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Experiments with the Dragon Machine

American Nuclear Society
2011 ANNUAL MEETING
June 26-30, 2011
Hollywood, Florida

Richard E. Malenfant
Sumner Associates, Inc., supporting
N-2 Advanced Nuclear Technology Group Los Alamos National Laboratory
Based on work by Otto Frisch, Louis Slotin, Phillip Morrison, and others.

EXPERIMENTS WITH THE DRAGON MACHINE

- Introduction
- Background
- History
- The Dragon Machine
- The Experiments
- The Results
- The Significance of the Results
- Conclusions
- Dragon Follow-On

Introduction

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.

Background

A set of handwritten notes entitled:

"Dragon – Research with a Pulsed Fission Reactor"

was discovered in the bottom drawer of a file safe at
Pajarito Site
bearing the identification:

"49 Book"
"ORF – July 1945"

Research with a Pulsed Fission Reactor

ORF July 1955

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^{18} neutrons can be produced in one burst. (30 kg of Uranium are heated to 100°C by 10^{18} 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 3/2 power of the velocity of the slug.

By falling from a height of say 30 ft the slug acquires a velocity of 1.9×10^3 cm/sec and in a critical 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 could be realized 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/sec could probably be realized 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 eg. 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 which involve other equipment which can be kept alive for short periods only eg. cloud chambers, very high currents or magnetic fields.

③ Experiments where short-lived after-effects are to be studied eg 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 target material eg. 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 is a suitable or even essential tool.

Reactor Design

The design of such a reactor depends on the fissile material available. U^{235} would be very suitable, about 30 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 1.5 times longer.

If such large amounts are hard to obtain, hydrogen or deuterium might be added eg. by using plastic bonded uranium hydride. This greatly reduces the amount of critical amount (by a factor of 3 if UH_4 is used) but also

Background - Continued

- “49 Book” – the shorthand notation of the time identified nuclear material as the second digit of the atomic number and the last digit of the atomic mass. As a result plutonium 239 with an atomic number of 94 would be “49”, uranium 235 with an atomic number of 92 and an atomic mass of 235 would be “25”, and neptunium 237 with an atomic number of 93 and an atomic mass of 237 would be known as 37, etc.
- ORF was Otto R. Frisch
- July 1945 was the date of the record.

Background - Continued

The 49 Book included a note - highlighted by being surrounded by a box:

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

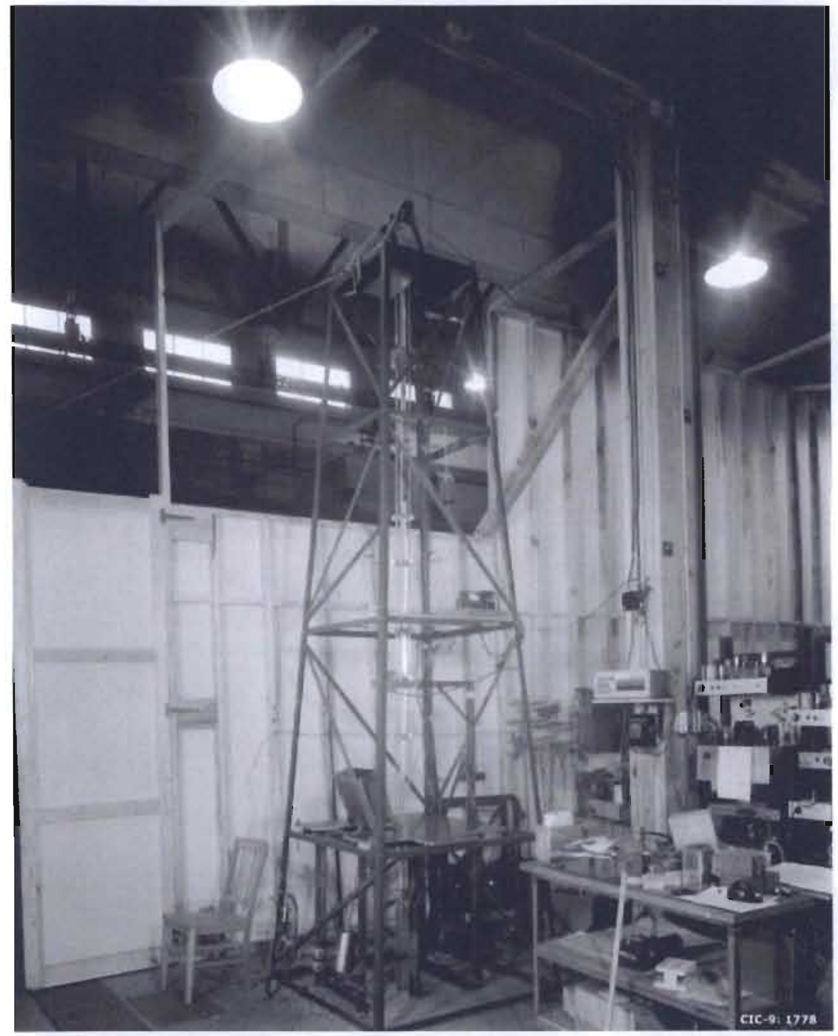
Of course LS is Louis Slotin. In addition to Slotin and Frisch, work on the Dragon Machine included H. Daghlian, P. Morrison, and P. Stein. H. Daghlian was the victim of a fatal accident on Aug. 21, 1945 and L. Slotin received a fatal exposure on May 21, 1946. P. Stein was present at the accident that was fatal to Slotin.

History

Chicago Pile – CP-1	December, 1942
Oak Ridge Reactor – X-10	November, 1943
Water Boilers	
Low Power – LOPO	November, 1943
High Power – HYPO	December, 1944
Super Power – SUPO	March, 1951

The Dragon Machine

"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."



The proposal for the experiments was made by Frisch to the Coordinating Council that included Enrico Fermi and Dick Feynman.

Frisch reported that Feynman compared the experiment:

to "tickling the dragon's tail"
or to "tickling the tail of the sleeping dragon"

As a result, the machine became known as

The Dragon

Time Line of the Dragon

The "drop" experiment was suggested in memos from Frisch to Oppenheimer on 17 and 24 October, 1944.

Given the daring nature of the experiment, Frisch was surprised to learn that the Coordinating Council judged the experiment worth pursuing. Subsequently, it was observed that Oppenheimer indicated that this experiment was essential to the project.

NOTE: Some of the information appears contradictory. For example, dates given in various sources sometimes differ by a day or two, and the height of the tower is reported as 30' in the handwritten notes, and as 12' in LA-397. The most consistent values are given here.

Assembly 1

The equipment was ready by mid-December. During the next few weeks, the enriched uranium hydride (UH_{10}) was prepared and positioned. The world's first burst (a chain reaction using prompt neutrons alone) was produced "in the small hours of January 20". This assembly consisted of about 10 kg of UH_{10} surrounded by About 6" of BeO. The UH_{10} was made by pressing UH_3 with Styrex into cubes, some ½ in., some 1 in., on a side. The symbol U stands for Beta-stage material of 71 to 75% 25 content. The UH_{10} also contains about 4 atoms of carbon for each atom of U.

This phase of the program was completed by January 21, 1945. The size of the bursts were increased until a temperature rise of 0.01° C was observed. "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. The BeO tamper was replaced with tungsten carbide with the expectation that the effect of thermal neutrons from the BeO would be reduced. However-

The system would not go critical!

Assembly 2

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Why?

Assembly 2 – continued

The system would not go critical because of the gaps due to Guides, tray walls, and-

Assembly 2 – continued

The system would not go critical because of the gaps due to guides, tray walls, and-

the n-2n reaction in beryllium!

Assembly 2 – continued

Assembly 2 was used until February 1 when about 2/3 of the material was returned to CM Division for conversion to metal. The effect of thermal neutrons was reduced by placing a layer of cadmium between the BeO and the assembly.

Most of the data from the Dragon were taken with this assembly.

<u>Assembly 3</u>

The remaining 5.4 kg of UH_{10} were diluted with polyethlyene in the volume ratio of 1-UH_{10} to 5 Polythene. The tamper was replaced with 3 in. of graphite backed by 1 in. of Polythene (this was about as effective as 6 in. of graphite).

The large amount of hydrogen increased the τ_o to about 20 µsec. Although the kinetics were of less interest, the increased hydrogen content allowed for larger bursts.

The burst size was increased by decreasing the time between bursts. with the resulting greater initial neutron population. The final burst resulted in swelling and blistering of the material – the whole system expanded by about 1/8 in. Temperature and expansion terminated the reaction. No more bursts were produced!

The Experiments

- "The falling slug of active material was contained in a steel box, 14 in. long and with a 2-1/8 in. x 2-1/8 in. cross section. Its path was defined by 4 Dural guides, with a slack of about 1/8 in. so that even a considerable warping of the guides would not interfere with its drop."
- "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."

The Experiments

"In one particular burst a temperature rise of the active material by over 6°C was recorded, corresponding to the liberation of 12,000 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."

The results were finally reported in Sept. 1945 as LA-397

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Per [signature], FSS-16 Date: 11-8-95
By [signature], CIC-14 Date: 11-8-95

LA-397
[redacted]

September 27, 1945 C.1 This document contains 33 pages

CONTROLLED PRODUCTION OF AN EXPLOSIVE NUCLEAR CHAIN REACTION

WORK DONE BY:

C. P. Baker
J. A. Bistline
A. Cammac
H. K. Daghlian
B. T. Feld
O. R. Frisch
H. Hammel
F. de Hoffmann
M. G. Holloway
J. Hughes
J. Kupferberg
H. A. Lehr
P. Long
P. Morrison
J. Osborn
L. Slotin
P. Stein

REPORT WRITTEN BY:

O. R. Frisch

Classification changed to UNCLASSIFIED
by authority of the U. S. Atomic Energy Commission,
Per H. F. Carroll
By REPORT LIBRARY M. Allen 1-4-57

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Results -1

- The average time between fissions (τ_o) was measured to be 1.3 μsec.
- The e-folding time (the time to increase the fission rate by a factor of e=2.718…) was never shorter than 150 μsec.
- 1 Joule (watt-sec) resulted from ~3×10^{10} fissions
- The slug weighed 15.4 kg and it had a specific heat of 0.14 cal/gm-degree.
- 1° C temperature rise in the slug was produced by ~2.7×10^{14} fissions

Results - 2

- The delay neutron fraction was identified as 0.008.
- The definition of the dollar as a unit of reactivity is attributed to Louis Slotin
- Data from the Dragon and the Water Boilers were used to generate the coefficients in an inhour equation:

$$\delta K x 10^{6} = \frac{122}{\tau} + \frac{1000}{\tau + 0.7} + \frac{32{,}500}{\tau + 6.5} + \frac{50{,}900}{\tau + 34} + \frac{16{,}600}{\tau + 83}$$

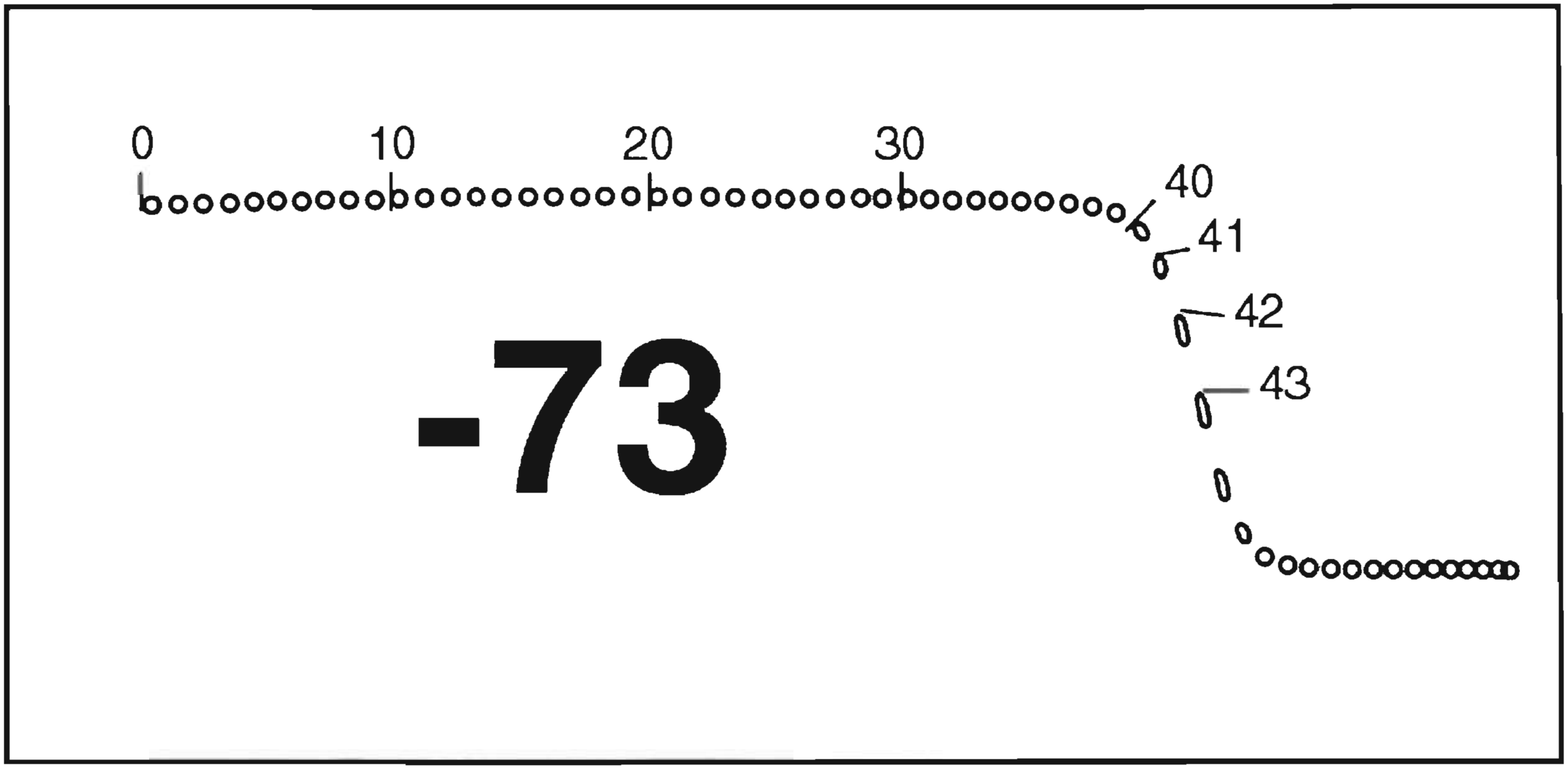


Fig. 5

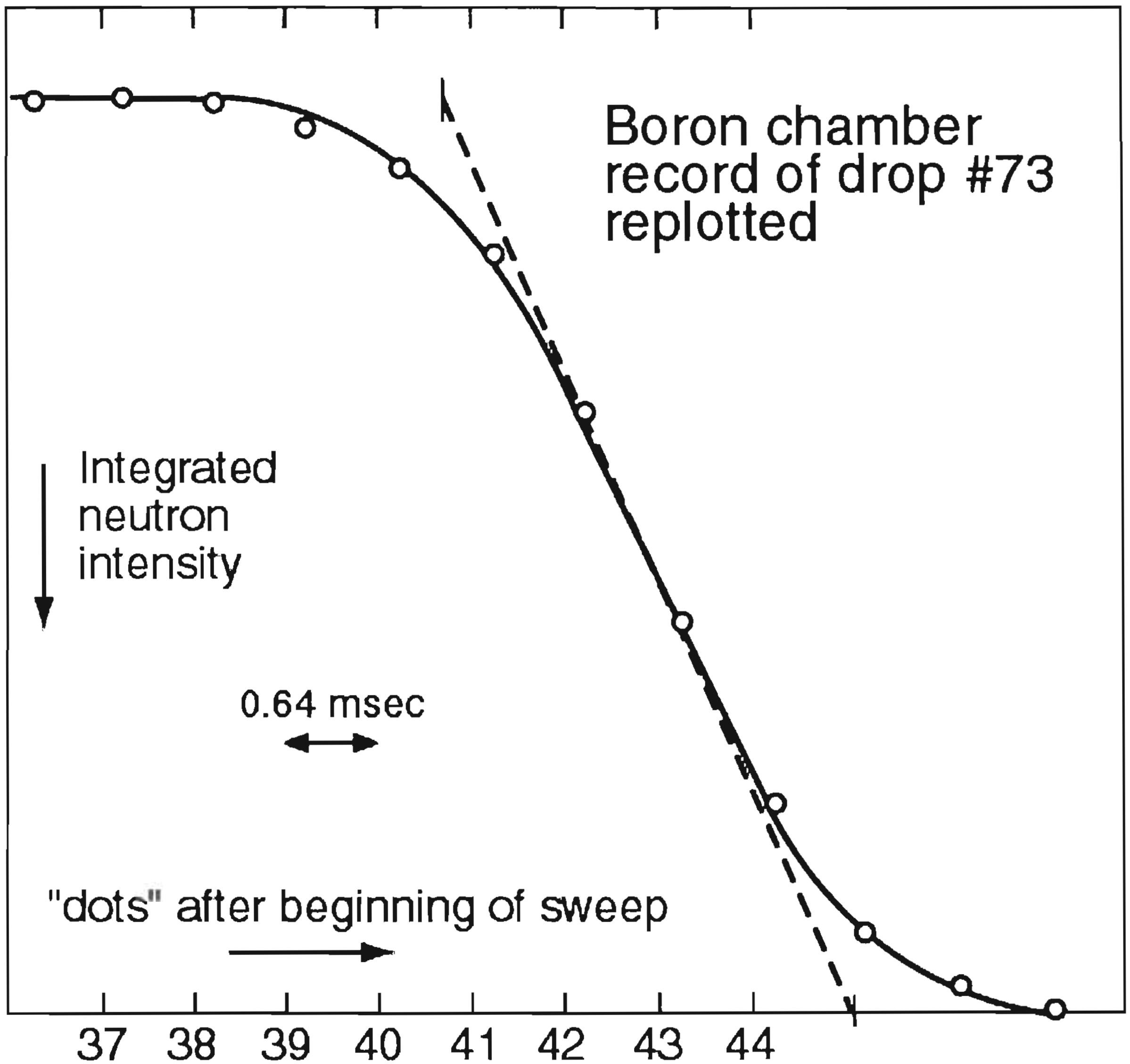

Boron chamber record of drop #73 replotted
Integrated neutron intensity
0.64 msec
"dots" after beginning of sweep
37
38
39
40
41
42
43
44

Fig. 7

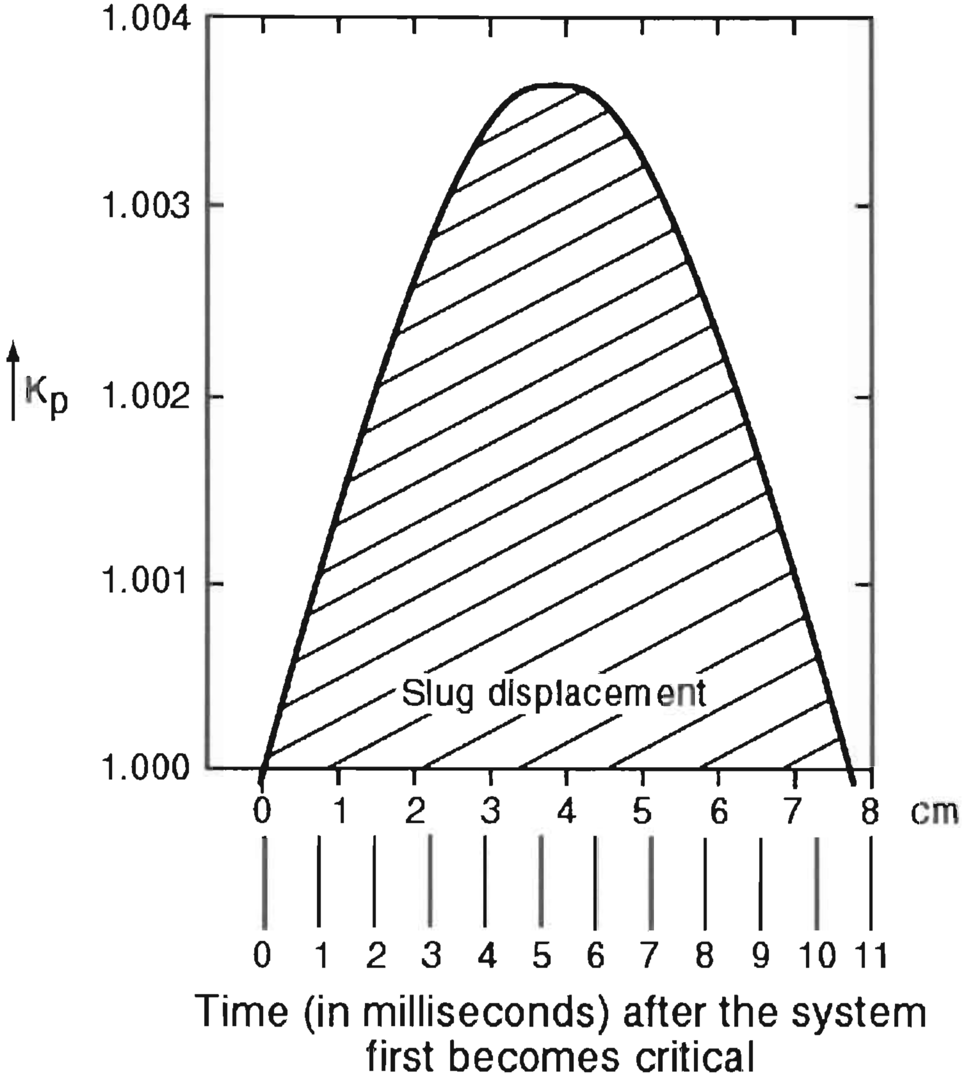

1.004
1.003
1.002
1.001
1.000
K_p
Slug displacement
0 1 2 3 4 5 6 7 8 cm
0 1 2 3 4 5 6 7 8 9 10 11
Time (in milliseconds) after the system first becomes critical

Fig. 8

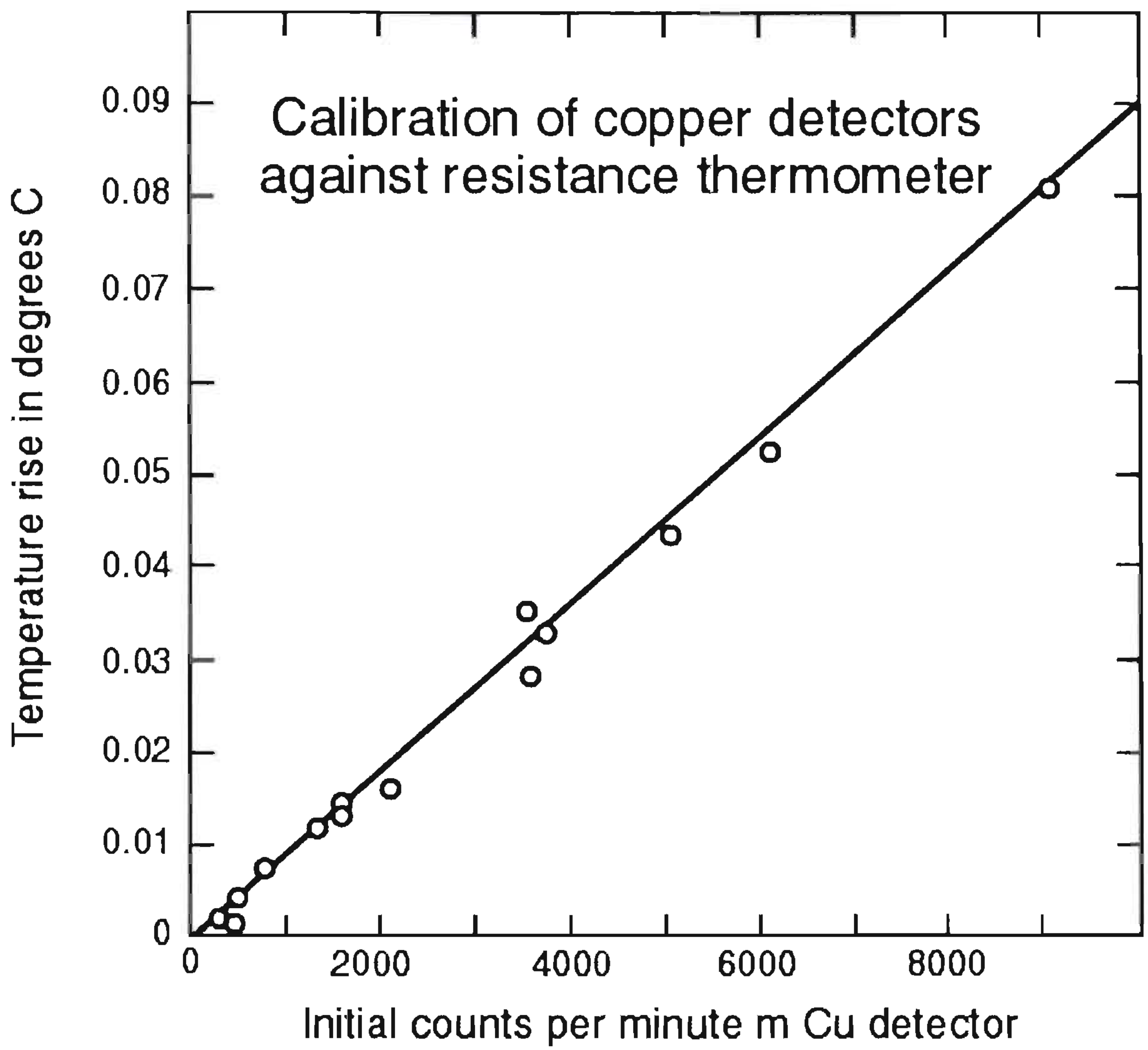
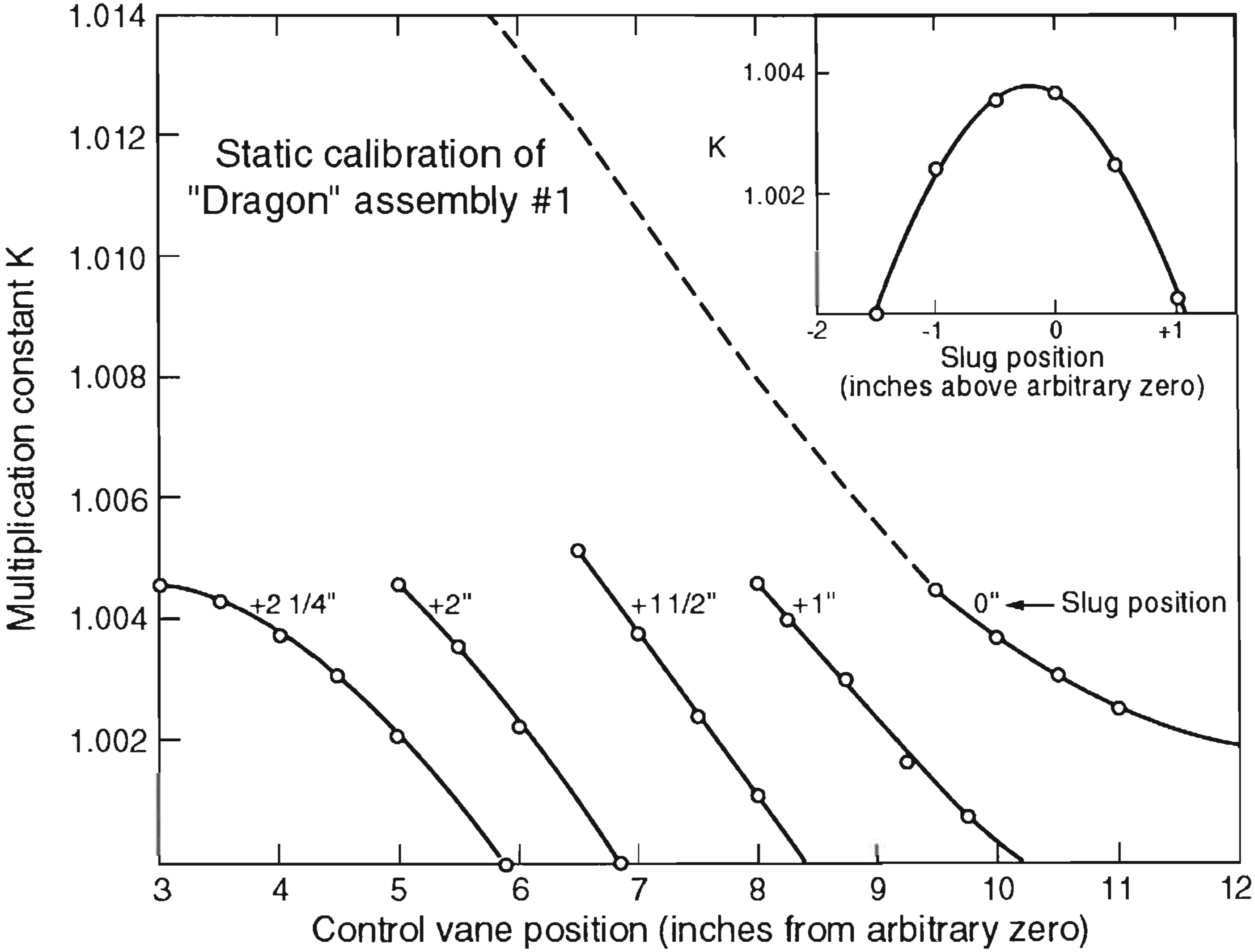

Calibration of copper detectors
against resistance thermometer
Temperature rise in degrees C
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0
2000
4000
6000
8000
Initial counts per minute m Cu detector

Fig. 9



Static calibration of
"Dragon" assembly #1
Multiplication constant K
1.014
1.012
1.010
1.008
1.006
1.004
1.002
3
4
5
6
7
8
9
10
11
12
Control vane position (inches from arbitrary zero)
+2 1/4"
+2"
+1 1/2"
+1"
0"
Slug position
K
1.004
1.002
-2
-1
0
+1
Slug position
(inches above arbitrary zero)

Fig. 2

Significance of the Results

- The Dragon was the first assembly machine to produce a chain reaction on prompt neutrons alone.
- The prompt shutdown mechanism of shock expansion due to heating provided the information to design future fast burst reactors such as the Lady Godiva, Godiva IV, SPR, Caliban, Viper, HPRR, etc.
- "The neutron bursts produced by the reactor were used in other experiments on delayed neutrons, gamma rays, the effect of intense radiation on coaxial cable, and on living animals."

Conclusions

These experiments were truly amazing! The majority of the experiments were conducted over a period of three days. With considerable ingenuity, simple apparatus, and a limited amount of material; experiments were conducted that evaluated the characteristics of a nuclear chain reaction sustained by prompt neutrons alone. Analyses before the fact made without the crutch of modern computers were verified, and most of the results were remarkably accurate, even when compared with results to this day.

Dragon Follow-On

The following record was recently located in the Laboratory Archives.

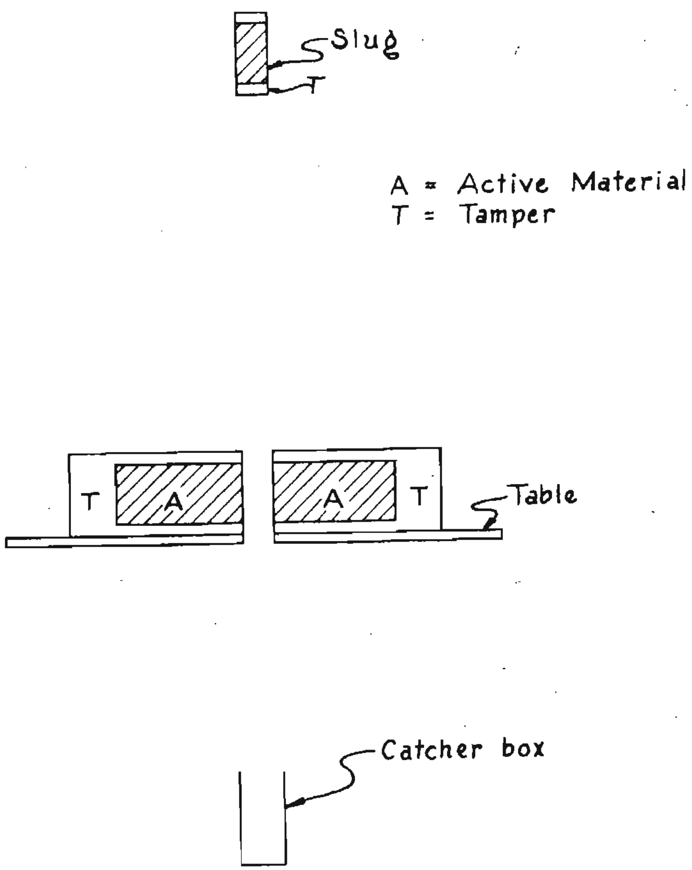
NOTES ON DRAGON MEETING, 28 August 1948

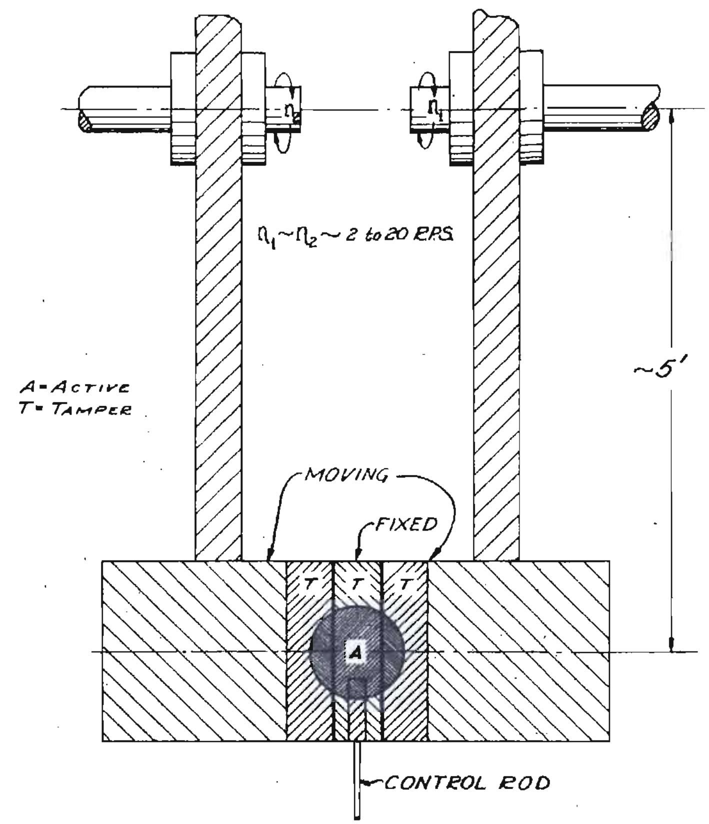
Those present: Critchfield, Josephson, McDaniel, Reines, Roberts, Schrieber, Stack, and Teller.

The purpose of the meeting was to summarize the present state of thinking about the Dragon and to discuss the feasibility and desirability of constructing such a machine.

A repetitive Dragon!

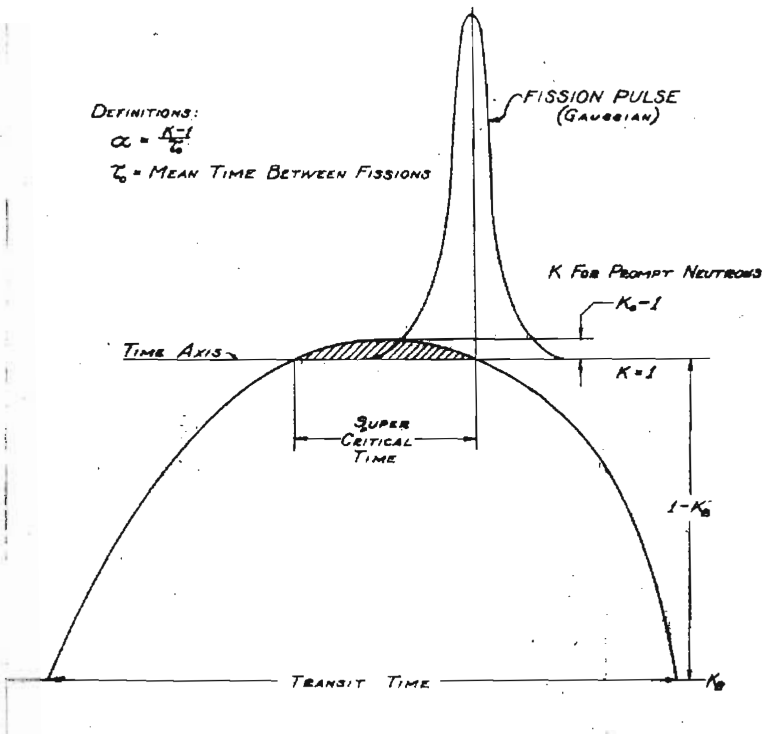
ONE SHOT DRAGON

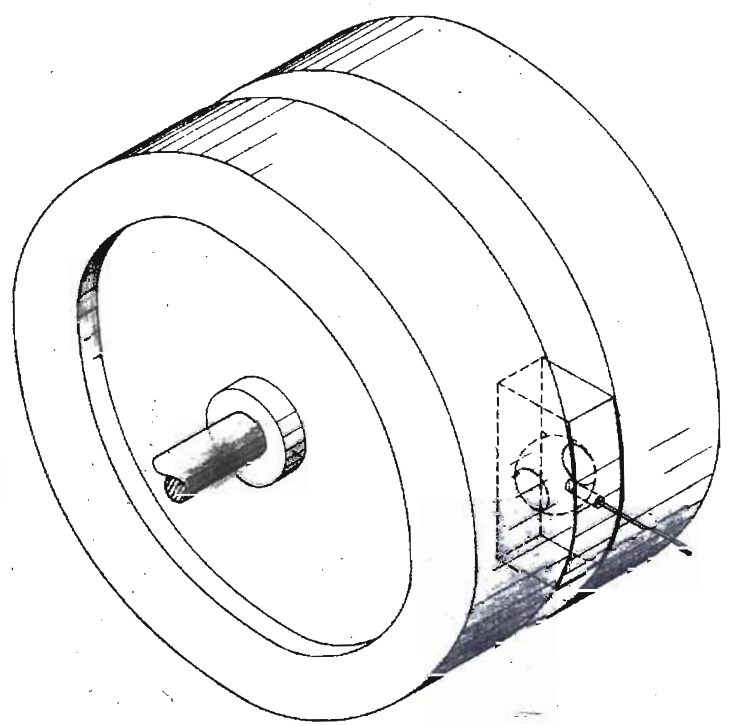




REPETITIVE DRAGON
(SCHEMATIC)

Note:
RADIATION SHIELD & HEAT TRANSFER MECHANISMS
NOT SHOWN





REPETITIVE DRAGON

“Teller reiterated the necessity of carefully investigating the safety of any proposed design. It was suggested that the AEC Reactor Safeguard Committee review any proposals and that Fermi be consulted.”

“Teller stated very strongly that a careful study must be made of the size of an explosion that might result. He felt that the Dragon must be abandoned unless one can guarantee that an accident will not contaminate or otherwise endanger the surrounding community.”

Raemer Schrieber, who recorded these notes, was present at the Slotin accident of May 21, 1946. The Dragon was to be placed at Pajarito Site (TA-18) where the Slotin accident occurred. The first critical experiment under remote control at Pajarito Site took place in Kiva I on April 12, 1947. The first critical assembly machine, Comet, was designed by Jano Haley. Comet was a general purpose vertical lift machine that used gravity to provide shutdown by separating components. A descendent of Comet is still operational today.

In conclusion,

I believe that a reconstruction of the Experiments with the Dragon Machine with a computer simulation could be very instructive. I believe that sufficient data exist to allow such a reconstruction.