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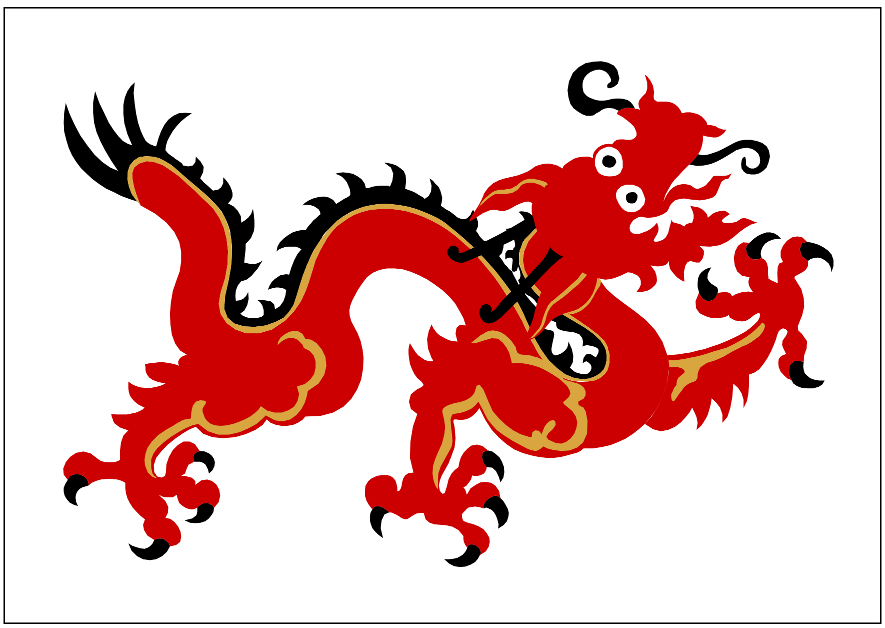
Experiments with the Dragon Machine



Los Alamos
NATIONAL LABORATORY
EST. 1943

The World's Greatest Science Protecting America

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Richard E. Malenfant

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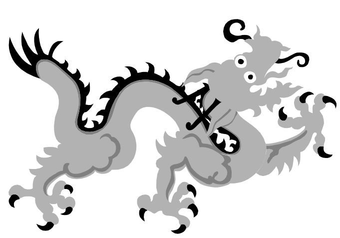
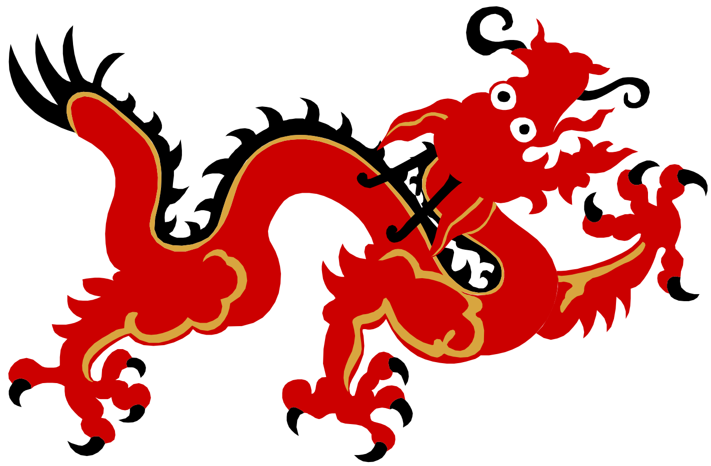
CONTENTS



Experiments with the Dragon Machine

January—July 1945

Richard E. Malenfant[1]



A summary and compilation of the first super-prompt-critical experiments performed in the early days of the Manhattan Project by Otto Frisch, Louis Slotin, Philip Morrison, and others.

ABSTRACT

The basic characteristics of a self-sustaining chain reaction were demonstrated with the Chicago Pile in 1943, but it was not until early 1945 that sufficient enriched material became available to experimentally verify fast-neutron cross-sections and the kinetic characteristics of a nuclear chain reaction sustained with prompt neutrons alone. However, the demands of wartime and the rapid decline in effort following the cessation of hostilities often resulted in the failure to fully document the experiments or in the loss of documentation as personnel returned to civilian pursuits. When documented, the results were often highly classified. Even when eventually declassified, the data were often not approved for public release until years later.[2] Even after declassification and

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[1] Richard E. Malenfant supports Los Alamos National Laboratory Group N-2 and the Criticality Experimental Facility (CEF) Project under a Task Order with Technology Management Consulting Services, Inc.

[2] For example, LA-397, "Controlled Production of an Explosive Nuclear Chain Reaction," by O. R. Frisch was written in September 1945; declassified in January 1957; and finally approved for public release in November 1995. In some instances, approval for public release was not obtained until it was specifically requested to provide documentation of historical experiments.

approval for public release, the records are sometimes difficult to find. Through a fortuitous discovery, a set of handwritten notes by "ORF July 1945" entitled "Dragon - Research with a Pulsed Fission Reactor" was found by William L. Myers in an old storage safe at Pajarito Site of the Los Alamos National Laboratory[3]. Of course, ORF was identified as Otto R. Frisch. The document was attached to a page in a nondescript spiral bound notebook labeled "49[4] Book" that bore the signatures of Louis Slotin and P. Morrison. The notes also reference an "Idea LS" that can only be Louis Slotin. The discovery of the notes led to a search of Laboratory Archives, the negative files of the photo lab, and the Report Library for additional details of the experiments with the Dragon machine that were conducted between January and July 1945. The assembly machine and the experiments were carefully conceived and skillfully executed. The analyses—without the crutch of computers—display real insight into the characteristics of the nuclear chain reaction. The information presented here provides what is believed to be a complete collection of the original documentation of the observations made with the Dragon Machine in early 1945.

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[3] The original notebook was placed in the archives of the Los Alamos National Laboratory.
[4] The shorthand of the time, to identify material, was to use the second digit of the atomic number and the last digit of the atomic mass. As such, ^{239}Pu would be 49, ^{235}U would be 25, ^{238}U would be 28, ^{237}Np would be 37, etc. ^{237}Np as 37 is included because of a reference to measurements on "37" in a 1942 Progress Report.

This report consists of a complete transcription of the handwritten notes by "ORF July 1945." The original terminology, units, and abbreviations are faithfully reproduced.

DRAGON[5]:
RESEARCH WITH A PULSED FISSION REACTOR

ORF July 1945

By dropping or driving a slug of fissile material thru a nearly critical assembly of similar material it is possible to realize for a short fraction of a second, the conditions for a prompt neutron chain reaction and thus obtain very brief and intense burst of neutrons. The intensity obtainable is limited by the heating of the material; up to about 10^{16} neutrons can be produced in one burst. (30 Kg of uranium are heated to 100º C by 10^{16} fissions) The rise and decay of the fission rate during the burst is represented by a gaussian, the width of which is inversely proportional to the 2/3 power of the velocity of the slug.

By falling from a height of, say, 30 ft the slug acquires a velocity of 1.4×10^{3} cm/sec and in a metal assembly of favorable design this should give neutron bursts of about 140 µsec width. To reduce the width to 10 µsec a velocity of 7×10^{4} cm/sec (2000 ft/sec) would be needed which can be reached by a gun. However, the use of artillery would introduce considerable complications and is not at present contemplated. (A width of 40 µsec corresponding to a speed of 10^{4} cm/sec could probably be reached by compressed air. It seems obvious that a source of such powerful neutron bursts could offer new possibilities for neutron research such as:

1 The study of effects which depend on the square of neutron density e.g. n-n scattering or interaction of neutrons with short-lived nuclear species produced by neutron bombardment. The problem of n-n scattering is very difficult but sufficiently important to warrant a considerable effort;

2 Experiments with involve other equipment which can be kept "alive" for short periods only e.g. cloud chambers, very high currents or magnetic fields;

3 Experiments where short-lived after-effects are to be studied e.g., short period β or γ emitters. In this class we might also place measurements of neutron velocities by the time-of-flight method.

4 Any search for weak effects which are likely to be masked by a background effect such as cosmic rays or the natural radioactivity of the

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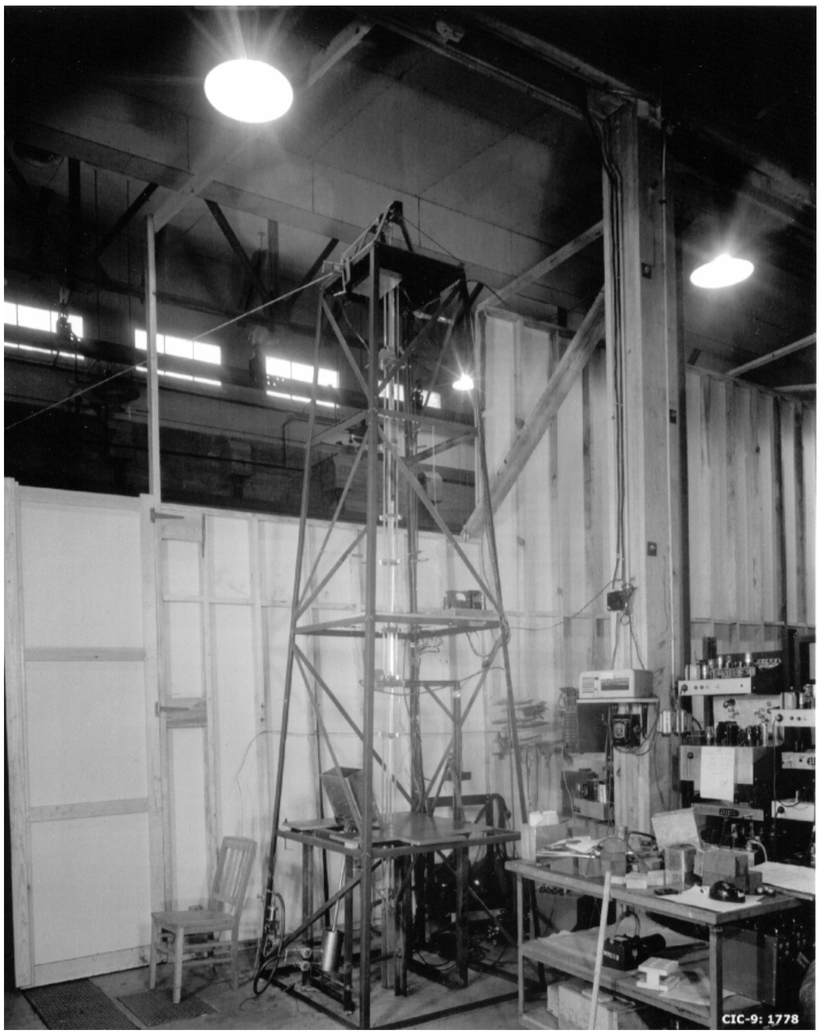
[5] The Dragon machine consisted of a slug of highly enriched uranium hydride that was allowed to slide down a piano wire through a cylindrical annulus of highly enriched uranium hydride. This critical assembly machine gave rise to the phrase "tickling the dragon's tail." Documented operation extended from early January through late July 1945.

target material, e.g. search for mesons or low energy α's emitted in fission or for very low fission cross-sections in strongly α-active isotopes (Ra, MsTh, etc.)

5 Biological and medical studies.

This list is incomplete and other problems will arise for which a PFR[6] is a suitable or even essential tool.



The Dragon Machine

[6] PFR - pulsed fission reactor

REACTOR DESIGN

The design of such a reactor depends on the fissile material available. U^{235} would be very suitable, about 80 Kg of 80% metal being required. To produce as large bursts as possible it might be worth while to try and get U^{235} of low isotopic purity, say 100 Kg of 40% material. However, the bursts would then last about 15 times longer.[7]

If such large amounts are hard to obtain, hydrogen or deuterium might be added, e.g. by using plastic bonded uranium hydride. This greatly reduces the amount of critical amount [*sic*] (by a factor of 3 if UH_{10} is used) but also increases the width of the bursts. With a following slug the shortest bursts obtainable are probably about 1 milli sec long with UH_{10} and the usual plastic bonded UH_{10} is not strong enough for acceleration in a gun.

Idea LS - artificial dragon by shooting Be bullets through an α emitter or Pu on the inside walls of a tube.

Burst of 1 millisec are too long for some important applications e.g. neutron spectroscopy by the time-of-flight method. One advantage of hydride is that an explosion if it should happen is less disastrous than with metal. We believe, however, that the arrangement can be made so safe that an explosion is humanly impossible. Some suggested safety measures are discussed below.

The design further more depends on the experiments planned and should be as flexible as possible. On the other hand, the material becomes very radioactive during the experiments and can then not be handled for some time. It is therefore important to design the reactor in such a way that it is not necessary to handle it in order to change from one experiment to another. Much more thought will have to be given to this before a definite design is attempted but some suggestions are set down here.

The reactor should be placed at some height, say 6 ft. above the floor of large room so that bulky equipment (screening walls, graphite piles, water tank, collimators, etc.) can be brought up, probably by means of a travelling crane or on tracks. Tubes should pass through the fissile material core, some for cooling (by gas or mercury so as not to slow down the neutrons) some for the introduction of samples which might be shot thru by compressed air so as to be available for rapid measurements in a well screened adjacent room.

As a tamper U^{238} would be good as it is a tamper which neutrons don't waste time. A good γ ray shield and a good protection for the core from neutrons reflected by the surroundings. Ordinary U surrounded or alloyed with some boron might be just as good. In the mechanical design provision must be made for the differential expansion of the various parts since the pulsed reaction creates sharp heat gradients between core and tamper and less so within the core.

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[7] The larger mass could absorb additional energy without melting but would increase the neutron lifetime and the peak width.

It is suggested that the core be made of two symmetrical plugs of tamper material which slides into a horizontal hole through the main plug assembly. Each plug is pulled out by a strong spring and pushed against an adjustable stop by compressed air acting on a piston. The adjustable stop controls the multiplication. If the air pressure is released wither by hand or by one of several safety circuits the plugs are pulled back by the springs and the multiplication is reduced well below the danger point.

The slug is dropped about 30 ft sliding in guides which pass through a vertical hole in the reactor and caught in a pneumatic catch box inside a lead shield. The catch box then opens and tips the slug into a carriage which runs on rails and by which the slug is towed away, first horizontally and then up and back to the tower ready for the next trip. There it waits until the delayed neutrons due to the previous drip have decayed to a pre set intensity. At that time it is dropped again. By adjusting the trigger intensity one can conveniently control the desired burst size. If one wants to lengthen or shorten the time between successive drops one has to increase or decrease the multiplication of the reactor. The whole sequence of events should be extremely automatic. Between one and two drops per minute seems a good rate of operation (see appendix).

There seems to be the following possible causes why such a system might blow up: (a) The following slug gets stuck or is appreciably slowed down near the center of the reactor. If the guides have sufficient clearance, are provided with covers to prevent the accidental entry of obstacles, and if test drops (with low multiplication) are made before each series of drops, then it is very hard to imagine how this could happen. (b) The slug goes thru the reactor at reduced velocity due to friction on the way down. This also appears improbable but can furthermore be rendered harmless by a delay circuit which operates the safety valve pulling back the active material if the slug has not passed thru the reactor within a set time after being dropped. (c) The multiplication is too high. It is suggest to provide a simple and purely mechanical device whereby the multiplication cannot be changed by more than a certain small amount between drops. If the material should get too hot a fuze melts and cuts off the power when the operator is satisfied with the adjustment he can lock it and retain the key.

It would probably be advisable to build the whole outfit without fissile material and run it for several months with a dummy slug to see if there were any dangerous kind of wear in the system. Finally, it should be remembered that the reactor never gets more than about 0.1% super critical and that even if the slug did get stuck at the center the explosion would only be equivalent to a few tons of TNT. It would no doubt destroy the labs, but if this were built a mile from other laboratories these would be safe.

NEUTRON SPECTROSCOPY

The study of slow neutrons by the time-of-flight methods is of interest. The resolution obtainable is not much larger than with the best modulated equation in existence. However, by means of special recording equipment (outlined below) it should be possible to collect data more rapidly and thus to make an accurate and comprehensive survey of the resonances of all the elements in a few years. Furthermore, a fission reactor is simpler and more reliable than a cyclotron and it produces no electric disturbances likely to affect the recording equipment.

With a drop height of 30' and favorable design of slugs & reactor it should be possible to produce a burst of about 150 μsec equivalent width if recording channels of 100 μsec are used the resolving time becomes about 200 μsec. The intensity (appendix) is sufficient to permit placing the recording equipment 3000 ft distance. An evacuated tube of that length (1 ft. diam.) is needed to prevent the air from scattering the neutrons. It is suggested that the tube be made of several pieces of increasing length say 200, 400, 800, 1600 ft with a few feet between ends so that the recorder can be placed closer if required.

A neut that flies 3000' = 10^5 cm in 200 μsec has an energy E_m of about 120 kev. The resolution at an energy E in $\Delta E = 2E \sqrt{E/E_m}$. Hence, with E_m = 120 kev it should be possible to measure the accurate shape of resonance lines up to four volts energy. Up to say 20 ev it might be possible to correct for the finite resolution of the instrument. Up to almost 100 ev one could still detect individual lines unless they are densely clustered; close groups may be recognized and then separation estimated from the way the recorded line shape varies with absorber thickness. At even higher energies certain averages and their fluctuations can be measured.

For recording the arrival of neutrons it is proposed to connect the detector (say BF_3 chamber) through an amplifier to a scalar which is automatically to zero at regular intervals - say every 100 μsec. To each stage of the scalar a gas discharge lamp is connected in such a way that a light flash is produced if at the time of resetting the scalar is not in its zero position, the bank of lamps is photographed on a moving film.

In this way the numbers of neutrons recorded in subsequent time intervals of 100 μsec are each printed on the film as rows of black dots with blank intervals, each dot corresponding to a binary digit of one while a blank indicates a digit zero.

The number of neutrons recorded during one drop is limited by the resolving power of the scalar rather than by the intensity available. The best scalar known to me resolve pulses separated by about 0.3 μsec, hence the counting rate should not exceed 3×10^5/sec (10% correction or 30 pulses per 100 μsec interval (because of the dE/E law for slow neutrons, the counting rate with a 1/v detector is substantially the same for all time intervals). In order to collect enough material for reasonable statistical accuracy, say 1000 pulses in each interval one has to combined the results of some 30 drops.

Since drops are to take place once every minute or less, and since each drop produces a film containing several hundred binary numbers, the processing of these films would be a bottleneck unless it were done by fast working machinery. It is proposed to build an electronic adding machine which reads by photo cells the numbers printed on two films passed through the machine & records their sum or a third film by repeating the process all the information is eventually compressed onto one film. After this compression the work could probably be continued by hand although it may be worth while to have some special equipment to convert the rows of dots into ordinary decimal numbers.

The handwritten notes referenced an appendix that is transcribed here.

APPENDIX

Some remarks on the theory of a pulsed fission reactor.

If neutron pulses are produced repeatedly under identical conditions their sizes will nevertheless vary because of the statistical nature of the pulse initiation. If τ_0 is the generation time and S the source strength, i.e., the time rate of fissions which are not caused by prompt neutrons, the relative mean square deviation of pulse size is:

$$(\overline{P^2} - \overline{P}^2)/\overline{P}^2 = \frac{1}{S\tau_0} \cdot \frac{\overline{\nu(\nu-1)}}{2\overline{\nu}}$$

Where the second term probably lies between 0.8 and 1.25. In order to get fairly uniform pulses, say mostly within $\pm$10% of the average size, $S\tau_0$ should be at least 100. With a metal reactor $\tau_0 \cong 10^{-8}$ sec, hence S should be 10^{10}/sec or more.

The simplest way to provide such a powerful neutron source is to produce pulses at sufficiently short intervals so that the delayed neutrons from each pulse serve as a neutron source for the next one. If the interval between pulses, the cycle, is C, then the delayed neutron intensity just before a pulse is:

$$N \cdot D(C) = Nf \sum a_i (e^{-\lambda_i C} + e^{-2\lambda_i C} + e^{-3\lambda_i C} + \ldots) = Nf \sum_i \frac{a_i}{e^{\lambda_i C} - 1}$$

Where N is the number of neutrons produced per pulse, *f* the fraction of delayed ones and a_i the intensity - immediately after a single pulse - of delayed neutrons with the period $1/\lambda_i$.

Table 1 shows D(C) for some typical values of C.

Table 1

C secs	16	20	24	30	40	60	80	100	120	180
D(C)	186	130	97	67	40	18	5.5	5.5	3.3	$.9 \times 10^{-6}$

The intensity of a burst can be written as:

$$N = e^M \cdot 2\pi S \Big/ \left(\frac{dK}{dt}\right)_i$$

For a reasonable arrangement and a drop velocity of 1400 cm/sec $\left(\frac{dK}{dt}\right)$ is about 5 sec^{-1}, hence N=*ln* (1/D (C)). If we want to get pulses with $N=10^{15}$ with a source of 10^{10} or more, then e^M must be 10^5 or less, or D(C) must be 10^{-5} or more. A glance at Table 1 shows that the cycle C must not be longer than 80 sec. For the reproducible production of pulses of 10^{14} neutrons, the cycle should be 24 sec or shorter.

There may be some difficulty in starting the machine when no delayed neutrons are yet present. A driving source of say 1 gm. RaBe has only a small chance of initiating a full size burst. However, I believe that by repeating drops one can gradually "kindle" the reaction despite the fluctuations. I shall try to make calculations on that point.

An estimate of the width of the pulses can be made as follows. The multiplication constant K depends on the slug position in a way indicated in fig. 1 and the middle section can be approximated by the parabola

$K=K_m-(X/L)^2$. L lies probably between the radius and the diameter of the assembly, let us assume L-10 cm. For calculating the pulse, the time $t=x/v$ is a more useful variable and we write $K=K_m-(tv/L)^2$. The intercepts $t_1=-t_2$ of this curve with K=1 are given by $\varepsilon=(t_1 v/L)^2$ where $\varepsilon \equiv K_m-1$. The area A between the curve and the line K=1 is $A=\frac{4}{3}t_1\varepsilon=\frac{4}{3}\varepsilon^{3/2}(L/v)$. L depends almost only on the design of the system, while v and ε can be adjusted at will. Now M should be equal to $ln10^5$ or about 11.5 as we have seen before, and $M=A/\tau_0$. Hence for a given L and v, ε must be adjusted so that $\frac{4}{3}\varepsilon^{3/2}(L/v\tau_0)=11.5$ or $\varepsilon=4.2(v\tau_0/L)^{2/3}$. For v - 1500 cm/sec, $\tau_0=2.7\text{x}10^{-8}$ sec, L=10 cm, and we get $\varepsilon=1.05\times10^{-3}$; $2t_1$, the time during which the system is supercritical is $2\varepsilon^{1/2}(l/v)=\frac{.64cm}{1500cm/\sec}$ = 430 μsec.

The equivalent width of the neutron pulse (i.e., the width of a pulse with the same peak and the same integrated intensity) is $W=\sqrt{2\pi\tau/(dK/dt)}$.

Now:

$$\left(\frac{dK}{dt}\right)_{t_1}=2t_1\left(v/L\right)^2=2\varepsilon^{1/2}\left(v/L\right),$$

and if we put $\varepsilon=4.2(\nu\tau_0/L)^{2/3}$ to get M right (see above), then the width becomes $W=1.24\tau_0^{1/3}(L/\nu)^{2/3}$. Using the same values for L, ν, and τ_0 as before, we find W=133μsec.

If the reactor is to be used for neutron spectroscopy, it is important to estimate the maximum distance *b* at which the detector can be placed and still receive enough intensity. If the detector has the target area a, of the N neutrons emitted per pulse, $Na/4\pi b^2$ will be recorded. We assume that a moderator (e.g. a paraffin block) is used which spreads all the neutrons uniformly over the energy region from 1 MeV to 1 eV. This is optimistic since some neutrons will escape with their original energy, some will become thermal and some will be absorbed; on the other hand we shall ignore the possible gain in intensity which may be obtained by shaping the moderator like a howitzer so that more neutrons are concentrated into the beam.

Since ln (1MeV/1eV)=$ln 10^6$=6×2.3=14, we can say that

$$N\left(\frac{a}{14 * 4\pi b^2}\right)\left(\frac{dE}{E}\right) or \cdot about \left(\frac{Na}{200b^2}\right)\frac{dE}{E}$$

neutrons in the energy interval between E and E+dE hit the detector. Since E is proportional to $1/t^2$ (t=time of flight), we can replace dE/E by 2dt/t. Next we assume that our detector is a 1/v detector, e.g. a boron chamber, containing n boron nuclei with the cross-section σ_0 at the velocity v_0. The total target area $a=n\sigma=n\sigma_0(v_0/v)=n\sigma_0 v_0 t/b$. Hence the number of neutrons recorded per time interval dt is

$$q = \frac{N}{200b^2}\cdot\left(n\sigma_0 v_0\, t/b\right)\cdot\frac{2dt}{t} = Nn\sigma_0 v_0 \cdot {}^{dt}\!\!\diagup_{100b^3}$$

Assuming pulses of 10^{15} neutrons, $n=4\times10^{22}$ (about 1500 cc of BF_3 at atmospheric pressure), $\sigma_0 v_0=7\times10^{-16}$ (for B^{10}), $dt=10^{-4}$ sec, we get $q=10^{15}\times4\times10^{22}\times7\times10^{-16}\times 10^{-4}/100b^3=3.10^{16}/b^3$. If we want 30 counts per time interval, we make $b=10^5$ cm = 3000 ft.

Professor Otto R. Frisch, Cavendish Laboratory, University of Cambridge, Cambridge, England, gave the Keynote Address at the FAST BURST REACTORS Conference held at the University of New Mexico, Albuquerque, January 28-30, 1969. The proceedings of that conference were edited and published by Robert L. Long and Paul D. O'Brien as U.S. Atomic Energy Commission Symposium Series. The complete keynote address is presented here.

THE DRAGON EXPERIMENT:
KEYNOTE ADDRESS

Professor Otto R. Frisch
Cavendish Laboratory, University of Cambridge, Cambridge, England

Just about 8 months ago my wife brought me a letter. I had overslept and was still rather sleepy, and I stared at the letter from the American Nuclear Society, National Topical Meeting, Fast Burst Reactors. And I said, "Do the Americans run a topical meeting on a nationwide scale because their reactors burst so fast?" After that I realized that I was being honored as the father, or I feel more like the grandfather, of pulsed reactors, having arranged the experiment which for the first time established a short-lasting harmless fast-fission reaction that did not depend on delayed neutrons.

A group of no less that 17 people worked on this first controlled fission experiment known as the Dragon experiment, and I want to tell you how it came about.

The purpose of Los Alamos was to assemble part of the scientists who were needed to develop an atomic bomb. In particular, we measured the cross sections, time constants, and so on, which would make it possible to design a bomb with a reasonable degree of efficiency and safety. One of the most difficult things was to determine that the fast reaction would really work as fast as the theory predicted. Nuclear theory, of course, said that once a neutron hits a uranium nucleus, fission follows almost instantaneously, if it follows at all. But electronic methods at that time were not really fast enough to decide whether it happens with the sort of subnanosecond speed which was theoretically foreseen and needed if the bomb was to be an effective explosive.

So a number of ingenious experiments were devised to test the speed of the fission reaction, and the limit was pushed fairly well toward the point where we wanted it. But even so, I for one thought it would be very nice to go one step nearer to a real atomic explosion. It is a bit like the curiosity of the explorer who has climbed a volcano and wants to take one step nearer to look down into the crater but not fall in! That chance came when we learned that around the beginning of 1945 some amounts of separated ^{235}U were to arrive. These shipments were meant mainly for us to carry out critical experiments to check the calculations of the theoreticians. The theoreticians, of course, had taken all the cross-section measurements—fission cross sections, elastic, inelastic, everything that we could produce for them—and from these, by complicated integrations, had worked out the critical size. However, experimental confirmation was desirable.

It was clear that we would not be able to test with a critical assembly of metallic ^{235}U or metallic plutonium because once such a quantity had been produced the military would want to use it immediately. Instead, the first amount of ^{235}U that came out of the mass separators was made into hydride, UH^3, and combined with a plastic binder into bricks of the approximate composition UH^{10} . You may ask why use that material; it would never make a useful bomb. That is quite true; but it enabled us to carry out critical measurements and compare them with calculations the theoreticians had performed for the same material. This comparison gave the theoreticians at least an idea about how reliable their calculations were and by how much and in which direction they might have to be corrected.

A large number of critical measurements were made, indeed, and the theoreticians were very pleased to have this corroboration of their calculations. In addition, I felt that here was a chance of looking a bit closer at the occurrence of a fast reaction, a reaction not limited by thermal neutrons, and I made the proposal that we should make an assembly with a hole in the middle, and that the missing portion should then be allowed to drop through the assembly under such conditions that for a few milliseconds the whole assembly would be critical with respect to prompt neutrons. I did a few simple calculations to be sure that this would be feasible, then sent this proposal to the coordinating council. Of course, I was not present when the proposal was discussed, but it was accepted; it was said that Enrico Fermi nodded his head in a pleased manner and said this was a nice experiment that we ought to try, and I was told that Dick Feynman, who was present, started to chuckle and to say that this is just like tickling the tail of a sleeping dragon. That is how the experiment was named.

When the ^{235}U arrived, we built the equipment for the experiment, and Fig. 1 roughly shows what this equipment looked like. It looks, crudely speaking, like an oil derrick, but it was only something like 6 m high. Near the bottom the uranium assembly was set upon a steel table. The material was available in the form of little bricks; I believe they were 1 in. by ½ in. by ½ in and very accurately made. (it was a joy to build little skyscrapers out of uranium hydride and other materials like that!) A slightly askew box that contained part of the assembly was mounted on a hydraulic pusher rod so it could be released and lowered—deliberately, rather slowly. The guides for the falling slug can also be seen.

Figure 1

Everybody, of course, asked me what if the slug gets stuck—you all blown up. We could not all be blown up. The material became only very slightly supercritical. It would have been a bomb of extremely low efficiency, and probably we would have been wise to clear out fast if the slug had stuck.

The top of the derrick contained a fairly elaborate device for holding the slug until everything was ready for the drop because we were aware that a danger much greater than the slug's getting stuck was the danger of the slug's falling before the supercriticality had been correctly adjusted. We made quite sure that the slug could only be dropped after the operator had checked a certain number of things and was convinced that they were okay. In the end, of course, a great responsibility did fall on the operator.

The steel table (about a centimeter thick) was placed so that material could rest firmly against the fuel box, which in actual use would be pushed up until it would be leaning against the guides or almost touching them. The gadgets attached to the guides measured the speed of the slug. You may say there is no reason to measure the speed if by some chance extra friction stops or slows the slug. The purpose of the measuring, however was to do a few dummy drops before beginning the day's work to make sure the slug was dropping according to Galileo's law. In fact it never did. It was always about 1% slower owing to friction. It did not fall freely in the guide; in fact, we deliberately leaned the whole tower a little to one side so that the slug was sliding down the guides rather than falling through them. This development was important because a very small sideways movement changed the multiplication constant and made a very big difference in the size of burst produced.

Much of the top of the assembly was crude and primitive. Parts were held together by ordinary mechanics clamps and there was a rope going up over several pulleys and holding an electromagnet that hauled up the slug. The electromagnet could not be switched off until after everything else was straightened out. I will not bore you with the safety precautions; they are completely out of date. What I really wanted to impress upon you is the rather primitive setup. This entire reactor was built in a matter of a few weeks, and all the experiments were performed during, I believe, three short periods in three weeks, each lasting only a few days. The reason we worked so fast was that the chemists were waiting for us to return the material so that together with further ^{235}U it could be turned into metal and this material into bombs as soon as possible.

With the very first material that arrived, we made a number of drops to make sure the device worked, and the first pulses were obtained just at this time of year 24 years ago. Then we replaced the material with a somewhat bigger assembly and performed a number of drops to test the theory, and they all came out as we expected. The pulses were of the duration that we had approximately predicted from nuclear data. Figure 2 shows the outcome obtained by having a boron chamber close to the arrangement, which was connected to a cathode-ray oscilloscope, and simply integrated the amount of charge deposited. The figure reads from left to right in units of 6 msec, the rate at which the oscilloscope was pulsed. The charge suddenly begins to increase, increase more rapidly, and then straighten out once again; this is the integrated pulse. This result could be compared with the theory, and the agreement was very good.

Well, so much for the Dragon. It was dismantled a few weeks after it had been built, and the whole group dispersed. And there, as far as I am concerned, the matter rests. I have never tried to build another one although I now hear to my great pleasure our Russian colleagues have realized.

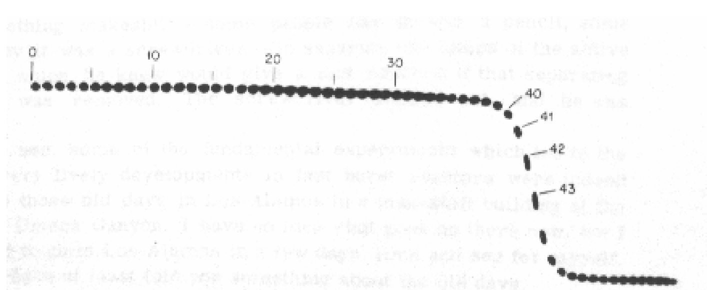

Figure 2. Integrated pulse reading.

We did perform a few Dragon-type experiments of the more modern variety unintentionally and with tragic results. Two men who worked on the Dragon experiment were killed within a few months after this experiment. Harry Daghlian, working by himself one night, which was breaking the rules, did not know how slippery the large blocks of tungsten carbide reflecting material were. While trying to put on one more block, he realized that the reaction was going up much too fast; he tried to pull the block away, but it slipped out of his hands. What then happened can only be reconstructed by theory; no one else was present. He saw a blue flash, and about 10 days later he died in the hospital from radiation damage. He had received well over a fatal dose. Probably what happened is that the material expanded thermally and thereby switched itself off, but the amount of radiation it had given off in that short time was enough.

Later I left Los Alamos and Louis Slotin took over the group working on critical assemblies. He told me that Fermi warned him, “You know that in this sort of work you have perhaps an even chance to survive your work here.” Slotin was rather shaken about it. Even so, he did use something makeshift—some people say it was a pencil, some people say it was a screwdriver—to separate two lumps of the active material which he knew would give a fast reaction if that separating material was removed. The screwdriver slipped out, and he was killed.

So you see, some of the fundamental experiments which led to the present very lively developments in fast burst reactors were indeed started in those old days in Los Alamos in a makeshift building at the bottom of Omega Canyon. I have no idea what goes on there now, but I am hoping to go to Los Alamos in a few days’ time and see for myself. Anyhow, I have at least told you something about the old days.

CONTROLLED PRODUCTION OF AN EXPLOSIVE NUCLEAR CHAIN REACTION

(LA-397)

September 27, 1945

Richard E. Malenfant

Based on work done by
Otto Frisch

ABSTRACT

A chain reactor (the “Dragon”) was constructed so that by dropping a slug through an assembly (both of active material), a divergent chain reaction supported by prompt neutrons alone was achieved for about 1/100 second. In this short time, neutron multiplications up to 10^{12} were obtained. Various measurements were made which permitted the calculation of the generation time in two independent ways: from the shape and from the size of the neutron burst, which occurred when the system became prompt-neutron supercritical. These calculations agreed reasonably well with each other and also with the time obtained from a Rossi time-scale experiment. The neutron bursts produced by the reactor were later used in other experiments: on delayed neutrons and gamma-rays, on the effect of intense radiation on coaxial cables, and on living animals.

The complete report prepared by Otto Frisch is reproduced here.
The report has not been edited.

CONTROLLED PRODUCTION OF AN EXPLOSIVE NUCLEAR CHAIN REACTION

INTRODUCTION

The neutrons emitted in fission are of two kinds: "prompt", i.e. emitted by the fission fragments presumably within less than 10^{-12} seconds, and "delayed", i.e. emitted after times of the order of seconds.

Chain reactors constructed so far (graphite piles, water boilers) always depend partly on the delayed neutrons; this makes them easy to control since even in a slightly supercritical state the neutron population grows at a moderate speed, doubling in a time of minutes or perhaps seconds. If the multiplication were to be increased so much that the prompt neutrons alone can support a divergent chain, the neutron population would grow very rapidly, doubling in a small fraction of a second. Such a "prompt" chain reaction has therefore an explosive character and therein lies its military value.

In the experiments described here a chain reactor was arranged so that for a short time of about 1/100 second the conditions for a prompt chain reaction could be realized. This was done by dropping a slug of active material through a vertical hole in an active assembly.[8] By adjusting the conditions properly, very large neutron bursts could be obtained, indicating a multiplication of the original neutron population by up to twelve powers of ten within this short time. In one particular burst a temperature rise of the active material by 6°C was recorded, corresponding to the liberation of 12000 calories, and over 10^{15} neutrons. Since most of this energy is liberated within about 3 milliseconds, the heating rate was about 2000°C per sec., corresponding to a peak power of 20,000 KW.

Measurements were made of the way in which the fission rate varied with time during the burst, of the slug position at the maximum of the burst, and of the dependence of the burst intensity on the adjustment of the multiplication. In conjunction with static calibrations, carried out with the slug in a fixed position, these measurements are in good agreement with what was expected. It is for instance possible to calculate from them the generation time, i.e. the mean time τ_o between a fission and its daughter fission in two

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[8] Because of the similarity of this procedure with that of tickling the tail of a dragon (pointed out by R. Feynman) the experiment has been sometimes called "the dragon experiment."

independent ways, and the results agree well with each other and with a third determination of τ_o by a Rossi time-scale experiment.[9]

The intensity varied considerably from one burst to another, even if the conditions were not changed; these fluctuations are to be expected because each burst is the result of an enormous multiplication of very few primary neutrons. A crude measurement of the size of these fluctuations again showed agreement with theory.

Some additional experiments were carried out in which the neutron bursts were used as a tool to study the delayed neutrons (see LA-252) and gamma rays, and also to investigate the effect of intense radiation on coaxial cable and on rates. An unsuccessful attempt was made to thermalize the neutrons and to use them in conjunction with a cloud chamber.

MECHANICAL STRUCTURE AND SAFETY DEVICES

The falling slug of active material was contained in a steel box, 14" long and with a 2-1/8" × 2-1/8" cross section. Its path was defined by 4 Dural guides, with a slack of about 1/8" so that even a considerable warping of the guides would not interfere with its drop. The guides were kept at the correct relative position by brass clamps every 2 feet or so, and held straight and vertical by guy wires attached to a steel derrick, about 12 feet high. They passed through a hole in a heavy (3/8") steel table on which the active material and tamper could be assembled around them, and led at the bottom into a catcher box into which the slug fitted with a few mils clearance; this close-fitting catcher box served as a pneumatic brake.

Part of the reacting assembly was contained in a pivoted steel box which could be raised into position by compressed air acting on a piston. This "safety box" could be raised and lowered by throwing a switch operating an electromagnetic air valve; during static calibrations this valve was connected to a neutron monitor[10] so that it would drop automatically whenever the neutron level increased over a preset value. When the safety box was down, the reactivity of the system was decreased so that even with the slug at the center no reaction would occur.

To control the multiplication, a flat brass box ("control vane") filled with a suitable absorber could be inserted between the safety box and the rest of the system, its position being adjustable by a screw drive.

Fig. 1 shows a view of the whole setup, without active material.

Before each drop the slug was picked up by an electromagnet hanging on a rope and hoisted to a suitable point near the top of the guides. To do this safely one had to lower the "safety box" first, and, lest one should forget it, the magnet was wired in series with a microswitch which was closed only when the safety box was down. On arrival the slug

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[9] Report forthcoming.
[10] R. J. Watts, LAMS-161

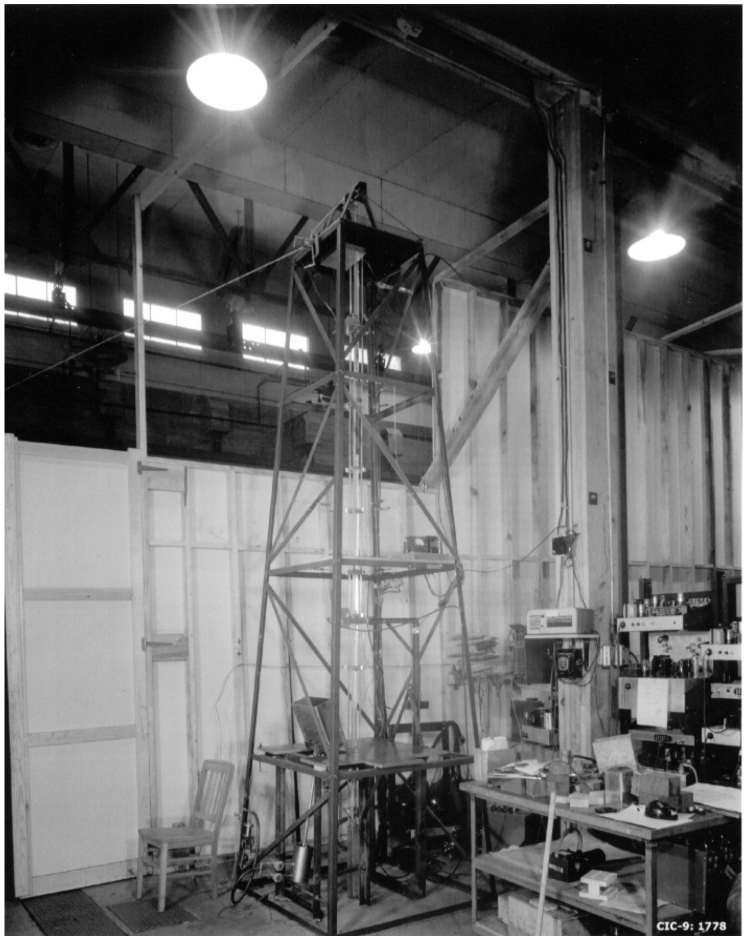

Fig. 1

was secured by pushing a "latch" through the guides below it (this was done by a pair of Selsyn motors). The purpose of the latch was to prevent the slug from being dropped unintentionally, e.g. because of a power failure. By pushing in the latch another microswitch was closed which provided an alternative path for the magnet current so that now the safety box could be lifted without dropping the slug on the latch. When the operator was sure that everything was ready for a drop (controls properly adjusted, no people near the system, etc.) he pressed the HWG ("Here We Go") button, establishing a third path for the magnet current and enabling him to remove the latch and subsequently, by releasing the HWG button, to drop the slug.

This whole somewhat complicated arrangement was designed to relieve the operator from any responsibility until he pressed the HWG button. If, for instance, he tried to raise the safety box before the slug was up on top and secured by the latch, the magnet would at once release the slug, which would fall into the catch box well within the time required for the compressed air to raise the safety box (about 10 sec). Again, if he tries to pull our the latch without pressing the HWG button, the slug falls on the latch which then can no longer be moved. (The latch was moved through a slow gear so that one could not pull it out in less than about 5 sec). Colored lights were arranged to keep the operator informed about the position of the safety box, latch, and magnet.

The velocity of the slug was checked in each single drop (see below under "timing system") and found to be constant well within 1%. At the beginning of each series of drops several dummy drops (with the safety box down) were made in order to make sure that the slug was falling freely and with the correct velocity.

All the operating and recording equipment was placed in a room about 40 ft away from the assembly and behind a 5-ft wall of concrete and earth. If (to assume the worst) the slug had got stuck at the center of the assembly, there would have been a rather inefficient explosion, probably equivalent to a few ounces of H.E. In this instance the control room would have afforded sufficient protection against the radiation, although it would have been advisable to leave it quickly before the active fumes had time to spread.

ACTIVE ASSEMBLIES

Three different active assemblies were used; we shall call them assemblies 1, 2, 3 in what follows.

Assembly 1 consisted of about 10 kg of UH_{10} surrounded by about 6" of BeO. The UH_{10} was made by the CM division by pressing UH_3 with Styrex into cubes, some of ½", some of 1" side. The symbol U stands for the beta-stage material of 71 to 75% 25 content. The UH_{10} also contains about 4 atoms of carbon for each atom of U.

The reactivity was controlled by means of the control vane which contained 5/16" of pyrex sheet. The safety box was filled with BeO. The UH_{10} did not extend beyond the control vane, but was built up in roughly spherical shape with its center outside the guides for the slug. It was found that moving the slug sideways inside the guides changed the multiplication constant K by about 0.1%, a change which would alter the size of burst by a large factor. We therefore tilted the whole arrangement by about 1.5^{o} and straightened the guides carefully in order to make sure that the slug would always slide down on one side of the guides. Tests with electric contacts showed that it always followed the same path to within 0.005" and the corresponding uncertainty of about 0.01% in K was considered tolerable.

This assembly gave the first evidence that a prompt-neutron reaction could be produced, and served to get some qualitative information. The control vane was pushed in far enough so that no prompt reaction could occur (see later under "static calibration"). The slug was then repeatedly and the control vane was pulled out in small steps. The first bursts were obtained in the small hours of January 20. Some more active material was added and the pyrex in the control vane was replaced by a mixture of B_4C and paraffin wax, to give a stronger control. The following night bursts were increased until a temperature rise of 0.01^{o} C was observed due to the strongest burst. After that the whole assembly was dismantled and the UH_{10} was used for various critical- mass determinations.

Assembly 2

On January 28, the UH_{10}, together with amounts which had arrived in the meantime, was reassembled, making about 15.4 kg in all. In order to make the best use of the material, the control vane was removed and control was effected by moving a tray containing a part of the core and tamper. The tray was moved by a screw and its position was read by a micrometer to the nearest mil; this arrangement was meant to eliminate slack but didn't completely. We tried to use tungsten carbide as a tamper in order to avoid the large contribution of thermal neutrons which results form the use of a BeO tamper. However, the system would not go critical because of the gaps due to the guides, tray walls, etc., and we had to come back to BeO. But we found it possible to cut the contributions of thermal neutrons by placing a layer of cadmium between the UH_{10} and the tamper, without reducing the multiplication too much.

Most of our information was obtained with this assembly. It was used until February 1 when we had to return about two thirds of our UH_{10} to the CM Division for conversion into metal.

Assembly 3

The remaining 5.4 kg of UH_{10} were "diluted" with polyethylene ("Polythene") bricks in the volume ratio 1 UH_{10} to 5 Polythene. As a tamper we used 3" of graphite backed by 1" Polythene. (This was about as effective as 6" of graphite, and better than any thickness of Polythene alone). The safety box contained 5" Polythene. The slug contained 6-1" cubes of UH_{10} in an unbroken row, surrounded by ½" Polythene and backed above and below by about 4" Polythene. The rest of the assembly was approximately a cube of 8" sides, the center of the guides being 1-1/4" off the center of the cube. The multiplication was varied by removing pieces of the outer 1" Polythene layer.

Because of the presence of large amounts of hydrogen and carbon, with no Cd present, the τ_o of this assembly was expected to be quite large (we found it about 20 μsec). Although this makes the experiment less "interesting" it has the advantage that the fluctuations are much smaller and that bursts can be made to order. This assembly was used to measure delayed neutrons and gamma rays and to make a rough test of the size of fluctuations. In the course of these experiments the size of bursts was gradually increased until in one burst the cubes became so hot that swelling and blistering occurred. The whole system expanded by about 1/8" and its multiplication became reduced so much that no more bursts could be obtained from it.

TIMING SHOTS

Two narrow light beams were arranged to cross the path of the falling slug, 92.3 cm apart, one above and one below the active assembly, and then to fall on two photocells of the multiplier type. The slug carried a small knife edge on top so that the instant when the light beam is re-established after interruption is sharply defined. The photocells operate a gate circuit, opening it when the knife edge passes the first light beam and closing it when the knife edge passes the second beam. The gate allows the signal from a 100-Kc crystal oscillator to pass into a large scaling system (three standard scales of 64 in series). Thus the scaler counts at a rate of 100,000 counts/second during the time it takes the knife edge on the falling slug to cover the distance between the light beams, and by reading the interpolator lights one obtains this time in units of 10 micro-seconds. The light beams were nearly a millimeter wide and hence the opening and shutting times are determined not better than to about 100 microseconds. The electronic equipment was built by W. C. Elmore of G-4.

STATIC CALIBRATION

It is obviously impossible to carry out static measurements in those configurations of the system in which a prompt-neutron chain can develop because the assembly would blow up in a small fraction of a second. We therefore had to be satisfied with measurements in a state of reduced reactivity, extrapolating to the region in which we are really interested. These extrapolations were based on the hypothesis that the different means by which we can change the reactivity have additive effects. This hypothesis was checked in a rough way in the region accessible to static measurements and found to be tolerably correct.

To obtain K for any particular position of slug and control, the exponential growth rate of the reaction was measured with an outside BF_3 chamber and DC amplifier. No great precision was aimed at. Doubling times down to about 2 sec were used; shorter times were too hard to measure, and also increasingly dangerous.

To convert doubling times into K values, the inhour formula for the water boiler[11] was used. This would be correct only if the contribution of delayed neutrons in our assembly was the same fraction of the prompt neutron effect as in the water boiler, namely 0.008. This assumption is probably not far from correct but we shall point out in the discussion how it affects the results.

Fig. 2 indicates the dependence of K on the position of the slug and of the control vane filled with B_4C and paraffin in assembly 1. The curves corresponding to different slug positions can be made to coincide approximately with the dotted extrapolated curve, by moving them up by a suitable amount, which means that our additivity hypothesis is approximately correct.

[11] LA-394

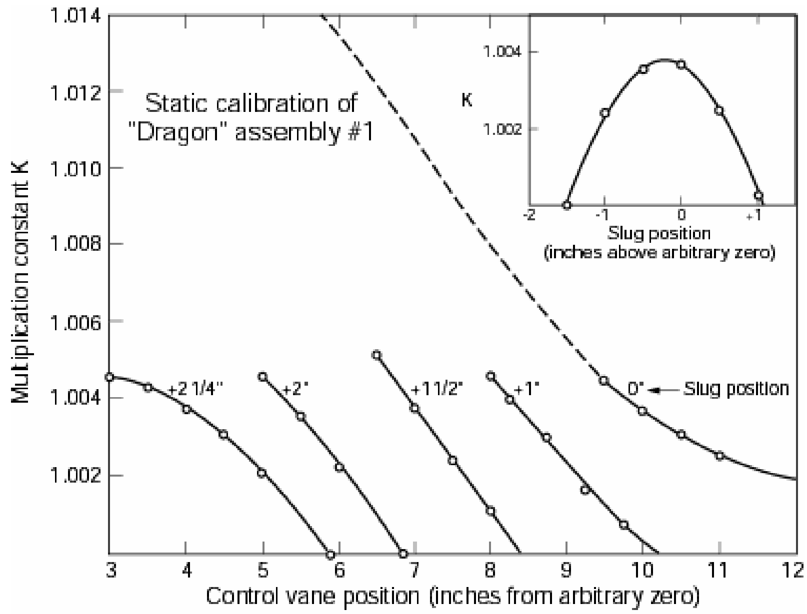

Fig. 2

Fig. 3 shows the calibration of assembly 2. The change of K with the control tray position is fairly linear and is believed to continue linearly into the prompt critical region. The effect of slug position was measured over a small range only, unfortunately, and the curve shown indicates what we believe is the best extrapolation.

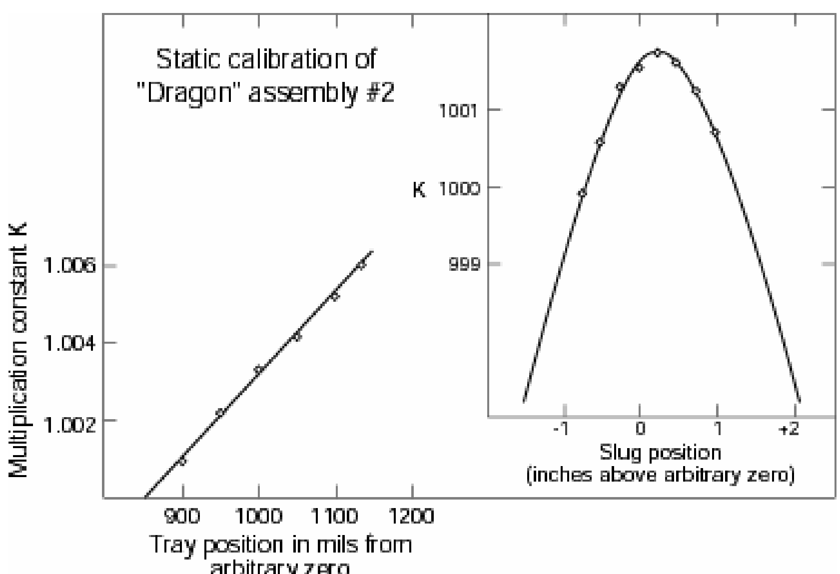

Fig. 3

Fig. 4 shows the effect of slug position on K in assembly 3.

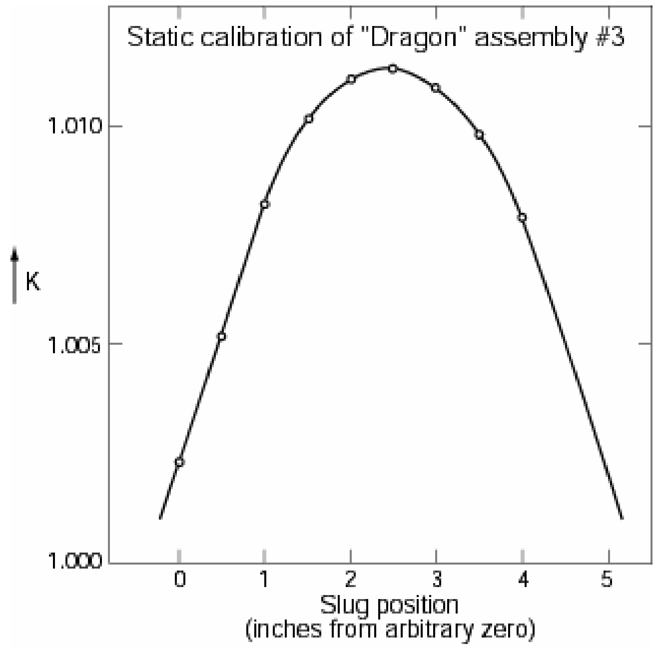

Fig. 4

RECORDING OF BURSTS

1) A boron-lined ion chamber (converted RaLa chamber filled with pure argon[12]) was placed close to the active assembly, so that the average time of flight of thermal neutrons from the assembly to the chamber was only about 0.1 millisecond. While the electrons produced in such a chamber are swept to the wire in about 1 to 2 microseconds, the positive ions will take several milliseconds to move to the outer electrode and will therefore be almost stationary during the burst. With strong bursts these ions would form a very substantial space charge and may slow down the collection of the electrons and distort the pulse shape. We therefore prepared, in addition, a chamber which contained only a small amount of boron, painted on the inside wall in the shape of a thin spiral line. Most records were obtained with the latter chamber. We found no evidence for distortion due to space charge. The collecting electrode (central wire) of the chamber was directly connected to the grid of a cathode follower tube, using a high grid leak ($10^{10}\ \Omega$). The cathode follower fed the pulse through a concentric cable to the input amplifier of a DuMond oscilloscope. The sweep of the scope was triggered from a suitable stage of the timing scaler (see section on timing system) and signals from another stage were fed to the intensifier so that the sweep took the form of a dotted line, the dots serving as time marks. Fig. 5 shows a typical record.

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[12] Mr. Nicodemus kindly filled the chambers for us.

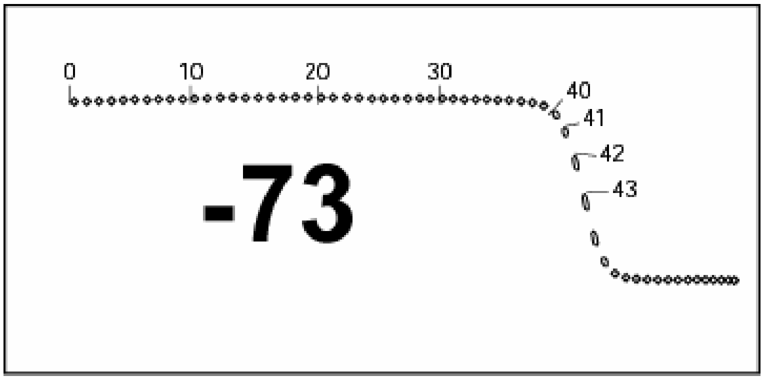

Fig. 5

2) Copper rings (about 1" high and 1" OD) were placed on the assembly in a standard position and after the drop the activity of the ring was measured on a G-M counter. This gave the integrated intensity of the neutron burst and by waiting or by using an absorber one could cover the very large range of actual burst sizes.

3) For absolute calibration of the bursts, a platinum resistance thermometer was stacked into the UH_{10} and connected to a potentiometer circuit and galvanometer. It was possible to observe a rise of 0.001°C of the UH_{10} due to a drop. The suddenness of the actual temperature rise did not show up since it took about a minute for the resistance element to follow a sudden change in temperature of the UH_{10}. Many of the pulses were too weak to be measured in this way. In assembly 3 no temperature measurements were made because it was felt that they would be too difficult to interpret, in view of the inhomogeneous structure of the system.

4) To record the delayed neutrons emitted after the burst, a flat fission chamber containing a thin layer of 25 and filled with argon was used. In the assemblies 1 and 2 the chamber was stacked in with the UH_{10} close to its surface; in assembly 3 it was placed on top of the graphite tamper and covered by 1" of Polythene. The chamber was connected to a fast amplifier, scalar, and photographic recorder. The whole arrangement and the results obtained with it are described in detail in LA-252.

In addition to the photographic recorder, an ordinary mechanical counter (Chicago type) was connected to the scalar and in some runs an Esterline-Angus recording milliammeter was connected in parallel with the counter. A recording obtained in this way is shown in Fig. 6 and while at low counting rates the individual counts (each corresponding to the 2048 particles) can be distinguished, at high counting rates the average current becomes large enough to shift the mean position of the pen. It would not be difficult to calibrate this shift in terms of counting rate and this arrangement is then a simple means of recording intensities varying over about 3 powers of 10.

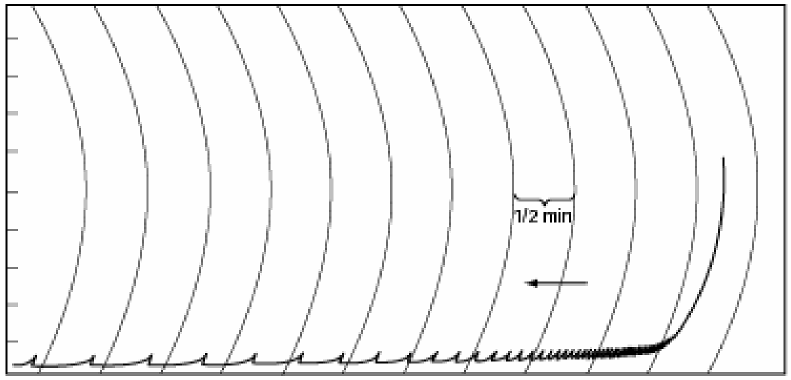

Fig. 6

THEORY

In order to calculate the expected neutron burst from the dragon we make S source fissions per second occur in the system, i.e. fissions that are not produced by prompt neutrons. S includes spontaneous fissions, and those produced by delayed neutrons and by neutrons from an external source (e.g. Po-Be).

1) Only prompt neutrons are assumed to contribute to the multiplication process; this is justified since the whole process takes only a few milliseconds.
2) The average time between a fission and its daughter fission is τ_o.
3) The prompt multiplication constant K_p varies in a smooth fashion with time. At the instant t_1 when it first exceeds unity its time derivative is $1/T_1$ and at t_2 when it goes below unity again, $1/T_2$. We write α for $(K_p-1)/\tau_o$.

Consider the Sdt_o source fissions which occur between t_o and t_o+d t_o. At a later time t the number of their offspring which occur between t and t+dt will be

$$(S/\tau_o)dt_o(\exp\int_{t_o}^{t}\alpha dt\, dt)\ dt.$$

The total number of fissions occurring between t and t+dt is found by integrating over t_o

$$F(t)dt=dt(S/\tau_o)\int_{-\infty}^{t}dt_o\exp(\int\alpha_o dt) = dt\ (S/\tau_o)\exp(\int_{t_1}^{t}\alpha dt)\int_{-\infty}^{t}\exp(\int_{t_o}^{t_1}\alpha\ dt)\ dt_o$$

The exponential under the second integral is appreciable only in the neighborhood of t_1 and by replacing α with $(t-t_1)/T_1\tau_o$ (see assumption 4) is found to be $\exp-(t_o-t_1)^2/2T_1\tau_o$. If we furthermore replace the upper limit of the second integral by $+\infty$ this integral becomes $\sqrt{2\pi T_1\tau_o}$ and hence the fission rate at the time t is:

$$F(t)dt=(S/\tau_o)dt\sqrt{2\pi T_1\tau_o}\ \exp\int_{t_1}^{t}\alpha\ dt$$

The integral in the exponent keeps growing as long as α is positive and hence the maximum intensity occurs when K_p passes unity on its way down. Around the maximum the intensity can be written:

$$(S/\tau_o)\ dt\ \sqrt{2\pi T_1 \tau_o}\ \exp\left(\int_{t_1}^{t_2} \alpha\, dt\right) \exp\left(\int_{t_2}^{t} \alpha\, dt\right)$$

where the second exponential again may be approximated by $\exp -(t-t_2)^2/2T_2\tau_o$.

Hence the shape of the burst is Gaussian around t_2, with an equivalent width of $\sqrt{2\pi T_2 \tau_o}$

And the total number of fissions in the burst is:

$$2\pi S \sqrt{T_1 T_2}\ \exp \int_{t_1}^{t_2} \alpha\, dt\ .$$

Actually the variation of α with time is nearly symmetrical, and we can therefore assume $T_1=T_2=\sqrt{T_1 T_2} = T$. The total number of fissions in the burst is then simply:

$$2\pi S T\ \exp \int_{t_1}^{t_2} \alpha\, dt\ .$$

RESULTS AND DISCUSSION

Before presenting any results we should like to emphasize that the experiments were done not so much in order to measure any definite quantity, but rather with the idea of demonstrating the existence of divergent chains supported by prompt neutrons only, and of keeping an eye open for any unexpected phenomena. We attempted to keep track of all quantities which could easily be measured and interpreted, but because of the shortness of time we could not interpret some of our data until after the active material had been returned to the chemists and then we found that some data were not accurate enough for reliable interpretation.

Perhaps the best way of demonstrating the internal consistency of the various measurements is to show how the generation time τ_o can be calculated both from the shape and from the size of the bursts, both results being in reasonable agreement with the figure obtained from a Rossi time-scale experiment.

A. Burst Shape

Fig. 5 shows the record for drop No. 73, obtained with assembly 2. Each dot represents a time interval of 0.64 msec. The ordinates of the center of each dot were measured and replotted on an extended scale in Fig. 7. They can be fitted very well by a Gauss integral, the curve shown. The deviation is probably due to the non-linear behavior of the cathode follower. The equivalent width is seen to be 2.8 milliseconds. From the number of dots preceding the pulse we see that the maximum of the burst occurred $42.9 \times 0.64 = 27.4$ msec after the beginning of the sweep, which in turn was triggered 40.96 msec ($= 2^{12} \times 10$ μsec, see under "timing") after the knife edge had passed the top light beam. The slug dropped 224.6 cm from its starting position to where it passed the top light beam and hence we can calculate that the slug (or, to be precise, the knife edge on it) was y=47.5 cm below the top light beam at the instant of the maximum of the burst. Since the static calibration showed the maximum multiplication at y=43.6 cm and since the maximum of the burst must occur at the instant when the system, on its way down, again becomes just critical for prompt neutrons, we conclude that the two points where the slug passed criticality were $2 \times (47.5-43.6) = 7/8$ cm apart.

Fig. 8 shows the variation of K_p with slug position (and hence with time). The solid curve is taken from Fig. 3 and shifted upward so that the two intercepts with the line $K_p - 1$ are 7.8 cm apart. From the slope at the intercept and the average speed of 722 cm/sec of the slug we can get T which is found to be about 1.0 sec. From this and the pulse width we can calculate τ_o: $W = 2.8\text{x}10^{-3}$ sec $= \sqrt{2\pi\tau_o T}$, hence $\tau_o = (2.8 \times 10^{-3})^2/2\pi = 1.3$ μsec.

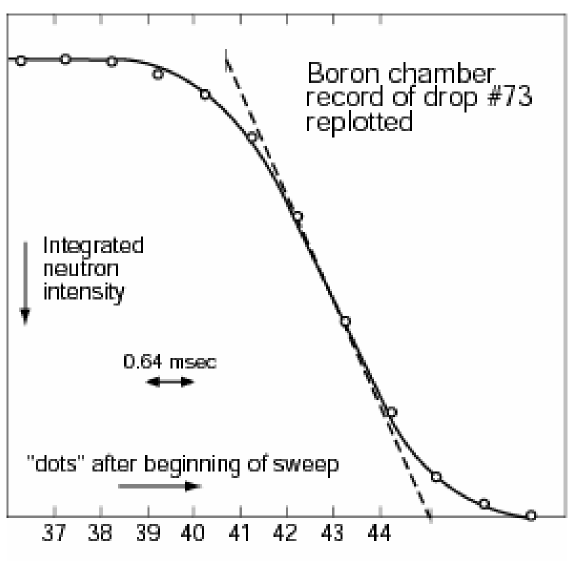

Fig. 7

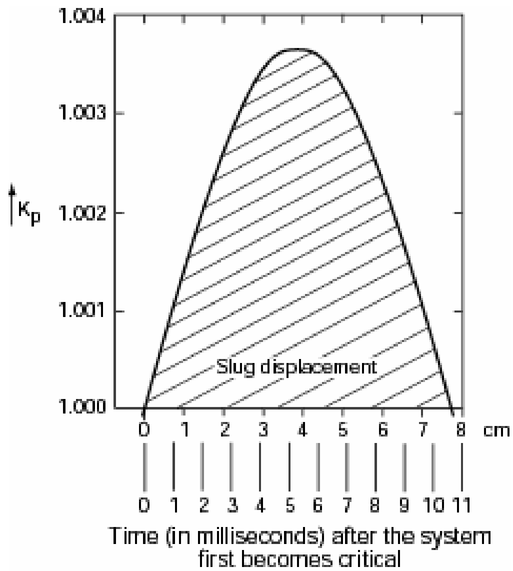

Fig. 8

B. Burst Size

Fig. 9 shows the initial counting rate of the Cu detectors plotted against the temperature rise of the system. The specific heat of UH_{10} was measured[6] as 0.14 cal/gm degree; hence the heat capacity of the whole active material (15.4 kg) is $0.14 \times 15400 = 2160$ cal/degree or $2160 \times 4.19 = 9000$ joule/degree. Since about 3×10^{10} fissions are needed to produce one joule of heat, 1° temperature rise corresponded to about $9000 \times 3 \times 10^{10} = 2.7 \times 10^{14}$ fissions. From Fig. 9 we see this gives an initial counting rate of 1.15×10^5 counts/minute, hence 1 count/min means a burst of 2.4×10^9 fissions.

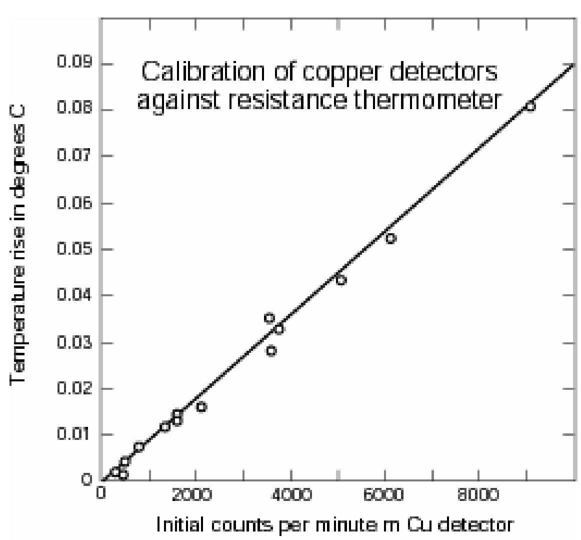

Fig. 9

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[6] Report Forthcoming

The counting rate shown by the Cu detector exposed at drop 73 was 80 counts/min, hence the burst contained $80 \times 2. \times 10^9 = 2 \times 10^{11}$ fissions. According to theory this must equal to $2\pi ST\exp(\int_{t_1}^{t_2} \alpha dt)$. S was due to a Po-Be source emitting about 5×10^5 n/sec and placed in a hole in the tamper; we estimate that this source caused 10^5 fissions per sec, hence S is 10^5. T=1 (see preceding section); hence the exponential is found to be 3×10^5, and

$$\int_{t_1}^{t_2} \alpha dt = \text{lognat}\,(3\times10^5) = 12.6.$$

This value must be equal to the shaded area in Fig. 8 if the time is measured in units of τ_o. Actually the area is 20 μsec and hence we find $\tau_o = 20/12.6 = 1.6$ μsec. The agreement of the value with that of 1.3 μsec obtained from the pulse shape is not unsatisfactory.

We tried to calculate τ_o from the way in which the size of burst varied with the adjustment of the multiplication. However the statistical fluctuations were very large and furthermore the adjustment showed some slack; as a result, while the variation of burst size comes out roughly as expected it is not possible to calculate any relevant figure for τ_o from it.

A third and independent value for τ_o was however obtained by performing a Rossi time-scale experiment[7] on the assembly. Nine gates of 40-μsec width were opened successively upon arrival of a fission pulse in the built-in fission chamber, and any pulse following the trigger pulse within 360 μsec was recorded in the appropriate channel. Fig. 10 shows the distribution of counting rates over the nine channels (after subtracting accidental coincidences, calculated from the counting rate) and indicates an exponential decay with a time constant of 120 μsec. The multiplication constant K was determined as 0.995_5 by extrapolating the calibration curve; hence (0.008 being the effective fraction of delayed neutrons) $1-K_p = 1-(0.995_5 - 0.008) = 0.0125$, and hence $\tau_o = 120\mu\text{sec} \times 0.0125 = 1.5$ μsec.

It was pointed out earlier that the static calibrations were based on the assumption that the delayed neutrons caused 0.008 times as many fissions as the prompts. If the true figure were higher by a factor g then all values of K-1 should be multiplied by g. The value $K_p - 1$ in the Rossi experiment would also be g times larger, and so would the value τ_o resulting from it . The same is true of the value of τ_o calculated from the size of the burst, and from the shape of the burst. The reasonable agreement between the various determinations of τ_o does not therefore constitute evidence for the correctness of our static calibration.

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[7] The electronic arrangement for this was built and operated by Nereson.

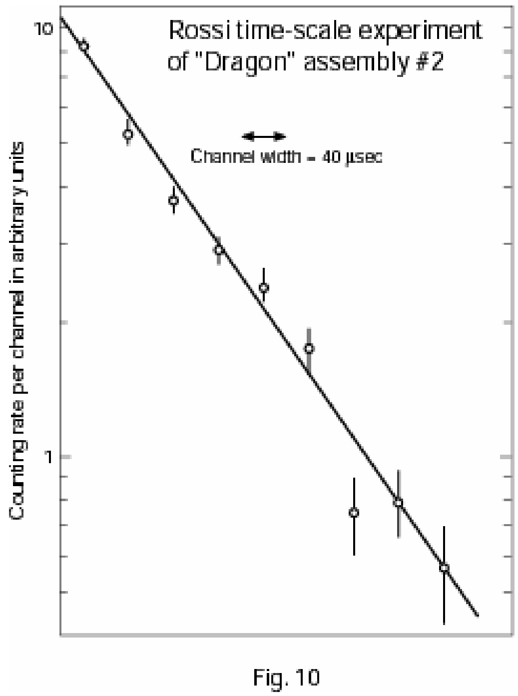

Fig. 10

It is difficult to set any definite upper limit to the presence of neutrons delayed by times greater than a few microseconds. In assembly 2 K_p-1 never became more than 0.01 and hence the e-folding time was never shorter that 150 μsec. Neutrons with delays up to say 50 μsec may well have been present if they were offset by short-lived neutrons of sufficient number to give the correct value (about 1.5 μsec) for the average time between a fission and its daughter fissions (excluding daughter fissions with a delay of more than 150 μsec). On the other hand, neutrons with much more than 150 μsec and less than a few milliseconds delay would not have contributed to the bursts. Their number could not have exceeded about 0.005 per fission since bursts were observed at positions of the control tray which were about as predicted from the static calibration under the assumption that there were no delayed neutrons of very short period. Neutrons with a delay of more than a few milliseconds were detectable as such and a period of about 6 msec was indeed found (see LA-252), containing about 10^{-4} neutrons per fission.

Fluctuations

Calculation indicates that if the size of a burst be N (in arbitrary units) then the relative mean square fluctuation ($\overline{N^2} - \overline{N}^2$)/ $\overline{N}^2$ should be $(1/S\tau_o) \cdot \overline{\nu(\nu-1)} / 2\overline{\nu}$ is 0.8 if we assume that $\overline{\nu}$ = 2.5 and that the fission can result in the emission of 2 or 3 neutrons but neither more nor fewer. If we assume a Poisson distribution for the number of neutrons per fission, the term becomes 1.25. The true value probably lies between these limits.

The observed fluctuations are illustrated by Table 1. Each column contains the intensities of a number of subsequent bursts obtained under identical conditions. Column A shows the large fluctuations of bursts obtained with assembly 2 where τ_o is small. Column B was taken with assembly 3 where τ_o was more than 10 times larger, and despite the use of a weaker source the relative fluctuations are seen to be smaller. Column C was obtained with the same adjustment of assembly 3 as column B, but the source used was about 9 times stronger. The relative mean square fluctuation should have been 9 times smaller; actually it only dropped by a factor of 4, which probably indicates the presence of another source of fluctuations, perhaps slight variations in the path of the slug. Column D differs from C by the fact that the multiplication was slightly reduced; this reduced the average burst size by about a factor 3 but did not alter the relative fluctuations. This is not surprising since the fluctuations arise mainly in the beginning of the burst and are not much affected by the later stages of multiplication when the number of fissions became large.

If one wants to produce a large burst , it is clearly better to increase S rather than the multiplication, in order to reduce the uncertainty in burst size. This can be done by dropping the slug twice within a short interval (2-3 minutes) so that the delayed neutrons from the first burst serve as a source for the second. By making the second drop when the delayed neutron intensity has fallen to the desired level the intensity of the second burst can be adjusted fairly closely. It may even pay to make three successive drops and thus build up the necessary delayed neutron intensity in two steps. We always used this technique of making one or two "leader" drops when we wanted to obtain very strong bursts close to what the assembly could tolerate.

Additional Experiments

The decay of the delayed neutrons was studied with considerable accuracy by F. de Hoffman et al, using the scaling and recording equipment briefly described on page 13. The work has been reported in LA-252.

The decay of gamma rays during the first few seconds was studied by P. B. Moon (LA-253).

Also the effect of the intense burst of radiation on the insulation of coaxial cable was observed in a preliminary way by Moon.

H. Richards set up a cloud chamber and synchronized it with the falling slug so that the bursts would occur during the sensitive time of the chamber. It was planned to expose the chamber to thermal neutrons only and then to observe recoil tracks from fission neutrons emitted by a piece of 25 placed in or near the chamber. However, in the short time available we did not succeed in eliminating the background of fast neutrons getting through or around the graphite moderator, and the attempt was abandoned.

Four rats were placed by R. Steinhardt at various distances close to the assembly. They all survived the exposure to a single drop in which about 10^{15} fissions were produced. Unless the high instantaneous intensity of the irradiation had greatly increased its detrimental effects this result was to be expected since the dose was only a few hundred R units.

Table 1

A	B	C	D
650	17	80	28
1690	13	106	30
470	7	97	36
610	9	91	32
360	8	91	22
1180	8	113	28
1190	9	94	32
1050	10	70	22
1410	9	111	27
1700	7	89	34
1500	7	69	30
830	21	70	34
690	6	58	21
$\overline{N}=1010$	2	81	39
$(\overline{N^2} - \overline{N}^2)/\overline{N}^2 = 0.20$	11	99	30
	7	89	27
	2	68	33
	8	73	26
	10	75	24
	10	86	32
	8	80	37
	14	75	21
	9	106	31
	8	83	34
	5	$\overline{N}=1010$	22
	$\overline{N}=1010$	$(\overline{N^2} - \overline{N}^2)/\overline{N}^2 = 0.036$	26
	$(\overline{N^2} - \overline{N}^2)/\overline{N}^2 = 0.148$		20
			34
			31
			39
			38
			30
			22
			$\overline{N}=1010$
			$(\overline{N^2} - \overline{N}^2)/\overline{N}^2 = 0.033$