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CONTROL SYSTEM FOR THE NBS MICROTRON ACCELERATOR[*]

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As various subsystems of the National Bureau of Standards/Los Alamos racetrack microtron accelerator are being brought on-line, we are gaining experience with some of the innovations implemented in the control system. Foremost among these are the joystick-based operator controls, the hierarchical distribution of control system intelligence, and the independent secondary stations, permitting sectional stand-alone operation. The result of the distributed database philosophy and parallel data links has been very fast data updates, permitting joystick interaction with system elements. The software development was greatly simplified by using the hardware arbitration of several parallel processors in the Multibus system to split the software tasks into independent modules.

1. Introduction

The National Bureau of Standards (NBS) racetrack microtron (RTM) control system offered an opportunity to try some innovative approaches to the general problem of small distributed-intelligence machine control because of several unique constraints. The major difference between this control system and many other accelerator control systems is that it had to be designed, tested, and largely debugged three thousand miles from the final machine location and had to be brought into operation a section at a time as the various components of the accelerator were developed. This constraint dictated a modular design of independent units that could be operated singly and then coordinated into an efficient integrated unit at the end of the development.

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As the control system was begun, the following criteria were imposed on the design:

- Commercial equipment would be used wherever reasonable to avoid costly maintenance and esoteric interfacing problems.

- The entire system would be based on distributed intelligence that could be modularized and brought into operation one station at a time. This requirement culminated in three secondary stations linked to a primary station and several tertiary stations. Each secondary station can be operated in a stand-alone mode to permit rapid development of the accelerator section by section.

- The link between secondary and primary stations had to be fast enough to permit timely response to operator control at the primary station. We decided that five data updates/second was a minimum response rate. In the end, this criterion dictated a parallel byte-wide link from the primary to each secondary in a star configuration.

- At each secondary station, sufficient flexibility had to be available to permit fairly complex closed-loop engineering tests to be implemented in minimum time. This criterion dictated a conversational engineering interpreter program in the secondary station that could be used to quickly set up or modify engineering field tests.

- At the primary station, the operator must be able to control a large number of system elements--perhaps as many as a thousand--quickly and easily. After much experimentation, two dual-axis joysticks equipped with push buttons of the type used in jet fighter aircraft were selected because these provide simple, fast, single-handed control of system components.

The final system configuration is shown in fig. 1, which clearly indicates the multiple hierarchy. The advantages of the central primary station linked to multiple secondary stations, which in turn are linked to several tertiary stations, are that each unit can be independently developed and checked (thus greatly shortening development time) and that local intelligence at the systems being controlled reduces the general wire plant with its concomitant lack of reliability. The major disadvantage of this hierarchical structure is that overall system response may be hurt by the many data links unless these are very fast and well handled at the primary station by custom software. This need for very fast data links was the compelling reason for the decision to use multiple parallel links between secondary and primary stations and to write the software drivers in assembly language.

2. Control-system overview

Figure 1 shows the overall control-system configuration. The basic structure is a triple hierarchy with a central control point (the primary station) linked to three secondary stations, which are linked to tertiary stations as necessary. In this system, four tertiary stations were used. The accelerator devices under control of the system, which fig. 1 does not show to this detail, are connected to appropriate I/O boards in the secondary Multibus crate and tertiary Multibus crates. At this time, all major control elements are fully operational and have been extensively used to test and develop various accelerator subsystems as needed. Secondary stations provide local control of a subset of the accelerator parameters by means of a local control panel, and can be operated separately from the primary station.

Tertiary stations are used to distribute the processing requirements of a secondary station, as in the case of the RTM magnet power supplies, or to provide control and monitoring functions in a hostile environment, such as the injector tertiary, which operates at 100 kV.

When the initial system requirements were specified [1], we underestimated the number of elements to be controlled, but the addition of database entries to the secondary systems attests the flexibility of the system. At present, each secondary database can service 340 entries if the system memory used is 16 kbytes, or 640 entries for the 32-kbyte memory. Operating experience has shown that system response has not been hurt by the additional entries. [2]

3. The primary station

Figure 2 shows the equipment layout and placement of the primary central control station. The main operator interaction point is the right-hand two-rack locations where the joysticks and keyboard are located. A photograph of this main control position is shown in fig. 3, where the joysticks with their display consoles are clearly shown. The block diagram of the primary station is included in fig. 1. As indicated in fig. 1, the primary station consists of two Multibus crates linked externally through dual-ported RAM. The foreground control system is a four-slot Multibus crate containing an Intel 80/24 single-board computer, an 8-kbyte RAM dual-port memory board, and two custom parallel interface boards, one for the joysticks and one for the four parallel links to the secondary stations. All operator interactions with the system control are channeled through this part of the system. Peripherals attached to the processor include a color alphanumeric video display; dual 2-axis joysticks with dual-position trigger and three thumb-operated push buttons; a 30-line by 80-character alphanumeric video green-screen display; keyboard; and a CP/M subsystem. The second Multibus crate contains the CP/M subsystem operating essentially in the background in order to provide software development functions, data plotting and analysis, and RS-232C serial link to the PDP-11/44.

The primary station functions as a central communications and display system. It does not contain the element database, but communicates with the system elements through the databases in each secondary station. Operator inputs are accepted from either the joystick controls or the keyboard, and the corresponding commands are directed either to the appropriate video display through the RS-232C serial links, or to a secondary station through the byte-wide parallel link.

The main control element display is a color monitor whose display has been divided into four fields. The largest field contains up to 15 database parameters, known as a data block, for which control functions will be accepted from the joystick whose cursor is positioned on the parameter entry. Control by the two joysticks is differentiated by different cursor colors for each joystick. Thus, 15 elements can be simultaneously controlled before a new control block is brought up on the screen. The three remaining video display fields are a warning field, which shows the title and identification number of any device whose data value lies outside predefined upper and lower tolerance limits; a fault field, which displays the title of any device failure producing a machine trip; and a single-line command field, through which the keyboard is used to perform complex commands to the system. The warning field can display 27 entries, and the fault field can display 49. In each case, additional entries are queued for display when the current entries are cleared.

The green screen video display to the far right in figs. 2 and 3 is used to show the individual element entries for inclusion in a control block on the color display, or the names of the control block currently in the system. At any time, this display will show a window of 30 entries from the total database list. The operator can scroll through the entire database list from all secondary stations by joystick control of the cursor on this green screen, selecting for control any elements from any secondary station on demand, by simply pressing one of the joystick push buttons with the cursor positioned on the desired element.

The operation of the primary station is based on the interaction between the operator and the system elements. The operator is provided with a green screen with which he can scroll through all the database entries in the system. Each entry shows him the type of entry (input, output, stepping motor, etc.), the tolerance bounds, the calibration factor between voltage (input or output) and digital value, and the conversion factor between voltage values and engineering units. Also, for each entry, a title and engineering unit label is given to help the operator understand what is being controlled. As the operator requests each entry on his screen, the primary station polls the relevant secondary station for the information from its database. No copy of the database need be retained in the primary station itself for purposes of control. Thus, value changes are made directly in the secondary database from the primary station, resulting in more timely control.

By means of one of the thumb-operated push buttons on the joysticks, the operator can toggle his cursor between the green screen database display and the color control monitor. The means of establishing control of a system element is to select one of the entries from the database and move it over to the color control monitor. An entry is moved by means of another of the push buttons. The operator moves the cursor on the green screen (by means of the joystick) to the element he wishes to control, presses the "select" push button, moving the element from the green screen to the color control monitor, then toggles his cursor over to the control monitor and controls the value (providing the selected element is one that can be controlled) by means of the joystick. At this time, only back and forth movement of the joystick is supported, but sideways motion could be implemented if the operators prove to be sufficiently coordinated to simultaneously control several elements from the same joystick.

The operator can select up to 15 database entries simultaneously for control on the color monitor. Any such group of entries can be designated a "block" and stored for future control. In this way, blocks of elements can be grouped together and selected immediately without having to select them element by element. Once he has moved the cursor to the control monitor, the operator moves the cursor up and down through the entries by means of the joystick. Should he desire to change a value on one of the entries, he positions the cursor at that element, pulls the trigger, and moves the joystick back and forth to increase or decrease the value. The primary station responds by immediately sending this new information to the relevant secondary station and reading the new value as it comes back. This total loop to control time is less than 200 ms for the entire system.

All of the control functions, as well as some of the more complex ones not available to the joysticks, can be implemented by using the keyboard. The keyboard can assign channels for control from the database to the control monitor, can assign blocks of elements and store them in memory and on disk, can change values of system elements, and can delete entries. In addition, the keyboard can be used to edit individual entries in the database, as well as changing tolerance values for the controlled parameters.

The background microprocessor system in the primary station consists of another Intel 80/24 single-board computer with a floppy disk controller and 64-kbyte nonvolatile memory. The operating system now used is CP/M, simply because so much software is already available for this system. Even today, the FORTRAN compilers available for this 8-bit system rival the best of the 16-bit FORTRAN compilers. This part of the primary station is used to communicate with the PDP-11/44 for complex data analysis, development of software for the system, and data plotting of real-time data. The plotting routines are written in FORTRAN and enable the operator to adjust various element parameters while watching the effect on plots of the affected data. Figure 3 shows the separate CRT terminal and keyboard for this system at the left of the figure, with the high-resolution color display to the immediate right of the CRT terminal. This system is also used for archival storage of parameter data and uploading and downloading of entire databases from the secondary stations. Communication between the two Multibus systems in the primary station is through the dual-port memory by means of mailbox semaphores. Thus, data can be snatched from the secondary stations and plotted without impairing system response time.

As future calculational needs become apparent, advanced computation and even closed-loop control are possible, using the power of the PDP-11/44 system. The present design uses a serial link for this computer, but a future parallel link into the system Multibus is not precluded.

4. Secondary stations

Figure 4 shows the secondary-station operator's console. As this figure shows, the secondary station is capable of four modes of operation, selected by the four large push-button switches in the center of the panel. Parameter units are selected by the smaller push-button switches at the top of the panel. The two knobs on either side of the panel are infinite-turn encoders, which permit scrolling on the screen and value changing of the element parameters.

These secondary stations are really the heart of the control system. All basic system control and monitoring functions can be performed, for a subset of accelerator components, at the appropriate secondary-station control panel. Furthermore, each secondary system is an independent control unit, capable of full operation without connection to the primary station. In fact, with an operator at each secondary station, the entire RTM could be controlled without a primary station.

The hardware configuration for a secondary station is shown in fig. 5. Each secondary station consists of a Multibus crate with at least two single-board computers. One of these, the Intel 80/24, provides operator interaction and database manipulation, as well as linkage to the primary station, while the other, a Zendex 80/15, provides control of "real-world" devices and updates the database at regular intervals. Use of the Multibus between these two processors is arbitrated by the bus hardware protocol, thus decoupling the software and permitting modular software development. The actual system database is distributed among the secondary stations in the form of data entries in the nonvolatile 32-kbyte CMOS RAM board. Regular commercial Multibus DAC and ADC boards are utilized as required in each individual system. All three secondary stations have at least one of each of these commercial boards. Because the RTM utilizes many stepping motors for system control, we decided early to design a Multibus board to handle stepping-motor control. This custom board is based on a commercially available, integrated circuit, controller chip and is interfaced to the Multibus control protocol. We configured the board for four stepping-motor control functions, including limit-switch monitoring, and individual parameter motor control. The rf control secondary uses six of these custom boards, but the RTM secondary needs none, which illustrates the flexibility of the system design. The same software is capable of driving whatever system elements are needed at a particular location.

Each secondary station also has two custom boards: the binary/link board, and the front panel/printer interface board. The binary/link board not only provides the parallel link to the primary station, but also provides 24 channels of binary I/O for the system. Addressing jumpers are provided so that two of these binary/link boards can be put in each secondary if needed.

Also included in the secondary system is a watchdog timer circuit, which must be periodically updated by each of the two processors. Should either of these updates fail to come within the prescribed time period, the watchdog timer resets the secondary system to avoid having the system "hang." The system can also be reset by a special signal from the primary station.

The modular software used in the secondary station is represented schematically in fig. 6. The central operating feature of this system is the main database in RAM memory. Both processors have access through the Multibus to this memory and, hence, to the control parameters of the system. The I/O drivers for all elements in the system are found in the Zendex 80/15 single-board computer, and the remainder of the indicated functions are implemented in the Intel 80/24 board. In this way, all elements are constantly updated from the database and to change a system parameter, only the value in the database need be changed.

The secondary software permits four operator-interaction modes. The default mode is the "clear" mode where the screen is blank and operation is remotely done from the primary station. This will be the normal operating mode when the secondary station is not being used locally.

The remaining three modes are clearly indicated in fig. 6. The console code provides an operator interaction mode where the database entries are shown on the video screen in double-spaced format with raw data values being constantly updated, and the value knob active for changing parameter values by the operator. Only in this mode are the four small push buttons shown at the top of the control panel in fig. 4 active. They are used to set the display format for data values. The "hex" and "decimal" units indicate raw data values and are generally used for debugging; the "volts" and "engineering units" show the data scaled appropriately by the calibration and conversion factors and displayed in floating-point format. These same format options are available at the primary station, although in actual operation engineering units are generally used. It has proved very valuable to have raw data values during the development stages of the system.

The edit mode is used to enter, delete, or change parameter entries. This is the main method by which new devices are put into the database. Although entries can be made from the primary station, it is normally done at the secondary because it is here that the actual hardware is put into operation. For this reason, considerable effort was taken to ensure that the editor has all the versatility necessary to reform the database and make new entries easily.

Each database entry consists of eight data fields. Two of these, the title field and the units field, are for operator convenience only and are not used by the software. These two fields provide the operator with a convenient method of assigning mnemonics to a given entry and identifying system elements by function. The other six database fields provide the necessary information to the device software drivers to update them and check for tolerance limits on the data. The channel-type field assigns a channel number to the element, informing the system which secondary station contains this element, and telling the I/O handler what type of service is required (that is, input or output, binary or analog, stepping motor or not, binary or binary-coded decimal format). The port-unit field tells the software what device code to use to service the board and what address to use within the board itself. The calibration and conversion-factor fields are entered in floating-point format, and are used by the system to scale the raw data to volts and engineering units. The low- and high-limit fields are used to establish tolerance limits for the data. These fields are entered by the operator in engineering units in floating-point format, but are stored in the database in raw data integer format. In this way, the I/O database service routines can quickly check for out-of-tolerance conditions on the raw data and inform the primary station of this condition. Because of this technique, the primary station is warned of an out-of-tolerance condition within 200 ms of its occurrence.

In the edit mode, 26 lines of the database are displayed in single-spaced format, and the cursor knob is used to scroll through the secondary station database. In addition to the normal editor insert and delete commands, there are commands to allow printing the database (with a portable printer attached to the secondary station); uploading or downloading the database into an auxiliary core memory for quick restoration in case of a system crash (not uncommon while debugging a system); string searching for particular database entries; and block moves of entries to arrange the database by function. In addition, individual memory locations can be examined and changed so that custom machine-language test codes can be entered for special debugging problems. Fields in the data entries can be quickly changed by a tab feature that permits scanning fields quickly and changing only those necessary.

The interpreter mode is designed to provide the engineer with a quick means of complex check-out by writing loop routines or repetitive commands in the interpreter. The command structure here was modeled after BASIC because most engineers are familiar with this interpreter language. Commands are as follows:

- PRN provides a means of printing data or program listings to the portable printer
- REN renumbers the program lines by tens
- NEW clears out program storage space for a new program
- GTO is an unconditional transfer to the line prefaced by the label in the operand field
- SAV moves the interpreter program from volatile RAM into nonvolatile memory for storage while the system is powered down
- RCL is the inverse of the SAV command
- SND ships a message from the secondary station keyboard to the primary station
- HLP provides at the console a brief synopsis of the command structure
- CLR erases all variables from memory storage
- TYP displays the pertinent information of each channel listed, permitting data viewing from within the interpreter in the console mode format
- DLY permits a delay as specified in program execution for program looping of milliseconds to minutes
- RUN executes the program defined by its operand field starting with the lowest numbered line statement and proceeding to the highest numbered statement
- LST lists the program lines as specified
- FOR is the looping structure of the interpreter
- IF is the conditional transfer structure of the interpreter
- The assignment command permits value assignments from the interpreter as demanded.

Within the interpreter, the normal arithmetic operations are permitted, providing a versatile method of testing system components and even doing closed-loop control. During the development phase of the rf control secondary station, we used the interpreter to hold the system on-frequency by doing closed-loop control through the interpreter operating the phase controllers from the temperature information in the tanks.

5. Tertiary stations

The RTM control system, as shown in fig. 1, now contains four tertiary stations connected to two secondary stations. Tertiary stations are used where special needs require that intelligent control be located apart from the secondary stations. They are used in this system for control of the magnet power supplies, where the very large number of supplies (240) mandates that the controllers be physically as close as possible to the magnets in order to eliminate numerous wires between control stations and power supplies; and in the injector head, which must operate at 100 keV above ground. The injector tertiary station is linked to the secondary station through a fiber optic transmission line. This injector-head tertiary is shown in fig. 7 as an example of the technique.

Each tertiary station is built around a single Multibus crate containing an Intel 80/24 single-board computer and additional boards as needed, with a watchdog timer board to reset the crate if a system hang occurs. In the case of the magnet power-supply tertiaries, the only additional boards are the DAC and ADC boards necessary for control. For the injector tertiary, binary control is provided as well as DAC and ADC control. In either case, the link to the secondary station consists of a full duplex, asynchronous, serial RS-232C link operating at 9600 baud. All tertiaries operate as slaves to their secondary stations and respond only to service requests from the secondary. They are not capable of initiating traffic with the controlling secondary station. On power up, or reset, the tertiaries initialize their DAC outputs to some predefined value, usually zero, and await commands from the secondary station. For control, the secondary station supplies an address of a DAC channel, followed by 2 bytes of raw data, which is written into the DAC by the tertiary CPU. On input, ADC data requested by address from the secondary is sent from the tertiary in the same 2-byte raw data format. The transmission format is echo-checked to guarantee data transmission integrity before device changes are made.

6. Conclusions

The secondary stations have been operated now for almost three years, with the primary station operational for about a year. During this time, a great deal of experience has been gained with the unique features of the system. Our original decision to go with the Multibus-based commercial bus system has been vindicated by the versatility of adding hardware. More importantly, the hardware bus arbitration permitted splitting the software tasks between operator interaction and real-world hardware updating, which greatly contributed to the simplification of system design and shortened debugging time.

The update speed and versatility of a distributed database has contributed to overall system response and has provided for expansion of the database in each secondary from the original [1] 250 entries to the present 320 or 640, depending upon which nonvolatile CMOS RAM board is installed in the system. Without the use of assembly-language service routines to update the database and service primary information requests, it would not be possible to achieve operator response consistent with the use of joystick controllers.

The joystick controllers have proved to be fast and simple to learn to operate. Compared to trackball, keyboard or knob systems, they offer single-handed control of all rudimentary control functions.

The innovative secondary-station concept with its interpreter and extensive engineering test capabilities has proved to be an excellent way to get subsystems up and running quickly without the necessity of the entire control system being operational.

Based on present experience, we anticipate very low system downtime because of control system failures.

References

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[2] R.L. Ayres, N.R. Yoder, E.R. Martin, R.E. Trout, B.L. Wilson, "NBS/LANL Racetrack Microtron Control System," IEEE Trans. Nucl. Sci. <u>32</u> (5), 2086 (1985).

Figure Captions

Fig. 1. Block diagram of RTM control system showing configuration of primary station and its interconnections to the other control subsystems.

Fig. 2. Equipment placement for primary control station: (A) top view, (B) front view.

Fig. 3. Primary control console.

Fig. 4. Operator console for secondary station.

Fig. 5. Hardware detail for secondary station.

Fig. 6. Modular software for secondary station.

Fig. 7. Tertiary station mounted inside injector.

RTM CONTROL SYSTEM CONFIGURATION

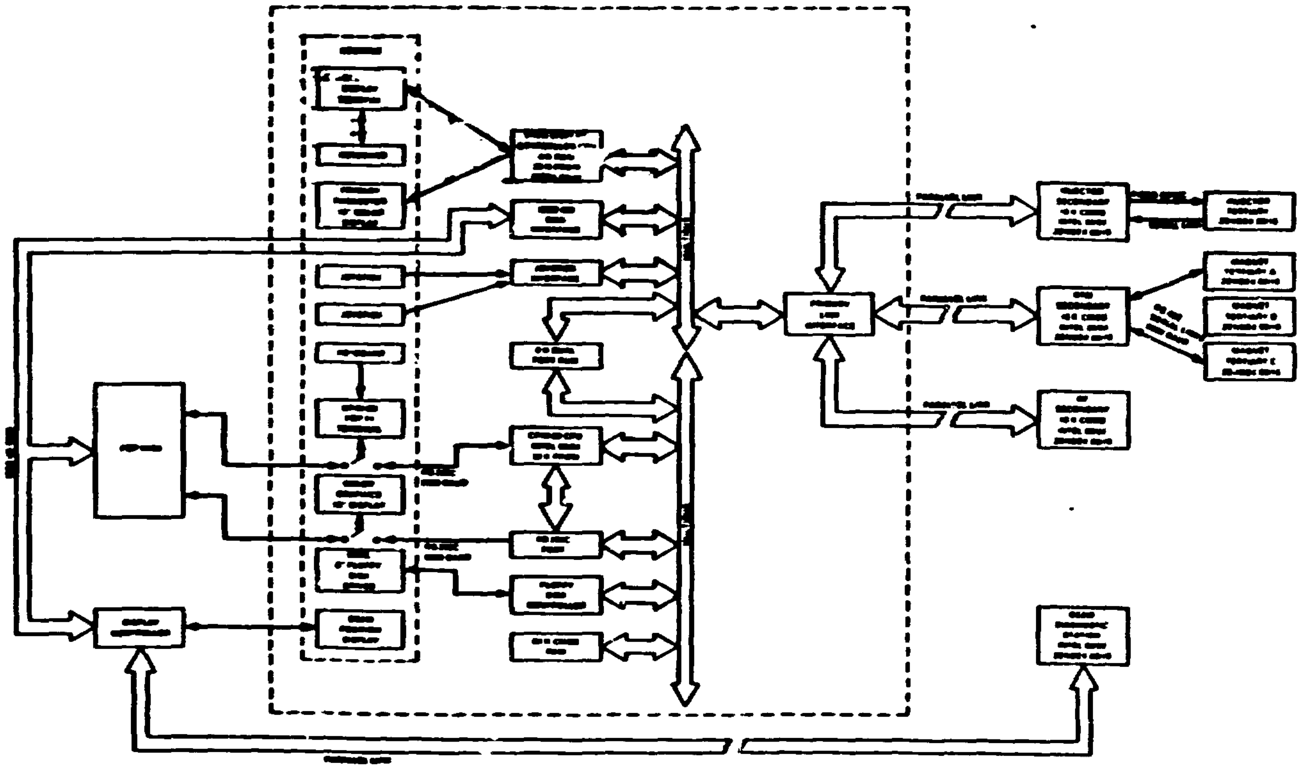

Figure 1. Block diagram of RTM control system showing configuration of primary station and its interconnections to the other control subsystems.

~~Work supported in part by the Division of Nuclear Physics, Department of Energy.~~

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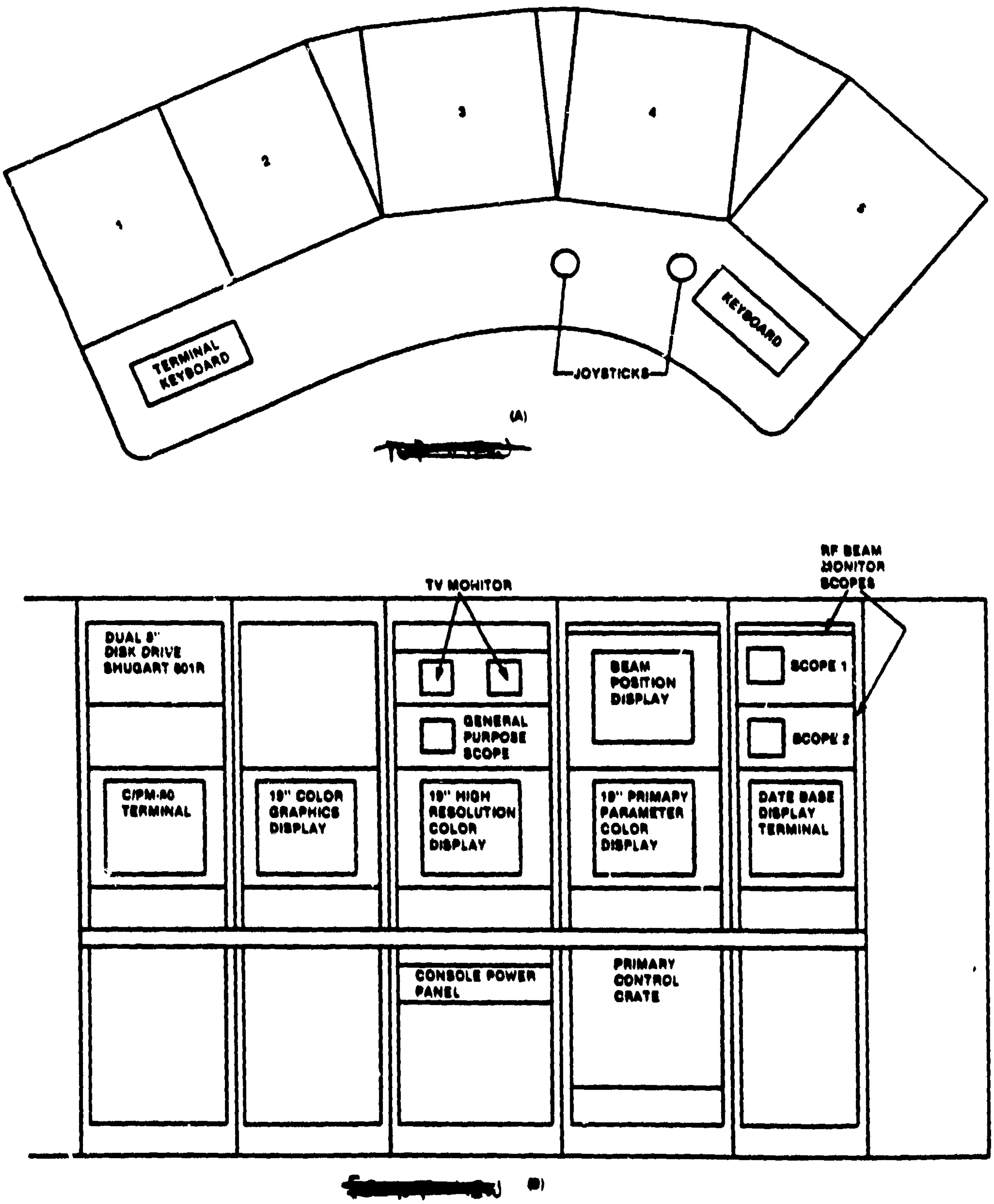

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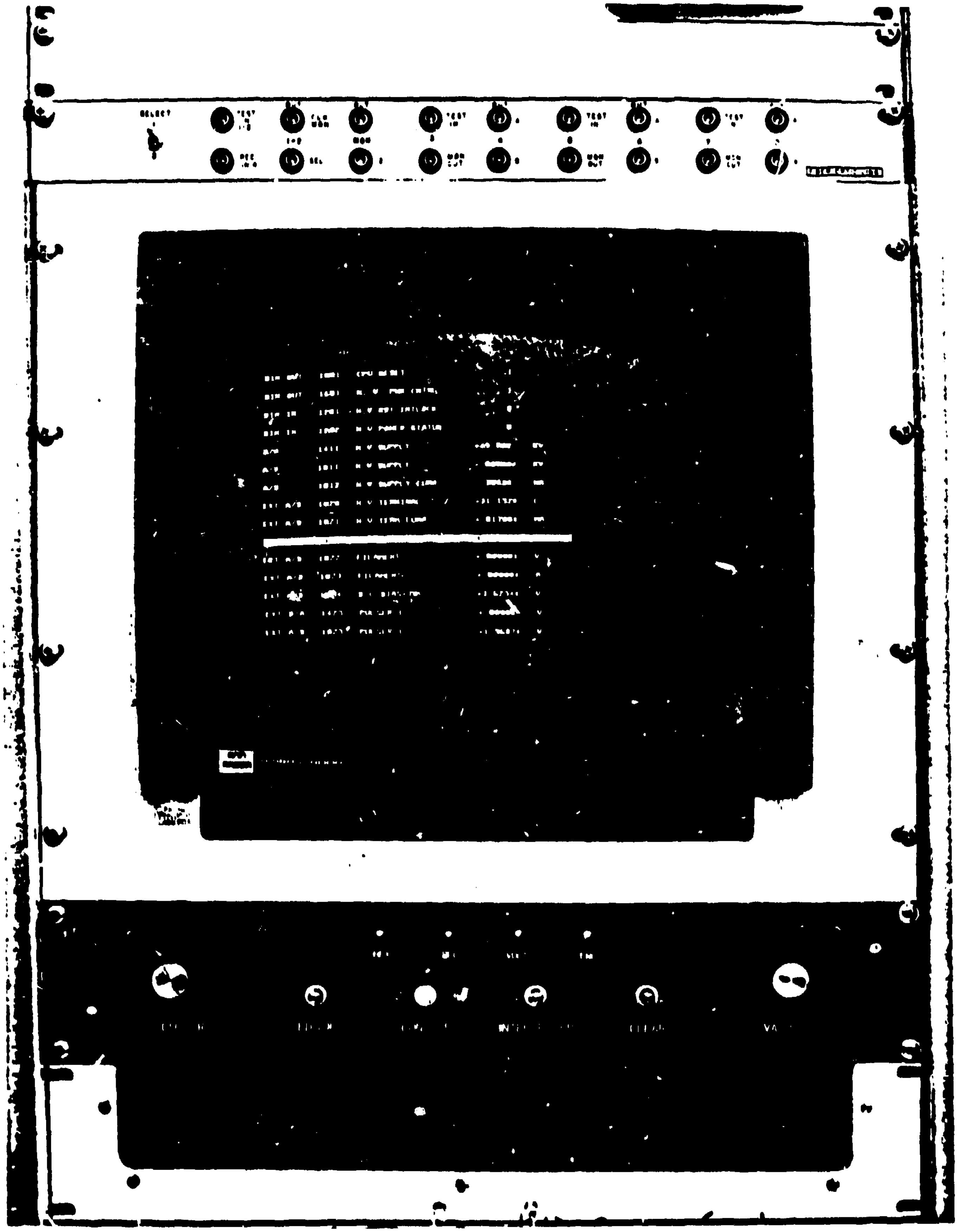
FIG. 2

FIG. 3 Primary Control Console



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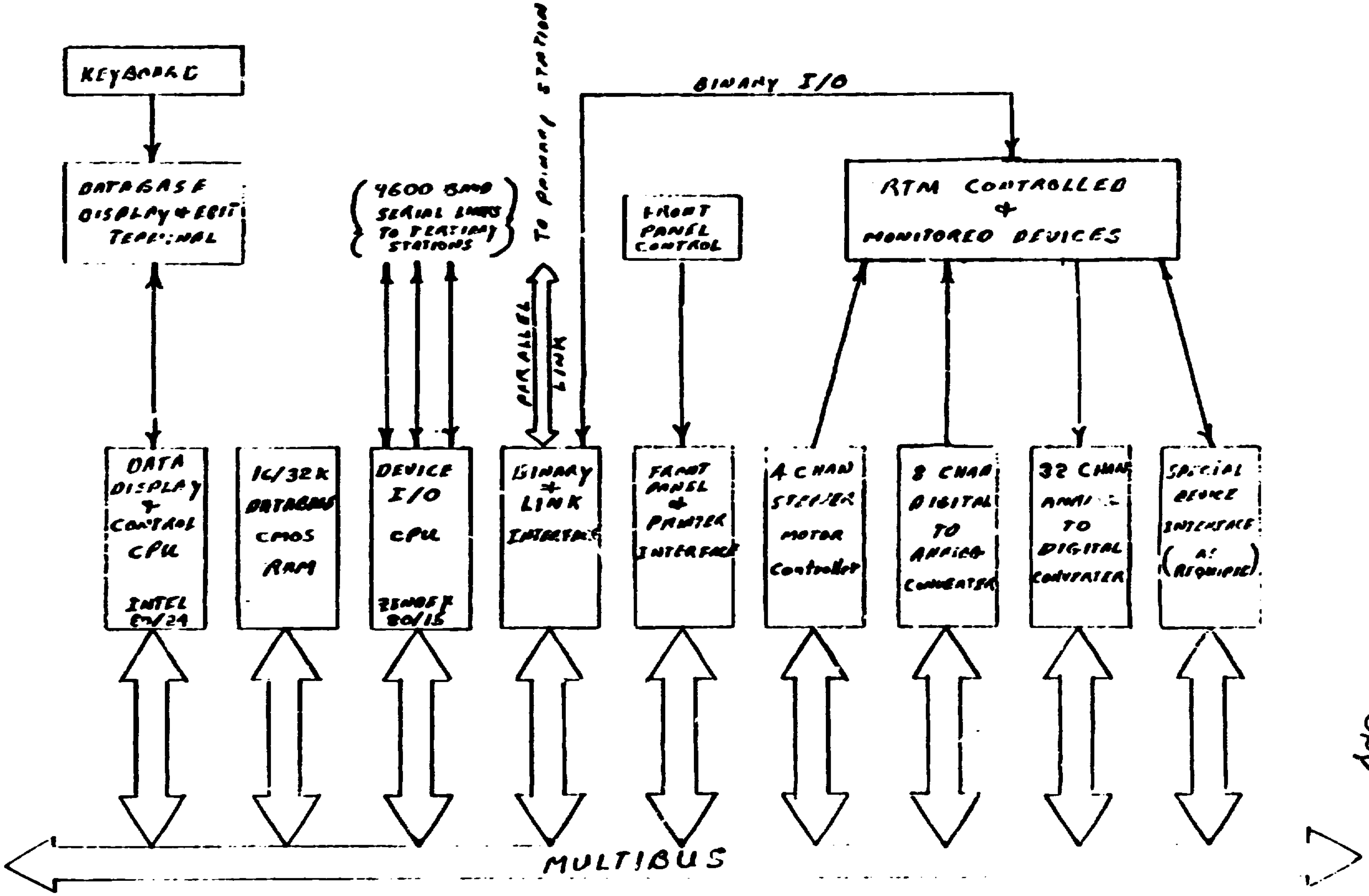

Fig. 5 Secondary Station Hardware Detail

~~SECONDARY STATION (SOFTWARE DETAIL)~~

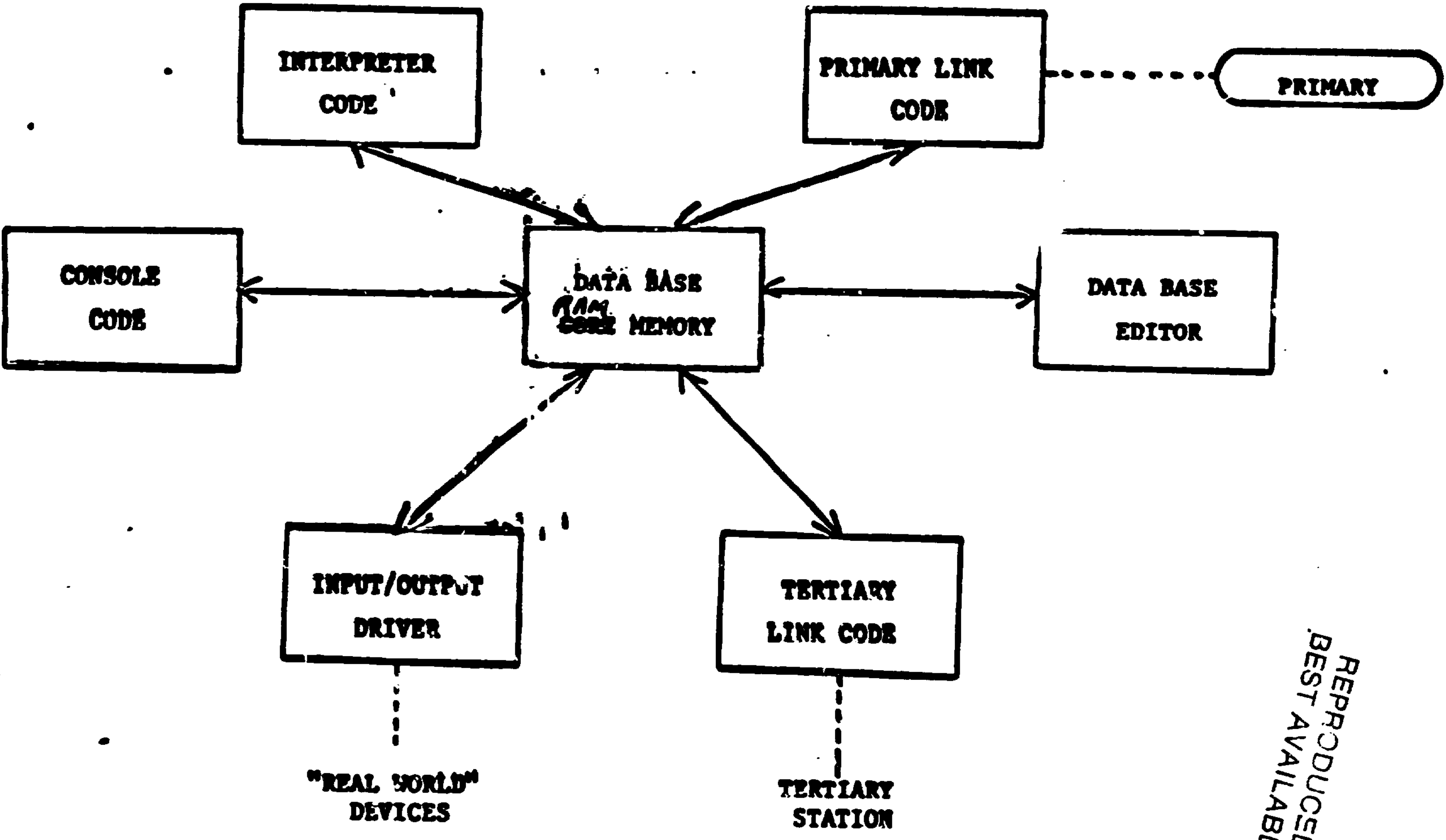

Fig. 6 Secondary Station
modular Software

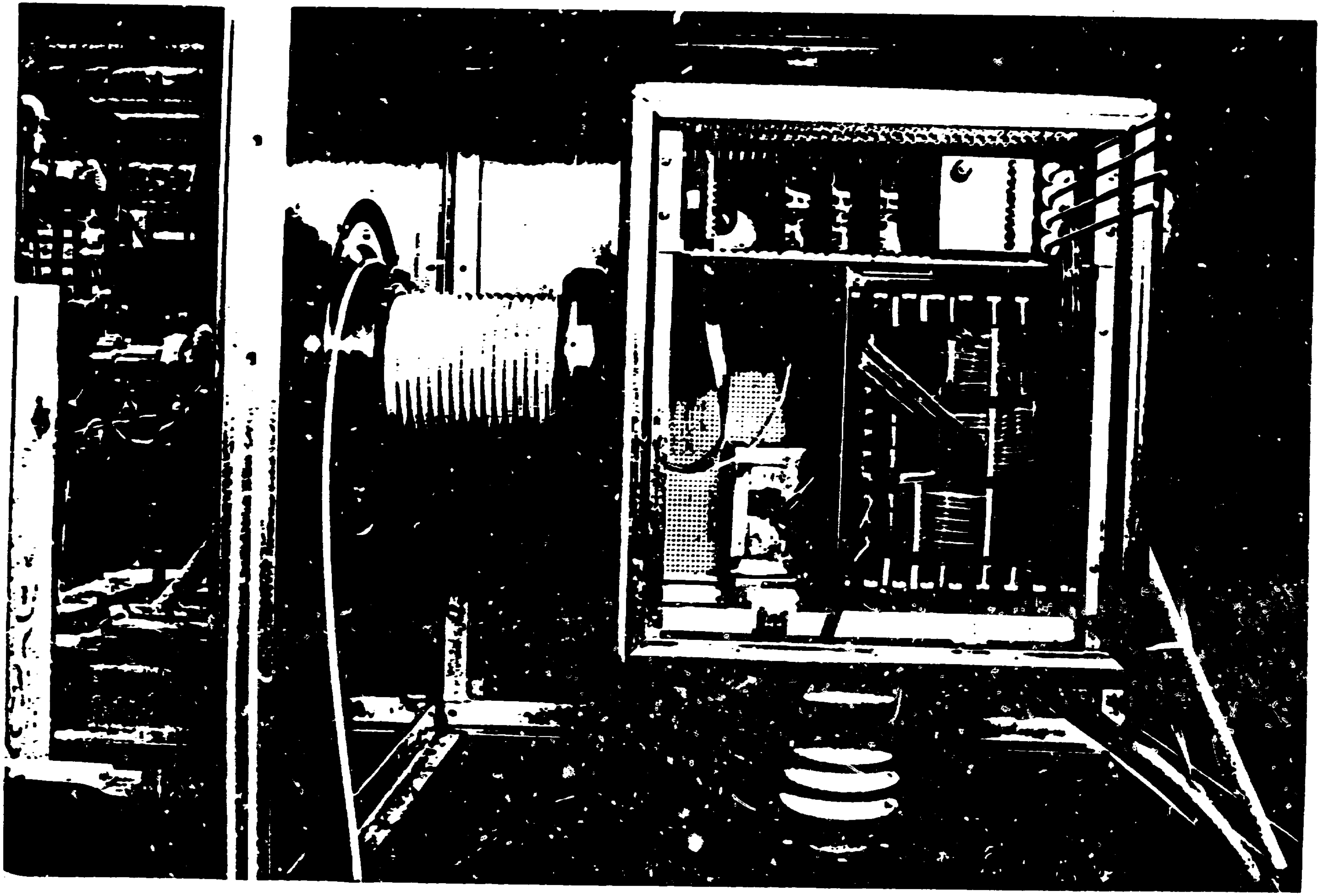

Fig. 7 Tertiary Station mounted inside Injector.