APPENDIX 1

ref: The Technology of Nuclear Reactor Safety, Vol 1 MIT Press Thompson + Beckerley

3.3 The NRX Reactor Accident [15, 16a, 16b, 17, 18]

The NRX Reactor is a heavy-water-moderated, light-water-cooled, research and testing reactor, using natural uranium fuel [15]. It is capable of operating at power levels up to 30 Mw. The reactor had 12 shutoff rods which operated on the basis that 7 rods in the down position were sufficient to hold the reactivity below critical for any approved change of fuel and load. The shutoff rods were thin steel tubes filled with boron carbide. The rods were driven into position through their 10-ft (3 m) travel by air pressure derived from a piston at the head of the rod. The air pressures were manipulated by electrical controls. In order to seat the solenoid valves which held the air pressure, an additional control room push button (No. 3) was provided which increased momentarily the solenoid current thereby more firmly seating the valves to prevent leak-off of the air. If the rods were driven in by air pressure, their travel time for half-insertion was 1/3 to 1/2 sec, whereas without air pressure they normally took 3 to 5 sec to drop the full 10 ft. Each rod was instrumented so that a red light showed on the control desk when the rod was fully up.

The rods were grouped as shown in Table 3-2: Group No. 1 was called the "safeguard bank" and the number of rods in that group was at least one greater than the number in any other group. The safeguard bank was brought up normally only from a condition in which all of the shutoff rods of the other banks were down. At some time prior to the accident, this bank had been interlocked in such a way that it was impossible to withdraw other rods before the safety bank was withdrawn.* "Owing, however, to defects in these switches and their being subject to flooding which could make them a hazard, this 'safety' circuit was not in operation at the time of the incident. The added responsibility was accepted by the operating supervisor."

"The design reason distinguishing the safeguard bank is that, for safety, no shutoff rod may be raised unless either (a) more than 7 shutoff rods would be left fully down, or (b) more rods are available for quick release than are being raised at any time. To make startup possible, some rods must satisfy condition (a) and not (b), and, if the total of shutoff rods is only 12, no more than 4 may be set for condition (a). All other rods must satisfy condition (b). To achieve a safe startup in the shortest time, as large a number as possible and the most highly effective rods were in the safeguard bank. The reason for allowing always one more than the minimum safe number is to allow for one undetected failure in the safety system." [16a]

To operate the rod banks, four push buttons were required. Push button 1 raised Bank 1. Push button 2 raised automatically and sequentially the remainder of the rods. Push button 4 was mounted on the wall panel to the left of the desk and charged air to the heads of the shutoff rod assemblies. It

Table 3-2

NRX Reactor Shutoff Rod Groupings

Bank No.	No. of Rods	
1 (safeguard)	4	Push Button 1
2	3	Push Button 2
3	2	
4	1	
5	1	
6	1	

was the release of this air which drove the rods down. Push button 3 increased temporarily the current to the solenoid valves, as mentioned previously.

At the time of the accident on December 12, 1952, only one fuel rod was air-cooled and that was a fresh unirradiated element. An experiment was being conducted on the reactivity of the reactor at low power levels. The object of the experiment was to compare the reactivity of long-irradiated fuel rods with that of fresh fuel rods. A number of rods had either a reduced H_2O coolant flow or else temporary cooling provisions.

"The immediate chain of events which led to the accident began with an error by an operator in the basement who opened by mistake three or four bypass valves on the shutoff-rod air system, thereby causing three or more shutoff rods to rise when the reactor was shut down. The supervisor at the control desk noticed this because the red lights came on. He phoned to the operator in the basement to stop and went down himself to investigate and rectify the situation, leaving his assistant at the control desk."

"He recognized the operator's mistake and was horrified at the possible consequences if the operator had continued to open these wrong valves (actually he could not have opened all valves since some handles had been removed for safety). The supervisor rectified all valves and checked air pressures."** "He assumed that all shutoff rods would drop back into position, but, on account of unexplained mechanical defects, it is apparent from subsequent events and inspection that two or three did not drop back, although they slipped down sufficiently to clear all the red lights on the control desk."

"The supervisor then phoned his assistant to press buttons 4 and 1. He had intended to say 4 and 3, but under normal circumstances 4 and 1 should have been safe (all the shutoff rod red lights were out). His assistant therefore did so. Having to leave the phone to reach simultaneously with two hands the two buttons, he could not be recalled to correct the mistake. Button 3 not having been pressed, the air pressure brought up by button 4 leaked away."***

---

*The chronological history of events is taken for the most part from the report of W. B. Lewis [16a].

**Note that it might have been possible for an ingenious operator to raise all the rods by transferring handles from one valve to another if these valves were of the usual type.

***In a recent (April 13, 1964) private communication to the author, W. B. Lewis has kindly supplied additional information on the reasons for

"Up in the control room it was soon evident when the first bank of shutoff rods was raised by button 1 that the reactor was above critical, which was of course a complete surprise."

"It takes a few seconds for this to be apparent. There was surprise but no alarm for the next step would be to trip the reactor and thus drop back the shutoff rods. This the assistant did about 20 sec after pushing button 1. But two of the red lights stayed on, and in fact only one of the four rods of the first bank dropped back into the reactor and that over a period of about 1-1/2 min. Even though, as it appeared, the air pressure had leaked from the header, all shutoff rods should have nevertheless dropped back under gravity."

"The galvanometer spot indicated that the power level was still climbing up. The assistant telephoned the supervisor in the basement urging him to do something to the air pressure to get the rods down."

"Others in the control room were worried: the physicists, the assistant superintendent of the reactors branch, and a junior supervisor. At least two thought of the last resort; namely, to 'dump the polymer' (D_2O). All were familiar with the process as it had been done the previous day for experimental purposes. The assistant superintendent gave the word; one of the physicists was already reaching for the dump switch and beat the others to it."

"However by this time the reactor power was up in the tens of megawatts, and the dumping took a few seconds to become effective. Then a fear arose that they might be dumping too fast as the helium pressure had dropped back sharply, and they envisaged danger of collapsing the calandria by vacuum. The assistant superintendent halted the dumping after about 1 min but after a little thought resumed. However, in 10 to 30 sec after starting to dump, the instruments were back on scale, and the power rapidly dropped to zero. The assistant superintendent went to report to the superintendent, but the consequences were only beginning."

"In the basement the door into the chamber under the reactor (the lower header room) was open. Through this an operator saw water gushing down, and immediately he called the supervisor. Their instant reaction was to suspect any water as being heavy water; therefore the supervisor and operator rushed in with a bucket and collected a sample, which was soon found to be light water but radioactive."

"The assistant superintendent, returning to the control room, was met by an operator who reported a rumble and a spurt of water up through the top of the reactor."

"Then the air activity began, and automatic radiation-level alarms sounded in the reactor building. A phone call to the control room from the adjoining chemical extraction plant reported atmospheric activity off-scale and requested the emergency stay-in procedure. The sirens for this were sounded. The radiation hazards control branch got busy reading instruments, making surveys, and collecting reports. Some minutes later the activity inside buildings with forced ventilation was found higher than outside; therefore on the advice of the Biology and Radiation Hazards Control Director the Project Head gave the order for the plant evacuation procedure, and that went into effect."

"Meanwhile in the reactor system not earlier than 30 sec before the dump began, helium began to leak at a rate of 140 cu ft/min. After 3-1/4 min, by which time the reactor power had been down to a negligible level for 2 min, the reserve gasholder was almost empty. Then suddenly in less than 30 sec the 535 cu ft gasholder rose to its fullest extent. The change of direction of motion of the gasholder was so abrupt on the record and its motion so well-timed by pen marks at 15-sec intervals that it can be deduced with certainty that within a period of 15 sec the gasholder became connected presumably to a mass of gas at high enough pressure to give a large acceleration to the massive four-ton gasholder.

"About the same time that the gasholder was forced up, the radiation level in the reactor building became high. Respirators were issued to those in the control room. All not concerned with the reactor operation were evacuated from the building."

"Holding discussions in gas masks is difficult so after a few further minutes those concerned with reactor operation also went to an adjacent building and planned further steps, returning to the reactor building to put them into effect." [16a]

A further post-accident investigation [17] has led to the conclusion that the unusual sequence of events which happened initially left the reactor supercritical by about 0.6$ and that the power rose rapidly. Control rods slowly dropping back into the reactor core made it appear that the power would level off at about 20 Mw(t). However, the reduced cooling rate which was being used for the test with some rods was insufficient at this power level and boiling in the H_2O cooling channels followed at a power level estimated to be about 17 Mw(t). Unfortunately, this reactor has a positive coolant void coefficient and it is surmised that boiling caused the expulsion of light water from the coolant annulus, thus increasing the reactivity by about 0.2$. The power began to rise again on a period estimated as being between 10 and 15 sec. It is estimated that the power was between 60 and 90 Mw(t) when the D_2O was dumped, thus shutting down the reactor. The reactor power was greater than 1 Mw(t) for no more than 70 sec and the total energy release is estimated to have been about 2000 Mw-sec or about 0.6×10^{20} fissions [16b].

Figure 3-1-[16b] shows a map of the core, in-

---

the location of the buttons. He says, "...the difficulty was not that either button was inaccessible to the telephone, but the two buttons were spaced apart and caused the operator to set down the telephone to push the two buttons simultaneously. The placing of these buttons had been deliberate to emphasize the special nature of the double operation. It would not normally be carried out by any one depending on telephone communication. In the event, it is clear that the design choice was wrong. It emphasizes the extreme care necessary in designing interlocks."

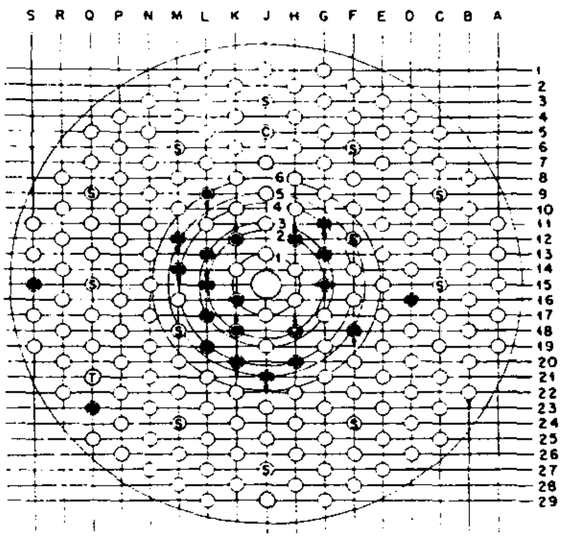

FIG. 3-1 Damaged elements in the NRX core. The plan of the lattice shows rods with abnormal cooling arrangements (indicated by small arrows, ↑ = temporary cooling upflow, ↓ = temporary cooling downflow); the rod at G-15 is air-cooled. The open circles indicate those rods not ruptured. The black circles with a white annulus (L-9, K-12, G-15, K-16, K-18) are the fresh rods whose outer sheaths were ruptured; similar circles with segmented annuli (e.g., G-11, H-12, M-12) are irradiated rods whose outer sheaths were ruptured. An encircled S, C, and T indicates the position of a shutoff rod, control rod, and thorium rod, respectively.

dicating those elements which ruptured as a result of the accident. At the time of the accident, only one rod (G-15) was air-cooled as mentioned earlier. The only rod which failed in Circle 1 was a fresh rod in K-16. (The parts of a typical fuel-tube system are shown in Fig. 3-2 [16a].) This rod had a small hole in the outer sheath and the calandria tube had a much larger hole. It is surmised that the heat from the very severe rupture of L-15 may have helped to cause the breakdown of K-16. In several instances failure of fuel in one pressure tube caused damage in an adjacent pressure tube. The six rods in Circle 2 were a part of the test being conducted and all were being fed with an upward stream of cooling water with a lower head than usual. As a result, these elements evidently voided first, causing additional local flux increases (in a sense, a local reactivity effect) and causing melting in these elements to be most severe. Other elements with temporary cooling melted shortly thereafter. Damage to some of the normally cooled rods in Circles 3 and 4 appears to indicate that the light water in a number of rods inside Circle 5 was boiling and being expelled by steam. Because of the fuel resistance to the escape of water, the steam pressure built up within the cooling section and at least two rods, M-14 and K-20, broke apart and the upper portions of their shielded sections leaped a foot or so into the air. The air-cooled rod, G-15, which is in Circle 2, the circle of maximum flux, did not damage the calandria tube so far as could be seen. The central parts of the aluminum sheaths melted and ran down the rod, congealing between the calandria tube and the rod. This aluminum formed a barrier on top of which molten uranium formed an

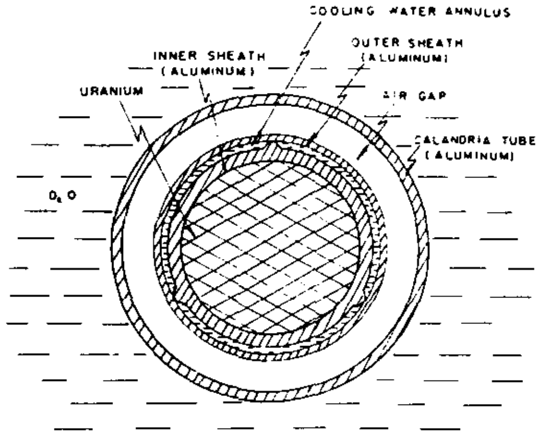

FIG. 3-2 NRX fuel tube cross section. Outer diameter of calandria tube is 2-3/8 in. (6.03 cm).

ingot contained by the calandria tube. At this point, heat transfer between the calandria tube and heavy water apparently preserved the tube itself. Since there was no damage to the calandria tube in this case, it is evident that steam considerably influenced the course of the accident. Steam under pressure in the rods caused the initial rupturing of the outer sheaths. There appeared to be considerable chemical reaction, and not just melting of the materials present. It cannot be decided whether or not the exothermic aluminum water reaction played a significant role. From the analysis, it seems unlikely.

Even though the metal-water reaction probably was not significant, there was a chemical reaction of some sort as evidenced by the behavior of the helium gasholder. This helium gasholder normally maintained a pressure of 12 in. water (22.5 mm Hg) above the heavy water and had a capacity of 550 ft^3 (15500 liter). Normally, when heavy water is dumped, helium flows from the storage tanks to the calandria and the gasholder merely rides on the system. Loss of helium pressure was noticed during the dumping. A possible interpretation was that the blockage in the return helium pipe caused a partial vacuum as the calandria emptied, and dumping was stopped momentarily to prevent collapse of the calandria. Dumping was resumed when the gasholder was seen to be emptying. Just as the gasholder was almost empty, it suddenly jumped to its full height of 48 in. (122 cm), as shown by the position recorder. It stayed at that position for some time...probably jammed there...and then fell in a series of steps backwards. The gasholder is connected to the rest of the system by 2-in. (5.08 cm) pipes, with an equivalent length of about 75 ft (~23 m). The weight of the dome is 4 tons (3630 kg) and its area is 133 ft^2 (12.4 m^2). In order that the dome be lifted in a normal manner, it is necessary that a supply of over 500 ft^3 (14200 liter) of gas be delivered within 30 sec. Hurst [16b] suggests that the release of uranium from its sheath was accompanied by the evolution of hydrogen. Much of this hydrogen escaped into the calandria and may have been augmented by further reaction of uranium in the calandria. The helium, escaping from the calandria through several holes, may have picked up hydrogen and burst into flame where the gas came in contact with the air. The escape of the helium continued until the gasholder dome reached the lower limit of its travel. This prevented further emission of helium and air then entered the calandria and the hydrogen-oxygen explosion took place.

The core and calandria were damaged beyond repair. Approximately 10^4 curies of long-lived fission products were carried to the basement in about one million gallons of cooling water. The calandria and the contents still remaining in it after initial salvage operations were eventually bagged and dragged away for burial. The auxiliary equipment was decontaminated and the reactor was put back into operation in about 14 months with a new and improved calandria and core [18]. During the cleanup a large number of people participated in order to hold down the dose to any one individual. In general, health physics control was able to adhere to 3.9 r total dose per man. The highest total dose received by anyone was 17 r.

Comments, Conclusions, Recommendations

(1) System design and interlocks should make it impossible for an unauthorized and unassisted operator, either by mistake or on purpose, to withdraw or to influence the performance of control rods.

(2) The instrumentation should record the position of the control and the safety rods at all times, including the position during scrams...not just the limits of travel of the control rods. Since many rods fall free under gravity, this is often a difficult or impossible design requirement, but it should be a design goal.

(3) It should always be possible to maintain two-way communications between groups carrying out related key operations. In essence this means that there must be a satisfactory public address-call box system over which one can talk and listen while making use of his hands. A telephone does not answer these requirements.

(4) Vital controls should be arranged on the control console so as to be easily accessible in an emergency.

(5) The design of reactors with positive reactivity coefficients which can be rapidly brought into play during transients, or by other reasonably ordinary perturbations of the system, should be avoided or is at least open to serious question. The post-accident analysis seems to indicate that the transient would probably have been terminated with little or no damage if it had not been for the positive voiding effect. It is certainly possible to operate such reactors safely as long as their behavior is close to normal. However, if a difficulty or perturbation of normal operations should develop it is very likely to be aggravated by positive reactivity coefficients and a minor incident can easily turn into a major accident.*

(6) From a safety point of view, it is good design and operating practice to ensure that a relatively small perturbation does not create a major effect. In this experiment the cooling was reduced for all of the six rods in circle 2, symmetrically placed, in order to give an adequate signal and, to permit interpretation, they all had to be in identical situations. It is likely that they all voided almost simultaneously, greatly increasing the severity of the transient that followed. What would have been a ramp if they had voided over a longer period became almost a step addition of reactivity. In retrospect, it might have been better, from the safety point of view, to carry out the experiment with fewer rods involved at each stage.

3.4 BORAX-I Destructive Experiment [19, 20, 21, 22]

BORAX-I [19, 20] was a swimming pool type reactor utilizing 0.020 in. (0.508 mm) thick aluminum clad U-Al plates in an MTR type fuel element. It was the first reactor designed for studies of transient behavior and for that reason was located at the National Reactor Testing Station in Idaho.

The reactor consisted of four quadrants separated by gaps to accommodate five cadmium control blades. Each blade was connected to the control mechanism through spring-loaded magnetic couplings. The central blade was cruciform in cross section and so designed that the cocked or raised position was with the cadmium in the core. On appropriate signal the transient was initiated by ejecting the central blade downward out of the core from a predetermined partially down (slightly out of the core) starting position. The other four blades, which filled the gaps between the quadrants, were raised above the core before the experiment started and were injected into the core to terminate the experiment. Each blade traversed the height of the core in about 0.2 sec.

The reactor core was contained in a tank 4 ft (1.22 m) in diameter and 13 ft (3.96 m) high and filled with water. In turn the reactor tank was contained in a larger shield tank sunk part way into the ground with earth piled around it for additional shielding. Adjacent to the shield tank was a concrete-lined pit housing the equipment for filling and emptying the tank and for heating the water.

In a highly successful set of experiments carried out in the summer of 1954 considerable information had been gained in regard to the nature of transients in this type of reactor (see chapters on Mathematical Models of Fast Transients and Water Reactor Kinetics). These tests led to the development of the USAEC's SPERT program. During the course of these experiments in which successively shorter periods were studied, the fuel elements began to show signs of hard use. Some bulged or

---

*In a private communication (quoted in a letter dated April 13, 1964 from W.B. Lewis to the author) D. G. Hurst states, "The author takes too strong a stand on positive reactivity coefficients. The substandard cooling and delayed dump were much more important. Perhaps the opposite conclusion could be drawn, i.e., even though channels were being emptied of light water by boiling there was no difficulty in shutting down by dumping ..."