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International Comparison Calculations for a BWR Lattice with Adjacent Gadolinium Pins

C. Maeder, P. Wydler

Würenlingen, September 1984

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C. Maeder and P. Wydler

EIR, 5303 Würenlingen, Switzerland

September 1984

Summary

In this report the results of burnup calculations for a simplified BWR fuel element with two adjacent gadolinium rods are presented and discussed. Ten complete solutions were contributed by Denmark, France, Italy (3), Japan (3), Switzerland and the UK. Partial results obtained from Poland and the USA are included in an Appendix.

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1. Introduction

From 1974 till 1977 the Nuclear Energy Agency Committee on Reactor Physics (NEACRP) sponsored a BWR lattice benchmark exercise (1). Two of the considered lattices contained isolated gadolinium fuel rods. In the meantime fuel elements with adjacent poisoned fuel pins have been introduced in BWRs to enhance the performance of the fuel. It has to be checked whether the calculational methods used in BWR core analysis can adequately predict the resulting mutual shielding of the pins and, in particular, its effect on the depletion of the burnable poison.

In view of this development, the Swiss Federal Institute for Reactor Research (EIR) in 1980 proposed a new gadolinium benchmark for a simplified BWR fuel element with 14 unpoisoned and 2 adjacent poisoned fuel rods. The intention was to investigate whether calculational methods used for isolated Gd pins are capable of treating this more complex geometry with sufficient accuracy. A preliminary calculation, in which an azimuthal variation of the flux was taken into account in the Gd pin cells (cf. Appendix A), indicated that the shadowing effect of neighbouring Gd rods is small.

First results for the benchmark problem with adjacent Gd rods, contributed by EIR, EPRI and the Institute of Nuclear Research Swierk, were presented at the European Nuclear Conference at Brussels in April 1982 (2). In autumn 1981 the NEACRP provided an organizational basis for the new benchmark. In contrast to the earlier NEACRP lattice benchmark (1), in which 6-group macroscopic cross sections were prescribed, the participants were asked to use their own cross section libraries and group structures and to perform burnup calculations up to 10 GWd/t. In addition, a reference solution for the normal unpoisoned cell was requested, allowing checks on basic data and calculational methods to be made (3).

Results have been obtained from 12 organizations in Denmark, France, Italy, Japan, Poland, Switzerland, the UK and the USA. Preliminary results of the benchmark exercise were reported in two NEACRP documents (4,5).

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To be able to present consistent standard deviations in the tables of the present report, the submitted results were divided into 10 complete solutions, which are discussed in the main part of the report, and 2 partial solutions (from Poland and the USA) for which multiplication factors only are given in Appendix D.

2. Problem Specification

The simplified fuel element, as shown in Fig. 1, consists of 14 initially identical normal UO_2 fuel cells and 2 Gd cells. Taking the symmetry into account, the 16 pins can be reduced to 5 different UO_2 pins (numbered 1 to 5 in Fig. 1) and a single Gd/UO_2 pin (number 6). Reflective boundary conditions are prescribed on the four surfaces. The material properties are as follows:

Fuel: Material = UO_2, density = 10 g/cm^3, temperature = 600 ^oC, U-235 enrichment = 3 weight-%, diameter = 1 cm. The Gd pin contains 3 weight-% of Gd_2O_3 (i.e. 0.3 g/cm^3 Gd_2O_3 and 9.7 g/cm^3 UO_2).

Clad: Material = Zircaloy-2, density = 6.55 g/cm^3, temperature = 300 ^oC, inside diameter = 1 cm, outside diameter = 1.2 cm.

Moderator: Material = H_2O, void content = 0%, state of saturation at a temperature of 286 ^oC (pressure = 70.06 bar), lattice pitch = 1.6 cm.

The assembly average power density is 20 W per gram of the uranium metal in the fresh fuel.

The following results were requested for assembly average exposure steps of 1 GWd per metric ton of loaded U metal up to 10 GWd/t:

- The multiplication factor k_∞,
- the relative power of the 6 different rods normalized to an assembly average value of 1,

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- *the Gd pin average densities of the isotopes Gd-155, Gd-157, U-235, Pu-239 and Pu-240 in atoms/barn·cm,*
- *the spatial distribution of the Gd isotopes at 2 GWd/t.*

A burnup calculation had also to be performed for a regular lattice without burnable poison rods. The regular lattice is equivalent to a single UO_2 fuel cell. The infinite multiplication factor and the fuel pin average densities of U-235, Pu-239 and Pu-240 were requested for the same burnup intervals of 1 GWd/t.

In addition, the calculational method had to be briefly described.

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3. *Participants*

Complete solutions were received from the following organizations:

AEEW: *M.J. Halsall*
Atomic Energy Establishment Winfrith
Dorchester, Dorset
England

AMN: *P. Neuhold*
AMN Ansaldo Impianti
Via Gabriele D'Annunzio, 113
I-16121 Genova
Italy

CEA: *P. Chaucheprat, G. Girieud and B. Nouveau*
Département des réacteurs à eau
Centre d'études nucléaires de Cadarache
B.P. No. 1
F-13115 Saint Paul lez Durance
France

CISE: *G. Pierini*
Centro Informazioni Studi Esperienze
P.O. Box 12081
I-20134 Milan
Italy

EIR: *C. Maeder*
Eidg. Institut für Reaktorforschung
CH-5303 Würenlingen
Switzerland

ENEA: *F. Casali*
Centro Nazionale Energia Nucleare e Energie Alternative
Centro Ricerche Energie "Ezio Clementel"
Via G. Mazzini, 2
I-40138 Bologna
Italy

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JAERI: *K. Tsuchihashi and Y. Ishiguro*
Japan Atomic Energy Research Institute
Tokai-mura, Naka-gun, Ibaraki-ken
Japan

K. Kaneko
Japan Information Service Co. Ltd.
Shionogi-Shibuya-Biru, Shibuya-ku 2-17-5
Tokyo, Japan

NAIG: *M. Yamamoto and H. Mizuta*
Nippon Atomic Industry Group
4-1 Ukishima-cho, Kawasaki-ku
Kawasaki, 210
Japan

OSAKA: *T. Takeda and H. Sato*
Osaka University
Faculty of Engineering, Nuclear Engineering
Yamada-oka 2-1, Suita
Osaka, Japan

K. Shinhama and H. Kawabata
Japan Information Service, Inc.,
Tosabori 2-2-7, Nishi-ku
Osaka, Japan

RISØ: *H. Neltrup*
Risø National Laboratory
Postbox 49
DK-4000 Roskilde
Denmark

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4. Calculational Methods

An overview of the adopted calculational methods is given in TAB 1.

The following descriptions are based on the summaries provided by the participants.

4.1 AEEW

The solution is based on standard design calculation options normally used in LWRWIMS (6). The exercise was taken as an opportunity to test the relatively new CACTUS characteristics transport code in order to assess the importance of a detailed spatial calculation.

A 28-group condensed WIMS library of cross sections was used, with identifiers 2235, 7238, 5239 for U-235, U-238 and Pu-239 and the pseudo fission product scheme as defined in Ref.(6). Cross sections in 28 groups were generated using WIMS equivalence theory for the resonance groups, and a multicell collision probability calculation was used to generate 28-group fluxes for each region in the problem. For the design calculation there were nine regions: fuel, can and coolant for standard pins and 4 fuel zones plus can and coolant for the Gd pins. Condensation to 6 groups (with boundaries at 821 keV, 9118.4, 4, 0.625 and 0.140 eV) and pin cell smearing were followed by a straightforward diffusion theory solution in 4 x 4 meshes. For the regular lattice case a simple pin cell calculation was made as above, and the smearing and diffusion calculations were omitted.

Depletion is by numerical integration allowing only for the variation of gadolinium through the fuel pin. Adjustments were made by using the "FINE" option to radial reaction rates of gadolinium at 200 MWd/t intervals with the full lattice calculation interval of 1000 MWd/t. The so-called "DIFFERENTIAL" option was invoked to calculate the pin by pin isotopic compositions for use in evaluating the power distribution.

An alternative solution method which does not require pin cell smearing is the CACTUS option in LWRWIMS. This method is based on explicit tracking through the problem, integration of the transport equation along each track segment, and numerical integration of the scalar flux by means of tracks at appropriate spacing and angles. A detailed CACTUS calculation with 170

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spatial zones was made for the poisoned lattice at start of life.

The results given in this report are based on a depletion calculation using the diffusion theory method with "FINE" and "DIFFERENTIAL" options. However, the calculation was normalized to the detailed CACTUS eigenvalue by adjusting the poison pin dimensions. To reduce the initial k_∞ from the value of the unadjusted design calculation (1.0253) to the value of the detailed CACTUS calculation (1.0093) it was found necessary to increase the poison pin radius from 0.5 cm to 0.5775 cm. The fuel density was correspondingly reduced and the clad density increased to preserve the total numbers of atoms. This technique is currently used at Winfrith in PWR design calculations to correct the initial worth of boron poison pins (7).

4.2 AMN

Modules of the BLA code system were used to perform the following calculation steps:

1) Preparation of (one-group) thermal cross sections.
A transport theory method was used for averaging cross sections in the pin cells. An additional supercell calculation provided the fluxes for collapsing the energy groups in the Gd pin cell.

2) Preparation of epithermal and fast cross sections (one broad group in each energy range). Epithermal cross sections were generated using a GAM type resonance calculation and a B-1 flux solution. In the top (fast) broad group a discrete collision probability calculation was performed. This allowed the fast fission effect to be treated appropriately. The exposure dependence of the resonance cross sections includes effects due to isotope concentration, Dancoff factor and neutron spectrum.

3) 2-D lattice calculation.
Three-group diffusion theory was used, and each square fuel cell was divided into a square fuel pin and a surrounding homogenized clad-water region (this procedure permits the modelling of spatially varying void contents).

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4) *Effects of exposure.*

The thermal/epithermal cross sections and 2-D fluxes were recalculated after specified exposure steps.

4.3 *CEA*

The calculations were performed with the APOLLO-NEPTUNE code which is being developed by the CEA for light water reactor calculations (8). The APOLLO code solves the transport equation in its integral form by the collision probability method in the multigroup approximation. In the calculation 99 energy groups with 52 fast and 47 thermal groups were used (the thermal cut-off is located at 2.8 eV).

The lattice calculations were performed with the ROT 4 option of the EURYDICE code (9), which is based on the following approximations:

- *Four entering currents per cell.*
- *WIGNER cylindrization with respect to the cell volume.*
- *The current anisotropy on the cell surfaces is neglected.*

The calculations were carried out with a spatial mesh consisting of 56 points (22 independent points), these being distributed as follows:

- *7 points in each Gd pin cell. The fuel was divided into 5 spatial zones of equal volume to be able to calculate the fine spectrum flux in the poisoned pin.*
- *3 points in every UO_2 cell.*

In the burnup calculations the depletion chain U → Np → Pu and the complete gadolinium chain from Gd-154 to Gd-160 were considered. The self-shielding of the resonance nuclei was recalculated for each burnup step.

4.4 *CISE*

The calculations were performed with the NUOVO AUTOBUS code (10) which provides libraries of nuclear parameters for LWR fuel elements. The code is capable of describing several types of compositions (fuel, fuel with Gd content, borosilicate, structural materials, cross control rods, Ag-Cd-In rods) and solves two-dimensional finite difference diffusion equations in five groups with energy boundaries at 183 keV, 5.5 keV, 0.625 eV and 0.2 eV.

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Correlated group constants are used for the regular cells. For the Gd pins the transport-evaluated cross sections are properly modified to preserve the corresponding absorption rate.

4.5 EIR

The solution is based on the code BOXER (11) and a 70-group library with resonance parameters which was derived from ENDF/B-4. The resonance range is treated by a two-region collision probability method in a few thousand energy points. The cylindricalized fuel cells were calculated in the 70 energy groups with an integral transport method assuming a first order spatial polynomial approximation for the scattering source in each zone. The Gd pin was divided into 4 annular zones of equal volume. The outgoing surface flux of the unpoisoned cell served as the boundary condition for the Gd cell calculation. The pin cell homogenization was performed by flux-volume weighting with an energy dependent heterogeneity correction in the Gd cell.

The lattice calculation in x-y geometry used 11 energy groups with upper boundaries at 15 MeV, 0.821 MeV, 907, 76, 16, 4, 0.625, 0.32, 0.14, 0.058 and 0.025 eV. The calculation is based on a transmission probability transport method which approximates the angular dependence of the mesh surface flux by a first order quadrupole spherical harmonics expansion and uses a linear spatial representation of the volume source and of the mesh surface flux.

The first two burnup step lengths were 0.1 and 0.4 GWd/t. These were followed by steps of 0.5 GWd/t up to 5 GWd/t and steps of 1 GWd/t beyond 5 GWd/t. After each step a cell calculation in the thermal energy range below 4 eV and a two-dimensional lattice calculation were performed. The time dependence of the microscopic cross sections is taken into account by recalculating the burnup step using the one-group cross sections at the end of the step (predictor - corrector method) and by a density dependent self-shielding factor for the isotopes Pu-239 and Pu-240. Within a burnup step the neutron flux is expanded into a second order Taylor series in the time variable.

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4.6 ENEA

The calculations were performed with the Monte Carlo code KIM (12). The data base for KIM was obtained from the UKNDL and ENDF/B-4 libraries, with the exception of the Gd isotopes for which the evaluation of the Joint European File was used. The energy range above 5 eV was divided into 80 groups, and a scheme with 256 energy points corresponding to a practically infinite number of groups was used in the thermal range. For the calculation of the time dependence of the microscopic cross sections and the nuclide densities the Gd pin was divided into 3 annular zones. The flux and microscopic reaction rates were determined at 14 time points between 0 and 10 GWd/t.

4.7 JAERI

The JAERI Thermal Reactor Standard Code System SRAC (13) with an ENDF/B-4 based library was used. The library contains fast data in 74 groups above 0.414 eV, thermal data in 45 groups below 3.93 eV and resonance data. In the resonance range below 130 eV an ultra fine-group spectrum calculation with a lethargy width of 0.00125 was performed.

For the lattice calculation the cross sections were condensed to 36 fast groups above 0.469 eV and 20 thermal groups below this limit. Using this group structure a collision probability calculation with a different spatial mesh in the fast and thermal energy range was carried out. In the fast range the lattice was divided into 62 zones. A finer mesh with 42 zones (3 per pin) in the normal pins, 10 zones (5 per pin) in the Gd pins, 16 zones in the cladding and 141 zones in the moderator was used in the thermal range.

The first two burnup steps of 0.1 and 0.15 GWd/t were followed by steps of 0.25 GWd/t until 7 GWd/t and by steps of 0.5 GWd/t thereafter. New lattice calculations were performed after each step.

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4.8 NAIG

The data base used for the calculations is ENDF/B-5 for the main fertile and fissile nuclides and ENDF/B-4 for the remaining isotopes. The cross section library contains 68 energy groups in the fast and epithermal range (GAM type structure) and 30 groups in the thermal range (THERMOS structure). The TGBLA model (14) uses a spatially dependent energy spectrum to generate three-group (fast, epithermal and thermal) cross sections with transport theory corrections for a diffusion theory calculation.

In the epithermal energy range the level-wise resonance integrals are calculated by an improved intermediate resonance approximation with parameters depending on the fuel temperature. The thermal neutron spectra in the fuel cells are calculated using a method which is similar to the THERMOS formalism with the improvement that the neutron leakage from rod to rod is taken into account. The leakage is determined by diffusion theory and fed back into the thermal spectrum calculation. Diffusion theory and thermal spectrum calculations were iterated until convergence was obtained. The Gd rods were subdivided into 10 regions of equal volume.

In the burnup calculations 100 isotopes are treated, including 25 fissile and fertile isotopes and 48 fission products plus one pseudo fission product. A burnup integration scheme using the 4th order Runge-Kutta-Gill (RKG) method is employed. The time steps were 0.2, 0.3, 0.5 and 1 GWd/t thereafter. Each time step comprises 4 RKG steps. Whole neutronic calculations are performed after each RKG step.

4.9 OSAKA

The solution was obtained with the RESPLA code (15). RESPLA uses the 69-group WIMS cross section library for all nuclides except Gd and 69-group cross sections generated from ENDF/B-3 for the Gd isotopes.

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The fine-group cross sections were condensed to 6-group microscopic cross sections with energy boundaries at 0.82 MeV, 9.12 keV, 9.88, 0.63 and 0.14 eV as follows: Condensation spectra of the normal cells were obtained from a 2-region bundle calculation. The central region of the bundle was formed by 2 normal and 2 Gd poisoned cells, while the remaining regular cells formed the outer bundle region. The condensation spectra in the Gd cell were obtained from a supercell calculation in which the Gd cell was surrounded by one Gd and seven normal cells.

The RESPLA lattice calculation utilizes a transmission probability method in which P_0 and P_1 angular components of the neutron flux can be considered. Each pin cell surface is divided into three subsurfaces to take account of the spatial distribution of the neutron current. The heterogeneity within each pin cell is treated with response matrices obtained from the pin cell calculations. The burnup calculation was performed using the time steps 0.1 GWd/t, 0.4 GWd/t and 0.5 GWd/t thereafter. The flux and the cross sections are assumed to be constant during a time step.

4.10 RISØ

The cross section preparation program CRS (16) and the fuel box program CDB were used.

CRS has a 76-group cross section library based on the 1973 UKNDL library. Self-shielded resonance cross sections are prepared with the routine RESOREX (17) which processes tabulated group resonance integrals generated by a separate program, RESAB (18). This program was also used to produce 76-group cross sections for Gd-155, Gd-156 and Gd-157.

With CRS collision probability calculations were performed for the normal and the Gd pin cell. The calculations provided fuel, cladding and moderator spectra for condensing the 76-group cross sections to the 10-group structure used in CDB. A single set of 10-group constants was

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generated, i.e. the cross sections were assumed to be independent of burnup. Given this approximation it was found to be preferable to use a zero rather than the intial Gd density in the Gd pin cell calculation (cf. Table B1, reactivity influence of Gd in the pin cell calculation).

The program CDB (19) combines 10-group collision probability calculations for the individual pin cells with a diffusion theory solution for the fuel box. The pin cell calculations provide homogenized cross sections for the diffusion calculation, and the diffusion calculation determines cell leakages which are used by the pin cell calculations in the form of greyness factors. For each burnup step this procedure was repeated until convergence was obtained. In the normal pin cell 3 regions were used as in CRS. In the Gd cell the pin was subdivided into 5 concentric regions, the volume fractions being 3·0.25 and 2·0.125 in the order of increasing radius. The burnup time steps were 0.2, 0.3, 0.5, 9·1.0 GWd/t and 4·0.1, 13·0.2, 2·0.3, 0.4, 4·0.5, 4·1.0 GWd/t respectively for the regular and the Gd poisoned lattice.

5. *Definitions and Method of Evaluation*

In the evaluation of the results the following notation is used:

Variables and calculated quantities:

N = 10 = number of participants
E = exposure (GWd/t)
k = infinite neutron multiplication factor (-)
d = isotopic density (atoms/barn·cm)

Indices

reg = regular lattice (= normal cell)
poi = poisoned lattice (= 14 normal + 2 Gd poisoned cells)
25 = U-235
49 = Pu-239
40 = Pu-240
155 = Gd-155
157 = Gd-157

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From the submitted results the following quantities are derived:

Densities (dimensionless)

U-235 destruction: $$D_{25}(E) = \left[d_{25}(0) - d_{25}(E) \right] / d_{25}(0)$$

Gd destruction: $$D_{Gd}(E) = \left[d_{Gd}(0) - d_{Gd}(E) \right] / d_{Gd}(0) ,$$

where $$d_{Gd}(E) = d_{155}(E) + d_{157}(E) = \text{total Gd density (atoms/barn·cm)}$$

Plutonium ratio: $$r(E) = d_{40}(E) / d_{49}(E)$$

Reactivities (dimensionless)

Gadolinium reactivity worth:

$$\rho_{Gd}(E) = \left[k_{reg}(E) - k_{poi}(E) \right] / k_{reg}(E)$$

Reactivity loss in the regular lattice:

$$\rho_{reg}(E) = \left[k_{reg}(1) - k_{reg}(E) \right] / k_{reg}(1)$$

Reactivity gain in the poisoned lattice:

$$\rho_{poi}(E) = \left[k_{poi}(E) - k_{poi}(1) \right] / k_{poi}(1)$$

In these formulae $k(1) = k(E = 1$ GWd/t) is chosen as the reference multiplication factor in order to separate the xenon effect from the calculated reactivity effects.

Standard deviations

If $y_n(E)$ denotes any of the submitted or derived quantities of participant n (n = 1, 2, ..., N), the mean value of all participants is defined by

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$$\bar{y}(E) = \frac{1}{N} \sum_{n=1}^{N} y_n(E) \ .$$

The standard deviation (called ST DEV in the tables) is

$$s(E) = \sqrt{\frac{1}{N-1} \sum_{n=1}^{N} \left[y_n(E) - \bar{y}(E) \right]^2} \quad ,$$

and the coefficient of variation (called VAR in the tables) is

$$v(E) = s(E) \ / \ \bar{y}(E) \ .$$

In TABs 2 - 26, in addition to the mean value, the standard deviation is given for normalized quantities (relative power, reactivity and destruction) and the variation for the other quantities (multiplication factor and densities).

In TABs 16 - 17 the reactivity deviation from the mean is calculated as

$$\Delta\rho_n(E) = \left[k_n(E) - \bar{k}(E) \right] \ / \ \bar{k}(E) \ .$$

6. Results

The submitted results are listed in TABs 2 - 13 and represented graphically in FIGs 2 - 13 (figure numbers agree with the corresponding table numbers). Corresponding tables for the regular and the poisoned lattice are shown on the same page.

The spatial distributions of the Gd isotopes at 2 GWd/t were presented by all participants as average values in annular zones. However, as can be seen in TAB 1, the different participants chose different numbers of annuli and different annular boundaries. To determine comparable quantities,

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quadratic interpolation functions as a function of r^2 (r = radius) were fitted to the submitted radial distributions. From these functions average values in 4 zones of equal volume (as used in the EIR solutions) were derived. The values are listed in TABs 14 - 15 and plotted in the form of histograms in FIGs 14 - 15.

From the submitted multiplication factors and densities the following quantities as defined in section 5 were derived:

- *Reactivity deviations (TABs 16 - 17 and FIGs 16 - 17),*
- *gadolinium reactivity worth (TAB 18 and FIG 18),*
- *gadolinium destruction (TAB 19 and FIG 19),*
- *reactivity gain in the poisoned lattice as a function of exposure and of the Gd destruction (TABs 20 - 21 and FIGs 20 - 21),*
- *plutonium ratio (TABs 22 - 23 and FIGs 22 - 23),*
- *reactivity loss in the regular lattice as a function of exposure, U-235 destruction and Pu-239 density (TABs 24 - 26 and FIGs 24 - 26).*

A quadratic interpolation was used to determine the reactivity gain (loss) at given values of the Gd destruction, U-235 destruction and Pu-239 density (see TABs 21 and 25 - 26).

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7. Discussion of the Results

Fresh lattice

To improve the insight into the basic physical effects it is worthwhile to begin the discussion with an analysis of the influence of the Gd poisoning on the neutron flux and the microscopic reaction rates ($\sigma\emptyset$).

3-group flux spectra in the regular lattice and in the Gd poisoned cell at zero burnup are compared in TAB 27. Due to the large thermal cross section of the Gd isotopes 155 and 157 the flux below 0.6 eV is reduced in the Gd cell, while above this energy limit no appreciable effect on the flux spectrum can be detected. However, because of the normalization to the equal power density of 20 W/g in both lattices, the energy integrated flux is larger in all cells of the poisoned lattice.

The "hard" spectrum reduces the one-group cross sections of all nuclides in the Gd cell (TAB 28). The largest reductions occur for the Gd isotopes, U-235 and Pu-239. The cross sections of U-238 and Pu-240, whose resonances lie above 0.6 eV, are only slightly affected.

The net effects of the flux and cross section changes on the reaction rates can be seen in TAB 28 (microscopic absorption rates for EIR solution) and TABs C1 and C2 (microscopic capture and fission rates for 7 different solutions). The effects of the Gd poisoning are:

- *U-235 and Pu-239 capture and fission rates become smaller.*
- *U-238 captures remain practically unchanged.*
- *U-238 fissions and Pu-240 reaction rates become somewhat larger.*

The relative effects on the time variation of the nuclide densities in the regular and the poisoned case can now be explained:

- *The smaller absorption rate of U-235 in the poisoned cell causes a smaller amount of U-235 destruction (TABs 4 and 5).*
- *The smaller Pu-239 absorption, together with only a negligible change in U-238 capture increases the buildup of Pu-239 in the poisoned cell (TABs 6 and 7).*

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- *The larger Pu-240 absorption and smaller Pu-239 capture in the poisoned cell reduce the buildup of Pu-240 (TABs 8 and 9) and the Pu-240/Pu-239 ratio (TABs 22 and 23).*

The multiplication factors for the fresh regular lattice are given in the first line of TAB 2. The values predicted by CEA, CISE, EIR, JAERI and NAIG agree quite well, the variation being as low as 0.2%. 4 of these 5 organizations use (presumably unadjusted)ENDF/B data. The highest and the lowest multiplication factor is calculated respectively by AEEW and OSAKA using WIMS libraries with (presumably different) adjustments. The AEEW value can partly be explained by the comparatively low capture rates in U-235 and U-238 (cf. TAB C1). The low OSAKA value cannot be explained by the U-235 and U-238 reaction rates (the relatively high U-238 fission rate is compensated by a correspondingly high U-235 capture rate). The ENEA value, which is based on a Monte Carlo calculation, lies 0.008 Δk above the mean value, the deviation being in fair agreement with the deviations of the U-235 and U-238 reaction rates.

Gd reactivity worths in the fresh lattice are given in the first line of TAB 18. There is a tendency for the more sophisticated solutions to give higher and the less sophisticated solutions to give lower Gd worths. Thus, the ENEA Monte Carlo calculation predicts the highest value, this being closely followed by the AEEW "CACTUS" value. On the other hand, the lowest worth results from the homogeneous diffusion calculation performed by CISE. According to section 4.1 the CACTUS correction relative to homogeneous diffusion theory is - 1.6 % $\Delta k/k$. Applying this correction to the CISE solution one obtains a Gd reactivity worth of 0.247, i.e. a value which is in the range of worths predicted by the more sophisticated methods. This single correction reduces the standard deviation of the 10 different Gd worths from 0.007 to 0.005. Compared with the k-infinity variation of 0.009 for the fresh normal cell the standard deviation of the Gd worths seems to be acceptably small.

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Xenon Effect

By extrapolating the multiplication factors at 1 GWd/t and 2 GWd/t to zero burnup the xenon effects shown in TAB 29 have been derived. It can be seen that for both the regular and the poisoned lattice the standard deviation of the xenon effect is considerably smaller than the standard deviation of the multiplication factor at zero burnup. Furthermore, the magnitude of the xenon effect seems to be insensitive to the Gd poisoning. In the following discussion of the deviations between the solutions it can therefore be assumed that effects related to xenon are negligible.

Burnup Effects

The calculated multiplication factors in the burnup range 0 to 10 GWd/t are compiled in TABs 2 and 3 and plotted in FIGs 2 and 3. Deviations from the mean multiplication factor are shown in TABs/FIGs 16 and 17. It can be noted that for the regular lattice the CEA, CISE and EIR multiplication factors are in excellent agreement. Over the whole range of burnup the variation of the 3 solutions is less than 0.15 %, to be compared with a 0.7 to 0.9 % variation for all solutions. For the Gd poisoned lattice the variations are 0.7 to 1.2 %, the maximum being reached at intermediate burnups, where relatively large reactivity fluctuations (FIG 17) occur. These fluctuations can be associated with different Gd destruction rates (TAB/FIG 19) and the resulting effect on the Gd reactivity worth (TAB/FIG 18). In particular, the troughs and humps in the reactivity deviation curves are caused respectively by low and high Gd destruction rates.

To separate the burnup effects from the reactivity effects for the fresh lattice reactivity losses and reactivity gains above 1 GWd/t were calculated (TABs/FIGs 24 and 20). Fig. 24 shows that for the regular lattice CEA, CISE and EIR predict nearly identical reactivity loss curves. Within the statistical accuracy the overall slope of these curves appears to be consistent with the ENEA Monte Carlo calculation. The NAIG and OSAKA curves deviate only little from the above mentioned curves. The highest

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curve is predicted by AEEW, and relatively low curves are predicted by AMN, JAERI and RISØ. As can be seen in TAB/FIG 25 the reactivity loss is correlated with the U-235 destruction. Only a week correlation exists between the reactivity loss and the Pu-239 build-up (TAB/FIG 26). A comparison of FIG 20 and FIG 21 shows that in the Gd poisoned lattice the reactivity gain is more strongly correlated with the Gd destruction than with the burnup. A plot of the reactivity deviations as a function of Gd destruction would therefore show smaller fluctuations than are visible in FIG 17.

The densities of the heavy isotopes U-235 and Pu-240 (TABs/FIGs 4, 5, 8 and 9) as well as the Pu-240/Pu-239ratio (TABs/FIGs 22 and 23) show larger variations in the poisoned than in the regular lattice. The opposite is true for the Pu-239 density (TABs/FIGs 6 and 7). Surprisingly, in the regular lattice the variation of the Pu-240 density is noticeably smaller than that of the Pu-239 density. Such a systematic effect could be caused by spectrum variations in the regular cell.

The pin powers are compared in TABs/FIGs 12 and 13. For the pin with the highest rating (pin 4) and the poisoned pin the maximum standard deviations are respectively 0.008 and 0.036 (relative to the average power of the lattice this corresponds to pin power variations of 0.8 and 3.6 %). During burnup the standard deviation for the poisoned pin is gradually decreasing to 1.9 %.

Target Accuracies

Although for this benchmark exercise experimental bias factors are unknown, it may be interesting to compare the observed standard deviations with typical target accuracies for power reactors. In TAB 30 variations of some important parameters are listed together with target accuracies recommended by a 1971 IAEA panel on reactor burnup physics (20). More recently (in 1978), the same target accuracies were adopted by Crowther et al. (21).

TAB 30 shows that for the regular lattice the variations are larger than the target accuracies, except for U-235 depletion. This is true particularly for the Pu-239 concentration which exceeds the target accuracy by a factor of nearly 3. For the multiplication factor of the poisoned lattice only a small increase of the variations can be observed. However, the

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variation of the (deduced) reactivity life-time is rather large compared with the target accuracy. Except for Pu-239, as one would expect, the variations of the isotope concentrations at 10 GWd/t are somewhat larger for the poisoned than for the regular lattice. The pin power variations are acceptable, especially in the case of pin number 4 with the highest rating.

8. Conclusions

The results of the comparison calculations can be summarized as follows:

- *The uncertainties in the prediction of important parameters of the regular lattice are relatively large. An examination shows that the k-infinity differences can partly be explained by the U-235 and U-238 reaction rates. For the solutions which are based entirely on ENDF/B the agreement of the multiplication factors is much better over the whole range of burnup.*
- *A systematic trend has been detected that the predicted initial Gd reactivity worth increases with the sophistication of the calculational method. Nevertheless, taking into account the complexity of the problem, it can be said that the Gd worths are in reasonably good agreement.*
- *Both in the regular and the poisoned lattice the xenon effect does not contribute significantly to the variations of the parameters. It is interesting to notice that the magnitude of the xenon effect is rather insensitive to the Gd poisoning.*
- *The uncertainties in the prediction of the reactivity loss and the reactivity gain above 1 GWd/t lead to relatively large uncertainties for the reactivity life-time. This is particularly true for the poisoned lattice.*
- *In the regular lattice the variation of the Pu-239 build-up is unexpectedly large both absolutely (in comparison with a typical target accuracy) and relative to the variation of the Pu-240 build-up. This suggests that the build-up of the heavy isotopes may be influenced by a systematic effect such as a spectrum effect.*

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- *If systematic biases are small compared with the variations it can be deduced that pin powers in the poisoned lattice are predicted adequately. For the Gd pin a larger power variation than for a normal fuel pin seems to be acceptable, since the rating is lower and the number of Gd pins is small.*

- *None of the solutions takes an azimuthal dependence of the Gd depletion into account. Appendix A shows that the azimuthal variation of the flux and the power is relatively small, indicating that in normal design calculations azimuthal effects can be neglected.*

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TAB. 1: Summary of calculational methods

Participant	AEEW[a]	AMN	CEA	CISE	EIR	ENEA	JAERI	NAIG	OSAKA	RISØ
Data library	WIMS	ENDF/B-4	ENDF/B-3 + ENDF/B-4	MUFT-IV+ TEMPEST	ENDF/B-4	ENDF/B-4+ UKNDL	ENDF/B-4	ENDF/B-4+ ENDF/B-5	WIMS + ENDF/B-3	UKNDL
Code name	LWR-WIMS	BLA	APOLLO	NUOVO AUTOBUS	BOXER	KIM	SRAC	TGBLA	RESPLA	CRS+CDB
Pin cell calculation: nr. of groups	28	68	no condens.	30	70	no condens.	119	98	69	76
nr. of zones in Gd-pin	4	4	5	16	4	3	5	10	6	5[d]
Lattice calculation: method[b]	DI/CH	DI	DPO	DI	QP1	MC	CP	I+DI	DP1	CP+DI
nr. of groups	6	3	99	5	11	336	56	3	6	10
nr. of zones	16/170	32	56	144	16	52	209	16	58	56
nr. of time points	11	14	16	14	17	14	35	49	22	29
hom. or het. calculation[c]	hom/het	het	het	hom	hom	het	het	hom	het	het

a First/second entry: Calculation between 1 and 10 $\frac{GWd}{t}$ / at zero burnup

b DI: Diffusion calculation
DPO, DP1, QP1: Transport calculation with double P_o, double P_1 or quadruple P_1 approximation at cell boundaries
CH: Characteristics transport method
MC: Monte Carlo
CP,I: Collision Probability, Integral Transport Method

c hom: Fuel cells (fuel pin, clad and moderator) are homogenized
het: Heterogenous calculation without cell homogenization

d For lattice and burnup calculations

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TAB. 2 K-INFINITY FOR REGULAR LATTICE

BURNUP (GWD/T)	AEEW	AMN	CEA	CISE	EIR	ENEA[a]	JAERI	NAIG	OSAKA	RISOE	MEAN	VAR
0:NO XE	1.3514	1.3400	1.3298	1.3278	1.3316	1.3390	1.3285	1.3340	1.3060	1.3180	1.3306	.009
1	1.2926	1.2794	1.2742	1.2752	1.2744	1.2869	1.2723	1.2767	1.2537	1.2637	1.2749	.009
2	1.2773	1.2681	1.2623	1.2613	1.2626	1.2692	1.2617	1.2646	1.2424	1.2538	1.2623	.007
3	1.2630	1.2563	1.2495	1.2488	1.2501	1.2618	1.2506	1.2515	1.2301	1.2427	1.2504	.008
4	1.2489	1.2445	1.2369	1.2357	1.2373	1.2449	1.2393	1.2381	1.2172	1.2310	1.2374	.007
5	1.2349	1.2329	1.2240	1.2238	1.2245	1.2354	1.2279	1.2246	1.2040	1.2192	1.2251	.007
6	1.2213	1.2214	1.2111	1.2111	1.2119	1.2226	1.2167	1.2114	1.1908	1.2074	1.2126	.008
7	1.2080	1.2098	1.1987	1.1993	1.1996	1.2067	1.2058	1.1985	1.1779	1.1958	1.2000	.008
8	1.1951	1.1986	1.1865	1.1876	1.1875	1.2000	1.1951	1.1860	1.1652	1.1845	1.1886	.008
9	1.1825	1.1882	1.1747	1.1764	1.1758	1.1844	1.1847	1.1739	1.1529	1.1734	1.1767	.008
10	1.1703	1.1781	1.1633	1.1652	1.1645	1.1740	1.1747	1.1621	1.1410	1.1625	1.1656	.009

a *Statistical deviations between 0.0018 and 0.0026*

TAB. 3 K-INFINITY FOR POISONED LATTICE

BURNUP (GWD/T)	AEEW	AMN	CEA	CISE	EIR	ENEA[a]	JAERI	NAIG	OSAKA	RISOE	MEAN	VAR
0:NO XE	1.0093	1.0140	.9970	1.0164	1.0110	.9965	.9983	1.0004	.9899	.9815	1.0014	.011
1	1.0024	1.0036	.9991	1.0058	1.0093	.9935	.9973	1.0044	.9895	.9798	.9985	.009
2	1.0295	1.0316	1.0314	1.0286	1.0403	1.0187	1.0270	1.0368	1.0162	1.0093	1.0269	.009
3	1.0625	1.0631	1.0658	1.0531	1.0727	1.0504	1.0596	1.0699	1.0439	1.0435	1.0585	.010
4	1.1042	1.1002	1.1035	1.0884	1.1083	1.0846	1.0964	1.1051	1.0742	1.0855	1.0950	.010
5	1.1516	1.1412	1.1433	1.1196	1.1477	1.1250	1.1399	1.1419	1.1105	1.1379	1.1359	.012
6	1.1866	1.1747	1.1731	1.1501	1.1754	1.1595	1.1745	1.1714	1.1465	1.1739	1.1686	.011
7	1.1989	1.1895	1.1811	1.1717	1.1895	1.1828	1.1910	1.1834	1.1651	1.1866	1.1840	.008
8	1.1939	1.1891	1.1756	1.1788	1.1861	1.1811	1.1901	1.1803	1.1650	1.1837	1.1824	.007
9	1.1832	1.1819	1.1654	1.1728	1.1765	1.1756	1.1822	1.1707	1.1566	1.1747	1.1740	.007
10	1.1715	1.1727	1.1546	1.1621	1.1657	1.1705	1.1728	1.1595	1.1466	1.1642	1.1640	.007

a *Statistical deviations between 0.0018 and 0.0027*

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TAB. 4 U-235 DENSITY FOR REGULAR LATTICE(1.0-4/BARN X CM)

BURNUP (GWD/T)	AEEW	AMN	CEA	CISE	EIR	ENEA	JAERI	NAIG	OSAKA	RISOE	MEAN	VAR
0	6.777	6.776	6.774	6.777	6.775	6.777	6.777	6.775	6.776	6.777	6.776	.000
2	6.261	6.254	6.261	6.253	6.257	6.258	6.238	6.251	6.243	6.261	6.254	.001
4	5.784	5.789	5.789	5.769	5.780	5.778	5.743	5.770	5.757	5.787	5.775	.003
6	5.341	5.359	5.350	5.319	5.337	5.330	5.284	5.325	5.308	5.347	5.330	.004
8	4.927	4.959	4.940	4.898	4.924	4.911	4.857	4.911	4.892	4.937	4.916	.006
10	4.539	4.586	4.556	4.503	4.538	4.517	4.458	4.525	4.504	4.553	4.528	.008

TAB. 5 U-235 DENSITY IN POISONED PIN(1.0-4/BARN X CM)

BURNUP (GWD/T)	AEEW	AMN	CEA	CISE	EIR	ENEA	JAERI	NAIG	OSAKA	RISOE	MEAN	VAR
0	6.573	6.572	6.571	6.574	6.572	6.574	6.574	6.572	6.572	6.573	6.573	.000
2	6.353	6.352	6.340	6.374	6.338	6.352	6.346	6.339	6.332	6.378	6.350	.002
4	6.059	6.077	6.036	6.115	6.032	6.083	6.048	6.038	6.041	6.106	6.064	.005
6	5.678	5.728	5.658	5.794	5.663	5.748	5.671	5.668	5.683	5.747	5.704	.008
8	5.256	5.342	5.248	5.411	5.249	5.350	5.246	5.259	5.269	5.341	5.297	.011
10	4.847	4.969	4.853	5.003	4.861	4.938	4.831	4.862	4.860	4.941	4.897	.012

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TAB. 6 PU-239 DENSITY FOR REGULAR LATTICE(1.0-5/BARN X CM)

BURNUP (GWD/T)	AEEW	AMN	CEA	CISE	EIR	ENEA	JAERI	NAIG	OSAKA	RISOE	MEAN	VAR
2	2.075	2.529	2.233	2.137	2.225	2.061	2.232	2.215	2.393	2.133	2.223	.065
4	3.808	4.557	4.020	3.848	4.011	3.714	4.014	4.048	4.281	3.902	4.020	.061
6	5.211	6.199	5.471	5.227	5.464	5.062	5.437	5.529	5.789	5.330	5.472	.059
8	6.354	7.532	6.656	6.393	6.654	6.151	6.582	6.737	6.998	6.484	6.654	.058
10	7.287	8.614	7.627	7.253	7.632	7.025	7.505	7.725	7.970	7.430	7.607	.058

TAB. 7 PU-239 DENSITY IN POISONED PIN(1.0-5/BARN X CM)

BURNUP (GWD/T)	AEEW	AMN	CEA	CISE	EIR	ENEA	JAERI	NAIG	OSAKA	RISOE	MEAN	VAR
2	2.268	2.227	2.241	2.136	2.408	2.140	2.381	2.185	2.410	2.217	2.261	.046
4	4.210	4.207	4.097	3.964	4.385	3.943	4.322	4.052	4.401	4.174	4.176	.039
6	5.671	5.891	5.542	5.427	5.856	5.315	5.781	5.498	5.975	5.664	5.662	.038
8	6.765	7.289	6.667	6.539	6.943	6.397	6.857	6.624	7.185	6.758	6.802	.041
10	7.639	8.440	7.581	7.385	7.815	7.204	7.701	7.537	8.145	7.615	7.706	.046

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TAB. 8 PU-240 DENSITY FOR REGULAR LATTICE(1.0-6/BARN X CM)

BURNUP (GWD/T)	AEEW	AMN	CEA	CISE	EIR	ENEA	JAERI	NAIG	OSAKA	RISOE	MEAN	VAR
2	.878	.977	.944	.919	.949	.954	1.046	.945	1.035	.884	.953	.058
4	3.062	3.218	3.146	3.100	3.175	3.187	3.508	3.247	3.438	3.083	3.216	.046
6	5.978	6.138	5.997	5.990	6.096	6.083	6.732	6.281	6.463	6.027	6.179	.040
8	9.314	9.428	9.223	9.260	9.422	9.437	10.390	9.723	9.692	9.409	9.530	.036
10	12.894	12.922	12.653	12.759	12.976	13.030	14.290	13.390	12.880	13.052	13.085	.036

TAB. 9 PU-240 DENSITY IN POISONED PIN(1.0-6/BARN X CM)

BURNUP (GWD/T)	AEEW	AMN	CEA	CISE	EIR	ENEA	JAERI	NAIG	OSAKA	RISOE	MEAN	VAR
2	.605	.521	.625	.520	.676	.657	.692	.612	.750	.471	.613	.142
4	2.492	2.102	2.438	2.080	2.634	2.423	2.731	2.487	2.799	2.067	2.425	.110
6	5.506	4.643	5.194	4.533	5.661	5.154	5.916	5.398	5.813	4.864	5.268	.091
8	9.127	7.745	8.479	7.725	9.193	8.392	9.789	8.870	9.479	8.428	8.723	.079
10	12.919	11.073	11.928	11.340	12.750	12.557	13.880	12.540	13.410	12.250	12.465	.069

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TAB. 10 GD-155 DENSITY IN POISONED PIN(1.0-4/BARN X CM)

BURNUP	AEEW	AMN (GWD/T)	CEA	CISE	EIR	ENEA	JAERI	NAIG	OSAKA	RISOE	MEAN	VAR
0	1.47E+00	1.47E+00	1.47E+00	1.47E+00	1.47E+00	1.47E+00	1.47E+00	1.47E+00	1.47E+00	1.47E+00	1.47E+00	.000
2	9.94E-01	9.88E-01	9.34E-01	1.04E+00	9.67E-01	9.40E-01	9.78E-01	9.53E-01	1.01E+00	9.61E-01	9.77E-01	.034
3	6.95E-01	7.01E-01	6.39E-01	7.81E-01	6.79E-01	6.72E-01	6.97E-01	6.72E-01	7.47E-01	6.71E-01	6.95E-01	.059
4	4.19E-01	4.43E-01	3.85E-01	5.31E-01	4.21E-01	4.42E-01	4.39E-01	4.21E-01	4.89E-01	4.03E-01	4.39E-01	.097
5	1.97E-01	2.31E-01	1.88E-01	3.12E-01	2.10E-01	2.51E-01	2.26E-01	2.17E-01	2.61E-01	1.96E-01	2.29E-01	.164
6	6.56E-02	9.15E-02	6.24E-02	1.47E-01	8.12E-02	1.11E-01	8.32E-02	8.23E-02	9.95E-02	6.76E-02	8.91E-02	.285
7	1.59E-02	2.82E-02	1.65E-02	5.05E-02	1.93E-02	3.55E-02	2.15E-02	2.32E-02	2.65E-02	1.82E-02	2.55E-02	.417

TAB. 11 GD-157 DENSITY IN POISONED PIN(1.0-4/BARN X CM)

BURNUP	AEEW	AMN (GWD/T)	CEA	CISE	EIR	ENEA	JAERI	NAIG	OSAKA	RISOE	MEAN	VAR
0	1.56E+00	1.56E+00	1.56E+00	1.56E+00	1.56E+00	1.56E+00	1.56E+00	1.56E+00	1.56E+00	1.56E+00	1.56E+00	.000
2	5.00E-01	5.43E-01	5.10E-01	6.06E-01	5.45E-01	4.63E-01	5.52E-01	5.37E-01	5.45E-01	5.29E-01	5.33E-01	.070
3	2.18E-01	2.66E-01	2.39E-01	3.21E-01	2.56E-01	2.35E-01	2.66E-01	2.58E-01	2.55E-01	2.34E-01	2.55E-01	.111
4	5.95E-02	9.27E-02	6.99E-02	1.32E-01	8.29E-02	9.88E-02	9.18E-02	8.93E-02	8.63E-02	6.46E-02	8.68E-02	.236
5	5.80E-03	1.59E-02	8.71E-03	3.96E-02	9.42E-03	2.52E-02	1.48E-02	1.53E-02	1.29E-02	5.52E-03	1.53E-02	.675
6	9.48E-05	1.23E-03	1.65E-03	4.94E-03	2.56E-04	3.31E-03	1.87E-03	1.90E-03	3.70E-04	3.72E-04	1.60E-03	.965
7	2.75E-07	7.10E-04	4.04E-05	1.21E-04	9.32E-07	1.35E-03	1.30E-03	1.26E-03	1.82E-06	2.00E-06	4.78E-04	1.271

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TAB. 12 POWER IN PIN 4 (-)

BURNUP (GWD/T)	AEEW	AMN	CEA	CISE	EIR	ENEA	JAERI	NAIG	OSAKA	RISOE	MEAN	ST DEV
0	1.163	1.165	1.159	1.153	1.159	1.154	1.158	1.166	1.178	1.174	1.163	.008
2	1.118	1.123	1.111	1.116	1.113	1.137	1.114	1.113	1.126	1.126	1.120	.008
4	1.060	1.074	1.057	1.070	1.062	1.055	1.064	1.060	1.071	1.066	1.064	.006
6	1.004	1.027	1.009	1.023	1.014	1.027	1.021	1.012	1.014	1.007	1.016	.008
8	.989	1.010	.996	.994	.997	.999	1.003	.996	.992	.992	.997	.006
10	.988	1.008	.995	.991	.996	1.000	1.002	.995	.991	.991	.996	.006

TAB. 13 POWER IN POISONED PIN (-)

BURNUP (GWD/T)	AEEW	AMN	CEA	CISE	EIR	ENEA	JAERI	NAIG	OSAKA	RISOE	MEAN	ST DEV
0	.381	.462	.384	.355	.373	.368	.374	.391	.411	.324	.382	.036
2	.546	.592	.563	.507	.540	.533	.546	.566	.559	.506	.546	.026
4	.771	.755	.769	.674	.736	.716	.752	.757	.731	.737	.740	.029
6	.985	.919	.956	.870	.921	.924	.951	.936	.935	.962	.936	.031
8	1.045	.982	1.007	1.022	.990	1.022	1.025	1.003	1.018	1.026	1.014	.019
10	1.047	.990	1.010	1.041	.994	1.033	1.028	1.008	1.022	1.028	1.020	.019

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TAB.14 RAD. GD-155 DISTRIBUTION AT 2 GWD/T (1.0E-4/BARN X CM)

RADIUS (CM)	AEEW	AMN	CEA	CISE	EIR	JAERI	NAIG	OSAKA	RISOE	MEAN	VAR
.125	1.273	1.264	1.278	1.363	1.299	1.279	1.279	1.264	1.331	1.292	.026
.302	1.176	1.188	1.174	1.276	1.216	1.197	1.187	1.167	1.188	1.197	.028
.393	.947	.952	.879	1.004	.946	.956	.914	.969	.898	.941	.040
.467	.579	.548	.407	.525	.407	.479	.431	.648	.427	.495	.173

TAB.15 RAD. GD-157 DISTRIBUTION AT 2 GWD/T (1.0E-4/BARN X CM)

RADIUS (CM)	AEEW	AMN	CEA	CISE	EIR	JAERI	NAIG	OSAKA	RISOE	MEAN	VAR
.125	1.027	1.088	1.038	1.157	1.081	1.067	1.074	1.041	1.211	1.087	.055
.302	.705	.797	.715	.885	.812	.796	.780	.744	.715	.772	.076
.393	.335	.396	.228	.350	.277	.320	.276	.335	.178	.300	.223
.467	.000	.000	.058	.032	.008	.024	.018	.062	.012	.024	.972

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TAB.16 REACTIVITY DEVIATION FROM MEAN FOR REGULAR LATTICE(-)

BURNUP (GWD/T)	AEEW	AMN	CEA	CISE	EIR	ENEA	JAERI	NAIG	OSAKA	RISOE	MEAN	ST DEV
0:NO XE	.016	.007	-.001	-.002	.001	.006	-.002	.003	-.018	-.009	.006	.009
1	.014	.004	-.001	.000	-.000	.009	-.002	.001	-.017	-.009	.006	.009
2	.012	.005	-.000	-.001	.000	.005	-.000	.002	-.016	-.007	.005	.007
3	.010	.005	-.001	-.001	-.000	.009	.000	.001	-.016	-.006	.005	.008
4	.009	.006	-.000	-.001	-.000	.006	.002	.001	-.016	-.005	.005	.007
5	.008	.006	-.001	-.001	-.001	.008	.002	-.000	-.017	-.005	.006	.007
6	.007	.007	-.001	-.001	-.001	.008	.003	-.001	-.018	-.004	.007	.008
7	.007	.008	-.001	-.001	-.000	.006	.005	-.001	-.018	-.004	.006	.008
8	.005	.008	-.002	-.001	-.001	.010	.005	-.002	-.020	-.003	.007	.008
9	.005	.010	-.002	-.000	-.001	.007	.007	-.002	-.020	-.003	.007	.008
10	.004	.011	-.002	-.000	-.001	.007	.008	-.003	-.021	-.003	.007	.009

TAB.17 REACTIVITY DEVIATION FROM MEAN FOR POISONED LATTICE(-)

BURNUP (GWD/T)	AEEW	AMN	CEA	CISE	EIR	ENEA	JAERI	NAIG	OSAKA	RISOE	MEAN	ST DEV
0:NO XE	.008	.013	-.004	.015	.010	-.005	-.003	-.001	-.012	-.020	.011	.011
1	.004	.005	.001	.007	.011	-.005	-.001	.006	-.009	-.019	.006	.009
2	.002	.005	.004	.002	.013	-.008	.000	.010	-.010	-.017	.005	.009
3	.004	.004	.007	-.005	.013	-.008	.001	.011	-.014	-.014	.007	.010
4	.008	.005	.008	-.006	.012	-.010	.001	.009	-.019	-.009	.007	.010
5	.014	.005	.007	-.014	.010	-.010	.004	.005	-.022	.002	.007	.012
6	.015	.005	.004	-.016	.006	-.008	.005	.002	-.019	.005	.006	.011
7	.013	.005	-.002	-.010	.005	-.001	.006	-.000	-.016	.002	.006	.008
8	.010	.006	-.006	-.003	.003	-.001	.007	-.002	-.015	.001	.005	.007
9	.008	.007	-.007	-.001	.002	.001	.007	-.003	-.015	.001	.004	.007
10	.006	.007	-.008	-.002	.001	.006	.008	-.004	-.015	.000	.005	.007

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TAB.18 GD-REACTIVITY WORTH(-)

BURNUP (GWD/T)	AEEW	AMN	CEA	CISE	EIR	ENEA	JAERI	NAIG	OSAKA	RISOE	MEAN	ST DEV
0:NO XE	.253	.243	.250	.235	.241	.256	.249	.250	.242	.255	.247	.007
1	.225	.216	.216	.211	.208	.228	.216	.213	.211	.225	.217	.007
2	.194	.186	.183	.184	.176	.197	.186	.180	.182	.195	.186	.007
3	.159	.154	.147	.157	.142	.168	.153	.145	.151	.160	.154	.008
4	.116	.116	.108	.119	.104	.129	.115	.107	.117	.118	.115	.007
5	.067	.074	.066	.085	.063	.089	.072	.068	.078	.067	.073	.009
6	.028	.038	.031	.050	.030	.052	.035	.033	.037	.028	.036	.008
7	.008	.017	.015	.023	.008	.020	.012	.013	.011	.008	.013	.005
8	.001	.008	.009	.007	.001	.016	.004	.005	.000	.001	.005	.005
9	-.001	.005	.008	.003	-.001	.007	.002	.003	-.003	-.001	.005	.003
10	-.001	.005	.007	.003	-.001	.003	.002	.002	-.005	-.001	.004	.002

TAB.19 GD-DESTRUCTION IN POISONED PIN (-)

BURNUP (GWD/T)	AEEW	AMN	CEA	CISE	EIR	ENEA	JAERI	NAIG	OSAKA	RISOE	MEAN	ST DEV
2	.507	.495	.524	.456	.501	.537	.495	.509	.486	.509	.502	.022
3	.699	.681	.710	.636	.691	.701	.682	.693	.669	.702	.687	.021
4	.842	.823	.850	.781	.834	.821	.825	.832	.810	.846	.826	.020
5	.933	.918	.935	.884	.928	.909	.921	.923	.910	.933	.919	.016
6	.978	.969	.979	.950	.973	.962	.972	.972	.967	.978	.970	.009
7	.995	.991	.995	.983	.994	.988	.993	.992	.991	.994	.992	.004

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TAB.20 REACTIVITY GAIN FOR POISONED LATTICE(-)

BURNUP (GWD/T)	AEEW	AMN	CEA	CISE	EIR	ENEA	JAERI	NAIG	OSAKA	RISOE	MEAN	ST DEV
2	.027	.028	.032	.023	.031	.025	.030	.032	.027	.030	.029	.003
3	.060	.059	.067	.047	.063	.057	.062	.065	.055	.065	.060	.006
4	.102	.096	.104	.082	.098	.092	.099	.100	.086	.108	.097	.008
5	.149	.137	.144	.113	.137	.132	.143	.137	.122	.161	.138	.013
6	.184	.170	.174	.143	.165	.167	.178	.166	.159	.198	.170	.015
7	.196	.185	.182	.165	.179	.191	.194	.178	.177	.211	.186	.013

TAB.21 REACTIVITY GAIN(-) AND GD-DESTRUCTION(-)

GD-DES	AEEW	AMN	CEA	CISE	EIR	ENEA	JAERI	NAIG	OSAKA	RISOE	MEAN	ST DEV
.50	.026	.029	.029	.027	.031	.021	.030	.031	.029	.029	.028	.003
.60	.040	.043	.044	.040	.045	.036	.046	.047	.043	.043	.043	.003
.70	.060	.064	.064	.061	.065	.057	.067	.067	.059	.065	.063	.003
.80	.085	.088	.087	.086	.087	.084	.091	.090	.083	.088	.087	.003
.90	.128	.127	.125	.119	.123	.127	.131	.125	.117	.138	.126	.006
1.00	.200	.192	.185	.177	.183	.203	.200	.183	.185	.216	.192	.012

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TAB.18 GD-REACTIVITY WORTH(-)

BURNUP (GWD/T)	AEEW	AMN	CEA	CISE	EIR	ENEA	JAERI	NAIG	OSAKA	RISOE	MEAN	ST DEV
0:NO XE	.253	.243	.250	.235	.241	.256	.249	.250	.242	.255	.247	.007
1	.225	.216	.216	.211	.208	.228	.216	.213	.211	.225	.217	.007
2	.194	.186	.183	.184	.176	.197	.186	.180	.182	.195	.186	.007
3	.159	.154	.147	.157	.142	.168	.153	.145	.151	.160	.154	.008
4	.116	.116	.108	.119	.104	.129	.115	.107	.117	.118	.115	.007
5	.067	.074	.066	.085	.063	.089	.072	.068	.078	.067	.073	.009
6	.028	.038	.031	.050	.030	.052	.035	.033	.037	.028	.036	.008
7	.008	.017	.015	.023	.008	.020	.012	.013	.011	.008	.013	.005
8	.001	.008	.009	.007	.001	.016	.004	.005	.000	.001	.005	.005
9	-.001	.005	.008	.003	-.001	.007	.002	.003	-.003	-.001	.005	.003
10	-.001	.005	.007	.003	-.001	.003	.002	.002	-.005	-.001	.004	.002

TAB.19 GD-DESTRUCTION IN POISONED PIN (-)

BURNUP (GWD/T)	AEEW	AMN	CEA	CISE	EIR	ENEA	JAERI	NAIG	OSAKA	RISOE	MEAN	ST DEV
2	.507	.495	.524	.456	.501	.537	.495	.509	.486	.509	.502	.022
3	.699	.681	.710	.636	.691	.701	.682	.693	.669	.702	.687	.021
4	.842	.823	.850	.781	.834	.821	.825	.832	.810	.846	.826	.020
5	.933	.918	.935	.884	.928	.909	.921	.923	.910	.933	.919	.016
6	.978	.969	.979	.950	.973	.962	.972	.972	.967	.978	.970	.009
7	.995	.991	.995	.983	.994	.988	.993	.992	.991	.994	.992	.004

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TAB.20 REACTIVITY GAIN FOR POISONED LATTICE(-)

BURNUP (GWD/T)	AEEW	AMN	CEA	CISE	EIR	ENEA	JAERI	NAIG	OSAKA	RISOE	MEAN	ST DEV
2	.027	.028	.032	.023	.031	.025	.030	.032	.027	.030	.029	.003
3	.060	.059	.067	.047	.063	.057	.062	.065	.055	.065	.060	.006
4	.102	.096	.104	.082	.098	.092	.099	.100	.086	.108	.097	.008
5	.149	.137	.144	.113	.137	.132	.143	.137	.122	.161	.138	.013
6	.184	.170	.174	.143	.165	.167	.178	.166	.159	.198	.170	.015
7	.196	.185	.182	.165	.179	.191	.194	.178	.177	.211	.186	.013

TAB.21 REACTIVITY GAIN(-) AND GD-DESTRUCTION(-)

GD-DES	AEEW	AMN	CEA	CISE	EIR	ENEA	JAERI	NAIG	OSAKA	RISOE	MEAN	ST DEV
.50	.026	.029	.029	.027	.031	.021	.030	.031	.029	.029	.028	.003
.60	.040	.043	.044	.040	.045	.036	.046	.047	.043	.043	.043	.003
.70	.060	.064	.064	.061	.065	.057	.067	.067	.059	.065	.063	.003
.80	.085	.088	.087	.086	.087	.084	.091	.090	.083	.088	.087	.003
.90	.128	.127	.125	.119	.123	.127	.131	.125	.117	.138	.126	.006
1.00	.200	.192	.185	.177	.183	.203	.200	.183	.185	.216	.192	.012

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TAB.22 PU-240/PU-239 DENSITY FOR REGULAR LATTICE (-)

BURNUP (GWD/T)	AEEW	AMN	CEA	CISE	EIR	ENEA	JAERI	NAIG	OSAKA	RISOE	MEAN	VAR
2	.042	.039	.042	.043	.043	.046	.047	.043	.043	.041	.043	.054
4	.080	.071	.078	.081	.079	.086	.087	.080	.080	.079	.080	.056
6	.115	.099	.110	.115	.112	.120	.124	.114	.112	.113	.113	.058
8	.147	.125	.139	.145	.142	.153	.158	.144	.138	.145	.144	.062
10	.177	.150	.166	.176	.170	.185	.190	.173	.162	.176	.173	.067

TAB.23 PU-240/PU-239 DENSITY IN POISONED PIN (-)

BURNUP (GWD/T)	AEEW	AMN	CEA	CISE	EIR	ENEA	JAERI	NAIG	OSAKA	RISOE	MEAN	VAR
2	.027	.023	.028	.024	.028	.031	.029	.028	.031	.021	.027	.118
4	.059	.050	.060	.052	.060	.061	.063	.061	.064	.050	.058	.092
6	.097	.079	.094	.084	.097	.097	.102	.098	.097	.086	.093	.082
8	.135	.106	.127	.118	.132	.131	.143	.134	.132	.125	.128	.079
10	.169	.131	.157	.154	.163	.174	.180	.166	.165	.161	.162	.082

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TAB.24 REACTIVITY LOSS FROM 1 GWD/T FOR REGULAR LATTICE (-)

BURNUP (GWD/T)	AEEW	AMN	CEA	CISE	EIR	ENEA	JAERI	NAIG	OSAKA	RISOE	MEAN	ST DEV
2	.012	.009	.009	.011	.009	.014	.008	.009	.009	.008	.010	.002
4	.034	.027	.029	.031	.029	.033	.026	.030	.029	.026	.029	.003
6	.055	.045	.050	.050	.049	.050	.044	.051	.050	.045	.049	.003
8	.075	.063	.069	.069	.068	.068	.061	.071	.071	.063	.068	.004
10	.095	.079	.087	.086	.086	.088	.077	.090	.090	.080	.086	.006

TAB.25 REACTIVITY LOSS(-) AND U-235 DESTRUCTION(-) FOR REGULAR LATTICE

U25-DES	AEEW	AMN	CEA	CISE	EIR	ENEA	JAERI	NAIG	OSAKA	RISOE	MEAN	ST DEV
.08	.013	.010	.011	.012	.010	.015	.008	.010	.009	.009	.011	.002
.14	.032	.026	.028	.028	.027	.031	.023	.028	.026	.024	.027	.003
.20	.051	.043	.046	.046	.045	.046	.038	.047	.045	.041	.045	.003
.26	.071	.061	.065	.064	.064	.063	.054	.066	.065	.059	.063	.004
.32	.091	.078	.085	.082	.083	.083	.071	.086	.085	.078	.082	.006

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TAB.26 REACTIVITY LOSS(-) AND PU-239 DENSITY(1E-5/BARN X CM) FOR REGULAR LATTICE

PU-239	AEEW	AMN	CEA	CISE	EIR	ENEA	JAERI	NAIG	OSAKA	RISOE	MEAN	ST DEV
2.80	.020	.011	.015	.018	.015	.022	.013	.015	.013	.014	.016	.003
3.90	.035	.021	.028	.032	.028	.035	.025	.028	.024	.026	.028	.005
5.00	.052	.032	.043	.047	.042	.049	.038	.043	.039	.040	.042	.006
6.10	.071	.044	.059	.063	.059	.067	.053	.060	.055	.056	.059	.007
7.20	.093	.059	.079	.085	.078	.092	.071	.080	.074	.076	.079	.010

9203003043

TAB. 27 Average fluxes in the regular and in the poisoned pin cell (EIR results at 0 GWd/t)

Energy range (eV)	Flux ϕ (10^{13}/cm^2 sec)		Φ_{poi} / Φ_{reg}
	Regular lattice	Poisoned cell	
$1.5 \cdot 10^7$ - 900	8.95	11.52	1.29
900 - 0.6	2.86	3.69	1.29
0.6 - 0	2.53	2.04	0.81
$1.5 \cdot 10^7$ - 0	14.34	17.25	1.20

TAB. 28 Cell-average, microscopic, one-group cross sections and reaction rates (EIR-results at 0 GWd/t)

Quantity	Nuclide	Regular lattice	Poisoned cell
σ_a (barn)	Gd-155	2860	160
	Gd-157	12240	600
	U-235	65	19
	U-238	1.01	0.87
	Pu-239	207	81
	Pu-240	242	227
σ_c / σ_a (-)	U-235	0.18	0.25
	U-238	0.89	0.87
	Pu-239	0.36	0.39
	Pu-240	1.00	1.00
$\sigma_a \phi$ (10^{-10} sec^{-1})	U-235	93	33
	U-238	1.45	1.50
	Pu-239	297	139
	Pu-240	347	392

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TAB. 29 Xenon reactivity worth at 0 GWd/t in mk (1 mk = 0.001)

Solution	Regular lattice	Poisoned lattice	Reg.-poi.
AEEW	32.2	33.7	- 1.5
AMN	36.8	37.9	- 1.1
CEA	32.9	30.3	2.6
CISE	29.1	32.9	- 3.8
EIR	34.1	32.3	1.8
ENEA	25.1	28.3	- 2.6
JAERI	34.3	30.8	3.5
NAIG	33.9	28.4	5.5
OSAKA	31.4	27.4	4.0
RISØ	33.7	31.8	1.9
Mean	32.4	31.4	1.0
Sta. dev.	3.1	3.1	3.0

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TAB. 30 Target accuracy and variation of results

Parameter	Target accuracy (%) from Ref. (13)	Variation (%)	
		Reg.lattice	Pois.lattice
Multiplication factor	0.25-0.5		
0 GWd/t		0.9	1.1
5 GWd/t		0.7	1.2
10 GWd/t		0.9	0.7
Reactivity life-time	2-5	6.1[a]	13.2[b]
Changes in isotope comp.			
U^{235} depletion	2	0.8	1.2
Pu^{239} build-up	2	5.8	4.6
Pu^{240} build-up	-	3.6	6.9
Pin power relative to lattice	2		
Pin no. 4 (max. rating)			0.8
Gd pin			3.6

a) From a 0.55 % standard deviation of the reactivity loss between 1 and 10 GWd/t (deduced from TAB 2) and assuming a reactivity swing of 1 % per GWd/t at the end of life

b) From a 1.19 % standard deviation of the reactivity gain between 1 and 10 GWd/t (deduced from TAB 3) and assuming the same reactivity swing of 1 % per GWd/t.

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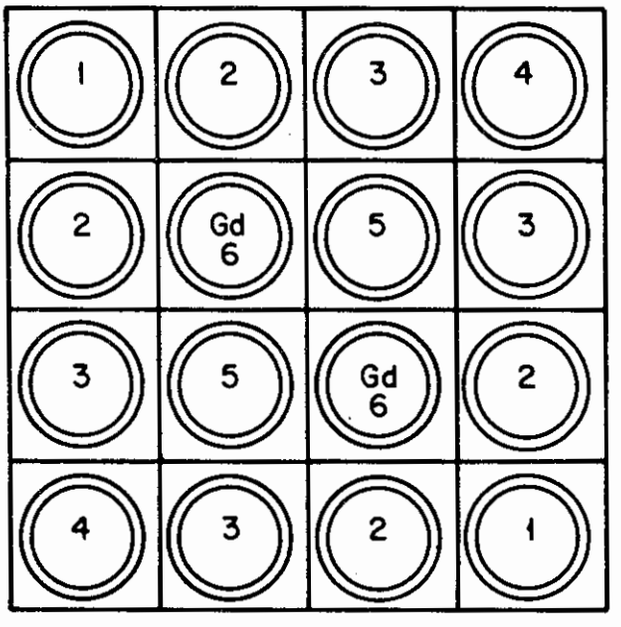

FIG. 1 Fuel element with adjacent poisoned pins

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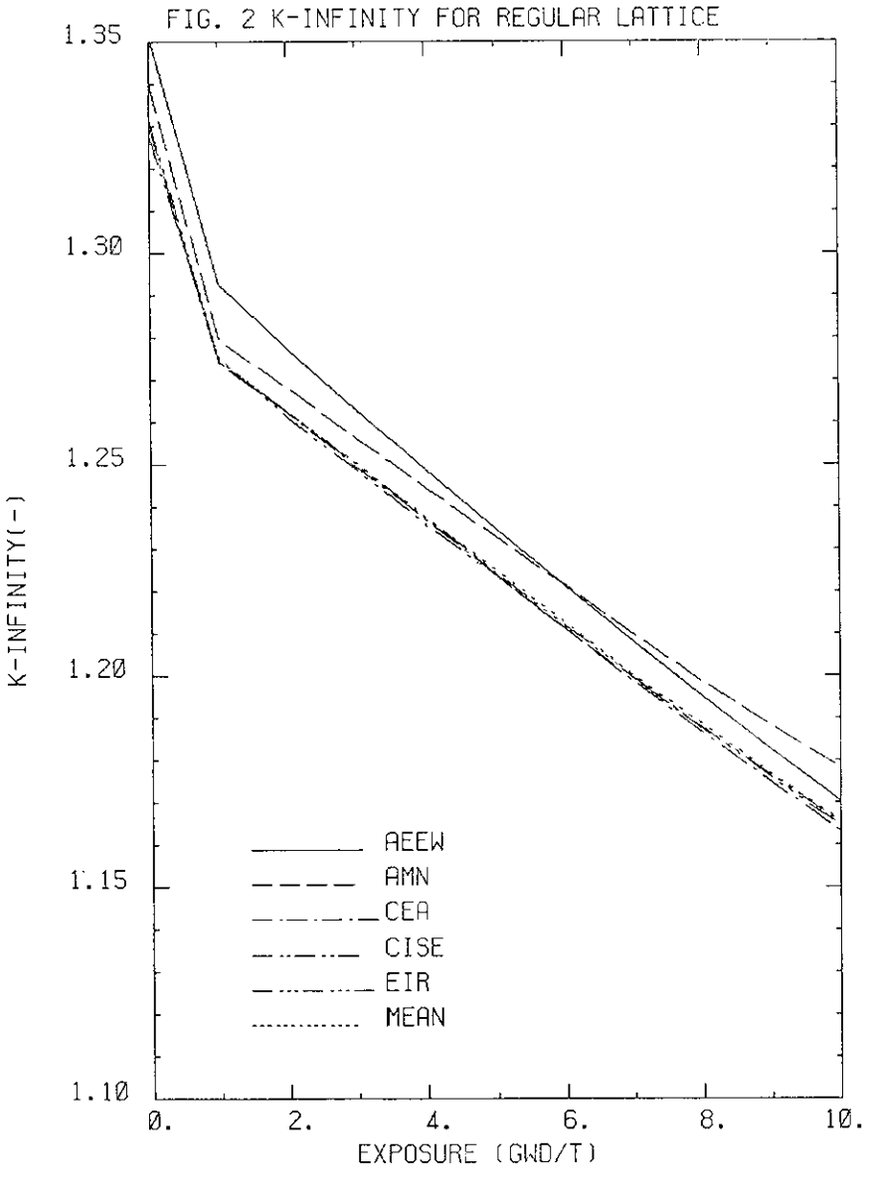


FIG. 2 K-INFINITY FOR REGULAR LATTICE
K-INFINITY(-)
1.35
1.30
1.25
1.20
1.15
1.10
0.
2.
4.
6.
8.
10.
EXPOSURE (GWD/T)
AEEW
AMN
CEA
CISE
EIR
MEAN

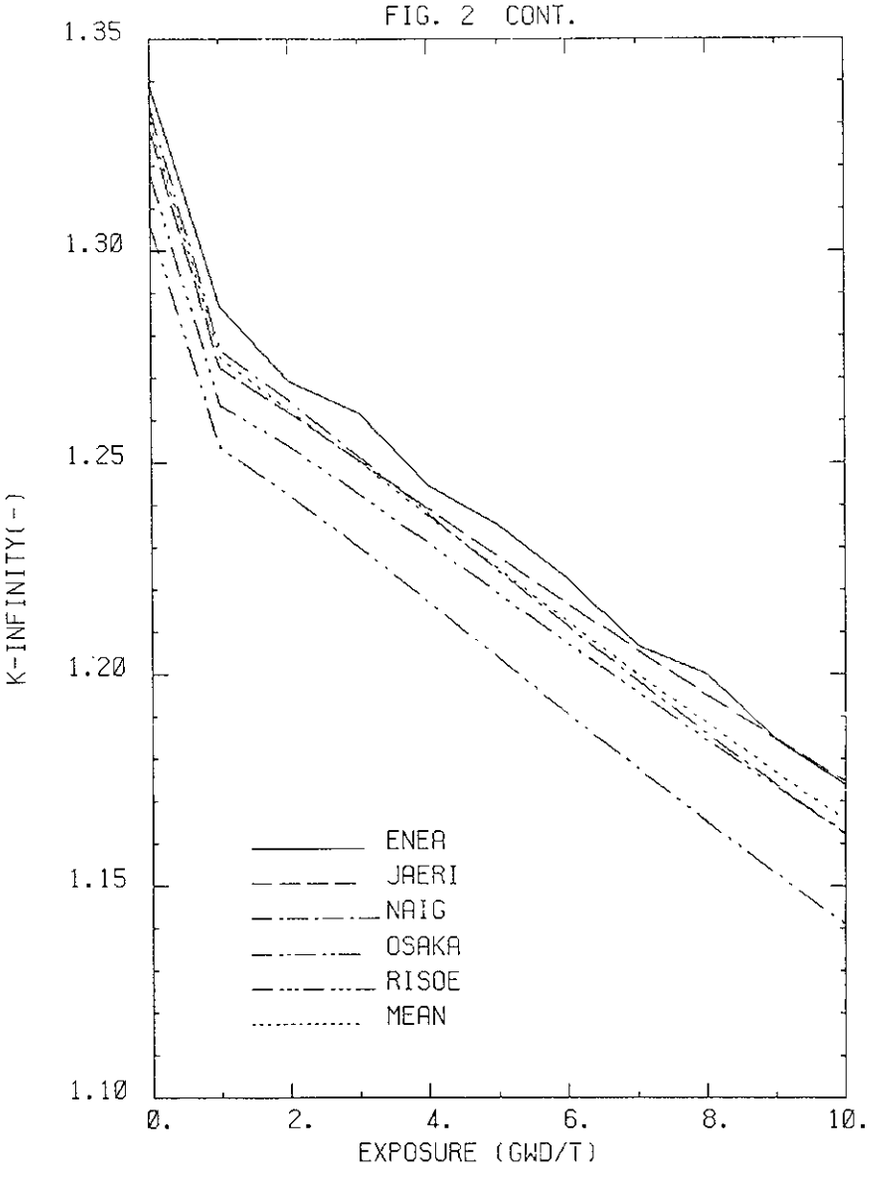


FIG. 2 CONT.
K-INFINITY(-)
1.35
1.30
1.25
1.20
1.15
1.10
0.
2.
4.
6.
8.
10.
EXPOSURE (GWD/T)
ENEA
JAERI
NAIG
OSAKA
RISOE
MEAN

9203004B

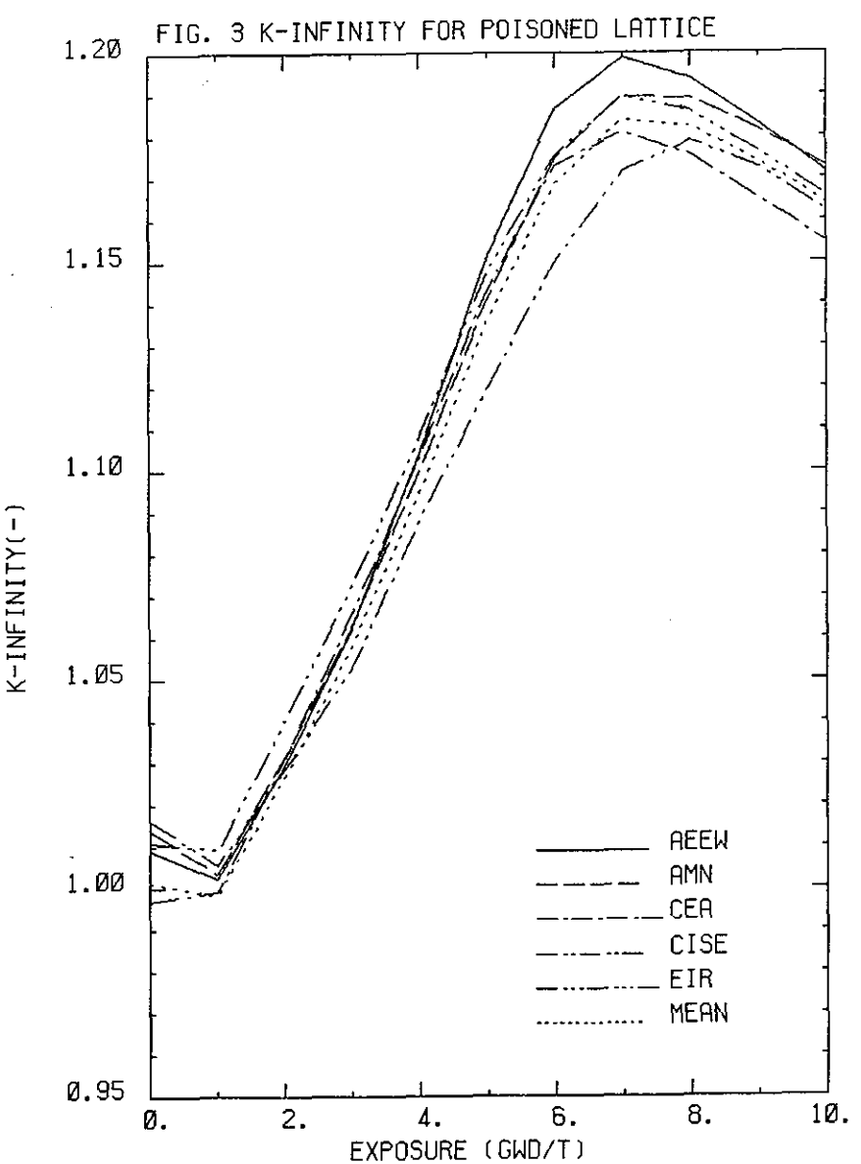


FIG. 3 K-INFINITY FOR POISONED LATTICE
K-INFINITY(-)
1.20
1.15
1.10
1.05
1.00
0.95
0.
2.
4.
6.
8.
10.
EXPOSURE (GWD/T)
AEEW
AMN
CEA
CISE
EIR
MEAN

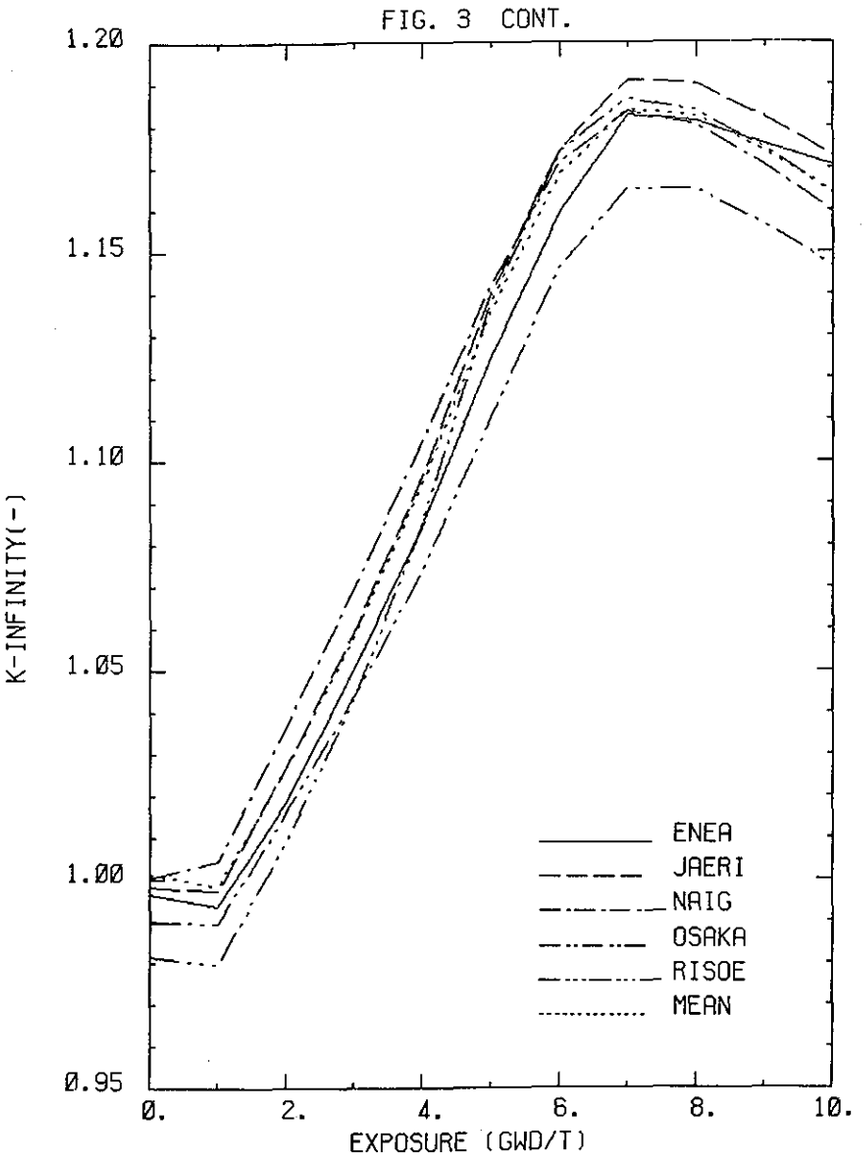


FIG. 3 CONT.
K-INFINITY(-)
1.20
1.15
1.10
1.05
1.00
0.95
0.
2.
4.
6.
8.
10.
EXPOSURE (GWD/T)
ENEA
JAERI
NAIG
OSAKA
RISOE
MEAN

9203004 9

9203050

FIG. 4 U-235 FOR REGULAR LATTICE

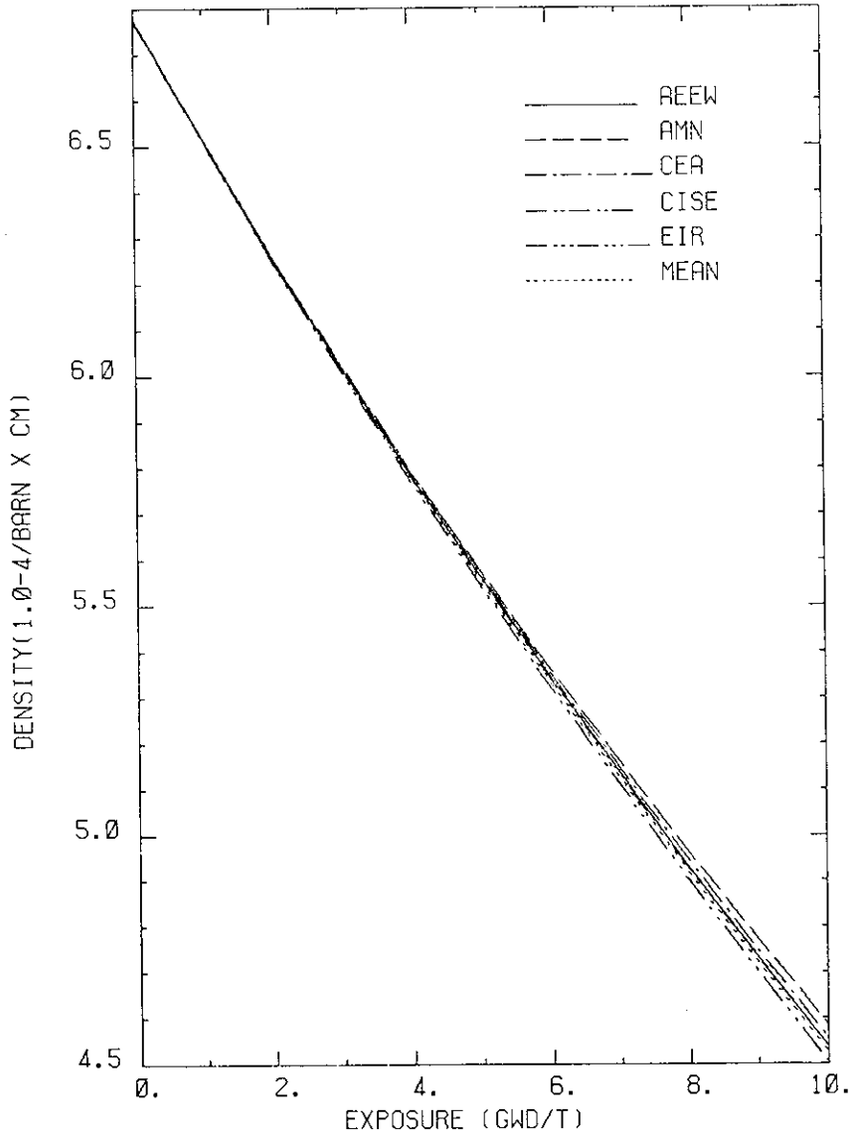


FIG. 4 CONT.

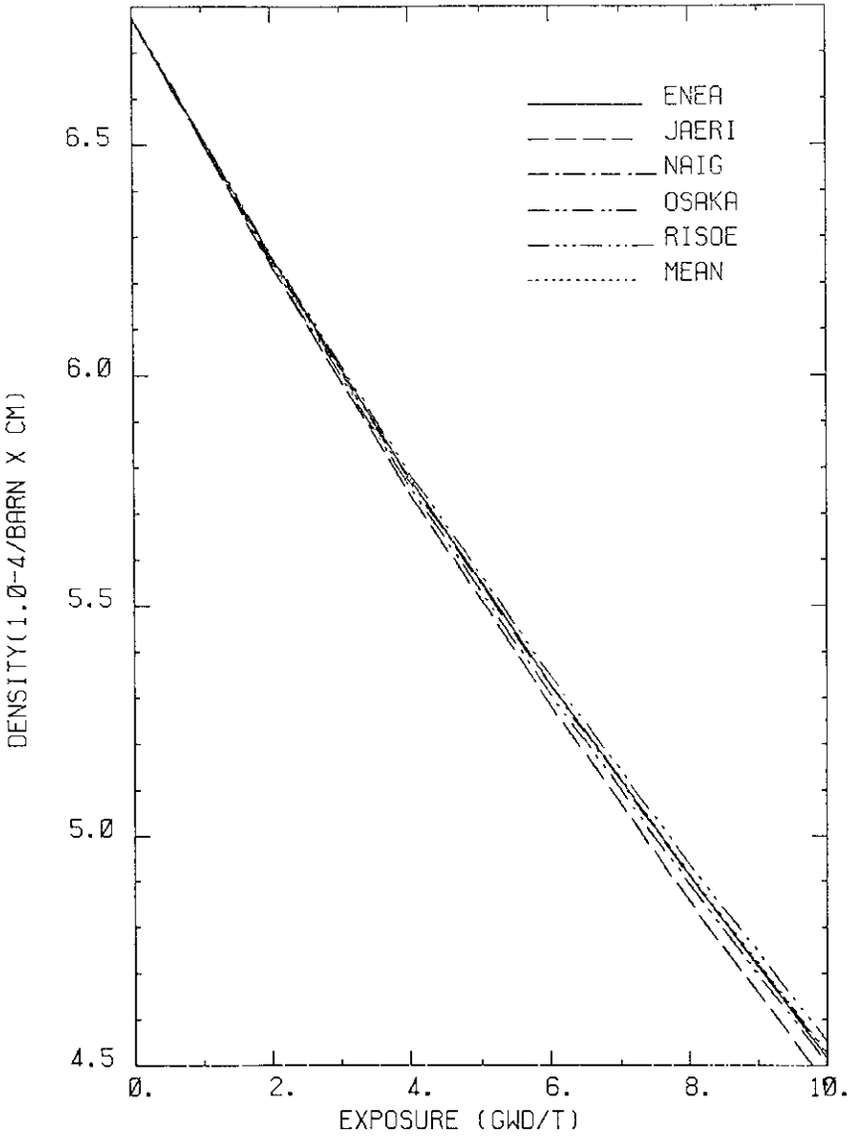


FIG. 5 U-235 IN POISONED PIN

FIG. 5 CONT.

9203051

9203052

FIG. 6 PU-239 FOR REGULAR LATTICE

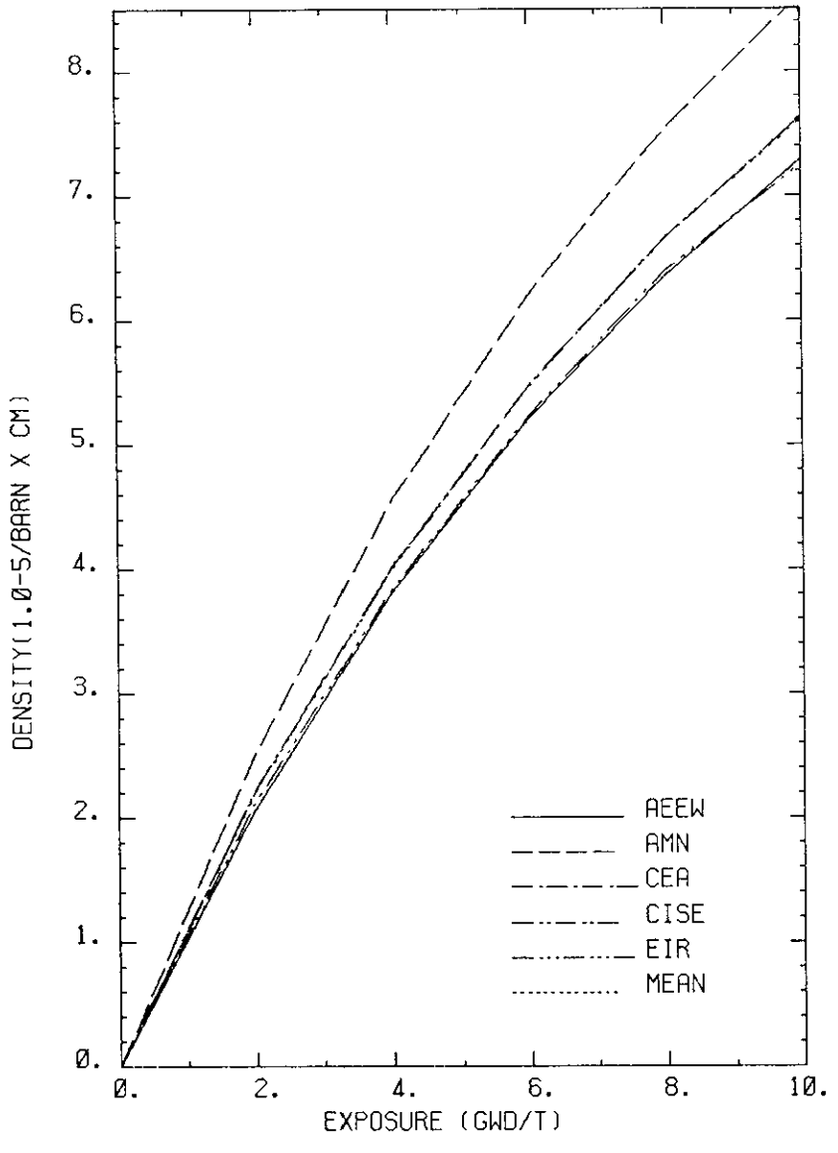


FIG. 6 CONT.

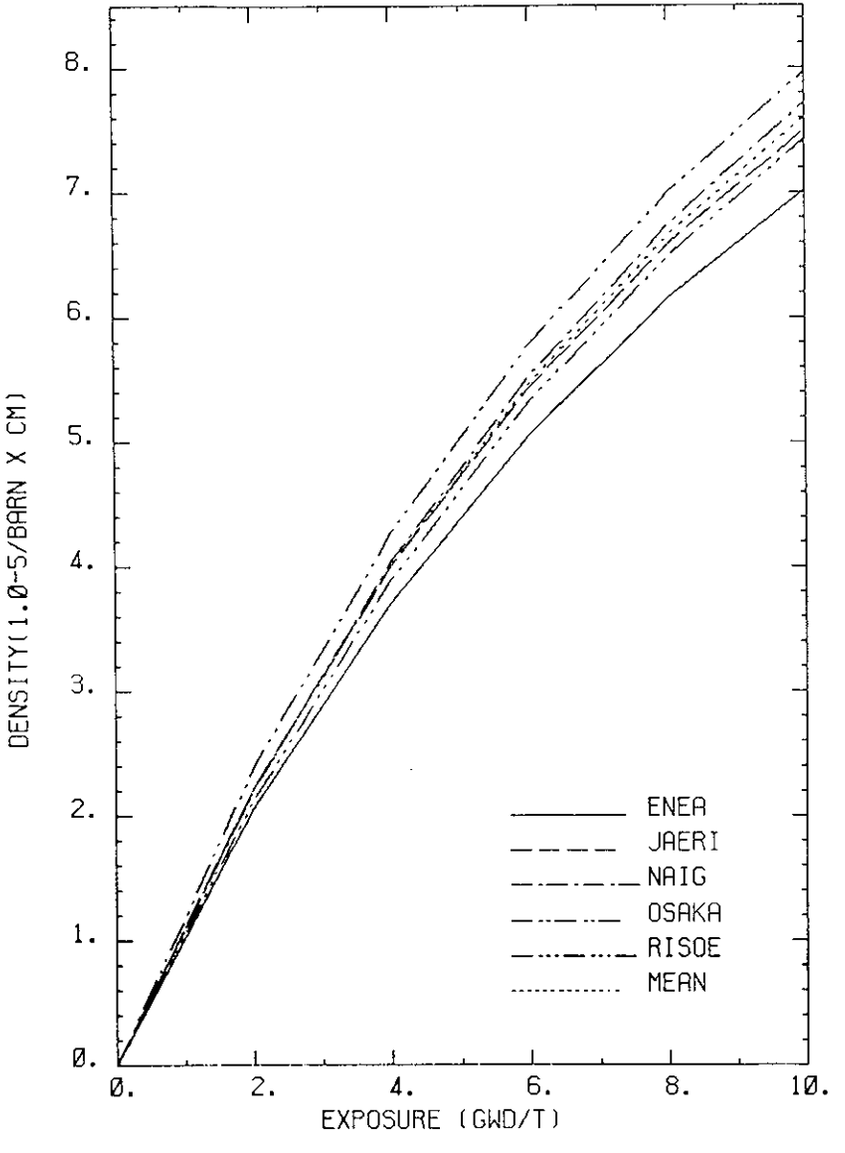


FIG. 7 PU-239 FOR POISONED PIN

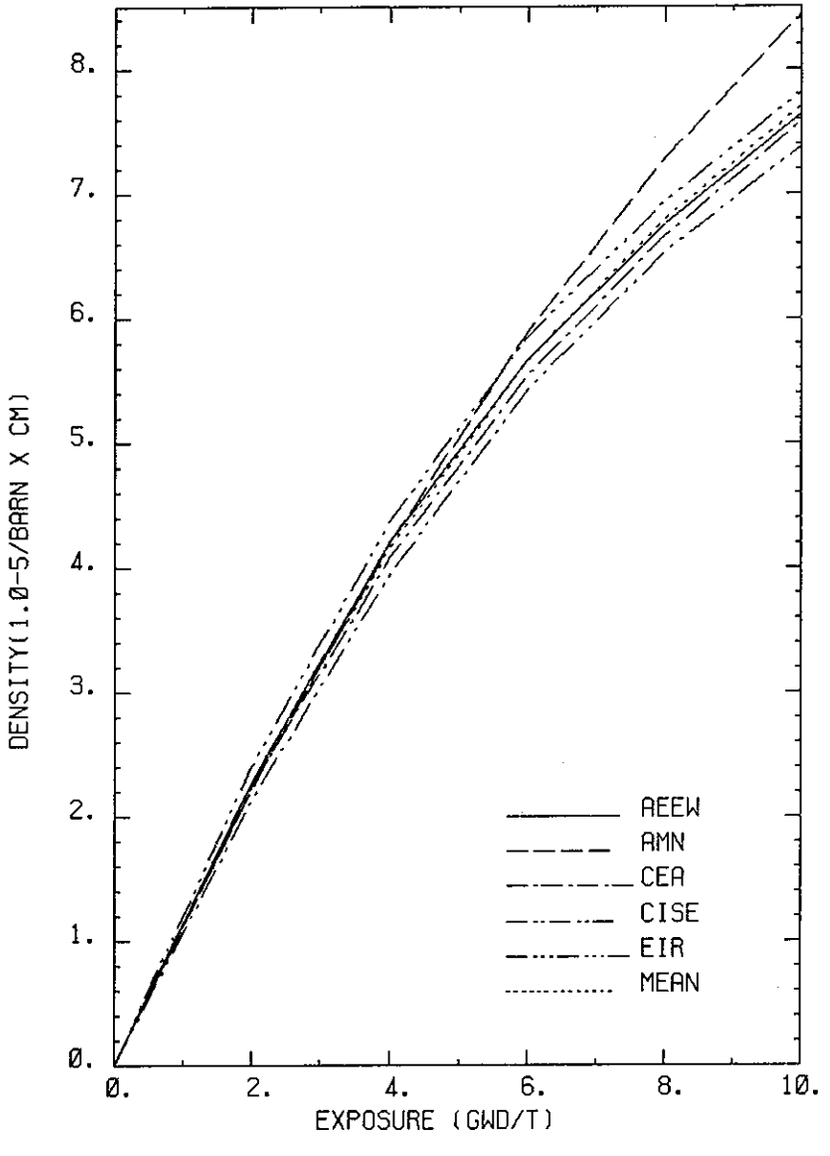
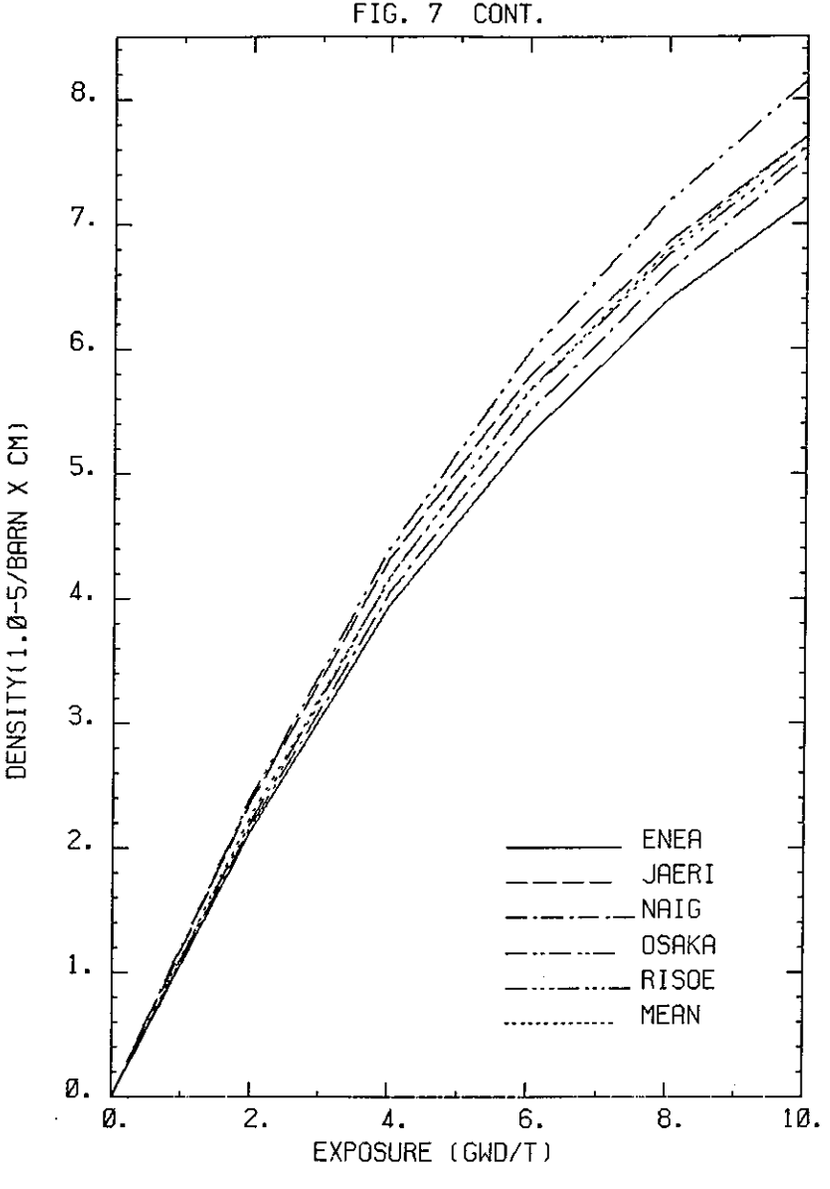


FIG. 7 CONT.



9203053

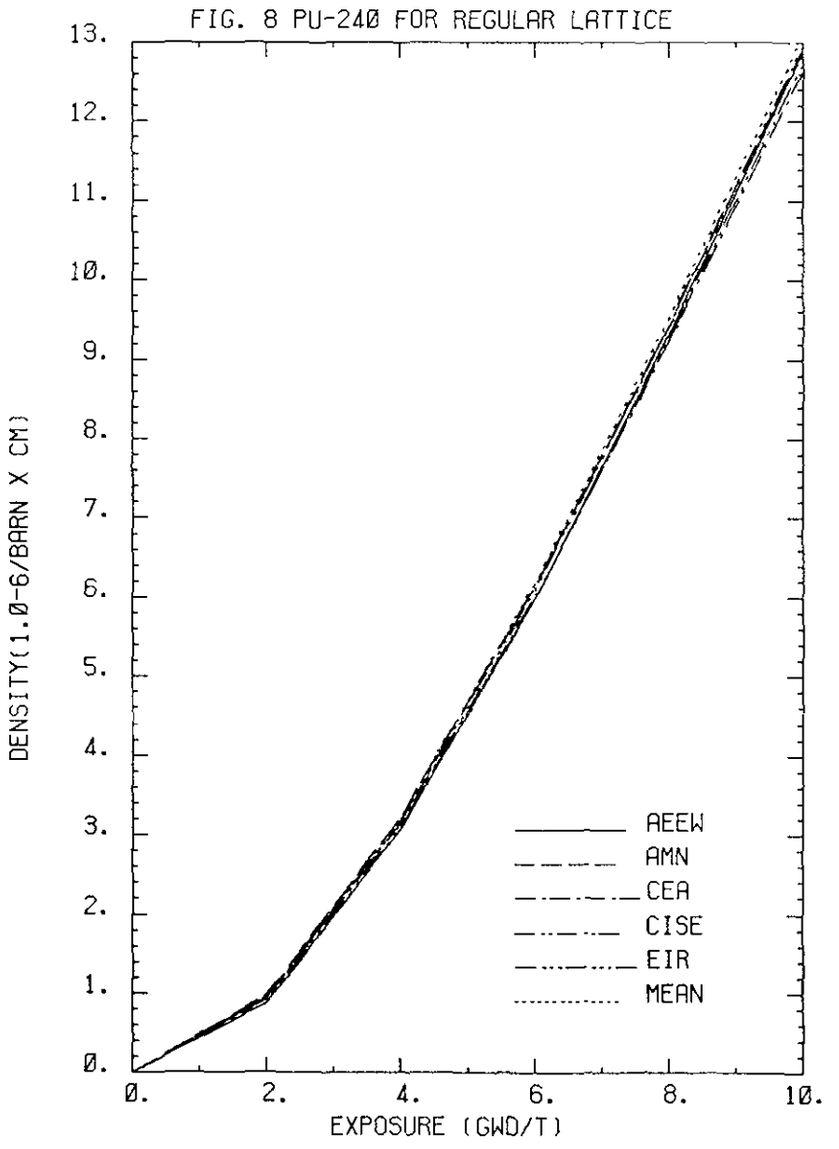


FIG. 8 PU-240 FOR REGULAR LATTICE
DENSITY(1.0-6/BARN X CM)
EXPOSURE (GWD/T)
AEEW
AMN
CEA
CISE
EIR
MEAN

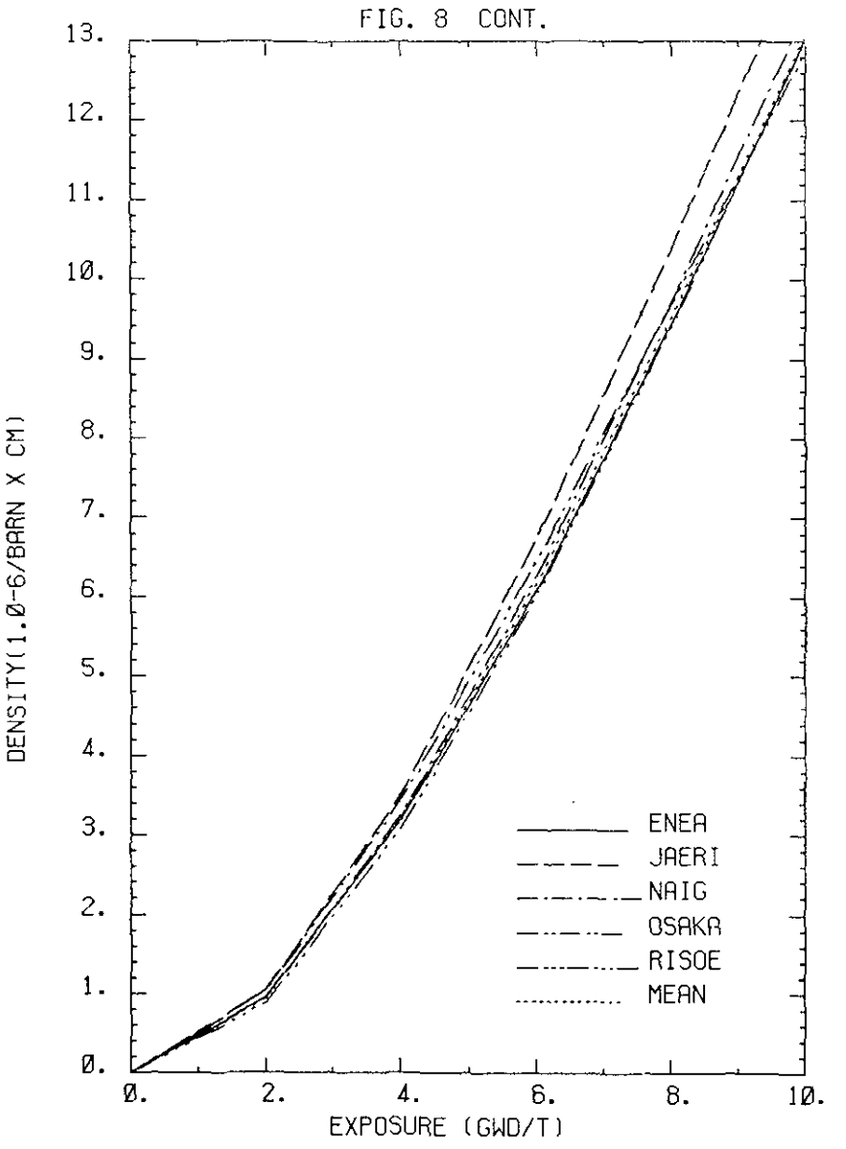


FIG. 8 CONT.
DENSITY(1.0-6/BARN X CM)
EXPOSURE (GWD/T)
ENEA
JAERI
NAIG
OSAKA
RISOE
MEAN

92030054

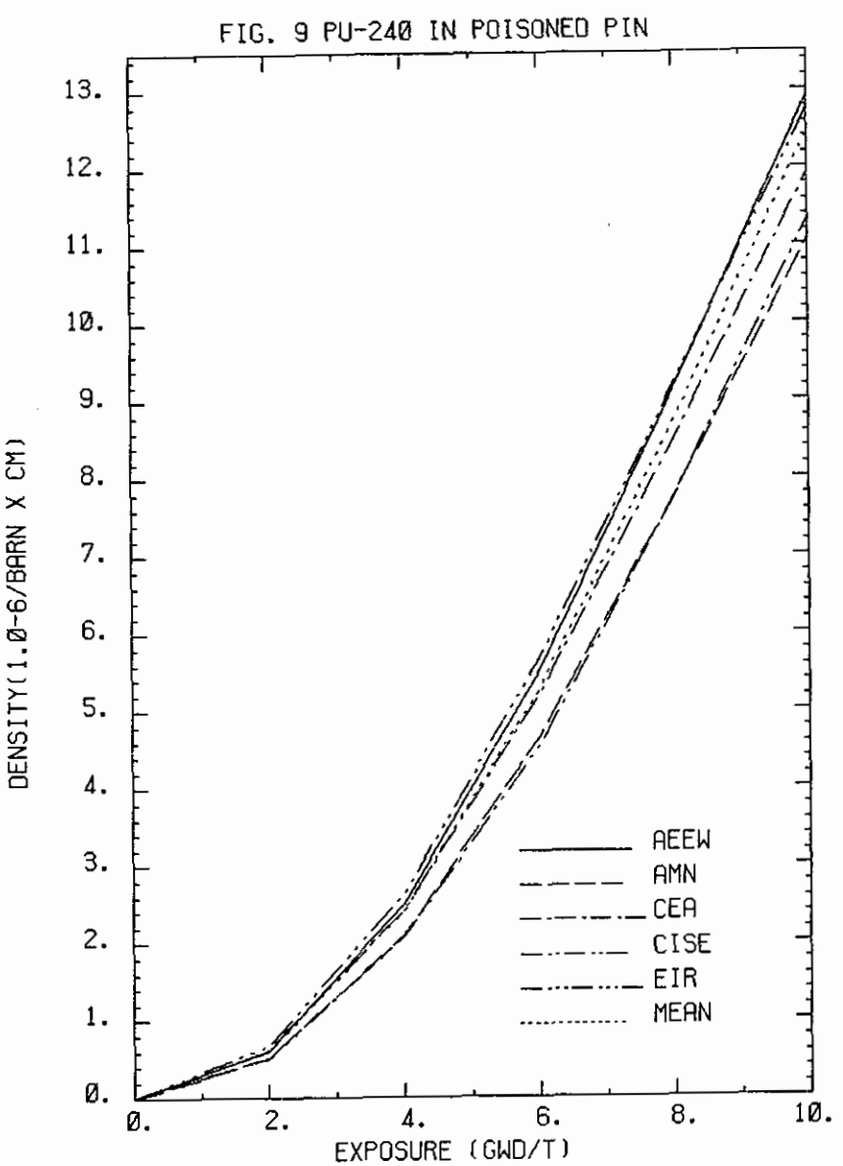


FIG. 9 PU-240 IN POISONED PIN
DENSITY(1.0-6/BARN X CM)
EXPOSURE (GWD/T)
0.
1.
2.
3.
4.
5.
6.
7.
8.
9.
10.
11.
12.
13.
0.
2.
4.
6.
8.
10.
AEEW
AMN
CEA
CISE
EIR
MEAN

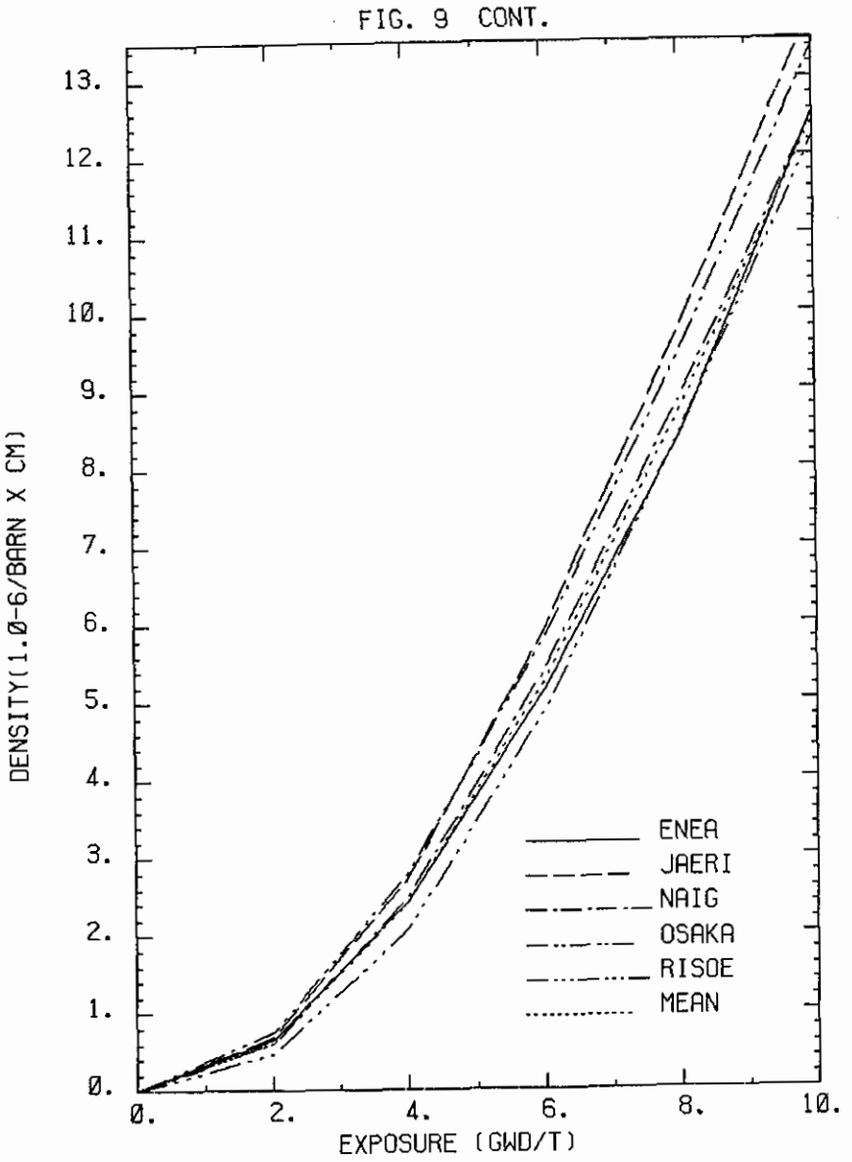


FIG. 9 CONT.
DENSITY(1.0-6/BARN X CM)
EXPOSURE (GWD/T)
0.
1.
2.
3.
4.
5.
6.
7.
8.
9.
10.
11.
12.
13.
0.
2.
4.
6.
8.
10.
ENEA
JAERI
NAIG
OSAKA
RISOE
MEAN

9203005

9200056

FIG.10 GD-155 IN POISONED PIN

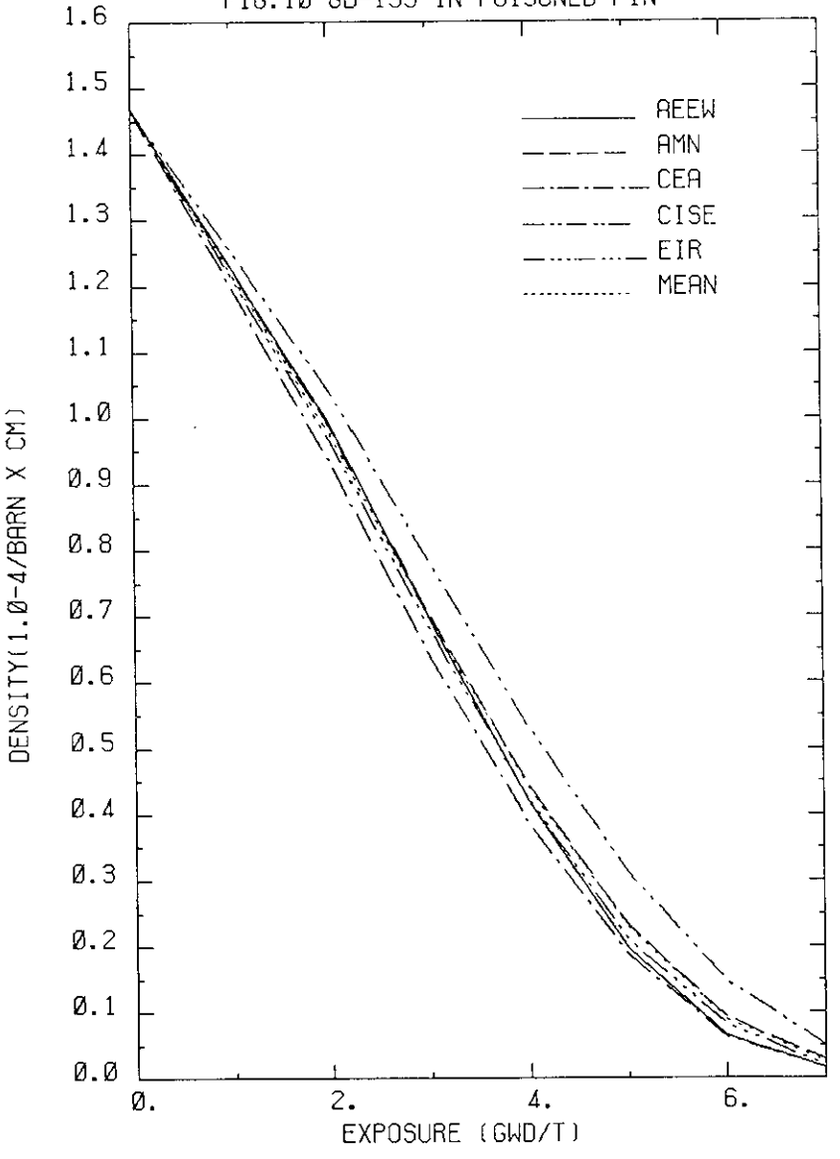
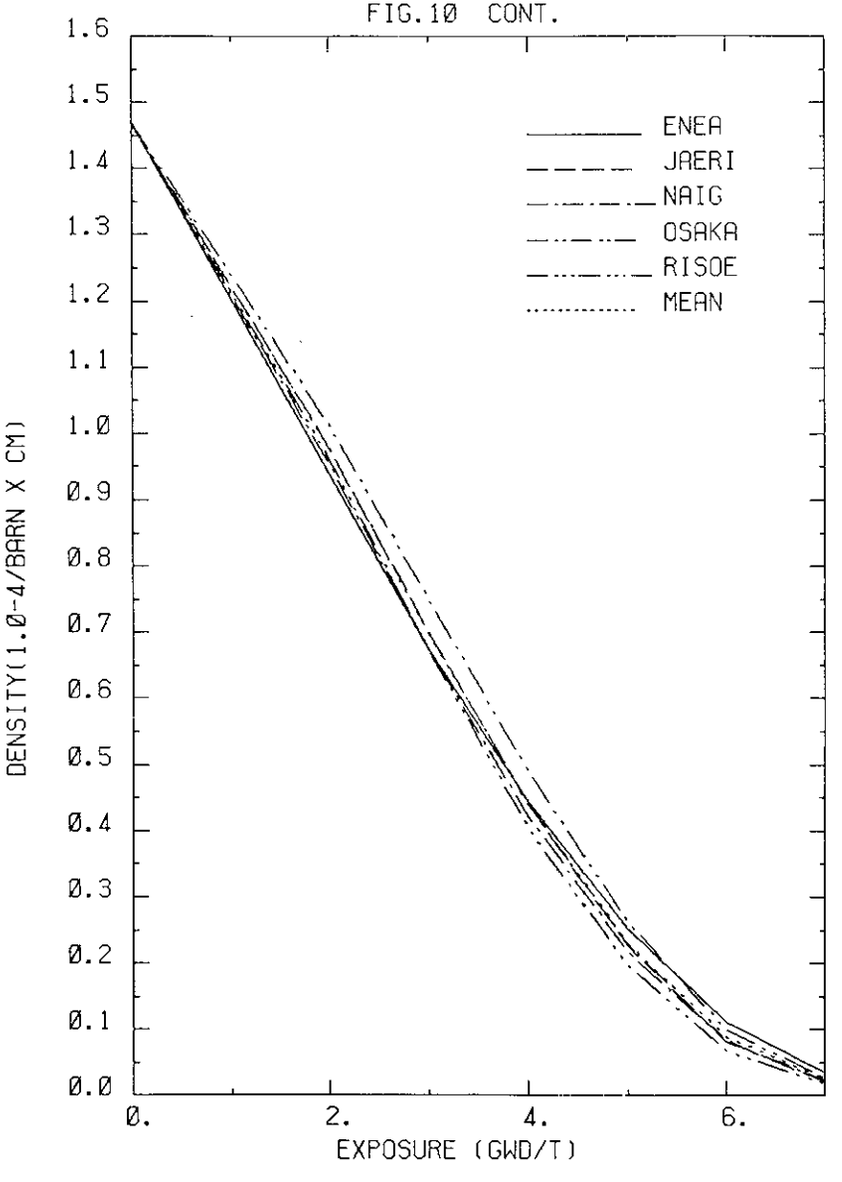


FIG.10 CONT.



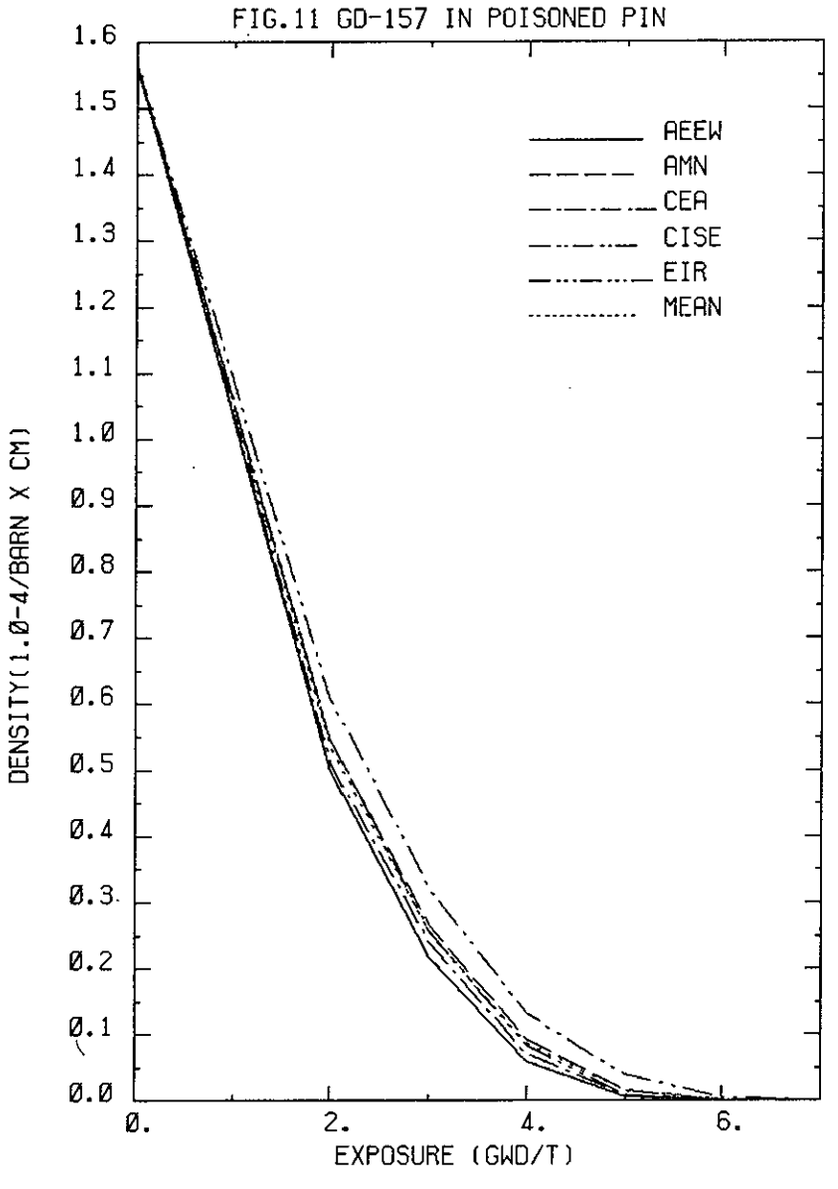


FIG.11 GD-157 IN POISONED PIN
DENSITY(1.Ø-4/BARN X CM)
EXPOSURE (GWD/T)
AEEW
AMN
CEA
CISE
EIR
MEAN
1.6
1.5
1.4
1.3
1.2
1.1
1.Ø
Ø.9
Ø.8
Ø.7
Ø.6
Ø.5
Ø.4
Ø.3
Ø.2
Ø.1
Ø.0
Ø.
2.
4.
6.

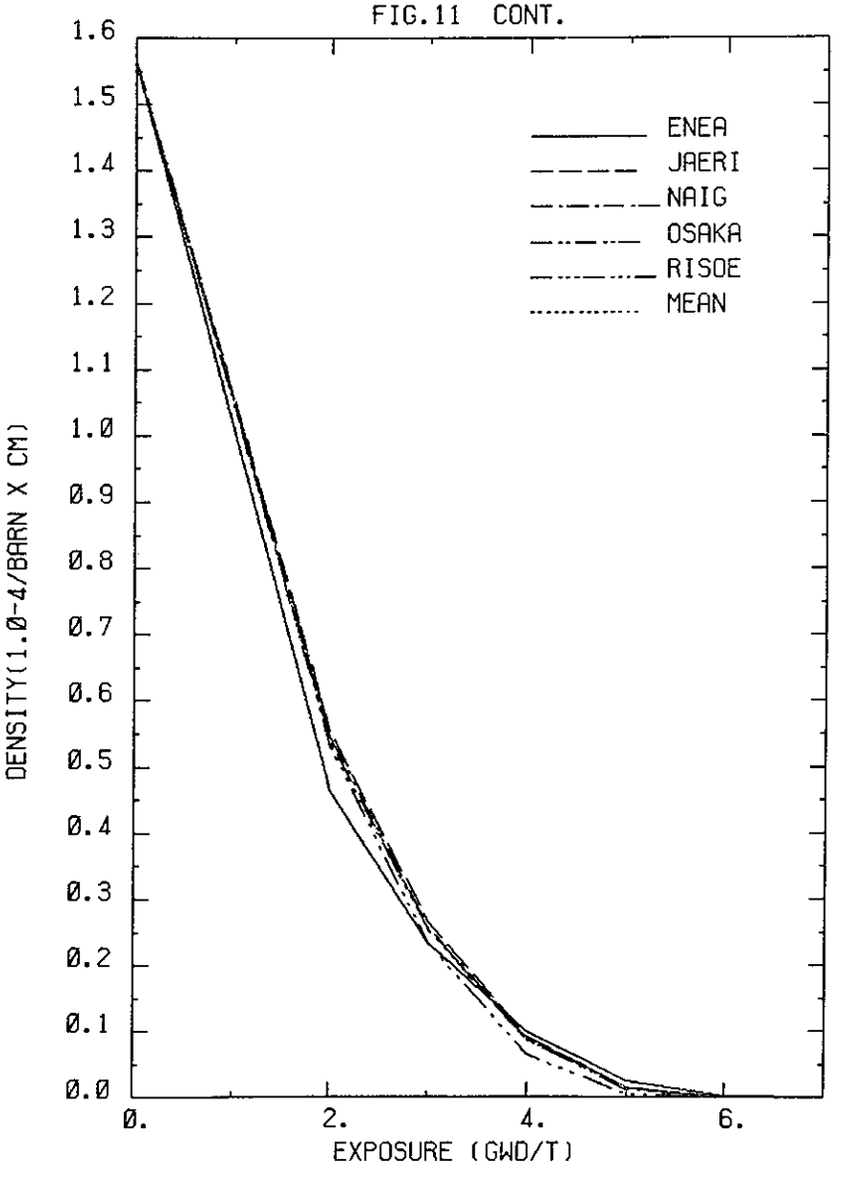


FIG.11 CONT.
DENSITY(1.Ø-4/BARN X CM)
EXPOSURE (GWD/T)
ENEA
JAERI
NAIG
OSAKA
RISOE
MEAN
1.6
1.5
1.4
1.3
1.2
1.1
1.Ø
Ø.9
Ø.8
Ø.7
Ø.6
Ø.5
Ø.4
Ø.3
Ø.2
Ø.1
Ø.0
Ø.
2.
4.
6.

9203005?

9202005 8

FIG.12 POWER IN PIN 4

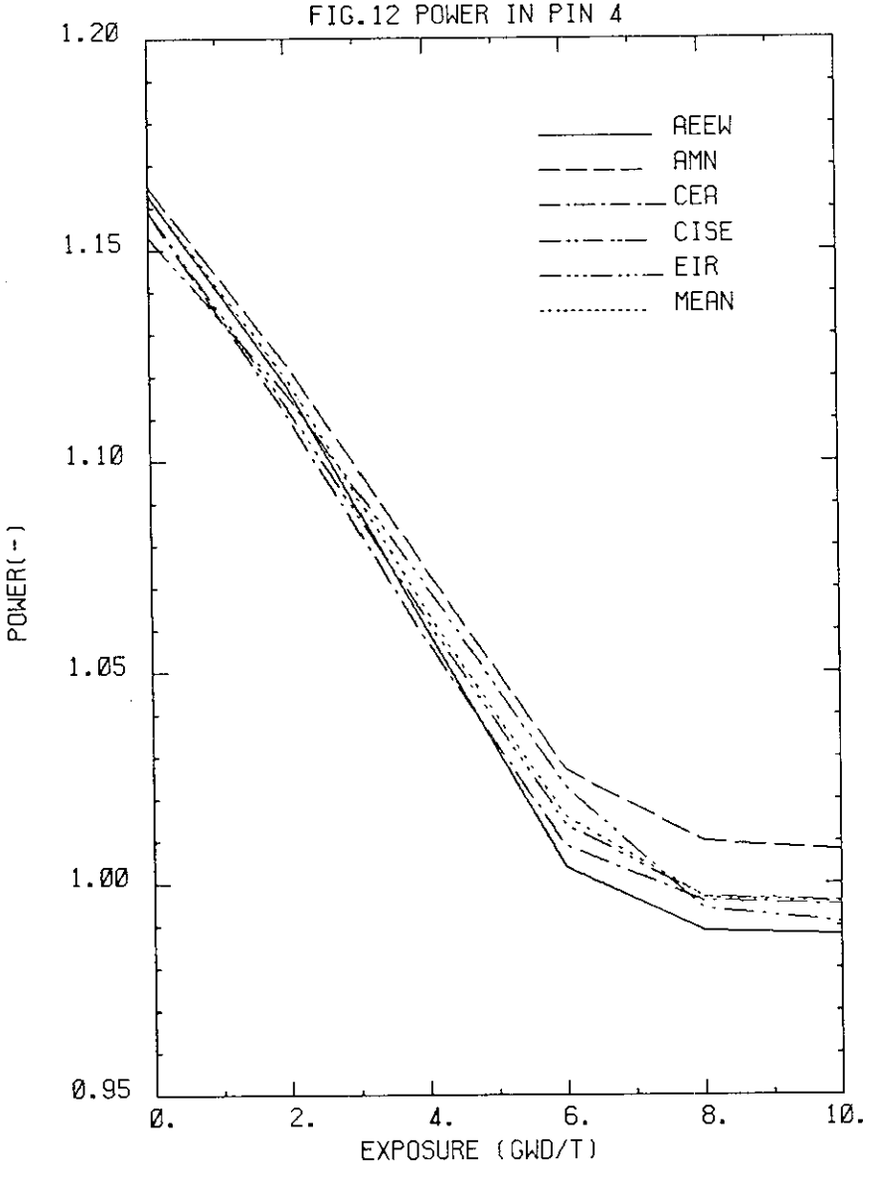


FIG.12 CONT.

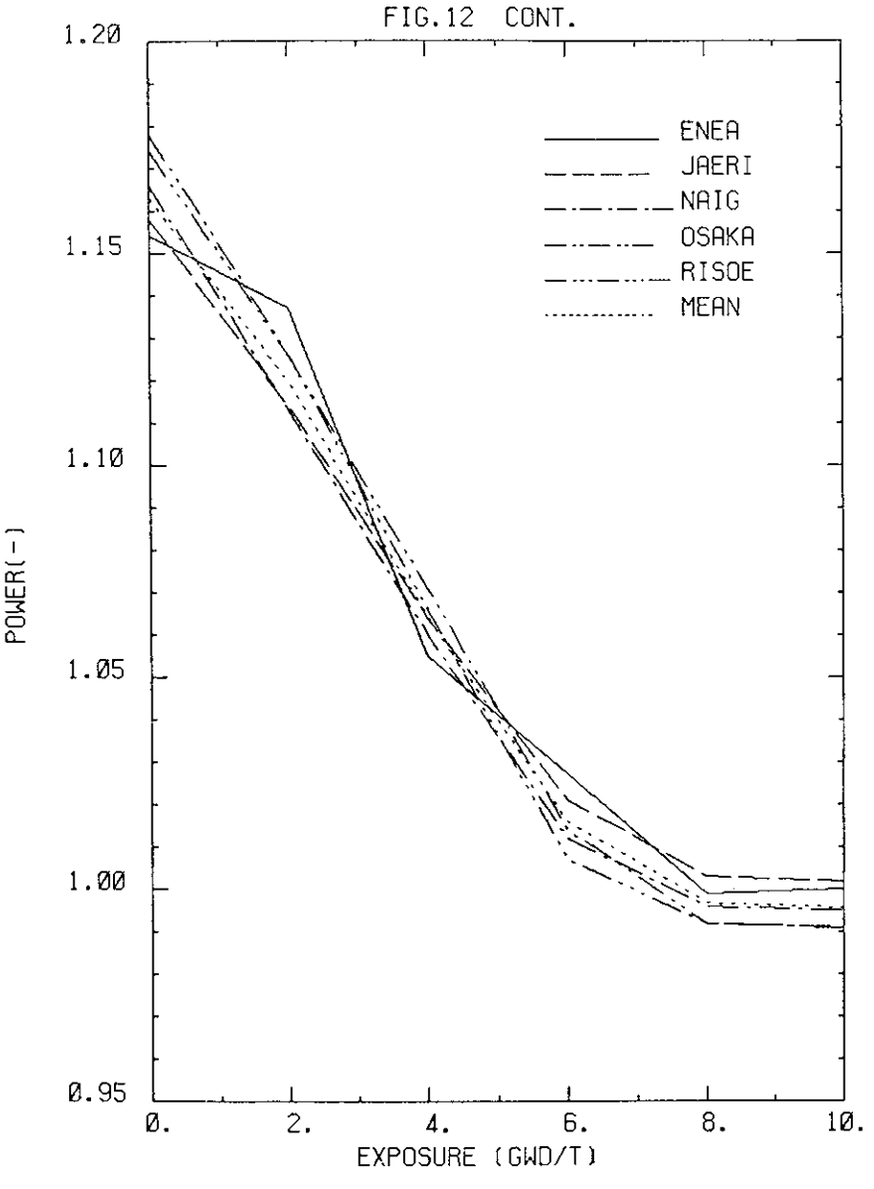


FIG.13 POWER IN PIN 6
POWER(-)
EXPOSURE (GWD/T)
AEEW
AMN
CEA
CISE
EIR
MEAN

FIG.13 CONT.
POWER(-)
EXPOSURE (GWD/T)
ENEA
JAERI
NAIG
OSAKA
RISOE
MEAN

9203059

FIG.14 RAD. GD-155 DISTRIBUTION AT 2 GWD/T

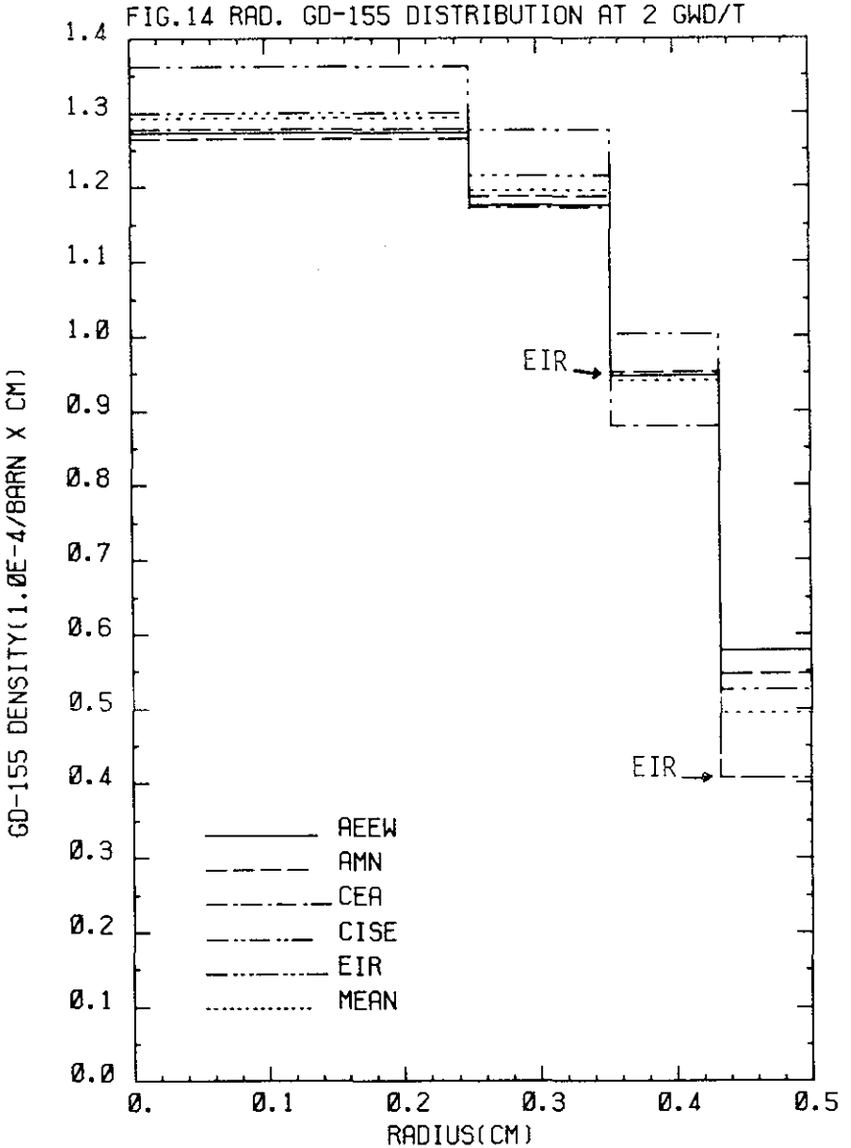
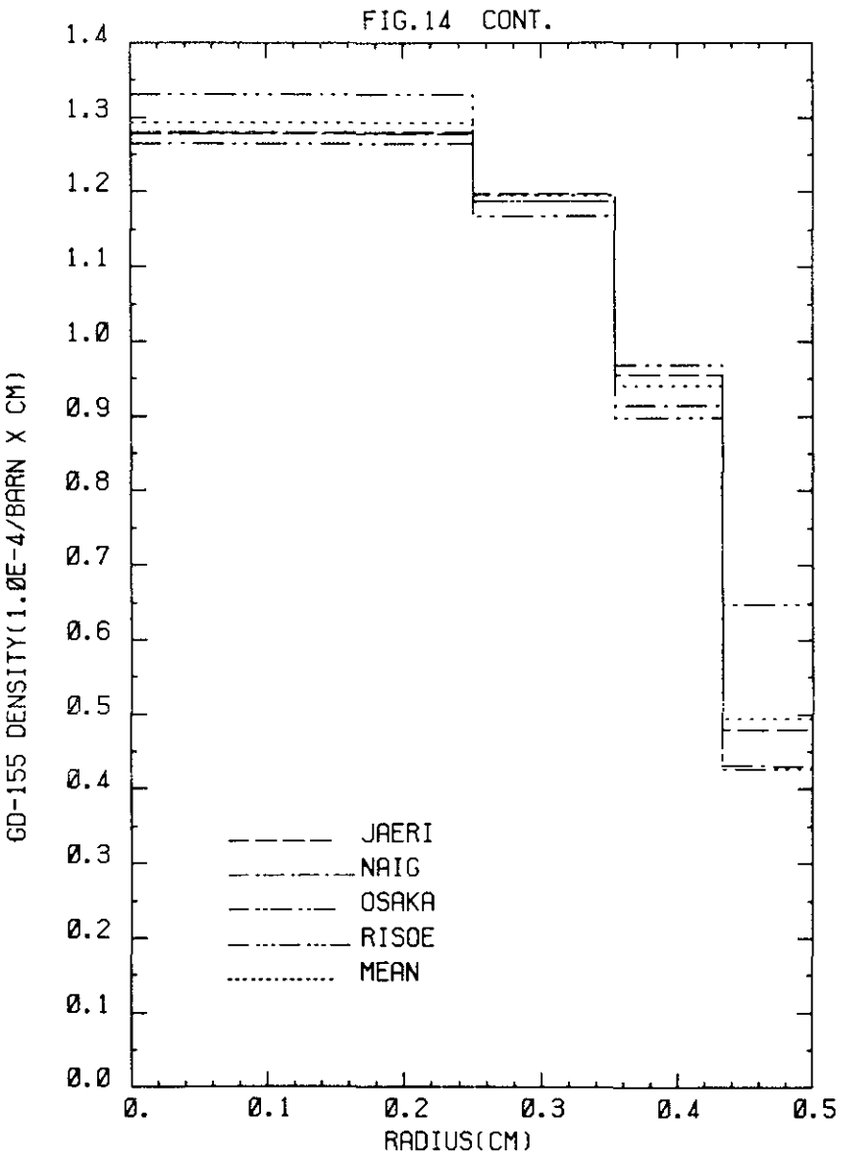


FIG.14 CONT.



92030060

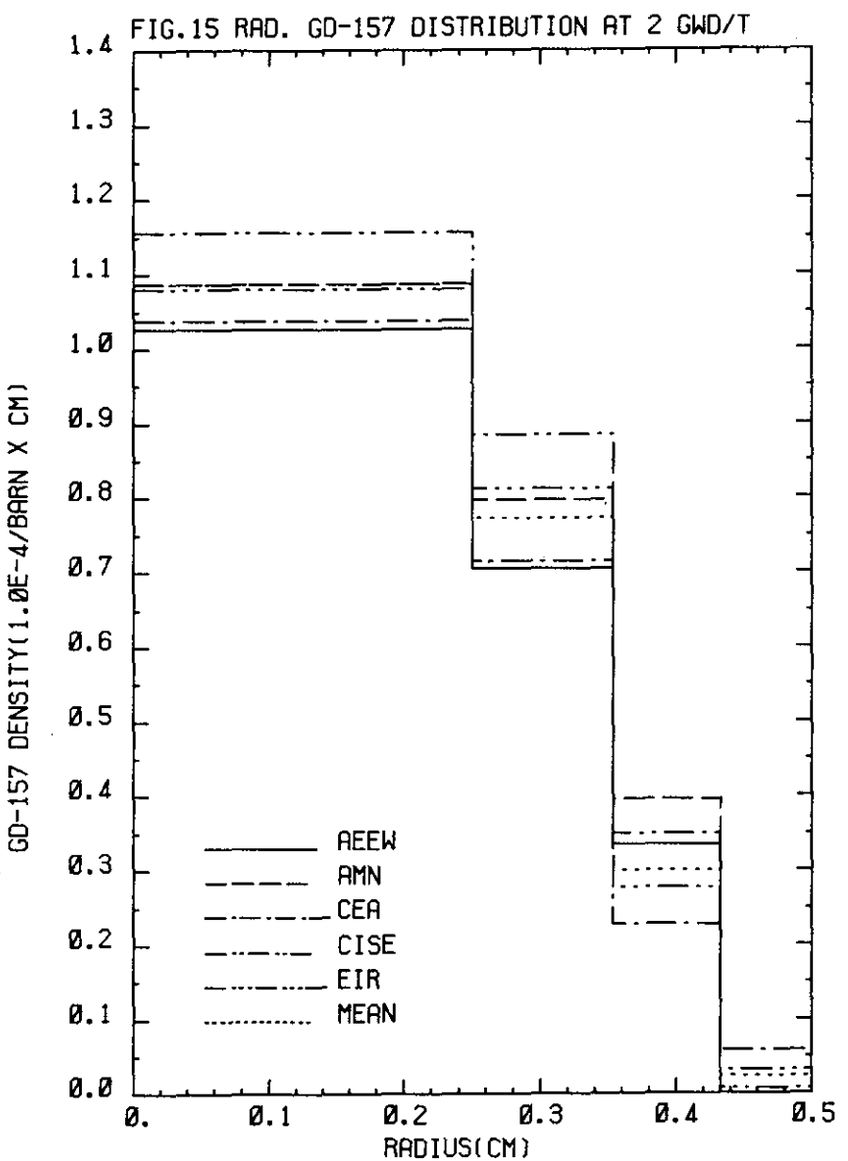


FIG.15 RAD. GD-157 DISTRIBUTION AT 2 GWD/T
GD-157 DENSITY(1.0E-4/BARN X CM)
RADIUS(CM)
AEEW
AMN
CEA
CISE
EIR
MEAN

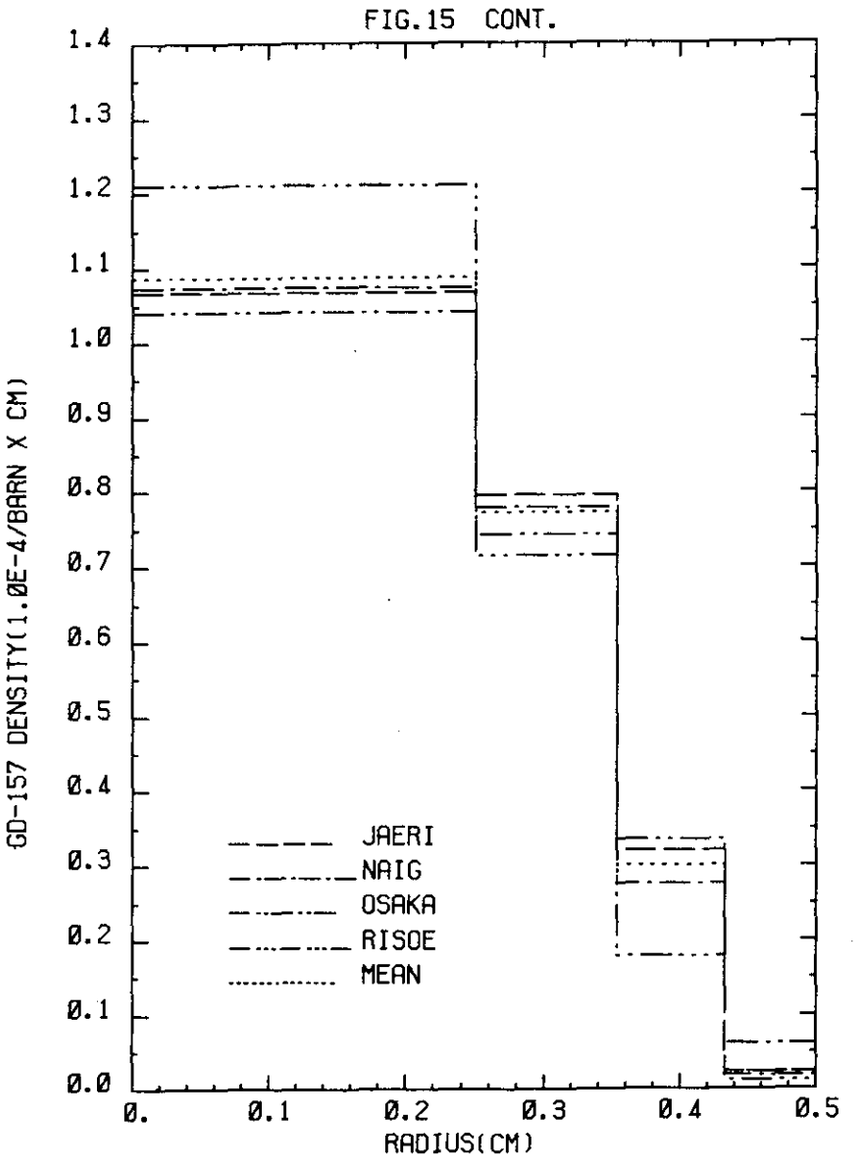


FIG.15 CONT.
GD-157 DENSITY(1.0E-4/BARN X CM)
RADIUS(CM)
JAERI
NAIG
OSAKA
RISOE
MEAN

9203006 1

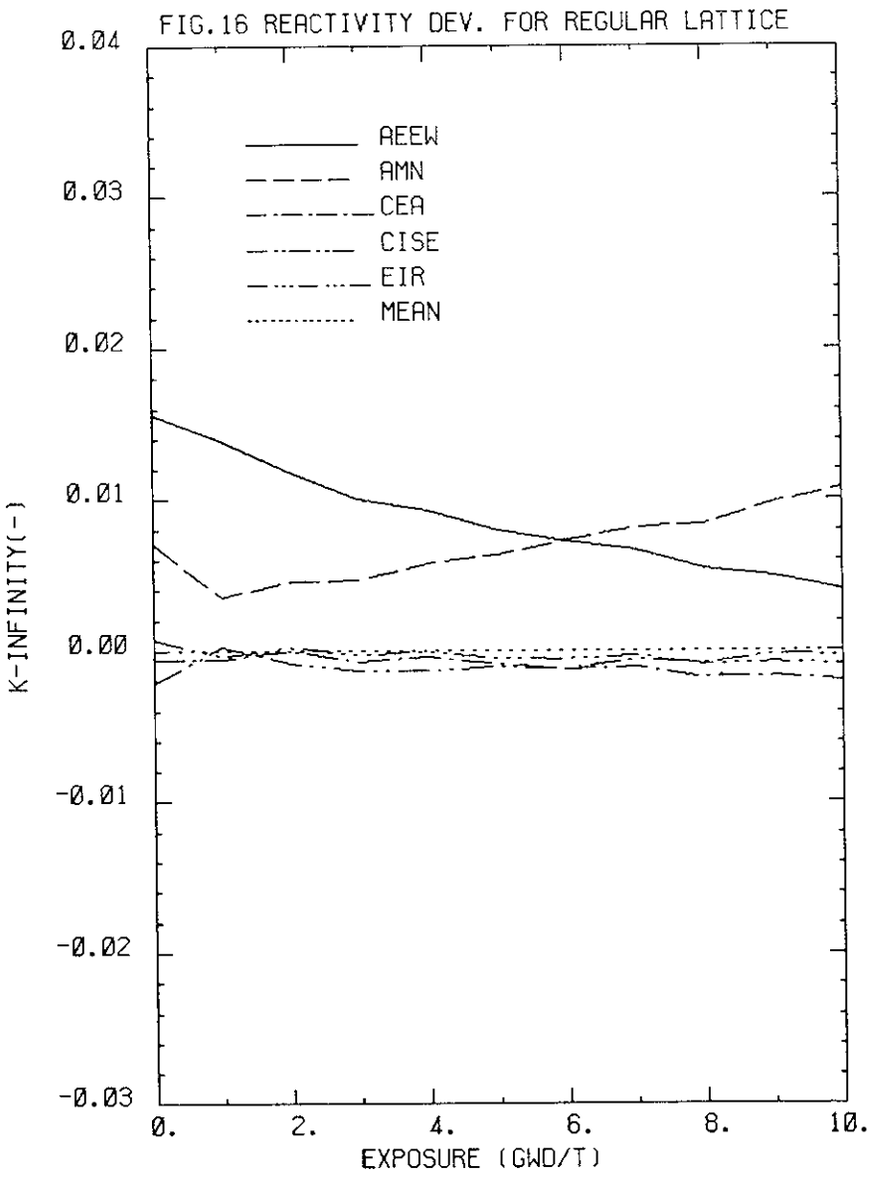


FIG.16 REACTIVITY DEV. FOR REGULAR LATTICE
AEEW
AMN
CEA
CISE
EIR
MEAN
0.04
0.03
0.02
0.01
0.00
-0.01
-0.02
-0.03
K-INFINITY(-)
0.
2.
4.
6.
8.
10.
EXPOSURE (GWD/T)

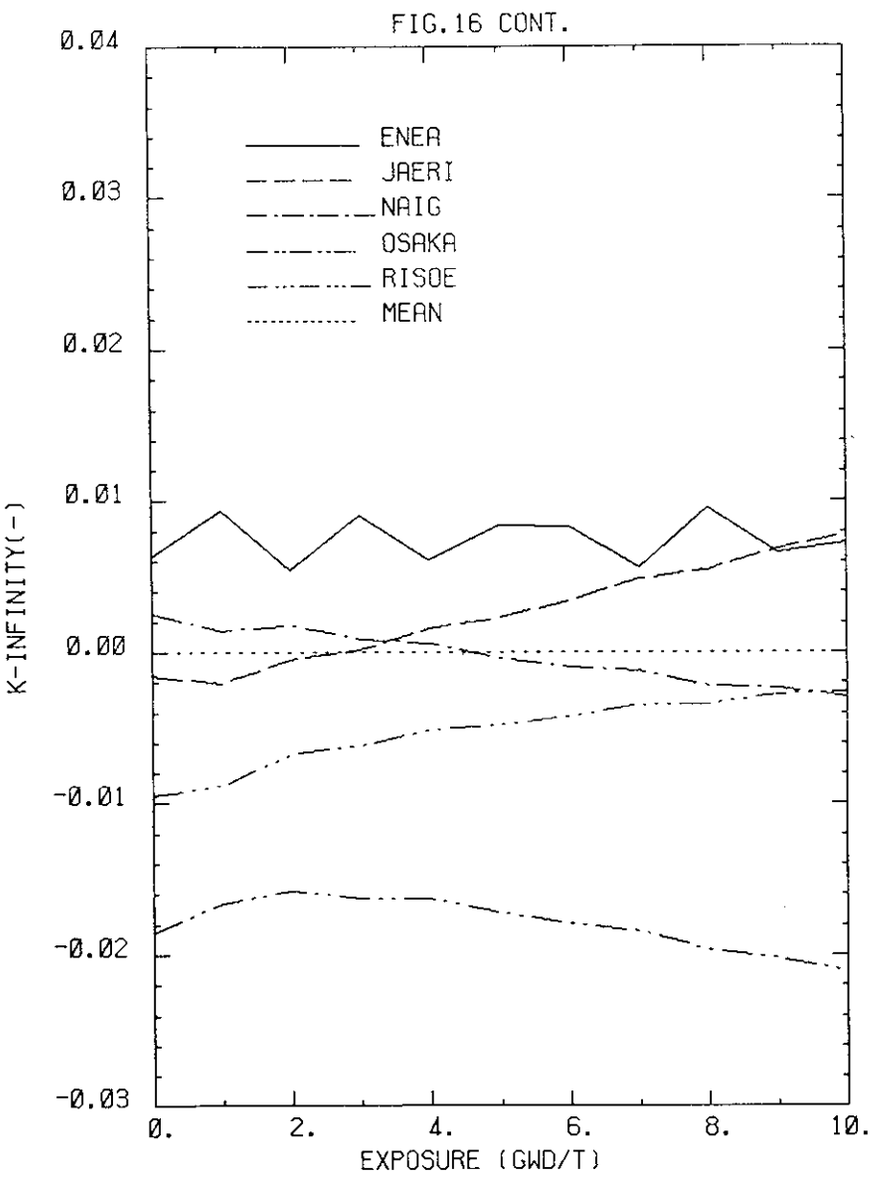


FIG.16 CONT.
ENEA
JAERI
NAIG
OSAKA
RISOE
MEAN
0.04
0.03
0.02
0.01
0.00
-0.01
-0.02
-0.03
K-INFINITY(-)
0.
2.
4.
6.
8.
10.
EXPOSURE (GWD/T)

9203006 2

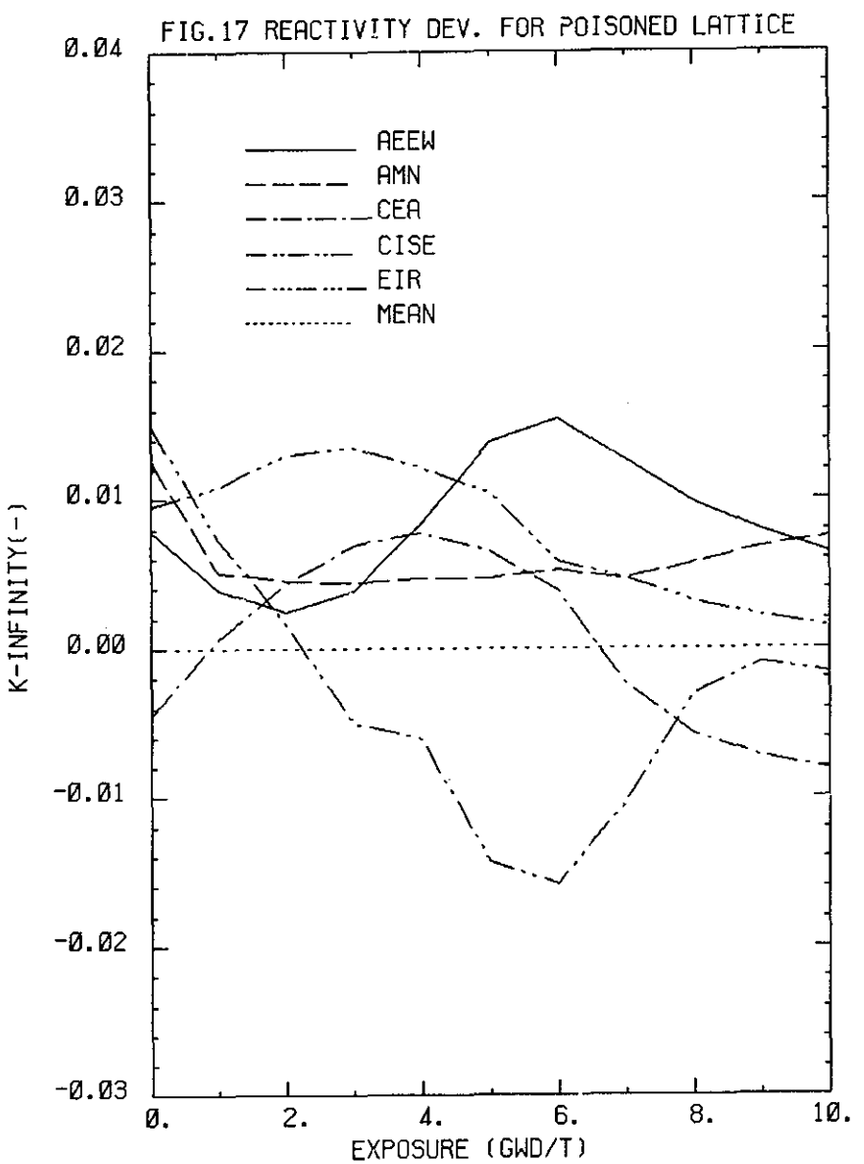


FIG.17 REACTIVITY DEV. FOR POISONED LATTICE
AEEW
AMN
CEA
CISE
EIR
MEAN
K-INFINITY(-)
0.04
0.03
0.02
0.01
0.00
-0.01
-0.02
-0.03
0.
2.
4.
6.
8.
10.
EXPOSURE (GWD/T)

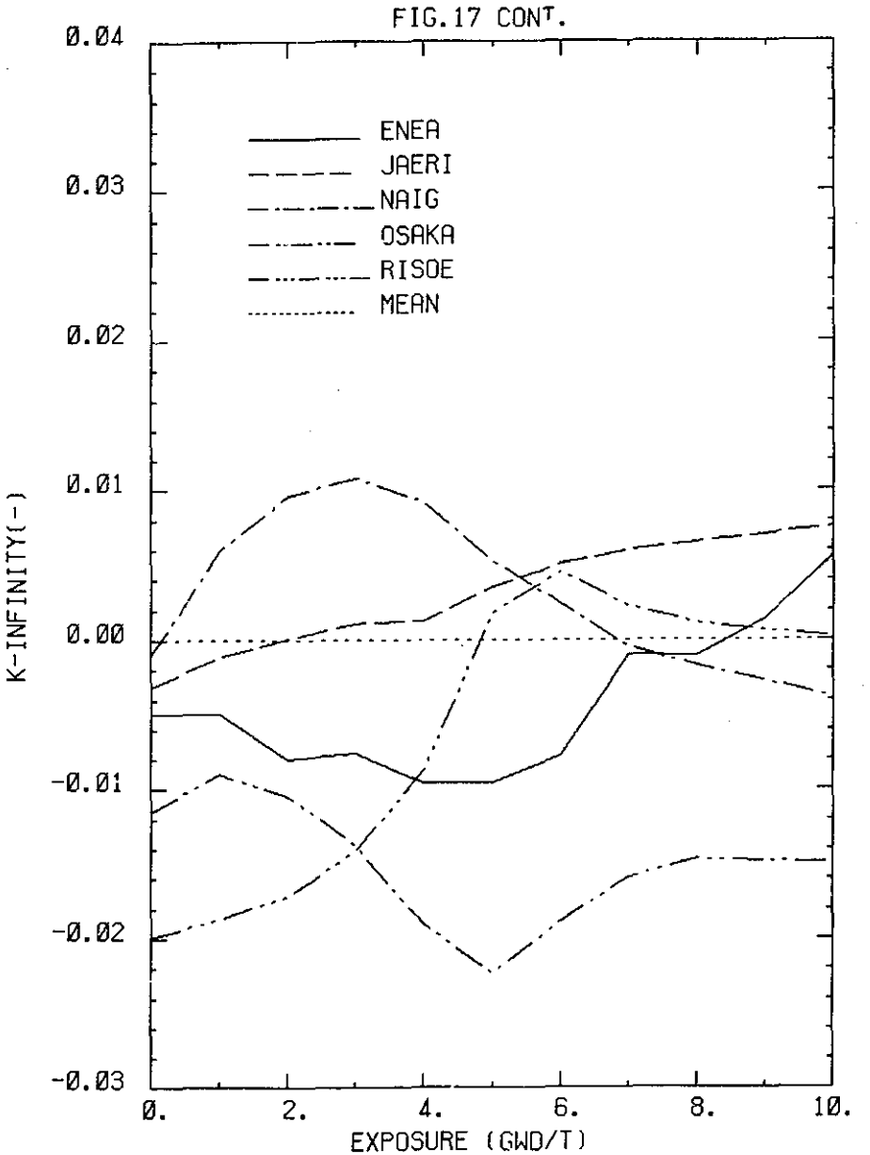


FIG.17 CONT.
ENEA
JAERI
NAIG
OSAKA
RISOE
MEAN
K-INFINITY(-)
0.04
0.03
0.02
0.01
0.00
-0.01
-0.02
-0.03
0.
2.
4.
6.
8.
10.
EXPOSURE (GWD/T)

9203006 3

9203006 4

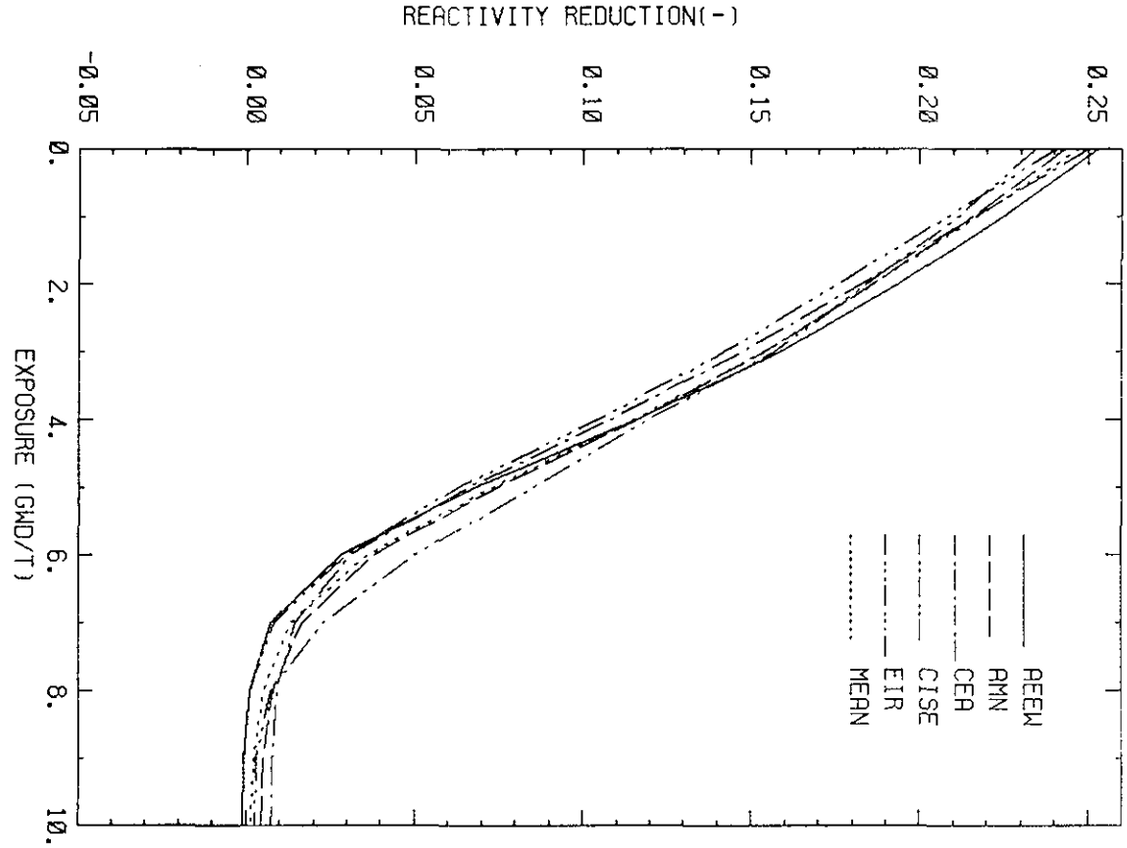


FIG.18 GD-REACTIVITY WORTH

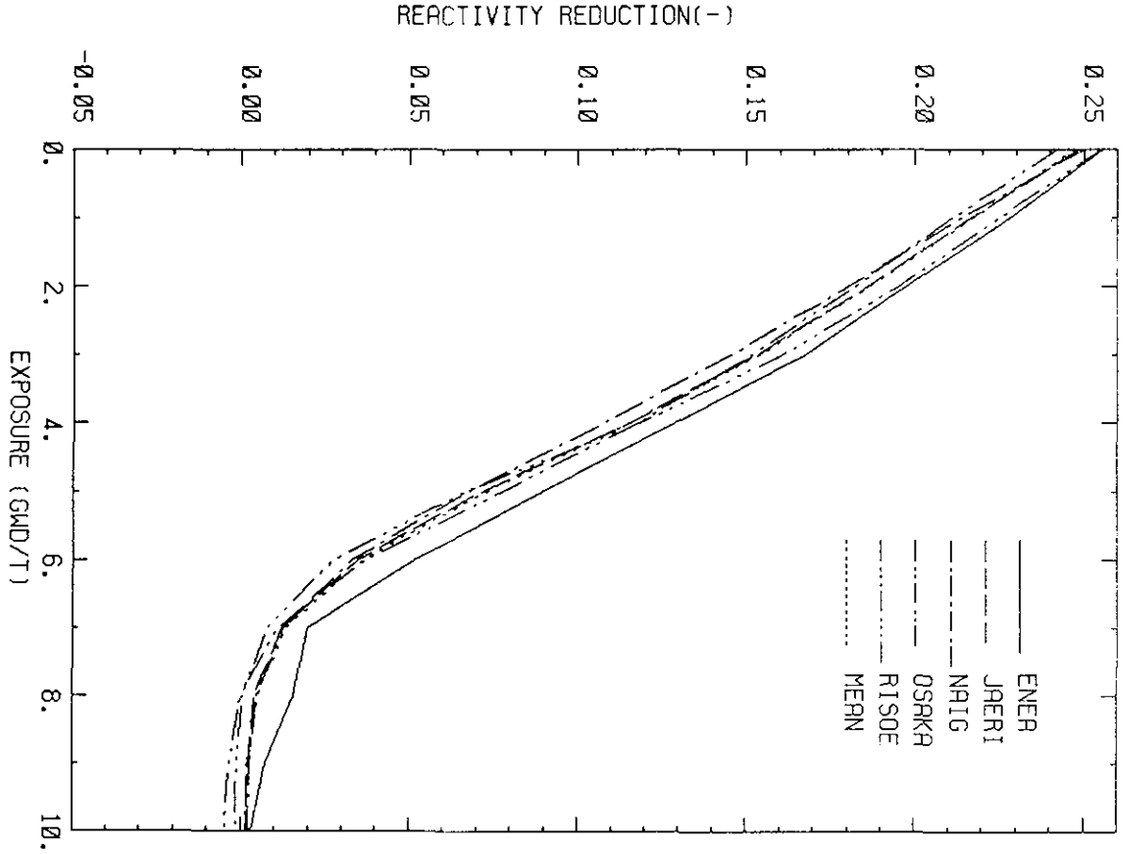


FIG.18 CONT.

FIG.19 GD-DESTRUCTION IN POISONED PIN

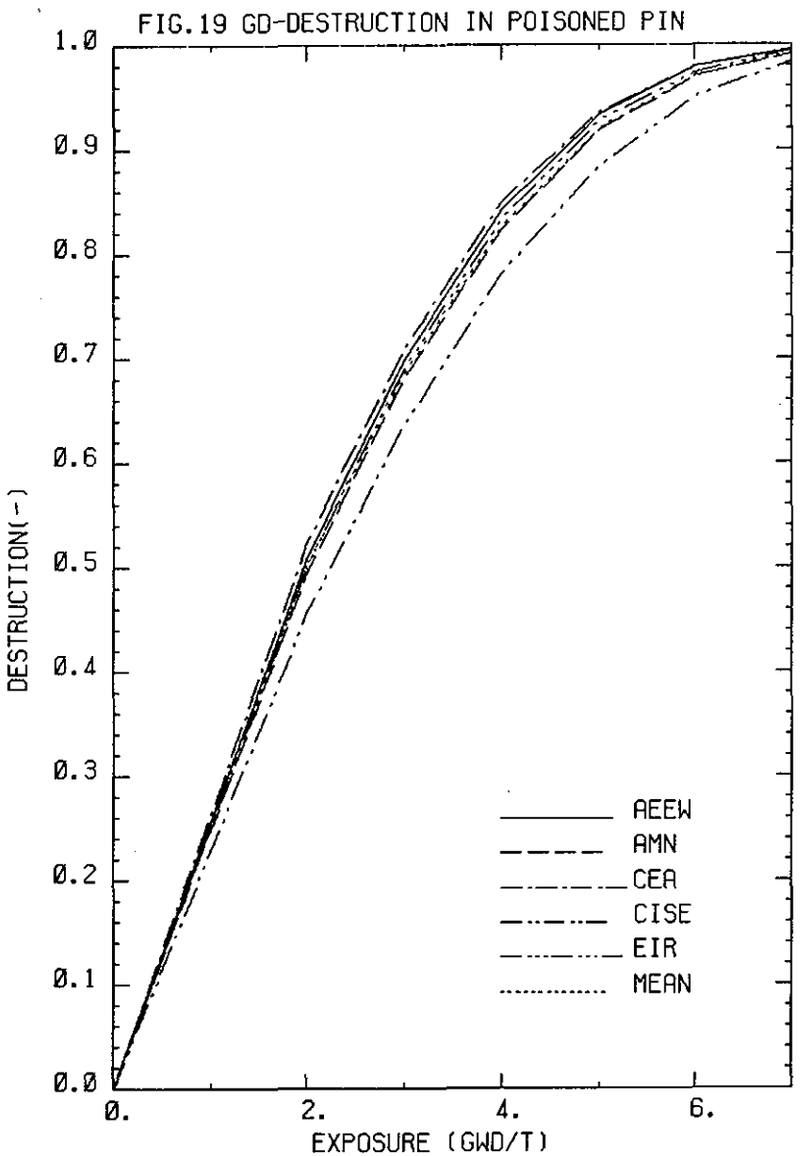
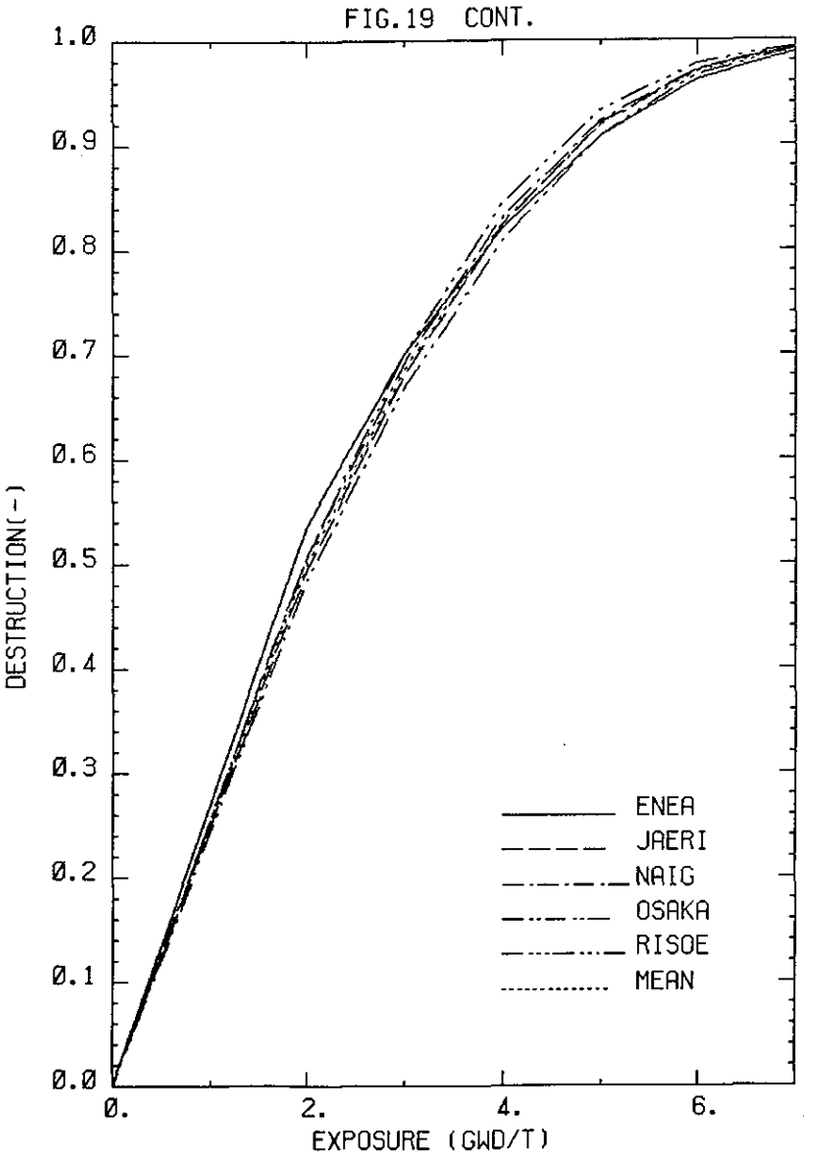


FIG.19 CONT.



92030065

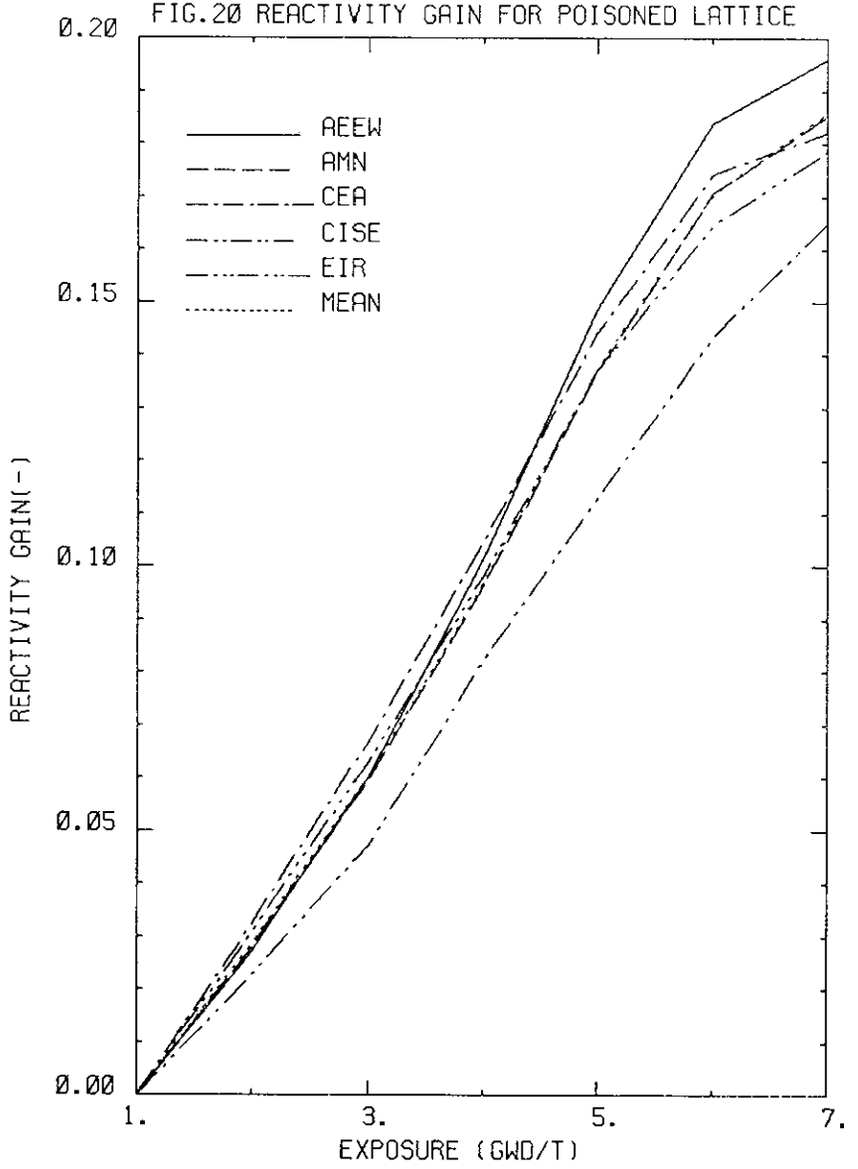


FIG.20 REACTIVITY GAIN FOR POISONED LATTICE
0.20
0.15
0.10
0.05
0.00
REACTIVITY GAIN(-)
AEEW
AMN
CEA
CISE
EIR
MEAN
1.
3.
5.
7.
EXPOSURE (GWD/T)

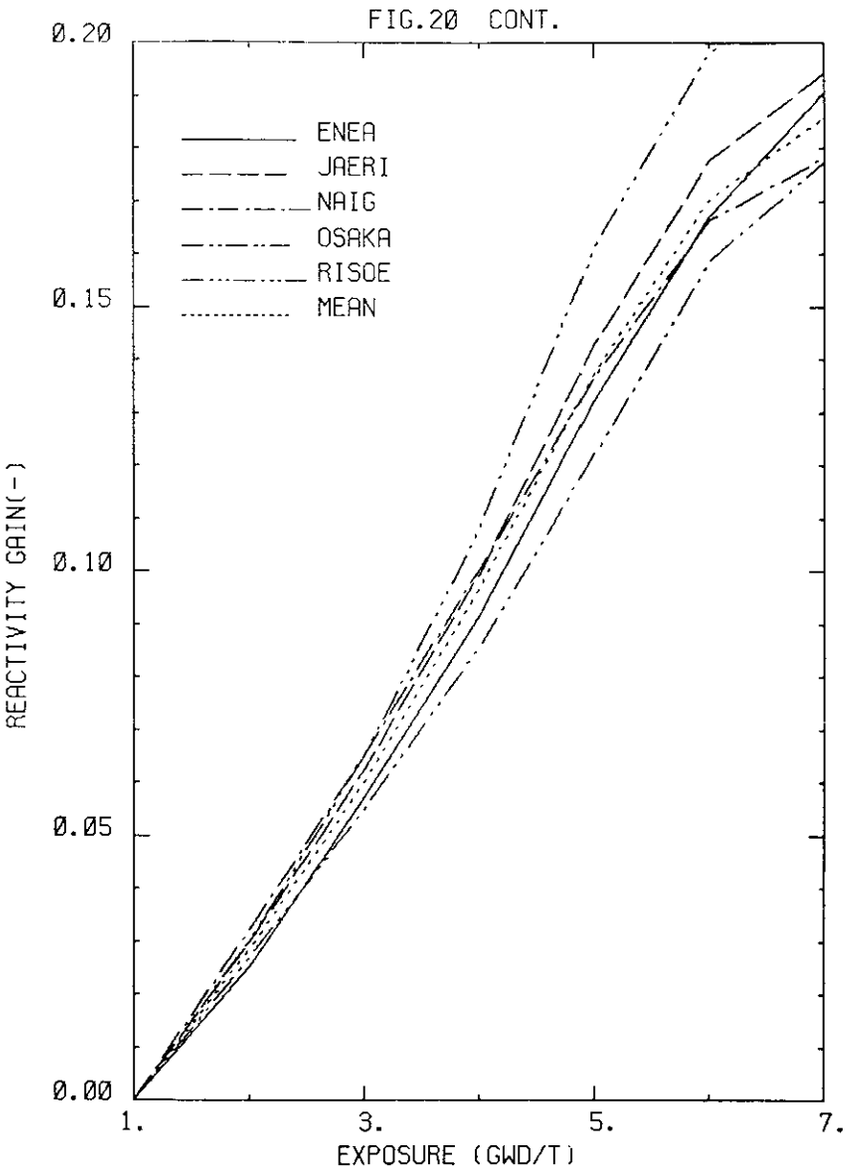


FIG.20 CONT.
0.20
0.15
0.10
0.05
0.00
REACTIVITY GAIN(-)
ENEA
JAERI
NAIG
OSAKA
RISOE
MEAN
1.
3.
5.
7.
EXPOSURE (GWD/T)

9200066

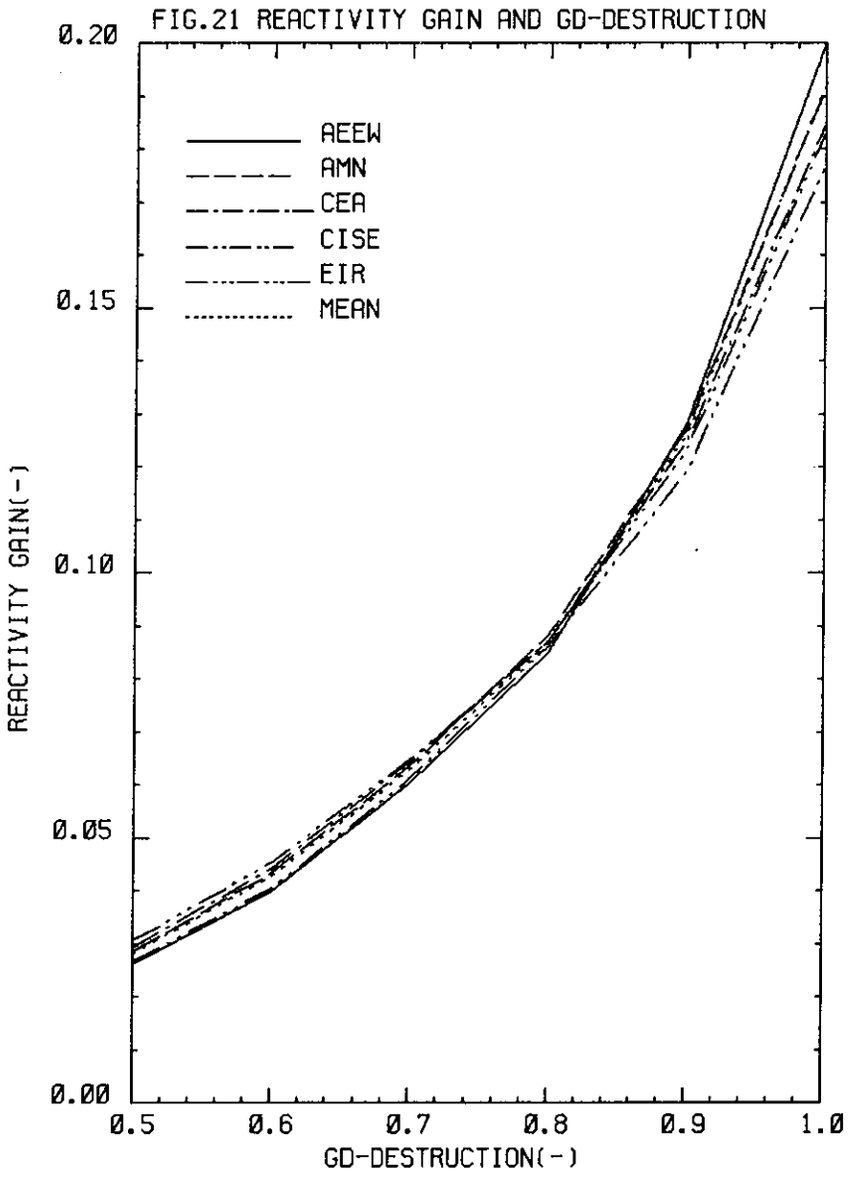


FIG.21 REACTIVITY GAIN AND GD-DESTRUCTION
AEEW
AMN
CEA
CISE
EIR
MEAN
REACTIVITY GAIN(-)
GD-DESTRUCTION(-)
0.00
0.05
0.10
0.15
0.20
0.5
0.6
0.7
0.8
0.9
1.0

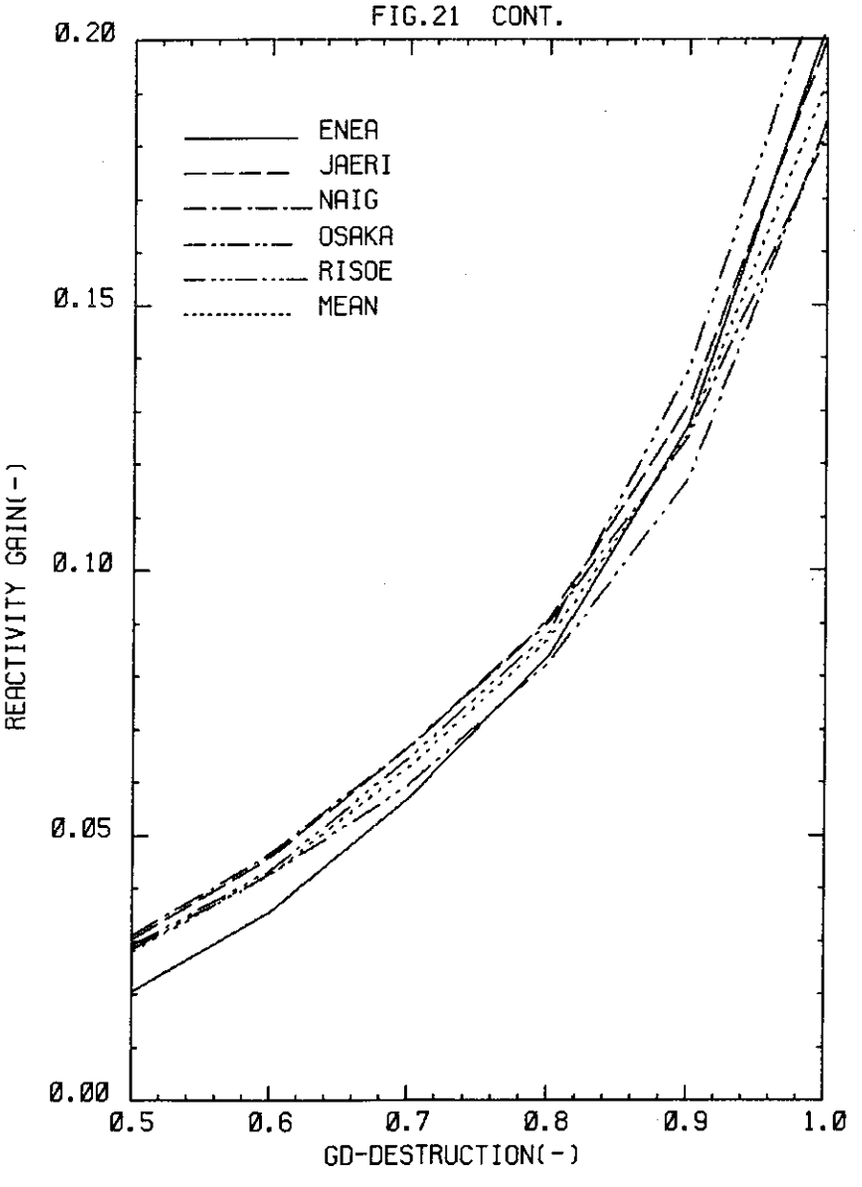


FIG.21 CONT.
ENEA
JAERI
NAIG
OSAKA
RISOE
MEAN
REACTIVITY GAIN(-)
GD-DESTRUCTION(-)
0.00
0.05
0.10
0.15
0.20
0.5
0.6
0.7
0.8
0.9
1.0

9203006?

FIG.22 PU-240/PU-239 FOR REGULAR LATTICE

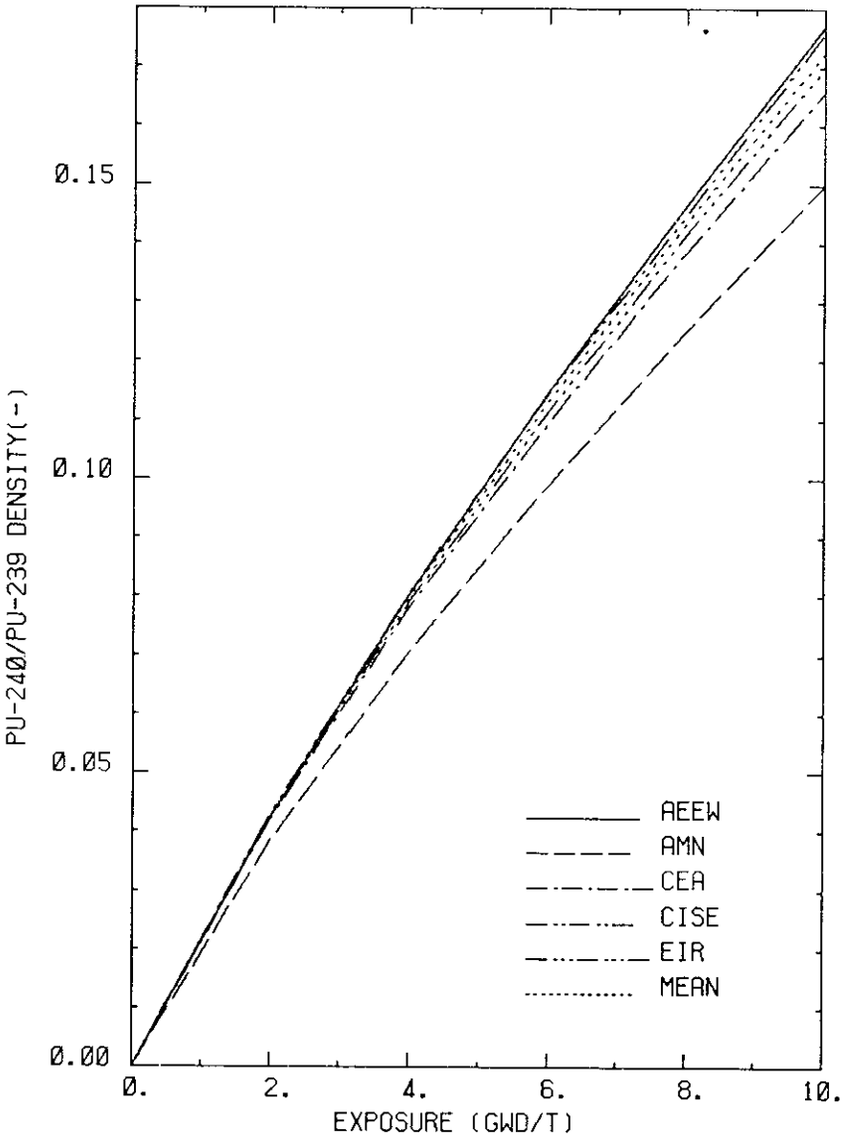
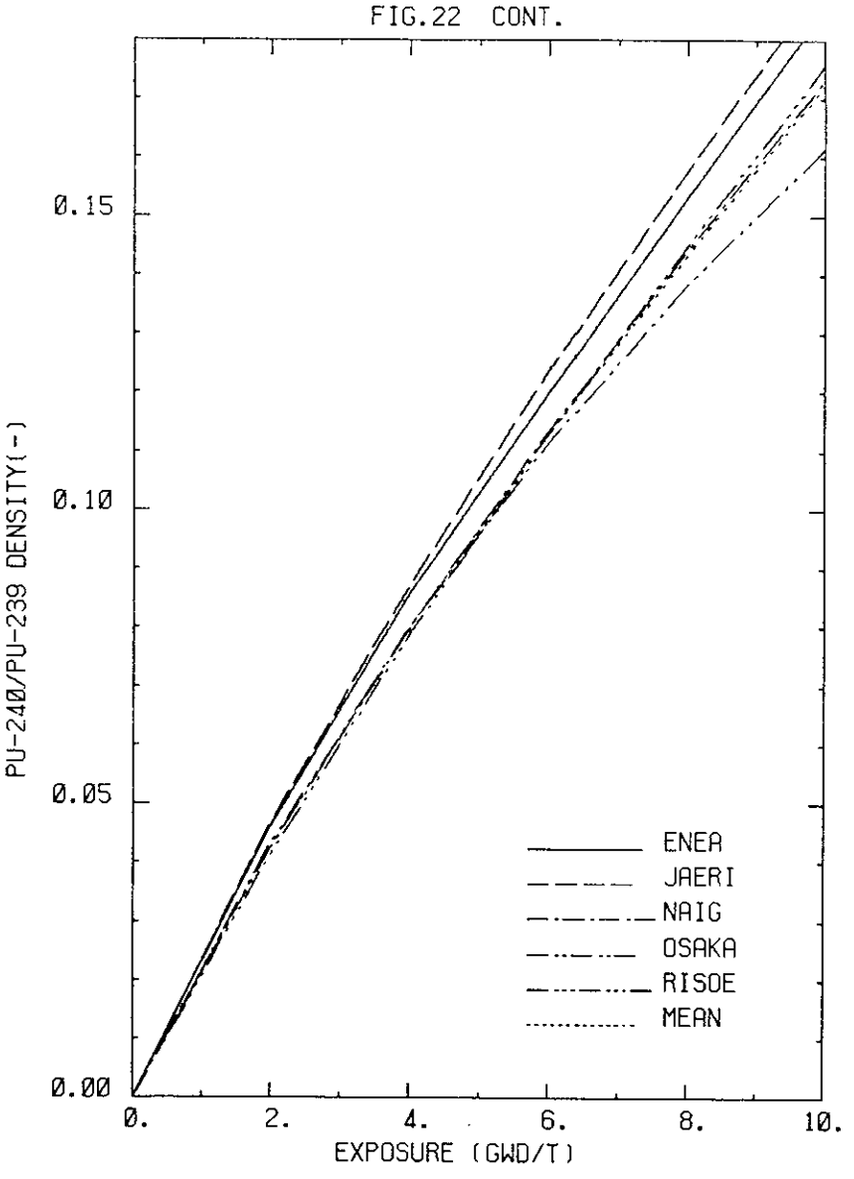


FIG.22 CONT.



9203006B

FIG.23 PU-240/PU-239 IN POISONED PIN

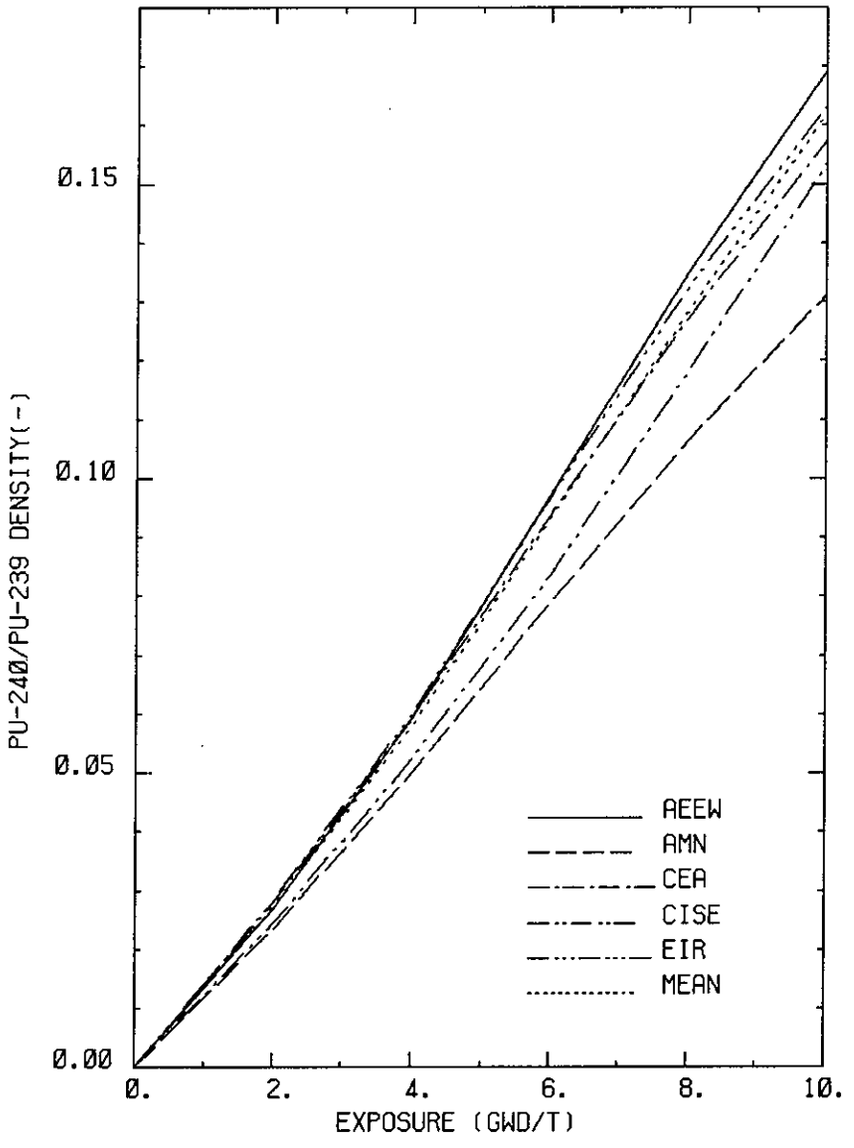
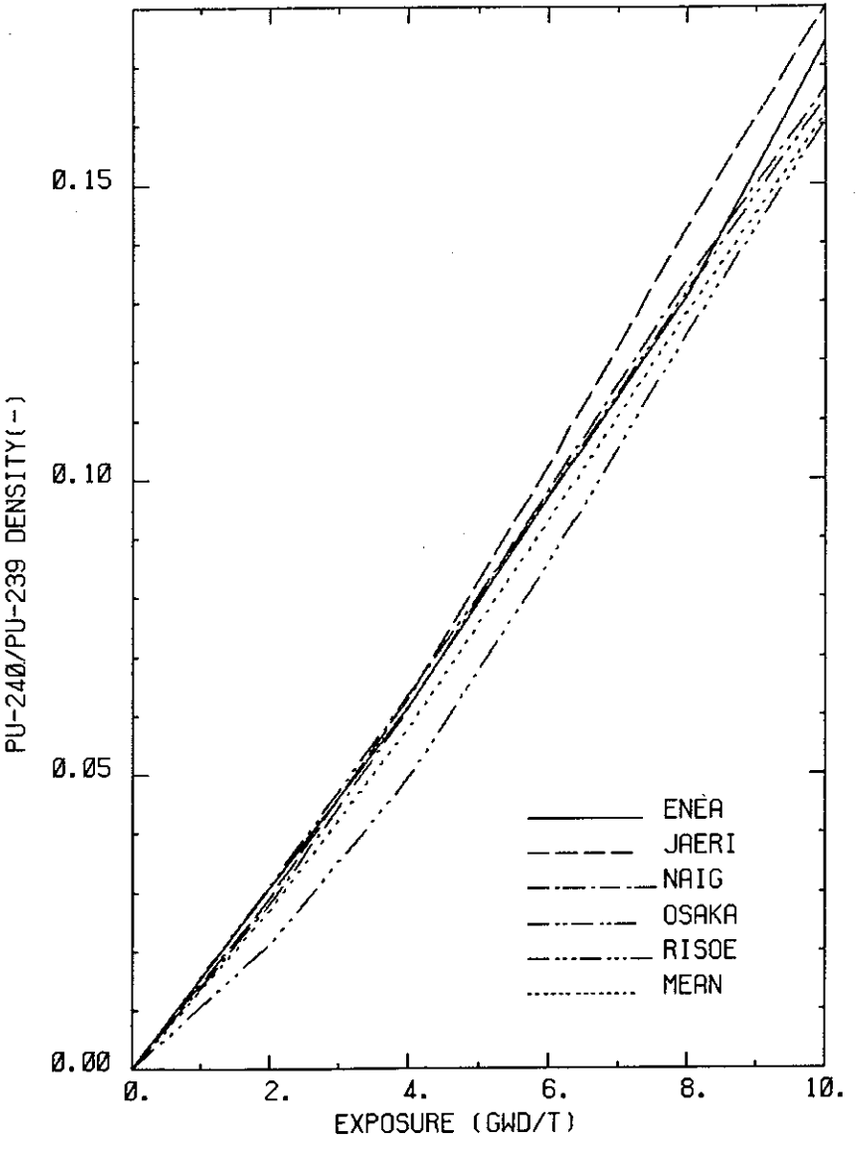


FIG.23 CONT.



9203006969

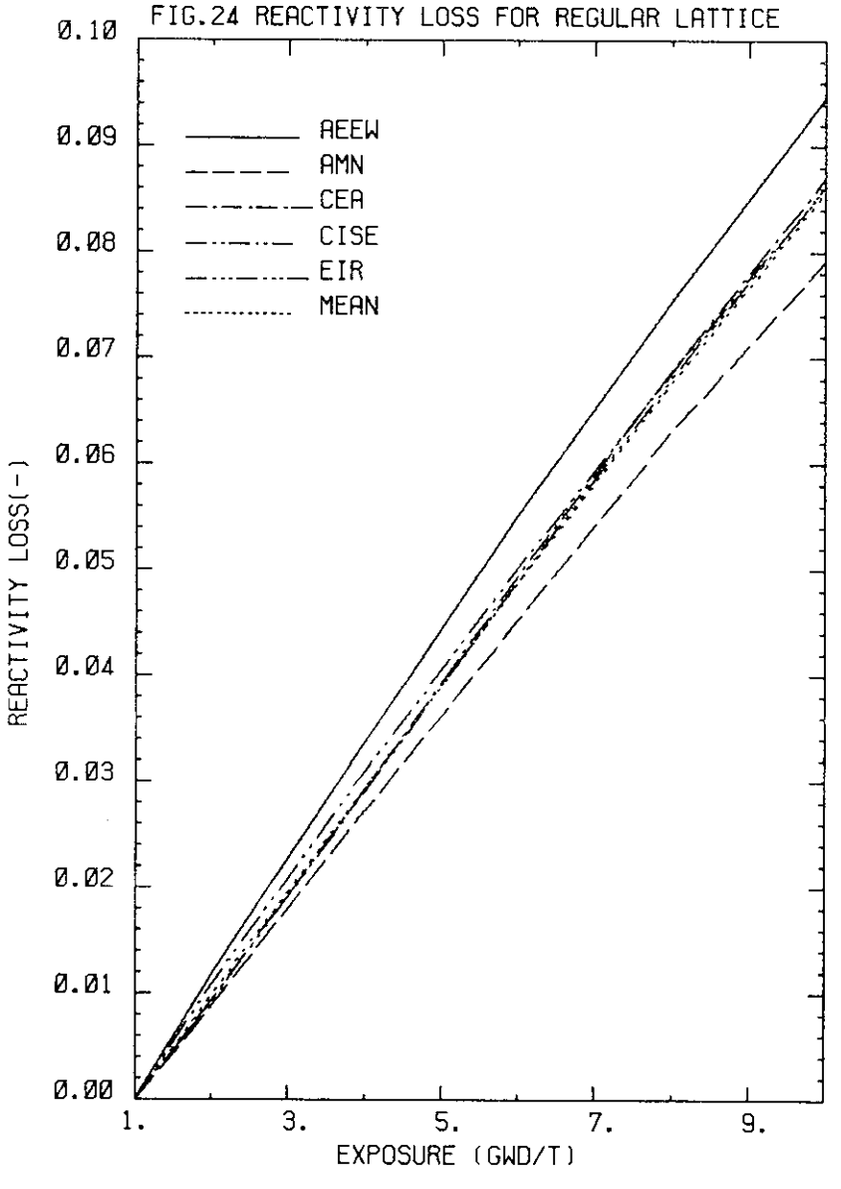


FIG.24 REACTIVITY LOSS FOR REGULAR LATTICE
0.10
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
REACTIVITY LOSS(-)
AEEW
AMN
CEA
CISE
EIR
MEAN
1.
3.
5.
7.
9.
EXPOSURE (GWD/T)

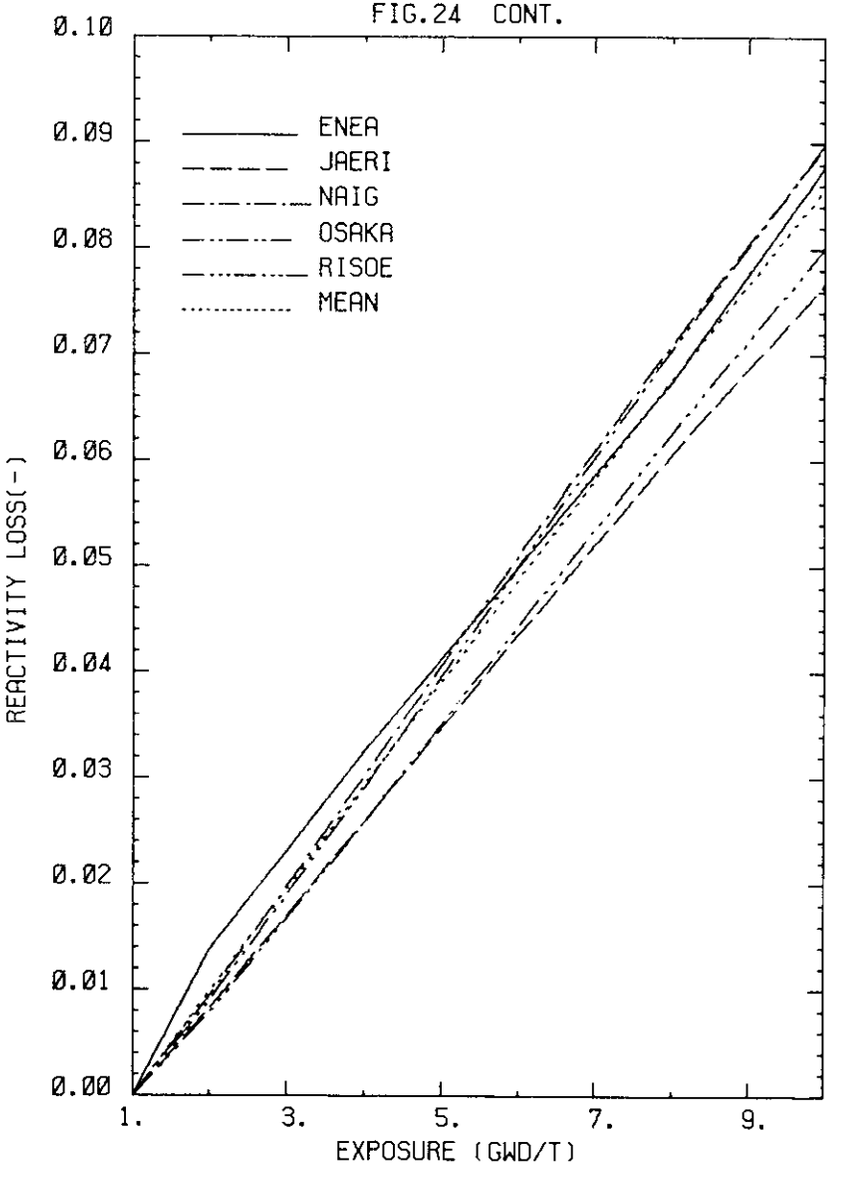


FIG.24 CONT.
0.10
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
REACTIVITY LOSS(-)
ENEA
JAERI
NAIG
OSAKA
RISOE
MEAN
1.
3.
5.
7.
9.
EXPOSURE (GWD/T)

9203070

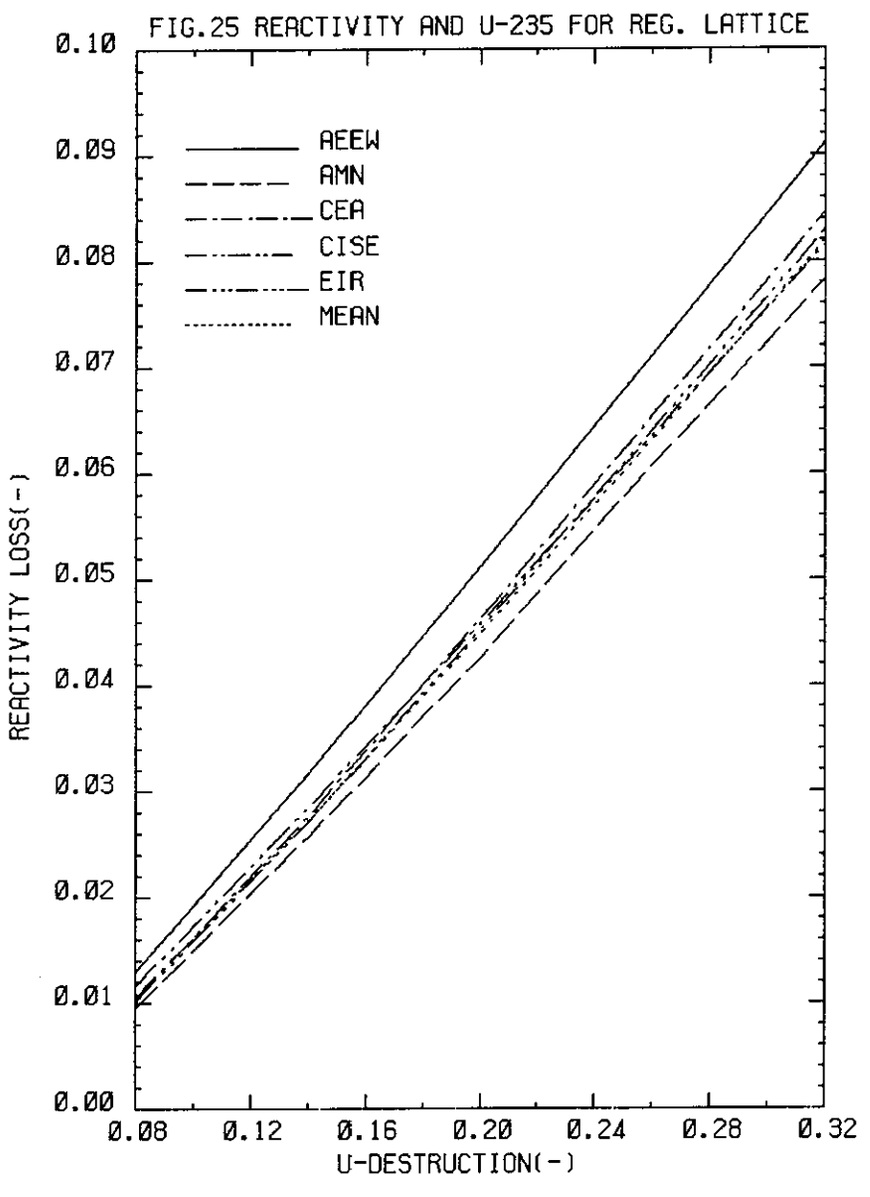


FIG.25 REACTIVITY AND U-235 FOR REG. LATTICE
AEEW
AMN
CEA
CISE
EIR
MEAN
REACTIVITY LOSS(-)
U-DESTRUCTION(-)
0.00
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.10
0.08
0.12
0.16
0.20
0.24
0.28
0.32

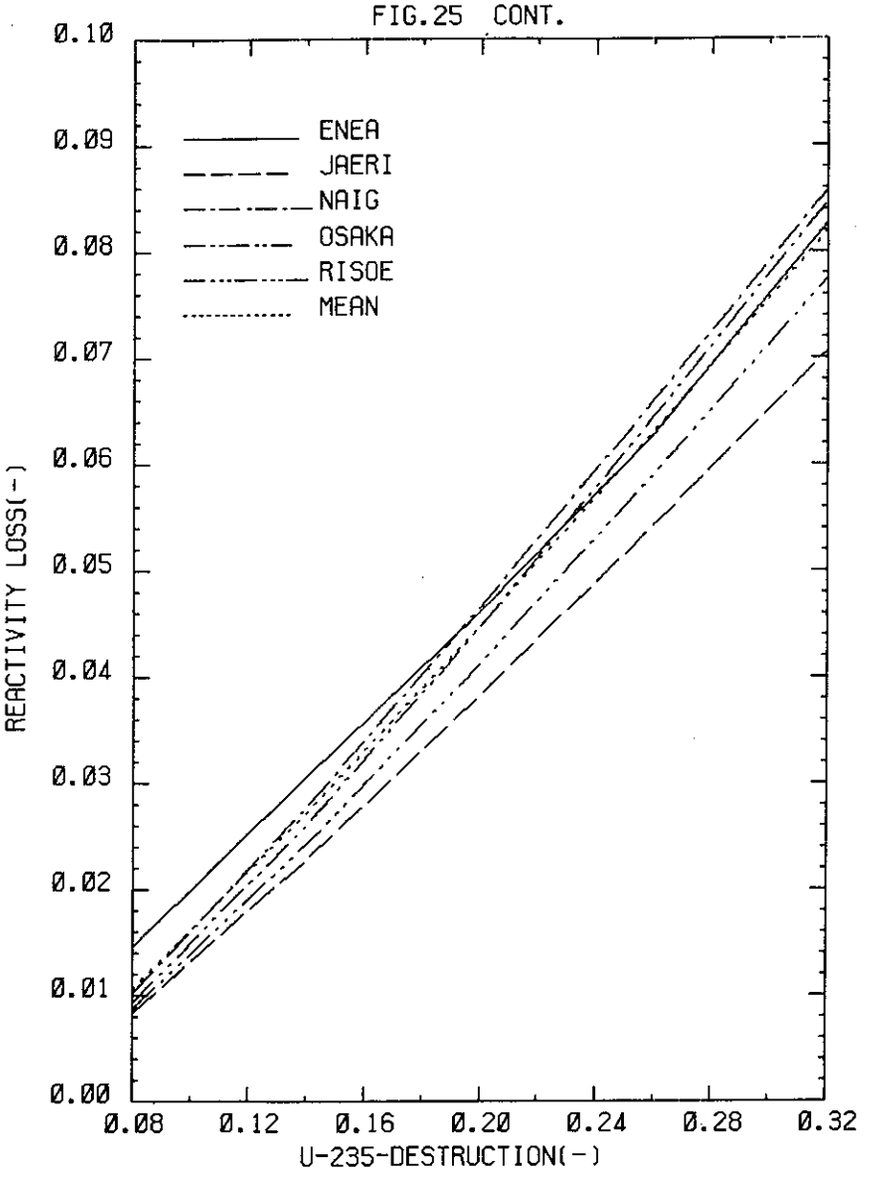


FIG.25 CONT.
ENEA
JAERI
NAIG
OSAKA
RISOE
MEAN
REACTIVITY LOSS(-)
U-235-DESTRUCTION(-)
0.00
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.10
0.08
0.12
0.16
0.20
0.24
0.28
0.32

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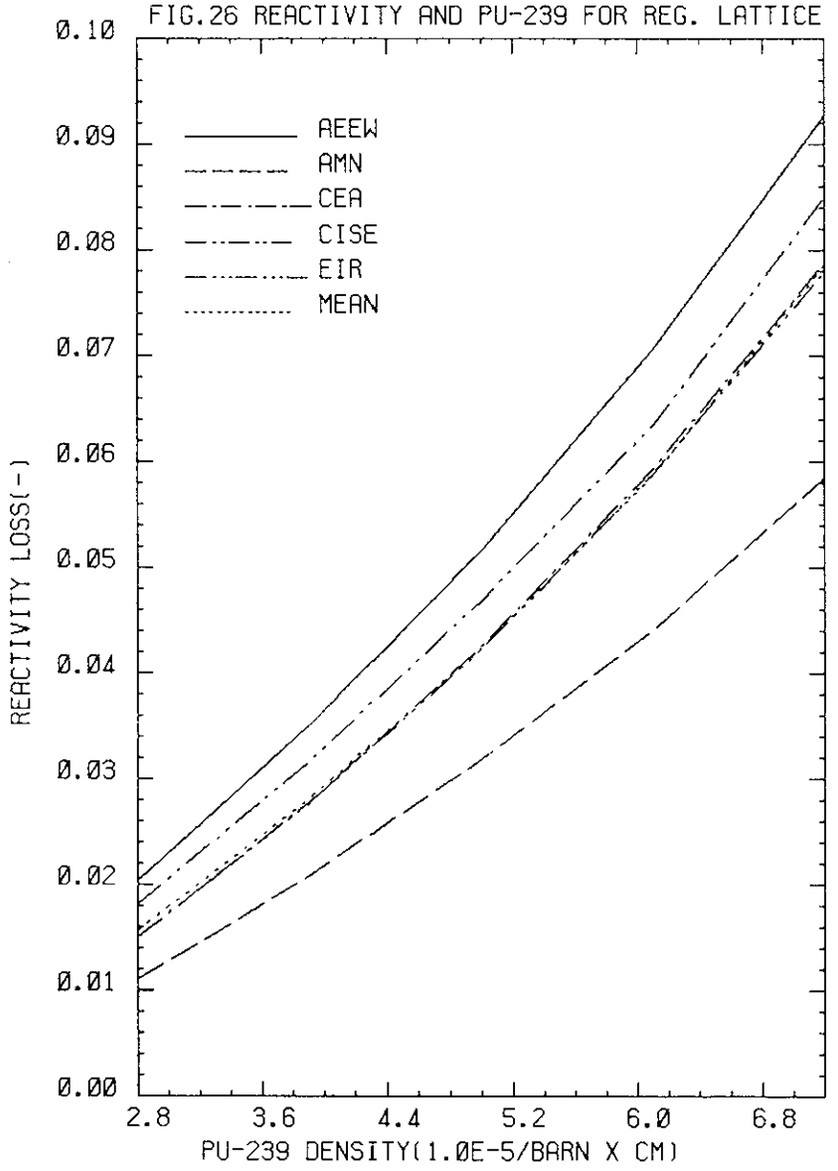
FIG.26 REACTIVITY AND PU-239 FOR REG. LATTICE
REEW
AMN
CEA
CISE
EIR
MEAN
REACTIVITY LOSS(-)
0.10
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
2.8
3.6
4.4
5.2
6.0
6.8
PU-239 DENSITY(1.0E-5/BARN X CM)

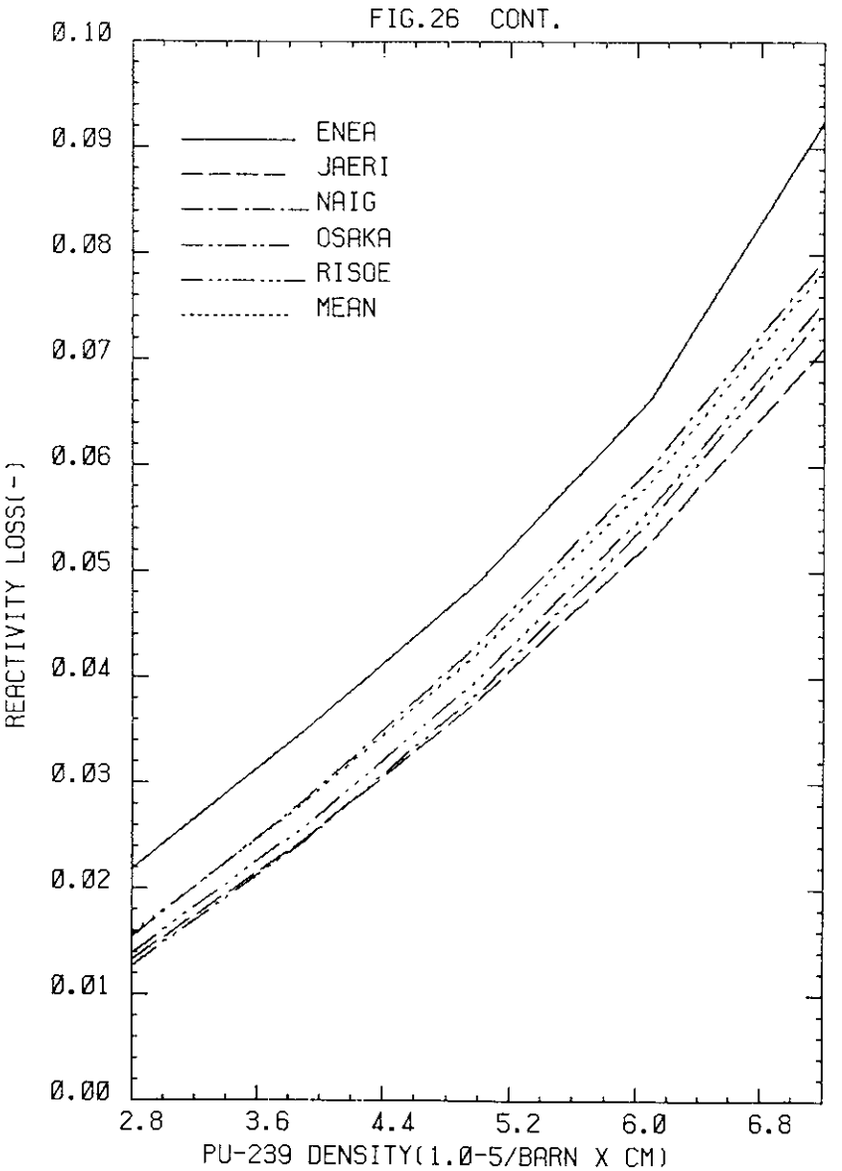
FIG.26 CONT.
ENEA
JAERI
NAIG
OSAKA
RISOE
MEAN
REACTIVITY LOSS(-)
0.10
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
2.8
3.6
4.4
5.2
6.0
6.8
PU-239 DENSITY(1.0-5/BARN X CM)

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APPENDIX A Shadowing Effect of Poisoned Pins

At EIR a burnup calculation up to 5 GWd/t with a subdivision of the Gd cell into 2x2 meshes for the few-group lattice calculation was performed (22). The subdivision is illustrated in FIG A1, Case A. During burnup the isotope densities in the Gd pin were tracked in 16 regions, 12 of which are different from each other. These regions were obtained by subdividing each annulus of the standard case (Case S in FIG A1) into 4 azimuthal regions (e.g. annulus 64 was divided into the regions 74, 84, 84 and 94). For the fine-group cell calculation, which was performed in cylindrical geometry as in the standard case, the regions lying in the same annulus were homogenized, thus neglecting the azimuthal flux dependence in the Gd pin. The superposition of the flux values obtained in the cell and in the lattice calculations provided the flux spectra which were used to determine the one-group reaction rates for the burnup calculation.

FIG A1 shows that the effects of the azimuthal subdivision of the Gd pin are small. The associated reactivity difference is less than 0.2 %, and the largest difference in the average power of the Gd pin (at 2 GWd/t) amounts to 0.6 %. An azimuthal power variation of 4 % can be observed in the four sectors of the pin.

At RISØ additional calculations at 0 burnup were performed by means of the response matrix program REPRO-FLUSO. In these calculations the pin cells were divided into 16 azimuthal sectors and a 6-group representation was used. For the regular lattice the square cell boundary assumed by REPRO-FLUSO yields a 0.4 % increase in k-infinity relative to the cylindrical CDB calculation. For the poisoned lattice the REPRO-FLUSO multiplication exceeds the CDB-value by 1 %. Along the diagonal connecting the poisoned pins REPRO-FLUSO predicts a flux tilt of 12 % in group 6, which is the most absorbing energy group. To assess the shadowing effect on the absorption in the poisoned pins a 3 x 3 lattice with only one central poison pin was also calculated. The total absorption in the two poisoned pins was found to be equal to twice the absorption in the isolated pin minus 5 %.

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Both the EIR and the RISØ investigations indicate that the usual BWR reactor physics design methods, which are based on one-dimensional cylindrical cell calculations, are adequate for adjacent Gd pins.

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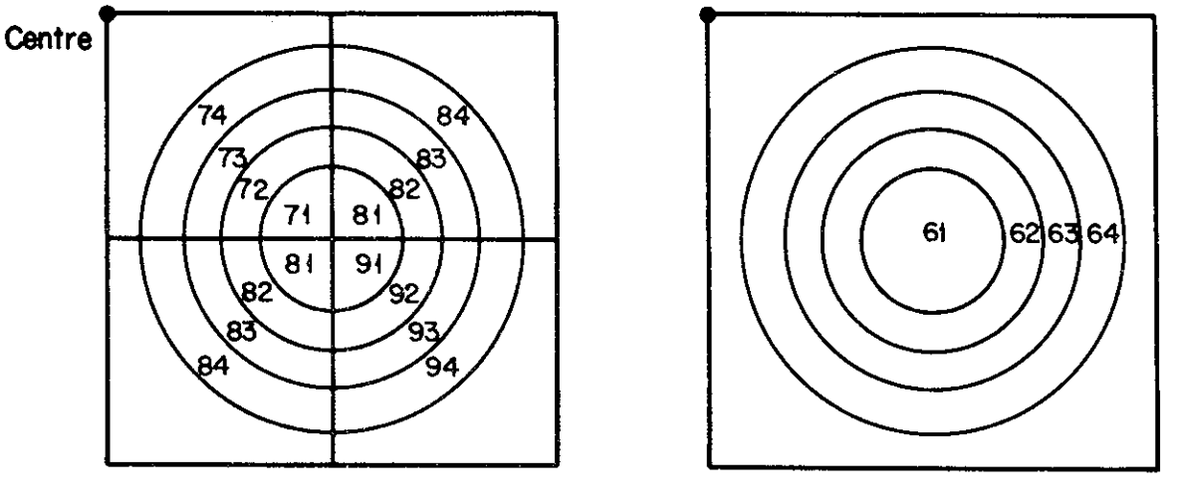
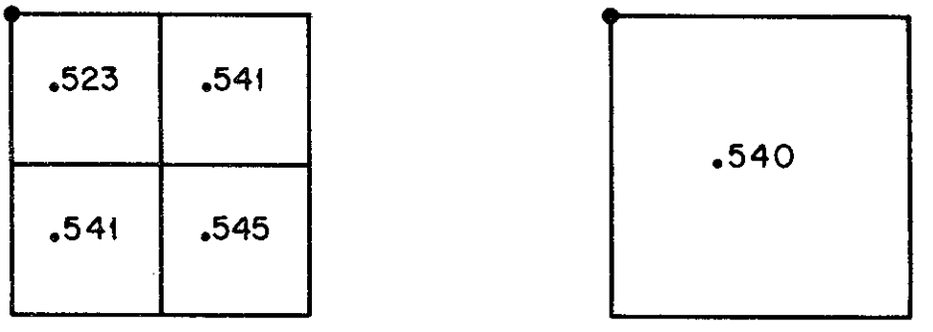


Case A (azimuthal subdivision)

Case S (standard case)



Relative power in Gd pin at 2 GWd/t

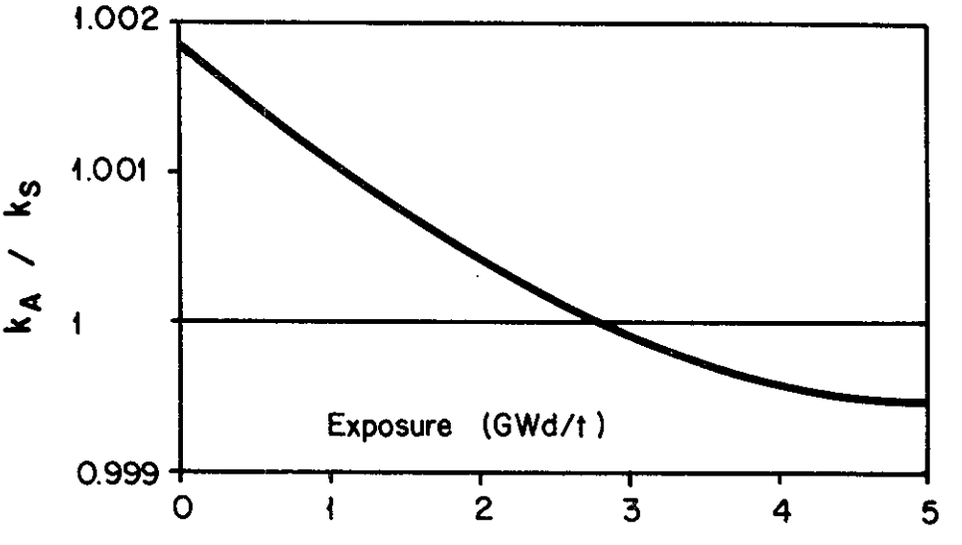


Fig. A1 Effect of Gd pin subdivision (EIR-results)

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APPENDIX B Influence of Calculation Models on Reactivity

Four participants (AEEW, EIR, OSAKA and RISØ) performed additional calculations in which they varied different parameters of the calculational models. In TAB B1 corresponding reactivity changes ($\Delta\rho = \Delta k/k$) are listed in the order of the calculation steps defined in TAB 1.

From lines 4 and 5 of the table it can be concluded that the usual homogenization method, i.e. a simple cell homogenization for the normal cells surrounding the Gd cell plus a supercell calculation with an unpoisoned buffer around the Gd cell, gives practically the same k-infinity as the more sophisticated OSAKA method.

The angular approximation of the cell surface flux and (above a certain minimum) the number of groups for the lattice calculation have a small influence on the results. Besides the data library, the most important model parameters are the lattice calculation method (diffusion versus transport theory), the number of time points during burnup and the spatial subdivision in the Gd pin.

APPENDIX C Reaction Rates

TABs C1 and C2 contain fuel pin averaged microscopic capture and fission rates for 7 different solutions. The data are useful for estimating k-infinity effects due to differences in the one-group cross sections of the heavy isotopes.

TAB C3 contains macroscopic absorption and production reaction rates, normalized to 100 % for each reaction, as a function of burnup. These values, which were provided by CISE, are useful for assessing burnup effects.

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TAB. B Reactivity Influence of Calculation Models

Calculation step	Modelling parameter	Supplemental calculation	Standard calculation	Participant	Exposure (GWd/t)	Reactivity effect (%)	
						Reg.lattice	Pois.lattice
Data library	Change of library	old version	1981 version	AEEW	0	- 1.2	- 1.4
					10	- 1.0	- 1.0
	15 % reduction of U^{238} resonance capture	yes	no	OSAKA	0	2.6	2.5
Cell calculation	Regular cells	isolated cell	bundle calc.	OSAKA	0		- 1.5
	Buffer around Gd-cell	unpoisoned	poisoned	OSAKA	0		1.7
	Poison density in poisoned pin	full	none	RISØ	0		1.6
					6		- 1.9
	Number of zones in Gd-pin	1	6	OSAKA	2		- 1.1
					6		2.0
Lattice calculation	Method	Diffusion	Transport	AEEW	0		1.6
	Group number	70	11	EIR	0		0.1
		8	11		0		- 0.2
		15	6	OSAKA	0	- 0.1	- 0.5
	Number of angular flux moments	1	2	OSAKA	0		0.3
				RISØ	0		0.2
	Azimuthal flux variation in Gd-cell (cf. Appendix A)	yes	no	EIR	0		0.2
				RISØ[a]	0	0.4	1.0
Burnup calculation	Number of time points	13	22	OSAKA	6		- 2.1
		11	29	RISØ	6		- 2.7

a Different calculational methods were used

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TAB.C1 MICROSCOPIC CAPTURE AND FISSION RATES FOR REGULAR LATTICE AT 0 MWD/T(SEC-1)

REACT.	AEEW	CEA	CISE	EIR	ENEA	NAIG	OSAKA	MEAN	VAR
C25	1.59E-09	1.65E-09	1.69E-09	1.65E-09	1.69E-09	1.65E-09	1.74E-09	1.67E-09	.029
C28	1.26E-10	1.34E-10	1.26E-10	1.30E-10	1.25E-10	1.30E-10	1.29E-10	1.29E-10	.026
C49	1.08E-08	1.06E-08	1.05E-08	1.07E-08	0.	1.08E-08	1.07E-08	1.07E-08	.009
C40	3.21E-08	3.58E-08	3.40E-08	3.46E-08	0.	3.29E-08	3.42E-08	3.39E-08	.038
F25	7.59E-09	7.57E-09	7.61E-09	7.62E-09	7.69E-09	7.58E-09	7.64E-09	7.61E-09	.006
F28	1.43E-11	1.62E-11	1.31E-11	1.46E-11	1.35E-11	1.40E-11	1.71E-11	1.47E-11	.099
F49	1.87E-08	1.89E-08	1.82E-08	1.90E-08	0.	1.91E-08	1.90E-08	1.88E-08	.017
F40	7.43E-11	8.28E-11	0.[a]	8.24E-11	0.	8.29E-11	8.99E-11	8.25E-11	.067

a 0. = value is not available

TAB.C2 MICROSCOPIC CAPTURE AND FISSION RATES IN POISONED PIN AT 0 MWD/T(SEC-1)

REACT.	AEEW	CEA	CISE	EIR	ENEA	NAIG	OSAKA	MEAN	VAR
C155	3.00E-08	3.10E-08	2.26E-08	2.80E-08	3.52E-08	3.02E-08	3.16E-08	2.98E-08	.129
C157	1.08E-07	1.09E-07	9.43E-08	1.03E-07	1.05E-07	1.07E-07	1.10E-07	1.05E-07	.051
C25	8.74E-10	8.82E-10	8.35E-10	8.27E-10	8.76E-10	8.71E-10	9.21E-10	8.69E-10	.036
C28	1.36E-10	1.32E-10	1.22E-10	1.31E-10	1.26E-10	1.32E-10	1.21E-10	1.29E-10	.044
C49	5.80E-09	6.05E-09	5.51E-09	5.45E-09	0.	6.05E-09	5.78E-09	5.78E-09	.044
C40	3.80E-08	4.13E-08	3.92E-08	3.91E-08	0.	3.73E-08	3.75E-08	3.87E-08	.039
F25	2.57E-09	2.60E-09	2.34E-09	2.50E-09	2.55E-09	2.65E-09	2.64E-09	2.55E-09	.042
F28	1.82E-11	1.78E-11	1.70E-11	1.85E-11	1.65E-11	1.84E-11	1.70E-11	1.76E-11	.045
F49	8.91E-09	9.47E-09	8.07E-09	8.46E-09	0.	9.40E-09	9.01E-09	8.89E-09	.061
F40	9.45E-11	9.12E-11	0.	1.05E-10	0.	1.08E-10	9.18E-11	9.80E-11	.079

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TAB. C3 Reaction Rates (%) in the Regular Lattice (CISE-Results)

Exposure (GWd/t)	*0*	*2*	*4*	*7*	*10*
Absorptions in U-235	*63*	*54*	*49*	*43*	*37*
Absorptions in U-238	*30*	*29*	*29*	*28*	*28*
Absorptions in Pu-239	*0*	*6*	*10*	*14*	*18*
Other absorptions	*7*	*11*	*12*	*15*	*17*
Productions by U-235	*94*	*86*	*79*	*71*	*64*
Productions by U-238	*6*	*6*	*6*	*6*	*6*
Productions by Pu-239	*0*	*8*	*15*	*22*	*28*
Other productions	*0*	*0*	*0*	*1*	*2*

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APPENDIX D Partial Solutions

B. Zolotar, EPRI, Paolo Alto, USA, performed a calculation for the poisoned lattice using the CASMO code (24), and K. Kowalska, Nuclear Institute of Swierk, Poland, provided results for both lattices up to 7 GWd/t obtained with S-WIMS (25), the latter code being an adapted version of the British WIMS-D code (26). The calculation methods and the detailed results of the EPRI and SWIERK solutions are described in Refs. (2) and (4).

The multiplication factors obtained by EPRI and SWIERK and the respective deviations from the mean values (cf. TABs 2-3) are listed in TABs D1 and D2.

TAB D1 SWIERK Multiplication Factors for the Regular Lattice

Exposure (GWd/t)	k	Δρ *
0 (No Xe)	1.3360	.004
1	1.2794	.004
2	1.2673	.004
3	1.2543	.003
4	1.2401	.002
5	1.2277	.002
6	1.2146	.002
7	1.2019	.002

* Δρ = Reactivity deviation from mean value of TAB 2

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TAB. D2 *Additional Multiplication Factors for the Poisoned Lattice*

Exposure (GWd/t)	EPRI		SWIERK	
	k	Δρ *	k	Δρ *
0 (No Xe)	1.0279	.027	1.0035	+ .002
1	1.0240	.026	1.0013	+ .003
2	1.0512	.024	1.0230	- .004
3	1.0834	.024	1.0440	- .014
4	1.1208	.024	1.0654	- .027
5	1.1618	.023	1.0880	- .042
6	1.1955	.023	1.1127	- .048
7	1.2109	.023	1.1389	- .038
8	1.2110	.024		
9	1.2020	.024		
10	1.1885	.021		

*Δρ = Reactivity deviation from the mean value of TAB 3

92030081

From: SMTP%"SGD00314@niftyserve.or.jp" 4-MAR-1996 15:04:35.21
To: SARTORI
CC:
Subj: Monte Carlo Burn

Message-Id: <199603011313.WAA19681@inetnif.niftyserve.or.jp>
Date: Fri, 01 Mar 1996 22:12:00 +0900
From: "=?ISO-2022-JP?B?GyRCPyJHNzg2ISFNOkZzGyhC?= "
<SGD00314@niftyserve.or.jp>
Subject: Monte Carlo Burn
To: sartori@nea.fr
MIME-Version: 1.0
Content-Type: text/plain; charset=iso-2022-jp

Dear Dr. Sartori

I received your information on MOX burnup problems. My major is Monte Carlo simulations. Since this problem is too complicated to apply Monte Carlo analysis, it is impossible for me to participate this problem.

---------- *Above lines are prepared for only Dr. Sartori* ----------

I'm trying Monte Carlo burn calculations of BWR bundles containing Gd rods. As you have recognized, much computing time is required for the precise Monte Carlo analysis of Gadolinium depletion. I have solved Gadolinium depletion problems for the BWR fuel bundles in commercial use.

I can show my results for typical bench-mark problem/1/. You'll find my results(MCNP-BURN) in that table. It took about two weeks to solve this bench-mark problem by the EWS Sun-Sparc-20. Work Station clusters(e.g. IBM-SP-2), however, will solve this problem in several hours, even if the size of clusters is small.(about ten nodes)

Do you have information on similar experiences? My information is only one case(Knoll Laboratory in USA). They used the expensive platform(CRAY-C90) and closed software(ACER). My system is economical and every body can access to.

If you desire, I'll show you more detailed information.

My e-mail address(rae@rcg.nel.rdc.toshiba.co.jp) may be closed until next April. Please send your mail to my private address(SGD00314@nifty.serve.or.jp).

/1/(C.Maeder and P.Wydler, "International Comparison Calculations for a BWR Lattice with Adjacent Gadolinium Pins," NEACRP-L-271 1984)

EXP. [GWD/MT]	MCNP-BURN	AEEW	AMN	CEA	CISE	EIR	ENEA	JAERI	NAIG	OSAKA	RISOE
0	1.0069	1.0093	1.0140	0.9970	1.0164	1.0110	0.9965	0.9983	1.0004	0.9899	0.9815
1	1.0094	1.0024	1.0036	0.9991	1.0058	1.0093	0.9935	0.9973	1.0044	0.9895	0.9798
2	1.0404	1.0295	1.0316	1.0314	1.0286	1.0403	1.0187	1.0270	1.0368	1.0162	1.0093
3	1.0763	1.0625	1.0631	1.0658	1.0531	1.0727	1.0504	1.0596	1.0699	1.0439	1.0435
4	1.1096	1.1042	1.1002	1.1035	1.0884	1.1083	1.0846	1.0964	1.1051	1.0742	1.0855
5	1.1521	1.1516	1.1412	1.1433	1.1196	1.1477	1.1250	1.1399	1.1419	1.1105	1.1379
6	1.1835	1.1866	1.1747	1.1731	1.1501	1.1754	1.1595	1.1745	1.1714	1.1465	1.1739
7	1.1949	1.1989	1.1895	1.1811	1.1717	1.1895	1.1828	1.1910	1.1834	1.1651	1.1866
8	1.1915	1.1939	1.1891	1.1756	1.1788	1.1861	1.1811	1.1901	1.1803	1.1650	1.1837
9	1.1819	1.1832	1.1819	1.1654	1.1728	1.1765	1.1756	1.1822	1.1707	1.1566	1.1747
10	1.1683	1.1715	1.1727	1.1546	1.1621	1.1657	1.1705	1.1728	1.1595	1.1466	1.1642

Distributions: LANL J.Hendrics
ENEA E.Sartori