

LMFBR--Safety: Base Technology  
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ANL--87-42

DE88 004142

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ANL-87-42

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Review of the Analyses of the  
Doppler-Effect Measurements in SEFOR

by

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July 1987

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## ABSTRACT

The SEFOR experimental results and the three original analyses are reviewed and discussed. The emphasis of the review is placed on aspects that are pertinent to a possible modern re-analysis of the experimental results. Looking at the analysis results in terms of zero and first order effects shows that the zero order effects, the Doppler constant of the two SEFOR cores, are obtained by the three analyses in satisfactory agreement. But the first order effects, the temperature variation of this Doppler-constant quantity, cannot be determined with any informative accuracy. Since this is likely due to limitations in the experiments, a re-analysis - except for methodological reasons - does not appear to be fruitful.

## I Introduction

After the transition from metal to oxide fuel around the time of the Vienna Conference on Fast and Intermediate Reactors in 1961, the Doppler reactivity effect gained in its importance as a reliable feedback mechanism, to provide inherent protection against conjectured superprompt critical reactivity transients. The use of dioxide fuel, with its two oxygen atoms per actinide atom, had as a consequence a considerable moderation of the neutron spectrum. Then, the negative Doppler feedback became more pronounced than for metal fuel.

The calculations of the Doppler feedback reactivity at that time were of questionable accuracy; the resonances in U-238 were resolved only up to about 2 keV and in Pu-239 only up to about 100 eV. Furthermore, the only experiments on Doppler feedback at the time were done with small heated samples with questionable applicability to whole core transients. Thus, there was an urgent need for integral, whole core, Doppler feedback experiments that on the one hand demonstrated the reliability of the inherent Doppler feedback and on the other hand provided an accurate quantification of the Doppler coefficient as such. This led to the joint U.S.(GE)-German SEFOR project, initiated in 1963 (Ref. 1), with SEFOR being the "Southwest Experimental Fast Oxide Reactor".

After SEFOR was built by General Electric, on schedule and within budget, a highly successful three-year experimental program commenced in 1969. The design, the lay-out of the experimental program and the analysis of the eventual experimental results have been published in several reports and conference papers (e.g. Refs. 2 to 7).

About 15 years have elapsed since the successful SEFOR experiments. There have been considerable changes during this time, which include:

\* Substantial improvements in the nuclear data base,

\* considerable advances in the computational capabilities

(note, some of the original SEFOR calculations were done in one-dimensional approximations with 18 energy groups),

\* increased accuracy and reliability requirements,

\* an even stronger emphasis on inherent safety.

This naturally brings up the question, as posed by several participants of the 1983 "Jackson Hole Colloquium on Fast Reactor Physics: The Doppler Effect in LMFBRs" (Ref. 8): can a modern re-analysis of the original SEFOR experimental results benefit the present LMR development? Additional input for an answer to this question is provided by the discussion of the current status of Doppler coefficient experiments and calculations in the review paper, Ref. 9.

The goals of this paper are a critical review of the original SEFOR work and a partial re-analysis. The review of earlier work is therefore combined with discussions and evaluations of aspects that have a bearing on the question of a modern re-analysis.

Section II covers those aspects of the SEFOR design that are relevant for a decision on a re-analysis effort. Also included in Sec. II is a review of some pre-analyses. Section III describes the three original transient analyses. The results of these evaluations are summarized in Sec. IV and combined with discussions and conclusions .

## II The SEFOR Design and Pre-Analyses

### II.1 The Rationale Behind the SEFOR Design

The goal of the SEFOR project, i.e. the experimental determination of the Doppler reactivity feedback for a large mixed oxide fueled fast reactor, determined its essential design features. For economic reasons, the features of a large reactor that are essential for the magnitude of the Doppler feedback had to be modeled in a small reactor. The maximum power was set to be 20 MWth.

The fuel had to be mixed  $\text{PuO}_2\text{-UO}_2$  oxide. The fuel elements were rods with a diameter close to one inch; a maximum of 640 rods in the core. The fuel rods were arranged in groups of six or seven per subassembly, with a total of 109 subassemblies. The center rod in about 40% of the subassemblies was a BeO rod in Core I. In Core II the BeO rods were replaced by stainless steel rods (SS-316).

The large diameter of the fuel rods had two major advantages:

- (1) The temperature buildup across the rod can reach the high temperatures of an operating reactor with about 1/16 of the power density (the square of the ratio of the fuel pellet diameters; pellet diameter in SEFOR: 0.88 inch, about four times the diameter of power reactor pellets). For the parabolic shape of the temperature profile across the rod one establishes the important characteristic that in SEFOR one has about the same fuel-volume exposed to a certain temperature as in an operating reactor.

(2) The mean time for heat release from fuel rods of one inch diameter is about 30 seconds (it is proportional to the square of the radius). Thus, during rapid transients most of the incrementally produced energy remains in the fuel and activates the Doppler feedback.

Core height and diameter were chosen to be about the same (about 90 cm). The core was surrounded by a nickel reflector and was also reflector controlled. Both measures allow criticality to be achieved with a relatively low enrichment, closer to the one in a commercial reactor than one might expect for such a small core. The fissile fuel fraction was about 19%.

The neutron spectrum for a small reactor with its large leakage can be fairly hard. As most of the Doppler feedback comes from the low end of the spectrum (about 80% from neutron energies below 10 keV) it was very important to soften the neutron spectrum so that it comes close to the one in a larger reactor. To this end the Core I was spiked with BeO rods, amounting to about 6% volume fraction. As the BeO rods were replaced by SS-rods in Core II, the spectrum hardened considerably as it is desirable for a possible application to medium-size metal fueled LMRs.

The core average coolant temperature was 760°F. The mixed temperature rise across the core was about 120°F.

## II.2 The Steady State Nuclear Analysis

The steady state nuclear analysis for SEFOR has been described in Ref. 2. Here is an excerpt of some of the aspects pertinent for this review. Some key nuclear parameters that are important for a possible application to the LMR are the following:

### (1) Fuel

The fuel was a fairly "clean" plutonium with 90.76% Pu-239, 8.51% Pu-240, 0.68% Pu-241 and 0.03% Pu-242 (plus 0.01% Pu-238). The fissile fraction in the mixed oxide was 10.05%, counting also the 0.17% of U-235.

### (2) Fissions by Isotope

Fission occurred primarily in Pu-239 and U-238: Pu-239: 86%, Pu-240: 2%, U-235: 1%, U-238: 11%.

### (3) Neutron Spectrum (Core)

For a comparison with other LMRs the neutron spectrum as well as the fission rate spectrum are of importance. The core average flux integrals and the fission rates below three key energies are given in the following table .

Table I Neutron Fission Rate Spectra

upper energy ( $E_g$ )	1.35Mev	180keV	9.1keV
spectrum integral below $E_g$	89.9%	50.6%	8.5%
fission rate portion below $E_g$	80.5%	49.5%	20.0%

The fact that the fission rate portion above 1.35 MeV (19.5%) is nearly twice the corresponding spectrum integral (10.1%) is due to fast fission, primarily in U-238; the fact that the fission rate portion below 9.1 keV (20.0%) is more than twice the corresponding spectrum portion is due to the average  $1/v$  dependence of the fission cross section. For the corresponding contribution to the Doppler feedback the dominance of the low energy wing is even more pronounced (90% of the Doppler feedback come from neutrons below 9.1 keV). Thus, the comparison of the low energy wings of the spectra is very important for any application to modern LMRs.

#### (4) Beta-Effective

The calculation of  $\beta_{eff}$  (denoted by  $\beta$  here) is based on Keppin's data<sup>(10)</sup> for fast fission. The use of fast fission data is justified for U-238, but not for Pu-239. Only 20% of the fissions are fast fissions as indicated in Table I. About 50% of the fissions occur below 180 keV, and another 30% between 180 keV and 1.35 MeV, but on the average much closer to the spectrum midpoint at 180 keV than to 1.35 MeV. Therefore, thermal fission data are more appropriate. The reason is that delayed fission yield data change very little on a linear energy scale; and on a linear scale 180 keV is much closer to thermal energies than to 2 MeV.

The lower energy of the delayed (as compared prompt) neutrons is accounted for by a calculated 0.91 reduction factor of the physical  $\beta_k$  ( $\beta_k^{ph}$ ), which is assumed to be the same for all delayed neutron groups (k). This yields  $\beta = 0.0032$ . (The orginal data source for the neutron spectra was likely "Batchelor and McK. Hyder, 1956")

$$\beta_k = 0.91 \beta_k^{ph} (= \beta_{k,eff}) .$$

#### (5) Average Neutron Lifetime

The SEFOR mock-up in ZPR-3 gave for  $\lambda / \beta$  :

$$\lambda / \beta = 2.05 \cdot 10^{-4} s.$$

The calculated  $\beta$ - value was used to obtain

$$\lambda = 0.66 \mu s.$$

This compares well with a 60 group 2-dimensional calculation (0.65  $\mu s$  ); but the 1-dimensional calculation gave only 0.54  $\mu s$  .

As an experimental mock-up value was used for  $\lambda / \beta$ , and as the prompt kinetics is strongly determined by  $\lambda / \beta$ , the prompt kinetics predictions rely therefore on the accuracy of this experimental value. The subprompt critical transients however are virtually unaffected by the value of the lifetime. They depend on the delayed neutron data, on  $\beta$  as well as on  $\bar{\lambda}$  , the average delayed neutron-decay constant.

#### (6) Doppler Feedback Reactivity Isotopic Contributions

The small sample measurements in the ZPR-3 mock-up are believed to show that there is no contribution to the Doppler feedback from Pu-239. Thus, all Doppler feedback is assumed to come from U-238 (96%) and Pu-240 (4%).

#### (7) Doppler Calculation

The reactivity effect is calculated by k-calculations for elevated fuel temperatures mostly in a spherical SEFOR model. The temperature distribution is assumed to be "isothermal" in the calculation. A group constant set with 18 groups (9 of which were below 9.1 keV) at five temperature values (300K, 700K, 1400K, 3000K and 5000K) was used in the calculations.

Spatial weighting of "local" coefficients (i.e.  $\frac{d\rho}{dT}$  -values for T being a function of space) to account for the temperature distribution across the core, using either squares of total flux or the power, received much attention. Either a spherical model or a r-z separation was applied.

#### (8) Expansion Effects

As the goal of the SEFOR experiments is to measure the Doppler coefficient, the reactivity effects of expansions have to be reduced as far as possible. A combination of Doppler and (overall) expansion effects appear in the power coefficient or its integral between zero (350°F) and full power (1494°F at 10 MWt). In the power-coefficient integral the Doppler effect is only 50% larger than expansion effects:

$$\Delta k_D \text{ (zero to full power)} = -3.0\$ \quad \text{(Doppler)}$$

$$\Delta k_{ex} \text{ (zero to full power)} = -2.0\$ \quad \text{(expansion)}$$

The effect of expansions can be largely eliminated compared to the Doppler effect if the power is increased very quickly. The SEFOR oxide fuel rods, with their one inch diameter, have a heat release time of about 30 seconds. Thus, any transient that allows a reactivity determination in a time that is much shorter than 30 seconds, shows nearly exclusively the reactivity effect of the fuel. Then only the expansion effect of the fuel appears combined with the Doppler effect.

The expansion effect of the fuel is reduced by two design features: First, the fuel "pellets" are dished, so that only the cooler outer rim causes the axial expansion of the stack of pellets. Second, the pellet column has a gap at about 2/3 of the core height; the closing of this gap during a temperature rise, by an axial expansion of the lower 2/3, compensates a large part of the expansion effect of the column.

The success of this fuel design can be seen in slow power changes: For a certain change for which

$$\Delta k_D = -40.0\phi \text{ (Doppler)}$$

$$\Delta k_{ex} = -46.7\phi \text{ (for flat end pellets),}$$

the following reductions of  $\Delta k_{ex}$  could be achieved:

$$\Delta k_{ex} = -9.1\phi \text{ (for dished pellets)}$$

$$\Delta k_{ex} = -2.6\phi \text{ (for segmented fuel column).}$$

Thus, the residual expansion amounts to about 5% of the negative fuel feedback (2.6 out of 40 + 2.6 $\phi$ ). After correcting it by means of the calculated value its residual effect should be much less than 5%.

### II.3 The Temperature Dependence of the Doppler Coefficient

The temperature dependence of the Doppler coefficient is generally expressed as a "power-law"

$$\gamma_D(T) = \left[ \frac{d\rho}{dT} \right]_D = \frac{a_D}{T} \left[ \frac{T_R}{T} \right]^{x-1}, \quad (1)$$

with  $T_R$  being a reference temperature;  $a_D$  is then  $a_D = T(d\rho/dT)_D$  at  $T = T_R$ . The GE calculations of  $k(T)$  showed that  $x = 0.9$  provides a close approximation. However,  $x = 1$  was chosen for simplicity, as the reactivity feedback is considered "fairly insensitive" to  $x$ .

The following table, Table II, shows a comparison of the GE-calculations of  $\Delta k(T)$  with a fit per Eq. (1), using  $x = 0.9$  and  $x = 1.0$ :

Table II Doppler - $\Delta k(T)$ Comparison			
T	calculated	$x = 0.9$	$x = 1.0$
300K	0	0	0
700K	-.00821	-.00828 (+.8%)	-.00858 (+4.5%)
1400K	-.01559	-.01559 (0%)	-.01559 (0%)
3000K	-.02415	-.02444 (+1.2%)	-.02330 (-3.5%)
5000K	-.03000	-.03041 (+1.4%)	-.02887 (-5.1%)

Apparently, by choosing  $x = 1.0$  one accepts in the middle temperature range 700 to 1000K,  $\Delta k$  error of about 5%. Nevertheless, the  $1/T$  temperature dependence has been used in the GE analysis for all the spatial weighting investigations, as well as for the eventual analysis of the

experiments.

In Ref. 5 (Freeman) it is stated that  $x$ -values "ranging from 0.8 to 1.2 showed only small variations in the Doppler feedback over the average fuel temperature range of the SEFOR data. Calculations of the isothermal Doppler feedback up to 3900K indicate that for SEFOR,  $x = 1$  gives a good representation of the Doppler feedback."

The statements about the temperature dependence appear to all be based on the comparison of the integral quantity  $\Delta k_D(T)$ . As integration tends to smooth out errors, the corresponding differential quantity, the Doppler coefficient,  $\gamma_D(T)$ , should show considerably larger deviations than the ones exhibited in Tab. II. The Doppler coefficient is important for short times, shortly after the onset of a transient at  $T = T_o$ , when  $\Delta\rho(t)$  is approximately given by:

$$\Delta\rho(t) = \gamma_D(T_o)\Delta T(t). \quad (2)$$

It is therefore important to consider the magnitude of the error in the Doppler coefficient as such in addition to a comparison of  $\Delta k_D(T)$ . Table III gives a comparison of  $\Delta k_D(T)$  fits for  $x = 0.9, 1.0$ , and  $1.2$  with calculated values. Table IV shows the corresponding comparison of the coefficients,  $\gamma_D(T)$ , for  $x = 1.0$  and  $1.2$ . The  $x = 0.9$  results are taken as a reference because of the very small deviations shown in Table III.

In Table III, the  $k(T)$  trajectories calculated with  $x = 1.0$  and  $1.2$  appear to be quite acceptable over a large temperature range. The comparison of the Doppler coefficients however (Table IV) shows significant deviations, ranging from  $+8.1\%$  to  $-9.1\%$  for  $x = 1.0$  and  $+25$  to  $-25\%$  for  $x = 1.2$  across the practical temperature range from  $300K$  through  $1700K$ . Of course these deviations would be much larger if the temperature range up to  $5000K$  would be considered as in Table II.

Table III Comparison of k-values

T(K)	k(T)			
	calculated	x = 0.9	x = 1.0	x = 1.2
300	1.04804	1.04804	1.04804	1.04804
700	1.03983	1.03976	1.03946	1.03976
1400	1.03245	1.03245	1.03245	1.03245
3000	1.02389	1.02384	1.02474	1.02634
5000	1.01804	1.01763	1.01917	1.02274

Table IV Comparison of Doppler Coefficients

	$10^5 \gamma_D / K$	$\gamma_D(x) / \gamma_D(0.9) - 1$ (%)	
T(K)	x = 0.9	x = 1.0	x = 1.2
300	3.12	8.1	25.6
500	1.97	2.7	17.8
700	1.46	-0.7	-2.6
900	1.16	-3.1	-9.6
1100	.970	-5.1	-14.9
1300	.834	-6.6	-19.1
1500	.733	-8.0	-22.5
1700	.655	-9.1	-25.3
1900	.593	-10.1	-27.8
2100	.582	-11.0	-30.0

#### II.4 The German Pre-Analysis of the Subprompt Critical Transients

During the preparatory phase of the SEFOR project the GE effort concentrated on the design and showed that such a small reactor can well simulate the relevant physics of a large LMFBR, as it has been outlined in the previous sections. The German effort during this phase - in complementary fashion - concentrated on the pre-analysis of possible Doppler feedback experiments. Häfele (Ref. 1) investigated superprompt critical transients, Calderola (Refs. 1 and 11) proposed and investigated oscillator tests, and Ott (Ref. 12) developed the analysis of special subprompt critical transients that appeared to allow the most accurate determination of the Doppler coefficient.

The results of Häfele's investigations contributed to the understanding of the most important superprompt-critical demonstrations, and Calderola participated in the eventual analysis of the SEFOR oscillator tests. The experience of the pre-analysis of Ref. 12 has only marginally affected the analysis of these transient experiments. As a modern re-analysis may benefit from improved evaluation of the subprompt critical tests, the results of this pre-analysis are briefly reviewed in the following. See Ref. 13 for a more recent description of this analysis.

The investigations of Ref. 12 consist of two parts. The first part is more exploratory in nature and the second part outlines an accurate analysis method. (The notations of Ref. 13 are employed here).

### (1) Exploratory Investigations

For the exploratory investigations two simplifications have been applied in order to see clearly the characteristics of these subprompt-critical transients:

- (a) The very rapid reactivity insertion is approximated by a reactivity step,  $\rho_1$ .
- (b) The very small term  $\Lambda \dot{p}$  on the LHS of the first kinetics equation

$$\Lambda \dot{p}(t) = (\rho - \beta)p(t) + s_d(t) \quad (3)$$

is neglected (prompt jump approximation). Here  $\Lambda$  is the neutron generation time and  $s_d$  the reduced delayed neutron source.

The consequence of these two approximations is that the flux amplitude  $p(t)$  (or relative power in the point reactor model) increases (along with the reactivity) as a step, from its initial value  $p_o$  to the prompt jump flux,  $p_{pj}$ . Then, two effects compete with each other and determine the slope,  $p_1$ , of the subsequent flux change: The ensuing increase in the delayed neutron precursor population and the corresponding delayed neutron source provides a positive slope contribution. The feedback adds a negative contribution to the slope,  $p_1$ .

Assuming linear energy feedback as given by Eq. (9) yields for  $p_1$ :

$$p_1 = (\bar{\lambda} + \frac{\gamma}{\beta} p_{pj}) \frac{p_{pj} - p_o}{p_o} p_{pj} , \quad (4)$$

where  $\bar{\lambda}$  is the average delayed neutron decay constant:

$$\bar{\lambda} = \frac{1}{\beta} \sum_k \beta_k \lambda_k, \quad (5)$$

and  $\gamma$  denotes the relative energy coefficient [ $\delta\rho/\text{full-power-second}$ ], of which the Doppler effect ( $\gamma_D$ ) is the largest part;  $\beta_k$  and  $\lambda_k$  are the delayed neutron group values of the fractions

and decay constants respectively. If the actual power,  $P$ , is used instead of the relative power  $p$ ,  $\gamma$  is to be replaced by the energy coefficient,  $\gamma_e$  [ $\delta p/MWs$ ].

Equation (4) shows that the transient behavior after the completion of the prompt jump consists of a direct competition of delayed neutron effects, represented by  $\bar{\lambda}$ , and feedback, in form of  $\gamma p_{pj}/\beta$ . Thus, any inaccuracy of  $\bar{\lambda}$  affects directly the value of  $\gamma$  as it is derived from the subprompt critical transients.

Solving Eq. (4) for  $\gamma$  gives

$$\frac{\gamma}{\beta} = \frac{1}{p_{pj}} \left[ -\bar{\lambda} + p_1 \left( \frac{p_o/p_{pj}}{p_{pj} - p_o} \right) \right] . \quad (6a)$$

For the special reactivity insertion for which  $p_1 = 0$  follows the simple relation ( $p_{pj0}$  is then  $p_{pj}$ -value for which  $p_1 = 0$ ).

$$\frac{\gamma}{\beta} = \bar{\lambda}/p_{pj0} . \quad (6b)$$

This analysis method, expressed here only in exploratory but obvious terms, aims directly at the determination of the Doppler coefficient, using flux or relative power concepts ( $p_{pj}$  and  $p_1$ ) as experimental input. In contrast to this, the GE analysis (see Sec. III. 1) aims at the reactivity, using the energy deposition as experimental input, thus employing more integral concepts in a similar way as in the comparison of temperature dependency effects as discussed in Sec. II.3.

## (2) Inverse Kinetics for Reactivity Coefficients

Of course, the two assumptions that had been made to allow for a lucid exploratory investigation are only approximations: The prompt flux jump is not a step; the flux increases gradually along with the reactivity insertion. Therefore, the "slope" after the prompt jump also develops gradually and is difficult to quantify. A rigorous analysis must consider the time dependence of the reactivity insertion and it must leave  $\Delta\dot{\rho}(t)$  in the kinetics equation, thus allowing for a gradual power increase.

After the ejection of the central absorber rod, FRED for Fast Rod Ejection Device, the flux distribution in the SEFOR core remains fairly invariable with time. Thus, the point reactor kinetics model is applicable and probably quite accurate. This means that the transient is fully described by  $p(t)$ , the trajectory of the relative flux or relative power.

As  $p(t)$  is measured (in form of a relative count rate of a U-238 fission chamber) it can be inserted into the kinetics equation. The resulting algebraic equation can be readily solved for whatever is desired. Solving it for  $\rho(t)$ , as proposed in 1959 by Corben, is the "inverse kinetics."

In Ref. 12 (1963) a different way of solving this algebraic equation Eq. (1), was proposed, namely solving it directly for the feedback reactivity,  $\rho_{fb}$ , and eventually for the energy coefficient itself.

With

$$\rho(t) = \rho_{FRED}(t) + \rho_{fb}(t), \quad (7)$$

Eq. (1) gives

$$\rho_{fb}(t) = \frac{\beta p(t) - s_d(t) + \Lambda \dot{p}(t)}{p(t)} - \rho_{FRED}(t). \quad (8)$$

During the early part of the subprompt critical transient, shortly after the complete FRED ejection and prior to the significant heat transfer out of the thick fuel rod,  $\rho_{fb}$  is only a small part of the total reactivity, the first term on RHS of Eq. (8). Thus, if  $\rho(t)$  and  $\rho_{FRED}(t)$  were determined independently,  $\rho_{fb}(t)$  per Eq. (8) would be a difference of two comparatively large numbers, and thus would be affected by the amplified inaccuracies of both terms. Therefore, a way had to be found in all analysis methods to circumvent this problem:

All analysis methods, including the 1963 pre-analysis, start by first recognizing that  $\rho_{FRED}$  is a constant after the complete extraction of the rod, and secondly by devising an analysis procedure that does not require the knowledge of  $\rho_{FRED}$  itself.

In Ref. 12 the following procedure had been proposed: Inserting in Eq. (8)

$$\rho_{fb} = \gamma \int_o^t [p(t') - p_o] dt', \quad (9)$$

which holds as long as the transfer of the incrementally produced energy out of the rod can be neglected, and solving for  $\gamma$  gives

$$\gamma = \frac{\frac{1}{p(t)} [\beta p(t) - s_d(t) + \Lambda \dot{p}(t)] - \rho_{FRED}}{\int_o^t [p(t') - p_o] dt'} \quad (10)$$

Equation (10) yields the same result as the exploratory investigation if the prompt jump approximation is introduced and Taylor expansion is applied. Thus, Eq. (10) is the desired refinement of the simple formula, Eq. (6a).

Since Eq. (10) holds only for the correct FRED-reactivity, a trial and error procedure is employed to find simultaneously  $\rho_{FRED}$  and  $\gamma$ . Let the trial value of  $\rho_{FRED}$  be  $\rho'_{FRED}$ . The resulting LHS of Eq. (10), say

$$\gamma' = \gamma'(t, \rho'_{FRED}), \quad (11)$$

depends strongly on time. Only for the correct value of  $\rho'_{FRED}$  ( $= \rho_{FRED}$ ) is the LHS of Eq. (10) a constant, equal to the desired energy coefficient  $\gamma$ .

A test of this procedure in a computer experiment showed its enormous sensitivity (see Fig. 1). An error of 0.1¢ in  $\rho'_{FRED}$  caused a considerable time variation of the LHS. It therefore yielded  $\rho_{FRED}$  with an error of less than 0.1¢ and  $\gamma$  better than 1%.

Naturally this accuracy can not be achieved in a practical application for two reasons.

- a) because of errors in the  $p(t)$  measurement, but probably more so
- b) because of errors in the delayed neutron data.

The exploratory investigation of these transients showed that--except for the obvious proportionality of  $\rho$  to  $\beta$ --the delayed neutron data affect these transient primarily through  $\bar{\lambda}$ . Therefore special investigations in reducing the error that is due to  $\bar{\lambda}$ -inaccuracies are important for the analysis of subprompt critical transients.

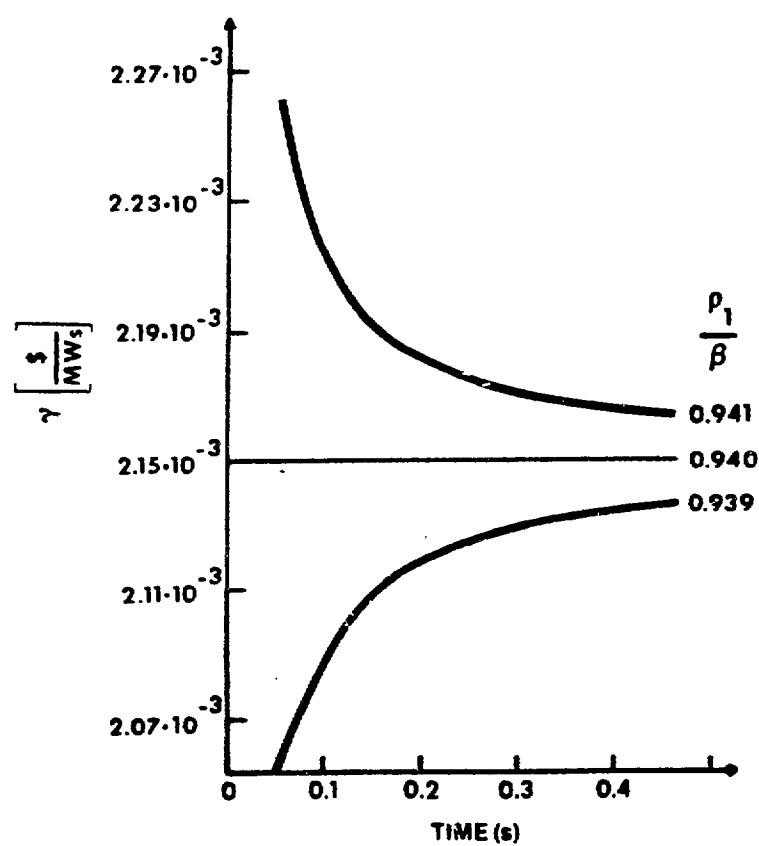


Fig. 1 Computer test of the inverse kinetics for reactivity coefficients, presenting  $\gamma(t)$  per Eqs. (11) and (10) with three trial values for  $\rho'$  *FRED*

### III Analyses of the Transient Tests

#### III.1 The GE-Analysis

The GE-analysis of the transient tests for Cores I and II is reported in Refs. 3 and 4 respectively. The analysis method and the results are reviewed in the following. Some of the results have been re-evaluated here.

##### III.1.1 The Analysis Method

As shown above (see II.4) the reactivity feedback coefficients in subprompt critical transients can be determined without the knowledge of the transient-initiating reactivity. One merely uses the fact, that after the control rod has been fully withdrawn, the externally applied reactivity,  $\rho_{FRED}$  is constant. Thus, any time- variation of the (total) reactivity

$$\rho(t) = \rho_{FRED} + \rho_{fb}(t) \quad (12)$$

is to be attributed to the reactivity feedback.

In the GE-analysis,  $\rho(t)$  is determined by inverse kinetics, using a smoothed power trajectory. An example of the power trajectory of one of the subprompt-critical transients (initial power  $P_o = 10$  Mw) is presented in Fig. 2. The reactivity insertion is completed after about 120 ms. In this example, the power level is lifted to about 25 times the initial power,  $P_o$ . The energy deposition of the increased power raises the temperature. This brings in the negative feedback, which reduces the reactivity and with it the power, as the power rise due to the increased precursor decay is weaker than the decrease caused by feedback (comp. Sec. II.4).

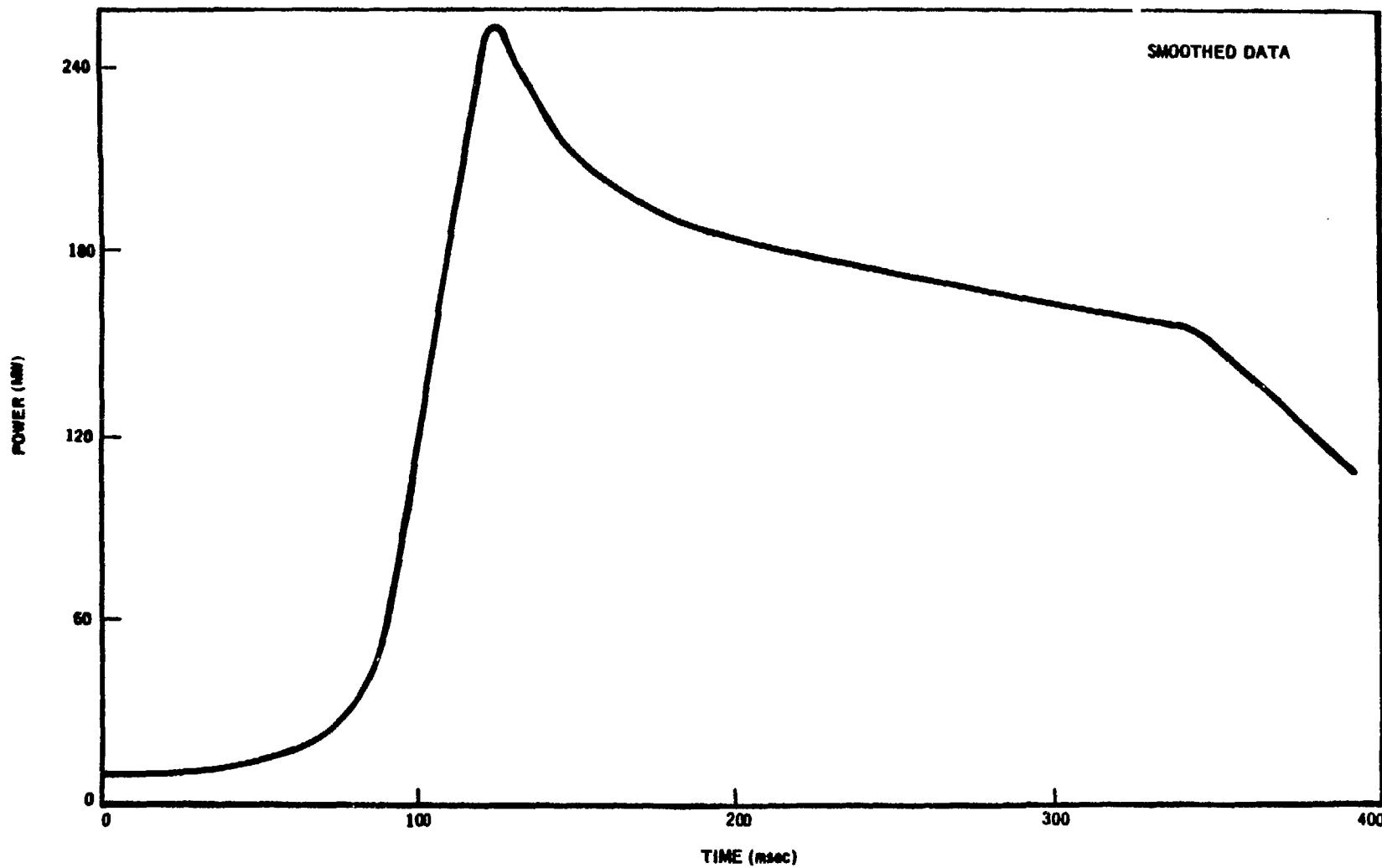


Fig. 2 Core I subprompt critical transient, smoothed data (from Ref. 3, GEAP-13837)

It is instructive to quantify for this typical example the competition of delayed neutron effect and negative feedback. Using values for  $\bar{\lambda}$  and  $\gamma_e$  that will be established below ( $\bar{\lambda} = 0.62/s$ ,  $\gamma_e = -0.30/MWs$ ) and a prompt jump power ( $P_{pj}$ ) of 250 MW one obtains

$$\bar{\lambda} + \frac{\gamma_e}{\beta} P_{pj} = 0.62/s - 0.75/s.$$

Thus in this example, the increasing delayed neutron source compensates about 85% of the negative slope caused by feedback. This strong compensation suggests that the large error of  $\bar{\lambda}$  (10%) is nearly fully reflected in  $\gamma$ . Therefore, efforts to eliminate the  $\bar{\lambda}$ -error (Refs. 14 and 15) are crucial for achieving high accuracy in the analysis of the subprompt critical tests (see Sec. III.3).

The power trajectory that is obtained from U-238 fission-chamber counts during the transient is based on an initial heat balance as calibration. From the power trajectory,  $P(t)$ , the energy deposition,  $E(t)$ , is calculated assuming that the heat rejection of the core remains unchanged (i.e. equal to  $P_o$ ) during the short time of the transient:

$$E(t) = \int_0^t [P(t') - P_o] dt' . \quad (13)$$

As  $E(t)$  is monotonic it may be readily inverted. The resulting inverse function  $t(E)$  is inserted in Eq. (12) and yields  $\rho$  as function of the energy deposited during the transient:

$$\rho(E) = \rho_{FRED} + \rho_{fb}(E) . \quad (14)$$

Equation (13) is plotted as basis for a linear fit, using

$$\rho_{fb}(E) = \gamma_e E , \quad (15)$$

with  $\gamma_e$  as energy coefficient. The linear relationship for a small energy release is shown in Fig.

3 which presents examples of these transients in Core I and of the analysis per Eq. (14) The inverse kinetics analysis that uses a continuous power trajectory such as the one presented in Fig. 2 yields per inverse kinetics an associated reactivity trajectory that is also continuous. Thus, the circle, square and triangular symbols in Fig. 3 do not represent experimental data points. The fit actually consists of a fit of a continuous curve to a linear approximation per Eq. (15)

Figure 4 displays the feedback reactivity as such; in this example for a superprompt critical transient in Core II for which the smooth power trajectory is shown in Fig. 5. Actually, the superprompt critical results have been fit with a parabola instead of the linear expression of Eq. (15), but the deviations from the linear shape were so small that a (linear) energy coefficient is generally given as result of the fit.

The energy obtained from Eq. (13) is the total fission energy of that power trajectory. However, only part of that energy (assumed to be about 88% in the GE-analysis) heats up the fuel:

About 6% of the total energy is decay heat of which only a minuscule amount is released during the 300 ms of the test. This leaves a fraction of 0.932 of the total energy produced that is released during the transient. Part of this immediately released energy, the part contained in neutrons and prompt gammas, is at first carried out of the fuel rods. Some of it is deposited in the cladding and in sodium, or it leaves the core as leakage. The GE-analysis assumes that an additional 6% of the total energy is leaving the fuel using a further reduction factor of 0.943. This 6% loss-value appears to be very high. A 4% value was suggested in Ref. 14 (i.e. a total reduction factor of 90% instead of 88%). The reason for the lower loss value is the fact that

GEAP-13837

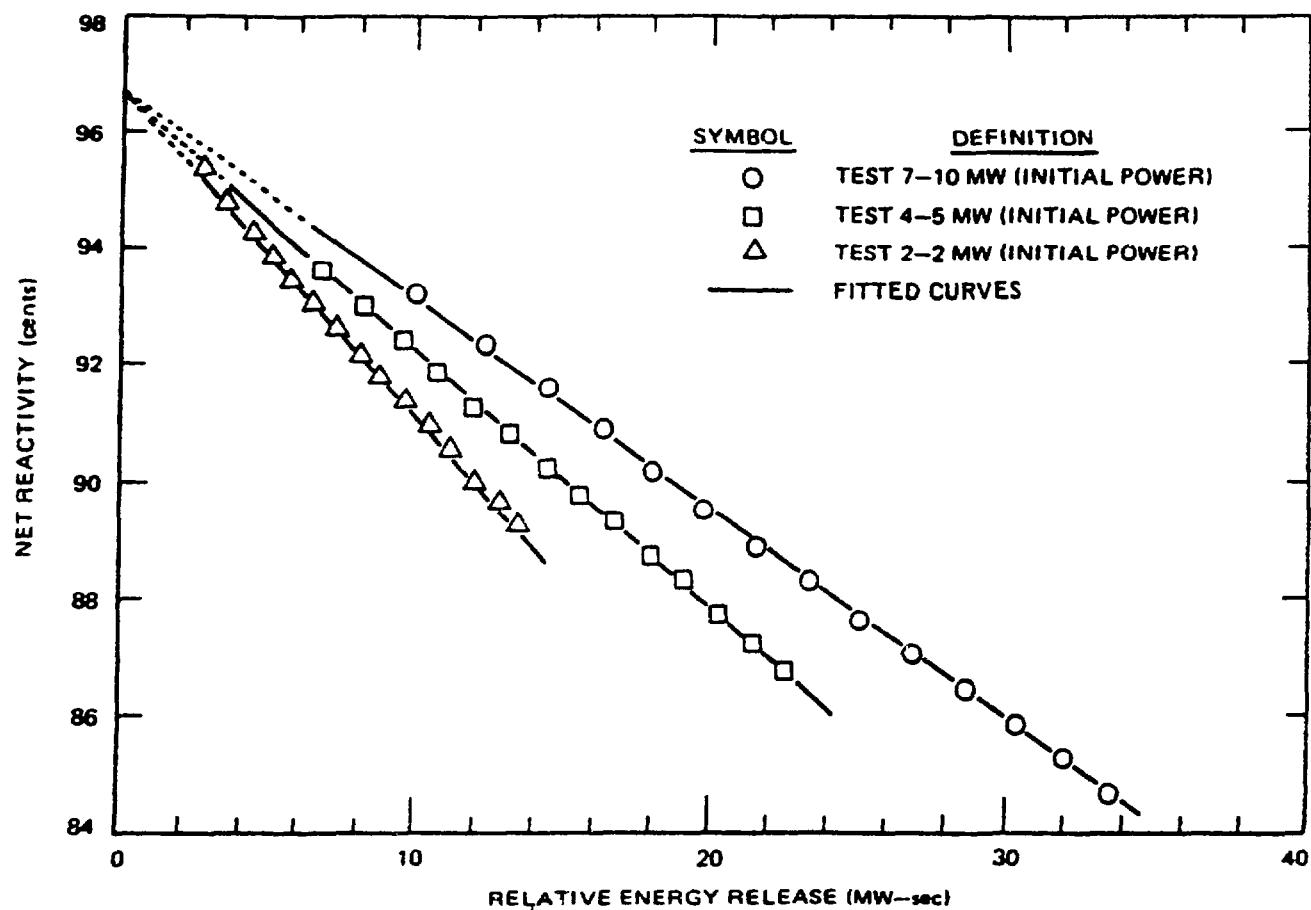


Fig. 3 Reactivity as function of the energy release in the fuel (from Ref. 3, GEAP-13837)

GEAP-13838

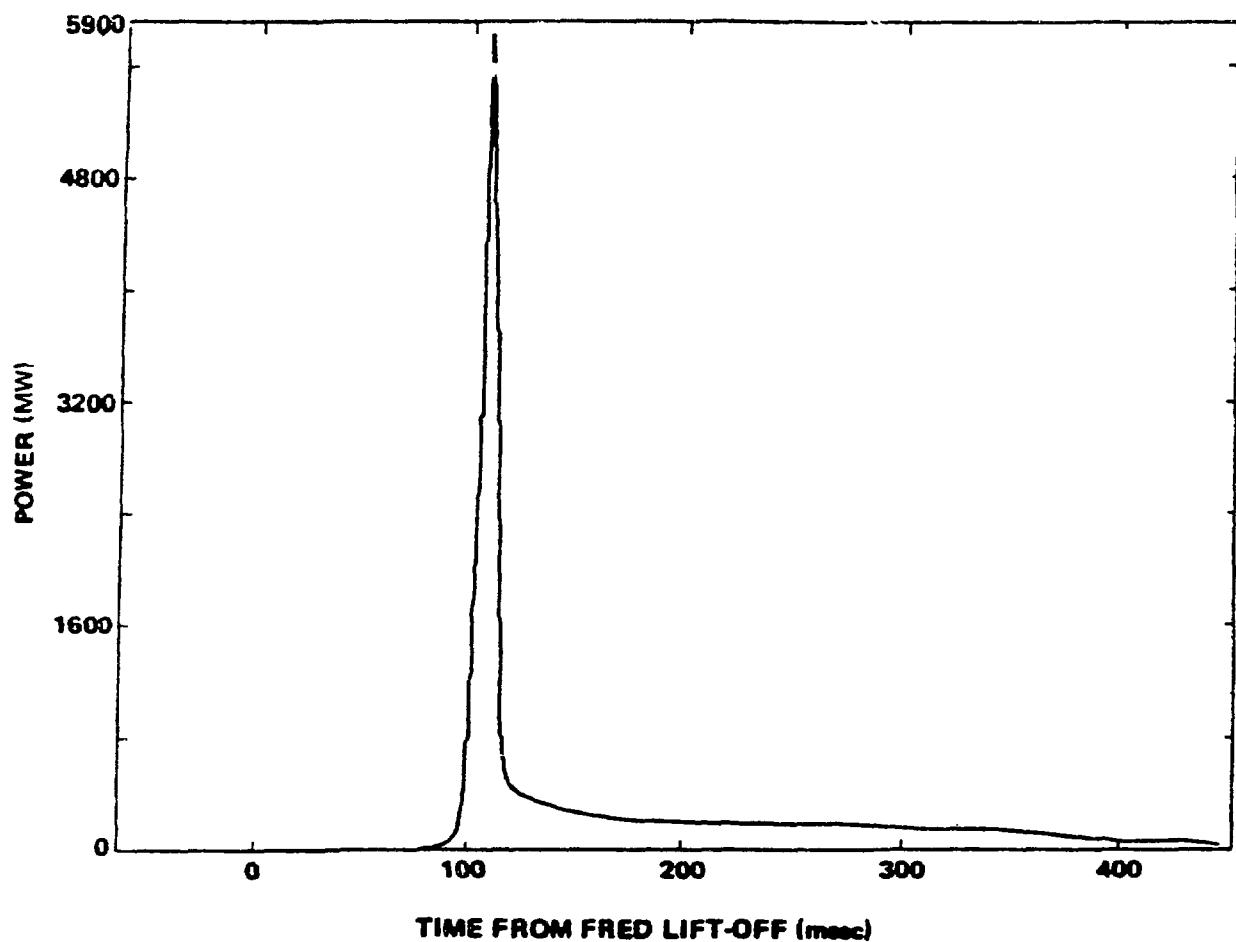


Fig. 4 Time-dependent power for superprompt transient in Core II ( $P_o = 2\text{MW}$ )

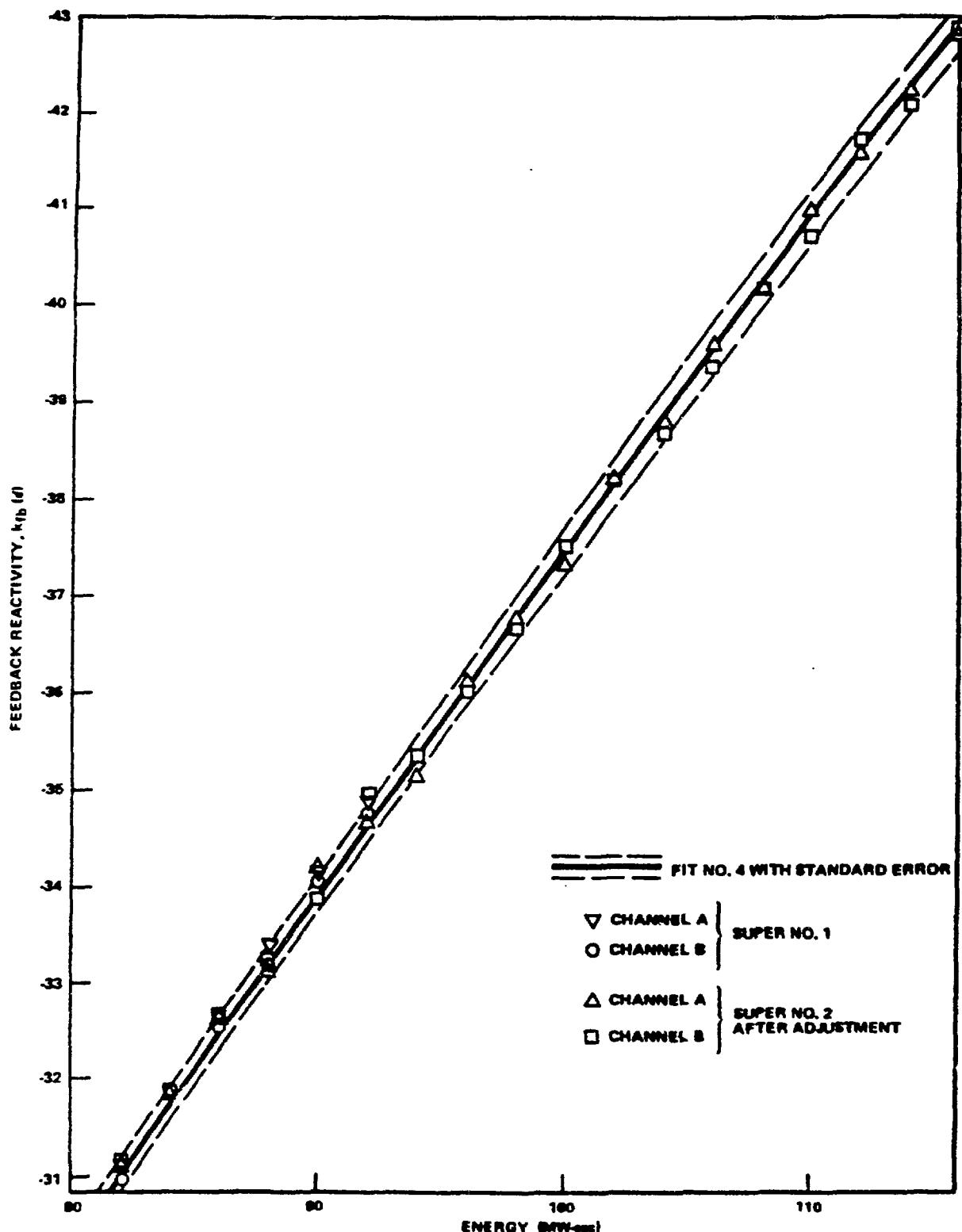


Fig. 5 Feedback reactivity vs energy release for  $P_o = 2MW$  (from Ref. 4, GEAP, 13830)

most of the  $\gamma$ -energy is deposited in the fuel because of its high  $Z$  value. There is a total of about 20 MeV (10%) available in form of neutrons (5-6 MeV), prompt gammas (6-7 MeV) and capture gammas (about 8 MeV). As most of the neutron energy is lost in the first two inelastic scattering collisions the total  $\gamma$ -energy (after accounting for gammas from inelastic scattering) is more like 18 MeV, with most of it quickly deposited in the fuel. A value of 0.98 for the corresponding reduction factor may therefore be more realistic than the GE-values of 0.943. Let  $c^f$  denote the factor that relates the total energy  $E$   $E^f$ , the energy deposited in the fuel:

$$E^f = c^f E, \quad (16)$$

with

$$c^f = 0.88 \text{ (or better 0.92).} \quad (17)$$

The German analysis, Ref. 15, includes a more adequate evaluation of the energy deposition, giving  $c^f = 0.924$ . This value will be used below.

The calculation of the fuel component of the feedback reactivity uses two different energy coefficients, depending on the use of  $E$  or  $E^f$ :

$$\delta\rho_{fb} = \gamma_e \delta E = \gamma_e^f \delta E^f, \quad (18)$$

with

$$\gamma_e^f = \gamma_e / c^f. \quad (19)$$

Which of the two formulas in Eq. (18) is used to calculate the feedback reactivity does not matter; one only needs to be consistent. Therefore, a deviation in the  $c^f$  value is irrelevant, as long as the energy coefficient is determined from measured reactivities as in Fig. 4. However, the fuel temperature rise is determined by  $\delta E^f$  alone. Thus, different  $c^f$  values give different

fuel temperatures and therefore different fuel temperature coefficients.

### III.1.2 Energy and Temperature Coefficients

The energy coefficients obtained from the transient analysis by the method described in the previous Section are actually average values over the interval of energy release, say  $\Delta E$ . For a linear relationship between,  $\Delta\rho_{fb}$  and  $\Delta E$  one has for  $\gamma_e$ :

$$\gamma_e = \frac{\Delta\rho_{fb}}{\Delta E} , \quad (20)$$

where  $\Delta\rho_{fb}$  is the reactivity change resulting from the energy deposition  $\Delta E$ .

The GE reports generally present energy coefficients for the individual transients, but as temperature coefficient of the Doppler feedback only a single  $T d\rho/dT$  value for each of the two cores. Here the results for individual transients are converted into temperature coefficients, as transients for different initial power and temperatures contain information on the temperature dependence of the Doppler coefficient per Eq. (2). It should be noted that the temperature change during these transients is so small that a curvature which would result from a temperature dependence can hardly be detected. But the initial temperature,  $T_0$ , varies over a much wider range as the initial power is increased from 2MW to 10MW. There is then a chance to find a  $T_0$  - dependence of the "Doppler constant". Equation (1) yields

$$T_0 \frac{d\rho}{dT_0} = a_D \left[ \frac{T_R}{T_0} \right]^{x-1} = a_D(T_0) , \quad (21)$$

A drift of the values of the LHS can be used to find approximately a value for  $x$  per Eq. (21).

The measured Doppler energy coefficients ( $\phi/\text{MWs}$ ) are given in Tables 4-5 of Ref. 3 for the subprompt critical tests in Core I, and in Tables 5-10 for the superprompt critical tests. They are listed here in Tables V in column 2. As stated in Table footnotes, these values have been

obtained for energy deposited in the fuel (indicated by a superscript f). The next column contains the initial average fuel temperatures for the respective initial power levels. The  $T_0$ -values are taken from Tables 6-1 through 6-5 of Ref. 3. The same Tables are also used to obtain the conversion factor

$$\frac{dT}{dE^f} = 1.44 \frac{K}{MWs} . \quad (22)$$

The next column in Tables V gives the energy deposition  $\overline{\Delta E^f}$  during the transient that is subsequently converted into a corresponding temperature change using Eq. (22). The  $\overline{\Delta E^f}$  values in Tables V are taken as one half of the total energy deposition, which then attributes the measured value to the middle of the respective energy intervals. The same holds for the average temperatures; i.e.,

$$\bar{T} = T_0 + \overline{\Delta T} , \quad (23)$$

listed in column 6 is the average fuel temperature during the transients ( $\overline{\Delta T}$  is one half of the total fuel temperature rise).

The Doppler temperature coefficients in the next column,  $\gamma_T$ , are obtained from  $\gamma_e^f$  by dividing with the conversion factor, Eq. (22). The product of  $\gamma_T$  times  $\bar{T}$  gives then the Doppler constant  $T(d\rho/dT)_D$ . A correction factor is applied to indirectly account for the effects of the temperature distribution across the core.

All three original analyses of the SEFOR tests account for the temperature distribution of the fuel across the core by a suitable weighting procedure. This results in a reduction of the "effective" Doppler constant for the core by about 10%. This reduction reflects the fact that the fuel temperatures as well as the neutronic importance are higher in the core center than in the

Table Va

Doppler Energy and Temperature Coefficients from Subprompt Critical Tests in Core I

$P_o$ (MW)	$\gamma_e^f$ ( $\phi$ /MWs)	$T_o$ (K)	$\bar{\Delta}E^f$ (MWs)	$\bar{\Delta}\bar{T}^{(a)}$ (K)	$\bar{T}$ (K)	$\gamma_T^{(a)}$ ( $\phi$ /K)	$T \frac{d\rho}{dT} \Big _D$ ( $\phi$ )
2	-.548	775	10	14	789	-.381	-267
5	-.422	903	15	22	925	-.293	-241
10	-.363	1085	27	39	1124	-.252	-252

Table Vb

Doppler Energy and Temperature Coefficients from Superprompt Critical Tests in Core I

$P_o$ (MW)	$\gamma_e^f$ ( $\phi$ /MWs)	$T_o$ (K)	$\bar{\Delta}E^f$ (MWs)	$\bar{\Delta}\bar{T}^{(a)}$ (K)	$\bar{T}$ (K)	$\gamma_T^{(a)}$ ( $\phi$ /K)	$T \frac{d\rho}{dT} \Big _D$ ( $\phi$ )
2	-.514	775	58	84	859	-.357	-272
2	-.489	775	80	115	890	-.340	-270
5	-.432	903	70	101	1004	-.300	-268
5	-.420	903	92	132	1035	-.292	-269
8	-.363	1016	80	115	1131	-.252	-254
8	-.363	1016	100	144	1160	-.252	-260

(a) Converted with  $dT/dE^f = 1.44$  K/MWs

peripheral region. Thus, the smaller Doppler coefficients at the higher temperatures have the higher importance and reduce the average. As no explicit adjoint flux weighting was available for the reevaluation of the individual transient results, the importance weighting is approximately accounted for by adjusting the average of the individual  $T(d\rho/dT)$  values to the single value obtained in the GE-analysis. This is effected by multiplying the individual  $(Td\rho/dT)$ -values by 0.890 for Core I and by 0.907 for Core II. The resulting values are given in the last column of Tabs. V and VI.

The results are plotted in Fig. 6 as a function of  $T_0$ . Other results shown in this figure are discussed below.

The  $a_D(T_0)$ -values seem to indicate a tendency toward smaller values with increasing temperature. Applying Eq. (13) gives an x-value of about 1.1 for Core I. This value would suggest that the  $1/T$  approximation is not conservative: the Doppler effect would then decrease stronger than  $1/T$  for increasing temperature. However, the value for x-1 obtained in this way is statistically not significant.

The GE study determined only a single value for each core. The GE -value for  $Td\rho/dT = -0.0081$ , or  $-261.3\%$  (if multiplied with  $\beta = 0.0031$ ).

The results for the transients in Core II are reported in Ref. 4 using a somewhat different format. They are re-evaluated here in Tables VIa and VIb. The first column gives the initial power levels which for the subprompt critical transients are given with 2 additional digits. The next column presents the measured energy coefficient, taken from Tables 4-2 and Tables 4-6 of Ref. 4 for the sub- and superprompt critical transients respectively. These values are average

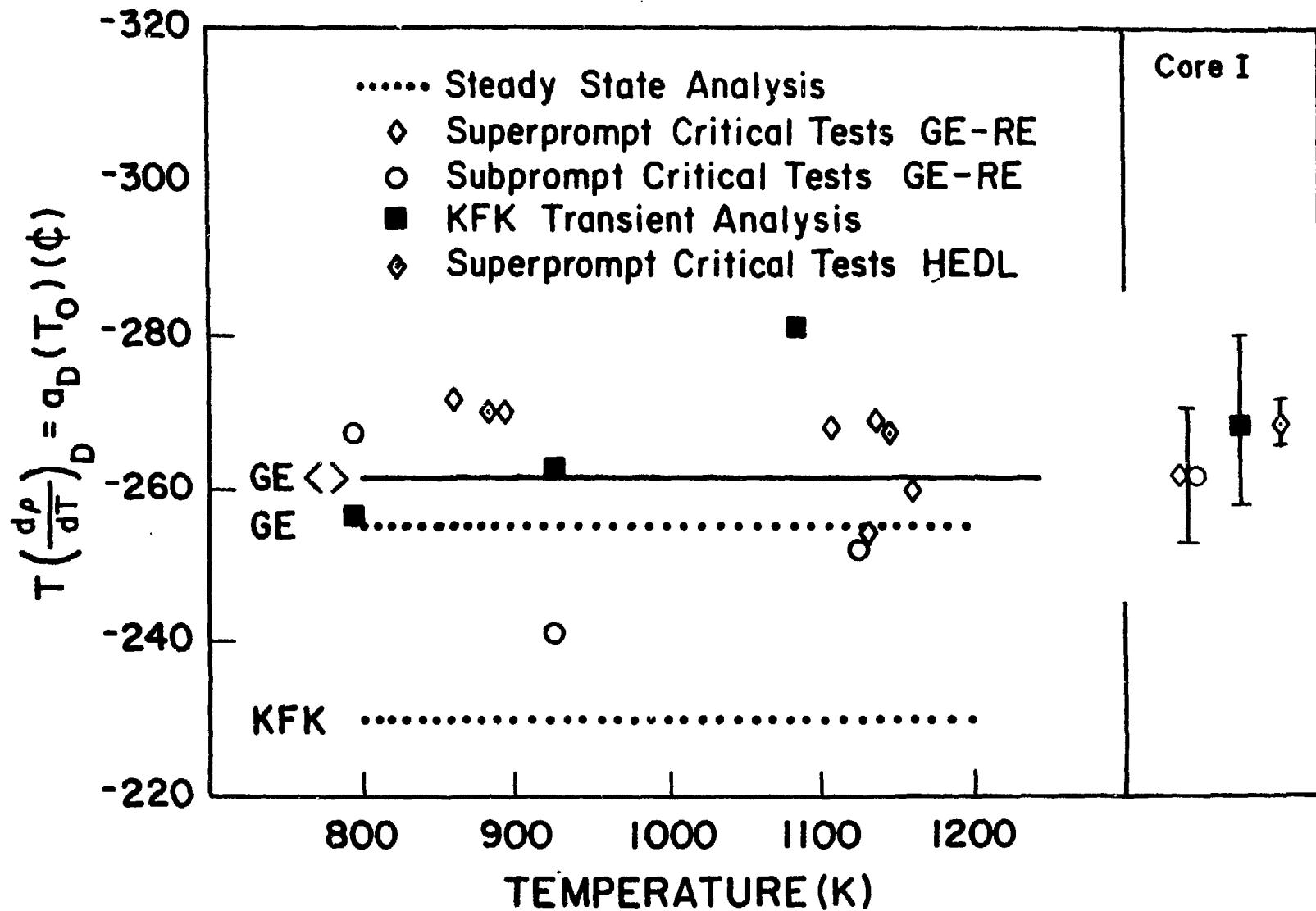


Fig. 6 Evaluated results for  $T(dP/dT)$  as function of the average fuel temperature during the transients for Core I. Steady state results are given as single values.

values for the two counting channels. These  $\gamma_e$  -values contain the fuel expansion, (non Doppler) for which a value of -0.050¢/MWs is subtracted, giving the Doppler portion of the energy coefficient in column 7. The range of non-Doppler coefficients is given as -0.038 to -0.056¢MWs with -0.050 suggested on p. 4-3 of Ref. 4. The energy coefficients are, per total energy, different from the Core I report. Thus, a different conversion coefficient had to be applied ( $1.27 = 0.88 \times 1.44$ ). The results obtained this way are the same as the GE results because of the weighting adjustment applied. The average Doppler constant is obtained as

$$T \left. \frac{dP}{dT} \right)_D = -195.4 \text{¢} .$$

Multiplying with 0.01  $\beta = (0.01 \times 0.0031)$  gives then

$$T \left. \frac{dP}{dT} \right)_D = -0.0060 .$$

The results of Tables VI are plotted in Fig. 8. The other results shown in this figure are reviewed below.

Doppler Energy and Temperature Coefficients for Core II

Table VIa

Subprompt Critical Tests

$P_o$ (MW)	$\gamma_{e(D+x)}$ ( $\phi$ /MWs)	$\bar{\Delta E}$ (MWs)	$\bar{\Delta T}$ (a)	$T_o$ (K)	$\bar{T}$ (K)	$\gamma_{e(D)}$ (b)	$\gamma_T$ (a)	$T \frac{dp}{dT} \Big _D$ ( $\phi$ )
2.12	-.388	22	28	780	808	-.338	-.266	-195
5.12	-.342	10	13	908	921	-.292	-.230	-192
5.29	-.342	17	22	913	935	-.292	-.230	-195
5.20	-.346	17	22	910	932	-.296	-.233	-197
10.01	-.294	17	22	1085	1107	-.244	-.192	-193
10.06	-.294	22	28	1086	1114	-.244	-.192	-194
9.91	-.290	15	19	1080	1099	-.280	-.189	-189

Table VIb  
Superprompt Critical Tests

$P_o$ (MW)	$\gamma_{e(D+x)}$ ( $\phi$ /MWS)	$\bar{\Delta E}$ (MWs)	$\bar{\Delta T}$ (a)	$T_o$ (K)	$\bar{T}$ (K)	$\gamma_{e(D)}$ (b)	$\gamma_T$ ( $\phi$ /K)	$T \frac{d\phi}{dT} \Big _D$ ( $\phi$ )
2	-.375	75	95	775	870	-.325	-.256	-206
2	-.344	98	124	775	899	-.294	-.231	-189
5	-.316	90	114	903	1017	-.266	-.209	-193
5	-.300	125	159	903	1062	-.250	-.197	-189
8	-.283	105	133	1085	1218	-.233	-.183	-202
8	-.280	137	174	1085	1259	-.230	-.181	-207

(a) converted with  $dT/dE = 1.27K/MWs$

(b) non-Doppler feedback of  $-0.0050 \phi/MWs$  subtracted

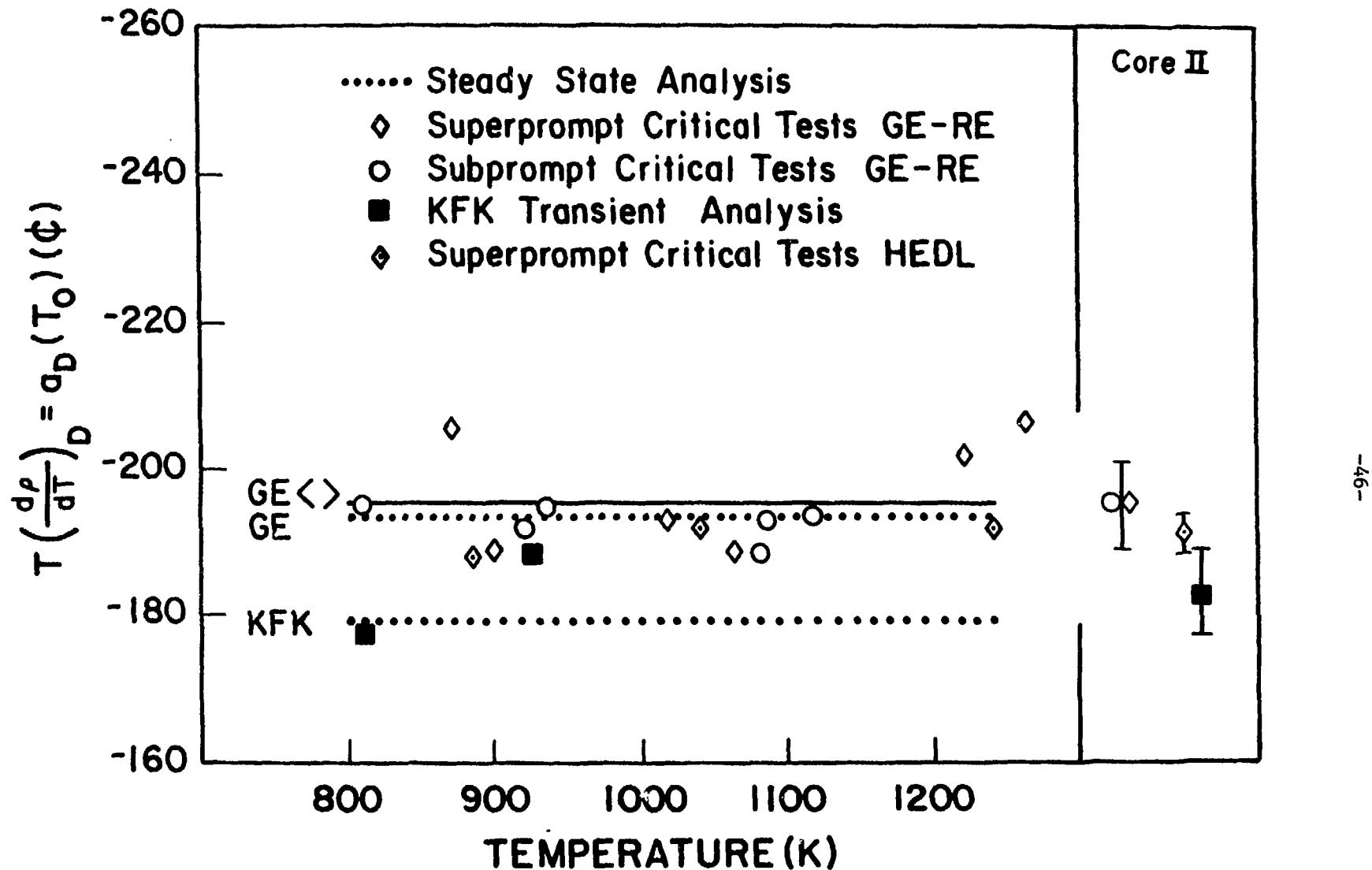


Fig. 7 Evaluated results for  $T_d \rho/dT$  as function of the average fuel temperature during the transients for Core II. Steady state results are given as single values.

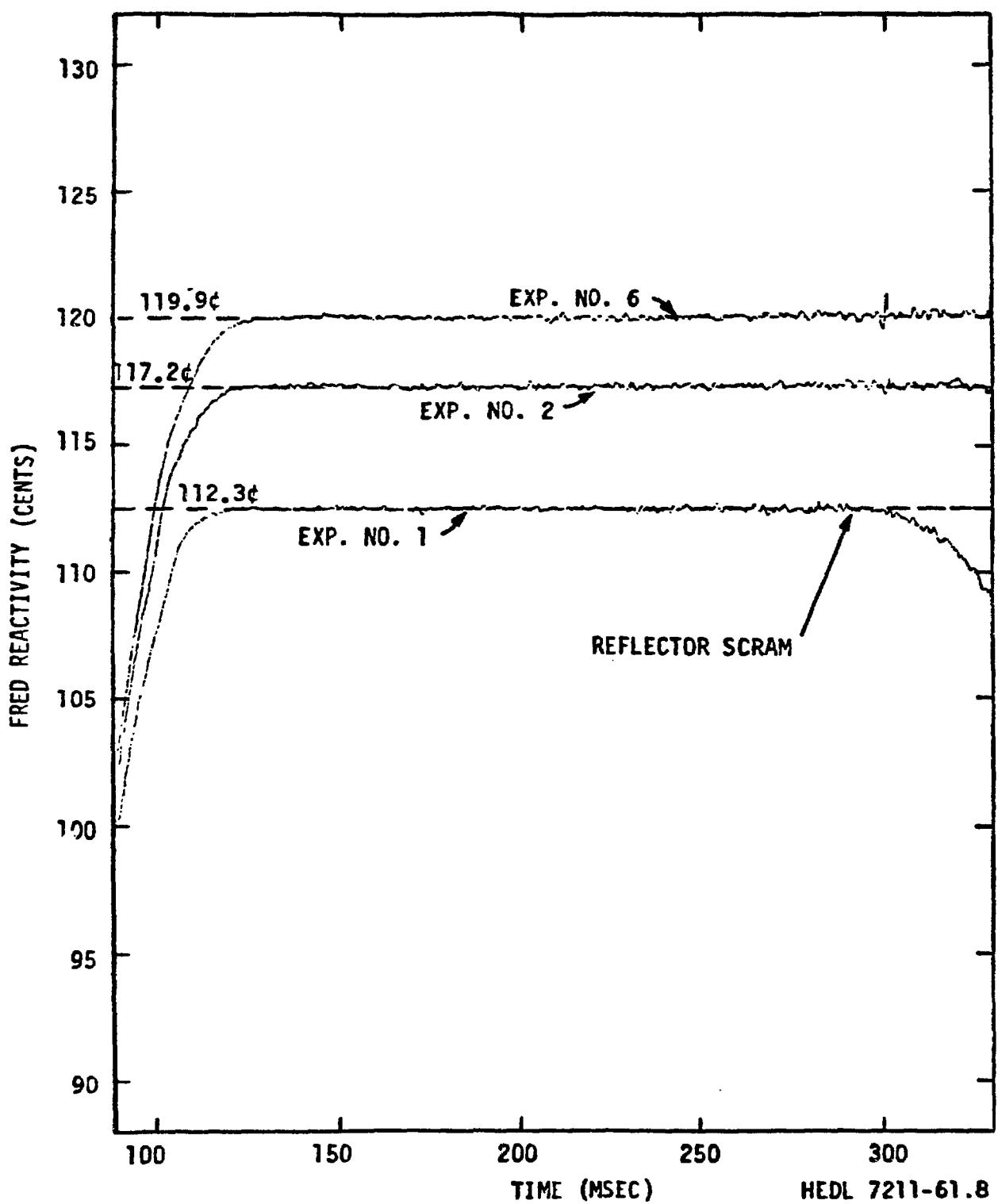


Fig. 8 Inferred *FRED* reactivities for Core II transients 1, 2 and 6 (see Tab. VII)

### III.2 The HEDL Analysis

The HEDL analysis by Harris, Ref. 16, addressed only the superprompt critical transients (see also Ref. 17). Harris applied a completely different analysis method than GE, a method that has the potential to give results of high accuracy.

The idea of this method is to exploit the fact that the FRED-reactivity is constant during the major part of the transient more fully than it had been done in the GE-analysis. With  $\rho(t)$  in Eq. (3) determined by inverse kinetics ( $\rho_{IK}$ ) and  $\rho_{fb}$  split into a Doppler ( $\rho_D(t)$ ) and non-Doppler ( $\rho_{ND}(t)$ ) one obtains

$$\rho_{FRED} + \rho_D(t) + \rho_{ND}(t) - \rho_{IK}(t) = 0 . \quad (24)$$

Harris treats  $\rho_{FRED}$  as a free parameter, say  $\rho_{FRED}$ , assumes for the Doppler feedback a  $1/T$  temperature dependence with a free parameter, b, takes for the small non-Doppler reactivity the calculated variation with time and minimizes the residual in a least square sense that part of the transient ( $t_0 \dots t_1$ ) for which the externally applied reactivity is constant:

$$\int_{t_0}^{t_1} \left[ \rho_{FRED} + b \rho_D(t) + \rho_{ND}(t) - \rho_{IK}(t) \right]^2 dt = \min . \quad (25)$$

The minimum of Eq. (25) determines the free parameters  $\rho_{FRED}$  and b. After the minimization Harris plots

$$\rho_{FRED}(t) = \rho_{IK}(t) - b \rho_D(t) - \rho_{ND}(t) , \quad (26)$$

to find out if a good fit with a constant value has been obtained across the major part of the transient.

Figure 8, taken from Harris' report, shows that this procedure appears to work extremely

well. The fact that a very constant value for  $\tilde{\rho}_{FRED}$  is obtained over the entire range of the transient lets one expect that the resultant FRED-reactivity and Doppler constant are of high accuracy. This view is supported by the very small statistical fluctuations of the Doppler constants for the variety of transients as it is clearly evident from Table VII.

The detailed results presented in Tab. VII are combined for each power level and divided by the HEDL  $\beta$ -values (see footnote of Tab. VII). The resultant Doppler constants are attributed to the initial temperatures for each initial power as given in Tables V and VI and depicted in Figs. 7 and 8. The crystalline binding effects for  $UO_2$  that are included in the original HEDL analysis are eliminated in Figs. 7 and 8 in order to make the results more comparable. These HEDL values ( $a_D^I = -269\text{¢}$  and  $a_D^{II} = -190.7\text{¢}$ ) are close to the GE-results.

*Table VII*

Doppler Constants Inferred from  
Super-Prompt Experiments  
(Ref. 16)

Core I <i>Experiment</i> (channel)	Initial Power(MW)	<i>Inferred Doppler Constant<sup>(a)</sup></i>	Inferred Maximum <i>FRED Reactivity(¢)</i>
1	2	-0.0089	116.2
2	2	-0.0088	126.0
3	2	-0.0091	125.9
3	2	-0.0089	125.0
8	8	-0.0089	125.3
8	8	-0.0088	123.4
Average -0.0089			

Core II <i>Experiment</i> (channel)	Initial Power(MW)	<i>Inferred Doppler Constant<sup>(a)</sup></i>	Inferred Maximum <i>FRED Reactivity(¢)</i>
1(A)	2	-0.0063	112.3
1(B)	2	-0.0063	112.1
2(A)	2	-0.0061	117.2
2(B)	2	-0.0060	116.6
3(A)	5	-0.0064	112.4
3(B)	5	-0.0063	112.3
4(A)	5	-0.0064	120.4
4(B)	5	-0.0061	119.1
5(A)	8	-0.0063	112.7
5(B)	8	-0.0063	112.3
6(A)	8	-0.0063	119.9
6(B)	8	-0.0063	119.4
Average -0.0063			

(a) These results have been corrected for crystalline binding effects (increased by 3.5% for Core I and 3.0% for Core II). The delayed neutron data set adopted for the design of FTR was used in the analysis ( $\beta_I = 0.00319$  ;  $\beta_{II} = 0.00318$ )

### III.3 The German Transient Analysis

The German analysis (Ref. 15) of the SEFOR transient experiments has more similarity to the Harris' approach (Ref. 16) than to the GE-analysis. As in the HEDL analysis the Doppler feedback reactivity  $\rho_D(t)$  during the transient was calculated for a  $1/T$  dependence and a detailed spatial flux and temperature distribution. The non-Doppler feedback was also calculated and applied directly, because its contribution is small. The Doppler constant was then adjusted to make the resulting external reactivity ( $\rho_{FRED}$ ) constant.

The German report does not indicate to which degree the constancy of  $\rho_{FRED}$  could be achieved, as Harris did, e.g. in Fig. 9. However, the German approach was also applied to the subprompt critical transients, thus yielding a broader spectrum of results. The  $T(d\rho/dT)$  values in cents are depicted in Fig. 7 for Core I and in Fig. 8 for Core II (taken directly from Tab. I of Ref. 15), -267¢ and 182¢ respectively.

The German analysis goes beyond the GE and HEDL analyses by evaluating directly the effect of an error in  $\bar{\lambda}$  (mean delayed neutron precursor decay constant) upon the energy coefficient (see the related discussion in Sec. II.4). Their analysis actually yielded a corrected value for  $\bar{\lambda}$ :

$$\bar{\lambda} = 0.625 \pm 0.02/s ,$$

which is considerably larger than the calculated value of 0.57/s. Having an independently determined and fairly accurate value of  $\bar{\lambda}$  suggests to adjust the delayed neutron data - within their uncertainty band - to conform with this more accurate value of  $\bar{\lambda}$ .

The accuracy of the GE-analysis of the subprompt critical transient is affected by this apparent large difference of  $\bar{\lambda}$ . A re-analysis could remove part of this inaccuracy.

#### IV Summary Discussion and Conclusions

##### 1 The SEFOR Project

The need for more accurate information on the important Doppler-effect feedback for the oxide-fueled fast reactor development as well as the desirability of an actual demonstration of its shut-down capability led in 1963 to the joint U.S-German project SEFOR, with GE and the Nuclear Research Center, Karlsruhe (KFK) as technical partners. Extensive pre-analysis, primarily on the German side, showed that accurate quantitative information on the Doppler feedback can indeed be obtained from the analysis of transient experiments, a fact which was important for the eventual realization of the project. Unfortunately, the pre-analysis effort was not continued to the point where it would have become a determining factor for the planning of the details of the experimental program.

The SEFOR was designed and built by GE on schedule and within budget. The entire experimental program, with zero power experiments, start-up tests, step-wise power ascension measurements, oscillator experiments, sub-prompt critical and superprompt critical transients all for two different core configurations, was conducted in a three year period, 1969 through 1972.

## 2 Doppler Constant Evaluations

The original SEFOR experimental results were analyzed by three different groups, GE, KFK and HEDL. GE analyzed all of the experimental data, KFK most of them, but HEDL considered only the superprompt critical transients.

The identical set of data was analyzed with three considerably different methods. If the three analysis methods would be highly accurate, the results would be in close agreement. Indeed, if one combines all results for transients starting at different power levels, and for different sub- or superprompt critical reactivity insertions into a single average value for  $a_D = T d\varphi/dT$ , the so-called Doppler constant, the three analyses are in fairly good agreement. The values obtained by GE, KFK and HEDL for the two cores, Core I and Core II, are

$$a_D^I = -261.3\text{¢}, -267\text{¢} \text{ and } -269.0\text{¢}$$

$$a_D^{II} = -195.4\text{¢}, -182\text{¢} \text{ and } -190.7\text{¢}$$

Wider differences appear in the individual values of the transients (see Figs 7 and 8). They range

from  $-230\text{¢}$  to  $-280\text{¢}$  for Core I, and

from  $-178\text{¢}$  to  $-208\text{¢}$  for Core II.

The error bars on the right of Figs. 7 and 8 give the  $1\sigma$  variations of the individual results about the respective average values of the three analyses (indicated by the symbol).

Statistical errors in the original data (e.g. from counting statistics and power calibration) should affect all three analyses in the same way. Therefore, the substantial deviations in the individual results indicated here have to be attributed to "systematic" differences; they have to

be considered as "systematic errors" of the analyses.

An additional argument for these deviations being systematic errors is provided by the apparent small magnitude of the statistical errors as such. Taking the data of the most accurate analysis, the one done by HEDL, Tab. VII, as basis to form a standard deviation of the individual results around the mean gives  $\sigma = 1.0\%$  for Core I and  $\sigma = 1.2\%$  for Core II.

Also reported in the original literature are comparisons with calculations (using codes and data of 10 to 15 years ago). There appears to be general agreement between these calculations and the average experimental results.

### 3 The Temperature Dependence of the Doppler Feedback

The temperature dependence of the Doppler coefficient,  $\gamma_T(T)$ , is generally expressed in the form,  $\gamma_T(T) \propto 1/T^x$ , with  $x$  being near the mid-point of the two theoretical limits:  $x = 1/2$  for thermal reactors, and  $x = 3/2$  for very hard neutron spectrum. A value of  $x = 1$  is widely favored for its simplicity, although it has no theoretical basis, the way the two limits have. The value of  $x$  affects the Doppler reactivity (the integral over the coefficient  $\gamma_T$ ) over a large temperature interval. Thus, accurate information on  $x$  is important for safety assessments.

However, the theoretical predictions of  $x$  are quite uncertain, as they are affected by the combined uncertainties of the nuclear data, the group constant generation technique, and the flux calculation method. Therefore, experimental information on the temperature dependence appears to be needed.

Experimental information on this temperature variation can only be obtained from varying the initial temperature of the SEFOR transients. The temperature change during the transients is far too small to provide useful experimental information.

The  $a_D$ -values in Figs. 7 and 8 are plotted as function of the mean temperature during the transient, which is moderately above the initial temperature  $T_0$ . The plotted  $a_D$ -values are generally within a  $T$ -independent band, suggesting an approximate  $1/T$  temperature dependence of the Doppler coefficient. The observation of the variation of the individual values suggests a temperature dependence characterized by

$$x = 1.0 \pm 0.15 , \quad (27)$$

a range that does not appear to be better than what one would obtain from an educated guess.

The systematic and statistical errors do not allow a more precise determination of the power of  $T$ . Actually, a value of  $x$  somewhat outside the band given in Eq. (27) would not be inconsistent with the data of Figs. 7 and 8.

Even taking the most accurate set of results, the HEDL values, alone shows that a determination of a more accurate  $T$ -dependence from the SEFOR tests is not possible: The HEDL values yield for Cores I and II

$$\begin{aligned} 1/T^{1.06} & \text{ Core I} \\ 1/T^{0.87} & \text{ Core II} . \end{aligned} \quad (28)$$

As Core II has a neutron spectrum that is considerably harder than the one in Core I, the power of  $1/T$  should be closer to the hard spectrum limit of 1.5 and not closer to the thermal core limit of 0.5 as compared to Core I. Taking a value of  $\delta x = +0.1$  for the change of  $x$  between cores I and II and combining it with  $\delta x = -0.19$  from Eq. (28) gives a total span for the apparent error of  $\delta x \approx -0.29$ , consistent with the uncertainty of  $x$  in Eq. (27). Thus, even the HEDL results are not accurate enough to determine a more accurate  $T$ -dependence as given by the  $x$ -range of Eq. (27). As it can be easily seen from Figs. 7 and 8, the GE and the KFK analyses have inaccuracies in the temperature dependency that are much larger than the ones of the HEDL-analysis results given in Eq. (28). They are therefore useless for deriving information on the temperature dependence of the Doppler coefficient.

The major problem of a determination of a more accurate temperature dependence or at least of a consistent change between the two cores is the limited range of initial temperatures for the transients as given by the initial power values which ranged from 2 to 10 MeV for the subprompt and from 2 to 8 MeV for the superprompt critical tests. The use of a range of  $T_0$ -

subprompt and from 2 to 8 MeV for the superprompt critical tests. The use of a range of  $T_0$ -values that corresponds to initial power values of 0.1 to 20 MW would have been a better basis for the determination of the temperature dependence.

#### 4 Conclusions

- \* The three independent analyses of the SEFOR tests yielded useful information for the overall average of the "Doppler constant" ( $a_D$ ), for both cores. The three results are within a very few percent of each other. A comparison of modern calculations with these results, especially with the values of the more accurate HEDL analysis, should provide a good test of the overall magnitude of the Doppler feedback.
- \* The inaccuracies of the  $a_D$  values for the individual transients are, however, so large that no meaningful information is provided by the original analyses of the SEFOR tests on the temperature dependence of the Doppler coefficient, i.e. there is no information that could narrow down the inaccuracies one would have to assign -more or less arbitrarily- to theoretical predictions.
- \* The impossibility of the SEFOR tests to provide information on the temperature dependence is largely the result of an inadequate lay-out of the experimental program, with its small range of initial temperatures and its lack of repetition of key experiments.
- \* The determination of first order differences, as they are represented by the temperature dependence, is hampered further by the considerable "systematic-error" type deviations among the individual results of the three analyses. These large deviations make it inadvisable to consider a combined result of the three analyses in order to possibly increase the accuracy of the analysis of the experimental data on the temperature dependence.

- \* An additional problem is the strong influence of the large errors of the mean precursor decay constant  $\bar{\lambda}$ . This is an example of a major deficiency in the analyses which could have been avoided by a suitable lay-out of the experimental program.
- \* A re-analysis of the SEFOR tests could yield a somewhat better overall average value for  $T d\rho/dT$ , but it is very unlikely that it could generate valuable information on its temperature dependence. Thus, a re-analysis of the original data does not appear to be useful to obtain better results. The only goal that could justify a re-evaluation of the SEFOR tests would be an in-depth investigation of the three analyses, aiming at an understanding of their sizable systematic errors as a basis for the development of a considerably refined procedure. Such a procedure, applied in dry-run computer analyses of trial tests, could then be used for the detailed planning of future experiments. Planning the experiments in conjunction with sophisticated analysis procedure may be required for the eventual results to have the desired accuracy.
- \* To the extent that these conclusions pertain to shortcomings of the SEFOR tests and their analysis they may contain lessons for future investigations and demonstrations of safety characteristics.

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