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A New Instrument for the Confirmation of Declared Power Histories of Central Station Nuclear Power Plants

by

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Abstract

An operationally simple, portable, microprocessor-based, unattended reactor power monitor was developed for International Atomic Energy Agency inspector use in confirming operator records of the power history of nuclear power plants. The monitor is based on the principle that the leakage neutron flux outside the biological shield is proportional to the thermal power level. The leakage flux is detected and compared with the leakage flux from the same reactor for a confirmed calibration period. Several output options are available, and a record of more than three months of hourly measurements of the thermal power of the plant can be obtained. The monitor has battery backup power for interruptions of host power of duration up to 18 hours.

Introduction

The International Atomic Energy Agency (IAEA) is responsible for the timely detection of the diversion of significant quantities of special nuclear materials from peaceful purposes to weapons production in participating states. Part of this responsibility is discharged by the confirmation of operator records of normal operations in declared facilities in the nuclear fuel cycle. One of the obviously important facilities is the central station nuclear power plant, which represents the only declared site of plutonium production. To account for the plutonium production, the operating history, as well as the important neutronic characteristics, of each operating power plant must be known. The operating history is a record the operator is required to make available to the IAEA inspectorate. As part of a scenario for production of undeclared plutonium for use in nuclear weapons, unusual actions in the facility might be expected. Such actions would include a deviation from the normal electrical power producing mode of operation: this could be discovered by an examination of the power history traces from the normal power range monitors. However, at facilities where undeclared plutonium is being produced, the falsification of such records would be an obvious concomitant action of the plant operator, requiring an

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independent confirmation of facility operating history records. The IAEA consequently desires the capability of making operator independent power measurements.

There are several ways in which the power of a plant can be determined, most of these being process parameter measurements such as bulk steam flow or electrical power supplied to the grid. We have deemed each of these to be either too indirect or too easily defeated. Since plutonium production is directly proportional to the neutron flux in the reactor, a measurement of that flux would be the most appropriate measurement to make for comparison with the operator records.

An instrument for measuring the flux near the core was developed earlier, based on the solid state track recorder (SSTR) technique. This particular instrument contains fissionable material in proximity to a slowly spooling polycarbonate resin film. The fission fragments from induced fissions strike the film, producing microscopic damage tracks that are enlarged by chemical etching after retrieval of the film cassette. A measurement of the track density as a function of position on the film is made and related to the flux on the fissionable foil at the time that portion of the film was in the vicinity of the foil. Several disadvantages of this technique are recognized: 1) the instrument must be placed in a rather high flux, requiring a shield penetration, resulting in activation of the instrument itself, and requiring synchronization of instrument emplacement and removal with reactor shutdown periods, 2) the enlargement of the microscopic damage tracks requires the use of caustic chemicals and strict adherence to specific development procedures, 3) the determination of track density is done by specular reflection of a light beam that is subject to effects other than track reflection, e.g., reflection from chemical crystal residues resulting from incomplete cleansing, or reflection from surface blemishes such as scratches, 4) the record is not immediately attainable at the facility, and 5) the instrument contains radioactive and special nuclear materials, the transporting of which is strictly regulated.

We have developed, in collaboration with the computer systems and electronic engineering group at the Los Alamos Scientific Laboratory (LASL) and under the U.S. Program for technical assistance to IAEA Safeguards, an alternate instrument for confirming operator records of the plant power history that avoids the specific disadvantages described above. The instrument is based on our assumption that the leakage neutron flux intensity outside the biological shield wall is a reasonably accurate representation of the central neutron flux intensity. Thus, a high sensitivity neutron detection system, conveniently located, can provide estimates of the internal flux.

Two versions of the instrument have been constructed with significant differences between the two. The final version incorporates many improvements recognized as necessary or desirable in the prototype. The details of both units are contained in this report. The following sections cover the principles of operation, the design details, method of operation, and the results of tests of the prototype at two quite different operating power plants, the High Temperature Gas-cooled Reactor (HTGR) at the Ft. St. Vrain Station and the Pressurized Water Reactor (PWR) Unit #2 of the Zion Station.

Description

A. Mechanical

Figures 1 through 3 show the prototype of the instrument. It is contained in a 57 cm x 37 cm x 27 cm steel case with hermetic seals and weighs 25 kg. The smaller of the two portions of the case contains the gel cell battery power supply and the battery chargers. The larger section contains the neutron sensor, the analog and digital circuit cards and card cage, the control interface, and the cassette tape decks.

The neutron sensor in this version is a single ^{3}He-filled proportional counter. For the test at the Ft. St. Vrain Station, a bare proportional counter, 5 cm diameter and 50 cm long, filled to a pressure of 400 kPa with ^{3}He, was used. For the test at the Zion Station, the proportional counter was 2.5 cm in diameter with the length and fill pressure the same as for the detector used in the Ft. St. Vrain test. In this latter test, the detector was in a housing consisting of a 0.05-cm-thick inner layer of cadmium metal and a 4.5-cm-thick outer layer of polyethylene. The housing was open toward one surface of the instrument case, allowing neutrons to enter from this direction, and providing shielding against neutrons coming from other directions.

Output ports are provided for a digital data terminal, a strip chart recorder, and analog signal observation. Since the instrument is designed to be supplied host power for maintaining charge on the battery pack, an AC power jack and cord are provided.

The final version, shown in Figs. 4 through 6, weighs approximately 14 kg, is contained in a 54 cm x 34 cm x 18 cm aluminum case. The gel cell power supply has been reduced in stand-alone operating capacity from approximately 100 hours to approximately 18 hours with the CMOS microprocessor, with an attendant reduction in the weight of the power supply. The use of an aluminum case instead of steel also affected the weight reduction.

The neutron sensor in the final version consists of two proportional counters, 2.5 cm in diameter and 37 cm long, filled to a pressure of 400 kPa with ^{3}He. A cadmium metal and polyethylene shield, similar to that used for some of the testing of the prototype, is provided for the proportional counters in the final version.

Figure 6 shows the operating panel for the new control interface. One change is obvious: the final version contains a single cassette deck instead of the redundant decks in the prototype. In addition, considerable improvements in operational simplicity are incorporated in the control panel. These are discussed in the functional description and operating sections.

Whereas it was intended that the prototype be placed inside a tamper-resistant, tamper-indicating enclosure against the reactor biological shield wall, the case of the final version is intended as the enclosure, with attachment to the biological shield wall accomplished by a stud-in-sleeve arrangement with a nut attached at the parting plane of the two halves of the instrument case. The stud is visible in Fig. 4 and the attachment nut is seen in Fig. 5. The halves of the case are then sealed by the inspector.

B. Electronic

Gel cells provide +6 and ±12 VDC for operation of the instruments. Bias voltage for the proportional counters is provided by DC-to-DC converters that convert the +12V to +1900V. The analog pulses resulting from the $^3He(n,p)^3H$ reactions in the proportional counters are amplified, routed to a lower level discriminator where standard 5V logic pulses are generated. The logic pulses are scaled in a 24-bit scaler for one-hour periods. The one-hour periods are fixed by a timer associated with a precision clock. This clock is also used to provide a Julian date and time of day for the real time record keeping.

An RCA 1802 CMOS microprocessor is used for the data acquisition and analysis in the prototype of the instrument. The final version uses an Intel 8748, which is pin-for-pin compatible with the Intel 87C48, CMOS version, imminently due on the commercial market. The replacement of the 8748 with the 87C48 will affect a much lower power consumption.

In addition to the data being written on magnetic tape, an 8k Random Access Memory (RAM) is used for data storage. The data in RAM can be read out via an RS232 port to an external data terminal or through a digital-to-analog converter to an external strip chart recorder.

C. Functional

The control panel for the prototype can be seen in Fig. 2 and for the final version in Fig. 6. Although a visual comparison of the control panels in the two versions might lead one to the conclusion that the prototype is simpler, the operating procedures given in the next section should change that impression. The functions of the two versions are identical; to maintain a record of the operating power on an hourly time base. This is accomplished by reference to a calibration period that is one hour long in the prototype and eight minutes long in the final version. The final version has a liquid crystal display of the contents of a scaler that scales the logic pulses for 10-s repetitious periods. This facilitates the placement of the instrument in a reasonable leakage flux intensity. The prototype contained no readout of the detector count rate. Calibrations of either version requires that the reactor be in a power producing state during the calibration period. The microprocessor obtains the scaled count for the calibration period, compares this number with the thumbwheel setting of declared operating power, in percent of rated capacity, and calculates a scaled count to operating power conversion factor that is retained in software for all subsequent power level determinations. All power levels, in percent of rated capacity, are stored in digital fashion in RAM and recorded each 24-hour period on cassette magnetic tapes, along with the Julian date. The data tapes are retrieved for subsequent analysis, or the contents of RAM read out to a data terminal, or through the digital-to-analog converter to a strip chart recorder.

The prototype had the clock setting accomplished via pushbutton advance and set in a manner identical to that of digital watches and clocks. The final version has clock settings accomplished by thumbwheels with pushbutton entry.

Operating Instructions

The instruction sets for operating each of the two versions of the instrument are given below.

Prototype

A. System Initialization

1. Insert cassette tapes in the two tape drives. These tapes must have been rewound and advanced to the load point.

2. Connect the system power cord to the battery pack. When the tapes have completed gapping, the display will show minutes and seconds.

3. Set the clock/calendar.

   a. Set the thumbwheel function switches to 00.
   b. Set the two least significant Julian Date digits by pressing the SET, DAYS, and ENTER buttons. This will cause these two digits to be incremented slowly. Pressing the ENTER button again will then freeze these values. The most significant date digit is incremented each time ENTER is pushed when the DAYS and HOURS buttons are held down, and can be set in this way. The day set can be viewed by pressing DAYS and ENTER. The date can be cleared (set to 000) by pressing DAYS, HOURS, MINUTES, and ENTER. Note that the ENTER button is always pressed last when it is used.
   c. Set the hour by pressing SET, HOURS, and ENTER to start the hour displayed incrementing and then press ENTER again to freeze at the hour displayed. View the hour and minute set by pressing HOURS and MINUTES and ENTER.
   d. Set the minute by pressing SET, MINUTE, and ENTER to start the minute displayed incrementing and then ENTER again to freeze at the MINUTES displayed. Set MINUTES several minutes ahead of the current time. Then by pressing SET and ENTER, the time will be stopped at its current value with SECONDS = 00. Pressing ENTER will restart the clock and should be done when the current time and the value in the RPM are synchronized.

e. Set the power calibration thumbwheel switches to the present reactor thermal power (as a percent of rated power).

f. Start operation by setting the most significant digit on the function thumbwheel switch to a nonzero number and pressing ENTER. The display will blank indicating that operation has begun. The time display can be recovered if desired by resetting the function switches to 00 and pressing ENTER. The calendar/clock can be viewed as above but the display must be in the MINUTES and SECONDS display (obtained by pressing ENTER) in order that data be properly recorded at midnight. After operation has begun the clock/calendar should not be reset.

B. Output

1. With an RS232-compatible data terminal connected to the instrument, a printed listing can be obtained by setting the function switch to 11 and pressing ENTER.

2. After the terminal output is done, a strip chart output may be obtained by connecting a strip chart recorder, setting the function switch to 22 and pressing ENTER. The output analog voltages are 0 to 2V corresponding to 0% and 100% power, respectively. Additional records may be obtained by returning to 1 above.

3. If the unit is run for longer than 120 days, its storage capacity will be exceeded and HALP will be flashed on the display to indicate any data acquired after 120 days has been lost.

Final Version

A. System Initialization

1. Insert a cassette tape in the tape drive. This tape must have been rewound and advanced to the load point.

2. Move the function switch from OFF to TIME SET. (Note that in the OFF position, AC power is still supplied to the battery chargers when the instrument is plugged in.) Set the Julian date, the hour, and the upcoming minute on the calendar/clock switches and press the EXECUTE pushbutton. Release the pushbutton when the minute dialed in begins.

3. Move the function switch to CALIBRATE, enter the present reactor thermal power level as a percent of rated power in the calibration switches. Press the EXECUTE pushbutton to start the calibration measurement.

4. In normal operations the function switch is left in the RUN position to avoid problems from accidental depression of the EXECUTE pushbutton.

B. Output

1. A listing of the hourly power levels stored in memory can be obtained by connecting the data terminal to the instrument, moving the function switch to DATA TERMINAL, and pressing the EXECUTE pushbutton.

2. A strip chart record of the hourly power levels stored in memory can be obtained by connecting the strip chart recorder to the instrument, moving the function switch to STRIP CHART, and pressing the EXECUTE pushbutton. The output analog voltages are 0 to 1V corresponding to 0% and 100% power, respectively.

3. If it is desired to start storing power levels from the top of memory again after an output listing or strip chart record has been obtained, move the function switch to RESTART and press the EXECUTE pushbutton.

C. Power Indicators

Two LEDs indicate proper functioning of the battery charger power supplies when the TEST pushbutton is depressed. Another LED is provided to indicate when the unit is receiving AC power. The AC power is fused with an accessable fuse on the panel. Interruptions of the AC power are sensed and the time of each occurrence is written on the magnetic tape. The total number of occurrences is stored in memory and is written at the top of each listing of the data from memory.

Test Results

The prototype has been tested at the Ft. St. Vrain nuclear station of the Public Service Company of Colorado and at the #2 unit of the Zion nuclear station of the Commonwealth Edison Company. The former is an HTGR, rated at 841 megawatts thermal, 330 megawatts net electrical, and the latter is a PWR rated at 3250 megawatts thermal, 1090 megawatts net electrical.

At Ft. St. Vrain, the instrument was placed on top of the control rod drive covers, above the top head closure, directly on the metal cover plates. No attempt was made to insulate the instrument from the temperature fluctuations these plates experience during power changes. In this test, the immediate area was roped off to exclude personnel since the detector was bare and the presence of moderating materials was known to affect the measurements. This problem has been corrected with the addition of a 2π shield to the detector. The results of this test are shown in Fig. 7. Fortunately, for this testing period the Ft. St. Vrain HTGR was in an ascension to power testing phase, with significant changes in power occurring over the month-long testing period. The count rate at the 26% power level, at which the instrument was calibrated at the beginning of the test, was approximately 1 x 10^3 counts per second. The instrument power level records track the operators power level records quite well, with an average difference over the entire period of approximately 4% with the largest single point difference being approximately 20%.

The results of an abbreviated test at the Zion station are shown in Fig. 8. For this test, the instrument was placed just outside the second missile barrier, inside the containment building. The count rate at this position, with the reactor operating at 100% of rated capacity, was approximately 10^2 counts per second. This test was terminated at the end of approximately 100 hours because of battery failure. The host AC outlet was subsequently determined to be inactive and the instrument operated only so long as the batteries maintained proper circuit voltages. The average difference between the plant operators declared power listing and that obtained with the instrument over this period (which contains two load following power changes) is approximately 0.5%.

The results of a subsequent month-long test are shown in Fig. 9. During all but a small fraction of the time, the operators records indicate the unit was operating at 100% of capacity, dropping the electrical grid load around day #347, picking it back up around day #349. The average difference between the operator's records and the instrument's records is approximately 4.7% during the period, with the greatest discrepancy occurring during the no-load period.

Since the reactor power monitor measures the leakage neutron flux intensity, factors other than power changes that affect the leakage neutron flux intensity will result in erroneous power determinations. Obviously, since the leakage flux intensity is sampled only at one spatial point, flux tilts will result in erroneous readings. However, good fuel management schemes are designed to eliminate flux tilts, and a signficantly difficult strategy would be required to greatly affect the recorded power history. We recognize[1)] two additional factors affecting the leakage neutron flux intensity in light water reactors. One is related to the nonuniform fuel burnup rate. Fresh fuel is generally loaded in the outer core regions and experiences a greater burnup rate, resulting in a gradually increasing neutron flux in these regions. The leakage flux intensity would consequently slowly increase at a given power level. Such an increase is seen in Figure 8, resulting in a slope of about 5% for the month-long period. The other factor affecting leakage is the spectrum hardening occurring from increasing coolant temperature. The dip in the instrument record at day #338 and discrepancy between the instrument and operator power records around day #348 are correlated[1)] with such a temperature change.

The fine structure in the reactor power monitor record has no counterpart in the operator's records and is presumed to result from statistical fluctuations in count rate and truncation in arithmetic operations done in software.

Conclusions

Measurement of the leakage neutron flux intensity and correlation of that flux with the reactor power level has been shown to be a suitable technique for confirmation of plant operator records. We have constructed microprocessor-based portable instruments to satisfy unattended detection and analysis requirements. The units are simple to operate, are suitable for assuring tamper-resistant/tamper-indicating operation, and can provide hourly average records of the plant power for periods in excess of 120 days.

Acknowledgements

We express our appreciation to the operations staff of the Ft. St. Vrain Nuclear Station of the Public Service Company of Colorado and the Zion Generating Station of the Commonwealth Edison Company for their assistance in the tests of the instrument at their facilities. Special thanks go to Donald Alexander of the former organization and to George Perdikis of the latter. We acknowledge the invaluable assistance of the personnel of the computer systems and electronic engineering group at LASL. These instruments were developed through support from the International Safeguards Project Office.

References

1. George Perdikis, Commonwealth Edison Technical Staff, private communication 1979.

Figure Captions

Figure 1 — The prototype of the microprocessor-based reactor power monitor.

Figure 2 — Operating panel of the prototype reactor power monitor.

Figure 3 — The prototype reactor power monitor with major components of the lower portion exposed. All electronic circuits, including the microprocessor, are on the cards in the card cage. The neutron sensor, not visible in the figure, is also in this lower portion.

Figure 4 — The exterior of the final version of the reactor power monitor. The mounting stud is seen protruding from the case. A tang for attaching seals is positioned just above the case manufacturer's logo.

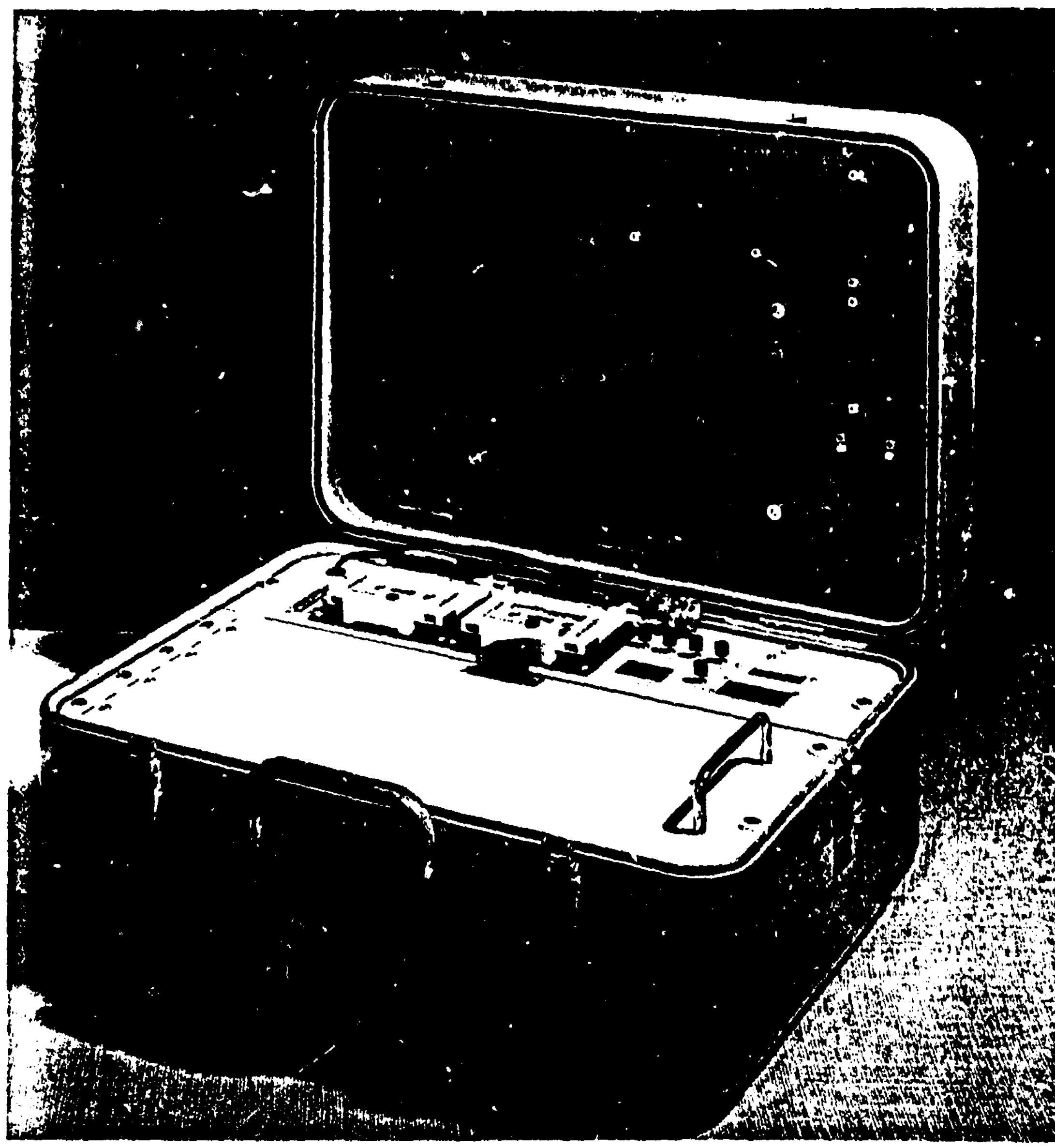
Figure 5 — The final version in an open position. The nut for the mounting stud is seen just above the ribbon cable connecting the two portions of the instrument.

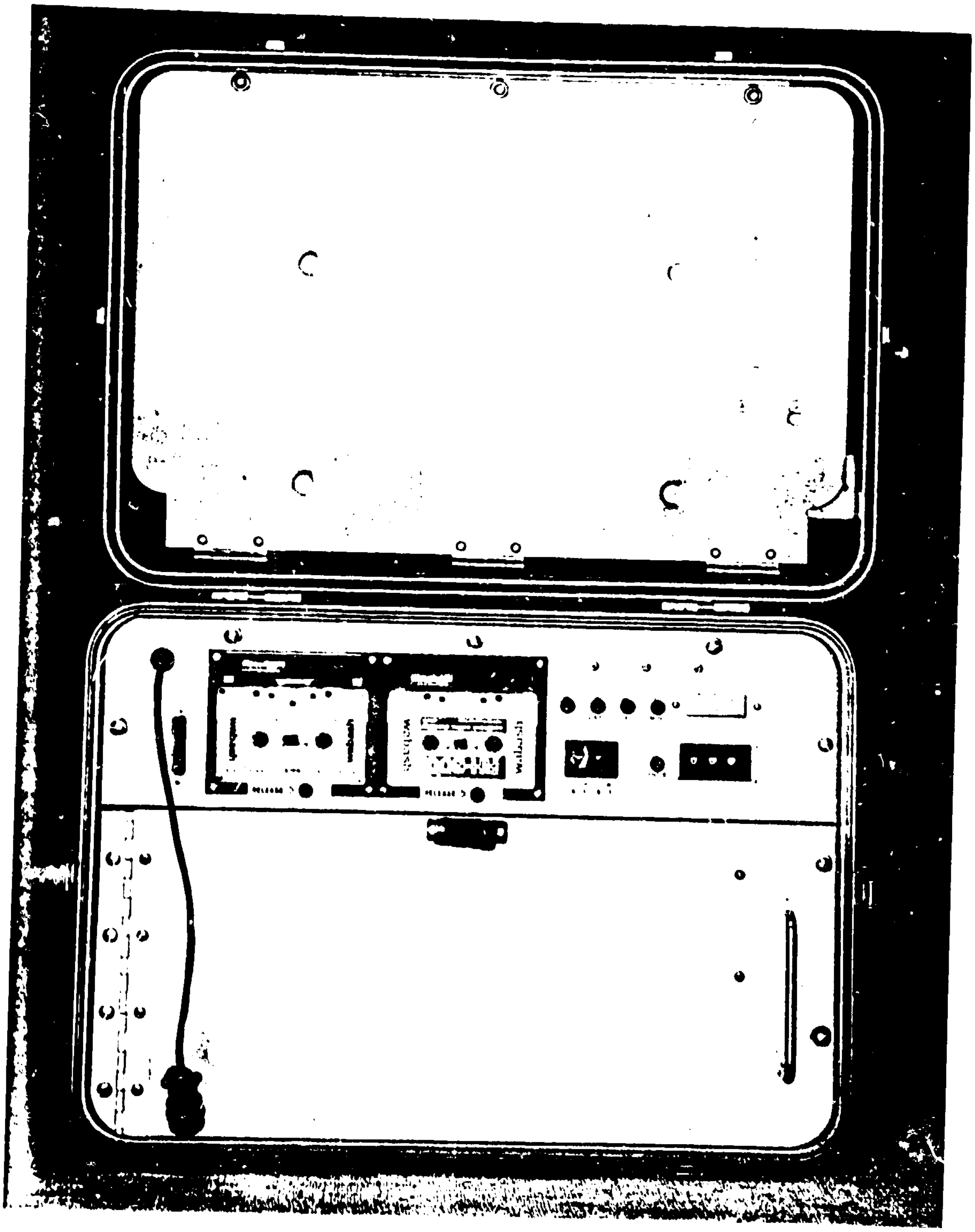
Figure 6 — The operating panel of the final version of the reactor power monitor.

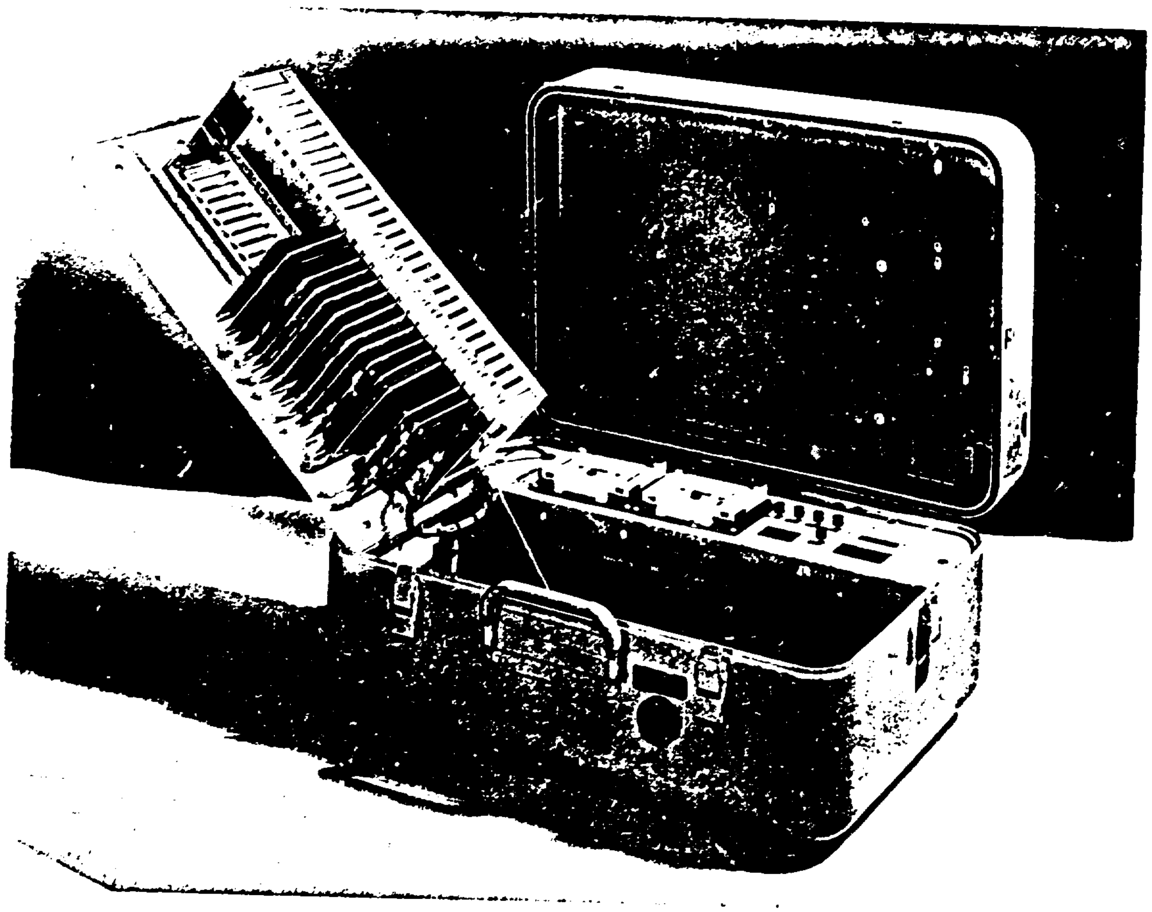
Figure 7 — Records of the power output of the Ft. St. Vrain Power Station during April 1978.

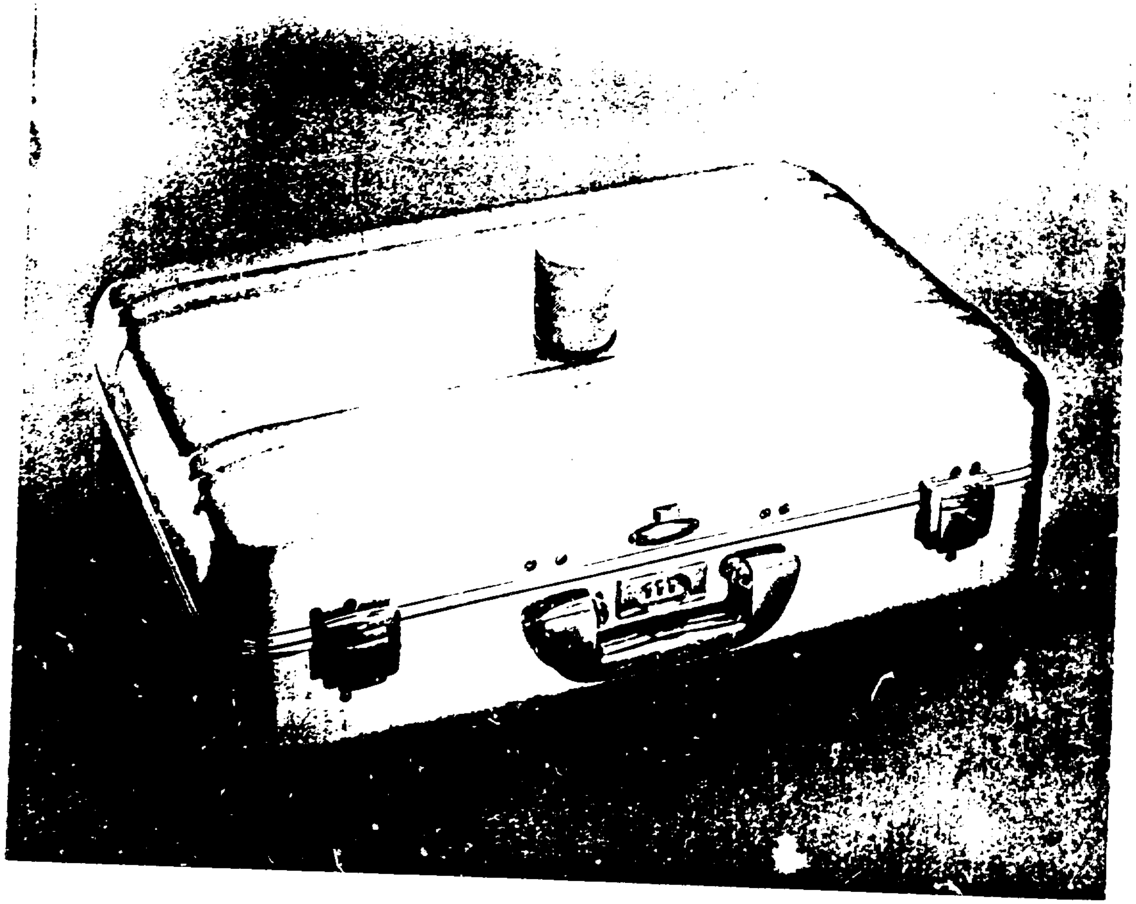
Figure 8 — Results of an abbreviated test of the reactor power monitor on Unit #2 of the Zion Generating Station.

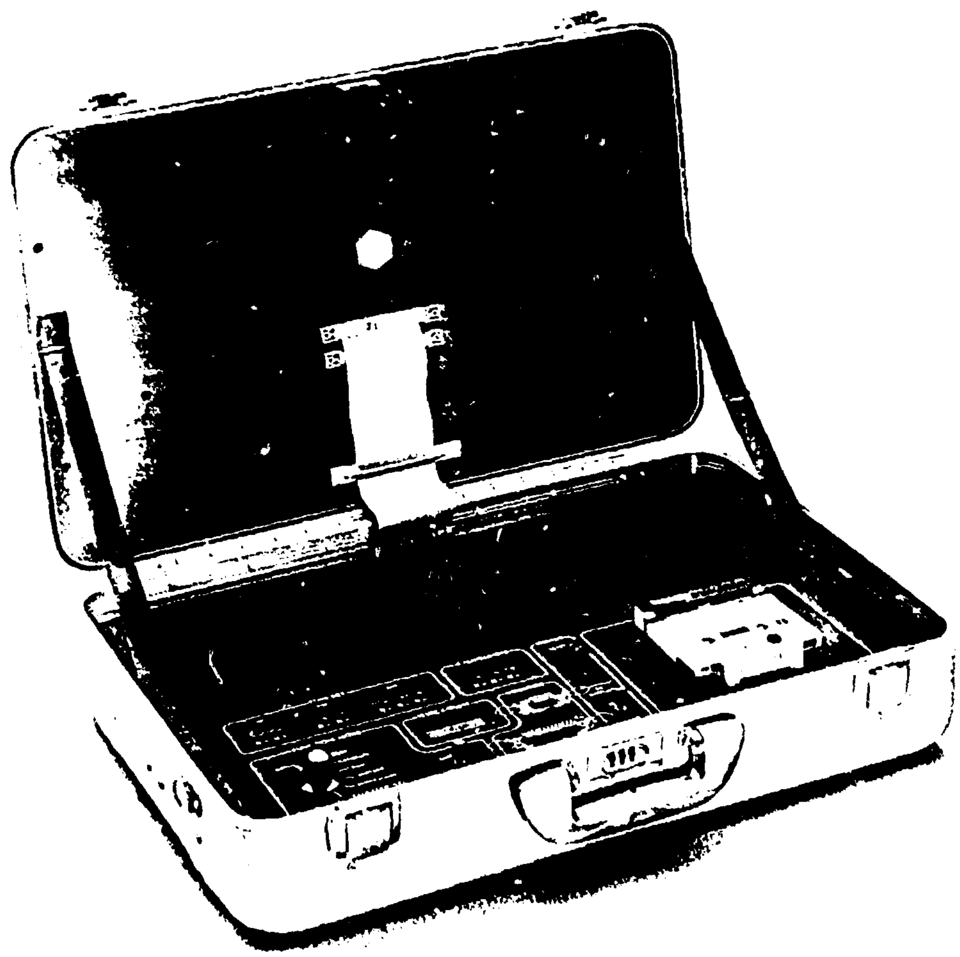
Figure 9 — Results of a completed power monitor test conducted on Unit #2 of the Zion Generating Station.

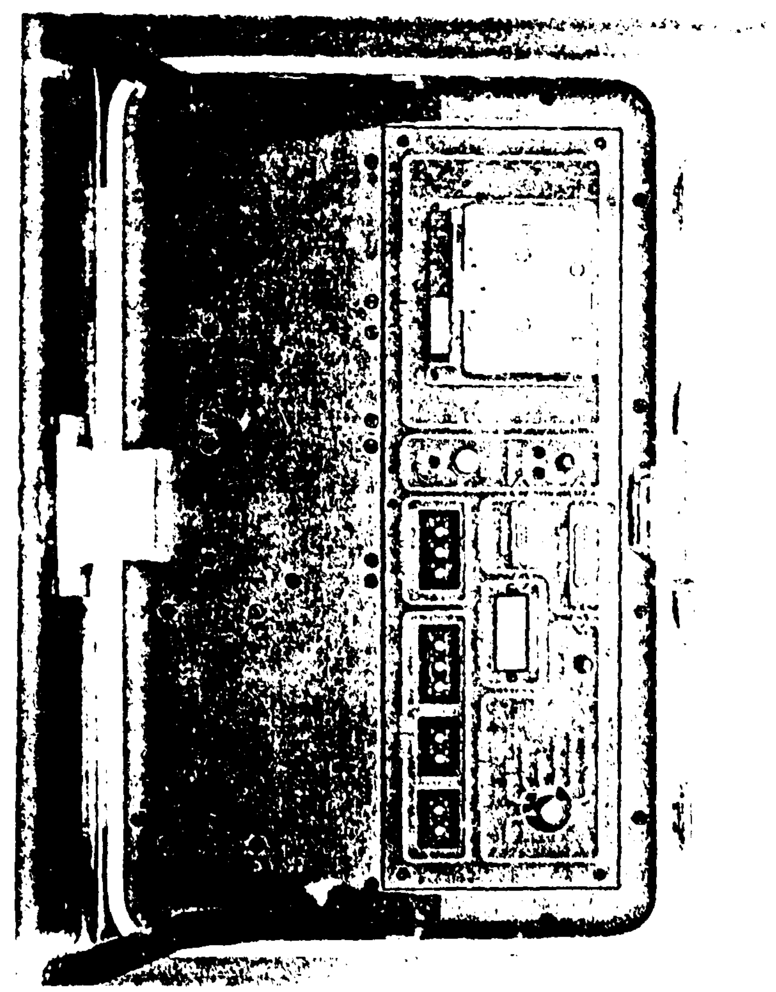












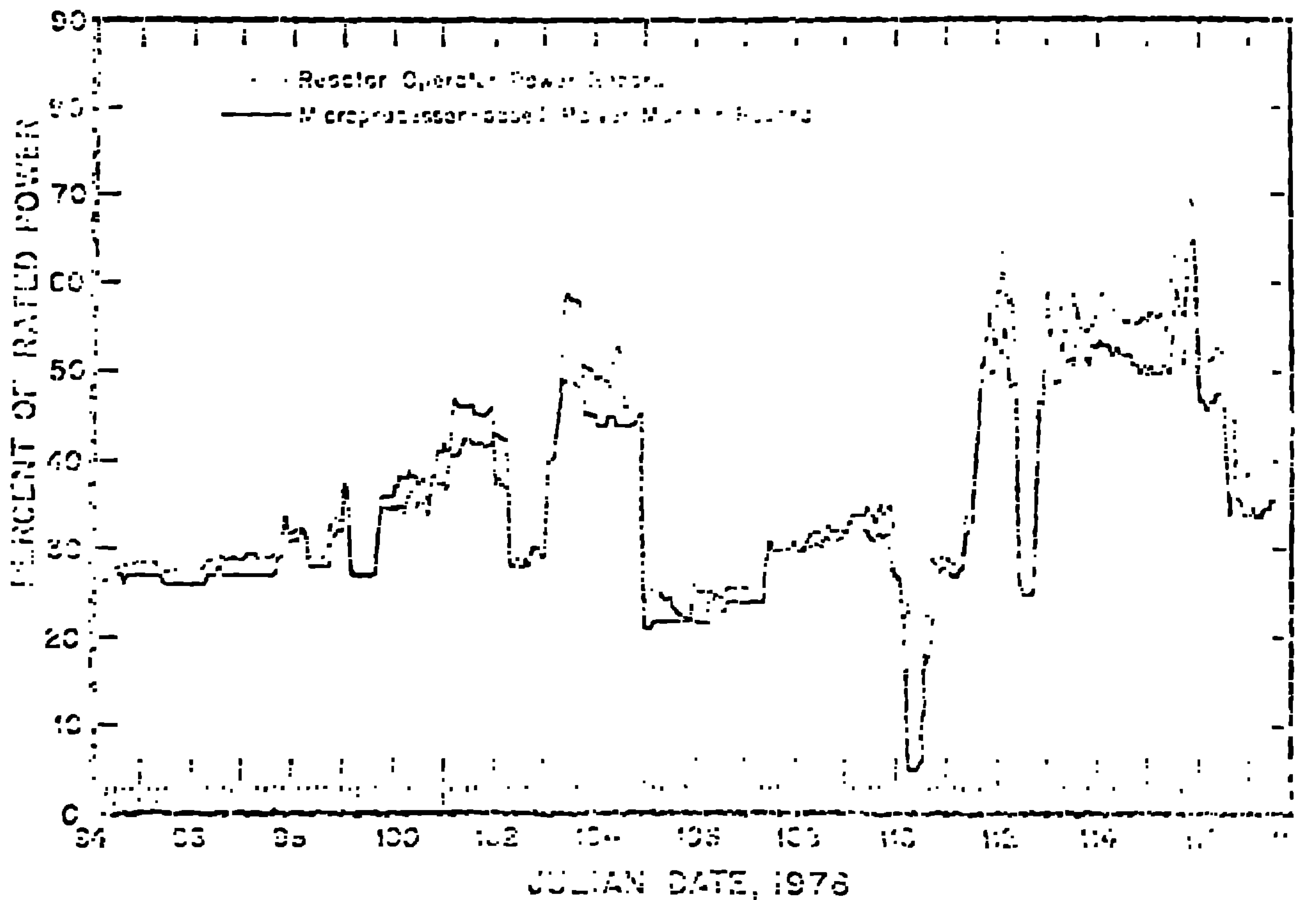


Fig. 7. Records of the power output of the Ft. St. Vrain power station during April 1976.

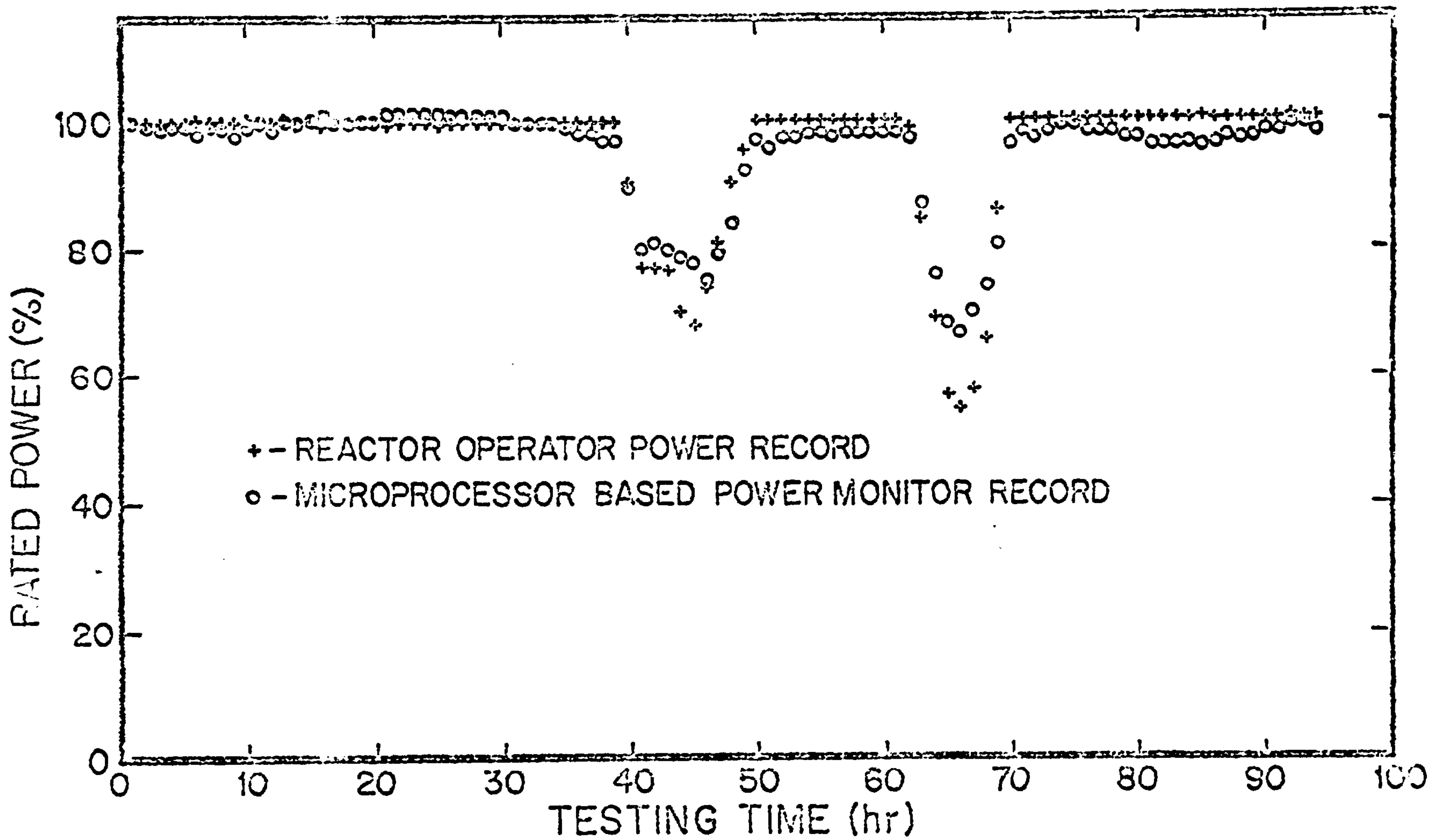


Fig. 8. Results of an abbreviated test of the reactor power monitor on Unit #2 of the Zion Generating Station.

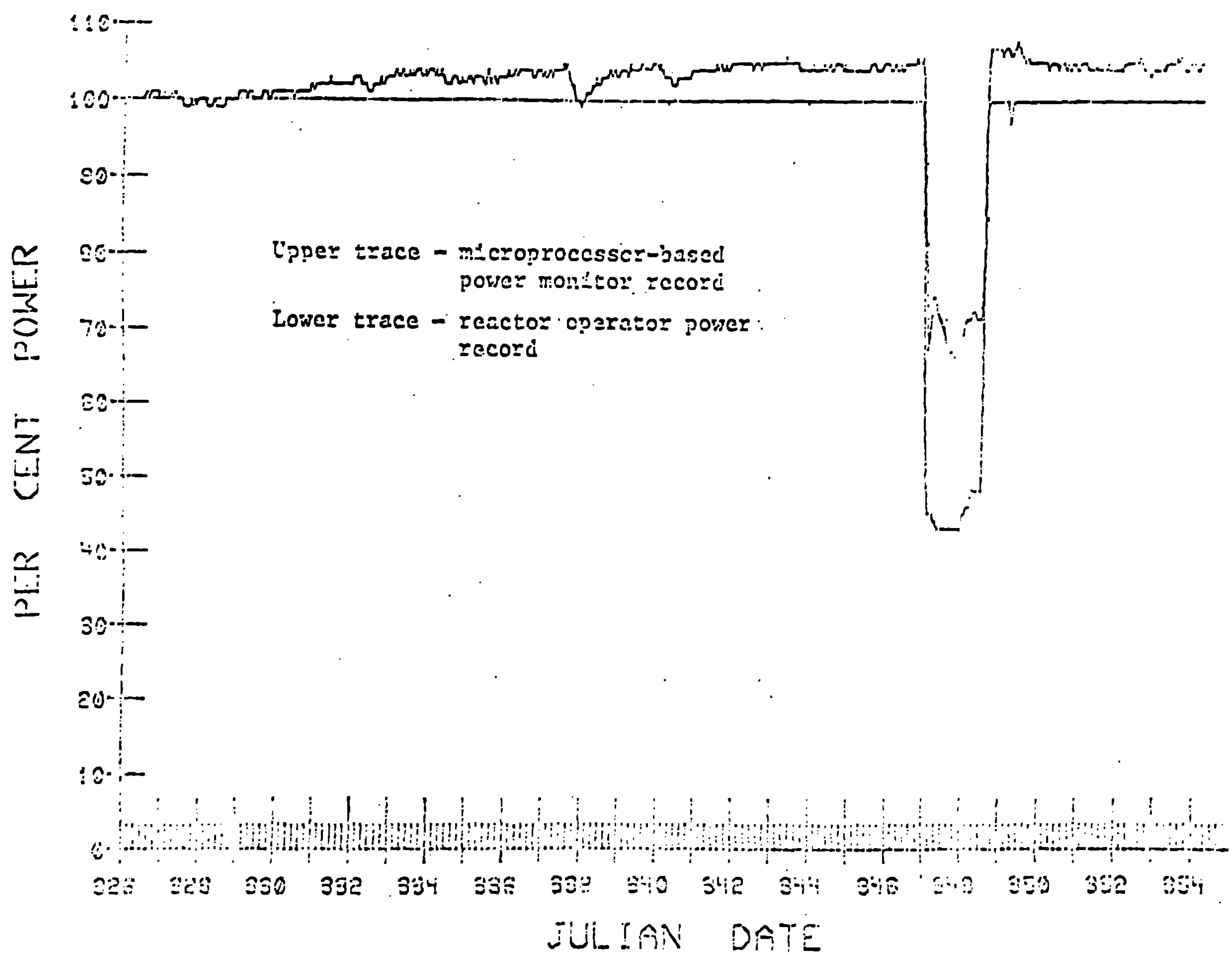


Fig. 9. Results of a power monitor test conducted on Unit #2 of the Zion Generating Station.