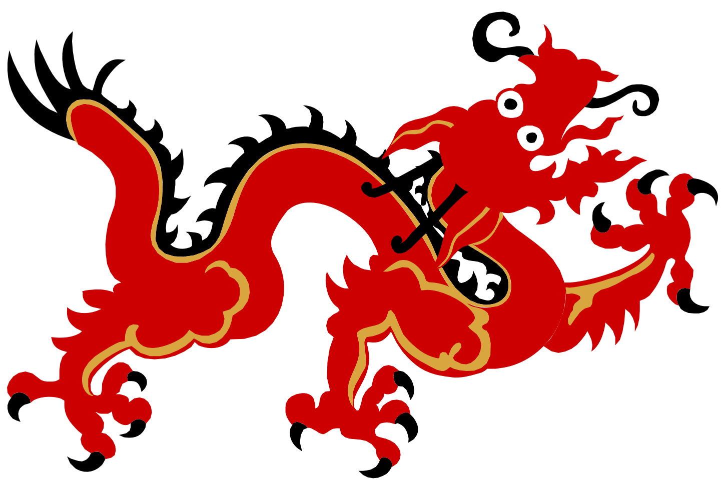
Experiments with the DRAGON MACHINE

An After Dinner Virtual Presentation
for the Trinity Section of the American Nuclear Society
February 23, 2021



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Based on work by Otto Frisch, Louis Slotin, and Phillip Morrison
and several years of experience at the Pajarito Laboratory

EXPERIMENTS WITH THE DRAGON MACHINE

- Introduction
- Background
- History
- The Dragon Machine
- The Experiments
- The Results
- The Significance of the Results
- Conclusions
- Lessons learned – early accidents
- Short History of TA-18
- Questions

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”

"Dragon"

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 100°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 1.9×10^3 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 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 cm/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_{10} 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 1/1000 second. In this short time neutron multiplications up to 10^{12} were obtained."

Prompt neutrons resulting from fission are produced in about 10^{-14} seconds, that is, 0.00000000000001 seconds!

A small fraction of the neutrons resulting from fission, about 0.0073 or 0.73%, are "delayed" with half-lives up to 15 sec.

The mean delay time, averaged over all of the delayed neutrons, is about 0.1 sec.

If keff is 1.005, the fission rate will increase by a factor of $e^{0.05}$, that is a factor of about 1.05 per sec.
In 100 sec. this would result in an increase of $e^{(100x0.05)}$ or a factor of ~150 – a rather slow reaction.

This example is given in ¶ 1.130, p. 37, *"Principles of Nuclear Reactor Engineering"* by Samuel Glasstone

In a burst reactor, like Godiva IV, operating on fast neutrons, the neutron lifetime (time between fissions in a chain reaction) is about 10μsec (10 micro-sec.) or 0.00001 sec. As a result, the fission rate increases 10,000 to 100,000 times as fast as in a slow reactor.

The Dragon was critical on prompt neutrons alone for ~1/100 sec (0.01 sec.).

One significant observation on the Dragon was that the termination of the reaction (shutdown) was due to thermal effects
rather than the mechanical effect of the slug dropping out of the annulus.

NEUTRON BALANCE IN A REACTOR AT STEADY STATE

100 fast (fission) neutrons

↓ 5 leak out during slowing down
10 absorbed in moderator, coolant, etc.

85 slow neutrons

↓ 5 leak out as slow neutrons

80 slow neutrons available for absorption

↓ 33 absorbed by U-238, moderator, poisons, etc.
7 non-fission capture in U-235 (producing U-236)

40 captured inU-235 to cause fission

↓

100 fast neutrons

NEUTRON BALANCE TO INCREASE FISSION RATE

100 fast (fission) neutrons

↓ 5 leak out during slowing down
10 absorbed in moderator, coolant, etc.

85 slow neutrons

↓ 5 leak out as slow neutrons

80 slow neutrons available for absorption

↓ 30 absorbed by U-238, moderator, poisons, etc.
7 non-fission capture in U-235 (producing U-236)

43 captured inU-235 to cause fission

↓

107 fast neutrons

EXPLOSIVE CHAIN REACTION IN A BOMB

100 fast (fission) neutrons

↓ 5 escape

95 fast neutrons neutrons

↓ 7 captured without causing fission

88 captured in U-235 to cause fission – 2.5 neutrons per fission

↓

220 fast neutrons!

An Appreciation of Time continued

How long is a μsec?

There are 86,400 seconds in a day.

There are 1,000,000 μsec in a second

There are about 1,000,000 seconds in 12 days!

An Appreciation of Energy Release

Each fission releases about 185 MeV (million electron volts) within ~.01 µsec.

1 thermal watt requires a fission rate of ~3×10^{10} fissions/sec (30,000,000,000 (30 billion) fissions/sec.

The Dragon produced pulses of ~10^{15} fissions in 1/100 (0.01) sec. This was a rate of 10^{17} fissions/sec.

10^{17} fissions/sec. corresponds to an energy release (power) of ~3 MW-sec (3,000,000 Watt-sec) at a peak rate of ~10,000 MW

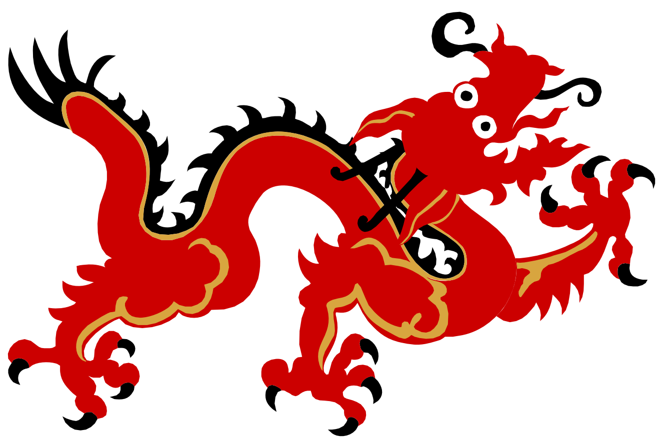
The proposal for the experiments was made by Frisch to the Coordinating Council that included Enrico Fermi and Dick Feynman.

Frisch reported that Feynman compared the experiment:

to "tickling the dragon's tail"

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.

The equipment was ready by mid-December. During the next few weeks, the uranium hydride was prepared and positioned. The world's first chain reaction using prompt neutrons was produced on January 18, 1945. This phase of the program was completed by January 21, 1945, and the majority of the uranium hydride was returned for reduction to the metal.

The Dragon Machine

- Three different active assemblies were used.
- Assembly 1 consisted of about 10 kg of UH_{10} surrounded by about 6" of BeO.
- Assembly 2 was constructed on January 28, 1945 when additional material was delivered from Oak Ridge making the assembly about 15.4 kg of UH_{10} surrounded by a tungsten carbide tamper to minimize slow neutrons from the beryllium. However, the system would not go critical so the tungsten carbide was replaced with beryllium oxide.
- Assembly 3 was constructed on February 1 when all except 5.4 kg of UH_{10} had to be returned to the chemists.

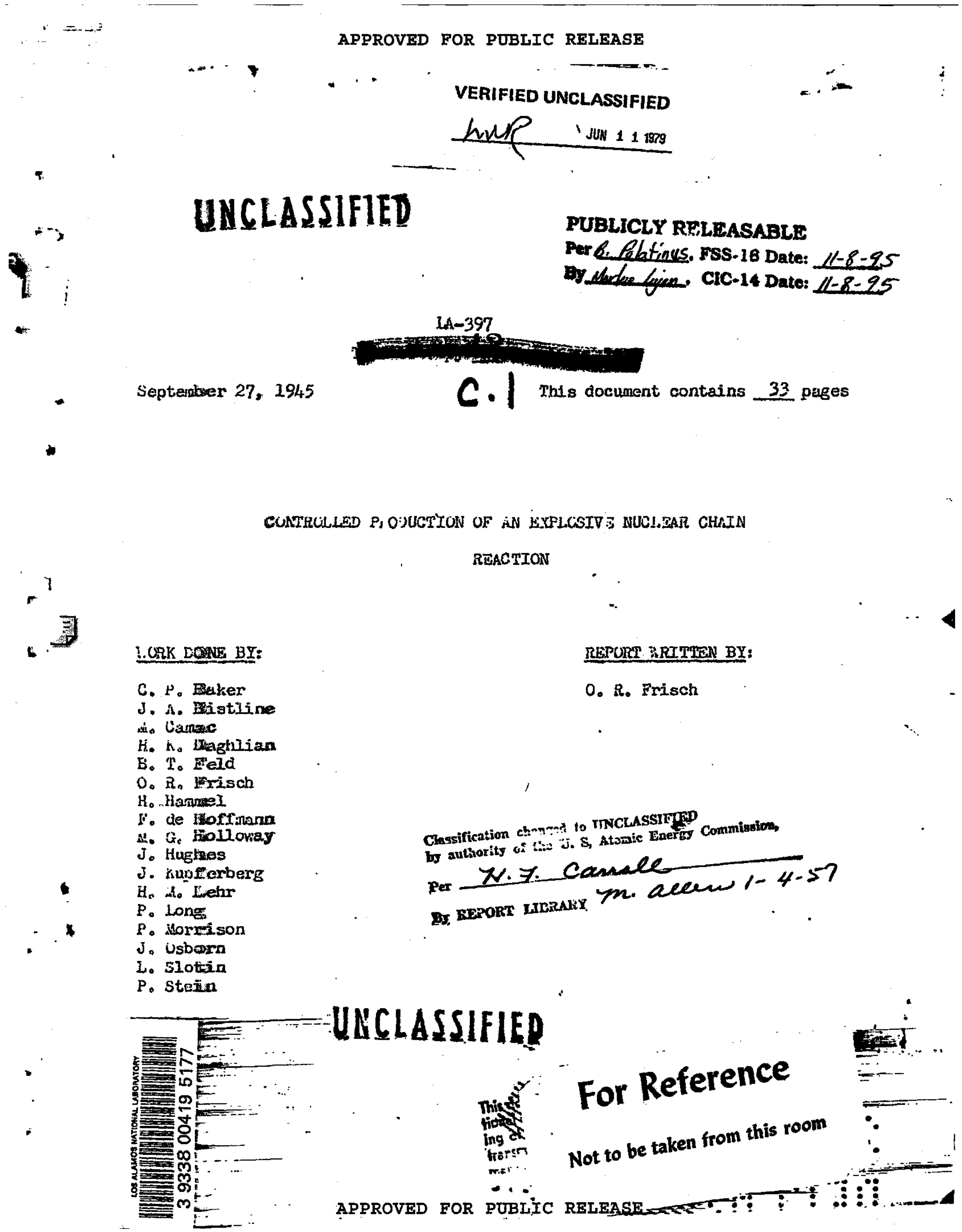
The Experiments

- "The falling slug of active material was contained in a steel box, 14" long and with a 2-1/8" x 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."
- "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 6ºC 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 2000ºC 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 B. Pelatinus, FSS-16 Date: 11-8-95
By Marlene Lujan, 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
M. Camac
H. K. Daghlian
B. T. Feld
O. R. Frisch
H. Hammel
F. de Hoffmann
M. G. Holloway
J. Hughes
J. Kupferberg
H. M. 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 ~$3x10^{10}$ fissions
- The slug weighed 15.4 kg and it had a specific heat of 0.14 cal/gm-degree.
- 1^o C temperature rise in the slug was produced by ~$2.7x10^{14}$ 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:

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

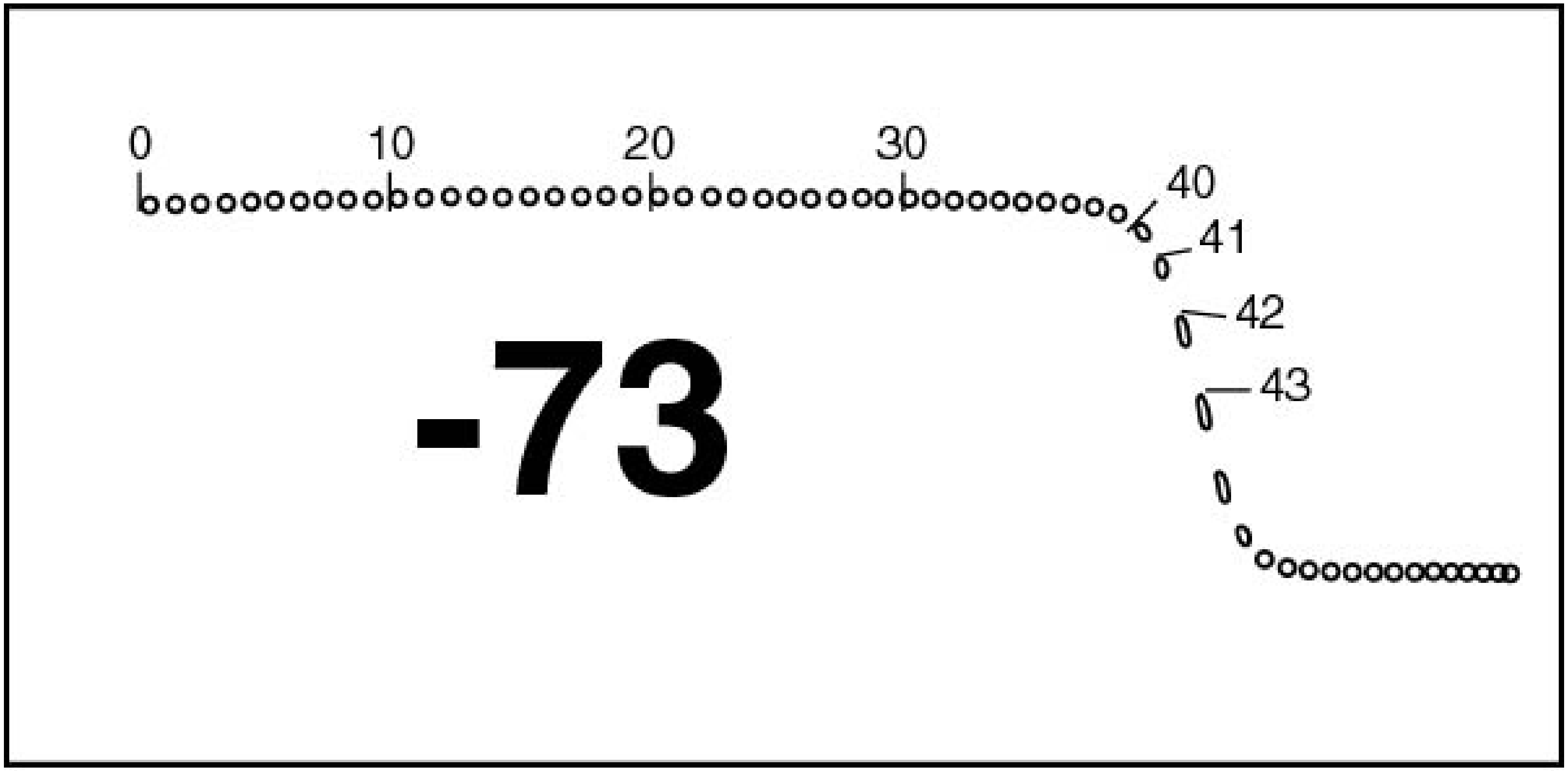


Fig. 5

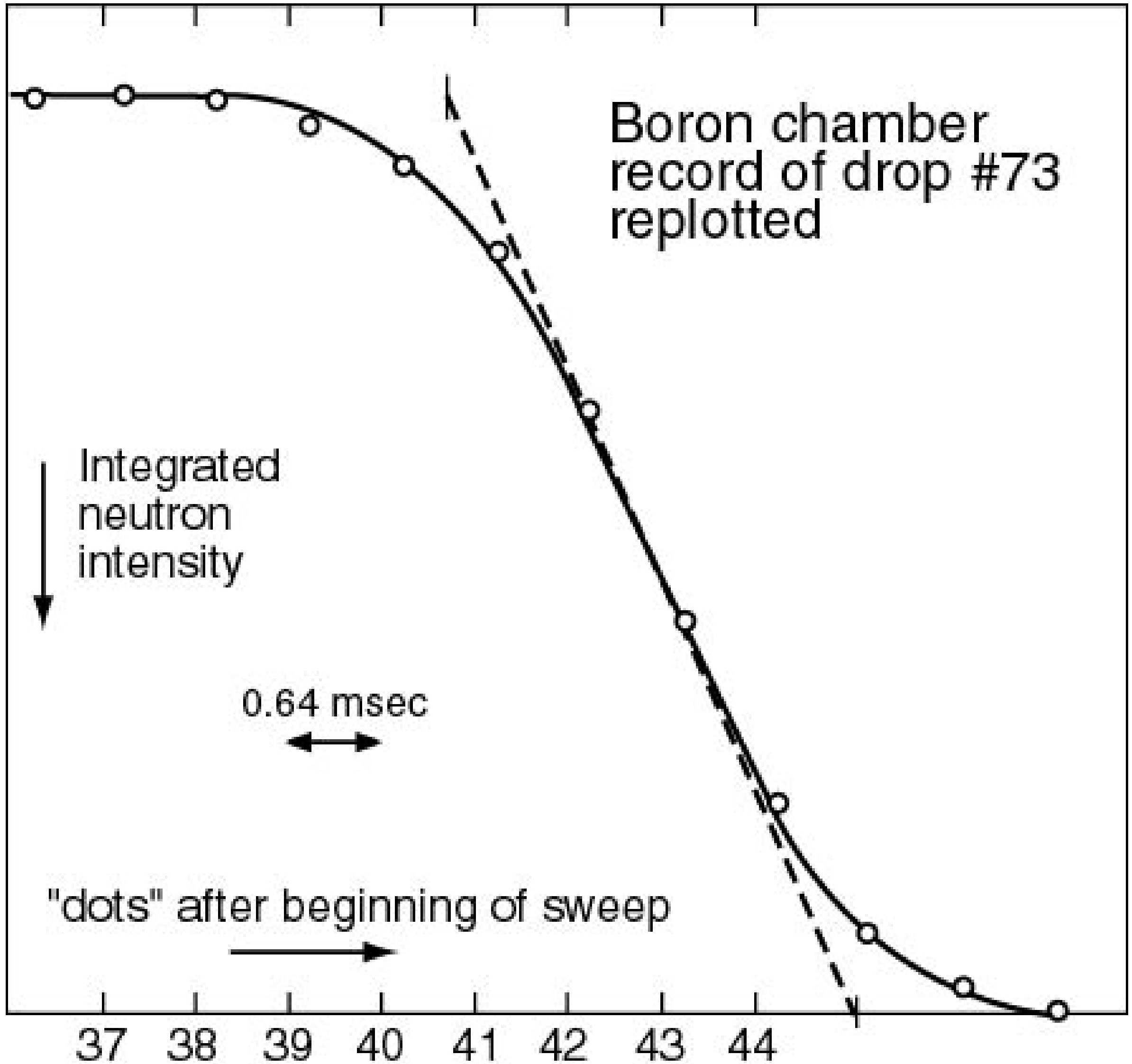
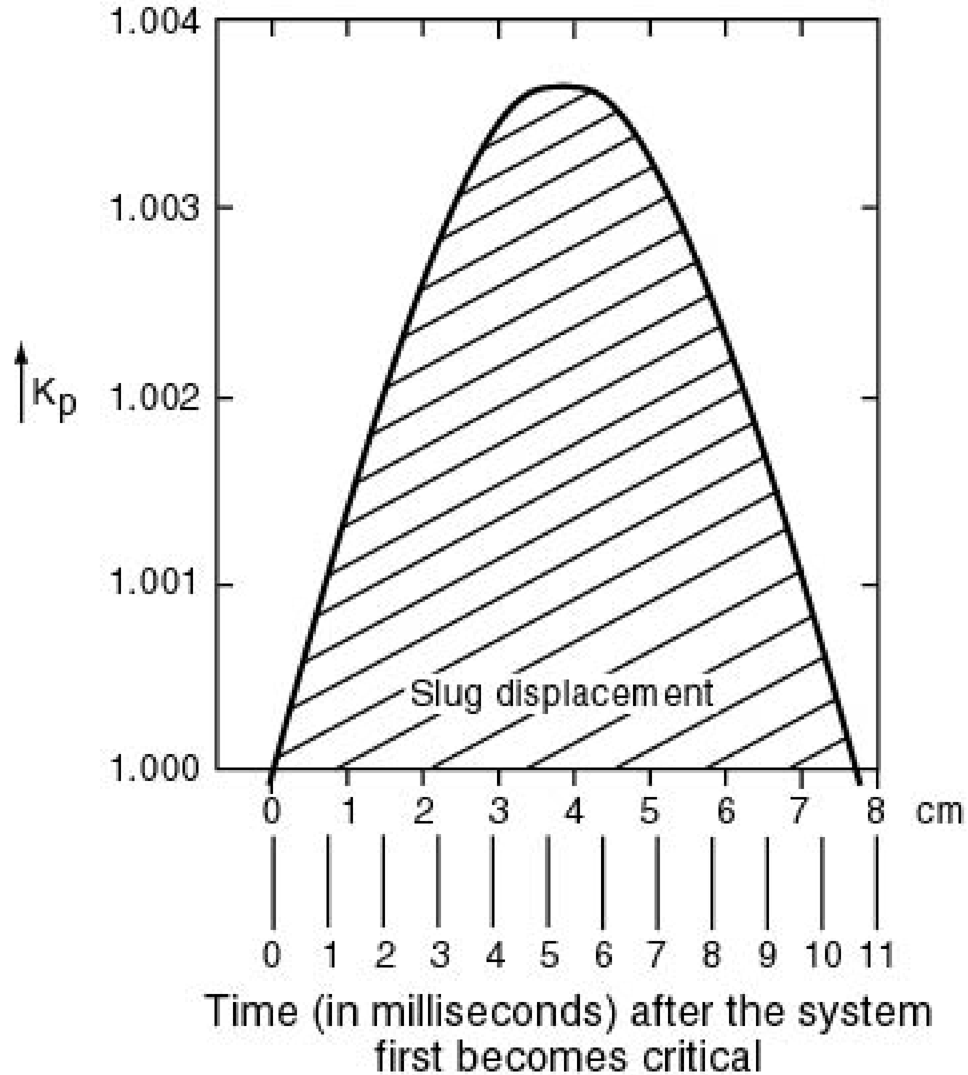

Boron chamber
record of drop #73
replotted
Integrated
neutron
intensity
0.64 msec
"dots" after beginning of sweep
37
38
39
40
41
42
43
44

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

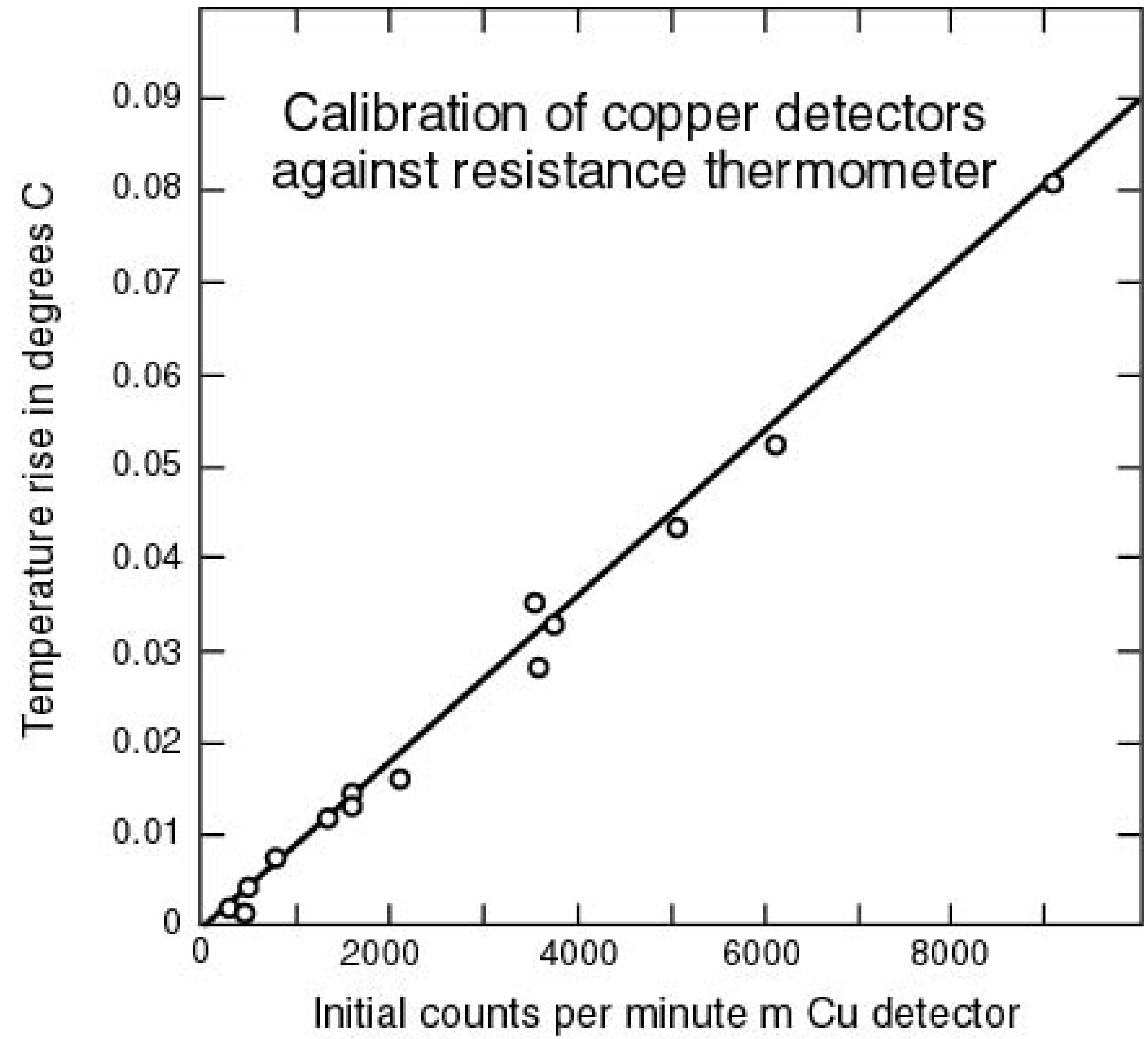
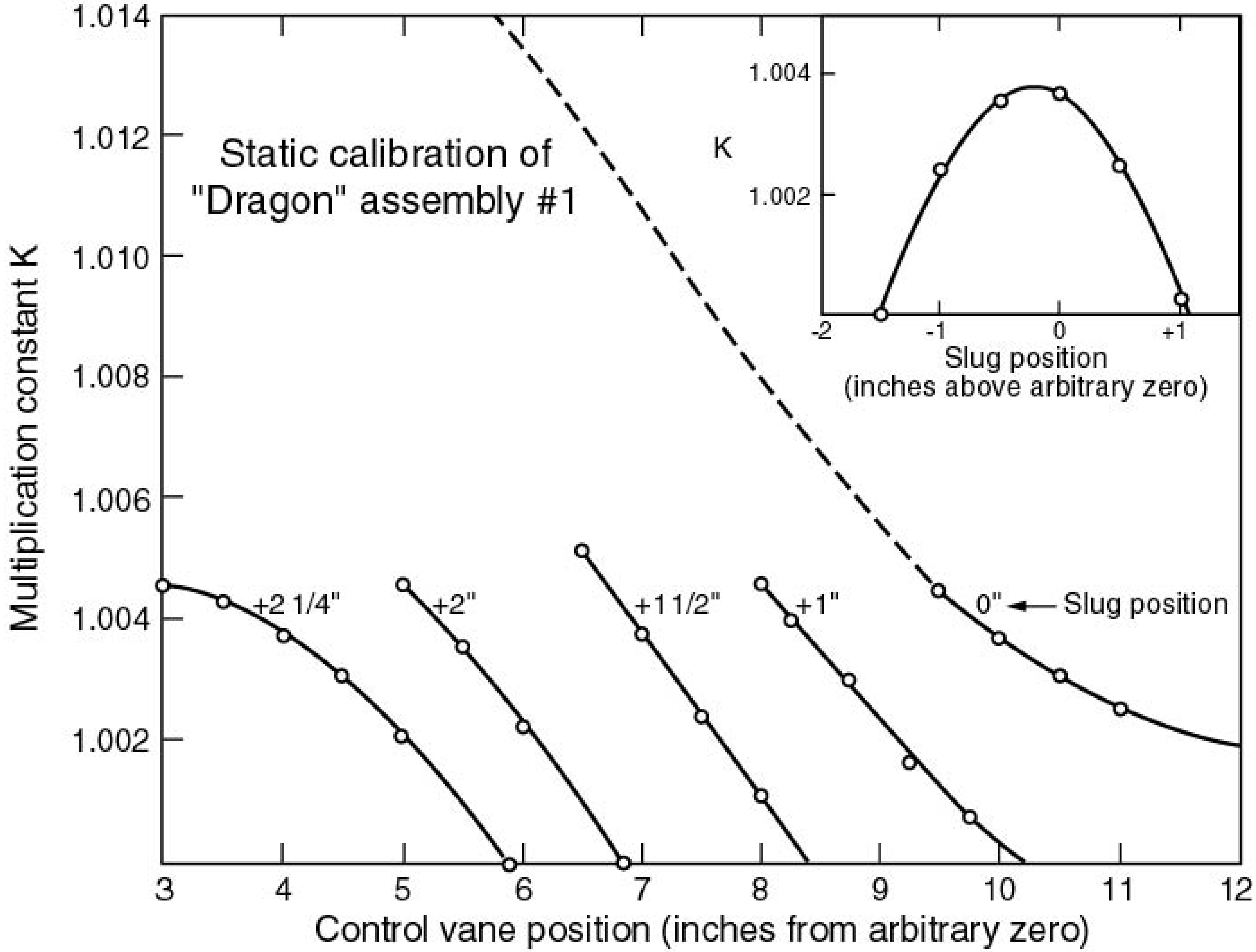

Calibration of copper detectors
against resistance thermometer
Temperature rise in degrees C
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0
2000
4000
6000
8000
Initial counts per minute m Cu detector

Fig. 9



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