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Reactivity Coefficients of Steam-Cooled Fast Breeders

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+) Work performed within the association in the field of fast reactors between the European Atomic Energy Community and Gesellschaft für Kernforschung m.b.H., Karlsruhe.

INTERNATIONAL ATOMIC ENERGY AGENCY

SYMPOSIUM ON FAST REACTOR PHYSICS AND RELATED SAFETY PROBLEMS

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REACTIVITY COEFFICIENTS OF STEAM-COOLED FAST BREEDERS+

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1. INTRODUCTION

In the first generation of Fast Power Reactors the fuel expansion coefficient of the metallic fuel was the most important quantity correlating the neutron physics with the safety behaviour of the reactor. For the second generation of Fast Reactors fuelled with ceramic fuel, the Doppler reactivity feedback, characterized by the Doppler-coefficient (DC) of criticality, is the dominant nuclear quantity with regard to the safety and stability-behaviour of the reactor. For Steam-Cooled Fast Breeders the Steam-Density-Coefficient (SDC) of criticality turns out to possess also a great influence on the stability behaviour, and there are other quantities to be considered in a reactor design which are equally related to changes in criticality resulting from changes in the coolant density. These quantities are shown in Fig.1.

As reported elsewhere [1] the Karlsruhe design of a Steam-Cooled 1,000 MW(e) Breeder [2], the so called D1-Reactor, is in the vicinity of the boundary which exists between the stable region and the unstable region. Taking

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into account the uncertainties of the DC and the SDC it would be possible for the D1-Reactor to move into the unstable region (Fig. 2). This fact underlines the necessity to measure both coefficients precisely, a task which will be fulfilled by the SNEAK-facility. Furthermore, the influence of the design parameters on both coefficients and the other quantities shown in Fig. 1 should be examined in order to get an idea of how important various design parameters are with regard to the nuclear quantities and find out the possibilities of influencing these quantities in the desired direction by suitable changes in the design parameters. This will be done in this paper.

2. THE DESIGN PARAMETERS AND THEIR VARIATIONS

Starting from a reference point corresponding to the D1-reactor a very large number of design parameters has been varied which are listed in Table I.

The values of the design parameters corresponding to the D1-reactor which are listed in Table II together with the resulting atom densities have been used as a reference point.

2.1 Reasons explaining the variation of the parameters

2.1.1 Large variations

1. Besides the variation during burn-up the isotopic composition of plutonium depends on the origin of the plutonium and on the fuel management in the fast reactors: reprocessing the fuel elements of the core together with those of the blankets of a steam-cooled breeder results in the composition ß) of Table I; separate reprocessing and selling the excess plutonium of the blankets leads to composition γ) which shows a higher content of plutonium 240 and is often called "dirty plutonium" . In order to get the other extreme, i.e. "clean plutonium", composition α) has been introduced.

2. For metallurgical reasons there is only one cladding material available at present which probably could meet the requirements made on strength and creep behaviour at the high pressures and cladding temperatures for which the D1-reactor is designed. Nevertheless, it is interesting to take a look at the advantages shown by a cladding material which has been used in steam cycles and which is more favourable from the neutron physics point of view because of its lower neutron absorption probability.

3. D_2O instead of the normal H_2O is an interesting coolant alternative because of its smaller moderation effect which leads to an increase of the mean neutron energy and, to a strong decrease of the low energy part of the neutron spectrum. Several ratios of D_2O/H_2O have been used in the study in order to see whether the interesting quantities show a linear dependence on the D_2O content. The compensation of long-term changes in criticality by a variation of the D_2O content, as in the spectral shift reactors [3] , is another reason for studying this coolant alternative.

4. The advantages of the fuel nitrides (UN, PuN) are a higher density and a lower moderation effect, as compared to the fuel oxides (UO_2, PuO_2), the disadvantage being, however, the greater neutron absorption in one nitrogen atom, as compared even to that in two oxygen atoms. The fuel carbides which apparently offer remarkable advantages in sodium-cooled reactors [4] have not been studied because they cannot be used together with steam as a coolant.

5. It is well known that the geometric arrangement of the core has an important influence upon the breeding and safety behaviour of the reactor; see, e.g., the pancake-shaped cylindrical core of GE [5], [6]. Therefore, the effect of a drastic increase in geometric buckling has been studied.

6. Nearly all calculations have been made by using the well-known Russian group cross-section set of BONDARENKO et. al. which will be abbreviated in the following to read ABN-Set [7]. In order to get an insight into the influence of the group cross-sections used, two additional calculations have been made for the reference point with the two sets prepared at Karlsruhe,i.e., the KFK-Set and the SNEAK-Set described in [8] and [9] respectively.

2.1.2 Small variations

These variations will be studied since we are not quite sure with regard to some of the design parameters that the desired values are obtainable with the present or future technology (e.g., the fuel densitiy at a high burn-up) or because we will intend or are forced to change the parameters by a small amount to match other requirements or to get a more economical reactor. In case of an increase of the coolant volume fraction the volume fractions of the cladding and the fuel would change in a consistent manner keeping the ratio of cladding-to-fuel volume constant.

When changing the design parameters criticality at normal steam density ρ_N was maintained by an appropriate variation of the enrichment ($k_{eff}(\rho_N) = 1.0 \pm 10^{-5}$).

3. RESULTS

All results of this study have been obtained from fundamental-mode diffusion calculations for the homogeneous reactor. During the design of the D1-reactor a lot of one- and two-dimensional diffusion calculations have been carried out [10], dealing partially with similar questions. However, due to the various design steps these calculations are not referring to the same reference point. It can be concluded from these calculations that with respect to safety and stability behaviour the fundamental-mode calculations are sufficiently accurate for a large reactor of the type chosen in the D1-design, even Δk_L is not influenced very much by the change in the buckling respectively the corresponding savings which occurs when the steam density is reduced. The relative tendencies observed upon the variation of some parameters, in particular, are reproduced pretty well by the fundamental-mode results, with the possible exception of strongly changing the geometric form of the core. It goes without saying that for the determination of the power distribution or the total breeding ratio two-dimensional calculations are necessary.

A number of interesting quantities have been determined from the nuclear calculations: as mentioned before, the Doppler-coefficient (DC) = dk/dT and the Doppler-constant (DK) = $-Tdk/dT$ respectively, as well as the Steam-Density-Coefficient (SDC) = $(dk/d\rho)_N$ and the reduced Steam-Density-Coefficient (RSDC) = $(dk/k)/(d\rho/\rho)_N$ respectively are the most important nuclear quantities related to the stability behaviour of the reactor. Apart from these, the other quantities shown in Fig. 1, Δk_L and Δk_F, are reported which may influence to some degree the safety of the reactor; the quantity Δk_{max} has no special meaning for the cases studied in this paper, because in all cases, except for one, it is identical to Δk_L, the only exception occurring for "clean plutonium" for which Δk_{max} coincides with Δk_F. For the sake of completeness some other quantities have also been included into the study:

(a) the atom-ratio AR of fissile to fertile material = $(N_{Pu239} + N_{Pu241})$ / $(N_{U238} + N_{Pu240})$ which is correlated in a simple manner to the enrichment E = AR / (1+AR) and, therefore, provides a hint to changes in fuel cycle cost, fuel rating and related quantities, e.g. the doubling time; (b) the conversion ratio CR as a measure of internal breeding; (c) the diffusion area M^2 which characterizes the diffusion process and together with the geometric buckling B^2, to some degree, the external breeding and (d) the prompt neutron generation time ℓ which is important to strong short-term perturbations of reactor criticality. As to the accuracy of the methods of calculation used for the determination of the quantities studied, some remarks may be found in [10].

For all the changes in the design parameters the results for the interesting quantities DK, RSDC, Δk_L, Δk_F, AR, CR, M^2, ℓ are given numerically in Table III and graphically in Figures 3 - 6.

We will now discuss the influences which the changes in the design parameters exert on the quantities studied.

3.1. Plutonium-composition 100:0:0:0

It is known that the multiplication factor of ^{241}Pu is superior to that of ^{239}Pu, whilst the multiplication factor of ^{240}Pu is superior to that of ^{238}U, the latter being due to the lower fast-fission threshold in ^{240}Pu. Therefore, with the use of "clean plutonium", AR has to be increased. The same effect of a reduction in fast-fission processes causes a considerable decrease in $|RSDC|$ and Δk_L which favourably influences the stability-behaviour. Because of the absence of ^{240}Pu with its low-energy resonance at about 1 eV, Δk_F shows a tremendous increase, an effect which has been already described in [11]. The influence of the resonance self-shielding causes (a) a reduction of the effective cross section of the fuel, especially of the fertile material, and (b) an increase of the low-energy part of the neutron spectrum (softer spectrum) giving rise to a decrease in CR and an increase in DK, M^2 and ℓ , the increase of DK also influencing the stability behaviour in the favourable direction.

3.2. Plutonium-composition 63.7:30.5:3.4:2.4

In all cases the influence of "dirty plutonium" is opposite to that discussed in 3.1. for "clean plutonium" and can be explained by similar arguments.

3.3 Incoloy 800

Due to the smaller parasitic absorption of Incoloy 800 as compared to Inconel 625 (with its high nickel content and the "neutron poisons" molybdenum and niobium) AR is decreased by a considerable amount which causes an increase in CR. A reduction of the total absorption and transport cross section and a softening of the neutron spectrum are further consequences of the change in the structure and cladding material which cause the changes in DK, M^2 and ℓ. The changes in RSDC and Δk_L which are quite remarkable and the slight change in Δk_F are due to the energy dependence of the absorption cross section of the structure and cladding materials considered.

3.4 D_2O

The criticality difference resulting from the use of D_2O instead of H_2O in a reactor, the other conditions of which remain unchanged, is small. Therefore, the change in AR or in enrichment which is necessary to preserve criticality, is also small. The influences on most quantities (DK, Δk_F, CR, M^2, ℓ) are caused by the smaller cross section and the smaller moderation of D_2O compared to H_2O leading to a harder neutron spectrum and an increased leakage rate. The change in the leakage rate following a reduction in the steam density is always smaller than with H_2O, but for Δk_L the effect of the expected and considerably smaller difference in k_∞ - the multiplication factor of an infinitely large reactor of the same composition - is dominating, thus producing a lower value of Δk_L. As to RSDC, the corresponding difference in k_∞ is a little larger for the reasons explained below, so that together with the smaller difference in the leakage rate RSDC adopts a more negative value. For small steam densities the criticality depends almost linearly on the steam density when the coolant is D_2O; however, when it is H_2O, the slope of the curve $k_{eff}(\rho)$ becomes flatter (less negative) with increasing steam density. This is due to the fact that for the same density and with H_2O as a coolant much more neutrons have a chance to be slowed down into the low energy (thermal and epithermal) region of high neutron importance than with D_2O. This effect causes the larger difference in k_∞ for D_2O which is responsible for the more negative RSDC mentioned above.

3.5. Nitride

Due to the higher density of the fuel nitrides (UN, PuN), as compared to the oxides (UO_2, PuO_2), the diffusion area M^2 is considerably smaller and the same applies to the neutron-leakage out of the core. Consequently, AR is reduced which results in an increase of CR. The larger macroscopic capture and fission cross sections of the fuel, giving rise to a hardening of the neutron spectrum and, therefore, to a reduction of DK, also causes a reduction of ℓ and a slight decrease of Δk_F. The variation of RSDC and Δk_L may be explained easily, when we take into account that both quantities depend on (a) changes in the leakage rate, and (b) changes in k_∞, which are produced by a variation of the steam density. Both, the leakage rate and k_∞ become larger when the steam density is reduced; thus they have opposite influences on k_{eff}. With the use of nitride the differences in the leakage rate following a reduction of the steam density are smaller than with oxides. The reason is mentioned above; on the other hand the differences in k_∞ following a reduction of the steam density show a small increase, so that $|RSDC|$ and Δk_L become larger than with oxides.

3.6. B^2 doubled

A doubling of the geometric buckling B^2 requires an increased value of AR and, therefore, reduces CR. Because of the higher enrichment and the hardened neutron spectrum, DK decreases (ℓ too), but RSDC increases by a larger amount so that the stability behaviour is more favourable. The effect on Δk_L and Δk_F is the expected one, since an increase in B^2 decreases criticality, the more so, the smaller the coolant density will be (keeping the enrichment at a constant level in this case).

3.7. KFK-Set and SNEAK-Set

The group cross section set can, of course, not be regarded as a real design parameter. It is changed in our study in order to see how the uncertainties in the nuclear data finally give rise to uncertainties in the interesting quantities. The results show that besides the enrichment (characterized by AR) RSDC and Δk_L are changed by a considerable amount in the unfavourable direction. It is the same for DK, though by a much smaller amount. The stability behaviour would be much worse than with the ABN-Set, especially with the use of the KFK-Set, which is, of course, not very suitable for the calculation of steam-cooled reactors. But even with the probably more suitable SNEAK-Set the changes in RSDC, Δk_L and Δk_F are quite large. Although the enrichment has to be drastically increased, CR shows a small increase, indicating a better internal breeding; however, M^2 is reduced to a very low value.

Thus, the leakage rate and probably the external breeding is reduced. ℓ decreases because of the increase in AR.

3.8. Varying D_2O content

As may be seen from Figures 5 and 6 all quantities show a good linear dependence on the D_2O content of steam as long as the content is small. For contents of 50 % or more the loss of moderation comes into operation more strongly causing deviations from the linear behaviour. This is especially true for the quantities depending on the variations of the steam density. The reasons are the same as those given in section 3.4. for the change from H_2O to D_2O. For the normal steam density chosen the absolute value of the change in k_∞ corresponding to a small variation of the steam density (i.e. RSDC for $B^2=0$) would even show a maximum for a D_2O-content of 70 - 80 %. Thus, the partial compensation of changes in k_∞ and in the leakage rate are responsible for the special dependence of RSDC shown in Fig. 5.

3.9. Increase of a burn-up

A higher burn-up requires a higher value of AR to compensate for the higher parasitic absorption of the fission products Consequently, CR and M^2 slightly decrease. The decrease of DK and ℓ is caused chiefly by the harder neutron spectrum. Due to the fact that the absorption cross section of the fission products increases rapidly with decreasing neutron energy, $|RSDC|$, Δk_L, and $|\Delta k_F|$ become larger. Increasing the average burn-up from 2.75 to 5 atom-percent gives rise to the following changes, as reported in [10], which may be verified qualitatively by the present results: δDK: -12.4 % , $\delta|RSDC|$: +42 % , $\delta\Delta k_L$: +0.013 , $\delta\Delta k_F$: -0.024 , δAR: +3.3 % , δCR: -0.034 . δM^2: 2.1 [cm^2] , $\delta\ell$: -0,03 [μsec]. Going from 5 to 0 atom-percent, i.e. completely disregarding the fission products, would change criticality in the flooded stage by about 5 % the value of Δk_L by 0.03 and cause a change of sign for SDC (see [10]).

3.10. Decrease of fuel density

At a lower fuel density a higher value for the enrichment has to be chosen (larger AR) which causes a reduction of CR and DK and a slight increase of Δk_L and Δk_F. A natural consequence of the lower fuel density (lower macroscopic capture and fission cross sections) is the increase of ℓ and the considerable increase of M^2, the higher leakage rate being the reason for the small increase of RSDC.

3.11. Decrease of steam density

A reduction of the mean steam density reduces the moderation effect of the coolant and results in a harder neutron spectrum, which is the reason for the reduction of AR, DK, Δk_L and ℓ and for the increase of $|\Delta k_F|$ and CR. The harder spectrum together with the lower coolant density gives rise to an increase of M^2. The small increase in RSDC is not caused by this increase of M^2, but simply by the smaller steam density itself; the SDC becomes more negative; this means a steeper slope of the curve $k_{eff}(\rho)$, as mentioned before in section 3.4.

3.12. Increase of coolant volume fraction

A first consequence of this change is a softer neutron spectrum. This is the reason for the increase in DK and ℓ which are not so much influenced by the higher enrichment (larger AR) required by the softer spectrum and the lower fuel volume fraction. The two effects, which have just been mentioned, are responsible for the reduction of CR. The reduction of the fuel volume fraction has a stronger influence on M^2 than the softer spectrum and, therefore, M^2 increases causing a small increase in RSDC.

3.13. Increase of buckling

This change has been included for completeness only, in order to demonstrate the influence of a small change in the geometric configuration together with the influences of other small changes in the design parameters. The variations of the determined quantities and the reasons for these variations are analogous to those described in section 3.6.

4. CONCLUSIONS

4.1. Large variations

It can be easily seen from Fig. 3 that all changes in the design parameters, except for the cases where "clean plutonium" and Incoloy 800 are used, result in a decrease of the Doppler constant DK = $-T dk/dT$. Since the two exceptions show also a more favourable value of the reduced steam density coefficient RSDC = $(dk/k)/(d\rho/\rho)_N$, the stability behaviour would be much better. Doubling the geometric buckling B^2 has also a favourable influence on the stability behaviour because of the considerable reduction of RSDC, whereas nitride and D_2O, in particular, would make it much worse. The most important parameters influencing Δk_L, the change in criticality following a loss of coolant, are Incoloy and, as has been expected, "clean plutonium" as well as the doubling of B^2. Δk_F, the criticality change upon flooding the reactor, is very sensitive to the ^{240}Pu-content of the fuel and to the coolant used. Besides the expected changes in AR- the atom ratio of fissile-(^{239}Pu+^{241}Pu) to fertile-(^{238}U+^{240}Pu) material - which come about if we use nitride or double B^2, the use of Incoloy 800 instead of Inconel 625 gives rise to the largest reduction in AR. Cooling with D_2O-steam and the use of nitrides as a fuel or Incoloy 800 as a structure and cladding material would produce a considerable increase in internal breeding, characterized by the conversion ratio CR whilst the doubling of B^2 and the use of clean plutonium would have the opposite effect. The most important changes in the diffusion area M^2 are caused by D_2O and nitride and, to a smaller extent, by Incoloy 800. Together with "clean plutonium" the same design parameters lead to the largest variations in the prompt neutron generation time ℓ.

4.2. Small variations

All changes, except for an increase in the coolant volume fraction, cause a reduction of DK, the decrease in the steam density being the most important one. An increase in burn-up decreases RSDC, whereas an increase of the buckling increases RSDC bringing about a better stability behaviour in spite of the accompanying reduction of DK. The most pronounced improvement of stability behaviour is caused by an increase of the coolant volume fraction, since both important quantities, DK and RSDC, change in the desired direction. Increasing the burn-up or the coolant volume fraction causes an increase of Δk_L, whilst the decrease of the mean steam density shows the opposite tendency, as it has been expected. An increase in burn-up naturally leads to a lower value of Δk_F; an increase in the coolant volume fraction or a decrease in the fuel density has an influence which goes the opposite direction. Among all of these variations the decrease of the fuel density requires that the enrichment (characterized by AR)has to be raised to the largest extent; to a smaller extent an increase of the coolant volume fraction will yield the same effect. The corresponding tendencies are shown by CR, M^2 and ℓ. This underlines the fact that with regard to stability behaviour the determination of burn-up is the most important factor, whereas from the point of view of economics the determination

of the fuel density will be of the greatest importance.
The influence of the different cross section sets illustrates the uncertainties which exist in the determination of the interesting quantities and which are caused by uncertainties in the nuclear data; it, consequently, demonstrates the necessity to check the theoretical results by appropriate experiments, as it will be done, e.g., in the SNEAK-facility.

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TABLE I

List of varied parameters

A) Large variations (Step changes)

1. Plutonium isotopic composition

	^{239}Pu	^{240}Pu	^{241}Pu	^{242}Pu
α)	100	0	0	0
β)	74	22.7	2.3	1.0
γ)	63.7	30.5	3.4	2.4

2. Cladding and structure material

	Material	Density g/cm^3	Weight-percent of				
			CR	FE	MO	NB	NI
α)	Inconel 625	8.44	22	3	9	4	62
β)	Incoloy 800	8.01	20	48	0	0	32

3. D_2O-content in the normal H_2O steam coolant

	α)	β)	γ)	δ)	ε)
H_2O	1.	0.9	0.5	0.1	0.
D_2O	0.	0.1	0.5	0.9	1.

4. Type of ceramic fuel

α) Oxide

β) Nitride

5. Magnitude of geometric buckling

α) $B^2 = 5.69 \cdot 10^{-4}\ cm^{-2}$

β) $B^2 = 11.38 \cdot 10^{-4}\ cm^{-2}$

6. Set of group cross sections used

α) ABN-Set

β) KFK-Set

γ) SNEAK-Set

B) Small variations (quasi-continuous changes)

7.	Burn-up	increased by 10%
8.	Fuel density	decreased by 10%
9.	Steam density	decreased by 10%
10.	Coolant volume fraction	increased by 10%
11.	Buckling	increased by 10%

TABLE II

Design parameters for the reference point

	Type of material	Volume fraction
Fuel	UO_2 - PuO_2	0.454
Cladding + structure	Inconel 625	0.206
Coolant	H_2O - steam	0.32
Follower	Al_2O_3	0.02

Maximum core-averaged burn-up before reloading 1/3 of the core elements	3.0653 atom-percent
Fuel density	87 % of theoretical
Plutonium isotopic composition	74:22.7:2.3:1.0
Normal mean steam density	0.0706 g/cm^3 $\hat{\approx}$ 170 ata ≈ 2600 psi
Core height 150 cm Core diameter 260 cm	$\hat{\approx}$ $B^2 = 5.69 \cdot 10^{-4}$ cm^{-2}
Thickness of axial and radial blankets	35 cm

Atom densities • 10^{-24} per cm^3 of core volume (AD) for each isotope or element (I or E)

I or E	Al	Cr	Fe	H	Mo	Nb
AD	$7.34 \cdot 10^{-4}$	$4.43 \cdot 10^{-3}$	$5.62 \cdot 10^{-4}$	$1.498 \cdot 10^{-3}$	$9.82 \cdot 10^{-4}$	$4.51 \cdot 10^{-4}$

I or E	Ni	O	^{239}Pu	^{240}Pu	^{241}Pu	^{242}Pu
AD	$1.106 \cdot 10^{-2}$	$2.127 \cdot 10^{-2}$	$9.7044 \cdot 10^{-4}$	$2.977 \cdot 10^{-4}$	$3.016 \cdot 10^{-5}$	$1.31 \cdot 10^{-5}$

I or E	^{238}U	pairs of fission products
AD	$8.10235 \cdot 10^{-3}$	$2.977 \cdot 10^{-4}$

TABLE III

The influence of changes in the design parameters on $DK = -T\,dk/dT$, $RSDC = (dk/k)/(d\rho/\rho)_N$, $\Delta k_L = k_{eff}(\rho=0)-k_{eff}(\rho_N)$, $\Delta k_F = k_{eff}(\rho=1g/cm^3)-k_{eff}(\rho_N)$, $AR = (N_{Pu239}+N_{Pu241})/(N_{U238}+N_{Pu240})$
CR = internal conversion ratio, M^2 = diffusion area, ℓ = neutron generation time

Change Nr.	Parameter changed	DK $\cdot 10^2$	RSDC $\cdot 10^2$	Δk_L $\cdot 10^2$	Δk_F $\cdot 10^2$	AR	CR	M^2 [cm^2] $\cdot 10^{-2}$	ℓ [µsec]
0	Reference	1.69022	-1.84098	+3.7349	-4.6463	0.119118	0.980565	1.47213	0.444721
1	Pu 100	1.88161	-0.2155	+2.2217	+14.474	0.121568	0.883024	1.52407	0.551552
2	Pu 63,7	1.68410	-2.1615	+4.0693	-7.7078	0.116542	1.026592	1.45140	0.422241
3	Incoloy 800	2.10583	-0.74849	+2.0399	-3.3267	0.107520	1.054990	1.59404	0.525653
4	D_2O	0.97267	-2.606	+3.0419	-10.734	0.117581	1.087751	1.68866	0.335977
5	Nitride	1.53406	-2.602975	+4.4489	-6.4918	0.103127	1.081165	1.26323	0.304060
6	B^2 doubled	1.39856	-1.072005	+2.5202	-2.751	0.140696	0.844599	1.44561	0.383044
7	KFK-SET	1.67540	-3.085	+5.0207	-10.8771	0.129911	0.98097	1.33421	0.439911
8	SNEAK-SET	1.64679	-2.3965	+4.0027	-7.3327	0.139273	1.00264	1.32505	0.444475
9	$H_2O:D_2O=0.9:0.1$	1.64730	-1.9245	+3.7162	-5.0968	0.119073	0.98895	1.48951	0.435428
10	$H_2O:D_2O=0.5:0.5$	1.42217	-2.293	+3.5669	-6.8223	0.118743	1.02711	1.56702	0.395119
11	$H_2O:D_2O=0.1:0.9$	1.08168	-2.5885	+3.1950	-9.2064	0.117919	1.07431	1.66146	0.348715
12	Burn-up increased	1.66165	-1.9525	+3.8762	-4.9746	0.120087	0.974824	1.46918	0.440294
13	Fuel dens. decreased	1.64696	-1.8185	+3.8215	-4.4266	0.127015	0.926155	1.67446	0.482096
14	Steam dens. decreased	1.63217	-1.8180	+3.5156	-4.7432	0.118629	0.991698	1.50485	0.433141
15	Cool. vol. fract. incr.	1.72816	-1.7960	+3.9236	-4.1685	0.123016	0.943757	1.57010	0.479779
16	Buckling increased	1.65895	-1.7575	+3.6025	-4.4566	0.121163	0.965875	1.46959	0.438058

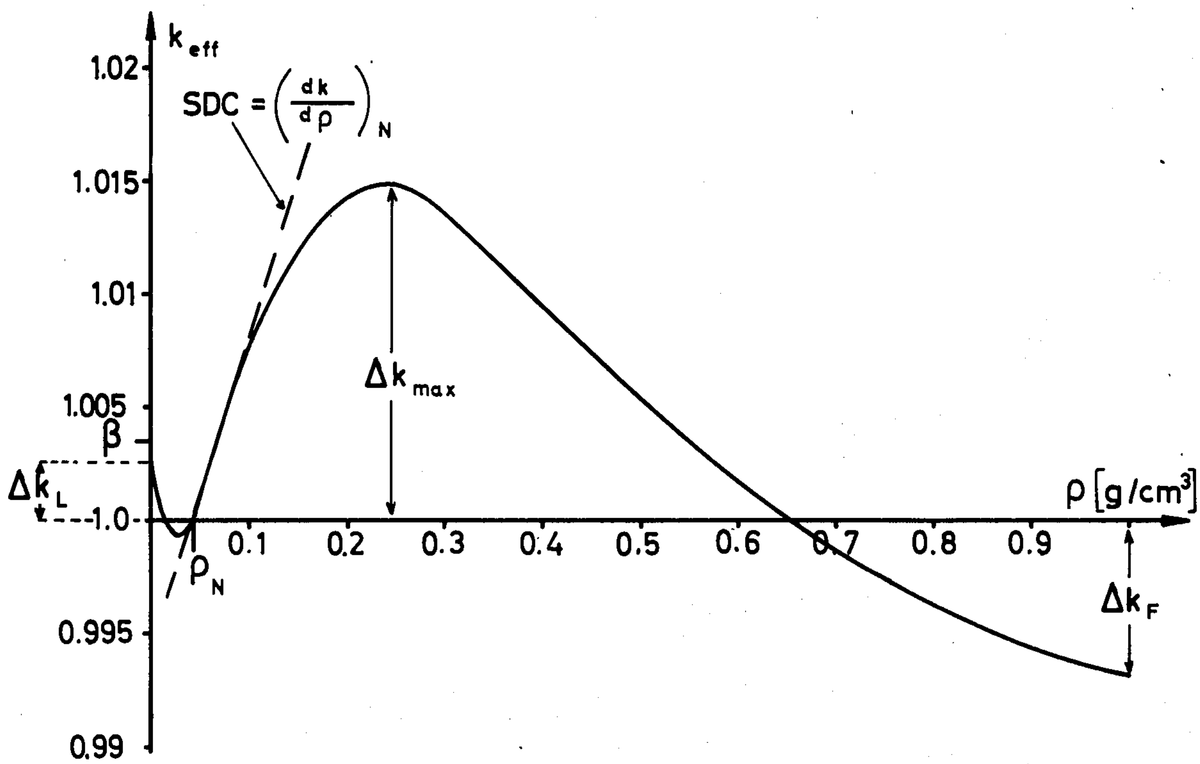

Fig. 1 Influence of coolant density on criticality

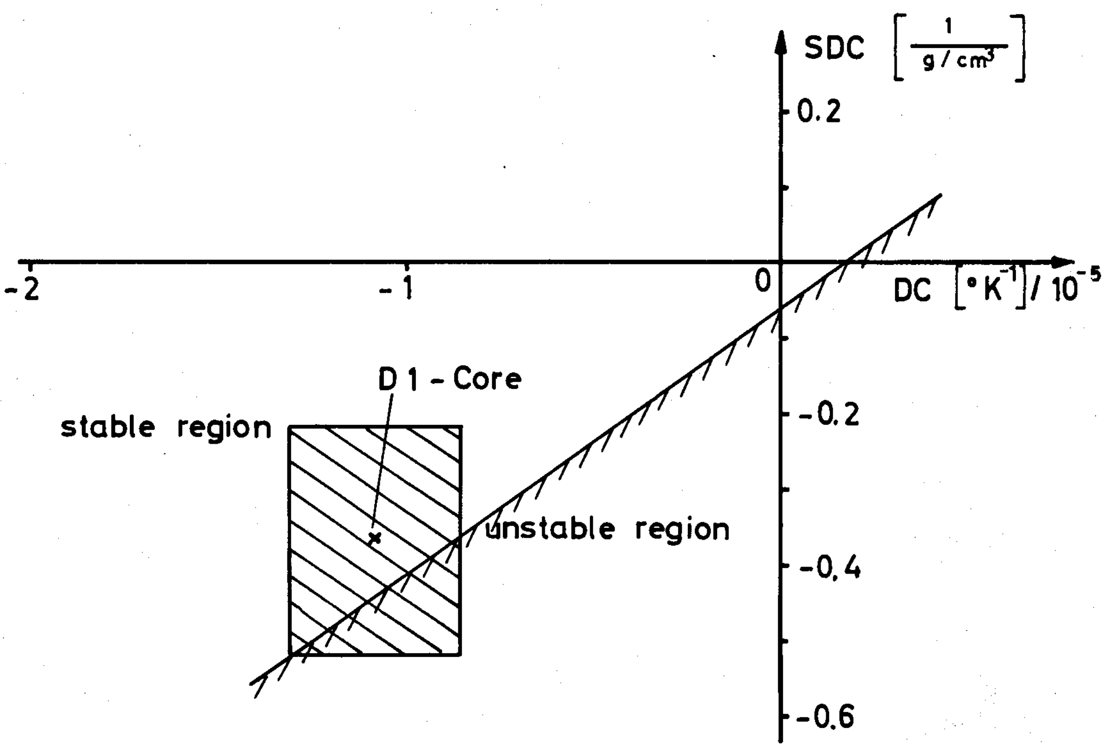

Fig. 2 Region of core stability

Fig. 3 Influence of Various Design Parameters on Reactivity Coefficients

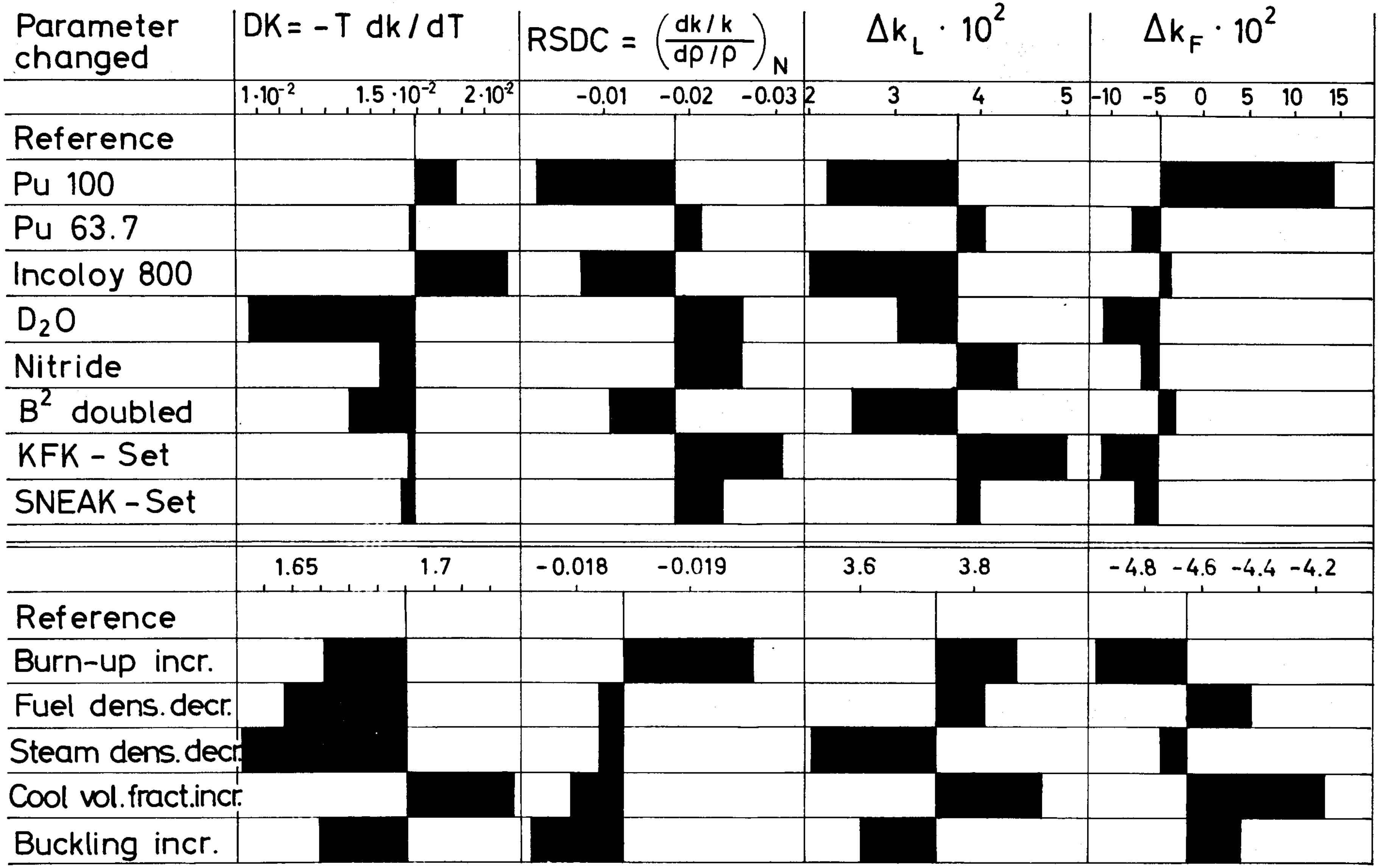

Fig. 4 Influence of Various Design Parameters on Several Nuclear Quantities

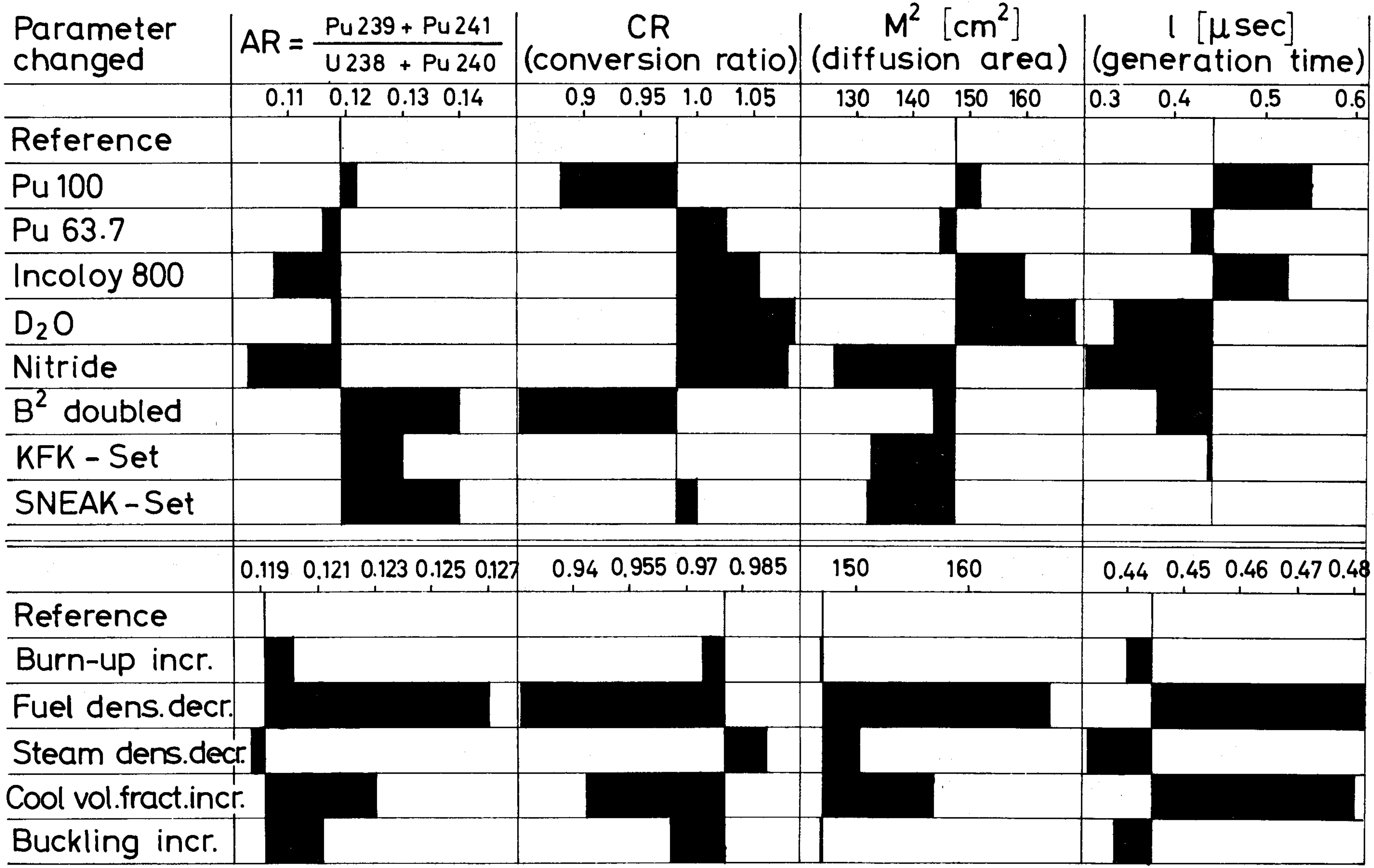

Fig.5: Influence of D_2O-content on reactivity coefficients

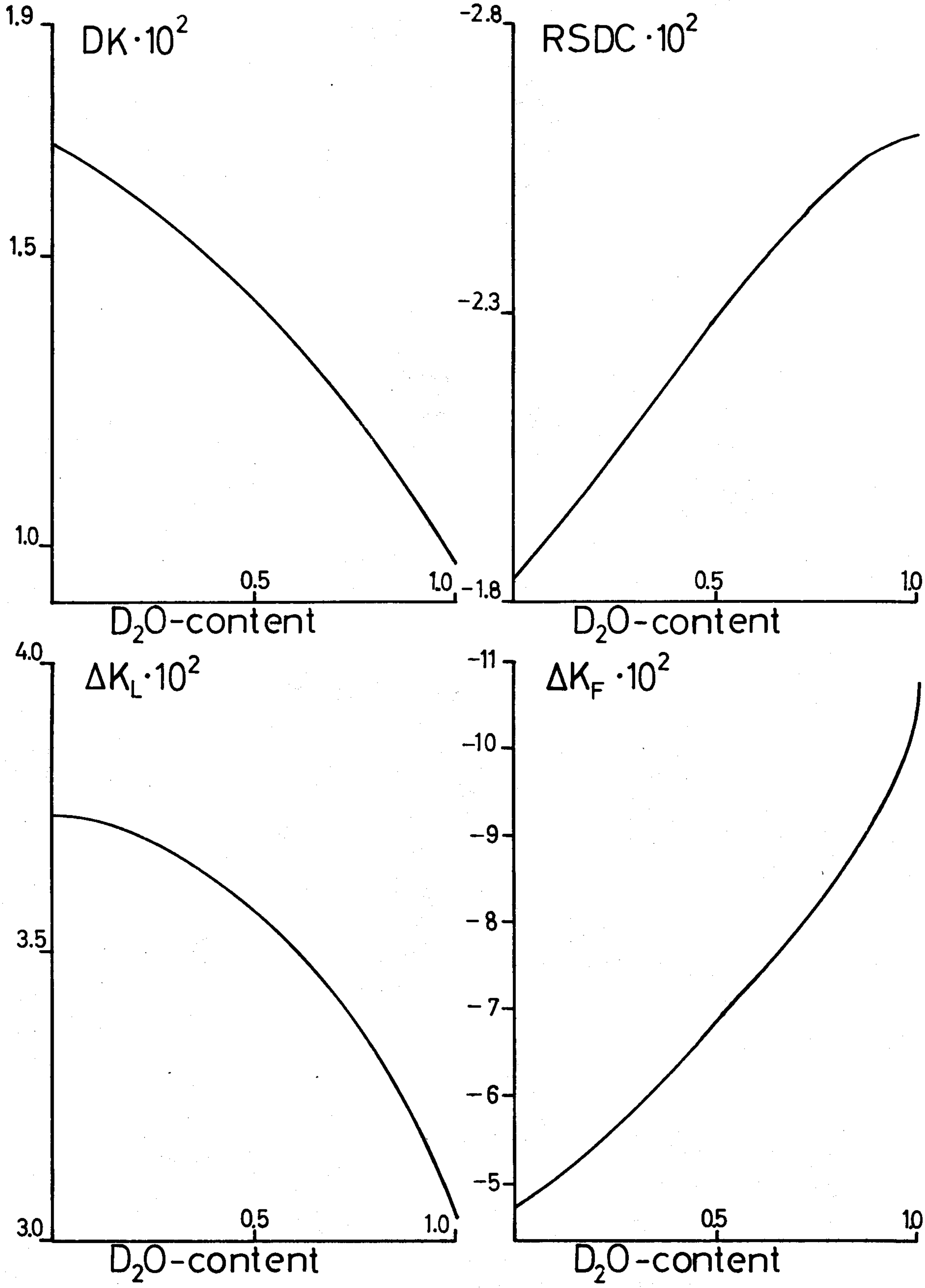

Fig.6: Influence of D_2O-content on several nuclear quantities