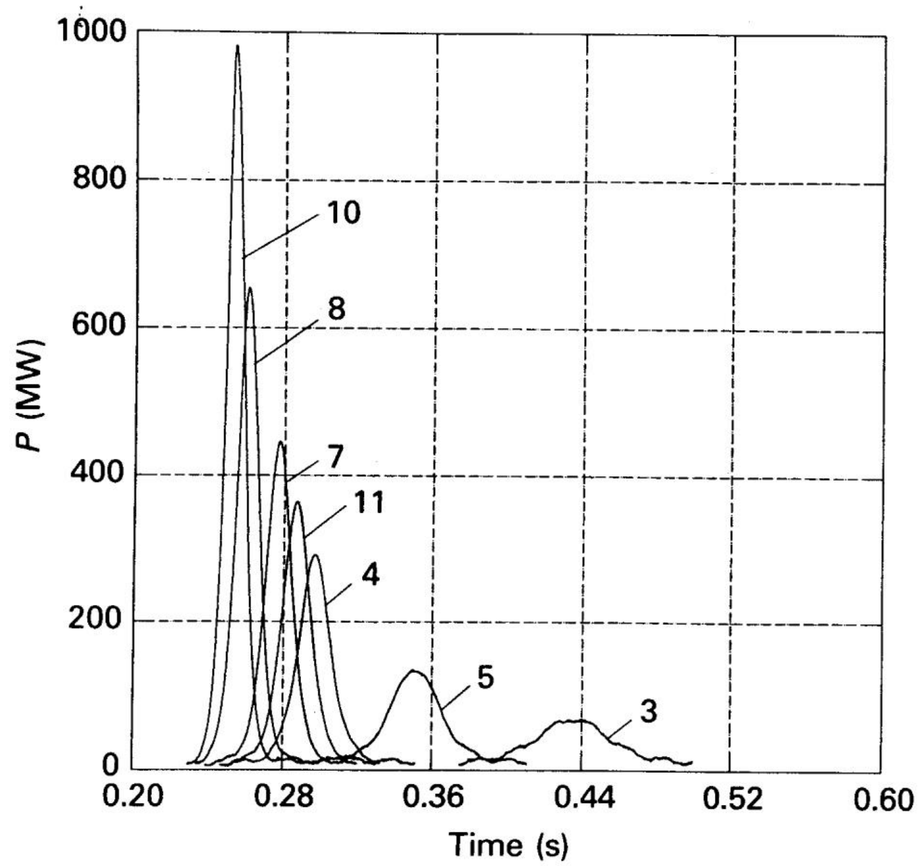
Luka Snoj
Andrej Trkov

PULZNI EKSPERIMENT



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KAZALO

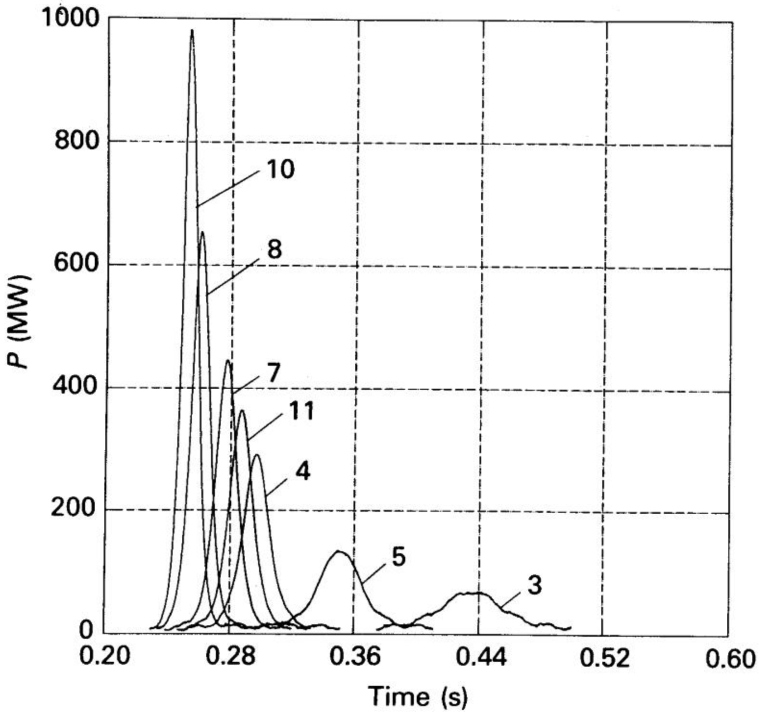
1 KRATEK OPIS IN NAMEN VAJE

Namen vaje je eksperimentalna preveritev fizikalnega modela, s katerim lahko popišemo parametre reaktorja (maksimalna moč, sproščena energija) pri pulziranju.

2 FIZIKALNI OPIS

Pulzni eksperiment se izvaja na reaktorju TRIGA. Podroben fizikalni opis reaktorja in pulziranja je podan na spletni strani http://www.rcp.ijs.si/ric/pulse_operation-s.html. V nadaljevanju je podan kratek povzetek.

Reaktor TRIGA je zgrajen tako, da lahko zelo hitro izvlečemo (pnevmatsko izstrelimo) eno od kontrolnih palic, ki jo imenujemo pulzna ali tranzientna palica. Reaktor postane v kratkem času močno nadkritičen in moč začne eksponencialno naraščati s časovno konstanto nekaj ms. Moč naraste za nekaj dekad. Skupaj z močjo pa začne naraščati tudi temperatura, ki povzroči povečanje absorpcije nevtronov predvsem zaradi Dopplerjevega efekta. Ko se temperatura dovolj poveča, se verižna reakcija upočasni ali prekine in moč se zmanjša na začetni nivo. Tako dobimo kratek a visok pulz moči. Posnetki časovnega poteka moči med pulzom so prikazani na Sliki 1 v prilogi za več pulzov, ki se med seboj razlikujejo po vstavljeni reaktivnosti.



Slika 1: Izmerjena moč v odvisnosti od časa za pulze z različnimi vstavljenimi reaktivnostmi.

Celotna sproščena energija v pulzu je relativno majhna (tipično 10 MWs) in ne povzroči poškodb reaktorja. Sproščena energija in višina pulza sta odvisni od tega, kolikšna je reaktivnost reaktorja po izstrelitvi pulzne palice. Reaktivnost lahko spreminjamo tako, da pulzno palico ne izstrelimo do konca iz sredice, ampak samo do določenega položaja. Namen vaje je preveriti zvezo med pulzno reaktivnostjo in osnovnimi parametri pulza, ki nam jo podaja teoretični model.

Časovni potek pulza lahko izračunamo s pomočjo enačbe točkovne kinetike, če zanemarimo prispevek zakasnelih nevtronov in če upoštevamo, da se med pulzom reaktivnost zmanjšuje sorazmerno s sproščeno energijo. Obe predpostavki sta fizikalno upravičeni: prva zato, ker je pulz kratek v primerjavi s časom, ko se sprostijo zakasneli nevtroni (10 μs) in druga zato, ker je pulz tako kratek, da v tem času ne pride do znatnega prenosa toplote iz goriva in se torej vsa sproščena energija v resnici porabi za gretje goriva. Zaradi tega tak približek imenujemo tudi adiabatski, celotni teoretični model pa ima ime Fuchs-Hansenov. Izpeljava je podana v dodatku, za razumevanje in izvedbo vaje pa povzemimo samo nekatere pomembne rezultate:

- višina pulza je sorazmerna kvadratu "promptne reaktivnosti" ρ'
- sproščena energija je linerno odvisna od ρ'
- širina pulza je obratno sorazmerna ρ'
- časovna konstanta pri eksponentnem naraščanju moči (imenujemo jo tudi 'perioda'), je sorazmerna ρ'

Promptna reaktivnost ρ' je po definiciji (glej prilogo) enaka dejanski vstavljeni reaktivnosti, zmanjšani za β,

$$\rho' \equiv \rho - \beta \tag{1.1}$$

kjer je β efektivni delež zakasnelih nevtronov, ki znaša za reaktor TRIGA β =0.007. V enotah β reaktivnost običajno tudi merimo. Kot oznaka za to enoto se je zakoreninil dolarski znak, torej 1 β ≡ 1 \$ ≡ 0.007, da bo zmeda večja pa se uporablja še 'enota' pcm$\equiv 10^{-5}$, torej 1 β ≡ 1\$ ≡ 700 pcm ≡ 0.007. Pri vajah bomo izvajali pulze s promptno reaktivnostjo ρ' med 0 in ρ'. Celotna reaktivnostna vrednost pulzne palice je približno 3 β, kar pomeni, da bomo pri največjih pulzih pulzno palico skoraj v celoti izstrelili iz rektorja.

Reaktivnost ρ je količina, ki meri odstopanje reaktorja od kritičnosti in jo izrazimo s pomnoževalnim faktorjem reaktorja k kot

$$\rho \equiv \frac{k-1}{k} \tag{1.2}$$

pomnoževalni faktor k pa je definiran kot

$$\mathrm{k} \equiv \frac{\text{število nevtronov j-te generacije}}{\text{število nevtronov } (\text{j-1}) \text{ generacije}} = \frac{\text{število cepitev}}{\text{število absorpcij + pobeg}} \tag{1.3}$$

Če bomo izvedli pulz s promptno reaktivnostjo 1β β, bo torej imel reaktor po izstrelitvi pulzne palice pomnoževalni faktor k ≈ 1.014. Po definiciji pomnoževalnega faktorja to pomeni, da bo vsaka generacija nevtronov za faktor 1.014 številčnejša od prejšnje. Ker je življenjski čas ene generacije približno 10 μs, število nevtronov in s tem število cepitev in sproščena moč hitro, eksponencialno naraščajo.

S pomočjo zgornjih relacij, ki jih formalno podajajo enačbe 9.82-9.89 v prilogi (Bell-Glastone), lahko določimo nekatere fizikalne lastnosti reaktorja. Iz zveze za totalno energijo lahko določimo efektivni temperaturni koeficient reaktivnosti γ (9.89), iz enačbe za širino pulza na polovični višini (izpelji!) ali s pomočjo enačbe 9.88 za višino pulza pa še življenjski čas promptnih nevtronov Λ.

3 IZVEDBA VAJE

3.1 Splošni napotki

Reaktor naj bo hladen in nezastrupljen, da ne moti meritev počasi spreminjajoča se negativna reaktivnost zaradi cepitvenega produkta ^{135}Xe. Z reaktorjem upravlja operater. Navodila operaterju daje vodja vaj oziroma demonstrator. Za vstop v halo reaktorja in na ploščad je potrebno dobiti dovoljenje operaterja.

Vse meritve si najprej zapiši in šele nato opravi preračune. Zraven meritev piši tudi komentarje, kaj si spremenil, kaj si izmeril in podobno.

3.2 Oprema pri vaji

- Reaktor TRIGA z vsemi sistemi, strukturami in komponentami
- procesni računalnik

3.3 Napotki

Izvedli bomo več pulzov z različno reaktivnostjo. Pri vsakem pulzu zabeleži:

- položaj pulzne palice pred izstrelitvijo in po njej
- položaj vseh ostalih palic
- moč reaktorja pred pulzom (biti mora zanemarljiva, 1-100W)
- temperaturo goriva pred pulzom
- temperaturo hladilne vode v reaktorju pred pulzom in po njem
- sproščeno energijo v pulzu (odčituj z NVT kanala)
- maksimalno moč v pulzu (odčituj z NV kanala)
- maksimalno temperaturo goriva po pulzu (odčitavaj z rekorderja)

Vsi instrumenti, s katerih odčitavaš, so na komandnem pultu reaktorja. Promptno reaktivnost določi iz položaja pulzne palice po izstrelitvi s pomočjo umeritvene krivulje za to palico, ki podaja zvezo med (negativno) reaktivnostjo palice in njenim položajem.

Časovni potek pulzov bomo v digitalizirani obliki posneli na procesni računalnik. Podatke bomo obdelali po končanem eksperimentu in bodo na voljo pri vodji vaje ali v komandni sobi. Ker so bolj natančni kot odčitki z merilnih instrumentov, jih uporabi za obdelavo rezultatov.

4 POROČILO O VAJI

1. Nariši naslednje diagrame:
    a. sproščena energija v pulzu v odvisnosti od promptne reaktivnosti,
    b. maksimalna moč v odvisnosti od promptne reaktivnosti
    c. maksimalna temperatura goriva po pulzu v odvisnosti od promptne reaktivnosti
    d. širina pulza na polovični višini kot funkcija promptne reaktivnosti.

2. Uporabi rezultate Fuchs-Hansenovega modela (enačbe 9.80 do 9.89 v prilogi) in oceni efektivni koeficient reaktivnosti temperature goriva γ in življenjski čas promptnih nevtronov Λ. Oceni napako in komentiraj odstopanja od modela. Določi začetno periodo naraščanja moči (9.82).

3. Oceni negotovosti rezultatov ter komentiraj rezultate in eksperiment

4. Razmisli, kaj bi lahko izmerili ali raziskali s pomočjo pulznega eksperimenta (v fiziki trdne snovi, jedrski fiziki, biologiji, medicini, kemiji, strojništvu,...). Skušaj biti izviren!

5 LITERATURA

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3. MELE, Irena, RAVNIK, Matjaž, TRKOV, Andrej. TRIGA Mark II benchmark experiment. Part II, Pulse operation. Nucl. technol., 1994, vol. 105, str. 52-59
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It should be mentioned that the partial meltdown of the core of EBR-I, Mark II, which occurred in 1956, was not due to the instability referred to above. The overheating developed during an experimental power excursion and was caused by a combination of circumstances which could have been avoided.[59] However, because of the meltdown, it was not possible to examine the feedback mechanisms in this case.

The Experimental Boiling Water Reactor

In boiling water reactors, the formation of steam voids represents an important feedback mechanism whereby the reactor power affects the reactivity. In the early consideration of such reactors,[60] it was accepted that they should be designed so that formation of steam voids would decrease the reactivity. It was feared, however, that because of the time delays between power generation and bubble formation, the reactor might exhibit instability or oscillatory behavior (§9.4g).

Measurements of the transfer function were made on the Experimental Boiling Water Reactor (EBWR), a heterogeneous reactor moderated and cooled by ordinary water, with natural (convection) circulation. Some of the results obtained, at an operating pressure of 550–600 psig, are shown in Fig. 9.18; there are indications of a resonance at a power close to 20 megawatts, and it is quite marked at 50 megawatts. Fairly good agreement with the observed transfer functions was obtained from calculations based on feedback mechanisms arising from various effects, including the formation of steam voids.[61]

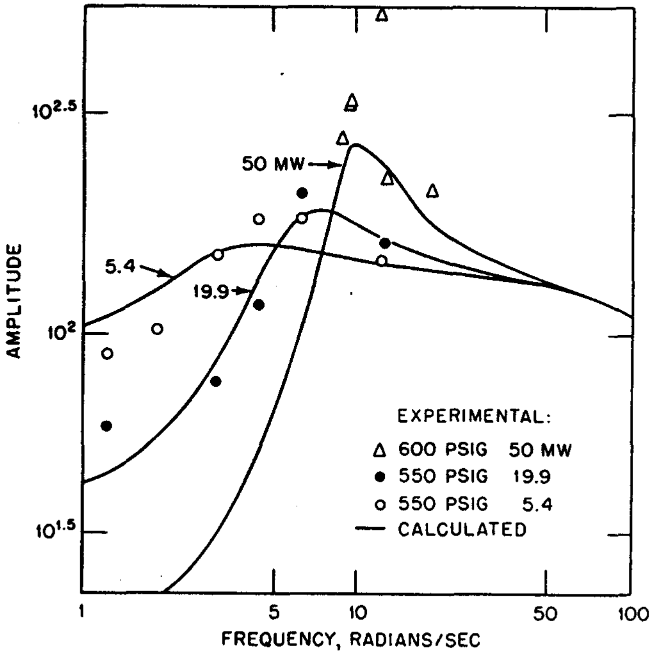

FIG. 9.18 EXPERIMENTAL AND CALCULATED TRANSFER FUNCTIONS FOR THE EBWR (AFTER T. SNYDER AND J. A. THIE, REF. 61).

The resonances in Fig. 9.18 occur at frequencies in the vicinity of 10 radians (1 or 2 cycles) per sec; the oscillation period is thus 0.5 to 1 sec, which may be too short to be controlled. Hence, the design or operating conditions of a reactor must be adjusted to avoid the instability.[62] Fortunately, it is possible to design boiling water reactors so that these instabilities do not occur even at high power, and currently such reactors are operated at power levels up to 1000 megawatts.

In addition to the oscillations referred to above, as implied by the transfer function, spontaneous power oscillations of small amplitude were observed in the EBWR at about the same frequencies. But they presented no hazard during operation and they are not important in modern boiling water reactors.

9.6 LARGE POWER EXCURSIONS

9.6a The Fuchs-Hansen Model

Large power excursions are of interest in a variety of situations, both real and hypothetical.[63] These include (*a*) pulsed reactors, such as Godiva, TREAT, and TRIGA, (*b*) intentional large increases in reactivity, as in the SPERT, BORAX, and KEWB tests, and (*c*) the analysis of postulated reactor accidents. In all of these cases a system is brought rapidly to a state above prompt critical, so that the neutron population then begins to multiply at a rapid rate. The normal cooling cannot remove the heat being generated and so the temperature rises until some compensation sets in that reduces the reactivity to zero, thereby terminating the excursion. In practice, the manner in which the reactivity is reduced may depend in detail on the reactor design and on the rate at which the neutron population (and power) increases. Hence, for computing the reactivity reduction, a point-reactor model may not be adequate. Nevertheless some useful conclusions can be drawn from such a model of the excursion in which the reactivity reduction is included as a simple feedback parameter. This treatment is sometimes known as the Fuchs-Hansen model,[64] although similar conclusions were reached independently.[65]

Suppose that the reactivity is suddenly increased, i.e., as a step function, thus bringing the value to ρ' above prompt critical, i.e., $\rho' = \rho - \bar{\beta}$, where ρ is the actual reactivity. The assumption is now made that the feedback reactivity is proportional to the energy generated. Since the response to the sudden increase in reactivity is fast, it is justifiable to neglect the delayed neutrons while the transient is under way; hence, equation (9.8) becomes

$$\frac{dP(t)}{dt} = \frac{\rho(t) - \bar{\beta}}{\Lambda} P(t). \qquad (9.80)$$

The reactivity at time t is given by

$$\rho(t) - \beta = \rho' - \gamma E(t) = \rho' - \gamma \int_0^t P(t')\,dt', \tag{9.81}$$

where γ represents the energy feedback coefficient and $E(t)$ is the total energy generated between time zero and time t. Upon combining equations (9.80) and (9.81), the result is

$$\frac{dP(t)}{dt} = P(t)\left[\alpha_0 - b\int_0^t P(t')\,dt'\right], \tag{9.82}$$

where

$$\alpha_0 = \frac{\rho'}{\Lambda} \quad \text{and} \quad b = \frac{\gamma}{\Lambda}.$$

It will be noted that at $t = 0$, $dP(t)/dt = \alpha_0 P(t)$, and hence α_0 is the initial multiplication rate constant.

Equation (9.82) can be solved in closed form (see §9.7 for the solution); it is found that

$$E(t) = \frac{\alpha_0 + c}{b}\left[\frac{1 - e^{-ct}}{Ae^{-ct} + 1}\right] \tag{9.83}$$

and

$$P(t) = \frac{2c^2 A e^{-ct}}{b(Ae^{-ct} + 1)^2}, \tag{9.84}$$

where

$$c \equiv \sqrt{\alpha_0^2 + 2bP_0} \tag{9.85}$$

and

$$A \equiv \frac{c + \alpha_0}{c - \alpha_0}. \tag{9.86}$$

A number of interesting results can be derived from these solutions. In a pulsed reactor, it is the general practice to start from a low power in order to obtain a good approximation to a step function increase in reactivity. By starting from a high power, it may not be possible to add reactivity fast enough to do this. If the initial power is low, however, it is easier to increase the reactivity before the feedback term, i.e., $\gamma E(t)$ in equation (9.81), becomes appreciable; there is then effectively a step increase in the reactivity. In fact, it has been found experimentally,[66] in agreement with theory,[67] that a pulsed system, such as the Godiva device of unreflected uranium-235 metal (§5.4c), can be operated with such a weak neutron source that there is a high probability of assembly to a prompt critical state before a divergent chain reaction begins.

If, therefore, the power is assumed to be low before the reactivity is increased, $c \approx \alpha_0$ from equation (9.85), and then from equation (9.86)

$$A \approx \frac{2\alpha_0^2}{bP_0} \gg 1.$$

It is seen, therefore, from equations (9.83) and (9.84) that, at early times, $E(t)$ and $P(t)$ increase exponentially with time in proportion to $e^{\alpha_0 t}$. The power then reaches a maximum at a time which can be found by setting $dP(t)/dt$ equal to zero, i.e.,

$$\frac{dP(t)}{dt} = \frac{2c^3 A}{b}\,\frac{e^{-ct}[Ae^{-ct} - 1]}{[Ae^{-ct} + 1]^3} = 0.$$

Hence, the power is a maximum when

$$Ae^{-ct} = 1,$$

so that

$$t_{P_{\max}} = \frac{\ln A}{c} \approx \frac{\ln A}{\alpha_0}. \tag{9.87}$$

The value of the peak power is thus found from equation (9.84) to be

$$P_{\max} \approx \frac{\alpha_0^2}{2b} = \frac{(\rho')^2}{2\Lambda\gamma}. \tag{9.88}$$

At late times, beyond the maximum, the power decreases exponentially as $e^{-\alpha_0 t}$; the power pulse (or burst) is, therefore, approximately symmetrical in time. The power does not drop directly to zero but it tails off because of the fissions due to delayed neutrons, which have been neglected in the foregoing treatment. The contribution of these neutrons can be determined by calculating the number of delayed-neutron precursors produced during the prompt pulse and treating their decay as a neutron source at late times.[68]

The total energy released up to the time the power reaches its peak value, i.e., at the time given by equation (9.87), is obtained from equation (9.83) as

$$E(t_{P_{\max}}) \approx \frac{\alpha_0}{b}.$$

The total energy generated is the value at asymptotically large times, namely,

$$E(t) \xrightarrow[t \to \infty]{} \frac{2\alpha_0}{b} = \frac{2\rho'}{\gamma}. \tag{9.89}$$

This again indicates the symmetry of the power pulse, apart from the effect of delayed neutrons.

The results described above have an important bearing on the problem of reactor accidents arising from sudden reactivity excursions. In an excursion starting at a low operating power, the total energy release, as just seen, is $2\rho'/\gamma$,

and is thus independent of Λ, the prompt-neutron lifetime. The essential parameters are then the excess reactivity and the feedback coefficient, and it is immaterial whether the reactor is thermal ($\Lambda \approx 10^{-4}$ to 10^{-3} sec) or fast ($\Lambda \approx 10^{-8}$ to 10^{-7} sec). The peak power, on the other hand, is inversely proportional to the prompt-neutron lifetime. This indicates that the peak pressures and accelerations, caused by material expansion, would be much higher in a reactivity excursion in a fast reactor than in a thermal reactor even though the energy releases may be comparable. In fact, in some models, the peak pressure is found to be proportional to dP/dt and hence, approximately, to $(\rho')^3/\Lambda^2\gamma$; it is thus strongly dependent on the neutron lifetime.

It will be observed that the peak power, peak pressure, and total energy released in the excursion are all inversely proportional to γ, the energy feedback coefficient. From the point of view of reactor safety, it is desirable therefore that the system should have a large (negative) energy coefficient of reactivity. Since the temperature increase will be roughly related to the total energy release, this means a large negative reactivity temperature coefficient will tend to minimize the consequences of a reactivity excursion.

Although the foregoing discussion has referred in particular to a sudden (or step) increase in reactivity, it is also applicable, under certain conditions, to ramp reactivity excursions, i.e., in which the reactivity is increased at a constant rate. If the system exceeds prompt critical before the reactivity feedback becomes appreciable, then the behavior is similar to that for a sudden excursion.[69]

9.6b Pulsed Fast Reactor

The model described above has the advantage of containing only two parameters, namely, $\alpha_0(= \rho'/\Lambda)$ and $b(= \gamma/\Lambda)$. Because of its simplicity and physical content, it has been used extensively for the interpretation of pulsed reactor experiments.[70] A good example is provided by Godiva II, a critical assembly of bare, highly enriched uranium (about 93.5% uranium-235) metal. By means of adjustable rods of the same material, the reactivity can be increased suddenly by specified amounts, thereby causing a power excursion. This is terminated by the increase in temperature causing the fuel to expand, thus decreasing its density. The resulting decrease in the macroscopic cross sections produces a negative feedback of reactivity which makes the assembly subcritical within a short time. The power production (or fission rate) is determined as a function of time by neutron and gamma-ray detectors; the value of α_0 is calculated from the initial increase in the fission rate.

The results of a series of pulse experiments with Godiva II are shown in Fig. 9.19 for the various indicated values of $1/\alpha_0$, the initial reactor period.[71] The time at which the power maximum is attained is approximately inversely proportional to α_0 and the maximum power is roughly proportional to α_0^2, as required by equations (9.87) and (9.88). There is some deviation from theory

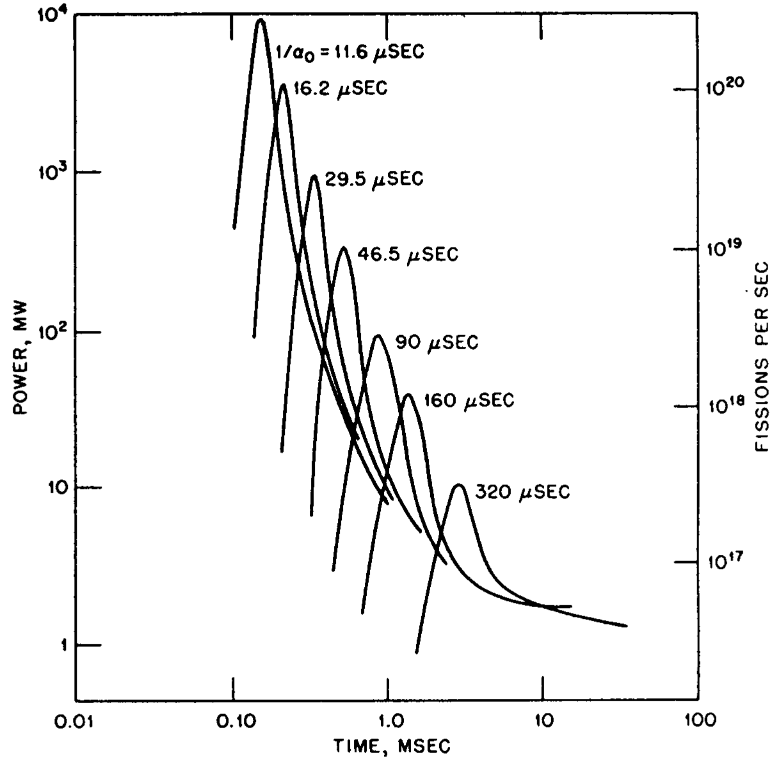

FIG. 9.19 RESULTS OF PULSE EXPERIMENTS IN THE GODIVA-II ASSEMBLY (AFTER T. F. WIMETT AND J. D. ORNDOFF, REF. 71).

for the more violent excursions, with α_0 greater than 5×10^4 sec^{-1} ($1/\alpha_0$ less than 20 μsec), to which reference will be made below. The power pulses are seen to be roughly symmetrical about the maximum except for late times when the delayed neutrons become important.

The total energy generated per pulse was computed both from the increase in temperature and the total activity induced in sulfur by the (n, p) reaction. The results are plotted, on linear scales, in Fig. 9.20[72]; the circles are experimental points and the full line is derived from equations (9.88) and (9.89) as $4P_{\max}/\alpha_0$. The agreement between observation and the simple theory is seen to be good up to α_0 values of about 5×10^4 sec^{-1}. The deviations for more violent excursions are due to inertial effects which slow down the expansion; in other words, the expansion, and hence the associated negative reactivity feedback, lags behind the temperature of the fuel. This time delay may be expected to be significant when $1/\alpha_0$ is comparable to (or less than) the time required for a sound wave to