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SUMMARY OF HRT RUN 21

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ABSTRACT

The HRT was operated experimentally during run 21 at powers up to 5 Mw to explore the limiting conditions of fuel stability and to demonstrate the reliability of the system.

The effect of core pressure on fuel stability was investigated over the range from 1250 to 1750 psig. Stable operation at 5 Mw (2.6 Mw in the core) was demonstrated at 1250 psig. At 1600 and 1750 psig, fuel instability accompanied by rapid loss of reactivity occurred at powers down to 2.5 Mw. The threshold power for reactivity loss at intermediate pressures was raised by increasing the fuel acid/sulfate ratio from 0.28 to 0.34. In other studies the fuel temperature was varied from 240 to 275°C at several different pressures. In some instances the reactor appeared more stable at the lower temperatures. The effects of suspended solids and oxygen concentration were examined briefly without conclusive results.

At times during operation at low pressure and high power, an increase in reactivity, indicating deposition of uranium on the core tank, was observed. During an experiment to investigate this effect, a hole was melted in the core near the equator. The reactor was shut down for examination and modifications to improve the core hydrodynamics.

(Continued)

ABSTRACT (Continued)

Experiments on internal recombination showed solution recombination-rate constants significantly higher than had been measured in out-of-pile experiments.

Equipment performance was generally satisfactory. A diaphragm failure in one head of the fuel feed pump, minor leakage through four valves, low efficiency of the low-pressure recombiners and rupture of the air-cooled condenser by freezing were the principal difficulties. There was one period of 105 days of continuous operation.

During run 21 operations, which extended from October 4, 1959, to January 23, 1960, the reactor was critical for 2455 hours and produced 5598 Mwh(th).

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INTRODUCTION

The power-dependent loss of uranium from the fuel solution, observed in earlier runs, was in run 20 shown to be affected by the core pressure.[1] Loss occurred at reactor powers as low as 1.5 Mw when the pressure was 1750 psig, but 16 hr of operation above 4 Mw at 1250 psig showed no signs of fuel instability. The low-pressure, high-power operation also revealed that the internal recombination of radiolytic gas was more effective than expected, but only a lower limit on the catalytic activity was determined. Run 20 was terminated by a shutdown for necessary maintenance before the interesting low-pressure performance of the reactor could be investigated thoroughly. A major objective of run 21 was to obtain more information pertaining to fuel stability, in particular during long-term operation at low pressure and 5-Mw power level. An accurate determination of the temperature- and power-dependence of the solution recombination catalyst activity was another objective. A third major objective was the study of the behavior of iodine and xenon in the reactor.

This report gives an account of run 21 operations, summarizes the performance of various components and systems, discusses miscellaneous aspects of the reactor operation and presents results of the experiments conducted during the run.

The section which follows gives a chronological account of the operation. Figures 1, 2 and 3 show reactor power, temperature and pressure. During run 21 between 45 and 55% of the power was generated in the core. Core and blanket steam systems were connected, so that core and blanket inlet temperatures were nearly equal. (For typical behavior of temperatures during a power increase, see Fig. 4.)

OPERATIONS

Preliminary and Startup Operations

Maintenance work[2] was completed and the reactor cell was drained on September 29, 1959. After sampling had showed that no shielding water had leaked into the system, the fuel was brought out of the storage tanks,

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[1] H. F. Bauman _et al._, _Summary of HRT Run 20_, ORNL CF-61-7-91 (July 19, 1961).

[2] Components which were replaced were: both heads of the fuel feed pump, the fuel dump valve, and the fuel-feed block valve.

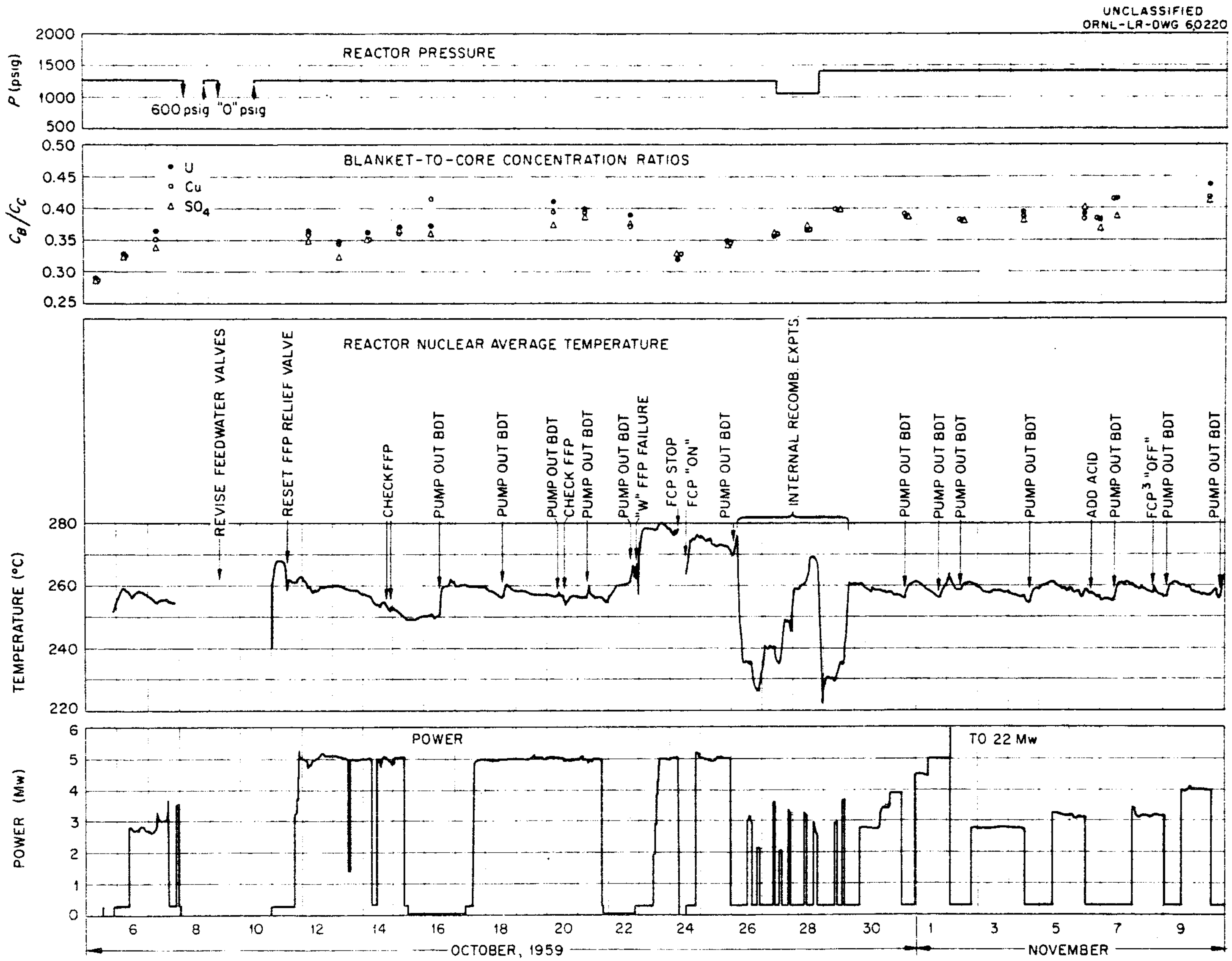

Fig. 1. Chart of Operations From October 5, Through November 10, 1959.

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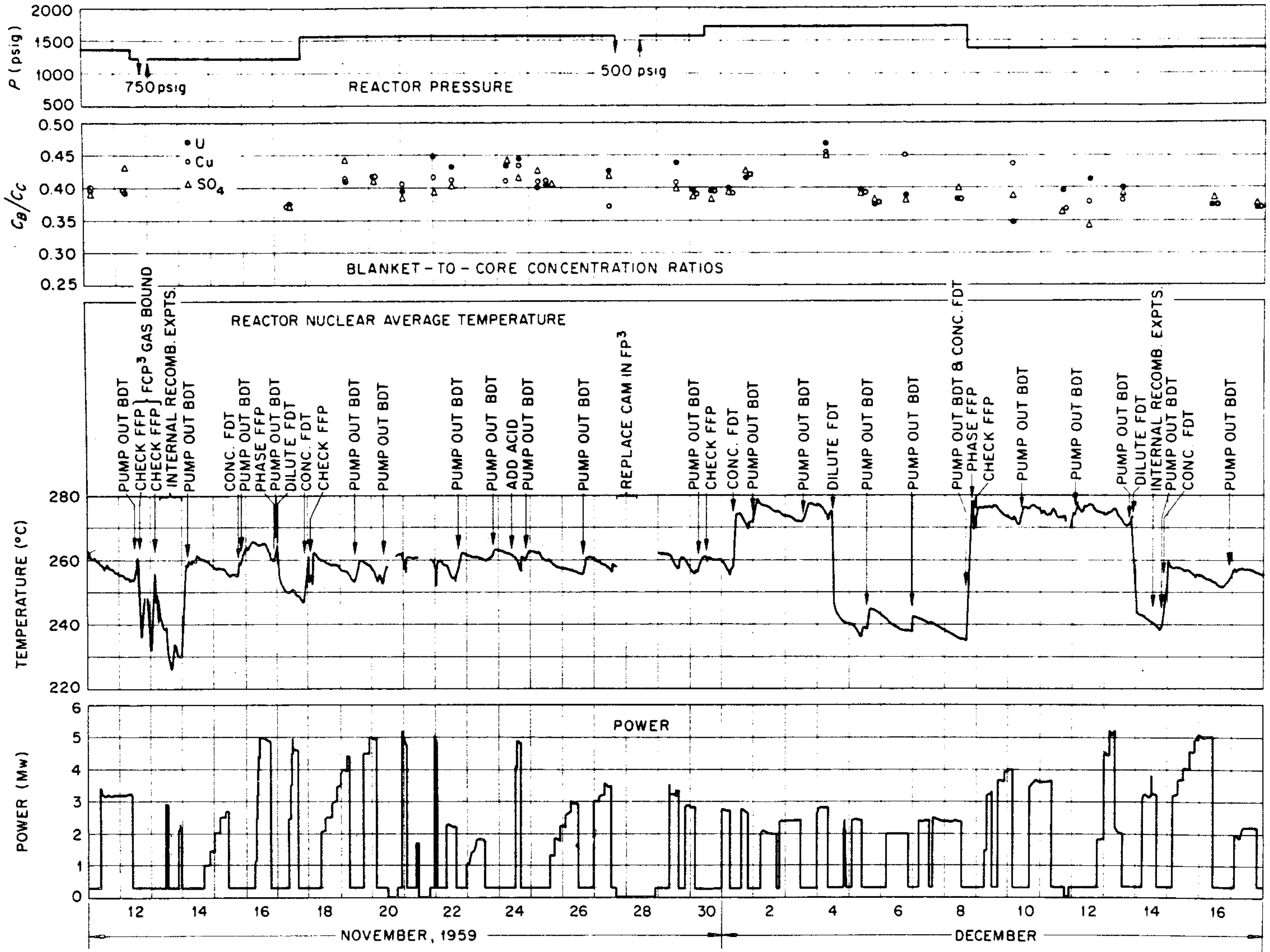

Fig. 2. Chart of Operations From November 11, Through December 17, 1959.

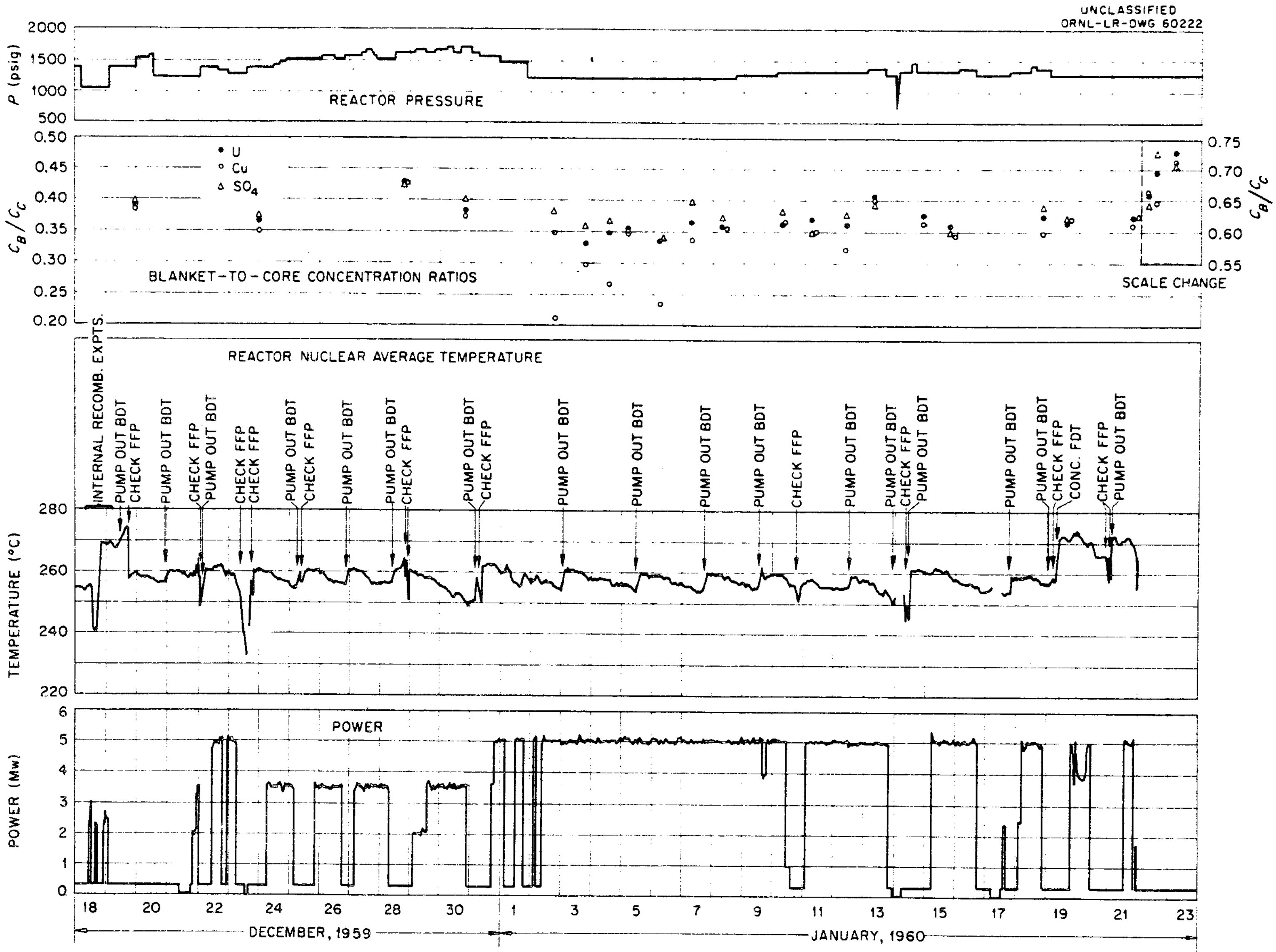

Fig. 3. Chart of Operations From December 18, 1959, Through January 23, 1960.

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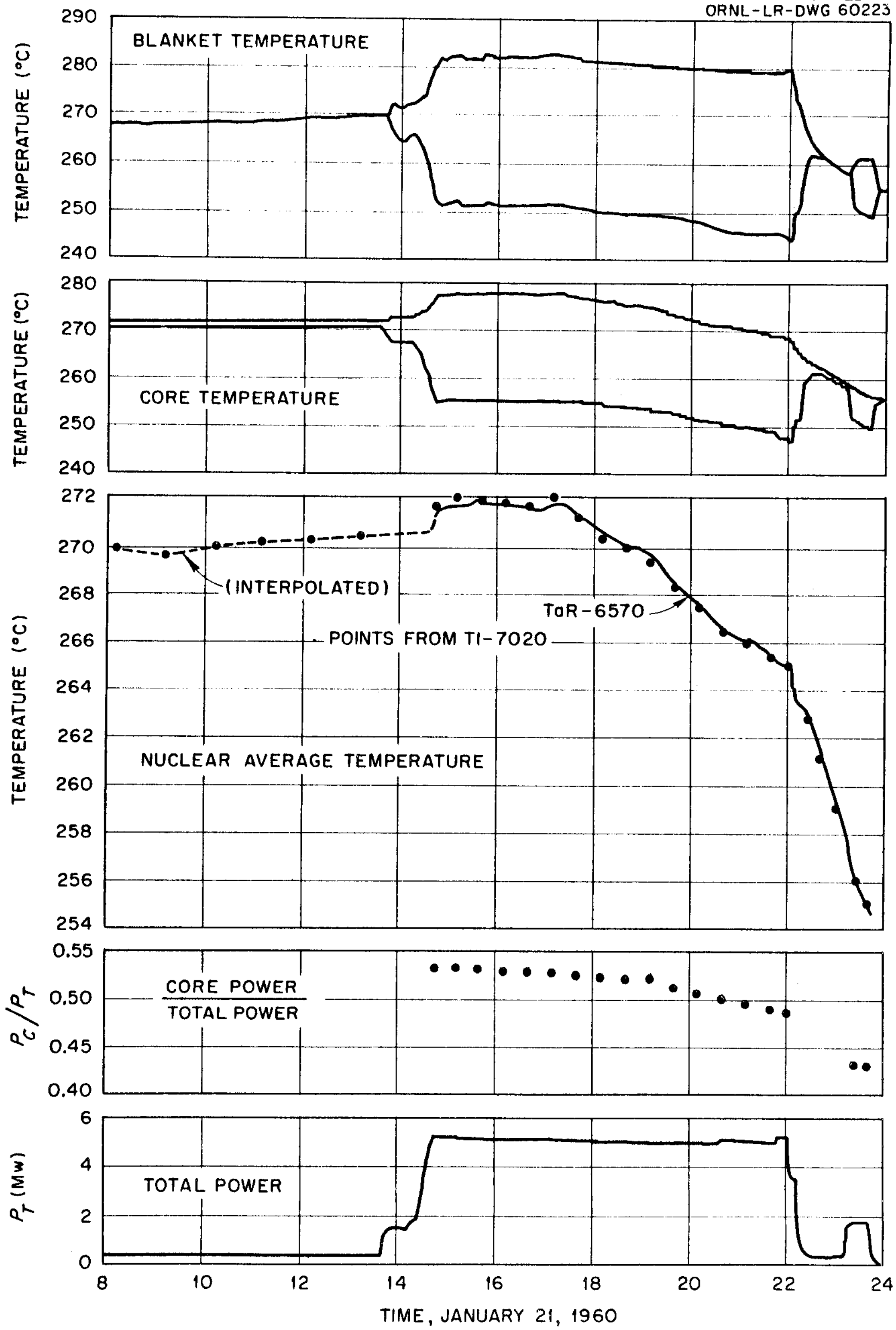

Fig. 4. Powers and Temperatures During Final Power Operation in Run 21.

and the high-pressure systems were successfully hydrotested at 2600 psig. The shield was pressure tested at 15 psig and the leakage proved to be acceptably low.

On October 4 the high-pressure systems were pressurized to 1250 psig, the pressure at which the first experiments were to be conducted. After the heavy water in the system had been heated to 265°C, fuel was pumped up from the fuel dump tanks. The maximum critical temperature which could be attained (without resorting to undesirably low dump tank weight or high feed rate) was only 247°C. On October 5 a fuel addition[3] was made to increase the attainable critical temperature and to raise the acid concentration of the fuel solution.

Iodine and Fuel Stability Experiments at 1250 psig

From October 5 through 25 the reactor was operated at 1250 psig and powers up to 5 Mw to observe long-term stability of the fuel solution and to investigate iodine and xenon behavior.

The intention was to raise the power directly to 5 Mw (to simplify analysis of the iodine data), but the rise to power, on October 6, was stopped below 3 Mw because the low-pressure recombiner failed to function and passed excessive amounts of deuterium to the off-gas system. The recombiners began to function after the catalyst temperature was increased with additional heating steam. But the next attempt to raise the power to 5 Mw, on October 7, was thwarted when the blanket-heat-exchanger feedwater valve would not open enough to pass sufficient water for high-power operation. The reactor was diluted, cooled and depressurized and circulation was stopped while the valve was repaired.[4] (See page 20.) The reactor was pressurized and circulation was resumed on October 10. (Circulation was continuous from this time until January 23.)

During the next twelve days, the reactor was operated at 5 Mw for periods of 77 and 100 hr to obtain data on iodine and xenon behavior.[5] Fuel samples were analyzed for iodine isotopes, a large quantity of gaseous fission products was collected and isolated on one of the charcoal beds, and iodine-bed temperatures were monitored during the sustained operation at high power and the periods at very low power (50 kw or less) which followed.

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[3]The addition contained 5.4 moles U (1175 g U-235), 2.6 moles Cu, and 11.3 moles SO_4.

[4]The fuel-heat-exchanger blowdown valve was repaired at the same time.

[5]The 77-hr period was interrupted twice: the power was reduced for two hours while a heat-exchanger feedwater pump was serviced, and on October 14 the power was taken to heat loss for four hours to observe NAT behavior.

Numerous pips, or small nuclear power disturbances such as had been observed in earlier runs, occurred during the first 77 hr at 5 Mw. All of the pips were smaller than 10% of the mean power, and the frequency decreased. None at all occurred during the 100-hr run. It appeared from the reactor nuclear average temperature (NAT) behavior during this period that there was little or no fuel instability. The NAT varied, but this was largely attributable to accumulation of uranium in the blanket dump tanks and fuel feed rate variations. (Leakage from the blanket to the blanket dump tanks through the dump line persisted throughout the run. The resulting accumulation of uranium caused the NAT to decrease at about 0.2°C per hr. The uranium was returned to circulation periodically by pumping the blanket dump tanks empty.)

On October 22 diaphragm leakage was detected in the new west head of the fuel feed pump. The west head was isolated with freeze valves, and the other head, which had operated for 19,000 hr in a test loop before installation in the HRT, was used for the remainder of the run.

On October 23 the NAT was raised to about 280°C to observe the effect of higher temperatures on the stability. Shortly after the power was raised to 5 Mw, the NAT rose about 2.5°C and small pips began to occur. This period of 5-Mw operation was interrupted after 16 hr when a transformer failure stopped the fuel circulating pump. (See page 35.) After this disturbance the power was again raised to 5 Mw and held for 27 hr. Again there were small pips and some NAT rise after the power was raised. On October 26 the power was lowered and the temperature was reduced in preparation for internal recombination experiments.

Internal Recombination Experiments

Four days were spent in measuring the catalytic activity of the fuel. The experiments were conducted at reduced temperature or pressure (to limit the internal recombination) and consisted of raising the power until there were indications of bubble evolution. The temperatures, pressure and core copper concentration at the bubble threshold were then used to compute specific rate constants. The experiments and results are described on page 27. Rate constants were significantly higher than had been measured in early operation of the HRT or in laboratory experiments.

Fuel Stability Experiments at 1400 psig

Beginning on October 30 the reactor was operated at 1400 psig and 260°C in the study of the effect of pressure on fuel stability.

The power was raised in steps to 5 Mw between October 30 and November 1 with no apparent fuel instability. Then, after about 8 hr of 5-Mw operation, small pips began to occur and the NAT began to rise.[6]

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[6]P. N. Haubenreich, Events Preceding the Large Power Excursion on November 2, 1959, ORNL CF-60-5-18 (May 18, 1960).

In the next 8 hr there were 33 small pips (3 to 14% of the mean power) and a NAT increase of 5°C. This period was climaxed by a reactor power excursion, evidently involving the movement of several hundred grams of uranium, in which the reactor power rose to 22 Mw.[7] Steam withdrawal was immediately stopped, reducing the power to heat loss. As a result of this experience, an operating rule was adopted which required the power to be reduced to heat loss in the event of an unexplained increase of 2°C in NAT.

After the power had been held at heat loss for 16 hr to permit the fuel distribution to return to normal, experiments were resumed. The next operation, at 2.8 Mw, produced a few very small pips. At 3.2 Mw there were more pips and some NAT changes indicative of fuel instability.

On November 6, 7.1 moles of H_2SO_4 was added to the fuel to bring the acid/sulfate ratio up from 0.24 to 0.30. Subsequent operation for 24-hr periods at 3.2, 4.0 and again at 3.2 Mw produced pips, but at a lower frequency than before the acid addition.

Operation at 1250 psig

On November 12 the core pressure was lowered to 1250 psig to permit measurement of the catalytic activity for recombination at the higher acid level. Two measurements were made at low temperatures (237 and 230°C), and then the temperature was returned to 260°C to permit high-power operation.

A group of distinguished nuclear scientists and engineers from the U.S.S.R. visited the reactor on November 16, at which time the reactor was operating at 5 Mw.

Another recombination experiment followed, at 1250 psig and 250°C, in which the bubble threshold was measured at 4.8 Mw.

Fuel Stability Experiments at 1600 psig

The next series of fuel-stability experiments was conducted at 1600 psig, in an effort to fix the threshold pressure for the "rapid-loss"[8] instability, which had been observed in earlier runs at high pressure.

The power was stepped up to 5 Mw on November 18 and 19. There were no signs of instability except two small pips at 5 Mw, but the experiment was cut short because of NAT decrease caused by accumulation of uranium in the blanket dump tanks and a decrease in fuel feed rate. After 18 hr

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[7] J. O. Kolb, Analysis of HRT Power Excursion on November 2, 1959, ORNL CF-60-5-78 (May 23, 1960).

[8] A rapid decrease in NAT, indicative of loss of uranium from circulation to a position of low nuclear importance.

at low power, including 6 hr subcritical while the fuel feed pump was being adjusted, the power was taken again to 5 Mw. Rapid loss ensued. The 5-Mw operation with rapid loss was repeated to check the results. Lower-power experiments fixed the threshold power for rapid loss at about 2 Mw with the acid/sulfate ratio at 0.31 and the pressure at 1600 psig.

On November 24 the fuel acid/sulfate ratio was raised by the addition of 7.2 moles of H_2SO_4. While the acid was still mixing into the system, the power was raised to 5 Mw. The NAT decreased rapidly, then began to rise, and the experiment was terminated by reducing the power. In the next three days the power was stepped up to 3.4 Mw. Some pips and NAT loss were observed, but only above 3 Mw. After a day subcritical, spent in work on the fuel-pressurizer purge pump, the reactor was operated at 3.2 and 2.8 Mw. The 3.2-Mw operation was distinctly unstable, and there was some NAT decrease and one pip at 2.8 Mw.

Experiments on Effect of Average Temperature

The next part of the program was intended to explore the effects of average temperature on the threshold power for fuel instability at 1750 and 1400 psig. The highest practicable temperature was 275°C, set by the uranium inventory; the lowest was set at about 240°C by bubble evolution at the lower pressure.

Experiments at 1750 psig were undertaken first, beginning on December 1. At this pressure, four experiments at 275°C and four at 240°C indicated the threshold for instability was near 2.4 Mw at either temperature.

At 1400 psig and 275°C there was no pronounced instability in operation at 3 to 4 Mw, only small changes in NAT and two small pips. On December 13, however, when the power was raised to 4.5 and then to 5 Mw, the NAT and the fraction of power generated in the core began to rise. These changes were reversed by lowering the power to 2 Mw.

At 1400 psig and 240°C the power at which bubble evolution occurred was determined to be 3.6 Mw, and since the threshold for fuel instability appeared to be higher than this, the temperature was raised to 255°C for further experiments. At this temperature the power was gradually raised to 5 Mw. Operation for 13 hr at 5 Mw disclosed no evidence of instability.

The last day allocated to this phase of the experimental program was spent at 2 Mw, observing the apparent cessation of the leakage to the blanket dump tanks, which up to that time had been relatively constant.

Internal Recombination Experiments

On December 18 threshold powers for bubble evolution were determined at 1050 psig and 256, 240 and 268°C. The purpose was to measure catalytic activity at an acid level higher than in earlier tests.

Circulation Rate Experiments

On December 21 experiments were conducted in which the core and blanket circulation rates were separately reduced to as low as one-half normal.

The first experiment, at very low power (about 50 kw), was to observe for possible reactivity effects which might occur if uranium-bearing solids were suspended in the upward flow through the reactor. Presumably, different flow rates would elevate the solids to different heights in the core and thus result in reactivity changes. However, such effects were not detected.

Flows were reduced at powers of 2 and 3.5 Mw to study effects of circulation rate on the small fluctuations normally present in the nuclear power.

Pressure Variation Experiments

Experiments on fuel stability in run 20 and up to this point in run 21 had followed one general pattern: At a chosen pressure and average temperature, the power was raised to determine the threshold for instability. When instability was encountered, the power was lowered to allow recovery. Usually the experiment was repeated before new conditions were explored.

A new approach to the study of the fuel stability was adopted for the last part of run 21. The plan was to raise the power to 5 Mw and then to vary the pressure. The immediate objective was to find the lowest pressure at which "rapid loss" could occur. The boiling point at this pressure was to be compared with temperatures on the solution phase diagram with the hope of identifying the "rapid-loss" mechanism.

Preliminary observations on the effect of pressure changes on NAT (indirect, through feed and purge rate changes) were carried out on December 19 and 20. On December 22 the power was raised to 5 Mw to begin the new series of experiments. The pressure was 1400 psig. Soon after the power was raised, the NAT began to increase from the initial 260°C and, after lowering the pressure from 1400 to 1350 psig did not stop the rise, the power was lowered to heat loss. After the NAT recovered, the power was returned to 5 Mw and again there was a NAT increase.

The rise in NAT at high power was regarded as a form of instability different from that responsible for the "rapid-loss" effect under investigation. If both effects occurred simultaneously, the occurrence of the "rapid-loss" effect might be obscured. Since the NAT rise had been observed only at powers above 4 Mw, and "rapid loss" had occurred at lower powers when the pressure was high, it was decided to conduct the experiment at 3.5 Mw to avoid the NAT-rise effect.

Through the week of December 24-30, the core pressure was changed up and down in 50-psi steps over the range from 1400 to 1750 psig. Much of the time the power was 3.5 Mw, with some reference data being taken at the "stable" power of 2 Mw. The power was lowered to heat loss about once a day, to observe NAT changes and to allow recovery of uranium from the blanket dump tank without confusing the experiment.

On December 31 and January 1, the reactor behavior was observed at 5 Mw and pressures of 1600 and 1500 psig. There were pips and NAT changes at each pressure.

Sustained Operation at 5 Mw

On January 2 a demonstration of sustained operation at full power was begun (see Fig. 3). The pressure chosen for this demonstration was 1250 psig, to minimize the chances of interruption because of fuel instability.

When the power was first taken to 5 Mw, the NAT rose more than 2°C in the first two hours and the power returned to heat loss. On the second rise to 5 Mw, the NAT rose at first, but soon came back to near the baseline, and operation at 5 Mw was continued.

During the next eight days the power remained at 5 Mw, with the exception of 3 hr at 3.8 Mw,[9] with no detectable fuel instability. The NAT varied between 253 and 260°C as uranium gradually accumulated in the blanket dump tanks and was periodically pumped out. The power was reduced to 1 Mw and then to heat loss on January 10 to permit servicing the feedwater pump.

Further Experiments at High Power

The threshold conditions for the "NAT-rise" form of fuel instability had not been well defined, and so experiments to do this were undertaken. Variation of pressure began on January 8, during the sustained 5-Mw operation. During the remaining two weeks of operation, the core pressure was varied between 1300 and 1450 psig. There had been some evidence that higher average temperatures encouraged the "NAT-rise" instability, so on January 19 - 21 experiments were conducted at 270°C.

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[9] The power was reduced after the dump tank pressure began to rise; see page 24.

During the period described above, on January 17 and 18, the oxygen input was maintained at twice the normal rate, and the power was taken to 5 Mw for 16 hr to observe for possible effects of the increased oxygen concentration.

Termination of the Run

On January 21 the power was taken to 5 Mw for the last time in run 21. The pressure was 1300 psig and the NAT was 270°C. As shown in Fig. 4, about three hours after the power was raised, the NAT and the power distribution began to indicate increased mixing between the core and blanket. The power was reduced to heat loss, then was raised briefly to check the core/total power ratio. When this ratio indicated that the blanket concentration had increased to above 0.6 of that in the core, external heating was applied to take the reactor subcritical. Three pairs of samples confirmed the high blanket concentration, and on January 23 the reactor was diluted and cooled.

During the cooldown the indicated inventory of D_2O in the reactor decreased about 400 lb for no known reason. (It was later found that a leak had developed in the fuel-circulating-pump purge line. See page 38).

While the high-pressure systems were being drained, observations of gas transfer and liquid heels indicated a new core-blanket interconnection above the level of the old hole in the core inlet cone.

A wide-angle periscope (Omniscope) was used on January 27 to examine the core, but no hole was discovered above the inlet screens. The scope could not be inserted below the third screen because the fourth and fifth screens were loose and the central 2-in. holes were misaligned. The first and second screens were also completely loose, but the third screen was still partially attached to the core wall. (This screen was later pulled loose during retrieval of strips cut from the upper two screens.)

On February 3, after some difficulties with viewing equipment, the Omniscope with a right-angle objective was inserted in the core. This gave a better view of the core walls, and a new hole was revealed, just below the core equator. The core wall was extensively pitted in the vicinity of the hole and the very edge of the hole was of brittle material which broke away when poked. (Subsequent examination of a specimen from the edge of the hole showed that the hole had been melted in a brief temperature excursion.[10]

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[10] F. W. Cooke and M. L. Picklesimer, HRP Quar. Prog. Rep. July 31, 1960, ORNL-3004, p 9-17.

After the photographs were made of the hole and its vicinity, the core access was closed and the system was given a final rinse in preparation for extended work in the core. This work, described in detail in other reports, included removal of five core screens;[11] detailed examination of the core, including systematic photography of all surfaces[12] and measurement of wall thickness;[13] plugging of both holes;[12] reversal of core flow; and replacement of four valves, two diaphragm-pump heads and the fuel low-pressure recombiners.

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[11] S. E. Beall *et al.*, HRP Quar. Prog. Rep. Apr. 30, 1960, ORNL-2947, p 6.

[12] S. E. Beall *et al.*, HRP Prog. Rep. Aug. 1 to Nov. 30, 1960, ORNL-3061, p 1-11.

[13] S. E. Beall *et al.*, HRP Quar. Prog. Rep. July 31, 1960, ORNL-3004, p 18-19.

AUXILIARY SYSTEMS

Reactor Steam System

Changes Before Run 21

Two changes were made in the reactor steam system before run 21; a new heat exchanger blowdown system was installed, and the turbine steam control valves were restored to service.

Heat Exchanger Blowdown.--Previously, both the fuel and blanket blowdown streams entered a common cooler, so that it was necessary to shut off one stream in order to sample or measure the flow rate of the other. In the new system the streams were completely separated. Each blowdown line was equipped with a cooler, rotameter, and sample point. An existing stainless-steel line was converted from water service to conduct the second blowdown stream from the east valve pit to the sample point in the waste evaporator building.

Steam Control Valves.--The valves controlling the flow of reactor steam to the turbine, PCV-552A and B, had been out of service since run 16, when the original PCV-552B was removed for use as a blanket steam-control valve. A new PCV-552B valve was installed, to restore the turbine reactor-steam system to service.

Operation

There were several malfunctions of reactor steam system components in run 21, particularly the blanket feedwater valve, the feedwater pump and the air-cooled condenser.

Blanket Feedwater and Fuel Blowdown Valves.--The stroke of the blanket feedwater valve LCV-546 had been shortened before run 21 to increase the seating pressure. When the reactor power was raised to 3.7 Mw on October 7, it was found that the valve did not have sufficient capacity to maintain the required feedwater level in the blanket heat exchanger. The reactor was made subcritical and the steam system vented to permit servicing the valve. The plug was altered to increase the valve C_v from about 0.7 to 1.0 with the stroke adjusted to give adequate seating pressure.

During the steam system venting operations, it appeared that the fuel heat-exchanger main blowdown valve HCV-539 would not close. The valve was removed, and the valve stem was found to be broken. The valve stem was repaired, and the valve was reinstalled.

Heat Exchanger Sample-Blowdown.--There was some plugging of the heat exchanger sample-blowdown lines during the run, apparently caused by the accumulation of solids in the 1/4-in. IPS throttling valves. Usually the plugging could be cleared by opening and closing the valves, but on October 11 it was necessary to blow back through the fuel heat exchanger sample-blowdown line with helium at 1100 psig.

On January 19 a leak was discovered in the copper water line to the new cooler on the fuel heat exchanger sample-blowdown line. The corroded line was examined metallurgically with the conclusion that the quality of the tubing was substandard for water service. The fuel blowdown was stopped while the faulty copper tubing was replaced.

Feedwater Pump.--It was necessary to interrupt the operation of the main feedwater pump (No. 2) on October 10, and again on October 23, to replace the piston packing. The center and south pistons, which were somewhat scored, were replaced with new pistons on November 9 and 12, respectively. (The north piston had been replaced, for the same reason, at the end of run 18.) All pistons were repacked. Even with all new pistons in the pump, it was necessary to repack the north piston again on November 24, and the north and center pistons on January 10. The pump drive belts became worn and noisy and were replaced on December 21.

On January 16 the feedwater pressure dropped low enough to actuate the interlock which closed the reactor steam withdrawal valves. The feedwater pump and the feedwater-pressure control valve were checked afterward and found to be operating normally. Possibly foreign material had lodged in the feedwater-bypass pressure control valve momentarily, preventing it from closing properly.

Air-Cooled Condenser.--On October 20, with the reactor operating at 5 Mw, the air-cooled-condenser fan was inadvertently shut off during reactivation and testing of the condenser-freeze-protection system. The condenser steam pressure rose rapidly to the relief pressure, about 150 psig, whereupon the relief valve opened, discharging the reactor steam to the atmosphere. The fan was restarted promptly and the pressure returned to normal.

On November 3 an experiment was conducted which showed that the condenser fan could be operated satisfactorily with the discharge louvers in the fully closed position. To provide greater latitude in the operation of the condenser, the limit switch, which had prevented operation of the fan with the louvers closed, was removed.

Starting on November 12, several experiments were performed in an attempt to use the louver control system (which was installed primarily for freeze protection) to control the condensate discharge temperature. The temperature control bulb was attached to the condensate discharge line under the insulation. It was found that the response of this system was too slow, resulting in wide cycling of the condensate temperature and louver position. The bulb was then moved into the discharge air stream near the condensate discharge end of the condenser. This position was more satisfactory; although close condensate-temperature control was not achieved, the system was effective in preventing extreme overcooling of the condensate at low reactor powers.

At about 0400 on November 30, the reactor power was lowered from 2.8 Mw to heat loss. Later in the day it was discovered that the center and west banks of the air-cooled condenser had frozen and ruptured. An investigation disclosed that the temperature element which controlled the auxiliary (steam) heaters was located in the discharge air stream, where it was warmed during power operation, keeping the heaters off. The heaters, located in the intake air stream, froze, so that when the reactor power was lowered, and the heater valve opened, no steam reached the auxiliary heaters and the main condenser banks froze. The control bulb for the heaters was later moved to the intake air stream, so that the heaters would remain on at all times in freezing weather. Also, a temperature recorder and annunciator were installed to monitor the temperatures at twelve points on the condenser.

The two ruptured sections of the condenser were blanked (and later removed for repair), so that the remaining east bank could be used for continued reactor operation. The repaired banks were reinstalled on January 17.

With only one bank in service, the condenser heat removal capacity limited the reactor power to less than 3 Mw. To enable higher power operation, the turbine-generator, usually operated on service steam as a standby power supply, was switched to operation on reactor steam. About 2.5 Mw of reactor heat could be utilized in this manner, so that the reactor could be operated at full power. Since the existing pressure controller for reactor steam to the turbine had proved inadequate, a new pressure controller, with a remote indicator and setpoint control on the main control panel was installed.

Steam System Shutdown.--At the end of the run, on February 10, the steam-system valves were hydrostatically tested for leakage, including leakage through the seats. Several valves showed minor leakage and were scheduled for maintenance. The steam system was then filled with treated water for corrosion protection during the shutdown period.

Steam and Cooling Water Systems Chemistry

The reactor steam system was treated as formerly with buffered phosphate solution to control the corrosion of carbon steel by water, and with hydrazine solution to remove radiolytic oxygen. Oxygen in the fuel heat exchanger steam was kept below 100 ppb and averaged less than 25 ppb with the exception of one period of several hours at 5 Mw when no hydrazine was added. At this time 2000 ppb was observed. The dissolved oxygen returned to less than 100 ppb after the hydrazine treatment had been resumed for about three hours.

There were three periods of steady operation at 5 Mw in run 21 when hydrazine was added at the rate of 1.24×10^{-5} parts N_2H_4 per part of steam produced. The average of seven analyses of dissolved oxygen in the fuel heat exchanger steam was 22 ppb. The range was from 0 to 39 ppb. Both higher and lower rates of addition of hydrazine were tested, but the dissolved-oxygen concentrations were not significantly different. It was concluded that more reproducible performance of the feedwater deaerator would be necessary in order to determine the minimum hydrazine requirement.

The demineralized cooling-water system was maintained at a nominal concentration of 0.1% potassium chromate. The pH remained about 9.

Oxygen and Off-gas

Throughout most of run 21 the oxygen injection rates to the fuel and blanket high-pressure systems were, respectively, 1.5 and 1.0 standard liters per minute. The one change from this condition was a 3-day period when the rates were approximately doubled to see if there was an effect on the fuel solution stability (see page 58).

On November 3 a diaphragm pump was installed in the oxygen feed system to maintain the supply pressure at 2000 psig. The primary oxygen supply is high-pressure gas cylinders and, since the minimum useable pressure is 1950 psig, only a small amount of the gas in each cylinder flows freely into the reactor system. With the compressor installation it was possible to reduce the pressure in the primary supply cylinders to 500 psig and still maintain the required feed pressure.

The reactor off-gas for this run was passed through charcoal adsorber beds A and C with the exception of the period of high oxygen injection, when bed B was used in parallel with A and C to limit the pressure in the reactor low-pressure systems. Bed D was used only to collect a sample of gaseous fission products (see page 34).

The deuterium content of the reactor off-gas was checked every four hours throughout the run with a portable Explosimeter. The maximum range of this instrument is about 8% deuterium and, except when the reactor was operated for extended periods at very low power, the deuterium concentration was above this value. Late in run 21 a Mine Safety Appliances Co. Thermatron hydrogen analyzer was installed to give a continuous indication of the deuterium concentration. The range of the new instrument is 6.5% deuterium, so the continuous indication was of no value during this run. However, provisions were made to dilute samples of the reactor off-gas to bring them into the range of the instrument. Readings on the diluted samples indicated deuterium concentrations in the off-gas as high as 10%. General experience with the hydrogen analyzer was very limited in this run. A few off-gas samples were taken for chemical analysis. The results of these were erratic (probably due to sampling technique) and ranged from 1.5 to 19.7% deuterium.

In spite of the relatively high concentrations of radiolytic gas in the off-gas, the oxygen material balance for run 21 shows a net loss. The total off-gas was only 96.9% of the injected oxygen. The precision of the oxygen input and off-gas measurements does not justify any attempt to evaluate the reactor system corrosion rate on the basis of oxygen consumption.

COMPONENTS

Recombiners

Both the primary and secondary fuel low-pressure recombiners were heated with superheated steam throughout run 21. On the first attempt at power operation the catalytic recombiners failed to function, and additional electric heaters were installed on the heating steam line. After the temperature of the superheated steam was raised from 400 to 475°C, low-pressure recombination began and, except on two occasions, continued throughout the run. On January 9, 1960, while the reactor was at 5 Mw, the fuel-dump-tank pressure and the off-gas flow rate began to increase. Conditions were such that gas bubbles were not being formed and it was concluded that the low-pressure recombination had stopped. The power was reduced to 3.8 Mw and recombination apparently started again as both the off-gas rate and dump-tank pressure returned to normal. They remained normal when the power was raised back to 5 Mw. On the next day the power was reduced to heat-loss to service the feed-water pump. The same evidence of lack of low-pressure recombination was observed when the power was returned to 5 Mw on January 11. After about 1 hr at 5 Mw, recombination apparently started spontaneously and the off-gas rate and dump-tank pressure again returned to normal. No other anomalies were observed in the run.

Measurements of the deuterium concentration in the reactor off-gas indicated that the net recombination efficiency was the lowest that had been observed outside of periods of complete lack of recombination. As a result of this and other experience, both the primary and secondary recombiners were replaced, following run 21, with new units of modified design.

Diaphragm Pumps

Fuel Purge Pumps

The fuel purge pumps became gas-bound several times when the fuel-to-blanket condensate transfer rates were high.[14] On one occasion (November 12) it was necessary to lower the reactor pressure to 750 psig in order to clear the fuel-circulating-pump purge pump of gas.

The fuel-pressurizer purge-pump check valves developed leakage which increased gradually throughout the run. The required pumping rate was maintained at first by increasing the drive speed. On November 27, after a stoppage, pumping could not be restored until a fast-suction-stroke drive cam was installed. Rates were adequate thereafter. At the end of the run, the old head (No. 18), reading only 500 mr/hr at contact, was removed after 9264 hours of service and replaced with a new head (No. 20).

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[14] H. F. Bauman *et al.*, *Summary of HRT Run 18*, ORNL CF-60-8-152 (Aug. 26, 1960) p 17.

Fuel Feed Pump

At the start of run 21, the west head of the fuel feed pump was in service and the east head was in standby. The pumping rate did not hold constant, apparently because of accumulation of gas in the intermediate system, and frequent phasing was required to remove the gas from the system. On October 22, after the west head had been phased, the process monitors detected radiation at the feed-pump intermediate drive line, indicating that the west-head diaphragm had ruptured. The west-head process lines were frozen off. A 20-ml sample taken from the intermediate system read 450 mr/hr at 2 in. The east pump head was placed in service and the run continued. The pumping rate again did not hold constant, and gas appeared to be leaking into the east-head intermediate system. On November 20 the new pulsator housing (designed to prevent air inleakage during the suction stroke) was installed, but the O-ring extruded from the seal grooves during installation and prevented proper sealing. The old pulsator housing was reinstalled and used throughout the rest of the run. The pump traces were watched for evidence of gas in the intermediate system and the pump was phased as necessary to remove it.

At the end of the run, the west fuel-feed-pump head (No. 20) was removed after 400 hr of service and stored inside the reactor cell. A previously stored fuel feed head (No. 23), which had a radiation level of 200 r/hr at 6 in., was removed to the storage pool. Head No. 27, which was reworked from test head No. 10, and had 19,000 hr of previous service out-of-pile, was installed on March 8.

Valves

Four of the process valves were replaced following run 21, three because of excessive leakage through the valve seat, and one (K-38) because of a galled valve stem (see Table 1). All of the valves had been in service since the startup of the reactor, or for about 12,000 hr.

The blanket dump valve also was known to be leaking through the seat during run 21, and it was necessary to empty the blanket dump tank to the high-pressure system periodically to return the accumulated uranium. However, the leakage (about 15 lb/hr) was not great and instead of replacing the valve it was decided to install a new condensate-transfer line to permit continuous purging of the blanket dump tanks, and to eliminate the uranium accumulation problem.

Samplers

The samplers operated without undue difficulty, except as noted below.

On December 31 a fuel high-pressure sample was taken with the flask holder not completely screwed together. The needle failed to completely penetrate the diaphragm, and most of the sample ran into the flask holder rather than the flask. There was no contamination outside the sampler.

Table 1. Valves Replaced Following Run 21

Process No.	Function	Identification No.	
		Removed	Replacement
HCV-136	Fuel high-pressure-sampler block valve	K-94	K-79
HCV-236	Blanket high-pressure-sampler block valve	K-86	K-93
HCV-336	Fuel-condensate-tank fill valve	K-02	K-23[a]
HCV-936	Fuel-transfer block valve	K-38	K-48[b]

[a]For convenience in subsequent alterations of the low-pressure system, valve K-23 was removed from service as HCV-344, leak-checked, and installed as indicated.

[b]Valve K-48 was removed from service as HCV-434, leak-checked, and installed as indicated.

On January 21 a fuel high-pressure sample flask was found to be shattered when the sample was removed at the laboratory. The sample was held without leakage by the plastic coating on the flask. Two or three similar flask failures have occurred in previous runs. The cause of the failures is not known; possibly an occasional flask is oversize and is strained by the flask holder.

During run 21, 85% of the reactor samples were of the required 5-ml minimum volume (compared with 90% in run 20). The relatively infrequent small sample volumes appeared to be caused by incomplete draining of the isolation chamber, so the sampling procedure was revised to require that the isolation chamber pressure be adjusted to between 2 and 4 psig before the sample was drained.

The volume distribution of the 201 samples taken during the run is shown in Table 2.

Process Radiation Monitors

Before the start of run 21, a pair of radiation monitors was installed to monitor the fuel low-pressure catalytic-recombiner heating-steam return line. This increased the number of monitors in service to twenty-two units.

There were two radiation sensing element failures during the run, both in the steam valve pit. One unit failed to calibrate and the other unit gave false high radiation readings. The failures were believed to be caused by high humidity due to steam leakage from valves in the pit.

MISCELLANEOUS

Internal Recombination Experiments

Copper ion, added as $CuSO_4$, is present in the HRT fuel solution as a catalyst for the internal recombination of radiolytic gases. Since the copper absorbs some neutrons and also increases the amount of free acid required for fuel solution stability, it is desirable to limit the copper concentration to that required for complete internal recombination. Therefore, an accurate knowledge of the recombination efficiency in the reactor system is required.

A single experiment in run 20, at reduced system pressure, indicated that the gas recombination rate in the HRT was significantly higher (about a factor of 2) than would have been predicted on the basis of out-of-pile experiments. Accordingly, a series of experiments was planned and carried out in run 21 to attempt to evaluate the quantities which describe the effective recombination rate under reactor conditions. A total of seventeen experiments was performed in the course of the run, at three different acid levels in the fuel solution. The first group, consisting of nine experiments, was performed in the period October 26 - 29, 1959. The second and third groups consisted of three and five experiments, respectively, and

Table 2. Sample Volumes in Run 21

Volume Range (ml)	Number of Samples		
	High-Pressure System		Low-Pressure System
	Fuel	Blanket	Fuel
0 - 3	7	8	0
3 - 5	8	9	0
5 - 8	18	17	1
8 - 10	46	18	0
10 +	21	46	2
Total	100	98	3

were performed in the periods November 13 - 17, and December 14 - 19, 1959. Acid additions to the fuel were made on November 6 and November 24, 1959.

Experimental Procedure

The general procedure for performing the recombination experiments was the same throughout run 21. This consisted of establishing steady operation at heat-loss power and then raising the power until bubbles appeared, indicating that the core outlet stream was saturated. In practice, the power was raised to a level somewhat below the predicted bubble threshold and precision temperature readings were taken to establish the relation between core power and neutron level for the existing conditions. The power at the bubble point was then obtained from the neutron level indication.

The appearance of gas bubbles was detected by the effects produced in the fuel low-pressure system. The experimental conditions were always such that the first gas bubbles appeared at the core outlet where they could be removed from the high-pressure system by the gas separator. Because of the low efficiency of the low-pressure recombiners, bubble letdown produced a sharp rise in dump-tank pressure rather than an increase in recombiner temperature. This method permitted detection of the bubble point with less than 50-kw overshoot in core power.

After the threshold power for bubble formation had been determined, the power was reduced and the core solution sampled to obtain the copper concentration.

Treatment of Data

Evaluation of the recombination experiments is complicated by the fact that the fuel solution circulates and the temperature varies around the loop. It may be assumed, without significant error, that all production of radiolytic gas occurs in the core, but recombination proceeds in the external loop as well as in the core. Therefore, it is necessary to consider the transit time and the temperature distribution of the fuel in the external loop to evaluate the net recombination rate.

At the bubble threshold the total production and recombination rates of radiolytic gas are equal and the gas concentration at one point in the loop is known (saturation concentration at the core outlet). The gas production rate used for the fuel solution was 1.59 molecules of D_2 per 100 ev, the value measured in run 13.[15] The gas solubilities were those reported by Stephan *et al.*[16] With this information it is possible to evaluate the solution recombination rate if the nature of the temperature dependence

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[15] J. R. Engel *et al.*, Summary of HRE-2 Run 13 (Initial Power Operation), ORNL CF-58-10-115 (Oct. 29, 1958) p 42.

[16] E. F. Stephan *et al.*, The Solubility of Gases in Water and in Aqueous Uranyl Salt Solutions at Elevated Temperatures and Pressures, BMI-1067 (Jan. 23, 1956).

is known. However, since the copper concentration was somewhat different in each experiment, the effect of this variable was eliminated by evaluating the specific rate constants for copper. In doing this it was assumed that: 1) all recombination was due to copper catalysis, 2) the solution rate constant is directly proportional to copper concentration, 3) the recombination reaction is first-order with respect to D_2 concentration, and 4) the copper specific rate constant follows the Arrhenius equation. From the last assumption, the specific rate constant may be written as follows:

$$k = A e^{-\frac{E}{RT}} , \tag{1}$$

where

k = specific reaction rate constant, $\left(\frac{\text{liters}}{\text{g-mole Cu, sec}} \right)$,

A = frequency factor (a constant) ,

E = activation energy for the catalyzed recombination reaction (cal/g-mole) ,

R = universal gas constant, $\left(\frac{\text{cal}}{\text{g-mole, } ^{\circ}\text{K}} \right)$,

T = temperature ($^{\circ}$K) .

The quantity, A, may be eliminated by writing the equation in terms of a specific rate constant, k_o, at some selected temperature, T_o. Then:

$$k = k_o e^{-\frac{E (T_o - T)}{R T_o T}} . \tag{2}$$

In the following analysis of the run 21 experiments, K_o was evaluated at 250°C.

As may be seen from equation (2), there are two constants which must be evaluated: the copper specific reaction rate constant at 250°C and the activation energy. Therefore, a single experiment can do no more than give a relationship between k_o and E. However, if several experiments are performed under similar[17] conditions, several such relationships are obtained. These relationships may then be plotted, in terms of k_o as a function of E, and the various points of intersection taken as possible values of the constants. (Theoretically, all of the lines should intersect at a single point but this is not to be expected under actual conditions.) An average of the several values thus obtained provides a good estimate of each of the terms. The values of k_o and E obtained by this method are not absolute because they contain the effects of other variables. If, for example, there is an effect of acid concentration on the net recombination rate, this effect appears as a difference in one, or both, of the evaluated terms.

One of the major uncertainties in evaluating the effective recombination rate constants in run 21 is the core temperature distribution. Since there was inadequate information for an accurate calculation, this temperature distribution was assumed. The effective recombination rate constants were evaluated for three different temperature distributions to obtain some information about the effect of the assumptions. In the first approach, the core was assumed to be perfectly mixed and all at the core outlet temperature. In the other approaches, the core was divided into two regions, each of which was perfectly mixed. In one case a small fraction of the volume was assumed to be at a higher temperature than the mixed mean, and in the other case the small region was assumed to be at a lower temperature than the mixed mean. For both of these cases it was assumed that no bubble letdown occurred until the mixed core outlet stream was saturated, even though bubbles existed within one of the core regions.

Experimental Results

The seventeen recombination experiments in run 21 were divided into three groups, according to acid level, and evaluated by the method described above. Table 3 shows the general conditions for the three groups. In each group the curves k_o as a function of E were plotted for each experiment and the points of intersection obtained. A few of the points were far outside the general range and these were discarded. The points of intersection obtained for the three groups of experiments by assuming a perfectly mixed core are shown in Fig. 5. Similar patterns were obtained for the other assumptions about the core temperature distribution. Table 4 shows the results obtained under each assumption for the three groups of experiments. This tabulation shows the number of independent values theoretically obtainable for each constant and the number actually obtained. Also shown are the average values of the copper specific rate constant at 250°C and the activation energy. The units of k_o express the absolute reaction rate, in gram-moles per second of D_2 reacted per

[17] Similarity here implies no changes in variables, which could affect the recombination rate, whose effect has not been mathematically defined, e.g., acid concentration or fission or corrosion product level.

Table 3. Conditions for Recombination Experiments in Run 21

Group	No. of Experiments	Condition	Average Acid Conc. $\left(\frac{\text{g-moles}}{\text{kg } D_2O}\right)$	Average Cu Conc. $\left(\frac{\text{g-moles}}{\text{kg } D_2O}\right)$
A	9	Before acid addition	0.0144	0.0112
B	3	After 1st acid addition	0.0174	0.0112
C	5	After 2nd acid addition	0.0212	0.0124

Table 4. Effective Recombination Rate Constants

Group	Number of Points		k_o	E	Assumption
	Theoretical	Actual	$\left(\frac{\text{sec}^{-1}}{\text{g-moles Cu/liter}}\right)$	$\left(\frac{\text{K-cal}}{\text{g-mole}}\right)$	
A	36	30	2.15	18.8	
B	3	3	1.98	22.2	Core perfectly mixed
C	10	8	1.74	17.9	
A	36	31	1.94	23.4	
B	3	3	1.60	22.5	Small hot region in core
C	10	8	1.56	25.0	
A	36	33	1.95	21.8	
B	3	3	1.63	21.7	Small cool region in core
C	10	8	1.58	21.9	

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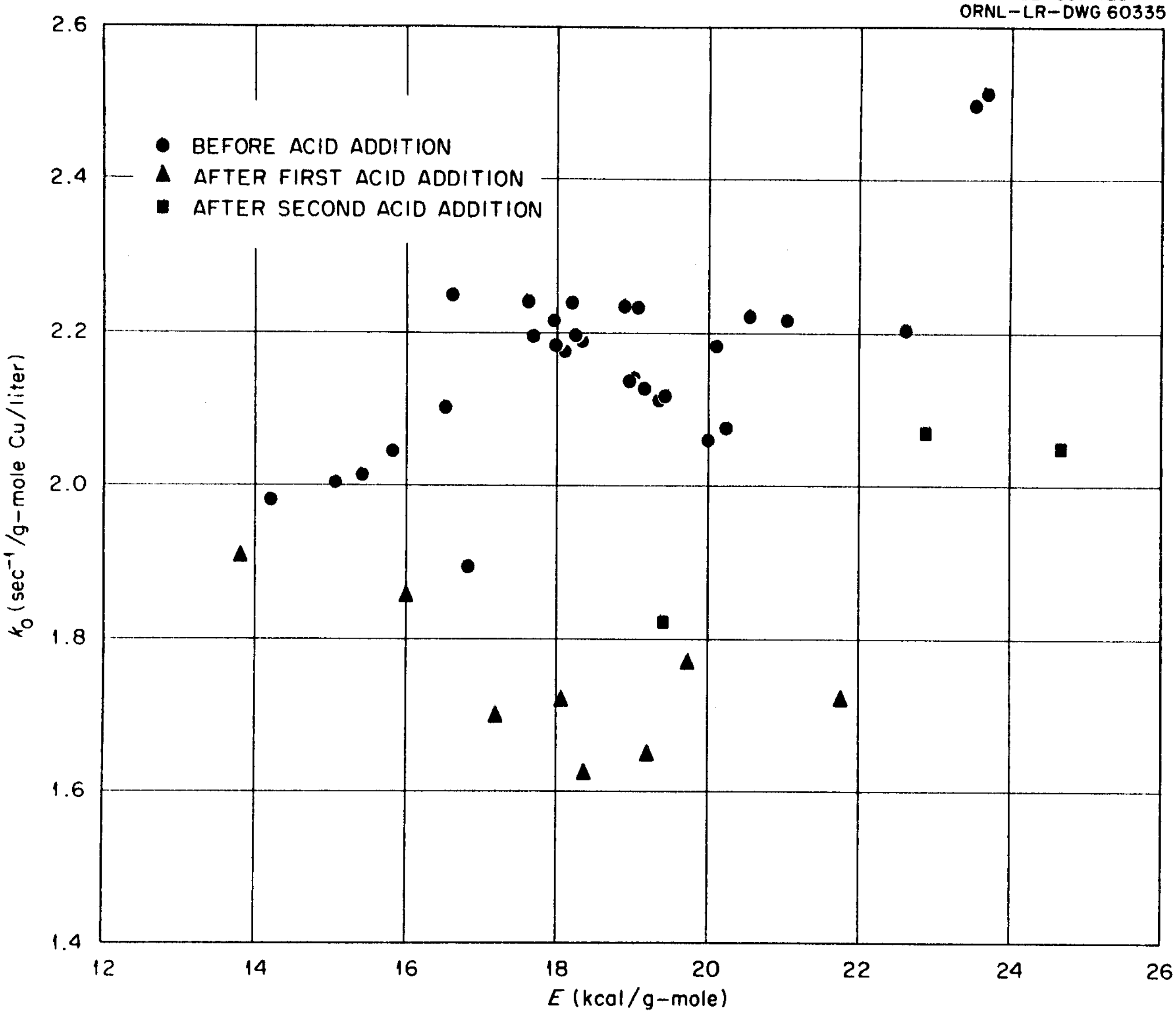

Fig. 5. Values of k_0 and E Obtained from Run 21 Recombination Experiments by Assuming a Perfectly Mixed Core.

liter of 250°C solution, at unit molar[18] D_2 concentration and unit molar Cu concentration.

Since the point scatter under each of the three assumptions is about the same, it is not possible to say which of the three best describes the actual core temperature distribution. However, the differences in k_0 resulting from the different assumptions are relatively small. The differences in the average values of E are larger, but the point scatter was also larger. The results appear to indicate an effect of acid concentration on the specific rate constant for copper, but the possibility that this effect is produced by some other variable is not precluded.

Comparison of these results with out-of-pile experiments indicates a significantly higher effective specific rate constant for copper in the HRT system. If the gas solubility data used here are applied to the experiments of McDuffie and Stone,[19] the out-of-pile rate constant is 1.2 $\frac{sec^{-1}}{\text{g-mole Cu/liter}}$ at an acid concentration of 0.016 g-moles/kg D_2O.

Xenon Poisoning

Neutron absorption in xenon-135 in the HRT was measured for the first time during run 21.[20] A sample of xenon taken from the reactor after three days of 5-Mw operation was analyzed for Xe-134 and Xe-136. A xenon poison fraction of 1.0% was computed from a comparison of the observed Xe-136/Xe-134 ratio with the fission yields. NAT transients following power changes could not be used to estimate xenon poisoning because of spurious effects from other system variables. Because xenon effects are relatively slow compared with fuel instability mechanisms, lack of knowledge of the xenon behavior did not interfere with the scrutiny of the NAT behavior for evidence of instability. (No allowance for xenon poisoning was made in following the rule which limited the NAT loss at power to 5°C, see page 41.)

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[18]In this context, molarity is defined as gram-moles of solute per liter of solution at the temperature in question.

[19]H. F. McDuffie and H. H. Stone, HRP Quar. Prog. Rep. Jan. 31, 1958, ORNL-2493, p 181-183.

[20]W. D. Burch and O. O. Yarbro, HRP Quar. Prog. Rep. Jan. 31, 1960, ORNL-2920, p 9.

Interruption of Forced Circulation at 5 Mw

On October 24 the reactor was operating at 1250 psig, 278°C NAT and 5 Mw total power when the fuel-circulating-pump control power transformer burned out, stopping the pump. Interlocks automatically closed the steam-withdrawal valves and switched the fuel-feed-pump supply to the condensate tank. The behavior of the nuclear power and certain reactor temperatures when the forced circulation through the core was interrupted is shown in Fig. 6.

When the pump stopped and the circulation rate fell, the fission power dropped rapidly, as had been predicted.[21] The power rose again as temperature differences developed which caused natural-convection circulation through the core. Heat losses, including steam leakage through the closed steam block valves and throttle valves, were greater than the afterheat and the fission power remained high (~ 0.5 Mw). The heat extraction was finally reduced after about 15 minutes by admission of package-boiler steam to the heat exchangers.

Before the pump stopped, the temperature of steam in the heat exchangers was low because of the high power level. When the fission power fell as a result of the slight increase in core temperature following the flow reduction, the core and blanket inlet temperatures decreased toward the steam temperature. Because of the reduced flow in the core, the temperature rise across the core became much larger than that across the blanket. Thus the blanket average temperature decreased and the core average and outlet temperatures rose.

There is abundant evidence that solution was boiling in the core for about 15 minutes. The most direct is the comparison of the temperature on the core outlet pipe and the temperature in the pressurizer steam space. The small difference indicated in Fig. 6 is probably due to error in the measurements, because it appears that steam from the core outlet flowed into the pressurizer, causing the temperature rise there. This is inferred from the pressurizer liquid level behavior. The level dropped offscale when the circulating pump stopped, went offscale high 100 seconds later (stopping the fuel feed pump) and then fell offscale low at 145 seconds.[22] It remained offscale low until 0647, when the feed pump was restarted. From that point on, the level remained in range of the level element. The core-pressure recorder chart shows that the pressure, initially 1250 psig, fell at first to 1180 psig, then rose to 1380 psig for about 15 minutes. These changes are consistent with the changes in D_2O

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[21] P. R. Kasten <u>et al.</u>, <u>HRP Quar. Prog. Rep. April 30, 1956</u>, ORNL-2096, p 30.

[22] The level dropped as a result of contraction in the blanket and in the core heat exchanger, rose as a result of expansion in the core.

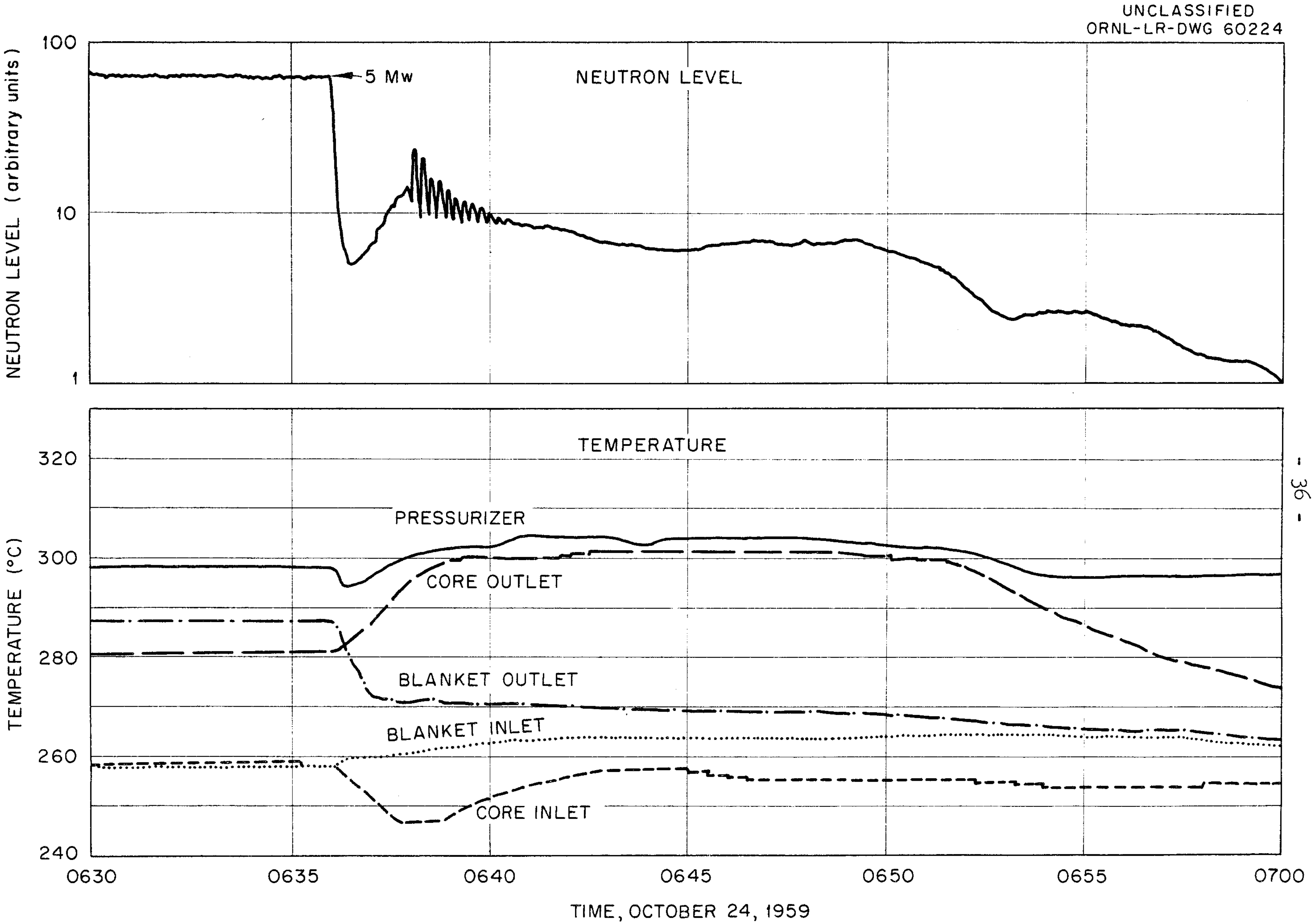

Fig. 6. Neutron Level and Temperatures after Interruption of Fuel Circulation at 5 Mw.

steam pressure at the observed pressurizer temperature. While the liquid level was offscale low, or in sight, the elevated pressure and temperature in the pressurizer could not be attributed to compression or to boiling of the pressurizer condensate (since the pressurizer heaters were cut off by the high pressure). The pressurizer steam must, therefore, have been supplied from the core outlet pipe.

The oscillations in neutron level, which began about 100 seconds after the pump stopped, are further evidence of boiling in the core. The oscillations ceased at a fission power of about 650 kw, although the temperature in the core outlet pipe remained at the boiling point until the fission power was reduced below about 400 kw.

Some information on convection circulation rates can be gleaned from the observed temperatures and neutron levels. The total fission power can be assumed to have been proportional to the ionization-chamber output, and about 53% of the total fissions were in the core. At the time the power oscillations ceased (0641), the core fission power was 350 kw and the estimated afterheat in the core was 24 kw.[23] From the heat generation rate of 374 kw and the temperature rise of 46°C, which was observed, a circulation rate of 30 gpm is calculated. At 0652 the temperature rise was nearly as great: 43°C. But the core power, including 17 kw of afterheat, was only 185 kw and the calculated core circulation rate was only 16 gpm. It appears that the higher circulation rate at 0641 was due largely to boiling in the core outlet. These apparent rates compare with 40 gpm predicted for natural-convection circulation under very similar conditions.[24]

Heavy Water Leak

A routine water inventory on January 25, after the high-pressure systems had been drained and refilled with condensate, showed about 400 lb less than the last routine inventory before the shutdown. An intensive investigation was immediately undertaken.[25] Chart records showed that there had been a steady loss of about 13 lb/hr during the last 30 hr before the system was depressurized. Samples from the fuel and blanket cell sumps, taken during the period of loss, showed 45 and 8% D_2O, respectively. (Later samples showed a progressive equalization of concentration in the two sumps, presumably because of evaporation and condensation.) Within the accuracy of the measurements, all of the missing

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[23] S. E. Beall and S. Visner, HRT Summary Report for the Advisory Committee on Reactor Safeguards, ORNL-1834 (Jan. 5, 1955) Fig. 45, p 144.

[24] P. R. Kasten *et al.*, HRP Quar. Prog. Rep. April 30, 1956, ORNL-2096, p 30.

[25] H. F. Bauman to S. E. Beall, "D_2O Inventory Loss on January 24, 1960," Internal correspondence dated Feb. 11, 1960.

heavy water was accounted for in the sumps. No uranium or sulfate was found in the sumps, and the air activity in the cell did not rise significantly because of the leak, indicating that condensate, rather than fuel solution, had leaked.

On February 18 a crack in the fuel-circulating-pump purge line was discovered by pressurizing the reactor with helium, scanning the flooded reactor cell for helium and finding the bubbles which brought the helium to the surface. The location of the leak in this place explained the low activity and the absence of uranium in the water which had leaked from the system.

Activity Releases

During run 21 there were several minor releases of gaseous activity to the stack as a result of sampling operations. In each case a few milliliters or less of fuel solution was exposed to the air in the sampler, but the liquid was contained within the sample flask holder so that no contamination of the sampler resulted.

Once a water manometer on the off-gas flowmeter downstream of the charcoal beds was blown empty and a small amount of gaseous activity, principally long-lived krypton, escaped into the building before the situation was corrected.

One contamination incident occurred during run 21, not a result of reactor operation. A fuel feed pump head which had failed during service in run 19 was being leak tested with gas, and particulate activity was spread in the high-bay area when the gas pressure was bled off. The most contaminated spots, on the floor near the storage pool, read only 5 mr/hr, and the contamination was quickly cleaned up.

Gamma Radiation Levels Inside Reactor Cell

High-level gamma ionization chambers inside the reactor containment cell are used to measure the radiation level at several points. Six chambers were installed originally, but during run 21 the chamber near the fuel circulating pump was not operative, having shorted out during run 20.

The high-level gamma chambers are read periodically during operation. Table 5 gives representative readings. Ratios of observed gamma dose rate to reactor power are also shown. The ratios are close to those observed in earlier runs.

Corrosion

Stainless Steel

The generalized corrosion rate of 347 stainless steel in the high-pressure system, calculated from the rate of change of nickel inventory shown by samples taken during stable operation, was 0.27 mpy over the

Table 5. Gamma Radiation Levels Inside Reactor Cell

A. Gamma Dose Rates

Date	Time	Reactor Status	Gamma Dose Rate (r/hr)				
			RM-2	RM-3	RM-4	RM-5	RM-6[a]
10-4-59	2230	Before power. Fuel in H.P. system.	84	220	160	50	310
10-12-59	2245	Operating at 5.0 Mw.	29,000	69,000	37,500	2,120	56,200
1-12-60	2130	Operating at 5.0 Mw.	30,000	72,000	39,000	2,100	79,000
1-22-60	2200	22 hr after shutdown. Diluting to FDT.	980	2,100	4,100	120	10,000
1-23-60	2135	46 hr after shutdown. Diluting to FDT.	890	3,800	4,200	97	6,900
1-24-60	2130	70 hr after shutdown. Diluting to FDT.	730	2,400	3,600	73	5,300

B. Gamma Dose Rate Factors

Date	Time	Power (Mw)	$\frac{\text{Gamma Dose Rate}}{\text{Reactor Power}} \left(\frac{r/hr}{kw}\right)$				
			RM-2	RM-3	RM-4	RM-5	RM-6[a]
10-5-59	2230	0.3	4.7	13.7	3.3	0.4	4.0
10-6-59	2230	2.7	5.9	14.1	7.0	0.4	9.3
10-12-59	2245	5.0	5.8	13.8	7.5	0.4	11.2
10-30-59	2230	3.5	5.7	14.6	7.7	0.4	12.9
11-9-59	2230	4.0	5.8	13.8	7.2	0.4	11.5
11-14-59	2230	1.5	5.3	14.0	8.0	0.5	12.7
11-25-59	2230	2.2	5.9	14.1	6.8	0.4	10.9
1-12-60	2130	5.0	6.0	14.4	7.8	0.4	15.8

[a] This element is exposed to direct radiation from the reactor vessel through openings in the thermal shield.

Location of monitors: RM-2, at blanket circulating pump, RM-3, above reactor thermal shield, RM-4, above fuel dump tanks, RM-5, above blanket dump tanks, RM-6, above fuel feed pump.

entire run. On the basis of the rate of change of the ratio nickel/copper in stable inventories, the rate was 0.19 mpy up to the time of the second acid addition and 0.48 mpy thereafter.

Zircaloy-2

Ultrasonic measurements of the Zircaloy-2 core tank thickness before and after run 21 showed that between the top of the core and 20 degrees below the equator the thickness was rather uniformly reduced by 6 to 8 mils during run 21.[26] (Comparison of post-21 measurements with original measurements showed a total reduction of about 14 mils during all operations through run 21.)

FUEL STABILITY

The behavior of the fuel solution during operation at power was of compelling interest in run 21, as it had been in earlier runs. This section describes the behavior as reflected in the reactivity and the physical inventories of the fuel constituents. Only a limited discussion of postulated mechanisms for instability is included. (A comprehensive summary report on fuel behavior in the HRT is expected at a later date.)

Operational Study of Fuel Stability

The experimental program in run 21 was devoted mainly to operation of the reactor at various pressures, temperatures, fuel acid levels and powers to "feel out" the limits within which the fuel was stable. (Explorations into the unstable regions were limited by restrictions which were intended to avoid reactivity hazards or extreme overheating of the core tank due to excessive amounts of separated uranium.) The limiting conditions for fuel stability and the way in which the fuel instability affected the reactivity furnished clues to the instability mechanisms.

Methods of Study

Two approaches were followed in the exploration of the limits of stable operating conditions. The first was variation of power. At a chosen temperature and pressure, the power was raised, and if instability was encountered, the power was lowered again to observe the effects of recovery of uranium. Samples were usually taken during such an experiment, unless loss was so rapid that a quick power reduction was required to avoid excessive loss. The other approach, suggested by H. F. McDuffie, was to hold the power constant and vary the pressure, observing the temperature and power behavior for evidence of instability and recovery.

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[26] F. W. Cooke and R. W. McClung, HRP Quar. Prog. Rep. July 31, 1960, ORNL-3004, p 18.

The first approach, used during the first part of run 21 and in earlier runs, evolved from the normal operating procedure of establishing the desired pressure and temperature before the power was raised. It had the advantage that when instability was encountered, it was very simple to drop the power to heat loss with confidence that this would stop any loss of fuel. The method of pressure variation at high power was adopted because it was the most direct approach to important questions concerning the part played by system pressure in preventing certain forms of fuel instability. Interpretation of the results of pressure variation experiments was somewhat complicated by the changes in NAT caused by the changes in feed and purge rates which resulted when the pressure was changed.

Symptoms of Fuel Instability

There are several known mechanisms for fuel instability, or separation of uranium and other constituents from the circulating fuel solution. These include boiling deposition, second-liquid-phase formation and hydrolytic precipitation. The way in which the fuel separates and the condition and location of the separated uranium determines what the external evidence of fuel instability will be. A change in reactivity, reflected in the reactor nuclear average temperature (NAT), will result if the separated uranium is at a different nuclear importance than that which it had while circulating. The transient behavior of the NAT during separation of the fuel depends, in addition, on whether the uranium separates from the solution in the core or in the blanket. Pips may occur as a result of disruptions of deposits and return to circulation of small quantities of uranium. The condition of the separated fuel and its location determine whether or not pips are likely to occur.

Experience prior to run 21 had been that as uranium went out of circulation, the NAT decreased, indicating deposition in a position of relatively low nuclear importance. (In run 17, when there was enough noncirculating uranium to make such calculations meaningful, the calculated importance of the noncirculating uranium corresponded to a location near the hole in the core entrance.) Fuel separation accompanied by a NAT decrease was experienced again in run 21; but under some conditions, the NAT rose after a high power level was reached, apparently as a result of uranium deposition at a position of higher than average importance. Pips sometimes accompanied both NAT-rise and NAT-loss instabilities, and sometimes there were pips when no significant change in the NAT had occurred.

Operating Restrictions

Before run 21 the restriction had been placed on the operations that a decrease in NAT of as much as 5°C below a baseline would be cause for immediate reduction of the power to heat loss. This restriction was calculated, assuming deposition of uranium at the average importance which had been observed in run 17, to limit the potential reactivity increase to 10% as a result of dispersion of the separated uranium. When the NAT-rise type of instability was encountered in run 21, a limit of 2°C was placed on the amount by which the NAT would be allowed to rise above the baseline. This was chosen as low as possible, to minimize core tank damage, and yet be outside the normal range of the fluctuations in NAT caused by factors other than instability, such as dump-tank-weight changes and core-blanket mixing.

The baseline NAT in run 21 was at first the NAT which existed at heat-loss power just before the power was raised in an experiment. Later, after the leakage rate through the blanket dump line to the blanket dump tanks had been determined, allowance for the accumulation in the dump tanks was made in the NAT baseline. The rate of accumulation was equivalent to a decrease of 5°C in about 30 hours. Allowance was also made for the collection of uranium in the blanket dump tanks when a blanket high-pressure sample was circulated. This amounted to 1.5°C for a standard 15-minute circulation. (Accumulation of 50 g of uranium in the dump tanks would cause a 1°C decrease in NAT.)

Stable Operating Conditions

One of the principal objectives of the run was to determine if there were actually any conditions at which the reactor could be operated for long periods of time at 5 Mw without fuel instability. The most favorable conditions which were found were 1250 psig and 260°C. Between October 17 and 21, the reactor was operated at 5 Mw, 1250 psig, and 260°C for 100 hours without interruption and with no evidence at all of instability. It appears, however, from other experience in the run that even under these optimum conditions, the system was on the verge of instability. In two other lengthy periods of operation at the same conditions, there was some behavior which, although not conclusive evidence of instability, cast a shadow of doubt on the complete stability. Furthermore, in other operation at conditions the same except for a slightly higher temperature, there was obvious fuel instability.

The questionable periods of operation at 5 Mw, 1250 psig and 260°C are worthy of discussion. The longer of these was for 152 hours, beginning on January 2. When the power was first raised to 5 Mw on that day, the NAT rose 2°C in two hours, at which point the power was reduced to heat loss. A few hours later the power was again raised to 5 Mw. After a rise of 1.5°C in the first two hours, the NAT settled back to near the initial value. (The decrease could have been due to xenon effects.) Operation was continued for the next six days at the same conditions, with no further indication of fuel instability. The other period of questionable operation was a 77-hour run just prior to the 100 hours of stable operation referred to in the preceding paragraph. When the power was first taken to 5 Mw, there were frequent small pips. The frequency decreased, however, and after 50 pips in the first 50 hours, there were none in 27 more hours. Near the beginning of the 77-hour period, fuel-feed-rate variations were responsible for at least part of the fluctuations observed in NAT, so that the effect of fuel instability, if any, was obscured. Later, when the power was lowered, there were no NAT changes which would indicate uranium returning to circulation. Thus if there was instability at the beginning of the 5-Mw operation, the separated uranium must have returned to circulation gradually while the reactor was at high power.

There were no other long periods of stable operation except at powers below 5 Mw. Operations during which there was no detectable instability are described in Table 6.

Effects of Fuel Instability

The diverse effects of fuel instability on the reactivity, or NAT, are described in this section with the help of numerous plots of individual experiments. The individual experiments are pictured so that the reader may realize that the results do not all fit neatly into one pattern of behavior or another.

In some of the run 21 experiments, fuel instability resulted in rapid loss of reactivity which continued until the power was lowered in accordance with the rules limiting the amount of separated uranium. Typical behavior in such cases is shown in Fig. 7. The decrease in P_c/P_t, the fraction of power generated in the core, shows that the reactivity decrease is due to loss of uranium from the core solution. (Data taken at equilibrium after such loss in run 17 showed that the separated uranium was at a position of low importance and cooled by the core fluid.) Conditions under which rapid loss was encountered in run 21 are described in Table 7. All but one instance occurred in the period from November 20 to December 5, while the reactor was being operated at 1600 or 1750 psig. The other instance was at 1600 psig on December 31. This experience corroborated the apparent effect of pressure observed in run 20, where rapid loss was encountered at 1600 and 1750 psig, but not at 1400 psig or below.

The determination of the threshold pressure for rapid loss was the objective of the pressure-variation experiments in late December. One of the experiments is shown in Fig. 8. The desired information was not obtained from this experiment because rapid loss did not occur even though the pressure was raised as high as 1750 psig at a power of 3.5 Mw. In the next experiment, shown in Fig. 9, rapid loss did occur at 1600 psig. While the NAT was still decreasing, the pressure was lowered to 1500 psig and the NAT stopped falling and began to rise. It appeared from this that the pressure reduction had somehow cured the instability. But when the power was next raised, at 1500 psig, the NAT behaved in the peculiar manner shown in Fig. 9. After an initial decrease in NAT and P_c/P_t, both began to rise. There were several pips, at least two of which were accompanied by noticeable rise in NAT. This behavior made it appear that the NAT rise following the pressure reduction in the preceding experiment might really have been a symptom of another form of instability, namely, the deposition of uranium at a position of higher than average importance.

Casting further doubt on the efficacy of the pressure reduction in the December 31 experiment is the fact that on other occasions, with no pressure changes, a NAT-loss condition developed into a condition in which there was a NAT rise accompanied by pips. The behavior on November 24 is shown in Fig. 10. Here the NAT was decreasing quite rapidly before it turned up.

Table 6. Conditions of Power Operation Without Evident Instability

Date	Pressure (psig)	NAT[a] (°C)	Acid Sulfate	Power (Mw) Total	Power (Mw) Core	Duration (hr)	Comments
Oct. 6, 7	1250	258-254	0.28	3.0	1.7	29	2 undersized pips.
Oct. 14, 15	1250	256-249	0.28	5.0	2.7	22	
Oct. 17-21	1250	260-255	0.28	5.0	2.6	100	
Oct. 30, 31	1400	260-256	0.28	2.8 3.4 3.9	1.5 1.8 2.0	16 7 10	
Nov. 1	1400	261-258	0.28	4.4	2.3	10	Possible gradual loss.
Nov. 2-4	1400	260-255	0.28	2.8	1.5	40	8 undersized pips near end.
Nov. 8, 9	1400	260-256	0.31	3.2	1.7	25	
Nov. 14, 15	1250	260-255	0.31	<3.0	<1.6	18	1 to 3 Mw in 0.5-Mw steps.
Nov. 18, 19	1600	260-254	0.31	<4.5	<2.3	22	2 to 4.5 Mw in 0.5-Mw steps.
Nov. 19	1600	259-258	0.31	4.5	2.3	4	
Nov. 25, 26	1600	259-255	0.34	<3.0	<1.5	22	5 powers from 1.3 to 3.0 Mw.
Dec. 2	1750	276-274	0.34	2.0	1.0	8	
Dec. 2, 3	1750	274-271	0.34	2.4	1.2	15	
Dec. 6	1750	241-237	0.34	2.0	1.1	16	
Dec. 7	1750	241-240	0.34	2.4	1.3	8	
Dec. 7, 8	1750	240-235	0.34	2.4	1.3	22	
Dec. 9	1400	276-275	0.34	3.2	1.7	5	
Dec. 9, 10	1400	275-272	0.34	<4.0	<2.1	11	5 hr at 3.6 Mw. 2 small pips at 4.0 Mw.
Dec. 10, 11	1400	276-273	0.34	3.6	1.9	16	
Dec. 11	1400	273-272	0.34	4.5	2.4	6	

[a]Reactor nuclear average temperature.

(Con't.)

Table 6. (Continued)

Date	Pressure (psig)	NAT[a] (°C)	Acid Sulfate	Power (Mw)		Duration (hr)	Comments
				Total	Core		
Dec. 12	1400	274-273	0.34	1.8	0.9	6	
Dec. 14	1400	241-238	0.34	3.2	1.7	10	
Dec. 15, 16	1400	257-252	0.34	<5.0	<2.6	31	3.2 to 5.0 Mw. 1 small pip in 14 hr at 5.0 Mw.
Dec. 17	1400	257-255	0.34	2.2	1.2	16	
Dec. 24	1400-1500	260-257	0.33	3.6	1.9	14	Pressure stepped up. Loss began at 1550 psig.
Dec. 25, 26	1550	260-256	0.33	3.5	1.7	11	Pips at 1600 psig.
Dec. 29	1650-1700	260-258	0.33	2.0	1.1	11	
Dec. 29, 30	1650-1700	258-252	0.33	3.5	1.8	14	Loss at 1750 psig.
Jan. 20	1300	272-269	0.33	3.9	2.1	6	After NAT rise at 5.0 Mw.

[a]Reactor nuclear average temperature.

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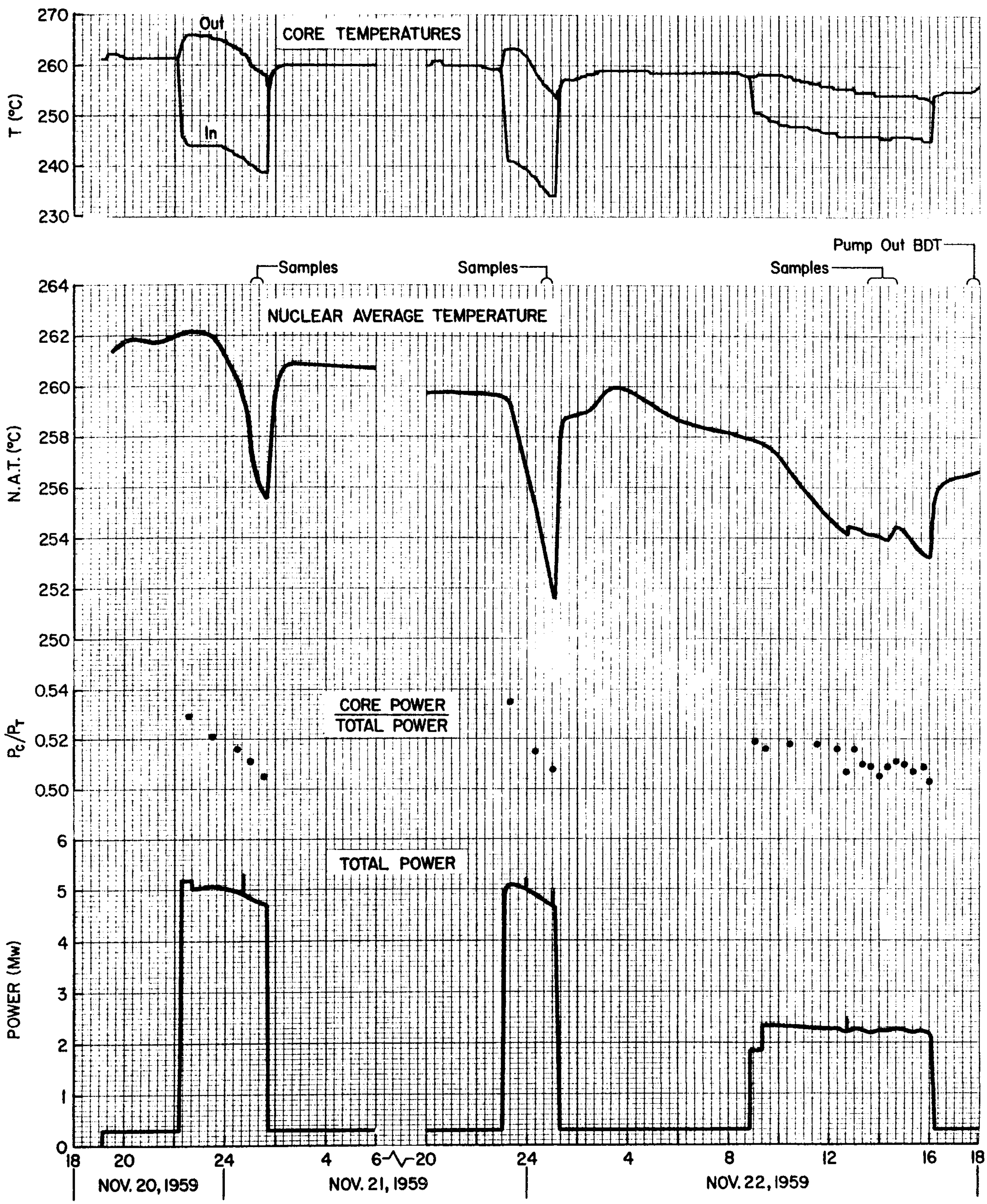

Fig. 7 Some Operations at 1600 psig Involving Rapid N.A.T. Loss

Table 7. Conditions During Rapid NAT Loss[a] Instability

Date	Pressure (psig)	NAT[b] (°C)	Acid / Sulfate	Power (Mw) Total	Power (Mw) Core	NAT Loss Rate (°C/hr)	Comments
Nov. 20, 21	1600	262	0.31	5.0	2.6	4.3	See Fig. 7.
Nov. 21, 22	1600	260	0.31	5.1	2.7	5.1	See Fig. 7.
Nov. 24	1600	260	c	4.9	2.5	2.1	NAT turned up at power.
Nov. 29	1600	262	0.34	3.2	1.7	0.9	NAT turned up at power.
Dec. 1	1750	259	0.34	2.8	1.5	0.9	
Dec. 1	1750	274	0.34	2.8	1.4	1.0	
Dec. 3, 4	1750	277	0.34	2.9	1.4	1.4	
Dec. 5	1750	240	0.34	2.5	1.3	0.8	
Dec. 31	1600	263	0.33	5.0	2.6	2.5	See Fig. 9.

[a]NAT decrease faster than 0.8 °C/hr.

[b]Reactor nuclear average temperature at which instability appeared.

[c]Power was raised 3 hr after acid was added to the fuel dump tanks. Acid/sulfate estimated to be 0.36 and 0.32 in the core and blanket, respectively.

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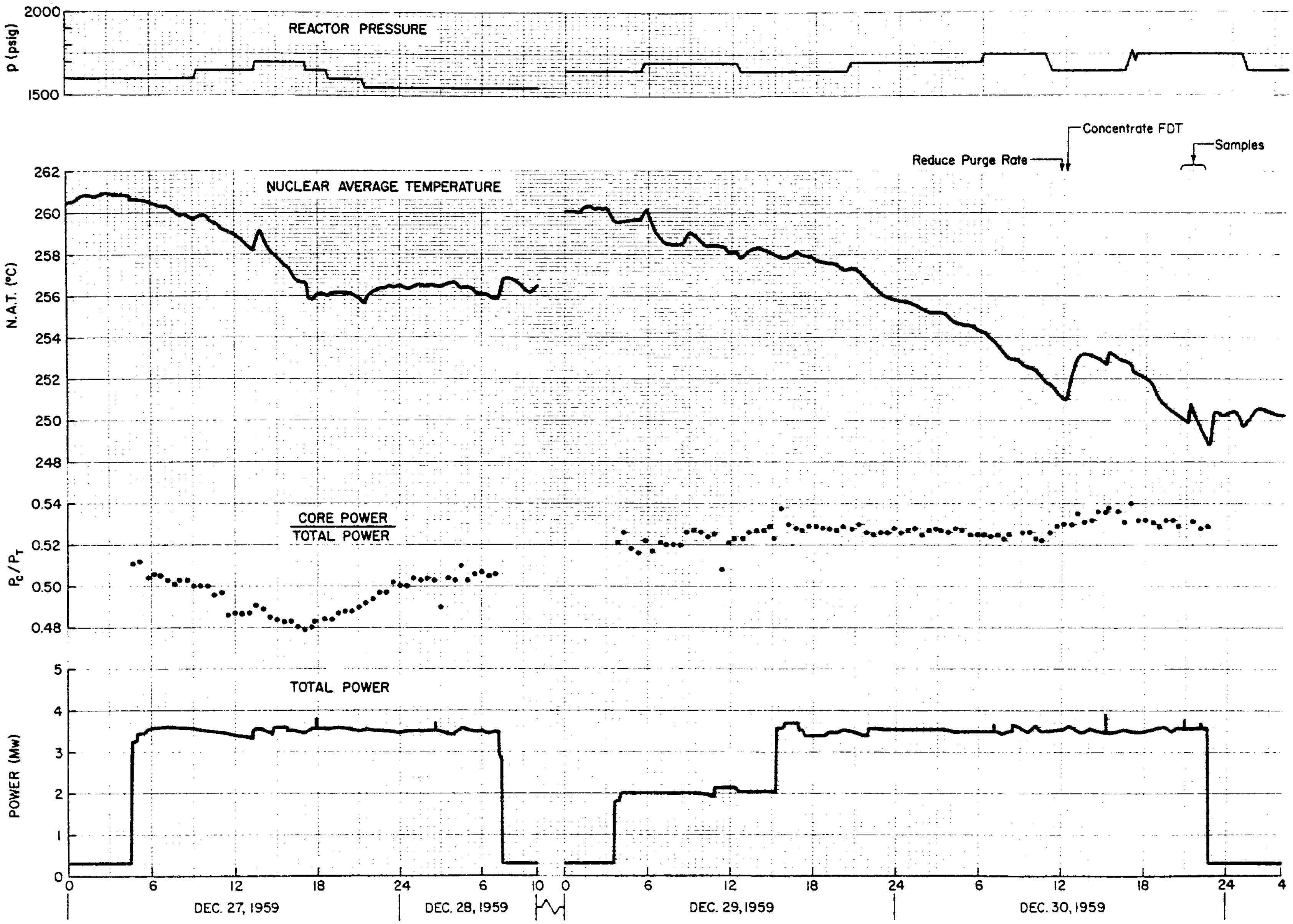

Fig. 8 Pressure Variation Experiments at 3.5 Mw and 1550-1750 psig

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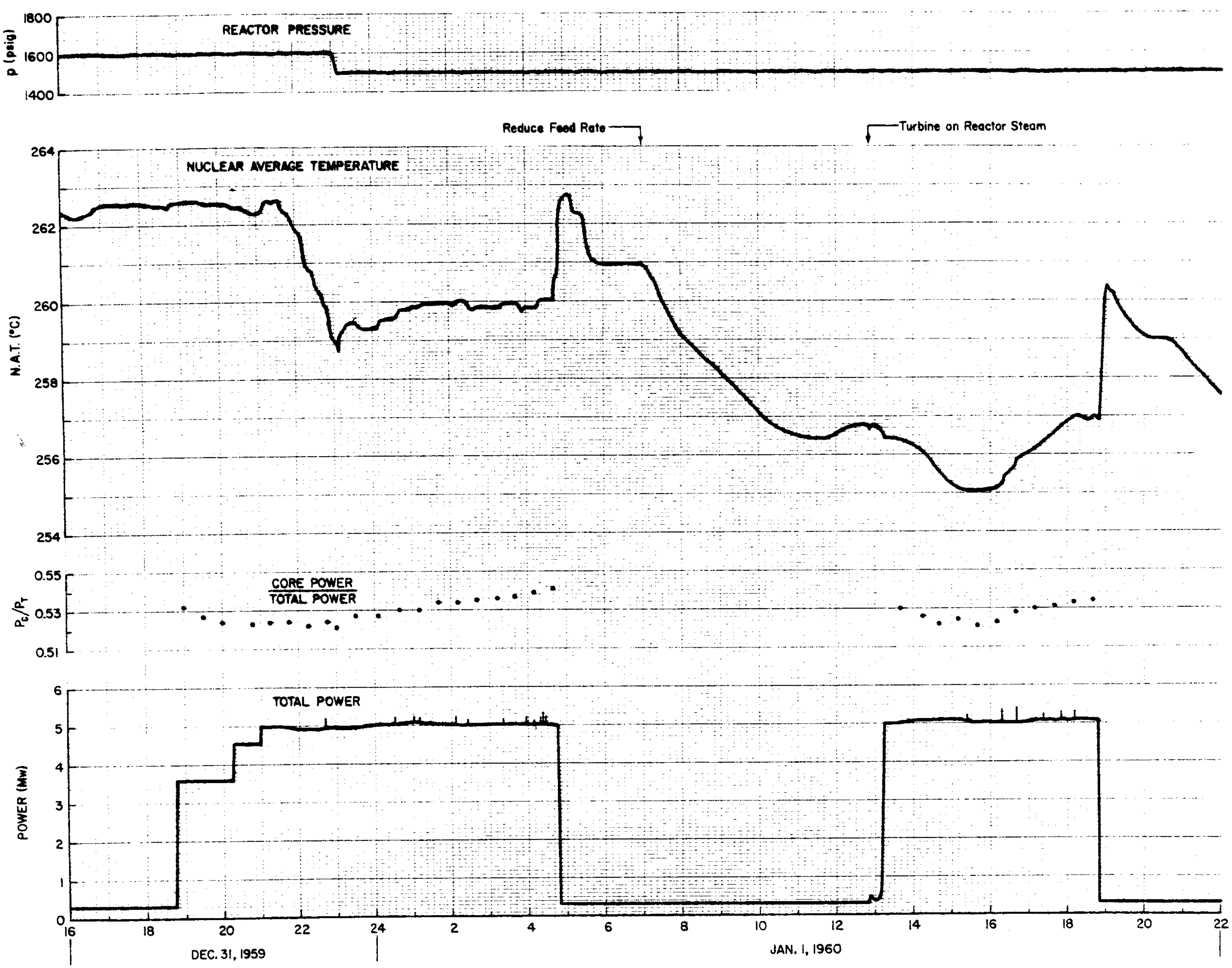

Fig. 9 Pressure Variation Experiments at 5 Mw and 1500-1600 psig

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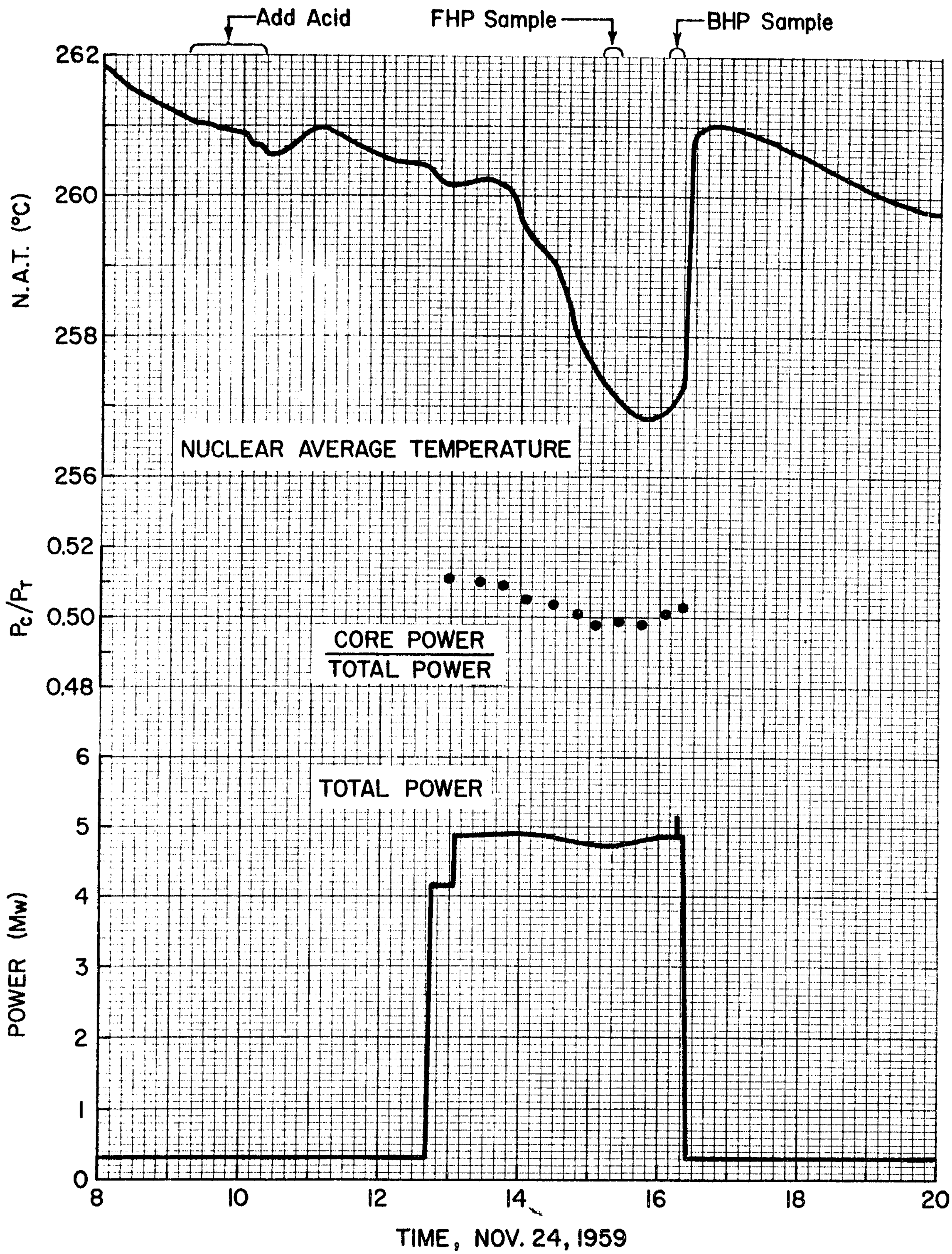

Fig. 10 Reversal of Rapid N.A.T. Loss at 5 Mw and 1600 psig

It appears that the increases in NAT in the cases just discussed were symptomatic of conditions in the core similar to those which developed just before the very large power excursion on November 2. The behavior on this occasion is shown in Fig. 11. (Note that the pressure was only 1400 psig at this time.) It appears that the reactivity was decreasing because of fuel instability before the NAT rise began, but the rate of loss by this cause was obscured by the recovery of an indeterminate amount of uranium as a result of pumping out the blanket dump tanks.

All of the operations illustrated in Figs. 9, 10, and 11 are similar in that the NAT decreased at first, then began to rise, generally to the accompaniment of pips. There were other occasions in which the NAT rose inexplicably at high power, without any preliminary decrease. Examples are shown in Fig. 12. Note that, unlike the instances shown before, there were no pips and following the reduction in power, the NAT decreased. In the experiment shown in Fig. 13, the power was held at about 2 Mw before and after the high-power operation so that the power distribution could be accurately calculated. The increase in both NAT and P_c/P_t are shown clearly, as is the recovery after the power reduction. There were a number of other similar instances, listed in Table 8. All were at high power (above 4 Mw) and at pressures of 1400 psig and below.

In addition to the types of instability described above, there were many periods of operation in which it appeared that an equilibrium was reached after a small amount of fuel had separated to a region of lower-than-average importance. The loss of reactivity in some cases was very slow, and the effects of uranium loss sometimes could not be distinguished from other effects. Rapid recovery of NAT when the power was reduced showed that there had been some separated uranium in these cases.

Finally, there were times when there were pips and no other detectable indication of fuel instability. The initial operation at 1250 psig and 5 Mw, which fits this category, has already been described.

Effect of Operating Conditions

Pressure.--Core pressure is the variable which had the greatest effect on the power-fuel stability relationship. Lower pressures permitted higher power operation without evident fuel instability. Figure 14 shows the results of all the run 21 experiments, classified into six categories. For this plot, a point was considered stable only if the conditions were maintained for at least ten hours, the unexplained changes in NAT were less than 1°C and there were no pips larger than 5% of the average power. "Rapid-loss" points are cases in which the NAT decreased faster than 0.8°C per hour (about 5 times the normal rate due to blanket dump valve leakage). "Small NAT loss" points represent changes greater than the 1°C limit, but slower than the "rapid-loss" criterion. Figure 14 includes operations at NAT's from 240 to 280°C, acid/sulfate ratios from 0.28 to 0.34, and one experiment with twice the normal oxygen concentrations. The effects of these variables will be discussed separately.

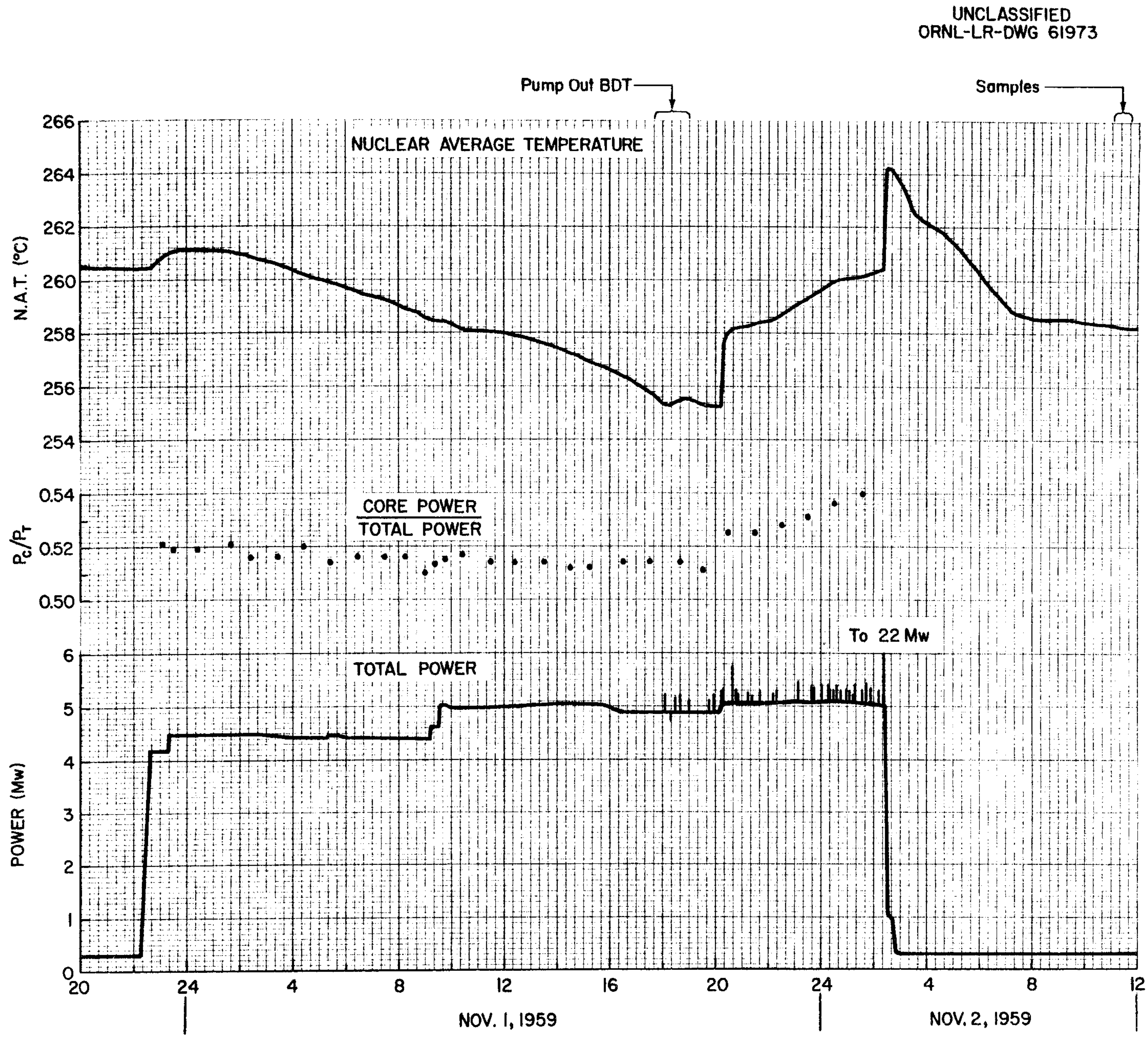

Fig. 11 Conditions Around Time of Large Excursion

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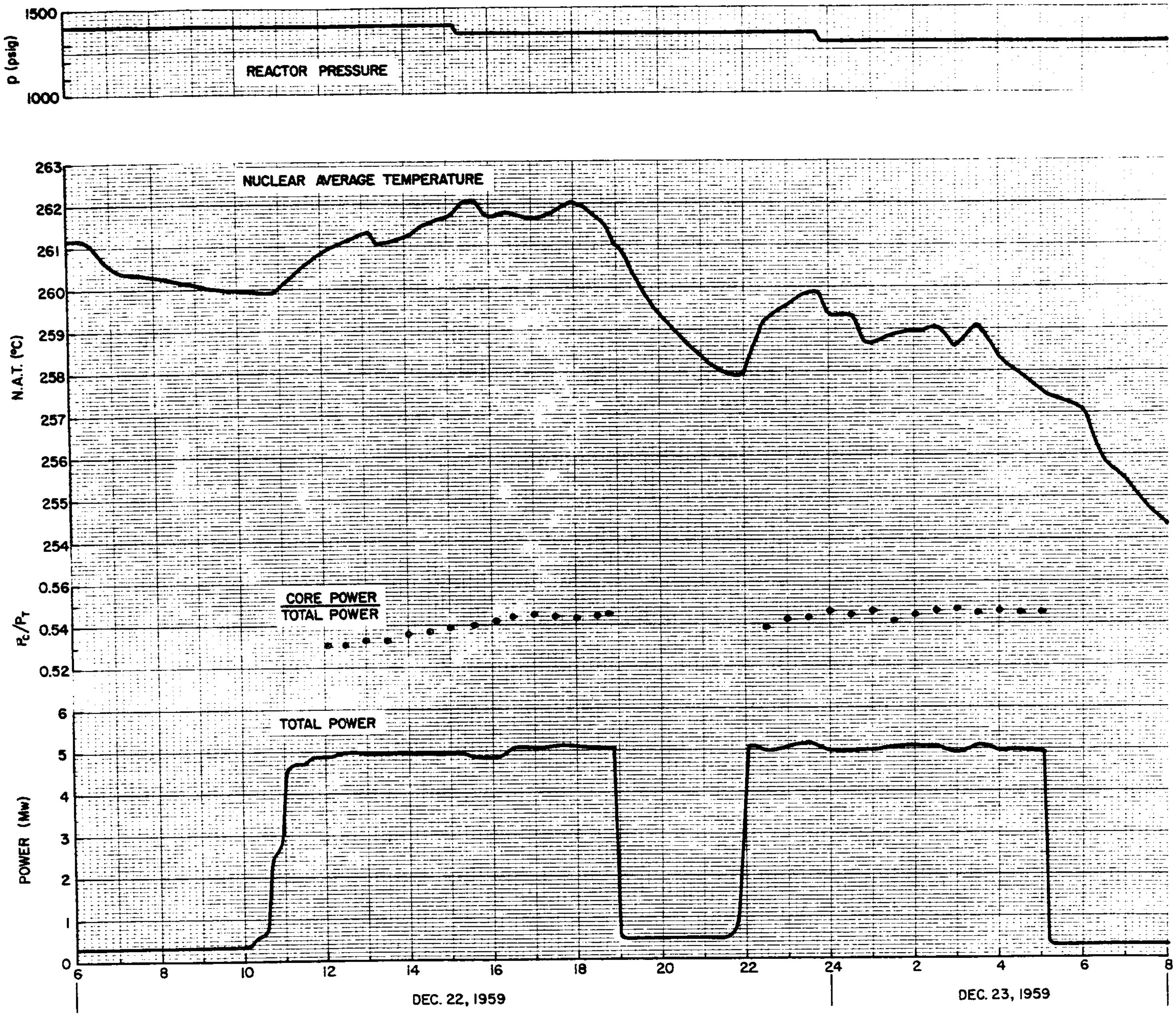

Fig. 12 Pressure Variation Experiments at 5 Mw and 1300-1400 psig

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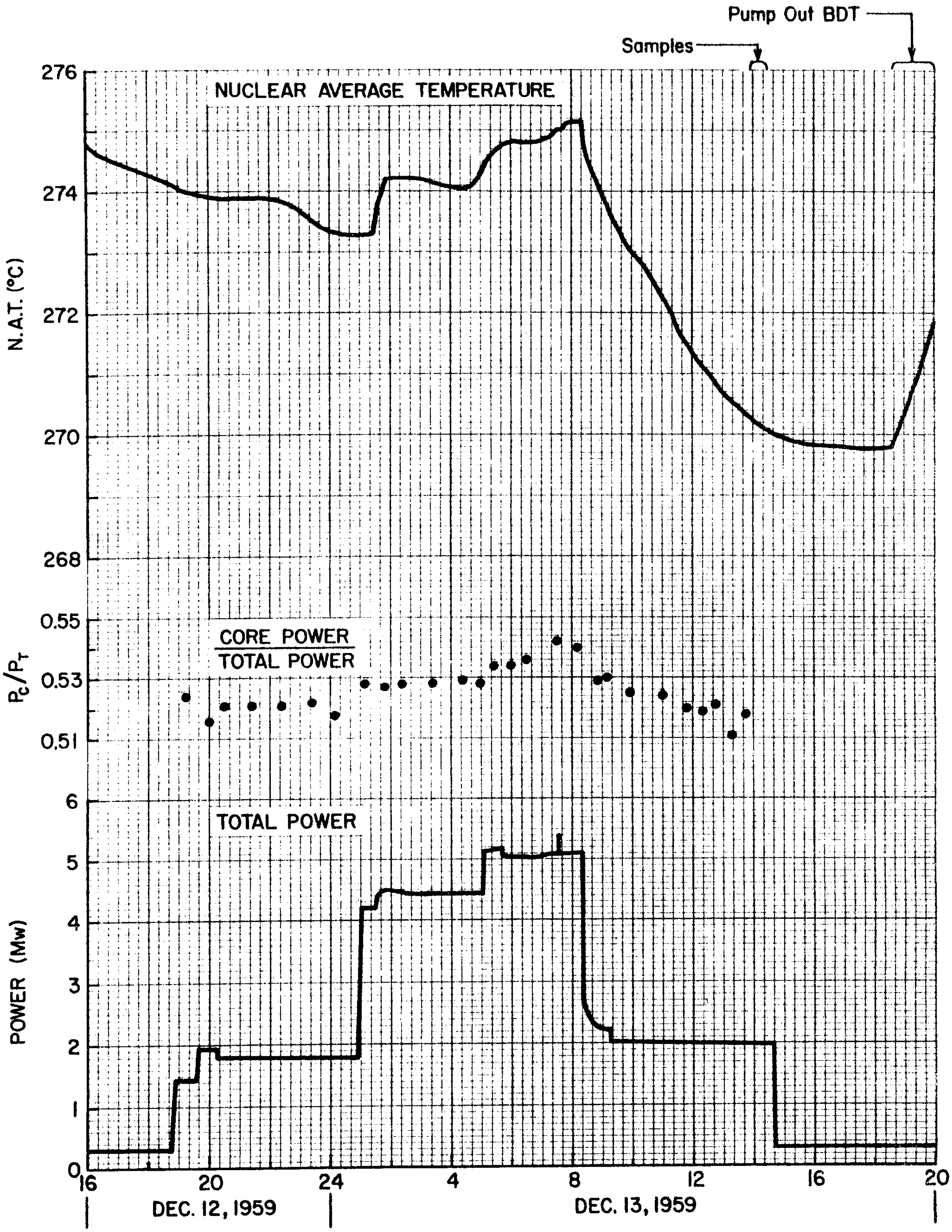

Fig. 13 Reversal of N.A.T. Rise by Partial Reduction of Power

Table 8. Conditions During NAT-Rise Instability[a]

Date	Pressure (psig)	NAT[b] (°C)	Acid Sulfate	Power (Mw) Total	Power (Mw) Core	Comments
Oct. 23	1250	278	0.28	5.0	2.7	Rose 2.5°C in 2 hr. Pips later.
Oct. 24	1250	275	0.28	5.1	2.8	Rose 1.5°C in 1 hr. Pips later.
Nov. 16	1250	265	0.31	5.0	2.7	
Nov. 17	1250	250	0.31	4.5	2.4	
Dec. 13	1400	273	0.34	4.5	2.4	See Fig. 13. One pip
Dec. 22	1400	260	0.33	5.0	2.6	See Fig. 12.
Dec. 22, 23	1350	258	0.33	5.0	2.7	See Fig. 12.
Jan. 2	1250	257	0.33	5.0	2.6	After 2 hr: up 2°C, rising.
Jan. 2	1250	256	0.33	5.0	2.6	Questionable. Discussed in text.
Jan. 15	1350	260	0.33	5.0	2.7	Peaked at 1.9°C after 1.5 hr.
Jan. 19, 20	1300	271	0.33	5.0	2.7	Repeatedly rose at 5 Mw, recovered at 4 Mw.
Jan. 21	1300	270	0.33	5.0	2.7	Rose quickly. See Fig. 4.

[a]NAT rise not preceded by NAT loss.

[b]Reactor nuclear average temperature at which instability first appeared.

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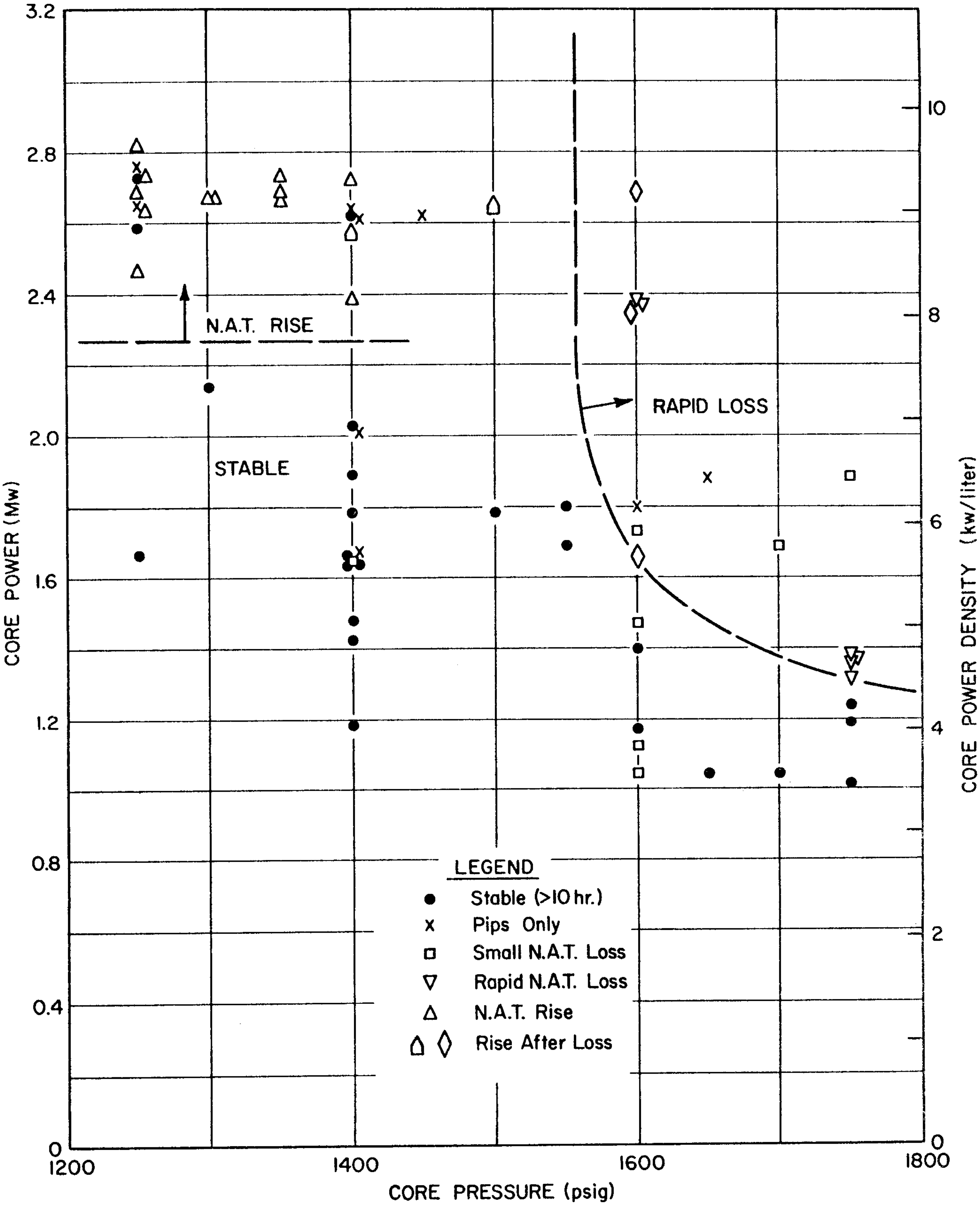

Fig. 14 Results of Run 21 Fuel Stability Experiments

It is evident from Fig. 14 that on such a plot, no clearcut boundary exists between stable and unstable regions of operation. Some features can be distinguished, however.

The rapid-loss cases are confined to a region at high pressure, whose boundary is suggested by the dashed line. As mentioned before, efforts were made to fix the vertical part of the line to check on the speculation that the rapid-loss phenomenon was evidence of second-liquid-phase formation. If this were true, a threshold pressure was expected to exist because second-liquid-phase formation could not occur if the pressure were low enough so that the boiling point of the solution were below the minimum temperature for such separation. During all of the experiments above 1400 psig, the acid/sulfate ratio of the fuel solution was between 0.31 and 0.34. (See Tables 6 - 8.) At these ratios and at the concentration of about 6 g U/kg D_2O which existed in the core solution, the second-liquid phase appears at around 335°C. The minimum temperature for second-liquid-phase formation in concentrates of simulated HRT fuel with acid/sulfate between 0.31 and 0.34 was observed to range from 315 to 322°C at concentrations around 30 g U/kg D_2O.[27] The vapor pressure of pure D_2O at these temperatures is 1553 to 1706 psia, and for 30 g U/kg D_2O solution the vapor pressure would be about 15 psi less. Thus the minimum pressure at which second-liquid-phase formation might be expected would be between about 1525 and 1675 psig.

Another fact brought out by Fig. 14 is that all of the cases of NAT rise (not preceded by a loss) occurred at low pressures and high powers. Deposition of salt on the core tank by film boiling has been suggested to explain the increase in reactivity and the apparent composition of the separated material. (See discussion of inventories on page 61.) Low pressures encourage film boiling.

Acidity.--The acidity of the fuel varied during the run because of consumption in corrosion and because of the two additions of acid. This would be expected to have an effect on fuel stability because increasing the acidity raises the temperature for both second-liquid-phase formation and hydrolytic precipitation. No effect of acidity appeared at 1250 psig. At 1400 psig the threshold power for pips was higher at the higher acid levels toward the end of the run. The only significant NAT loss at 1400 psig occurred at the lowest acid level, an acid/sulfate of 0.28. (At this level the minimum temperature for second-liquid phase coincides with the boiling point for D_2O at 1400 psia.[27]) Operations at 1600 psig covered core acid/sulfate ratios from 0.31 to above 0.34. At all acid levels, rapid loss of NAT occurred at the 5-Mw power level. (Laboratory experiments showed minimum second-liquid-phase temperatures higher than the boiling point at 1600 psig when the acid/sulfate ratio was above 0.32.[27]) The threshold power for small NAT loss at 1600 psig was higher

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[27] W. L. Marshall *et al.*, HRP Prog. Rep. Aug. 1 to Nov. 30, 1960, ORNL-3061, p 50-52.

at the higher acid levels. All of the 1750 psig experiments were at one acid level.

Temperature.--The average temperature in the core and blanket should affect fuel stability by its effect on heat removal from the hot spots which are potential centers for fuel instability. Run 21 produced some evidence which indicated that higher average temperatures promote the NAT-rise form of instability. The evidence is the contrasting behavior in successive periods of 5-Mw operation at 1250 psig in October. First there was 122 hours of 5-Mw operation at 260°C, completely free of pips or NAT aberrations. Following this, the power was twice taken to 5 Mw with the average temperature between 275 and 280°C. Each time the NAT rose and there were frequent pips. (On the other hand, in later operations at 1250 psig, there were NAT rises at temperatures around 260°C. On these occasions there were no pips, however.) At 1750 psig, experiments at 270°C and at 240°C showed that there was no appreciable difference in the threshold powers for NAT loss. Experiments at intermediate pressures showed that there was little or no effect of temperature.

Oxygen Concentrations.--Solution in the core normally contained 600 ppm of excess oxygen, with a partial pressure at 260°C of about 120 psi. A factor of two increase in the oxygen input was found to have no profound effect on fuel stability. On January 17 the oxygen input rates were doubled and after 29 hours the power was raised to 5 Mw at a pressure of 1350 psig. In 4 hours at these conditions there were no pips or NAT disturbances. The pressure was then raised to 1450 psig for 4 hours, during which time there were 12 pips. Eight hours at 1400 psig with 8 pips concluded the experiment. Operations with normal oxygen concentrations on January 2 through 16 had shown no pips at 1250 and 1300 psig, but pips and NAT rise at 1350 and 1400 psig. The experiment at high oxygen was too short to be really conclusive, but the results suggest a threshold pressure for pips which was raised slightly by the increased oxygen concentration or partial pressure.

Fuel Solution Inventory Studies

The study of the effect of reactor operation on fuel solution inventories was continued in run 21. Physical inventories were based on simultaneous core and blanket sample pairs and were corrected for the inventory held in the blanket dump tanks as the result of previous samples. An additional correction for leakage through the blanket dump valve was required. This leakage was determined to be fairly constant and an average rate was used in correcting physical inventories for the solute accumulated in the blanket dump tanks by this means. About 20% of the inventories obtained were rejected for the reason that there was evidence of analytical difficulties or that some of the other measurements required for physical inventory were thought to be unreliable due to unsteady conditions. Of the remaining inventories, 30 were obtained during stable operation and 27 during unstable operation. (Unstable operation was defined as that accompanied by pips in the neutron level or by unaccountable positive or negative NAT changes.) It was found in run 21, as in earlier runs, that the average circulating inventory of uranium and other components was lower at times of unstable operation. In addition it was found that the average composition of the missing solute was affected by the reactor operating pressure.

Inventory Baselines

The stable inventories were plotted against operating time at 200 to 300°C and each best straight line was taken as the baseline or reference to which the unstable inventories were compared. Two sulfuric acid additions divided run 21 into three periods of total sulfate and acid level, but because of the small number of stable inventories in periods A and B it was necessary to assume that the trends calculated for period C were also appropriate for the preceding periods. The trends of U, Cu, and Ni were calculated for the entire run. The baseline inventories for stable operation in run 21 are shown in Table 9.

Comparison of Acid Additions and Inventory Changes

Seven moles of sulfuric acid were added at the start of period B. The observed change in the acid baseline was 105% and the observed change in the sulfate baseline was 75% of this addition. Since the inventory of metals was not altered, the change in acid and total sulfate should have been identical. In view of the few inventories included in period B, the observed increase in inventory was in good agreement with the addition. In contrast, the changes of baseline inventories from period B to period C were less than half of the seven moles of sulfuric acid that were added at the start of period C. This discrepancy is believed to be the result of a permanent loss of sulfate that occurred sometime in a period of four or five days following this acid addition. This loss was unusual because it was not accompanied by the loss of any metal solute.

Events During the Period of Sulfate Inventory Loss

Several stable and unstable inventories taken in the three days following the second acid addition showed all of the sulfate that was added. However, all of these inventories were rejected for baselines because of unsteady conditions or analytical inconsistency. Three hours following the acid addition the reactor was taken to 5 Mw at 1600 psig to test whether the high acid-to-sulfate ratio would suppress instability. This operation lasted for four hours and was terminated because it appeared unstable (rapid NAT loss). In the following two days the reactor power was raised in slow steps to 3 Mw and then to 3.5 Mw before any instability was observed. On the fourth day after the second acid addition, with the power at 0.3 Mw, the reactor was suddenly depressurized from 1600 to 500 psig when the fuel pressurizer was inadvertently permitted to go dry as the result of leakage through the purge pump check valves. The system was back in operation twenty-four hours later following some temporary maintenance, repressurizing and reheating. The sulfate and acid baselines for period C were calculated from subsequent stable inventories.

Table 9. Baselines of Stable Inventory Trends in HRT Run 21

Run 21-A
(735 hours of operating time, 200-300°C)

Solute	Inventory (moles) (Based on 9 stable inventories)			Ratio to Sulfate at Average Inventory
	Intercept, zero hours	Change in 1000 hours	Average, 312 hours	
$SO_4^=$	87.0	+0.70	87.3	-
U	36.8	-0.90	36.5	.418
Cu	17.7	-0.28	17.6	.202
Ni	8.2	+1.34	8.6	.099
Mn (Est'd.)	0.8	+0.13	0.9	.010
Analyt. H_2SO_4	23.8	-3.28	22.7	.260
Calc'd. H_2SO_4	23.5	+0.99	23.7	.271

Run 21-B
(425 hours of operating time, 200-300°C)

Solute	Inventory (moles) (Based on 4 stable inventories)			Ratio to Sulfate at Average Inventory
	Intercept, zero hours	Change in 1000 hours	Average, 172 hours	
$SO_4^=$	92.9	+0.70	93.1	-
U	36.2	-0.90	36.0	.387
Cu	17.5	-0.28	17.5	.188
Ni	9.2	+1.34	9.4	.101
Mn (Est'd.)	0.9	+0.13	0.9	.010
Analyt. H_2SO_4	28.9	-3.28	28.3	.304
Calc'd. H_2SO_4	29.1	+0.99	29.3	.315

Run 21-C
(1440 hours of operating time, 200-300°C)

Solute	Inventory (moles) (Based on 17 stable inventories)			Ratio to Sulfate at Average Inventory
	Intercept, zero hours	Change in 1000 hours	Average, 735 hours	
$SO_4^=$	94.1	+0.70	94.6	-
U	35.8	-0.90	35.1	.371
Cu	17.4	-0.28	17.2	.182
Ni	9.8	+1.34	10.7	.113
Mn (Est'd.)	1.0	+0.13	1.1	.012
Analyt. H_2SO_4	31.6	-3.28	29.2	.309
Calc'd. H_2SO_4	30.1	+0.99	30.5	.322

Thus there was evidence early in period C that the inventory had been increased by 7 moles of sulfuric acid, but the baseline inventories four or five days later showed more than half of the added sulfate inventory to be missing. Although there were several unusual events during this period in which sulfate inventory was lost, the actual time or cause of disappearance is not understood. A plausible, though unproved, explanation is that the large change in the solution composition produced by the two acid additions caused the fraction of sorbed sulfate anion in the reactor corrosion solids to be correspondingly increased. Since the stable inventory composition of all reactor operations prior to these additions had been relatively low in free acid, it would be surprising if the accumulated reactor solids did not show some buffering action.

Comparison of Unstable Inventories with Baselines

The inventories of unstable samples at four levels of reactor pressure were compared with the inventory baselines of the stable samples. The average differences are shown in Table 10. The results at 1400, 1600, and 1750 psig are similar to those observed in run 20 in that the ratio U/Cu of the missing material was 3 or more and that the loss of Ni was greater at 1600 and at 1750 psig.[28] The average missing sulfate was greater than in run 20 at these pressures but was still a small fraction compared to the fuel solution composition.

The average missing solute of the unstable inventories at low pressure (1250 to 1350 psig) was quite different and was the approximate composition of the fuel solution, with the ratio U/Cu about 2 and the ratio $U/SO_4^=$ about 0.35. Thus the average missing solute at low pressures appeared to be concentrated fuel solution and was evidence that boiling and concentration occurred on the poorly cooled walls of the core vessel. The same effect would have been produced by a negative bias in physical inventories during full-power operation. However, it is believed that such large errors in measurements of weight, temperature and volume were unlikely.

It appeared, at 1250 and 1350 psig, that the chance that the concentrates would be immediately dispersed by the boiling action at full power were almost equal to the chance that the concentrates would remain in the core vessel. This was suggested by the fact that there were 6 stable inventories as well as 9 unstable inventories under these conditions in run 21. Of the 9 unstable inventories, 5 were accompanied by increases in NAT. This phenomenon was consistent with the deposition of uranium at positions of high nuclear importance such as on the core wall. All cases of increased NAT in run 21 were observed at the low pressures.

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[28] H. F. Bauman et al., Summary of HRT Run 20, ORNL CF-61-7-91 (July 19, 1961).

Table 10. Average Inventory Differences of Unstable Samples From Baselines of all Stable Samples

Reactor Total Pressure (psig)	Solute	Average Missing Solute (moles)	Standard Deviation (N-2)	Number of Samples Pairs	Minimum Missing Solute (moles)	Maximum Missing Solute (moles)
1250 to 1350	$SO_4^=$	3.33	2.0	9	-0.03	5.29
	U	1.12	0.6	9	0.33	1.94
	Cu	0.58	0.4	9	-0.06	1.16
	Ni	0.13	0.5	9	-0.42	0.95
	H_2SO_4	-0.90	1.0	9	-2.36	0.40
1400	$SO_4^=$	1.98	2.1	7	-1.77	4.26
	U	0.90	1.3	7	-0.79	2.38
	Cu	0.26	0.7	7	-0.55	1.44
	Ni	-0.04	0.4	7	-0.35	0.48
	H_2SO_4	0.10	2.1	7	-3.10	2.52
1600	$SO_4^=$	3.48	5.8	6	-3.04	11.00
	U	1.71	1.6	6	-0.36	3.36
	Cu	0.58	0.5	6	-0.03	0.99
	Ni	0.61	0.2	6	0.39	0.82
	H_2SO_4	-1.77	2.4	5	-3.80	1.46
1750	$SO_4^=$	0.87	4.8	5	-2.50	7.85
	U	1.38	1.1	5	-0.20	2.45
	Cu	0.26	0.3	5	-0.17	0.57
	Ni	0.63	0.5	5	0.33	1.30
	H_2SO_4	-1.01	0.9	5	-1.94	-0.21

Precipitation in the Blanket

Run 21 power operation was terminated following the melting of a new hole at the equator of the core vessel. This event occurred at 5 Mw and at 1300 psig system pressure when the Δ NAT was plus 1°C. At this time, also, the blanket fuel solution was 0.01 molal U and, as was later shown by out-of-pile equilibrium solubility experiments, was saturated with respect to hydrolytic precipitation at 300°C.[29] Thus it was possible that a precipitate on the blanket side of the core vessel may have contributed to the extreme local overheating and consequent melting.

In the period from January 2 to January 8, 1960, during operation at 5 Mw, it was observed that solids appeared in 4 out of 7 blanket solution samples after they had been in the analytical hot cells for 12 or more hours. The Cu concentration in the samples was lower than normal after the precipitate appeared. A sample of core solution was diluted to the blanket concentration with D_2O and a similar precipitate was observed. The solids could not be redissolved by heating and contained largely Cu and Fe according to spectrographic analysis.

The separation of uranium from solution has been demonstrated in a number of ways under simulated reactor conditions but at elevated temperatures. These are: hydrolytic precipitation;[29] heavy liquid-phase separation;[30] U sorption on metal oxides;[31-33] concentration and salt deposition by boiling.[34] It is believed likely that more than one process occurred when there was overheating of the walls of the core vessel, especially during operation at the higher pressures.

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[29] William L. Marshall and James S. Gill, "Aqueous Systems at High Temperature, III. Investigations on the System UO_3-CuO-NiO-SO_3-H_2O at 300°C," Journal of Inorganic and Nuclear Chemistry, In Press (1961).

[30] W. L. Marshall et al., HRP Prog. Rep. Aug. 1 to Nov. 30, 1960, ORNL-3061, p 50-52.

[31] Gerald Goldstein, Sorption of Uranium on Zirconium Oxide, ORNL-3177 (Aug. 28, 1961).

[32] J. C. Banter and S. H. Wheeler, Adsorption of Uranium on Hydrous Zirconium Oxide from Uranyl Sulfate Solutions at Elevated Temperatures, ORNL CF-61-3-94 (Mar. 1, 1961).

[33] H. W. Hoffman and C. S. Morgan, HRP Quar. Prog. Rep. Oct. 31, 1959, ORNL-2879, p 104-105.

[34] J. C. Griess et al., HRP Quar. Prog. Rep. April 30, 1959, ORNL-2743, p 103-108.

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