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PREDICTIONS OF THE DECAY HEAT OF NUCLEAR REACTORS BY MICROSCOPIC BETA DECAY CALCULATIONS

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Abstract: A new procedure for calculating the decay heat power of nuclear reactors is presented. Basis is a new program, THOR-I (Theory of Heat of Reactor-I), which calculates the isotopic inventory of a reactor as function of time during reactor operation and after shutdown by the analytical method and which uses a new set of β decay data, in which β decay of experimentally unknown nuclei has been calculated for the first time by microscopic nuclear structure calculations. The decay heat power for short time irradiation of ^{232}Th, ^{233}U, ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu by thermal and fast neutrons, as well as for realistic light water reactor (LWR) operation cycles, have been calculated as function of time after irradiation (or operation) and shutdown, respectively. The effect of neutron capture is explicitly taken into account. Comparison of the results with the ANS (DIN) standard shows that the current standards systematically overestimate the decay heat of LWRs by about 6-8% in the first 10^4 sec after shutdown. Similar results are found for other reactor types such as boiling water reactors, advanced pressurized water reactors and CANDU. It is shown that the accuracy of the new procedure is such that a) summation calculations of this type could be considered as basis of new standards, b) might lead directly to economic benefit.

(Nuclear Reactors, Decay Heat Prediction, Standards of Decay Heat)

1 Introduction

The decay heat power of nuclear reactors is an important quantity for design, safety and costs of operation of a nuclear reactor. Beyond for the safety analysis of the coolant-loss accident and for optimal dimensioning of heat removal loops a reliable calculation of the decay heat from the fission products is of importance further for safe handling of burnt fuels.

In a hypothetical loss-of-coolant accident (LOCA) in a light water reactor (LWR) after a few seconds the major source of heat in the fuel rods would be the beta and gamma rays from the decay of the accumulated fission products. This heat amounts to ~7% of the operating power of the reactor directly after the shutdown. Since the heat maximum in the fuel rods occurs typically 100 sec after shutdown in the beginning of the flooding phase, a precise knowledge of the decay heat is of particular importance for the first 200 sec after shutdown.

In spite of many efforts also nowadays there are open questions concerning our knowledge of the decay heat whose solution would have economic impact on reactor operation. The review paper "Decay Heat Data Needs" of T. Yoshida et al. at the 1983 NEANDC Specialists Meeting on Yields and Decay Data of Fission Product Nuclides [1] comprises the following statement: "There still exist, however, persistent needs for decay data of short-lived nuclides. Nowadays we are much more interested in the quality of the measured decay data than in 1970's, mainly because the average decay energies $\bar{E}_\beta$ and $\bar{E}_\gamma$ derived from incomplete decay data may lead to a large systematic error in decay heat calculations."

The concluding remarks of the same paper comprise the statement: "...there still remain unresolved discrepancies between calculations and measurement and between different measurements."

In the "Report of the Working Group on Decay Heat Data Status and Needs" of the same conference, the following is stated: "The meeting has reviewed recent measurements of fission-product decay heat. The Group suggests that the two most important discrepancies are:
(1) Among measurements and among measurements and calculation for ^{235}U and ^{239}Pu total decay heat for cooling times between 10 and 10^4 seconds; and..."

In this paper a procedure for calculating the decay heat is presented which has to be considered as a major step to solving these problems.

Current information on the decay heat power comes from two sources, measurements and calculations. The ANS Standard ANSI/ANS-5.1-1979/1985 [2] for the decay heat of LWR and in the same way the German DIN Standard DIN 25463 [3] (which in most parts is a copy of the ANS standard) prescribe methods for obtaining the decay heat power for an arbitrary reactor power history, basing for ^{235}U mainly on measurements of short time decay of fission products by Lott et al. [4] (using calorimetry), Friesenhahn et al. at IRT [5] and Dickens et al. at ORNL [6] (using radiation detection methods) and by Yarnell et al. [7] at LASL and Schrock et al. [8] at Berkeley (using calorimetry) and also on summation calculations, which accumulate the individual energy releases calculated for each fission product. A summary of the data basis for the new standard, including ^{238}U and ^{239}Pu is given by England et al. [9] and Schrock [10].

The above five experiments dominate the uncertainty analysis and thus exclude prior works statistically. Due to the paucity of direct experimental data at that time the standard values adopted for fast fission of ^{238}U are based solely on summation calculations. Fissionable nuclides other than ^{235}U, ^{238}U and ^{239}Pu are treated as ^{235}U.

Although the data adopted in the standards depend in part on the summation calculation method, the summation calculation itself at that time has not been chosen as the proposed standard. We shall show in this paper that it might

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[1] Invited speaker

be worthwhile, however, to take the latter alternative into serious consideration for the future, since for reasons to be discussed the precision of the method has been improved to an extent that it can at least compete with experimental possibilities mentioned above, particularly also for short times after shutdown. We shall show further that the new calculations to be presented here indicate that the decay heat of a typical LWR is overestimated by the order of 6-8% during the first 200 sec after shutdown and beyond by the present standards. This means that the prescription of the standards could be reduced by about the same percentage, by which ANS-5.1-1979/1985 was reduced relative to ANS-5.1-1973 for the first 200 sec after shutdown (see Ref. 2).

This should be of direct economic benefit for operators of ECC (emergency core cooling)-limited nuclear power stations.

2 The Present Standards, Experiments and Previous Summation Calculations

2.1 Present Standards and Experiments

Experiments exist up to now for the fissile isotopes ^{232}Th, ^{233}U, ^{235}U, ^{238}U, ^{239}Pu and ^{241}Pu. Beyond those cited above, individually mentioned should be the recent work of the Japanese group (Akiyama and An [11]) and the results on ^{239,241}Pu by Dickens et al. [12]. All of these experiments are limited, however, to short time irradiations of small samples of these isotopes by thermal or fast neutrons. This means that no detailed experimental information about the decay heat of a real nuclear reactor is available, since the above procedure, i.e., the measured "burst function" (decay heat following a fission pulse) does not give information about the effects of neutron capture by the fission products and by the actinides during realistic reactor operating conditions.

The two mentioned standards extract, therefore, the prescription (the same in both standards) for calculation of the decay heat power generated by the decay of the fission products of ^{235}U, ^{239}Pu--neglecting neutron capture by fission products--from measured burst functions. They add then in slightly different ways prescriptions for the calculation of the decay heat from

1. decay of ^{239}U and ^{239}Np
2. neutron capture in other actinides (no prescription in the ANS standard)
3. neutron capture in fission products (separated in the contribution for ^{133}Cs and from all others in the DIN standard).

These prescriptions tend to lead to conservative overestimates.

2.2 Previous Summation Calculations

It has been mentioned in section 1 that the prescriptions for the decay heat of ^{238}U are determined by summation calculations. The latter suffered up to now, however, in general from the problem of lacking information on the beta decay of short-lived nuclei far from stability which resulted in uncertain predictions for the first several 100 sec after shutdown (see, e.g., Dickens 1980 [6], Tobias 1980 [13]). That the by far main source of uncertainty of predicted decay heat for short cooling times are the β decay energies or in other words the shape of the beta strength function $S_\beta(E)$ of short-lived fission products has been shown already in the analysis by Schmittroth and Schenter [14] and discussed in detail by Klapdor [15].

Besides deficiencies in experimental decay schemes the main problem in summation calculations up to now was that oversimplified "theoretical" assumptions on the shape of $S_\beta(E)$ were made for the hundreds of fission products for which no experimental decay schemes exist. This led to the persisting discrepancy between calculated and measured γ and β decay heat for short cooling times.

An improvement of the decay heat calculations by improving the assumption on $S_\beta(E)$ has been tried by Yoshida (1977) [16] and Yoshida and Nakasima (1981) [17] by using the gross theory of beta decay [18] to calculate $\bar{E}_\beta$ and $\bar{E}_\gamma$. Their calculations give impressive results when part of the "experimentally known" decay schemes are replaced by calculated $\bar{E}_\beta$ and $\bar{E}_\gamma$. In view of the general serious problems of the gross theory to give a correct description of the beta strength function (see the discussion in Klapdor 1983, 1985 [15,19], the result of Yoshida and Nakasima [17] unfortunately has to be considered, however, as an improvement obtained by a kind of multiparameter fit which in principle limits the predictive power of the approach (see also [20]).

Prerequisite of an improvement of this situation is a better understanding and predictability of the shape of the beta strength function. In recent years there has occurred now a considerable progress [15,18,21] in the understanding of nuclear β decay, particularly for nuclei far from stability. It is this development which allowed for the first time a calculation of the decay heat power "from first principles" which will be discussed in section 4. Before this we give in section 3 a brief outline of the improvements in the understanding of β decay properties of nuclei far from stability obtained in recent years.

3 The Improvement in the Predictability of β Decay Properties of Nuclei Far From Stability

3.1 General

The understanding of nuclear β decay means: Reliable predictability of the energy positions of the coherent p-h excitations excited by the β operators and of the matrix elements of the transitions to them (Fig. 1), in other words: Knowledge of the β strength distribution $S_\beta(E)$ in the daughter nuclei, which then determines (Fig. 2) all other quantities like β decay half-lives, rates of β-delayed particle emission and fission, the shapes of the electron and antineu-

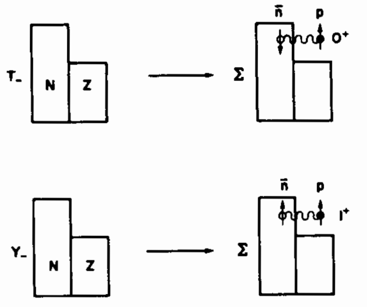

Fig. 1. Schematic representation of the particle-hole excitations excited by the Fermi ($T_- = \Sigma t^{(i)}_-$) and the Gamow-Teller beta operator ($Y_- = \Sigma\sigma^{(i)}t^{(i)}_-$).

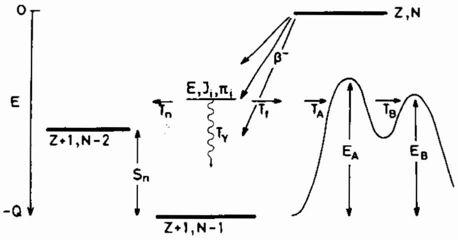

Fig. 2. The beta strength distribution determines the beta decay half-lives and rates for β-delayed particle emission and fission.

trino spectra produced in β decay (for formulae see [15,19]).

At first sight it might look surprising that at a time where we understand β decay on the next deeper level of quarks, there are still problems of calculating the β decay of nuclei with the desired and necessary accuracy. The reason lies in the problem of treating properly the residual interactions between the nucleons in the many-body system nucleus and the corresponding collective features occurring in the spin-isospin excitations and correspondingly in nuclear β decay (see Fig. 3).

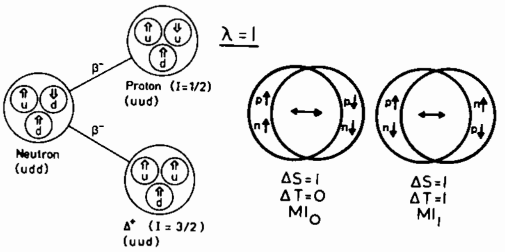

Fig. 3. (schematic) a) Beta decay of a neutron is understood as transformation of a d quark into a u quark; a proton or Δ particle is formed. b) Collective magnetic (M1) nuclear excitations (spin-isospin excitations) in which proton and neutron "liquids" with different spin direction oscillate against each other. Such excitations lead to collective features in Gamow-Teller beta decay (Gamow-Teller giant resonance, see Fig.5).

The progress in the understanding of nuclear β decay--particularly for nuclei far from stability--came from different spectroscopic sources which have shed light on different aspects of the beta strength distribution (for surveys see [15,19,21,22]). All this spectroscopic information led to a breakthrough in the following sense: It led to an understanding of the systematics of the distribution of the GT strength (see Fig. 4) with the consequence that schematic descriptions of the β decay far from stability like that by the gross theory [18] (see Fig. 5), which essentially ignores the existence of the nuclear shell model, but which actually for 10 years was the only theory predicting β decay properties far from stability--can be replaced now by microscopic descriptions putting the achievable accuracy on a new basis [15,19,21,25]. Figs. 5 and 4,6 may illustrate the principal difference between the two descriptions.

Basing on a Tamm-Dancoff approximation (TDA) approach, we have recently calculated microscopically the β^- decay of nuclei between line of β stability and neutron drip line (i.e., for ~6000 nuclei) and for various nuclei left from the β stability line [23].

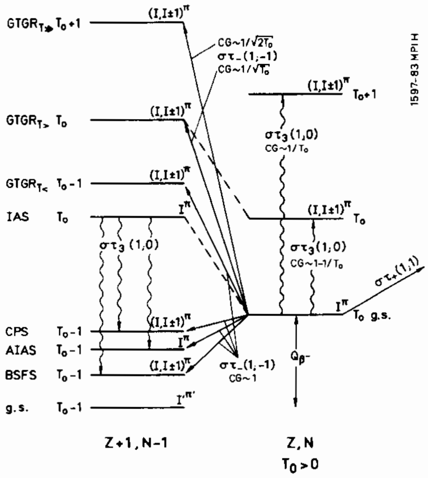

Fig. 4. The systematics of Gamow-Teller and M1 strength distribution in neutron-rich nuclei (see [15,19]).

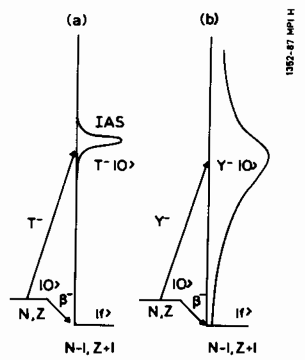

Fig. 5. Schematic representation of the strength distribution in Fermi (a) and Gamow-Teller (b) β^- decay. Part b) corresponds at the same time to the assumption made by the gross theory [18] for the β strength distribution (the latter thus ignores the structure of the low-lying strength, compare to Fig. 4).

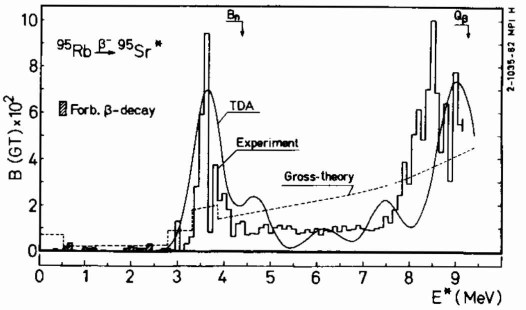

Fig. 6. The beta strength distribution for β^- decay of ^{95}Rb (reduced transition probability B as function of excitation energy e* in the daughter nucleus). The histogram denotes the experimental result (Kratz et al.). Solid line: microscopic calculation [15]; dashed line: gross theory prediction [18].

3.2 Results of Microscopic Calculations of Beta Decay Properties of Neutron-Rich Nuclei

3.2.1 β Half-Lives, P_n and $P_{\beta df}$ Values. The microscopically calculated β decay half-lives are published in At. Data Nucl. Data Tables [23]. The accuracy of their predictions is considerably improved over that of the only existing earlier prediction of [18] (see the discussion in [23]). The theoretical predictions [23] can be tested now on a rather large number of nuclei unknown at the time of the calculations. Fig. 7 (from [24]) compares the calculations of [23] with the new experimental half-lives of neutron-rich nuclei discovered since the calculation [23] (about 70 isotopes). The predictive power of the calculation corresponds to the expectations. A second generation microscopic calculation which leads to further improvements is in progress [24,40].

Calculated rates of beta-delayed fission and neutron emission are given in [15,19,26], complete tables of P_n and $P_{\beta df}$ values are under preparation.

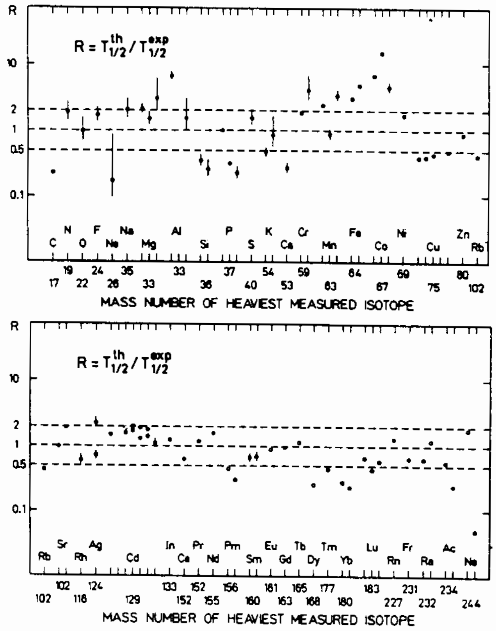

Fig. 7. Ratios R of predicted ($T^{th}_{1/2}$) to measured ($T^{exp}_{1/2}$) new β decay half-lives unknown at the time of calculation. Solid and open circles correspond to measured half-lives shorter or longer than 60 s, respectively.

3.2.2 The Electron and Antineutrino Spectrum from Nuclear Reactors. A kind of global test of our calculated beta strength functions is the calculated electron spectrum produced in thermal fission of ^{235}U, ^{239}Pu and ^{241}Pu by β decay of the ~1000 fission products (Figs. 8-10).

The calculations are described in [27,34]. In the case of ^{239}Pu, ^{241}Pu the more recent tabulation of fission product yields of Rider [35] (ENDF/B-VI) was used and radiative corrections were included. Figs. 8-10 show the large progress in the precision of the calculated electron spectrum compared to earlier calculations which suffer from a poor description of the beta strength function (see discussion in [15,19,27,41]).

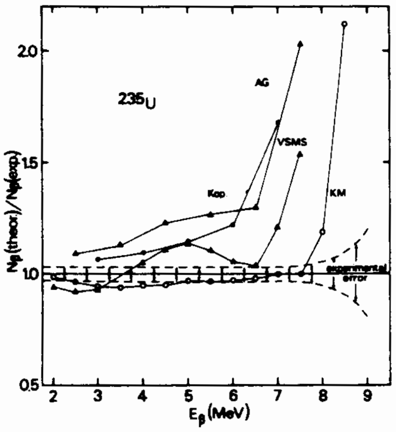

Fig. 8. The electron spectrum from thermal fission of ^{235}U. R denotes the ratio of various calculations (AG, Kop, VSMS, KM denote the calculations of [28,29,30,27], respectively) to the high precision experiment of [31] (from [31]).

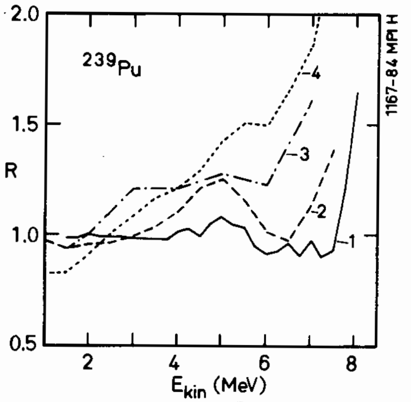

Fig. 9. The electron spectrum from thermal fission of ^{239}Pu. R denotes the ratio between the values of [32,30,33,28] (labelled 1,2,3,4, respectively) and our calculation [27,34] (curve 3 uses the ν spectrum of [28]). The microscopic calculation is seen to be in good agreement with the high precision experiment of [32].

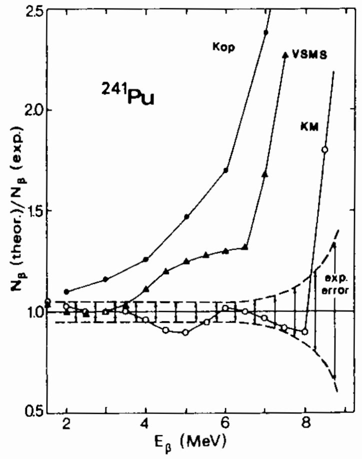

Fig. 10. The electron spectrum for thermal fission of ^{241}Pu. N_β denotes the ratio between various calculations (Kop, VSMS, KM denote the calculations of [29,30,34]) and the high precision experiment of [36].

3.2.3 Double Beta Decay. The more realistic description of the beta strength function is reflected also in a better description of double beta decay--particularly of 2ν transition matrix elements $M_{2\nu}$. We refer to [25,37].

4 The New Calculation of the Decay Heat of Nuclear Reactors

The success in the applications of the microscopic description of the nuclear beta strength of neutron-rich nuclei described in section 3 can be taken as a check of the reliability and internal consistency of the approach. It has encouraged us to also calculate the decay heat of nuclear reactors. In this section are given the results of the first attempt at all of a summation calculation of the reactor decay heat basing on a microscopic nuclear structure calculation of the β decay of the fission products. A detailed description of these new decay heat calculations and of their consequences is given also in [38,22].

4.1 The New Program THOR-I for Calculation of the Decay Heat Power

4.1.1 Calculational Method. In order to calculate the isotopic content of a nuclear reactor at any time during reactor operation and after shutdown two calculational methods have been developed in the last twenty years: a) numerical integration of the differential equations necessary for each pair of nuclides in a linear decay chain, and b) analytical solution for each decay chain in the reactor. Both methods are generally plagued by calculational problems. While b) in earlier times had a lot of problems with rounding errors by evaluation of differences of large almost identical numbers, mainly in the case of long decay chains and short time steps, a) is limited in a range of accuracy of a few percent by the numerical method itself.

The progress made in computer technology in recent years led us to prefer for the present calculation the analytical method discussed in detail by Tobias [13]. For this purpose we have developed the new reactor inventory code THOR-I (Theory of Heat of Reactors-I). It allows calculation of the reactor inventory of any type of reactor at present under consideration for arbitrary power history at any time during operation and after shutdown. The power history is described for this purpose in the usual way by a power histogram with suitably chosen time steps. Neutron capture in the fission products and in the actinides is included in the network.

The calculations have been performed with double precision arithmetic on a DEC KL 1091 computer with a 36 bit word length and an extended range of magnitude from 10^{-308} to 10^{308}. By this procedure all typical problems of the analytical method could be removed.

4.1.2 Data Sets. Experimental beta decay half-lives were taken from the Karlsruhe chart of the nuclides [42] complemented by values from the literature up to the end of 1984. Experimental beta and gamma decay data including isomeric transitions were taken from the Table of Isotopes [43], Nuclear Data Sheets and recent references (up to end of 1984). All these data were standardized in the sense that they were recalculated to be adapted to the 1983 Atomic Mass Table (Wapstra 1985 [44]). Experimental beta-delayed neutron emission rates (P_n values) were taken from the ORIGEN-2 decay data set [45]. For the neutron cross sections the spectrum-averaged cross sections of the ORIGEN-2 code [45] typical for LWRs were taken. For the fission yields we used the values of Rider [35].

For nuclei where experimental results on β decay are not available, beta decay half-lives, beta branching ratios and P_{1n} and P_{2n} values were calculated by microscopic nuclear structure calculations as described in [15,19]. The half-lives have been published in [23], part of the calculated P_n values are published in [26]. This set of β decay data is the first one ever produced for nuclei far from stability basing on microscopic nuclear structure calculations. We have outlined in section 3 that this set is the first one to allow the description of the decay heat together with a consistent simultaneous description of such different quantities like β decay half-lives, rates for β-delayed neutron emission and fission, double β decay, and the electron and antineutrino spectra produced by the fission products in the core of a nuclear reactor. It has to be noted that none of the sets presently in use for description of the contribution of experimentally uninvestigated nuclei is capable of doing this.

5 Results of Calculations of the Decay Heat Power

We show in this section the results of calculations with the program THOR-I of short time irradiations (burst functions) of several fissile samples with thermal and fast neutrons and results for the decay heat power of a realistic light water reactor operation cycle with a burnup of 38 MWd/kghm. (Figs. 11-24 are from [38]).

The results for the burst functions are compared to the existing experimental material and to the predictions by the ANS and DIN standards, the result for the realistic reactor cycle is compared to the requirements of the ANS and DIN standards.

5.1 Short Time Irradiations

In Figs. 11-14 we show the results of calculations of the total decay heat (from β and γ decay) of short time irradiations of samples of ^{235}U, ^{239}Pu, ^{241}Pu, ^{233}U with thermal and fast neutrons and compare them with the in our eyes most precise short time irradiation measurements. The figures do not show exactly burst functions (i.e., idealized curves showing the decay heat produced at time t after irradiation for infinitely short time) but the unmanipulated results of the measurements, and calculations in which the irradiation and detection history of the experiments have been exactly followed (according to the prescription used for example by Dickens et al. [6]). Lines are drawn to guide the eye through the calculations.

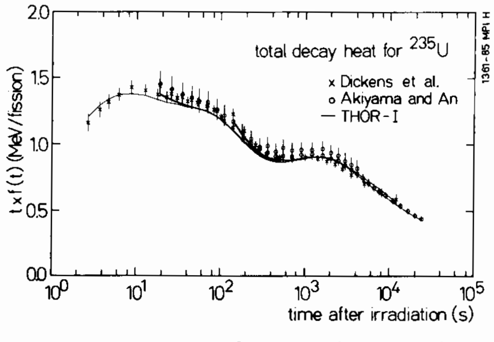

Fig. 11. Measured total ($\beta + \gamma$) decay heat power f(t) as function of time t after irradiation for short-time irradiation (different irradiation times) of ^{235}U by thermal neutrons (crosses, Dickens et al. [6]) and by fast neutrons (circles, Akiyama and An [11]) and the corresponding calculations by THOR-I.

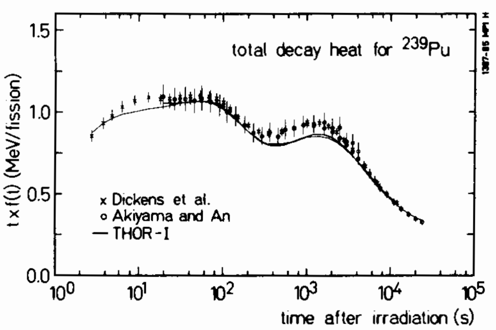

Fig. 12. Same as in Fig. 11, but for ^{239}Pu. The Dickens et al. data are from Ref. 12.

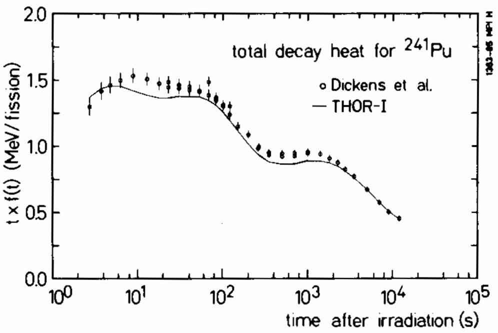

Fig. 13. Same as in Fig. 11, but for ^{241}Pu. The circles denote the experiment by Dickens et al. [12].

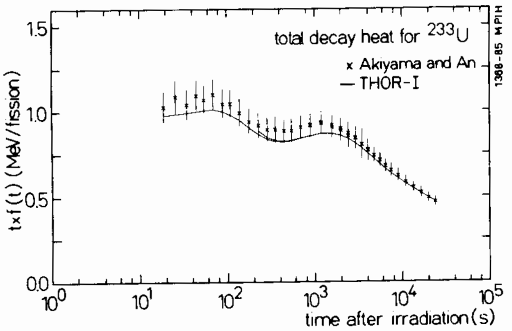

Fig. 14. Same as in Fig. 11 but for fast fission of ^{233}U. The crosses denote the experiment of Akiyama and An [11].

The experimental data shown in Figs. 11-14 consist of overlapping sets corresponding to different irradiation times in each of the measurements. For each set of the measurements there exists correspondingly one theoretical curve. It is seen that the calculations even reproduce details of the irradiation and detection history. The calculations are performed--corresponding to the measurements--for thermal fission in the case of the Dickens experiment and for fast fission in the case of the Akiyama experiment.

It is seen that both sets of experiments overlap within the error bars and that the calculations reproduce the experiments reasonably.

Figs. 15, 16 demonstrate the effect of the experimentally unknown nuclides far from stability on the decay heat power curve. The calculation in these cases considers only experimentally known decay schemes. Comparison of Figs. 15, 16 with Figs. 11, 13 may give a feeling for the quality of the description of the β decay of the unknown nuclei.

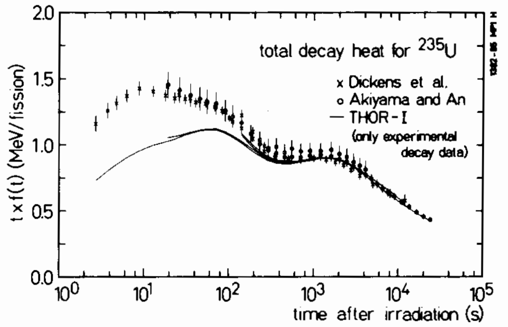

Fig. 15. Demonstration of the effect of the experimentally unknown nuclides far from stability on the decay heat power. The same experimental results as in Fig. 11, but the calculation performed taking into account only experimentally known decay schemes.

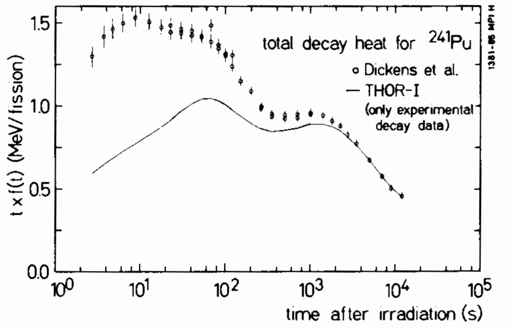

Fig. 16. Same as Fig. 15, but for ^{241}Pu. The experimental data are those of Ref. 12 (same as in Fig. 13).

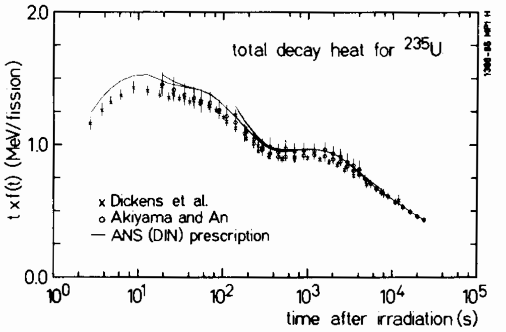

Fig. 17. Measured total decay heat power after short-time irradiation of ^{235}U by thermal and fast neutrons (crosses and circles, respectively, same as in Fig. 11) and the corresponding calculated total decay heat according to the ANS (DIN) standard prescription (only the fission product decay heat power neglecting any other contributions).

Figs. 17-19 show the same experimental results as Figs. 11-14, but instead of our calculations the expectations according to the ANS (DIN) standards (only the fission product decay heat power neglecting any other contributions).

The general good agreement between standard curves and experiment for ^{235}U and ^{239}Pu reflects the fact that one of these experiments was one of the main bases for the standards. It can be noted, however, that the ANS (DIN) standard tends to lie systematically slightly higher than both experiments in the first 1000 or 10000 sec. Figs. 19, 20 demonstrate the problems which can arise by following the prescription of

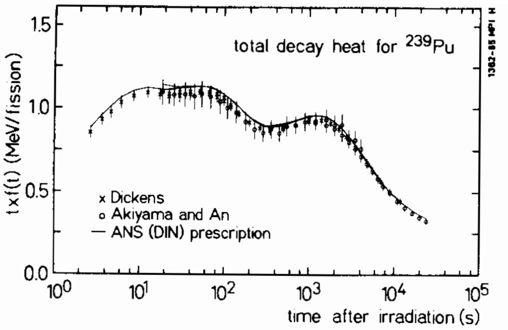

Fig. 18. Same as in Fig. 17, but for ^{239}Pu.

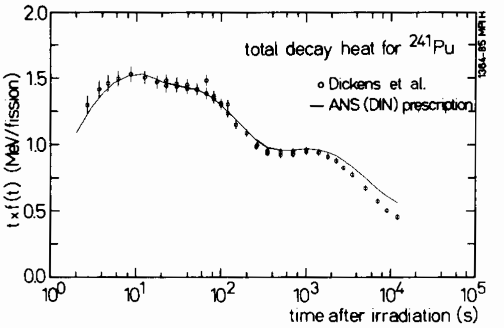

Fig. 19. Same as in Fig. 17, but for ^{241}Pu. Following the ANS (DIN) standard prescription the solid line is calculated treating ^{241}Pu as ^{235}U. The data are those of Ref. 12 (as in Fig. 13).

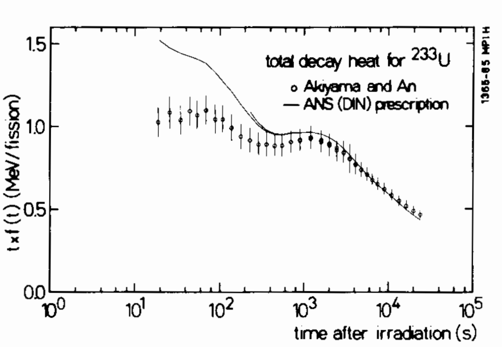

Fig. 20. Same as in Fig. 17, but for ^{233}U. The data are those of Ref. 11 (as in Fig. 14). Following the ANS (DIN) standard prescription the solid line is calculated treating ^{233}U as ^{235}U.

the standards to treat all fissile materials other than ^{235}U, ^{239}Pu, ^{238}U as ^{235}U. This procedure leads to a large overestimate of the decay heat in the first few hundred seconds for ^{233}U; in the case of ^{241}Pu the decay power is overestimated for times larger than a few thousand seconds.

5.2 Typical Light Water Reactor with Burnup of 38 MWd/kghm

Fig. 21 shows the total decay heat power as function of time after shutdown calculated by THOR-I for a realistic light water reactor operation cycle with a total burnup of 38 MWd/kghm in comparison to the ANS and DIN standards. The assumed cycle was 335-30-335-30-335 days (reactor on and off, respectively). The initial enrichment of ^{235}U was taken to be 3.4%. A constant average neutron flux of $3.25 \cdot 10^{14}$ cm^{-2} sec^{-1} was assumed. In the calculation of the ANS (DIN) expectations the contributions from neutron capture by the fission products and the actinides are taken into account according to the different given prescriptions.

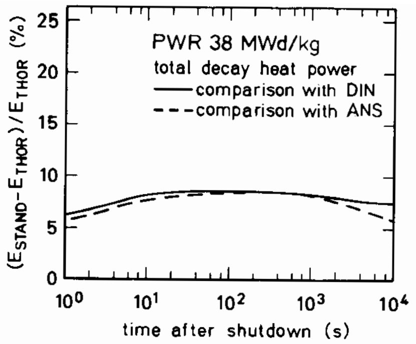

Fig. 21. Total decay heat power integrated up to time t after shutdown as function of t calculated by THOR-I for a realistic pressurized light water reactor (PWR) operation cycle (see text) with a total burnup of 38 MWd/kghm in comparison to the predictions of the ANS and DIN standards. All contributions of neutron capture are included.

Fig. 21 shows, and this is further discussed below, that in spite of differences in details the two standards make essentially the same prescriptions. It shows further that according to our calculations both standards overestimate the decay heat power by about 6-8% in the first 10^4 sec after shutdown.

It is of interest to look into this difference in more detail. In the ANS standard there are two corrections which have to be added to the fission product decay heat: a) from neutron capture in the fission products, b) from neutron capture in the actinides. In the DIN standard each of these is split into two parts (see section 2).

Figs. 22, 23 show separately the contributions of neutron capture by the fission products and by the actinides calculated by THOR-I in comparison to the prescription of ANS and DIN, respectively.

While the ANS standard underestimates the neutron capture in fission products compared to our calculation, it overestimates the contribution of the actinides. The DIN standard overestimates both contributions. The sum of all the different corrections is practically the same for both standards.

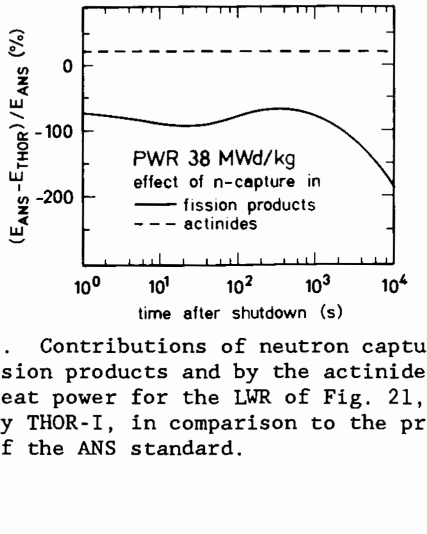

Fig. 22. Contributions of neutron capture by the fission products and by the actinides to the decay heat power for the LWR of Fig. 21, calculated by THOR-I, in comparison to the prescriptions of the ANS standard.

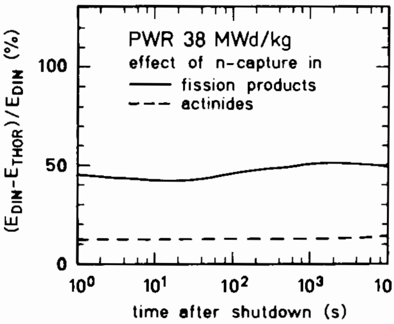

Fig. 23. Same as in Fig. 22, but the THOR-I results here compared to the DIN standard.

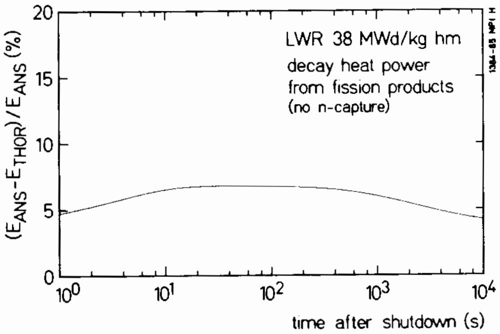

Fig. 24. Same as Fig. 21, but neglecting all contributions from neutron capture in fission products and actinides. In this case the ANS and DIN prescriptions are identical.

Fig. 24 shows finally the ratio of the calculated total reactor decay heat power originating only from the fission products (neglecting neutron capture) and the correspondingly calculated ANS (DIN) expectation. Comparison with Fig. 21 shows which parts of the total reduction seen in Fig. 21 originate from the treatment of the decay heat of the fission products and from the treatment for all corrections, respectively.

We have performed calculations like those shown in Fig. 21 also for longer and shorter burnup of 53 and 19 MWd/kghm and find with minor changes essentially the same result as for 38 MWd/kghm.

5.3 Other Types of Reactors

We have calculated the total decay heat power also for the following types of reactors: boiling water reactors, advanced pressurized water reactors, CANDU [39]. In all cases the standards overestimate the decay heat, the amount being different for DIN and ANS, respectively, for different reactors. Figs. 25-27 give some examples. It has to be kept in mind, however, that the DIN and ANS standards [2,3] are originally developed for light water reactors.

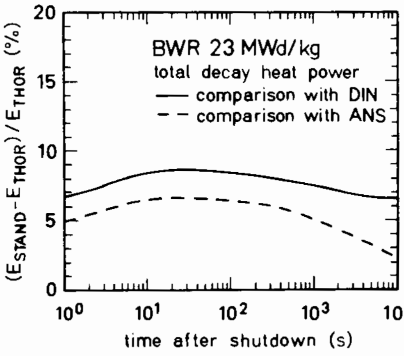

Fig. 25. As Fig. 21, but for a boiling water reactor (BWR) and a burnup of 23 MWd/kghm of the nuclear fuel mentioned with reference to Fig.21.

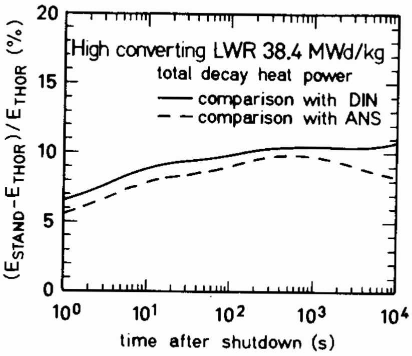

Fig. 26. As Fig. 21, but for a high-converting LWR and a burnup of 38.4 MWd/kghm of nuclear fuel consisting of 0.2% ^{235}U, 88.65% ^{238}U, 6.44% ^{239}Pu, 2.96% ^{240}Pu, 1.06% ^{241}Pu, 0.69% ^{242}Pu.

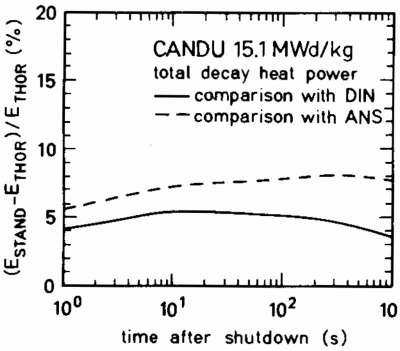

Fig. 27. As Fig. 21, but for a heavy water reactor of the CANDU type and a burnup of 15.1 MWd/kghm of nuclear fuel consisting of natural uranium.

6 Conclusion

A new approach for calculating the decay heat power of nuclear reactors is presented. A program THOR-I has been developed which allows calculation of the isotopic inventory of a reactor at any time during reactor operation and after shutdown by the analytical method. Typical problems of this method are avoided by performing the calculations with a 36 bit word length and an extended range of magnitude from 10^{-308} to 10^{308}.

Part of THOR-I is a new set of β decay data, in which β decay of experimentally uninvestigated nuclei has been calculated by microscopic nuclear structure calculations--the first attempt of this kind to our knowledge.

The internal consistency of this data set is reflected in the fact that it allows simultaneous description of decay heat power, β decay half-lives, rates for β-delayed neutron emission and fission, double β decay, and the shape (and absolute yields) of electron and antineutrino spectra produced in the reactor core. No other set presently in use for the description of experimentally uninvestigated nuclei is capable of doing this.

Calculations by THOR-I for short time irradiation of several fissile isotopes such as ^{235}U, ^{239}Pu, ^{241}Pu, ^{233}U by thermal and fast neutrons have been performed and are found to be in very good agreement with the most recent and precise experiments, while the ANS (and DIN) standard tends to slightly overestimate the decay heat for short time irradiation.

We have further calculated by THOR-I the total decay heat power as function of time after shutdown for realistic pressurized light water reactor operation cycles and also for other reactor types such as boiling water reactors, advanced pressurized water reactors and CANDU, and have compared the result with the ANS and DIN standards. It is found that according to our calculations both standards overestimate the decay heat power by about 6-8% in the first 10^4 sec after shutdown.

In view of the progress in the accuracy of summation calculations which we think we have demonstrated in this paper it might be worthwhile to take such calculations into serious consideration as a basis of future standards. To the extent that the present standards allow the users the option of computing the decay heat power by their own programs and justifying the calculations, the results presented here should be of direct economic benefit for operators of emergency core cooling- (ECC-) limited light water reactors, i.e., for a large part of the operating nuclear power stations.

The progress in the predictability of the decay heat power for arbitrary fissile materials should be of importance further for reactor technologies at present under development such as high-converting LWRs and fast breeders and also for the handling of burnt fuels.

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