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

Hazards Report

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February 28, 1956

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Hazards Report

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

By Herbert Kouts

Introduction: We are proposing here a series of critical experiments with lattices of slightly enriched uranium rods, moderated by light water. These studies are meant to supplement and extend our current series of exponential experiments on similar assemblies.

Critical experiments of this type done up to now at WAPD have been most useful in corroborating and extending experimental results we have been obtaining by other means. The pressure of PWR design has now forced the Westinghouse group to eliminate the experiments most useful to us, and since we feel an urgent need that they be resumed, we propose to do them at Brookhaven.

Description of Assemblies: A typical critical assembly will consist of from one to two tons of uranium rods, containing either 1.15% or 1.3% U^{235} by weight. The rods will have a diameter of either 0.387" or 0.250", will be clad with 0.028" of aluminum, and will be four feet long. The ratio of moderator to fuel volumes will vary from about 1.5 to 4, with generally uniform spacing of the fuel to form a cylindrical array.

The assemblies will be made in half of the pit of the Brookhaven critical experiments facility.⁽¹⁾ Since this pit is eight feet deep, the top of the fuel loading will be about two and a half feet below ground. Thus the side wall will serve as partial shielding for the experiment. A cross-section

view of the pit with an assembly is shown as figure 1.

The control and safety rod drives, flux detectors, electronic instruments, and water fill and dump lines will be the same ones now being used with the Brookhaven Medical Reactor mockup. These have given completely satisfactory performance up till now, with no cause for concern regarding their adequacy or reliability-with one exception. On February 17, 1956, after about four months of satisfactory operation, the water dump valve failed to respond immediately to a routine scram signal. The rods dropped properly, sending the assembly well subcritical, but the dump valve had to be actuated twice before it opened. The critical experiments were discontinued at once; it was found that dirt had got into the valve, preventing its compressed air release from functioning. We have now installed a second valve in parallel with the first, and each has been supplied with a signal light which shows at the console when a dump of each has occurred. Operation following this failure has not yet been resumed; when we start up again, we shall require that both valves be in working order on all runs. Thus the water dump system is not completely fail-safe, but does contain a double safety.

Safety Provisions: In no event will an assembly be loaded intentionally with more uranium than would lead to a ten second period when completely submerged, with all safety and control rods completely withdrawn. This limits the excess k to be about .0028, an amount achieved by approximately 15 rods of 0.387" diameter or 30 rods of 0.250" diameter uranium in excess of critical. In order to assure maintaining this limit, we are adding to our working rules one to be used specifically for these lattices: Above critical loading, fuel must be added in steps not greater than one-third the estimated number of rods between critical and a ten-second period.

The safety and control rods will be worth at least 1.5% in k , and the rod drives will not change the reactivity faster than 10^{-4} $\delta k/\text{sec}$.

Ultimately we shall depend for safety on the electronic and manual shut-down mechanisms of the assemblies. These consist of seven separate flux-sensing devices, each independently capable of producing a scram, and two manual scrams, one at the console and one in the assembly room.

Although the safety system is the same one described in reference (2) and now being used with the Brookhaven Medical Reactor mockup, it is important enough to be discussed again here.

Each safety rod is suspended from a cable which winds on a drum. The winding action is provided by a small electric motor coupled to the drum through a disc-type magnetic clutch. The clutch action is positive; a current must flow through its magnet coil in order to actuate the holding. When no current flows (as from a scram signal or a power failure) the clutch is released and the safety rods are free to drop by gravity into the core.

The water dump line consists of a three inch pipe feeding a dump tank buried well below the bottom of the pit. The remote-operated valve which permits water dump to take place also has a positive action. A compressed air supply keeps it closed. When current is cut, the air pressure at the valve is exhausted, and the valve opens by spring action.

The safety rods, clutches, and drives and the dump valve are all supplied by a common DC voltage from a rectifier unit at the console. Power failure at the console initiates a scram through cutting the currents to the safety units, with results as described above.

The safety rods are inserted fully about 0.6 seconds after the scram signal is given. Water dump is much slower, because of the large amount of water in the pit. After about 80 seconds of dump, the water alone will remove the .0028 g k permitted by the working rules.

After two minutes it will remove about .0086 g k. Thus the two safety units (rods and water dump) must be considered as respectively fast and slow systems. Even the slow water dump itself must be very effective, though, when its time scale is compared with the 10 second period maximum which is allowed, since 80 seconds of rise on this period would only carry the assembly from 10 watts to 27 kw (neglecting even the increase of pile period which would accompany the dropping water level).

In series with the D. C. line supplying the rod drives, clutches, and the dump valve are sixteen relays and sensitrol switches, which are (all but one) end products of scram circuits. These are served as follows:

One from the manual scram button in the assembly room.

Three from the manual scram bar at the console.

This is a triple safety feature.

Three from upper limit settings on three count rate meters. Each such count rate circuit is supplied by a neutron counter at the assembly.

Three from lower limit settings on the same count rate meters. These provide scram signals in case of counter failure or partial power loss.

Two from upper limit settings on two vibrating reed electrometers.

These are in turn fed by two boron lined ion chambers at the assembly.

One from the upper limit setting on a Beckman galvanometer, which is supplied by a third boron-lined ion chamber.

Two from the (1n N) and d (1n' N) sections of a period circuit - which

is supplied by a fourth boron lined ion chamber. This is the period trip.

The sixteenth unit is a self-latching relay, which insures a scram signal is being retained once it has been given.

Six of these relays are double pole - double throw, with the contacts wired in series. Thus either pair of contacts could hold shut and the relay still be operative.

Working rules do not require that all of these safety circuits be in use at the same time, only the manuals and five electronic trips being required. However, up till now at most one at a time has been inoperative because of instrument trouble and at least seven electronic and four manual trips have been the minimum number used. All scrams are tested every working day. Operation to date has involved over two hundred critical runs, with no cause for concern about the reliability of the console and its safety circuits.

Potential Hazards: Hazards not associated with a reactor runaway have been discussed in detail in references (1) and (2). Since they will not be augmented by the program we propose, we shall not treat them here.

For a runaway to take place, one of two things would have to happen.

(1) The following trips would all have to fail to operate at once;

All high level flux trips; working rules require at least four in good operating condition.

The period trip.

The three manual trip switches on the scram bar.

- (2) A period much shorter than 0.6 second shut-down time of the assembly would have to be achieved.

These two situations must now be considered in detail, to see how probable they are.

- (1) Operating rules require that every trip be tested individually every working day. This rule has been rigidly adhered to ever since the critical assembly facility became operative. In addition, some trips are tested each day under operating conditions. An obvious example is the manual scram, for routine shutdowns. It is standard practice to shut down on other trips too, simply to test them.. For example, one of the level trips is purposely set only a little above the assembly operating flux, the power is increased, and the trip is permitted to cause a scram. In this manner all the electronic trips are periodically tested under operating flux conditions. Of course, should any ever fail to operate under test, it would immediately be replaced or repaired, no reliance being given until it was shown to be trustworthy again.

To reiterate, this failure is compounded of the simultaneous failures of at least eight separate trip circuits - all of which have operated satisfactorily to date. The chance therefore seems remote enough for confidence that it will not happen.

- (2) In order to make possible a period short compared to 0.6 seconds, the operating rule limiting the available excess k would have to be violated (unintentionally, of course). As an indication of how much extra metal could lead to damage, the following

considerations are useful:

An appreciable number of e-folding times in 0.6 seconds would be needed. Certainly even a period of 0.1 seconds would not be very troublesome, because then the pile power could rise by only a factor of 400 in 0.6 seconds - and this estimate ignores the cumulative reactivity drop as rods fall. To achieve a period of 0.1 seconds would require an excess k of .0078, which in turn would presuppose an excess loading of at least 40 rods of 0.387" diameter or 80 rods of 0.250" diameter.

It is extremely unlikely that an excess loading of this amount would be made, since our working rules limit rod loading additions in this region to at most about six 0.387" diameter rods or twelve 0.250" diameter rods.

However, supposing that such an amount of excessive fuel could be added, to achieve such short periods without a scram would require that reactivities in excess of .0028 δk to be added in a time short compared with 0.6 seconds. Since fuel is to be loaded only when enough water has been removed to make the assembly well subcritical, so the only ways in which reactivity can be increased are by water addition or safety rod removal. As has previously been stated the rod worth and removal speeds are so chosen as to limit reactivity addition rate by the latter means to $10^{-4} \delta k/\text{sec}$. Thus it would take nearly thirty seconds of safety rod removal to achieve a ten-second period, and one could not reach a faster period without a scram signal.

The rate at which water adds reactivity is much slower. In fact, the water volume to be used is so large that about half an hour will be required for filling the assembly.

Thus even supposing the assembly to have been filled with an excessive amount of uranium, there is no way available for this to lead to very short periods without the prior occurrence of a scram signal.

To sum up, we have shown that accidents are possible only if the normal shutdown methods of rod drop and water dump, activated either by manual or electronic means, fail completely to operate. These contain so much duplication, and there are so many, that in the light of their fail-safe design we believe their simultaneous failure extremely remote.

There is one feature of these lattices which must be discussed at this point. Their temperature coefficients will vary from about -5×10^{-5} δ k/°C to about $+3 \times 10^{-5}$ δ k/°C. Approximately half of them will have positive temperature coefficients of reactivity.

We wish to point out, however, the difference in effect of a positive coefficient on the hazards of respectively a high power reactor and a low power critical assembly. In the case of the former, the operating temperature is determined very largely by the power level, and the effect on temperature of any sudden power surge is immediately seen. Thus the probability of runaway from a high power level must inevitably take the temperature coefficient into account.

On the other hand, a critical assembly is run at only low powers, and normally over the duration of a run temperatures remain fixed. The

effect of a positive coefficient would not be seen until an accident was well established.

We can give a simple example. A sample assembly we propose doing has the following features:

Temperature coefficient	$+ 3 \times 10^{-5} \text{ } ^\circ\text{K}/^\circ\text{C}$
Water heat capacity	$9.2 \times 10^{+5} \text{ Joules}/^\circ\text{C}$
Fuel heat capacity	$1.2 \times 10^{+5} \text{ Joules}/^\circ\text{C}$

The above coefficient would cause a $+ 5^\circ\text{C}$ temperature rise to cut the period from 10 seconds to 9 seconds, and approximately 5×10^6 Joules of heat would be required for this to happen. This heat development would have occurred after about 108 seconds of steady rise on the ten second period. Of course, almost all of the heat would be generated in the last few seconds of rise, and so the temperature coefficient would not be felt until then. A positive coefficient therefore could not contribute to the cause of a runaway. It could, however, help to determine the history and magnitude of whatever accident did occur.

Maximum Credible Accident: In reference 2 we derived an upper limit to a credible accident involving the Medical Research Reactor critical experiments. The limit there was based on assuming that an excursion could not generate more heat than required to evaporate all of the moderator water. The medical reactor criticals contain 8 ft^3 of water; the assemblies we are proposing here will have about 320 ft^3 of water moderator apiece. Thus the upper limit on a credible accident as set by arguments of this sort is about 40 times that derived in reference two. Actually, one can reduce this

factor in a very believable way by estimating the amount of water which must be boiled away to carry any given runaway to a level below criticality. To eliminate the excess k associated with an excursion at a period of 0.1 seconds would require boiling away 30% of the water - thus we can reduce the estimate of maximum power generated in an accident to

$$\frac{(0.3) (320)}{8} = 12 \text{ times a reference 2 accident.}$$

It is hard to see how the estimate of the maximum credible accident made by such means can be lowered much.

The details of a large scale excursion would be connected intimately with the type of fuel element we intend to use. The uranium rods in question are clad with aluminum, about 0.028" thick, with an air space of about 0.005" between the element and the cladding. Thus the heat transfer properties to the water moderator are quite poor. Being uncertain about the true value of the heat transfer coefficient from the uranium to the water, we have carried out a series of measurements intended to determine it. These have shown that the characteristic time for a transfer of heat from the rod to the water is about 5 seconds; that is: if a temperature differential is established, it drops by a factor e in 5 seconds. The implication of this result is clear. If the reactor power rose on a period long compared to five seconds, the water would be heated along with the uranium; if the period were much shorter than five seconds, the heat transfer would be negligible. In the latter case the rod temperature would increase rapidly (after about a 1 MW power level were reached), and would continue to do so until some process shut down the assembly. We are of

course forced to assume that the previously discussed safety mechanisms of the reactor have all for some reason or reasons failed to operate; otherwise the excursion would not occur at all. In event of such failure, though, some natural shut-down means must operate. Such a means is the boiling away of about 100 ft^3 of water, as discussed above. In other words, the upper limit to the credible accident we have established envisages a natural shut-down of the excursion which must have operated if all other artificial or natural shut-down means have failed.

Again supposing that somehow the assembly were put on a very short period and that the safety systems did not function, one could not rule out the possibility of chemical reactions between the uranium and the water. If the period were so short that the heat transfer to the water was small, the rod temperatures would rise until the aluminum melting point ($\sim 660^\circ\text{C}$) was reached. The thermal expansion of the uranium would then have cut the average air gap between the rod and the fuel to about $0.0025''$, and actual contact would exist in a number of places. Where such contact existed, the thin cladding would burn through, and water would be permitted to contact the hot uranium. This would inevitably start quite serious chemical reactions. Thus we must not reject the possibility that in these circumstances there could be a sizeable liberation of uranium and fission products as gas.

The upper limit excursion we have deduced would generate about 10^{20} fissions, or about 3.3×10^9 joules of heat. The heats of formation of the uranium oxides are all about 4.2×10^6 joules/kg of uranium. Therefore

the chemical heat which might be freed is at most about

$$\begin{aligned} (4.2 \times 10^6) & \quad (10^3) & = 4.2 \times 10^9 \text{ joules} \\ (\text{joules / kg}) & (\text{kg of uranium}) \end{aligned}$$

This is nearly the same as the fission heat given above, and so chemical heat could play a part in any explosive process.

The maximum credible incident can now be described as follows: By some means the assembly is put on a very short period ($\ll 5$ sec). The safety circuits all fail in some way we do not now visualize. At a power level of about 1 mw the fuel temperature begins to rise. It continues to rise rapidly, the heat generation well outstripping the rate of transfer of heat to the water. By the time the fuel temperature reaches about 100°C above its initial value, the negative metal coefficient ($\sim 2 \times 10^{-5} \text{ }^\circ\text{K}/^\circ\text{C}$) begins to be felt.

At this point the rate of power rise begins to slow. However, as heat is transferred to the water the positive moderator temperature coefficient prevents the period from becoming more than 5 seconds. When the uranium temperature reaches 660° , the aluminum cladding begins to melt, and water reaches the fuel. The uranium-water reaction begins to take place very quickly, and a film of oxide covers the rods, providing heat insulation. Thus the rods are not permitted to cool; the temperature continues to rise until the oxide cracks from thermal stress. This permits water again to contact uranium, and the corrosion process to continue. By this means uranium is converted quickly to oxide, some going off in the steam

generated. Fission products are also liberated freely. The excursion continues until enough heat has been liberated to remove sufficient moderator to stop the process. Since a considerable steam pressure must be built up in the reacting region, there must be appreciable expulsion of water and perhaps of fuel. However, the reaction certainly stops by the time the heat has been great enough to evaporate the necessary water; this amount is approximately 10^{20} fissions or 3.3×10^9 joules.

Supposing now that all fuel were to vaporize and form a cloud which completely escapes the assembly room, we can estimate upper limits on personnel dosage to be expected. The cloud doses can be taken from a nomogram by Holland; they are shown in figure 2 for a variety of assumptions regarding cloud height and wind conditions. One can see that the dose at the nearest regularly inhabited area (the boiler house) is under the worst conditions about 400 R. At the metallurgy building it is at most about 70 R. At the site boundary it is most about 16 R.

The exclusion radii as found by the same means used in reference 2 are as follows:

Weather	Exclusion Radius
Dry, average lapse, light wind	330 ft
Dry, average lapse, strong wind	370
Dry, stable air, light wind	530
Dry, stable air, strong wind	600
Rain, average lapse, light wind	1530
Rain, average lapse, strong wind	1900
Rain, stable air, light wind	2520
Rain, stable air, strong wind	3160

These are the distances from the excursion at which fallout would produce a dose of 300 R during the three weeks after the event. The exclusion distance taken from the simple Reactor Safeguards Committee formula is 2890'. The site boundary is at its nearest 2800' from the assembly area. A sizeable fraction (about 10-20%) of the on-site personnel are included in the circle with largest radius given above.

We must conclude that the upper limit we have derived is not a safe one. However, it contains a number of over-estimates which were included intentionally. If we have over-estimated the heat generation in the burst by only a factor of two, the fraction of fuel vaporized by a factor of two and the fraction escaping the assembly room by a factor of two, the size of the cloud must be cut by a factor of eight. The exclusion radius under the worst weather conditions would then be reduced to 1100 feet. This distance then includes on the average about four laboratory personnel during working hours (aside from those involved in doing the critical experiments).

In considering the history and consequences of a runaway, we have assumed a pile period short compared to 5 seconds. If it is not so short, heat will be transferred successfully to the moderator, and the rod temperatures will remain low. We should then expect no appreciable cladding failure and no sizeable radioactive cloud. The assembly would simply blow off water and steam until the volume were cut enough to stop the excursion.

Assessment of Hazard: We have shown that with certain assumptions it is possible to conceive of these experiments' leading to an intolerable accident.

The principle such assumptions are:

- (1) The assembly takes off on a period very short compared to five seconds.
- (2) The four level trips, the period trip, and the three manual trip circuits all fail

Or

All four safety rods fail to insert on receipt of the scram signal.

- (3) The incident is limited by the boiling away of sufficient moderator water.
- (4) All fuel is evaporated.
- (5) The radioactive cloud completely escapes the assembly building.
- (6) The worst possible weather conditions exist, so that fallout rates are a maximum.

Under these conditions, the site boundary does not quite include the full exclusion area, and an appreciable number of on-site personnel are within the exclusion radius.

We shall cover again briefly the points above.

- (1) We intend to limit the excess k so that these short periods cannot be realized. If somehow the excess fuel does by accident exceed the allowed amount, it is still difficult to see how the short periods can be reached, because reactivity addition rates are so low.
- (2) The electronics, trips, and rod drops have all shown themselves during extensive use to be completely reliable. The simultaneous failure of five electronic and three manual trips seems very far-fetched, inasmuch as none has failed yet. The rod drops have always operated successfully, and indeed it is difficult to

foresee how they could fail in an unsafe manner.

- (3) Some water is bound to be expelled forcibly during any incident; the assumption that it must be turned into steam first then over-estimates the heat required.
- (4) It is certainly pessimistic to believe that all fuel evaporates.
- (5) It is likewise very pessimistic to suppose that all which does evaporate will escape the assembly room.
- (6) This is of course the most likely of the pessimistic assumptions. We could conform to a requirement that we do not operate in certain weather conditions, but we would prefer not to be limited so.

After consideration of the safety factors involved in estimating the maximum credible accident, we feel that the likelihood of a severe incident is small enough to permit carrying through the proposed experimental program.

Attached as an appendix are our revised safety rules.

References:

- (1) Summary Report to the Committee on Reactor Safeguards,
Subject: Proposed Exponential and Critical Assembly Facility at
Brookhaven National Laboratory, November 10, 1954.
- (2) C-8988, Summary Hazards Report, Critical Experiments for the
Brookhaven Medical Reactor, June 10, 1955.

Appendix

General Safety Rules

Definitions:

1. A critical assembly is defined to be a physical arrangement of fissionable material and moderator, or fissionable material alone, which may under certain circumstances achieve a k_{eff} of 1 or more.
2. A type I critical experiment is defined to be one which involves taking to a k_{eff} of 1 an assembly whose criticality conditions are grossly unknown. This category would include the initial loading of new materials, the loading of previously used materials under new conditions, or achieving criticality after alteration of the assembly has made uncertain any previous knowledge of the general point at which criticality is to be expected.
3. A type II critical experiment is defined to be one which involves taking to a k_{eff} of 1 an assembly whose criticality is well known from previous type I critical experiments.

4. The list of responsible personnel is:

Kenneth Downes

Glenn Price

Rudolph Sher

Herbert Kouts

Joseph Hendrie

These personnel will be responsible as indicated later in these rules.

Additions to and deletions from this list may be made only with the

unanimous consent of those named above, and after the chairman of the Nuclear Engineering Department and the head of the Reactor Physics Division have been advised of the change.

Rules:

1. Assemblies are to be made only in the approved area in T-526.
2. A type I critical experiment will be supervised up to the point of criticality by at least two responsible personnel. These two must have agreed on each action which increases the reactivity of the assembly before that action is taken. After criticality has been reached, supervision by at least one responsible person is required.
3. A type II critical experiment must be supervised by at least one responsible person.
4. Before any related set of type I critical experiments is begun, a report must be prepared, to contain the following:
 1. Purpose of the experiments.
 2. Descriptions of the assemblies
 3. Controls to be used.
 4. Instrumentation.
 5. Probable duration of experiments.
 - 6.. Personnel expected to participate.
 7. Maximum expected power level.
 8. Special safety features, including loading procedures.

Operation in accordance with this report must be approved by the Critical Experiments Safety Committee before the experiments can be begun.

5. Before any individual type I critical experiment, an informal report must be prepared, to contain the information listed in rule 4. Operation according to this report must be approved unanimously by the responsible personnel present before the experiment is begun.
6. A running log must be kept during each critical experiment. This log must be kept up-to-date; it should when advisable list the data from pertinent instruments (counting equipment, water level, temperatures, rod positions, etc.). Each related set of actions which change the reactivity (such as change of water level or control rod positions) must be logged at the time they are begun. All other information thought pertinent must also be logged.
7. The log of a critical experiment must be begun by a brief description of the assembly and the experiment. It must be signed by the responsible personnel present. It must indicate that prior approval by the Critical Experiments Safety Committee (if necessary) was obtained.
8. No person is to be allowed in the assembly area while changes are made remotely to the critical assembly, if these changes are of hazardous type.
9. No person not directly connected with the experiment is to be allowed in the active assembly area unless he is accompanied by a member of the group connected with the experiment, and his presence is made known to all people connected with the experiment.

10. Periodically the Critical Experiments Safety Committee will review precautions taken to keep personnel out of possible hazard areas.
11. No manual addition to a critical assembly of fuel or moderator is to be made unless the person doing the adding has an audible indication of flux levels and is in direct communication with the operator at the console.
12. No critical experiment may be carried out without at least four instruments for radiation level measurement, all giving reliable count rates or ionization rates at the console position.
13. No critical experiment may be carried out without at least \$2 worth of control and safety rods, with scram mechanisms in working order and activated by at least three instrument level trips, a period trip, and a manual trip.
14. No critical experiment may be carried out with liquid moderator without an adequate dump system.
15. Each approach to critical in a type I critical experiment must be accompanied by suitable inverse flux plots, indicating the expected critical values of uranium and/or moderator loadings.
16. At all times during a critical experiment, at least two people must be present.
17. Each day critical experiments are to be carried out, and before they are begun, satisfactory operation of all necessary detectors, electronics, scram circuits, and rod drives must be assured by the responsible person or persons present. This assurance is to be made by running

down a suitable checklist, which has been approved by the Critical Experiments Safety Committee. The checklist is to be made a part of the record of the experiment.

18. No more than 90 % worth of reactivity in excess of critical will be available to the operator at the console.
19. At all times during a critical experiment, the console must be manned by a responsible person or by a previously authorized operator under the supervision of a responsible person.
20. The assembly must be scrammed upon demand by any person present in the building.
21. A manual scram must be available at the assembly.
22. Before a critical experiment is started a general announcement shall be made in all areas within the security bounds.
23. An individual will become authorized to operate or to be checked out to operate assemblies only on written memorandum to this effect from the Experimental Reactor Physics Group Leader to the Chairman of the Critical Experiments Safety Committee.

FIGURE 1

VIEW OF CRITICAL ASSEMBLY IN PIT

FIGURE 2