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EUROPEAN ATOMIC ENERGY COMMUNITY - EURATOM

REACTOR KINETIC BEHAVIOR AND MOTION PICTURE DOCUMENTATION OF THE DESTRUCTIVE TEST

by

A. SOLA (EURATOM)
R. SCOTT Jr., R.K. McCARDELL, E. FEINAUER (Phillips Petroleum Company)

1964

Joint Nuclear Research Center
Ispra Establishment - Italy

Reactor Physics Department
Applied Mathematical Physics

Paper presented at the Ninth Annual Meeting of the American Nuclear Society
Salt Lake City, Utah (USA), June 17-19, 1963

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The data discussed are those of transient power, energy, fuel plate surface temperature, pressure, power burst profile and extent of core damage resulting from each test.

The conditions existing during the destructive test are equally presented.

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REACTOR KINETIC BEHAVIOR AND MOTION PICTURE DOCUMENTATION OF THE DESTRUCTIVE TEST *

A. Sola, R. Scott, Jr. **, R. K. McCardell, E. Feinauer **

Experimental tests of the kinetic response of the Spert I destructive test core were conducted for various step-wise reactivity insertions up to a maximum insertion of 3.5 dollars. The aim of the series was to obtain a complete set of data on the reactor behavior prior to the voluntary destruction of the core. Some of the results obtained during the series are hereafter described.

The period domain covered in the series extended from 1 sec to 3.2 msec. The data recorded were those of transient power, energy, fuel plate surface temperature, pressure and extent of core damage resulting from each transient test.

Transient responses from a typical short test period, of initial period 6 msec, are shown on the first figure. The time in abscissa is taken as being zero at the time of peak power. The power rise begins to deviate from an exponential about a decade below peak power. At this time, the energy release is less than one megawatt-second and the temperature, which was measured on the surface of a fuel plate at the hot spot of the core, has risen only by about 30° C above ambient.

At this early stage of the transient, "negative reactivity feedback" is almost entirely due to thermal expansion of heated materials, which cause the moderator to be removed from the coolant channels. As the energy release continues, surface temperature eventually exceeds the boiling point of water (in this case about 5 msec before peak power) and boiling void formation starts to occur. Boiling, because of the large volume of steam produced, is a far more effective shutdown mechanism than thermal expansion in the removal of moderator from the core as is evident by the abrupt halting of the power rise immediately after the onset of boiling. As boiling spreads throughout the core, large amounts of reactivity are lost and the power declines rapidly. The decline in the temperature curve has been observed in most of the transients ans may probably be attributed to instabilities in film boiling.

The pressure trace shown was obtained in the reflector surrounding the core with a transducer located 3 in. from the core. The initial pressure rise, produced by fuel plate expansion, is expotential. At the time where boiling starts, the maximum pressure at the surface of the core is proportional to the square of the reciprocal period. As nucleate boiling develops, a sharp increase in pressure is seen. The slope of the logarithm of the pressure versus time curve has been found experimentally to be greater than the reciprocal period, a_0, by a factor comprised between two and six. When boiling is established, the pressure decreases.

Figure 2 shows transient data on peak power, total burst energy, energy to the time of peak power, maximum fuel plate surface temperature in the central fuel assembly, and maximum pressure as functions of the reciprocal period, a_0, of the tests.

The peak power values are very nearly colinear and were thus amenable to excellent extrapolation during all tests. A least square fit of the data shows that the power varies as $a_0^{1.72}$. The value extrapolated for the destructive test is 6 % higher than the observed experimental value, 2.260 Mw.

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* Work done at National Reactor Testing Station, Idaho Falls, Idaho (U.S.A.) under auspices of the U.S. Atomic Energy Commission.

** Members, American Nuclear Society.

The total energy values and the energy to peak power values appear to maintain uniform slopes for a_0 less than about 135 sec^{-1}. However in this region both energy functions begin to rise more steeply with decreasing periods. This change in slope, which is a consequence of the extend of film boiling established in the core, will be examined later. It is to be noted that for the destructive test, while the energy to the time of peak power is within 6 % of the extrapolated value, the experimental total energy is 20 % lower than the extrapolated value. (Experimental value is 30.7 Mwsec compared to extrapolated value of 38 Mws.)

The first part of the temperature curve, up to $a_0 = 50$ sec^{-1} corresponds to reactor transients during which boiling did not occur. A break in the temperature curve at about 600° C indicates both the accumulation of energy in heat of fusion as the aluminum plates undergo internal melting, and a tendency towards failure of the plate-mounted thermocouples. This failure of the thermocouples is probably due to the differential expansion between the meat and the clad.

The upper part of the temperature curve, which is shown as a dashed line, is a representation of the probable temperature behavior at time where melting occurs. The plateau takes into account the relative constancy of the temperature during the melting process of the plate, and the last part of the curve has been drawn proportional to the energy absorbed by the plate after completion of melting. Notice that below melting, the temperature curve is not strictly parallel to the total energy curve; this reflecting both the variation with temperature of the heat capacity of the plate and the fact that a part of the total energy is absorbed in the water channels and therefore does not contribute to the heating of the plates.

The pressure data were obtained with a detector located 15 in. below the core. Maximum pressures obtained with other transducers decreased approximately proportionally to the inverse of the distance. Low pressures were recorded throughout the series, the maximum pressure recorded during the destructive test, before the time of the explosion, being about 35 psig. The maximum pressures were recorded at times always immediately after the onset of boiling in the core and are therefore to be associated with the boiling process.

As the period became shorter, a larger part of the core was submitted to boiling at the time of peak power. While for periods longer than 7.5 msec nucleate boiling starts after the time of peak power, for a 5 msec period test there was film boiling in the central fuel element and nucleate boiling in the rest of the core before the time of peak power. For the 3.2-msec period test film boiling was established in the central part of the core (that is the central fuel element and the elements surrounding it) 3 msec before peak power.

Another observation which was recorded throughout the series was the power burst shape. A systematic change in the power burst shape was observed as the period decreased below about 9 msec. This was manifest as a broadening of the burst and as a subsequent power decline, as can be seen in figure 3 where the power curves have been normalized to peak power in magnitude and where the abscissa is in periods. It is seen that, after passing through peak power, high power levels were momentarily sustained prior to the fast decline which normally took place. For periods shorter than 4.6 msec, where film boiling is established in the central part of the core before peak power, the broadening of the burst is seen to occur equally before peak power. Similar observations can be made on figure 4 which shows the same curves as figure 3 but where the time scale is in milliseconds instead of periods. In the region of time just before peak power, the curvature of the curves increases as the period becomes smaller. The power decrease is delayed and a sharp decline in power follows.

A possible explanation of the burst shape can be made from what is known about moderator boiling in the core. With shorter periods film boiling arises over larger portions of the core and is established earlier in the burst with respect to peak power. This film boiling can inhibit the formation of larger amount of steam and retard the self shutdown process, leading to the observed broadening of the power peak. The power decrease is equally delayed but, when a sufficient degree of superheat exists, it appears that instabilities in film boiling arise, resulting in the production of a larger amount of steam and therefore increasing the rate of production of shutdown reactivity.

The eventual sharp power decline after peak power, which becomes sharper with shorter periods. might thus be associated with a break in film boiling. The broadening at the burst corresponds, to larger liberation of energy as was seen by the break in the energy curve shown previously.

Broadening of the burst is tantamount to a less effective mode of shutdown at the time of peak power. It was effectively observed that for long periods, longer than 10-msec, there is a fairly rapid and smooth compensation of reactivity up to several dollars, as seen on figure 5 were the compensated reactivity is shown as a function of time for various periods. A knee (or plateau) was first observed to occur at about a 7.5-msec period and became more abrupt at shorter periods. Peak power occurs before formation of the plateau for periods longer than 5 msec. When the period is 5 msec peak power coincides with the beginning of the plateau and shutdown is consequently delayed by several milliseconds. When the period is 3.2 msec peak power occurs after formation of the plateau. This plateau which corresponds to a slower compensation of reactivity may possibly be attributed to the existing state of film boiling in the core.

Fuel plate inspection was made after any test in which the temperatures exceeded a few hundred degrees to ascertain the amount of damage sustained from thermal distortions.

For periods as short as 6 msec damage was restricted primarily to fuel plate thermal distortion and, in two cases (for a 6.4-msec and a 6.0-msec period) to a temporarily loss of tensile strength of the fuel plates. Cracking of the clad was first observed for a 6-msec test. In a 5-msec test, melting and fusing together of several fuel plates in the central fuel assembly was also observed. In the 4.6-msec test partial melting was obtained in 52 of the 270 plates affecting about 2 % of the fuel area; melting of the clad surface was extensive and most of the melted plates were fused to adjacent plates. Pictures of melted plates are shown in the movies which were taken. These movies present various aspects of the destructive test which will now be briefly described.

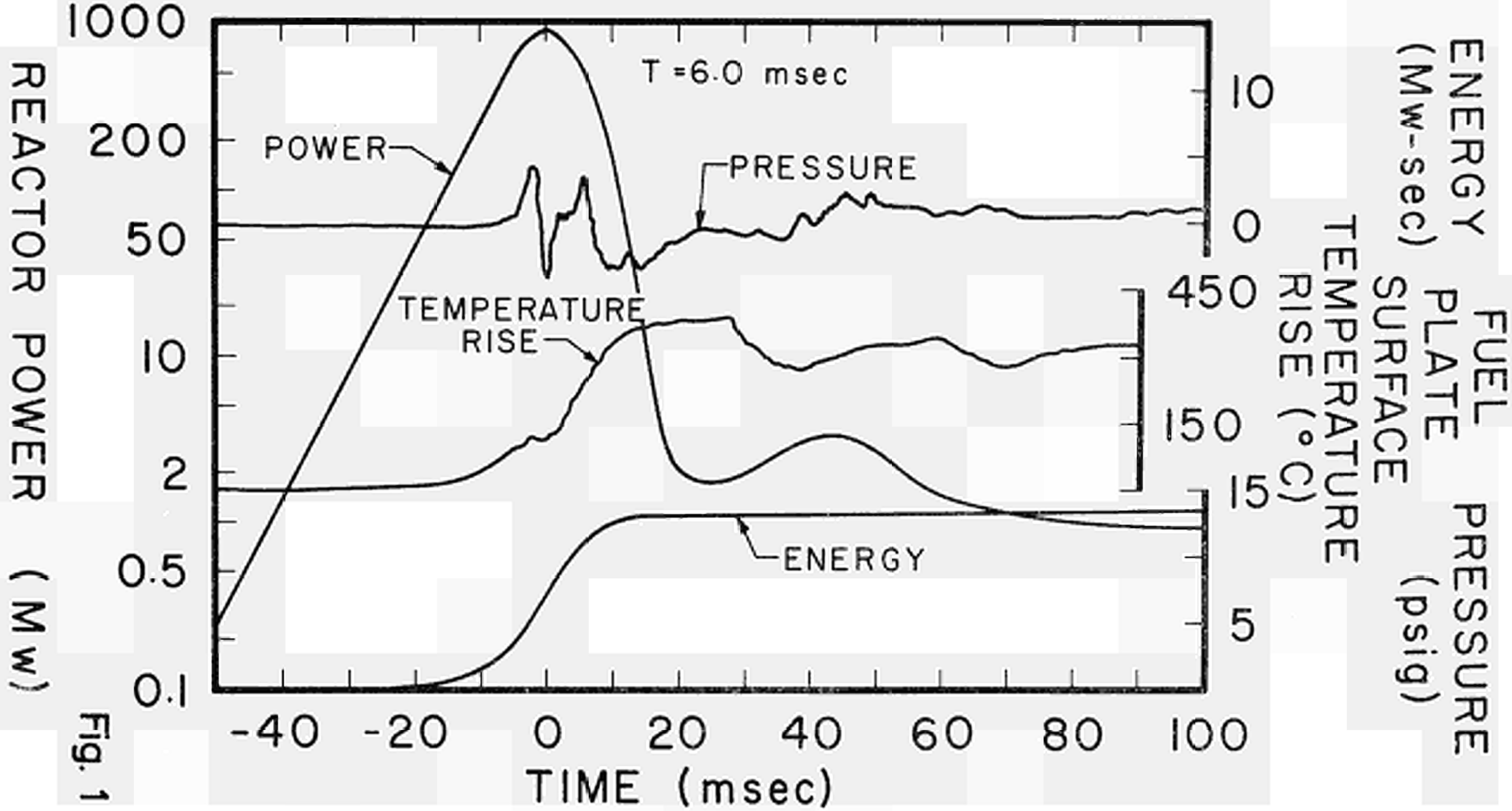
For the planned 3.3-msec test a fresh core was prepared, special instrumentation was installed, part of the building covering was removed and the surrounding area cleared to facilitate visual observation and photographic documentation of the test. Three high speed and six medium speed cameras were used during the test.

The destructive test was performed on November 5, 1962 under strict meteorological conditions. During and immediately after the test, the following observations were made: a loud noise was heard over the intercom, both television pictures were lost; control rod position indicator lights on the reactor console flashed on and off momentarily; and a water plume was observed to rise approximately 80 ft above the reactor building, at a rate later determined to be about 200 ft/sec at ground level.

Subsequent attempts to manipulate the control rods indicated that the control system was damaged. It was found that there was no positive indication of control rod seating; the B-10 pulse counters were saturated; and the operational neutron indicators were on scale and indicating a normal decay following a power excursion.

To insure that reentry was safe, the water in the reactor vessel was drained. Itinial reentry was accomplished within 4 hours after the test. Radiation levels were low enough to permit the reentry team to advance to the reactor building, remove the cameras, and make a rapid visual examination of the reactor.

The lower bridge which supported the control rod dashpots was seen to have been broken from its foundation in the concrete floor and thrust upwards causing extensive control rod damage. Visual observation into the vessel indicated that the core and all associated hardware had been violently disassembled. The movies clearly reveal the motion of the control rod bridge and the violent ejection of water from the reactor vessel.



REACTOR POWER (Mw)
1000
200
50
10
2
0.5
0.1
-40
-20
0
20
40
60
80
100
TIME (msec)
T =6.0 msec
POWER
PRESSURE
TEMPERATURE RISE
ENERGY
ENERGY (Mw-sec)
10
0
FUEL PLATE SURFACE TEMPERATURE RISE (°C)
450
150
15
PRESSURE (psig)
15
5

Fig. 1

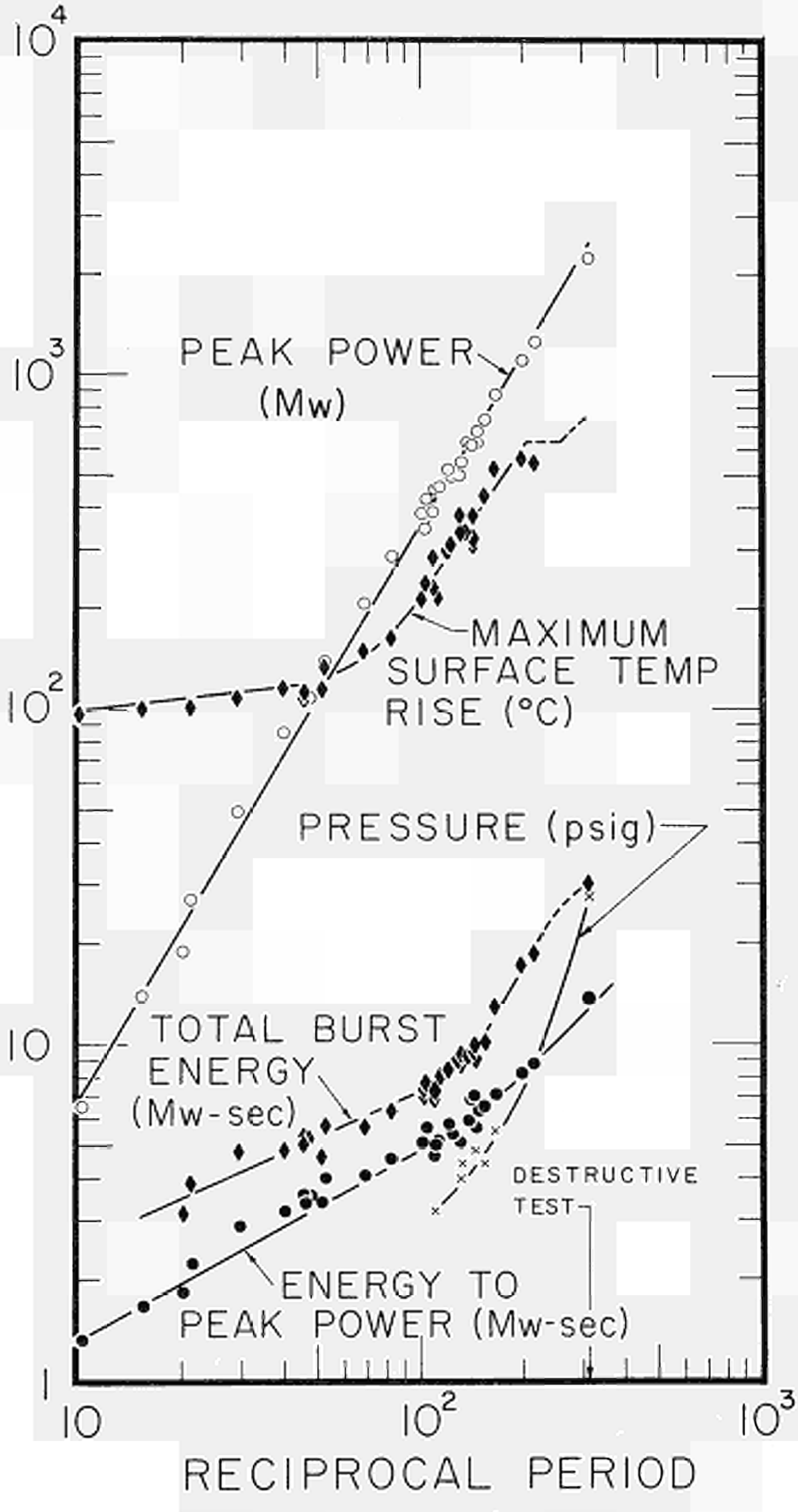

10^4
10^3
10^2
10
1
10
10^2
10^3
PEAK POWER
(Mw)
MAXIMUM
SURFACE TEMP
RISE (°C)
PRESSURE (psig)
TOTAL BURST
ENERGY
(Mw-sec)
DESTRUCTIVE
TEST
ENERGY TO
PEAK POWER (Mw-sec)
RECIPROCAL PERIOD
α_0 (sec^{-1})

Fig. 2

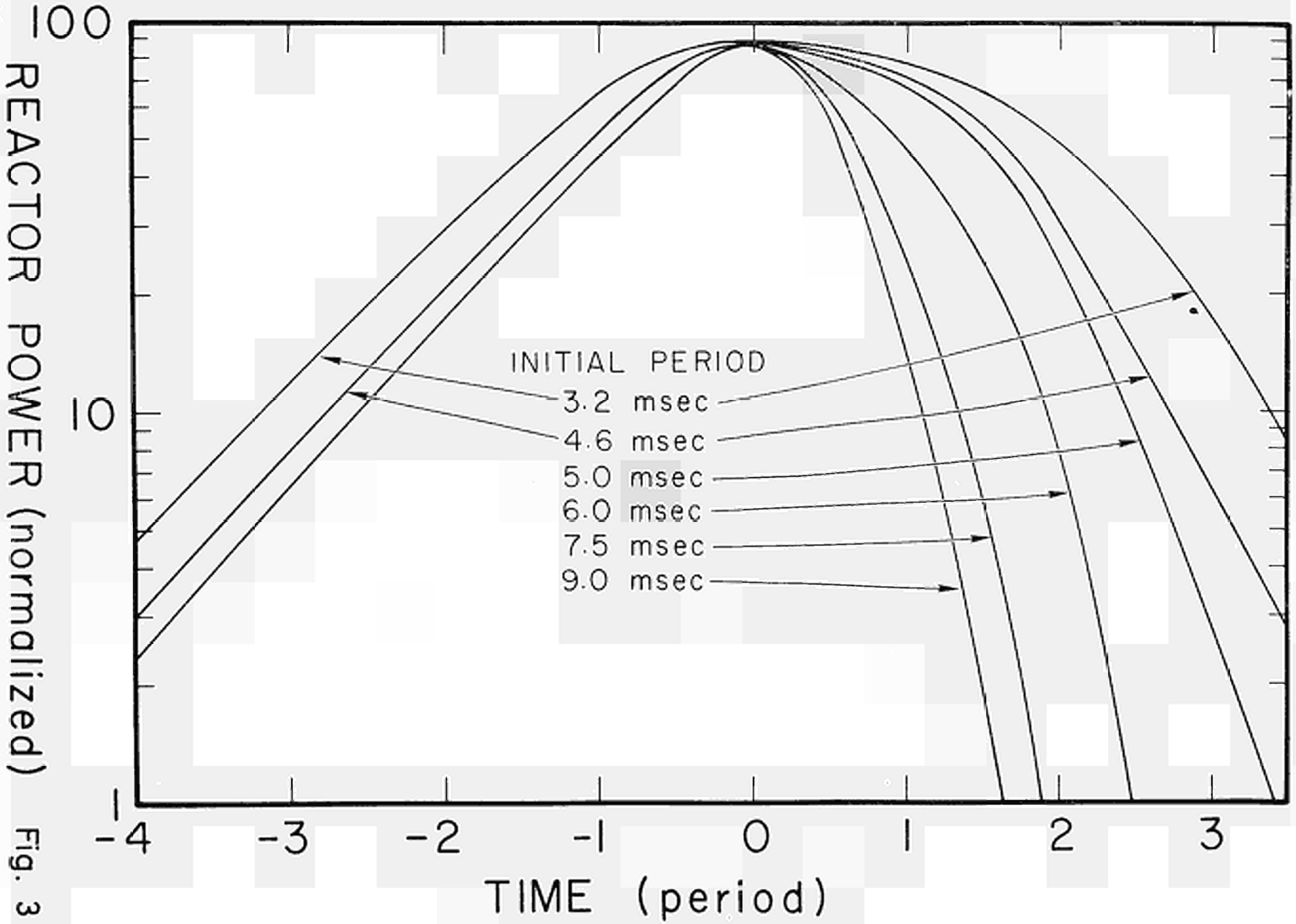

100
10
1
REACTOR POWER (normalized)
INITIAL PERIOD
3.2 msec
4.6 msec
5.0 msec
6.0 msec
7.5 msec
9.0 msec
-4
-3
-2
-1
0
1
2
3
TIME (period)

Fig. 3

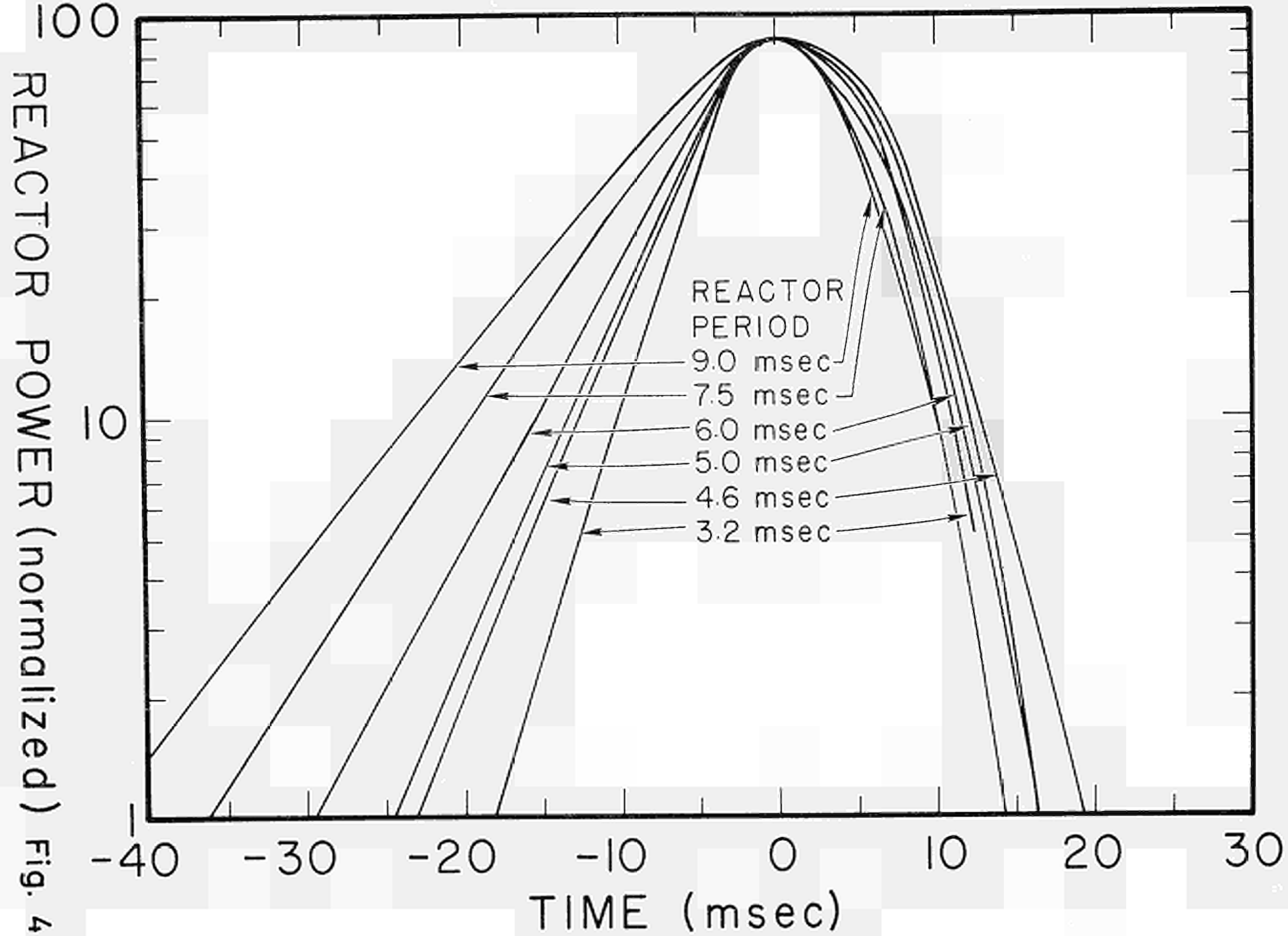

100
10
1
REACTOR POWER (normalized)
-40
-30
-20
-10
0
10
20
30
TIME (msec)
REACTOR PERIOD
9.0 msec
7.5 msec
6.0 msec
5.0 msec
4.6 msec
3.2 msec

Fig. 4

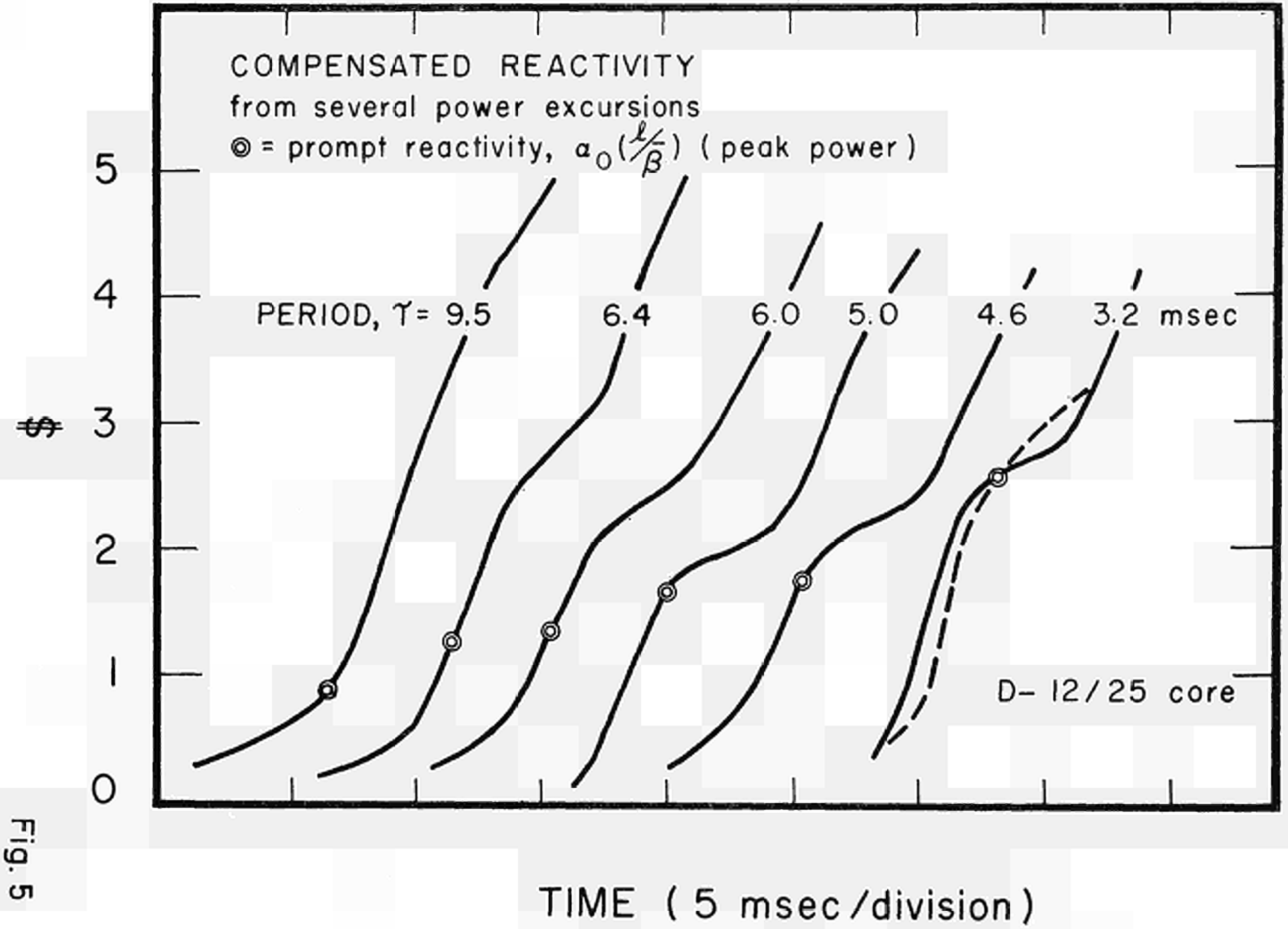

COMPENSATED REACTIVITY
from several power excursions
◎ = prompt reactivity, $\alpha_0(\ell/\beta)$ (peak power)
PERIOD, τ = 9.5
6.4
6.0
5.0
4.6
3.2 msec
D- 12/25 core
$
0
1
2
3
4
5
TIME (5 msec/division)

Fig. 5