottom of the scroll bar to scroll backward or forward a page or line at a time. A visual cue in the scroll bar itself shows the relative location of the displayed window. Operators can also pick at any point in the scroll bar to display the text at that relative location in the journal.

These specialized displays clearly show the wider variety of displays made possible by the addition of a mouse to the control system. Some features such as the plot rescaling would be impossible without the mouse. Some other features of these special displays could have been implemented using only touch panels for operator input. However we would have had to dedicate one of the touch panels for the operator controls and the code would have been considerably more complex reflecting the spread of the display over two separate panels.

Performance of SCDS during PACE Acceptance Test

Construction of the MFTF vessel and other systems was completed in the fall of 1985. This was followed immediately by a 5 month long period of testing in which all major systems of MFTF were operated. During this period we pumped the complete vessel down, activated the liquid nitrogen and liquid helium cryoplants and cooled the large cryopanels and all 42 magnets inside the vessel to the their operating temperatures. We tested each magnet individually, and operated all 42 simultaneously at their design currents. We also operated two neutral beam sources in the vessel as well as one ECRH source, and we verified the SCDS shot synchronization system by firing neutral beams and ECRH simultaneously. All of these major milestones were accomplished using the SCDS control system.

SCDS performed excellently during PACE test. The major software components of SCDS performed flawlessly and the few times that SCDS was unavailable during this period involved hardware failures. The changes we made after Technology Demonstration to eliminate the degradation of response time worked well. Operators found the SCDS response to quite adequate, and we rarely observed any significant degradation in response.

Much of SCDS success can be attributed to its modular design which permitted individual Execute-Action modules and displays to added, modified, or removed without affecting other code in use. Hence we were able to add major features such as the real-time plotting facilities very quickly, as well to update and to reinstall individual displays to reflect last-minute hardware changes. SCDS flexibility and ease of change was greatly appreciated. The only major component of SCDS that proved less than satisfactory was the exception handling system which under certain circumstances inundated the operator with too many reports and provided no way to examine them in any logical fashion.

Operators quickly learned how to use SCDS and in most cases chose to operate the facility (even during component checkout) from SCDS whenever possible. SCDS provided operators and the test directorate a number of features not available at the various local control stations. They had a wider range of control and display functions available at the SCDS console. The were able to take advantage of the time history and real-time plotting facilities. They had access to information from other major systems. And perhaps just as important was the quiet, well-climatized environment of the SCDS control room. Operators in general had high praise for SCDS, and the test director viewed SCDS as being one of the best functioning systems in all of MFTF.

We canvassed a few operators after PACE test for suggestions for improvements to the operator interface. They suggested a few enhancements including 1) the addition of a numeric keypad to the console itself to replace the soft keypad on control panels used to enter setpoints and other numerical parameters. This would free up space currently used for the keypad on a number of screens. 2) The addition of a "display data on demand" feature to allow operators to look at data for selected devices at greater detail for a short period of time. 3) A device map should be provided for certain dense and complicated displays to associate a device name with a display value. We made some preliminary attempts to provide this, but more effort is needed to complete this feature.

The Ramtek display controllers and CRT monitors were acquired before 1980, and our interface certainly suffered from the limited 256x640 pixel resolution as well as the single upper case character set. Modern display hardware has much higher resolution and usually offers character sets in a variety of sizes and shapes. The use of higher resolution graphics and along with judicious use of character size and shape would produce considerably enhanced graphics. In particular character attributes such as boldface could be used quite profitably to focus the operators attention to specific areas of the screen. These newer systems usually offer a richer palette of colors, but our experience indicates that subtle color variations are undesirable for many reasons including the need to maintain monitors to much higher standards to maintain color fidelity. Furthermore not all operators can distinguish subtle color differences.

The addition of a mouse allowed us to compare mice and touch panels as modes of operator input. The FCS operators (many of whom had little if any experience with a mouse) adapted to the mouse immediately. A large majority of these operators used the mouse exclusively even when the panel of interest was displayed on a monitor overlaid with a touch panel. Many reasons were expressed for their choice ranging from ergonomic and comfort (they didn't have to sit upright and close to the panel) to more reliable button touching due to the elimination of parallax and touch-panel miscalibration errors. On the other hand a few operators preferred using the touch panels whenever they could (some persisted even when the displays contained densely packed small buttons).

Operators in the other systems used panels that followed the traditional separate control/display philosophy and had little occasion to use the mouse on the 19 inch displays. Nevertheless many of them, for the reasons given above, used the mouse regularly in lieu of the touch panels.

Conclusions

SCDS provided a powerful and flexible alternative to the traditional hardware oriented control system. With SCDS information and control is brought directly and conveniently to the operator making his job simpler and safer to accomplish.

Operators were very satisfied with the SCDS response time during the PACE acceptance test. The addition of the mouse to the operator's interface was a major success. It permitted the extension of control functions to all screens on the console, allowed the creation of more densely packed panels that better matched the control requirements for certain major systems, and resulted in a series of mouse based specialized displays. Operators adapted to the mouse rapidly and many operators preferred the mouse to the touch panel.

Acknowledgments

The SCDS control system for MFTF was designed, implemented, and tested

by a large group of people in the Integrated Controls and Diagnostics group between 1978 and 1985 and it is impossible to list all members individually. Nevertheless the following people who were primarily responsible for upgrading SCDS prior to PACE testing should be acknowledged: Bob Pancotti and Jim Spann were responsible for the console upgrades including the addition of the mouse. Donna Nowell redesigned the FCS operator interface to meet that system's requirements, Bron Nelson redesigned much of the DBMS to greatly simplify data base access, while David Butner was responsible for the tailoring the operating system and the InterProcess Communication System software to satisfy the needs of rest of the group. John Woodruff designed and implemented the neutral beam/ECRH systems while Bob Palasek and Vickie Renbarger were responsible for magnet data acquisition. The author personally was responsible for the upgrade of the DBMS notification system as well as for the operator interface for the magnet power and protection system. This work was performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under contract number W-7405-ENG-48.

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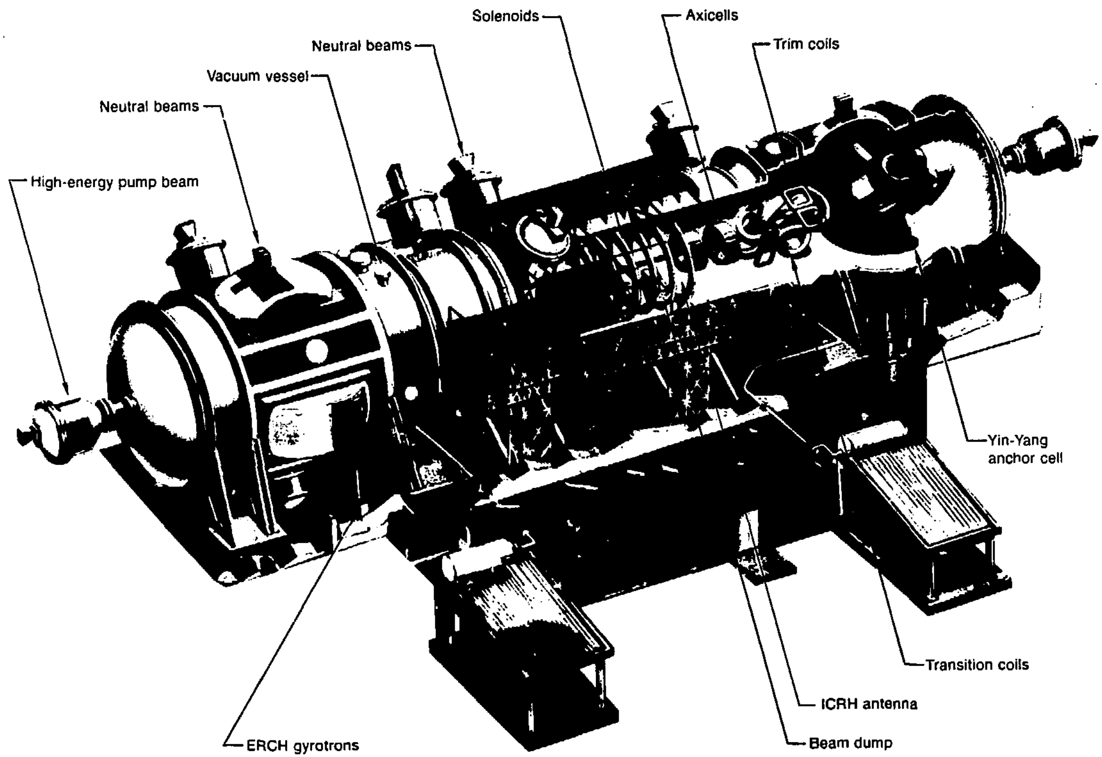

Figure 1. The MFTF vacuum vessel is shown in partial cutaway revealing the magnet and plasma heating systems. Not shown in this sketch are the vacuum and cryogenic systems.

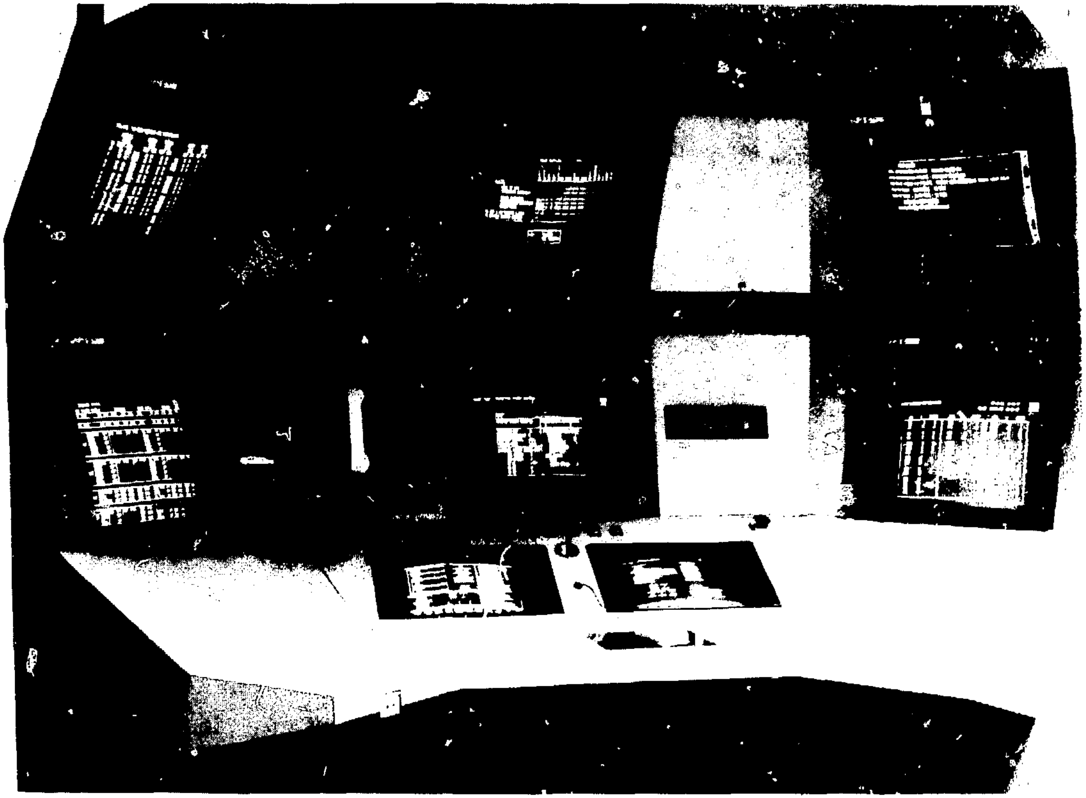

Figure 2. The MFTF operator console with 8 color CRTs used for displaying machine status and control panels. The operator controls MFTF by selecting items on the display using either the mouse or the touch-sensitive screens overlaying the lower two CRTs.

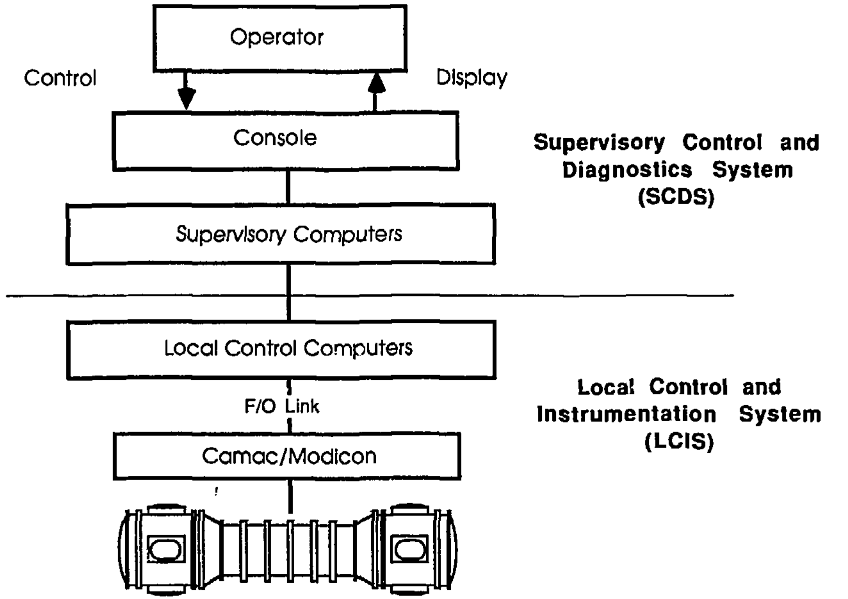

Figure 3. The MFTF hierarchical control system showing the division between the Supervisory and Local control systems.

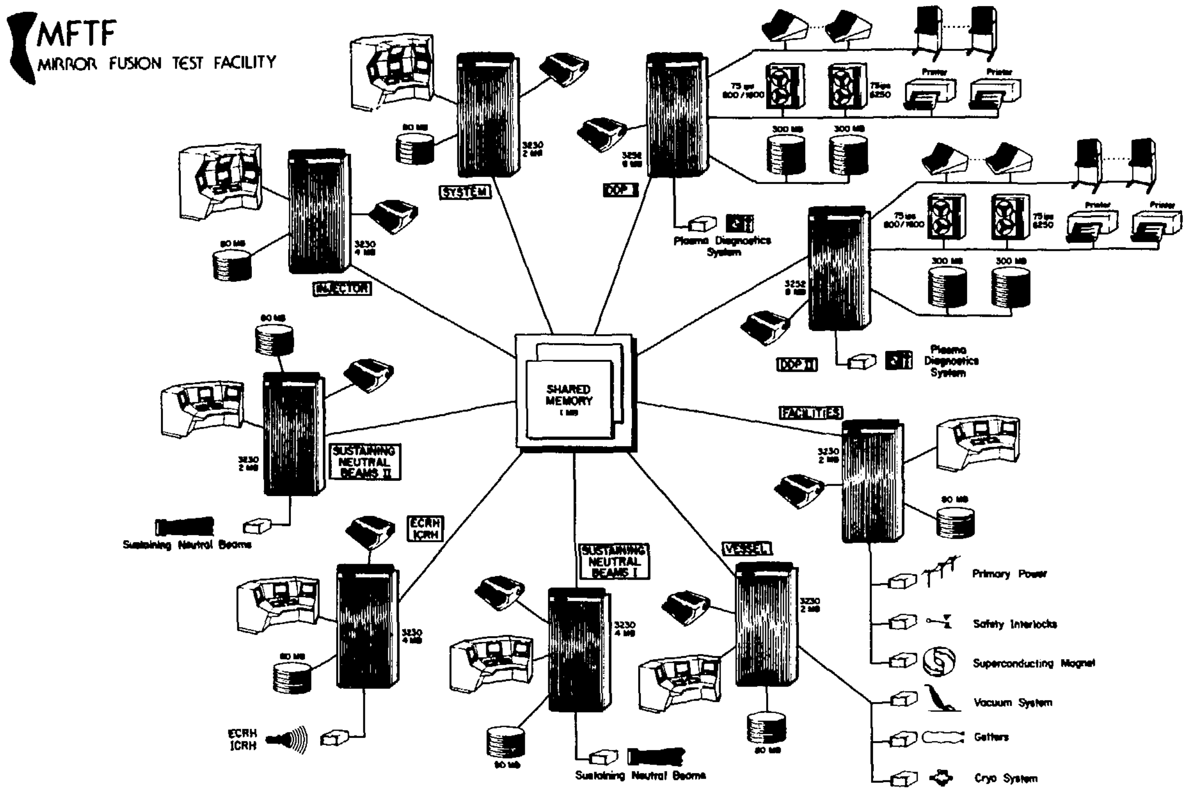

Figure 4. The SCDS computer network showing the 9 Perkin-Elmer minicomputers connected through one megabyte of shared memory. Also shown are some of the local control microprocessors attached to each SCDS node.

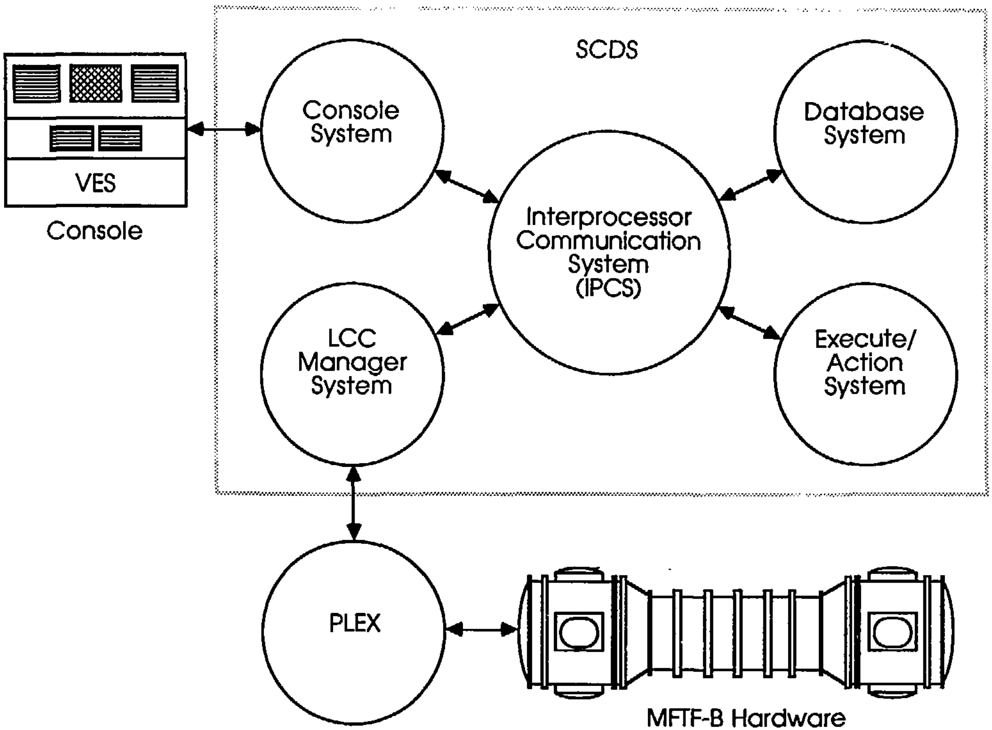

Figure 5 The major software components used to operate MFTF; those inside the rectangle reside on SCDS.

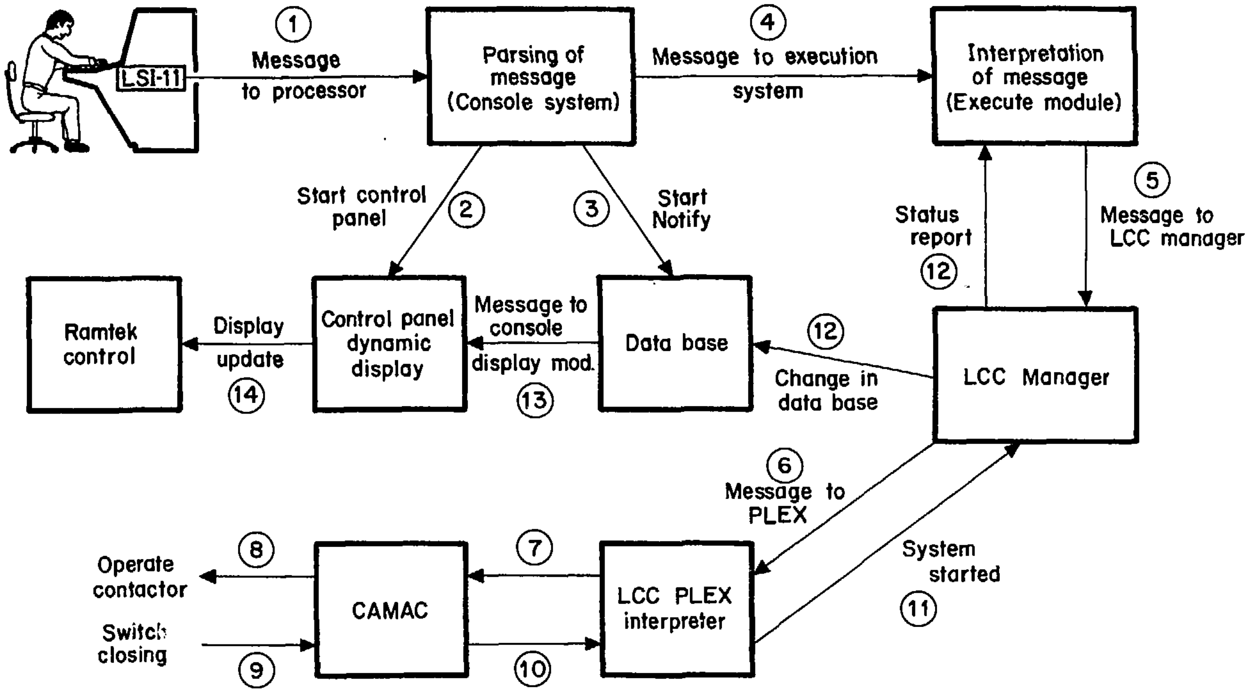

Figure 6. The sequence of events required to process an operator command to open a roughing valve.

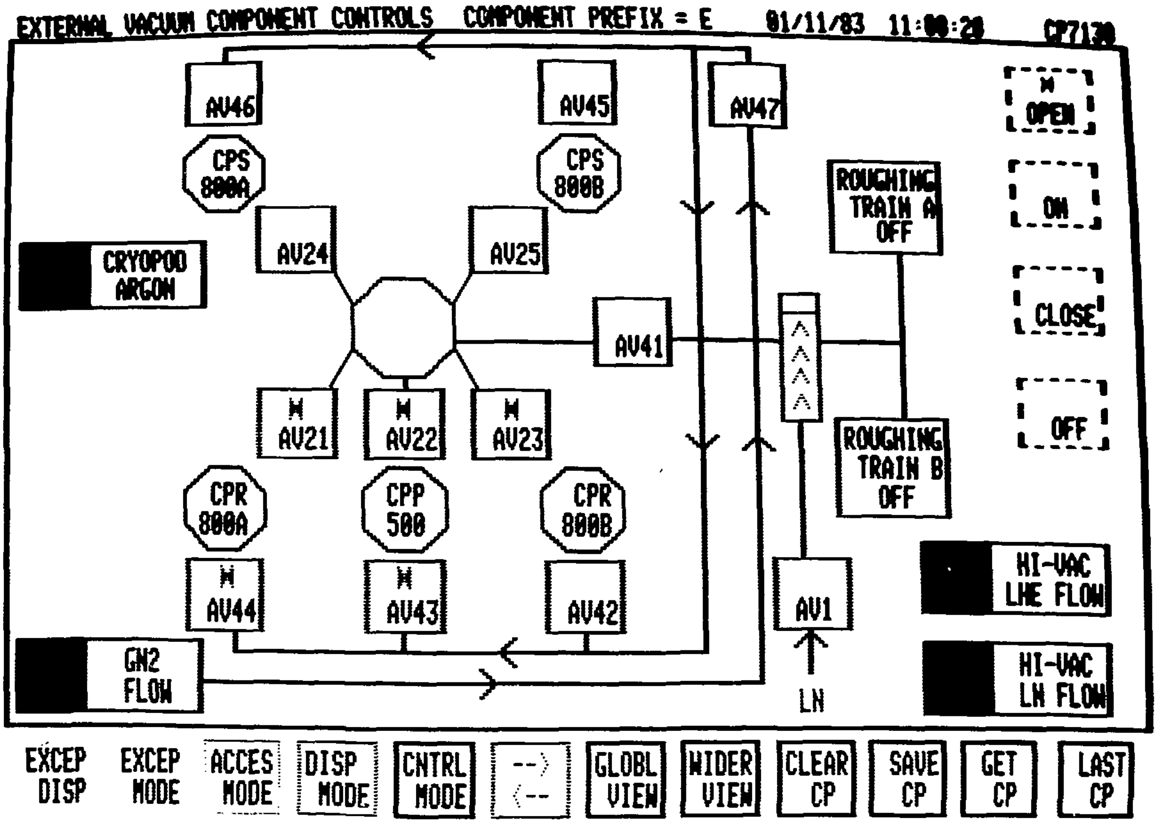

Figure 7. A first generation MFTF control panel illustrating buttons representing devices, actions, and other control/display panels.

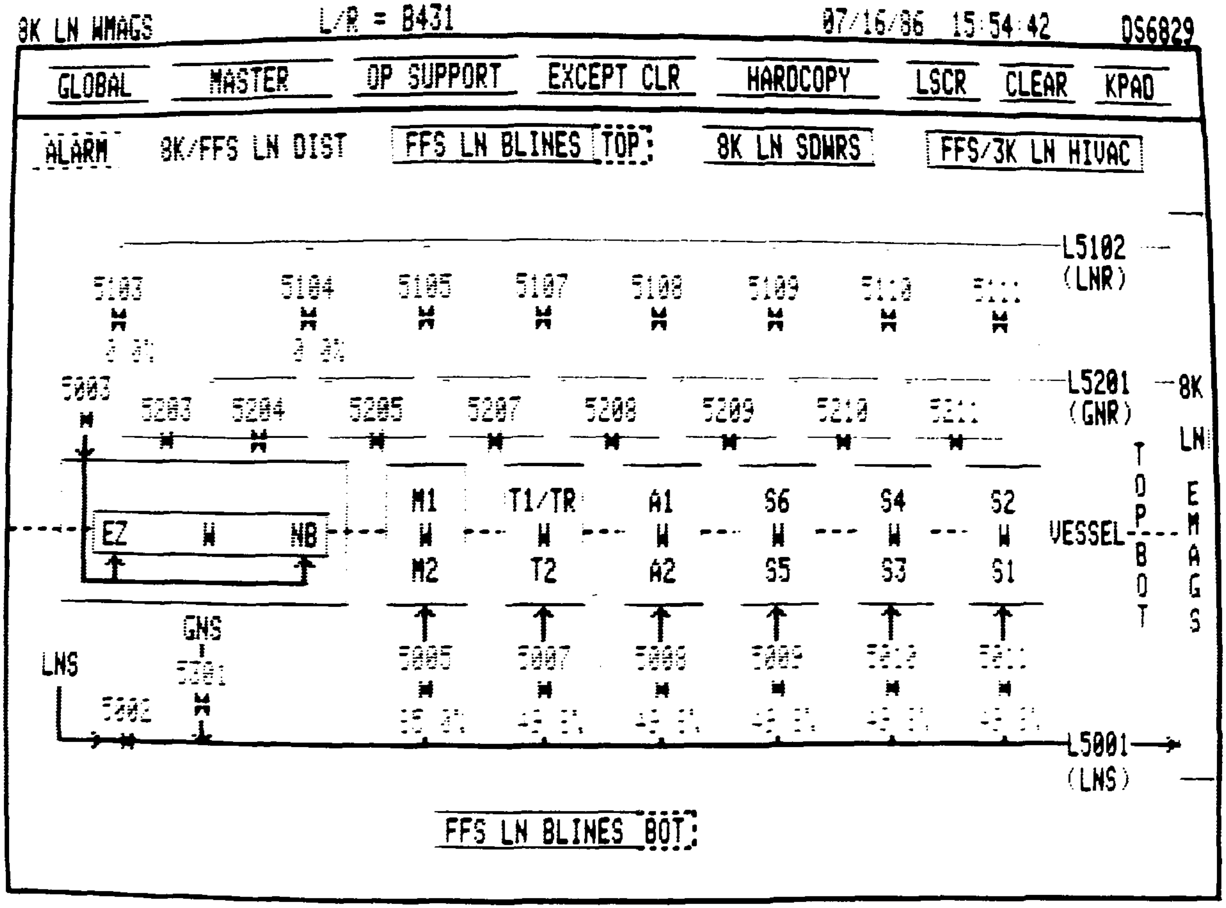

Figure 8. A modified Fusion Chamber System panel designed for use with the mouse.

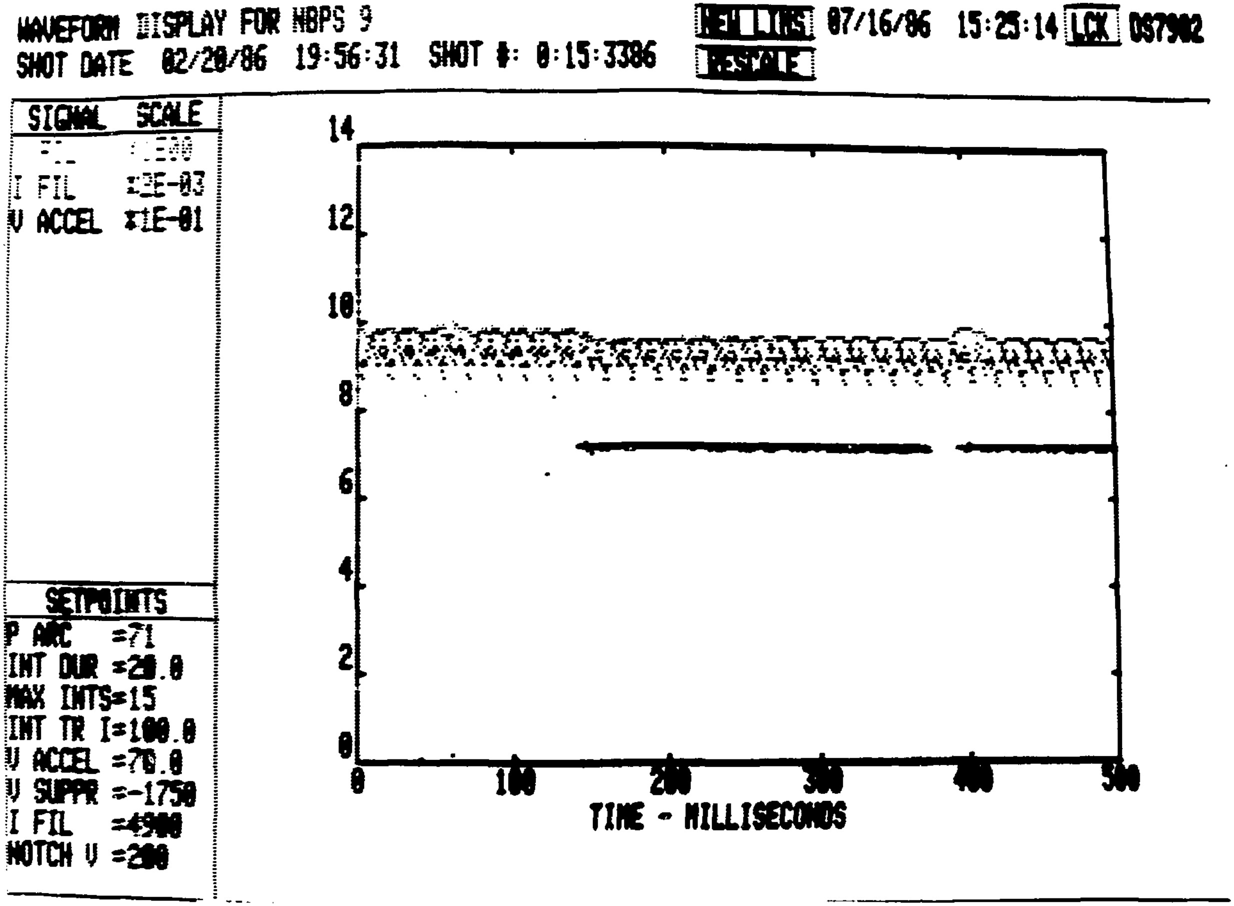

Figure 9. A SCDS waveform display showing waveforms for three neutral beam power supply parameters during a 0.5 sec shot.

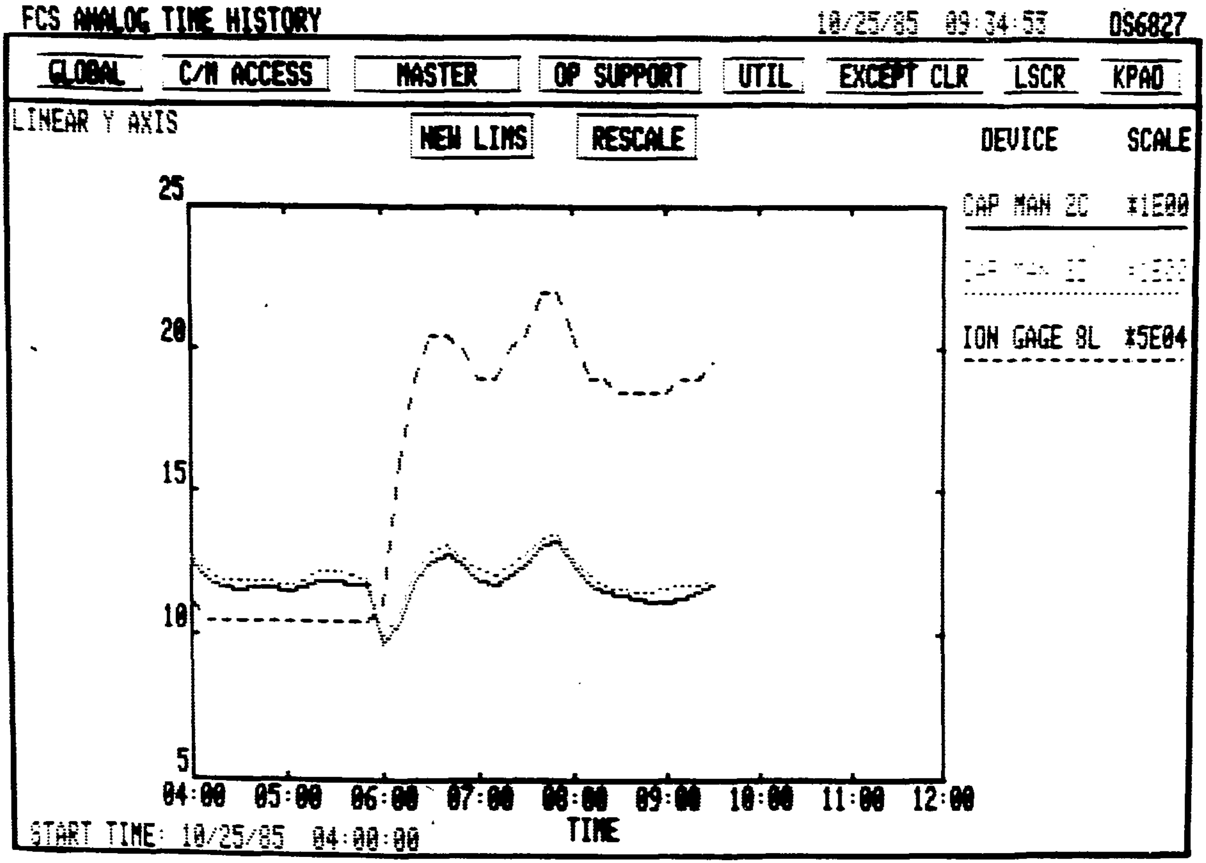

Figure 10. A time-history display showing the prior 5 hour history of three pressure monitors in the vacuum system.

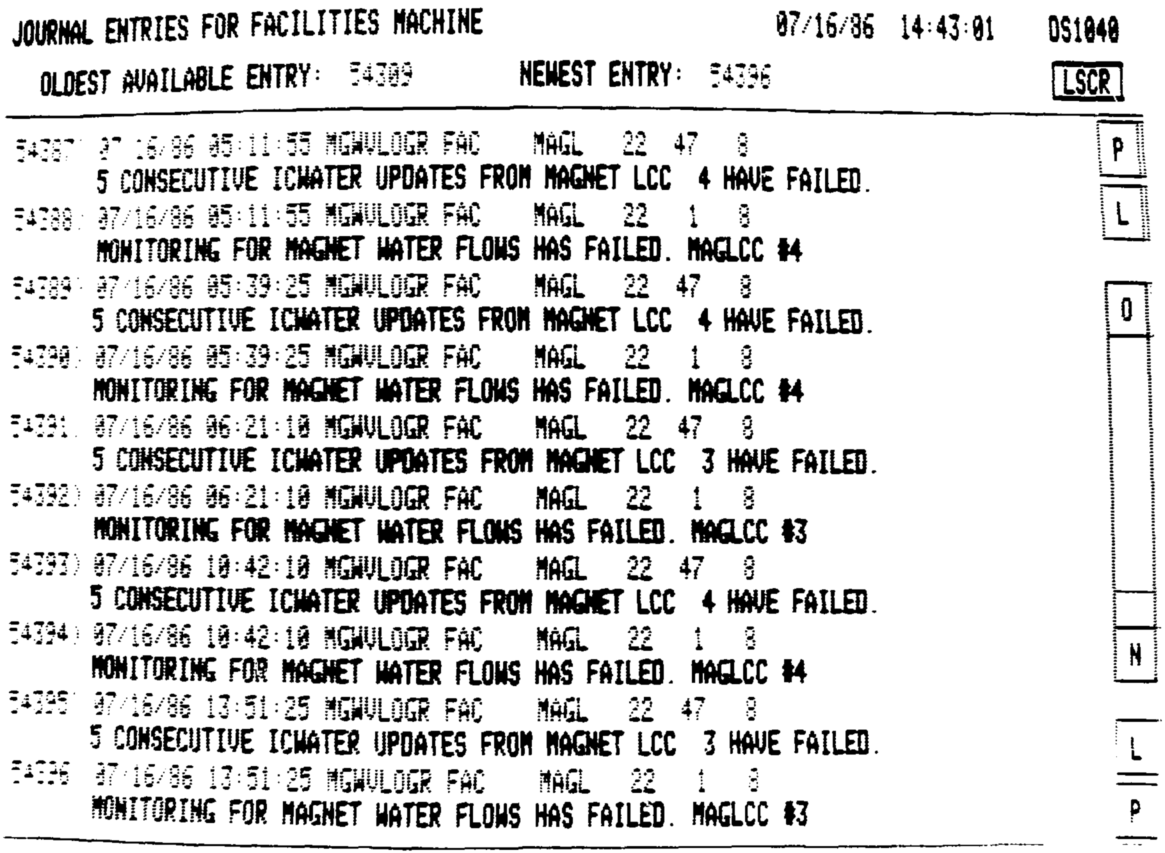

Figure 11. A text-window display used to scroll through the machine journals. Operators select icons in the scroll bar to move forward or backward through the journal.