UNCLASSIFIED

BNL-3145(Suppl.)

OFFICIAL FILE COPY

CRITICALITY STUDIES

UNITED STATES ATOMIC ENERGY COMMISSION

CRITICAL ASSEMBLIES OF LIGHT WATER
MODERATED, SLIGHTLY ENRICHED URANIUM
ROD LATTICES AT BROOKHAVEN

Supplement to Hazards Summary Report

By
Herbert Kouts

September 11, 1956

Brookhaven National Laboratory
Upton, New York

Technical Information Service Extension, Oak Ridge, Tenn.

UNCLASSIFIED

LEGAL NOTICE

This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission:

A. Makes any warranty or representation, express or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights; or

B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method, or process disclosed in this report.

As used in the above, "person acting on behalf of the Commission" includes any employee or contractor of the Commission to the extent that such employee or contractor prepares, handles or distributes, or provides access to, any information pursuant to his employment or contract with the Commission.

This report has been reproduced directly from the best available copy.

Printed in USA. Price 75 cents. Available from the Office of Technical Services, Department of Commerce, Washington 25, D. C.

BNL-3145(Suppl.)

Supplement to
Hazards Summary Report

Critical Assemblies of Light Water Moderated, Slightly Enriched
Uranium Rod Lattices at Brookhaven

Herbert Kouts

September 11, 1956

BROOKHAVEN NATIONAL LABORATORY
Upton, New York

Contents

I. Characteristics of the Assemblies	3
a. Fuel	3
b. Lattice support structure	4
c. Assembly tank	5
d. Plumbing	6
e. Control rods	7
f. Control rod drives	8
g. Flux detectors and electronics	10
h. Limit to reactivity	11
i. Temperature coefficients	11
j. Assembly building	12
II. The Experimental Program	14
a. Critical mass	15
b. Temperature coefficients	15
c. Neutron temperature	15
d. Control rod calibration	16
e. Neutron lifetime	16
f. Migration area	16
g. Pulsed neutron source measurements	16
III. Procedures	16
a. Initial loading practices	17
b. Responsibility	19
c. Qualifications of operators	19
d. Reactivity and power limitations	20
e. Emergency plan	20

I Characteristics of the Assemblies

a. The fuel used in the current series of experiments consists of two lots of uranium, containing respectively 1.30% and 1.15% U^{235} by weight. These have been formed into four-foot-long rods having a diameter of 0.387". Only one set (1.15%) is now at Brookhaven; the other is at Westinghouse, where it has been used in certain critical experiments directed partly toward PWR design.

Each uranium rod is canned in aluminum tubing with a 0.028" wall thickness and a nominal 0.005" radial air gap. The two ends are filled with close-fitting aluminum inserts, welded in so as to provide an air and water seal. The inserts are also tapped for screw fittings which serve in combination with the fuel locating plates to hold the rods rigidly in place in a lattice structure.

When we have finished the present experiments with the 0.387" diameter, 1.15% enriched rods, we shall send this uranium to the Fernald plant of National Lead, where it will be reduced in diameter to 0.250" and recanned as described above. Meanwhile, the 1.30% enriched fuel will be sent to Brookhaven and used in the critical experiments. Afterwards, the 1.30% enriched rods will also be reduced to 0.250" diameter by National Lead.

Thus the following sequence of fuel elements will be used in the critical experiments which are so far firmly scheduled:

- (1) 1.15%, 0.387" diameter rods
- (2) 1.3%, 0.387" diameter rods
- (3) 1.15%, 0.250" diameter rods
- (4) 1.3%, 0.250" diameter rods

The shipping and fabrication of this fuel are carried out under a long-standing contract between WAPD and National Lead. The hazards associated with these operations were considered by the Reactor Safeguards Committee in 1952, and in any case do not fall within the subject matter of this report.

At a later date we expect to carry out other experiments similar to those discussed above, but using uranium formed into flat plates. The method of cladding the uranium must differ somewhat from that which is now used, and the way by which fuel is located in a lattice must also be changed. The enrichments will however duplicate those of the rods we now use.

b. The means by which the fuel rods are held in place in a lattice has been chosen both for safety and scientific accuracy. Figure 1 is a photograph of the uranium support structure. Basically, this consists of two heavy circular metal plates, located one above the other, and held four feet apart by four heavy dural pipes. The bottom plate is made of 1" thick aluminum; the top is 3" thick armor-plate steel. The support pipes are welded to an aluminum ring fastened to the bottom aluminum plate, and are also welded to a second circular aluminum ring which fits into a milled groove in the bottom of the top plate. The whole structure is held together by four 1" dural tie rods, which run inside the aluminum pipes.

The bottom aluminum plate and the top steel plate have holes of approximately thirty inches diameter cut out of their centers,

and the actual fuel rod locating plates are inserted in these. As can be seen from Figure 1, each such set of fuel plates contains regularly spaced, accurately positioned and dimensioned holes which provide one predetermined ratio of moderator volume to fuel volume. A different set of fuel plates is used for each volume ratio. The top fuel plate is made of 2 1/2" thick 52S aluminum. The bottom plate consists of 1" thick 2S aluminum.

The top screw fittings for the fuel rods have heads which are larger than the holes in the top fuel plates, while the bottom screw fittings are the same size as the holes in the bottom plates. Thus a fuel rod can be lowered through the top plate into a fuel channel position. The oversize head will not go through the top plate, however, and accordingly all fuel rods are suspended from the top.

These lattice assembly frames are extremely rigid. We have been using them for nearly four years, with no observed indication of instability.

The water-to-uranium volume ratios provided by the fuel plates are: 4, 3, 2, 1.5, and 1.

We can foresee no way by which the volume ratios of lattices put together as above can suddenly and inadvertently be changed.

c. The critical assemblies are being carried out in a water tank in the pit below ground in T-526. This represents a change in procedure from that described in the previous hazards summary report. The tank is 7' in diameter and 6' high, and it therefore

contains somewhat less water than did the 8' x 6' rectangular section of the pit which we previously had planned to use. The reduction in water volume of course leads to correspondingly more rapid water dump.

The tank is a right circular cylinder made of 1/4" thick 52S aluminum. All joints are helium arc welded, and the whole has been tested for leak-tightness and has passed.

d. The tank is rigidly plumbed to the water fill and dump lines. The fill line is a 1" pipe; the main dump takes place through a 3" pipe. The dump tank is buried fifteen feet underground outside the assembly room (hence seven feet below the bottom of the critical assembly tank). The moderator water must thus be pumped up from below. The fill and dump operations are both accomplished through remotely activated valves operated from the console. As described in the prior hazards report, there are two dump valves in parallel, each supplied with an indicator light which shows when it has opened properly.

On receipt of a scram signal, the fill valve closes and the dump valves open. These automatic actions are both produced by springs.

It takes approximately one hour to fill the tank through the pump and the one-inch line. Approximately one minute of dump through the three-inch line removes the 0.0028 δ k permitted by the working rules.

There is also a fast water dump, which consists of a one-foot diameter stub of pipe welded onto the side of the tank at the bottom and capped with a rubber diaphragm. A section of aluminum pipe is pointed at the diaphragm; in the top of the pipe and held in place by a latch is a heavy, sharp pointed, steel projectile. The latch can be released manually from the console through a long length of cord. When the cord is pulled, the projectile is freed; it then drops down the pipe and punctures the rubber. The diaphragm tears apart under the force of water pressure, and a very fast dump takes place into the surrounding pit. The 0.0028 Sk is released in about five seconds. This system has been tested several times, and has worked properly each time it was tried.

We have not designed this secondary water dump to operate on an electronic scram, because replacing the diaphragm is a time-consuming operation. We prefer to consider it as a last-ditch system, completely dissociated from the electronics and electrical supply.

c. There are four control and safety rods, worth altogether approximately two dollars of reactivity. Each consists of a four foot long section of 0.370" O.D. aluminum tubing, filled solid with an alloy of lead-cadmium. To make room for the control rods, four fuel rods are removed from the lattice, and the vacant fuel positions are loaded with 0.397" I.D. aluminum tubing (the size normally used for fuel cladding). These constitute sleeves inside which the control rods move. Limit switches prevent any safety rod

from being fully withdrawn from the guide sleeves; the minimum amount of insertion is 6 1/2 inches. This amount has been shown to be more than ample for a stable drop of a safety rod into the lattice.

The guide sleeves have caps welded onto the bottoms; they are therefore water-tight, and the rods drop in air. This feature of course makes for faster drop, the time for full rod insertion after receipt of a scram signal being approximately 0.6 seconds.

f. The safety rods are suspended from steel cables which pass to the control rod drives through a system of pulleys. Figures 2 and 3 show the principal features of the rod drive mechanisms as they were set up for some earlier critical experiments.

Each contains:

1. A D.C. drive motor, attached through reducing gears to
2. A disc-type magnetic clutch, which requires a flow of D.C. current to hold. The secondary side of the clutch is rigidly attached to
3. A grooved drum on which the steel cable to the control rod winds. Connected to the drum through a step-up gear is
4. A selsyn master, to supply rod position information to the console. Also attached to the cable drum is
5. An automobile shock absorber which cushions the final few inches of rod drop.

A scram signal cuts the supply of power to all four magnetic clutches. These therefore release (disengagement is aided by spring action) and the rods fall by gravity. To counteract the inertia of the drum and cable, each control rod is lead-weighted to a total mass of thirty pounds.

The control rod drive systems were obtained from Argonne, where they were used with ZPR-1. In about six years of operation at Argonne and Brookhaven they have always worked in a satisfactory manner, with no apparent defects. Since any single rod can shut down the assembly, and since all four have proved to be reliable, we feel that the rod drive systems are completely trustworthy.

The rod drive switch is mounted on the right of the control panel at the console (see figure 4). A selector switch on the left of the control panel permits the operator to choose which rod drive is to be activated, and a separate position of this switch allows the choice of water input or output. The system does not allow ganged operation of any sort. The operator may choose to raise or lower one control rod, or he may choose to add or remove water through the one inch line. Once this selection is made, the operator may increase reactivity by raising or decrease reactivity by lowering the rod drive switch. Although the latter will hold itself in the down position, it will not do so in the up position - that is: positive action by the operator must be maintained in order to increase reactivity. This unit is what is industrially called "a dead man's switch".

The maximum rate at which the rod drives can add reactivity is less than 10^{-4} δ k/sec. The water input rate near critical is equivalent to about 3×10^{-6} δ k/sec.

g. The flux detectors being used in these experiments are: four BF_3 coated ion chambers, two fission counters, and one BF_3 gas-filled counter. The three counters supply scaling circuits, count rate circuits, Esterline-Angus recorders, and high and low level trip circuits. Two ion chambers supply vibrating reed galvanometers, Brown recorders and high level trip circuits. One ion chamber supplies a Beckman galvanometer, an Esterline-Angus recorder, and a high level trip circuit. The remaining ion chamber supplies a ln N circuit, a period circuit, two Brown recorders (one for period and one for power display), and period and high level trips. Altogether, the seven flux detectors feed eight paper strip recorders and eight trip circuits, any one of the latter set being able separately to produce a reactor scram. There has been no occasion when electronics should have shut down an assembly and it did not do so.

Working rules require that at least three level detectors and the period detector must be working satisfactorily during any critical experiment. The assembly may not be taken critical with fewer instruments. Furthermore, if the number of reliable instruments falls below this quantity during an experiment, the assembly must be shut down immediately. This is one of our most important regulations.

The assemblies are monitored by a closed circuit television unit, with the display tube at the console. This unit is intended primarily for emergency use, when it might be necessary for the operator to survey the critical assembly or the assembly room without entering the latter. The camera is equipped with remote pan and tilt and remote focussing.

The water height display is just off to the right of the photograph of the console shown as figure 4. This system balances the weight of a column of water against the weight of water at the bottom of the assembly tank, and it is read simply by noting the position of the meniscus of the column on a meter bar.

h. Our working rules limit excess reactivity to \$.90. In this particular set of experiments, however, we are restricting excess reactivity even more - to the amount which would lead to at most a ten second period with control rods full out and water full in. Both of these limits were mentioned in the report to which this is a supplement.

1. There is sufficient uranium to take to critical only one lattice of 1.15%, 0.387" diameter rods - that with the 3:1 volume ratio. It is unlikely that the amount of fuel available will permit any lattices of 1.15%, 0.250" diameter rods to be made critical. There will probably be enough uranium to take to critical all lattices of 1.30% enriched uranium which have the water-to-uranium volume ratios: 4, 3, 2, and 1.5.

Measurements at WAPD indicate that the lattices having volume ratios 4 and 3 have slight positive temperature coefficients. Other lattices have negative coefficients. All lattices have negative metal coefficients.

The most positive temperature coefficient should be obtained with the 4:1 volume ratio assembly; its value should be about $+ 5 \times 10^{-5} \text{ } ^\circ \text{K}/^\circ \text{C}$ at room temperature. We wish to point out that while these conclusions are only extrapolations from Westinghouse data, they are still more reliable than calculations would be. The theory of temperature coefficients of heterogeneous piles is still not well-established.

The temperature coefficients of all the lattices become less positive and more negative as the temperature is increased. This feature is readily predictable from the curves of critical size against volume ratio and it has been observed uniformly at Westinghouse as true of all water-uranium lattices. In fact, we expect on the basis of WAPD reports that above about 160°F , all the lattices studied will have negative uniform temperature coefficients.

j. The assembly room in which these experiments take place was constructed in 1955. It has a floor area of $24' \times 34'$, a height of $22'$, and has concrete block walls and a poured concrete floor. The roof consists of precast concrete planks, covered with standard commercial built-up roofing. The assembly room adjoins

building T-526, a fire-proofed concrete block structure 20' x 100' by 8' high. T-526 has a 5' thick stacked concrete block wall across its waist, dividing the building into an active area and a control area. An external view of the facility is given as figure 5, and the floor layout is given in figure 6.

From these two figures it can be seen that the active area is surrounded by a stacked shield of concrete blocks 2' thick and 8' high, except at the east access door. The area east of the assembly room is a "no access" region during experiments; exclusion is provided by wire fences and signs not shown in the photograph.

The assembly room and T-526 are not air-tight, and they are certainly not blast-proof. The ability of the assembly room to contain a fission-product-bearing cloud could be improved by two steps:

- (1) The east access door could be weather-stripped.
- (2) The fire door between T-526 and the assembly room could be made gas-tight and kept closed during operation.

However, we hesitate to make these changes. We have limited ourselves to very small excess reactivities, and have incorporated into the electronic system about twice as many safety circuits as are customarily used with critical assemblies. The shut-down devices are all of a fail-safe nature; that is: all failures lead to a scram and we do not know of any possible failure (other than

sabotage) which could prevent a scram. There are four individually released safety rods, each capable of shutting down any assembly, and there is a slow water dump and a fast mechanical water dump. The one observed weakness in all of these independent safety systems was a property of the slow water dump. It has been discussed in our original report, and we feel that the trouble has been eliminated.

To summarize the above, we feel that gasket seals on the doors to the assembly room are unnecessary, because sufficient overdesign of other kinds is already provided. We might point out also that such seals would reduce the ability of the assembly room to withstand a blast or a pressure buildup, inasmuch as the leaks we have now could act as safety valves.

II The Experimental Program

The purpose of these experiments is solely the development and improvement of information on the physics properties of light water moderated, slightly enriched uranium reactor cores. We have no present interest in the properties of reflectors, breeding blankets, or in fact in any materials external to the core proper. All of the assemblies are indeed reflected by ordinary water; the reasons why this is done are however only connected with the economy of uranium and the simplification of operation. Hence we do not propose to replace the water reflector by any other material.

a. We wish to obtain direct measurements of the critical mass, as a partial check on the information produced in our exponential experiments.

b. We wish to measure the uniform temperature coefficients over a narrow range near room temperature. Not only is this measurement conducive to greater safety of operation, but in the long run it should prove useful in improving the understanding of the quantities measured and the calculations which predict them.

The temperature coefficients will be measured by heating the moderator water and then cooling it, and simultaneously measuring reactivity changes. We expect the extreme temperature range not to exceed 100°F, and it is unlikely that it will exceed 50°F. The rate of temperature change will not exceed 25°F/hour, and the associated reactivity changes will be no greater than 1.2×10^{-5} δ k/minute. This amount of reactivity corresponds approximately to a two hour reactor period.

c. We shall measure the average neutron temperatures of the assemblies by a system involving successive additions to the moderator of boron and cadmium neutron poisons. The measurement consists in holding the reactor critical and noting the control rod position, adding a measured amount of boric acid to the water and noting the new critical position and finally adding a measured amount of cadmium sulfate and noting the critical position. Altogether this amounts to finding the reactivity coefficients of boron and cadmium in solution.

Since we have no enriched uranium solution and indeed do no work with uranium in solution, the possibility of accidentally increasing the reactivity by adding fissionable material instead of a neutron poison does not arise.

Of course, all additions of poison will be done by remote means. The amount of reactivity change caused by an individual addition of poison will be about five inhours.

d. We shall of course calibrate control rods, and shall probably study several sizes and compositions of rods, so as to provide experimental information on control rod worth.

e. Neutron lifetimes will be measured by the α -technique developed at Los Alamos. This consists in measuring the intervals between fissions and the lengths of fission chains in subcritical assemblies.

f. Migration areas will be found from measurements of the change of reactor period with loaded radius.

g. At a later date we expect to irradiate critical assemblies with a pulsed $D(D;n,p)D$ neutron source. Experiments of this type will lead to further information on migration areas, effective delayed neutron yields, slowing-down and diffusion times, etc.

III Procedures

Some of the procedures described here are contained in our

working rules, given as an appendix to the original hazards report. Others have been discussed in detail in earlier hazards reports. We shall enlarge on them, however, as we were asked to do.

a. The initial loading of an assembly is always done with great care. The number of fuel rods first inserted in the lattice does not exceed 10% of our best estimate of critical mass. The next addition does not exceed 5% of our best estimate of a critical mass. It should be pointed out that we are now able to predict the critical masses of our assemblies quite accurately, because of the accumulation of a considerable body of data from prior exponential experiments and from calculations which match the measurements quite well. It is in fact not likely that in any given case our best preliminary estimate of the critical mass of one of these lattices can be wrong by more than 20%.

After both the first and second fuel additions, the relative flux levels in the assembly are measured with all detection instruments, and we begin a set of standard reciprocal flux curves (plots of ϕ^{-1} vs number of rods loaded as indicated by each detector). The extrapolations of these curves to $\phi^{-1} = 0$ provide estimates of the critical mass. We then load an additional number of rods which does not exceed one third the indicated number remaining to critical. The basis for this choice is that curve which indicates the least critical mass. This criterion for selecting the amount of fuel to be added we call the "rule of a third".

The flux levels are measured again after the third loading, providing additional points on the inverse flux curves. The rule of a third is again applied as a basis for choice of a fourth loading, and so on. The procedure is iterated until it is estimated that k_{eff} is about 0.99. At this point, the criterion for the amount of fuel to be added at each stage is altered. The new upper limit is the number of rods equivalent to one-fourth the safety available in control elements.

Fuel additions are always made while the control rods are inserted half-way into the assembly. This practice assures a reserve of safety. If uranium were added while the rods were completely inserted, and this led somehow to a supercritical condition, nothing short of the consequences of a runaway could shut the system down. The person doing the loading would almost surely receive a massive dose. We feel strongly that the best way to avoid this eventuality is to have safety rods only half in whenever personnel are working on the assembly, and we cannot conceive of following any other practice.

Flux measurements during the initial loading are always made with control rods fully withdrawn, and the water height at a predetermined level at which water addition causes no appreciable gain in reactivity.

At several stages in the loading, the rods are dropped, and their worth in terms of fuel is found. These measurements provide the basis for fuel additions above $k_{eff} = 0.99$.

A running log is kept during all initial loadings and critical runs. Flux levels during the loadings are recorded in this log; also recorded are the times at which water is added and subtracted, and the times at which control rod changes are made. We do not however record minor rod position changes meant only to keep the power level fixed.

All instruments and safety circuits are checked each day before operation - if an operation is to be carried out. At this time it must be ascertained that all safety circuits are operative, and that at least four level detectors and the period circuit are providing reliable information.

b. At all times during loadings and experiments primary responsibility is held by one individual. During initial loadings, two responsible personnel on an established list must be present and must agree on the amount of fuel to be added at each stage.

c. Only critical assembly operators trained and certified locally are permitted to take an assembly to critical. We insist that before an individual becomes qualified he must have developed a good understanding of experimental and theoretical reactor physics, and must be able to interpret reactor transients. He must be psychologically stable, and he must have undergone an adequate apprenticeship at the assembly facility. In other words, our emphasis is on intelligence, understanding, and emotional fitness.

Our qualified operators are and have been ORSORT graduates or PhD scientists. The leader of the Experimental Reactor Physics group personally designates the people who may be qualified as critical assembly operators.

d. During these experiments, the excess reactivity available to the operator at the console will be no more than can lead to a ten-second reactor period. The maximum power level will be ten watts. Under the latter limitation, no reactor cooling is required.

e. The existing Laboratory Disaster Plan is intended to provide for rapid site evacuation in case of an extreme emergency (such as a physical explosion of the graphite research reactor). It is now believed that the plan should not be based on considerations involving an accident which is so very unlikely, and so the procedures to be followed are in process of being revised. The assumption upon which the new Disaster Plan is being based considers an accident equivalent to the release up the pile stack of a few fuel cartridges ($< 1\%$ of the loaded mass). The steps to be taken if this happens are meant to avoid the effects of the subsequent fallout.

No conceivable critical assembly accident could produce radioactivity greater than that contained in one Brookhaven pile fuel cartridge. Therefore our emergency plan conforms to the practices being adopted for the reactor.

In case of a runaway, the responsible operator will call

meteorology and the health physics duty office. The meteorology office will immediately on the basis of the prevailing wind and weather predict the part of the site most likely to be affected by fallout. This estimate can be done rapidly by means of a set of templates laid out on the area map. The mobile health physics unit is then able to proceed to the probable danger area to survey conditions.

In the meantime, if the critical assembly operator decides that there is a chance that a radioactive cloud has been liberated, he asks police headquarters to give the laboratory emergency signal. The emergency signal informs all laboratory personnel to take cover indoors and to remain there until they are notified by telephone or by roving police cars that all is clear.

Figure 1.

Figure 2.

Figure 3.

Figure 4.

Figure 5.