MCNP Models of ZEBRA CADENZA and MOZART Programme Fast Reactor Benchmarks.

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ZEBRA was a fast critical assembly facility operating at the Winfrith site of the UKAEA from 1962 until 1984. In this note input data are given for MCNP models of six ZEBRA Fast Reactor Assemblies, four of them being from the Cadenza programme and two from the Mozart programme. In addition there are two intermediate assemblies from the Cadenza programme. Full details of the assemblies can be found on:

http://www.zebra.webnik.org

1. The Cadenza Benchmarks

The Cadenza programme was carried out in the early 1980s. Four critical assemblies were built, using plutonium/natural uranium oxide as fuel either in plate form or in pin geometry:

Zebra 22.	Plate geometry.	Including sodium.	Pu metal plates plus UO_2 plates
Zebra 23.	Pin geometry.	Including sodium.	U-PUO_2 fuel in pin form.
Zebra 24.	Plate geometry.	Sodium region voided.	Pu metal plates plus UO_2 plates
Zebra 25.	Pin geometry.	Sodium region voided.	U-PUO_2 fuel in pin form.

In addition there were modified versions of Cores 23 and 25 containing central regions of plate geometry elements surrounded by the pin geometry elements.

The Cadenza cores were small, comprising U-Pu fuel, oxygen and steel structural material. Two cores contained sodium and two were without sodium, having a composition more typical of a gas cooled fast reactor. The proportions of fuel, steel and sodium (or void region) were roughly equal and the neutron spectrum was that of a fast reactor. The core region was surrounded by natural uranium axial and radial blankets with steel reflector regions around these. The k-effective values are the parameters of primary interest but reaction rate ratio measurements were made in Zebra 22 and a wide range of reactivity perturbation measurements was made in all the cores. Reaction rate scan measurements were also made.

Each Zebra assembly comprises an array of elements, about 5 cm square and 3 m long, located on a horizontal lattice plate. The elements consist of square steel tubes which hold the materials, either stacks of plates or steel calandria holding the 4x4 arrays of pins. Groups of 5x5 elements are held together and supported by the superlattice grid plates. Consequently the arrangement of elements is not completely regular, there being a small gap between the groups of 5x5 elements. A modification in the case of the Cadenza cores was the use of double elements designed to hold instruments such as fission chambers. These double elements were also used more generally in the cores but the compositions are the same as for the single elements and this is how they are modelled.

The Cadenza cores were built in two approximately equivalent versions, with one version using plate geometry materials and the other version pin geometry fuel, to provide a duplication in the measured results, Zebra 23 (pin geometry) being similar in average composition to Zebra 22 (plate geometry) and Zebra 25 similar to Zebra 24. However, the plate geometry cores had ~25% less oxygen because the plutonium was in metal form and was separate from the UO_2. The plate geometry cores also included copper cladding on the plutonium metal and gallium diluent in the plutonium metal. The axial and radial blanket regions were the same in all the Cadenza assemblies and the outer radial boundary of the radial blanket was the same in all the assemblies.

The pin geometry cores, Zebra 23 and 25, included an outer radial ring of plate geometry elements because there was not sufficient pin geometry material to fuel the whole of the core. The core plans for all four assemblies are shown in Figs. 3, 4, 5, 8 and 9 (page 10 et seq). The plans of the two pin geometry assemblies containing the central plate geometry zones are shown in Figs. 11 and 12.

The core sections were approximately 90 cm high and the diameters were also about 90 cm. Criticality was achieved by varying the number of core elements (and hence the core diameter), the sodium voided cores being slightly larger than the cores containing sodium and the pin geometry cores slightly larger than the plate geometry cores. The final critical balance was achieved by moving the fine control rod. Corrections were applied to the calculational models for the control rod insertion and for non-standard elements, based on measurements made in the assemblies, in order to simplify the models.

The arrangement of the plates in the core cells of Assembly 22 is shown in Fig. 1 (page 8). The cell comprises 7 plates reflected to form a “double” cell of 14 plates. The single cells contain 3 sodium plates, 2 uranium oxide plates, a plutonium metal plate and a steel plate. There are 12 of these “double” core cells in an element, stacked axially. However, the steel plate was absent from the top and bottom cell in order for the core height to match that of the pin geometry cells more closely. In Fig. 2 the arrangement is shown on a smaller scale to illustrate the superlattice structure of the assemblies. Groups of 5x5 elements are held by the superlattice grid plates located above and below the core sections.

The core cells of Assembly 24 are the same as those of Assembly 22 excepting for the sodium filled plates which are replaced by steel “dummy” plates having a similar thickness and steel content to the sodium plates. The number of core elements is increased because of the reduced reactivity of the core without sodium. There is a slight difference in plate thickness because the sodium plates are measured to be compressed by the weight of the stack of plates above and this difference is taken into account in the models. In fact, three different “dummy” plates were used in Assembly 24, two ring shaped and one “honeycomb” shaped, and the location of these can be seen in Fig. 5.

The cross-section of the pin geometry elements is shown in Figs. 6 and 7. The calandria contain a 4x4 array of pins and there are three calandria axially in the core section of each element. The pins in most cases are of two different enrichments chosen to give an average plutonium enrichment of about 24%. There are several different combinations of pins. Fig. 7 shows the array of 5x5 elements in the central superlattice square. All of these elements are the same but contain the two types of pin. The locations of different calandria are shown in Fig. 8. Assembly 25 differs from Assembly 23 in that the calandria of Assembly 23 core contain sodium whereas those of Assembly 25 do not. This also applies to the radial rings of plate geometry elements at the core radial boundary. The arrays of pin elements are the same in the two assemblies but the number of radial plate geometry elements in Assembly 25 is greater because the removal of sodium reduces the reactivity because of the greater leakage fraction. The locations of the plate geometry elements in the two cores can be seen in Figs. 8 and 9. For full details of the geometry and compositions please refer to the Cadenza programme document on the web site.

2. The Mozart Benchmarks

The Zebra Mozart programme was a joint Japan-UK programme of fast reactor critical assembly experiments, carried out in the early 1970s, in support of the design of the MONJU Fast Reactor. The second assembly in the programme, MZB, had the size of the MONJU reactor and a two zone core, with inner and outer core regions having fuel of different enrichments. A simpler assembly, having just one fuel enrichment in the core, MZA, was studied first. This core was similar to the Cadenza core, Zebra 22, but was surrounded by a more realistic axial and radial blanket, more representative of a power fast reactor blanket, instead of the natural uranium blanket of the Cadenza cores. The number of core elements was 213 which compares with 215 in Zebra 22. The MZA core fuel elements were then used to form the outer core region of MZB, and elements having a lower enrichment were used in the inner core of MZB. The arrangement of the plates in the core cells of MZA is shown in Fig. 13. It is similar to the double cell of Zebra 22 excepting that the steel plate in the upper cell is replaced by a graphite plate. As in Zebra 22 there are 12 of these cells per MZA core element. The materials of some of the plates are different, however. The inner core cell of MZB is illustrated in Fig. 14.

The axial blanket cells are illustrated in Fig. 15 and the inner region radial blanket cells are shown in Fig. 16. These are of the same form in both MZA and MZB, although some individual plates differ in different elements, in particular the sodium plates are slightly different and the MCNP models take these differences into account. There are also differences in the core cells, in particular in the compositions of the plutonium metal plates which were manufactured at different times. The positions in MZA of the four different types of core element are shown in Fig. 18 and in Fig. 20 the positions of these elements in the outer core region of MZB are shown. Fig. 21 shows the positions of elements in the inner core of MZB having different plutonium metal plates. Fig. 22 shows the positions of the steel and graphite reflector elements (the graphite elements need not be included in the models used to calculate core properties but are required for calculations of reaction rate distributions).

The MZA and MZB phases of the Mozart programme were followed by the MZC phase in which the reactivity worths and reaction rate distributions of different arrays of MONJU mockup control rods were studied in the MZB assembly, enlarged radially when necessary to compensate for the effect of the control rods in reducing core reactivity. Measurements were made for both absorber rods made of tantalum and different enrichments of boron, and for the simulations of sodium filled control rod followers. The MCNP models of the MZC experiments are not described in the present note.

3. The Input Decks for the Detailed MCNP Models

Both detailed and simplified models of the assemblies have been set up. Details of the dimensions and compositions can be found in the Cadenza and Mozart Programme documents on the web site and also deduced from the MCNP input data. The input decks for the detailed models are given as text files in the zip file MCNP Zebra.

The input decks using JEFF-3.1 data are named in the form Z22A.txt, the form of the instruction for a calculation being:

>mcnp5 inp=Z22A.txt outp=Z22AR1

The name of the output file, Z22AR1, is given here for illustration and is for the user to specify.

Z22A.txt is the form having JEFF-3.1 nuclear data (.31c) and the corresponding JENDL-3.3 input file is Z22Z.txt (using .42c, the same as ENDL, so please take care over the data library being accessed by correctly naming the xsdir directory).

The names of the Zebra Cadenza Assembly text files which use JEFF-3.1 nuclear data are:

Z22A.txt, Z23A.txt, Z24A.txt and Z25A.txt

and for the two pin geometry assemblies with central arrays of plate geometry elements:

Z3PA.txt (for the central plate array in Zebra 23) and Z5PA.txt (for the plate array in Zebra 25).

The MZA and MZB models are named MZAA.txt and MZBA.txt.

The versions which use JENDL-3.3 data have the names ending in Z.txt in place of A.txt. A difference in the materials used is that for gallium, the JEF-3.1 data being for the element, 31000.31c, whereas the JENDL-3.3 data are for the two isotopes, 31069.42c and 31071.42c

The standard deviation of the MCNP Monte Carlo k-effective calculation (and the running time) is determined by the number of stages specified in the input deck. This is the final number in the line near the end of the input deck:

kcode 10000 1.0 100 1500

The value of 1500 for the number of stages gives a standard deviation in k-effective of about +/- 0.00015. The initial guess at k-effective is 1.0 and the number of settling stages, for the calculation of the initial fission source distribution, is 100 (increased to 200 for the pin geometry cores).

The measured values of k-effective with which the calculated values are to be compared are as follows and these values are given at the top of the input decks. The JEFF-3.1 and JENDL-3.3 calculated values are included in the Table for interest:

Assembly	Measured value	MCNP/JEFF-3.1	MCNP/JENDL-3.3
Assembly 22	1.0022 ± 0.0010	1.00614 ± 0.00014	0.99656 ± 0.00015
Assembly 23	1.0016 ± 0.0013	1.00831 ± 0.00015	0.99902 ± 0.00015
Z23 Central plate zone	1.0029 ± 0.0013	1.00845 ± 0.00016	0.99972 ± 0.00016
Assembly 24	1.0023 ± 0.0010	1.00482 ± 0.00014	0.99507 ± 0.00016
Assembly 25	1.0013 ± 0.0013	1.00687 ± 0.00014	0.99788 ± 0.00014
Z25 Central plate zone	1.0014 ± 0.0013	1.00570 ± 0.00016	0.99610 ± 0.0002
Assembly MZA	1.0097 ± 0.0016	1.01418 ± 0.00015	1.00948 ± 0.00015
Assembly MZB/3	1.0044 ± 0.0009	1.00898 ± 0.00012	1.00518 ± 0.00012

The measured values for MZA and MZB/3 differ from earlier published values. In the earlier models the superlattice grid plates were not represented and a correction was made for this

effect. They are now represented in the models. In the case of the Cadenza Assemblies, 22, 23, 24 and 25, the earlier models also did not represent the superlattice plates but no correction was made for neglecting the effect. It was treated as negligible in the determination of the measured k-effective value to use with these models. Again, they are now represented in the models.

4. The Simplified MCNP models

In the detailed models there are small void gaps inside and outside the element sheaths and also larger void gaps between the groups of 5x5 elements. A set of models has been produced (called Model B) in which the steel element tube material has been smeared over the void regions between the plates (or calandria) and the sheath and between the sheaths within the groups of 5x5 elements, the superlattice void gap and grid plates being preserved . This has been done to investigate the effects of streaming in the void gaps. It is considered that the void gaps within the groups of 5x5 will not be continuous in reality because of slight bowing of element tubes. This set of models is denoted by Z22B.txt etc. (for the JEFF-3.1 versions) and Z22Y.txt etc. (for the JENDL-3.3 versions), with the final letters of the name being B or Y.

Also, the plan view of the elements is not completely regular, there being a small gap between groups of 5x5 elements. Simplified models have been produced which treat the assemblies as regular arrays having the average lattice spacing (Model C). The void gaps are treated in the same way as in Model B, with the wrapper material smeared over the void regions, with the lattice cell now being slightly wider. Model C can be more easily treated using deterministic methods than the detailed models, A and B. The MCNP input decks for these models are denoted by Z22C.txt etc. (for the JEFF-3.1 versions) and Z22X.txt etc. (for the JENDL-3.3 versions).

A further set of simplified models has been set up in which there is just one type of core element (or inner core and outer core in the case of the two region core, MZB). This is denoted by Model CS (with S for simplified added) and the MCNP decks fot these models have the name Z22J.txt etc. (for the JEFF-3.1 versions) and Z22K.txt etc. (for the JENDL-3.3 versions).

The dirrerences between the different models have been calculated using MCNP and also the MONK Monte Carlo code (Serco, UK).

Model Z22C is the same as model Z22CS because this core has only one type of element. In the plate geometry core, Zebra 24, the sodium plates of Assembly 22 are replaced by so-called "dummy" plates containing approximately the same quantity of steel and having about the same thickness as the sodium plates. There is a slight difference in thickness because the sodium plates are measured to be compressed by the weight of the stack of plates above and this difference is taken into account in the models. In fact, three different "dummy" plates were used but the simplified MCNP model for Zebra 24, Z24J uses just one type of "dummy" plate.

In the case of the simplified MCNP Models CS of the Cadenza pin geometry cores, Zebra Assemblies 23 and 25 (Z23J.txt etc) a further approximation has been made. There is an outer ring of plate geometry elements in these cores and these have been replaced in the simplified models by pin geometry elements. In Zebra 23 the effect of replacing 44 plate elements in the outer radial ring (out of the total in the ring of 49 plate elements) by pin elements was measured to be a reduction in reactivity of 0.7×10^{-4} dk. In Zebra 25 the reactivity effect of replacing 66 of the 69 plate elements by pin geometry elements was measured to be a reduction in reactivity of 2.1 x 10^{-4} dk. These reactivity changes are small compared with the uncertainty in the measured reactivities of these cores and so it is considered acceptable to make this approximation. Furthermore the cores have been approximated as containing just the one type of pin geometry element, the dominant one.

The question of whether adjustments should be made to the results of k-effective calculations made using these simplified models has been considered. The agreement between the different models for Assemblies 22, 23, 24 and 25 is within the uncertainty of the MCNP/JEFF-3.1 calculations. The values are compared in the following Table.

MCNP/JEFF-3.1 k-eff values Calculated using Different Models for Assemblies 22, 23, 24 and 25

	Assembly 22	Assembly 23	Assembly 24	Assembly 25
Reference Model A	1.00614 ± 0.00015 1.00619 ± 0.00014	1.00836 ± 0.00016 1.00826 ± 0.00016	1.00482 ± 0.00015	1.00687 ± 0.00015
Model B	1.00639 ± 0.00016	1.00831 ± 0.00014	1.00526 ± 0.00016	1.00723 ± 0.00014
B - A	+0.0002 ± 0.0002	0.0000 ± 0.0002	+0.0004 ± 0.0002	+0.0004 ± 0.0002
Model C	1.00594 ± 0.00015	1.00849 ± 0.00014	1.00495 ± 0.00015	1.00722 ± 0.00015
C - A	-0.0002 ± 0.0002	+0.0002 ± 0.0002	+0.0001 ± 0.0002	+0.0004 ± 0.0002
Model J=ModelCS		1.00818 ± 0.00015	1.00499 ± 0.00016	1.00668 ± 0.00015
CS - A		-0.0002 ± 0.0002	+0.0002 ± 0.0002	-0.0002 ± 0.0002

The quoted standard deviations are the ones calculated by MCNP from the variation about the mean for individual stages of the calculation. However, other factors can affect the accuracy of results, such as the initial fission source distribution, the number of settling stages and the number of histories per stage. Calculations made for the pin geometry Assemblies 23 and 25 have shown some convergence problems, in particular for the sodium voided Assembly 25, and so the number of settling stages has been increased from 100 to 200 for Assembly 25. There is also the question of how accurately the modelling is being reproduced in the code, representing the arrays of components within cells, cells within elements, forming groups of elements and then arrays of these groups.

For the Mozart Assemblies the following values have been obtained, and the values calculated using MONK/JEF-2.2 are included for comparison.

k_{eff} values calculated for MZA Models A, B, C and CS

	MZA MCNP-JENDL-3.3	MZA MCNP-JEFF-3.1	MZA MONK JEF-2.2
Model A	1.00948 ± 0.00015	1.01418 ± 0.00015	1.0121 ± 0.00015
Model B	1.00987 ± 0.00016	1.01412 ± 0.00016	1.0124 ± 0.00015
(B-A) Average = +3 x 10^{-4}	(+3.9 ± 2.1) x 10^{-4}	(-0.6 ± 2.1) x 10^{-4}	(+3 ± 2) x 10^{-4}
Model C	1.00931 ± 0.00016	1.01392 ± 0.00015	1.0124 ± 0.00015
(C-B)	(-5.6 ± 2.3) x 10^{-4}	(-2.0 ± 2.2) x 10^{-4}	(0 ± 2) x 10^{-4}
(C-A)	(-1.7 ± 2.2) x 10^{-4}	(-2.6 ± 2.1) x 10^{-4}	(+3 ± 2) x 10^{-4}
Model CS (one type of element)	1.00981 ± 0.00015	1.01430 ± 0.00019	
(CS-C) Average = +4 x 10^{-4}	(+5.0 ± 2.2) x 10^{-4}	(+3.8 ± 2.4) x 10^{-4}	
(CS-B)	(-0.6 ± 2.2) x 10^{-4}	(+1.8 ± 2.4) x 10^{-4}	
(CS-A) Average = +2 x 10^{-4}	(+3.3 ± 2.1) x 10^{-4}	(+1.2 ± 2.4) x 10^{-4}	

k_{eff} values calculated for MZB/3 Models A, B and C

	MZB/3 MCNP-JENDL-3.3	MZB/3 MCNP-JEFF-3.1	MZB/3 MONK JEF-2.2
Model A	1.00518 ±0.00012	1.00898 ±0.00012	1.0072 ± 0.00015
Model B	1.00523± 0.00014	1.00963 ± 0.00014	1.0066 ± 0.00015
Difference (B-A)	(+0.5 ± 1.8) x 10^{-4}	(+6.5 ± 1.8) x 10^{-4}	(-6 ± 2) x 10^{-4}
Model C	1.00502 ± 0.00010	1.00886 ± 0.00015	1.0069 ± 0.00015
Difference (C-B)	(-2.1 ± 1.7) x 10^{-4}	(-7.7 ± 2.1) x 10^{-4}	(+3 ± 2) x 10^{-4}
Difference (C-A) Average = -2 x 10^{-4}	(-1.6 ± 1.6) x 10^{-4}	(-1.2 ± 1.9) x 10^{-4}	(-3 ± 2) x 10^{-4}
Model CS (one type of element)	1.00427± 0.00014	1.00854 ± 0.00014	
Difference (CS-C)	(-7.5 ± 1.7) x 10^{-4}	(-3.4 ± 2.1) x 10^{-4}	
Difference (CS-B) Average = -10 x 10^{-4}	(-9.6 ± 1.7) x 10^{-4}	(-10.9 ± 2.0) x 10^{-4}	
Difference (CS-A) Average = -7 x 10^{-4}	(-9.1± 1.8) x 10^{-4}	(-4.4 ± 1.8) x 10^{-4}	

In the case of MZA and MZB the ways the results for models B and C differ from Model A vary with the method and nuclear data used and the effects are not systematic. For the simplified models CS (which have just a single type of inner core and outer core element, the dominant ones) the results show that the effects of the simplifications are small but probably not negligible. They are probably best calculated using deterministic methods and simpler models than the Monte Carlo methods which have been used here

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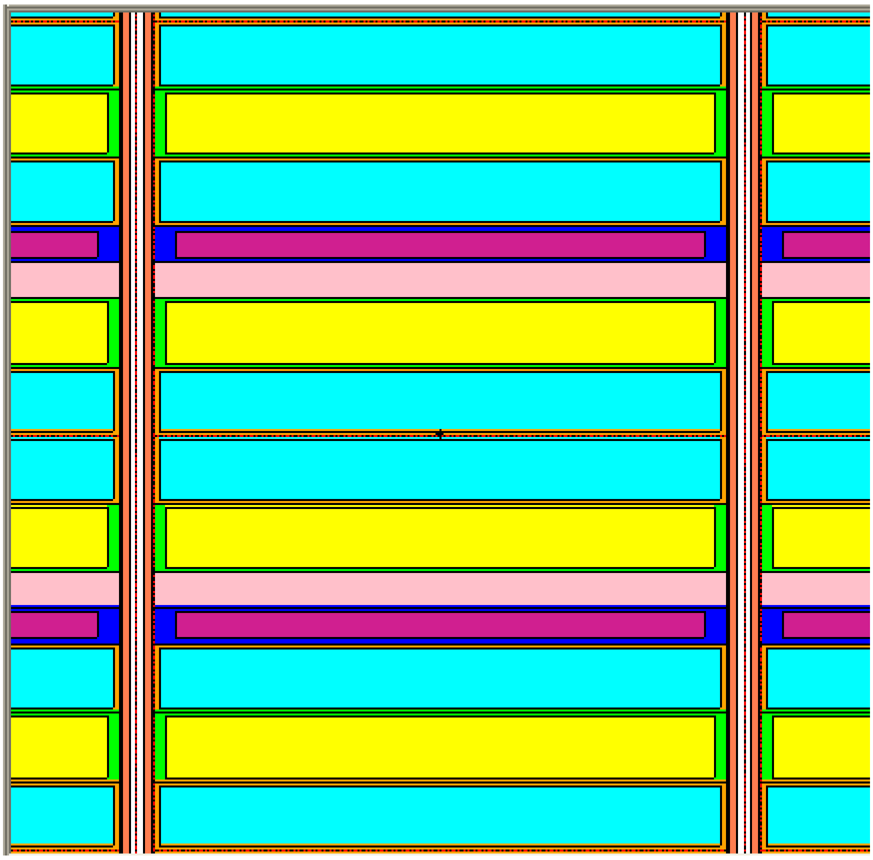

Fig. 1. Array of plates in the core cells of Zebra22 (as displayed by the MCNP Visual Editor). Cell pattern. The sequence of plates in these two core cells is:
Na; UO2; Na; Pu; SS; UO2; Na; Na; UO2; SS; Pu; Na; UO2; Na;

The cells of Zebra 24 differ only in the replacement of the sodium plates by "dummy" plates comprising steel and a void region replacing the sodium.
There are 24 core cells in an element. The bottom and top cell do not contain the steel plate, containing just 6 plates (3xNa, 2xUO2, plus Pu).
Above and below the core cells are natural uranium axial blanket regions, and outside these axial reflector regions.

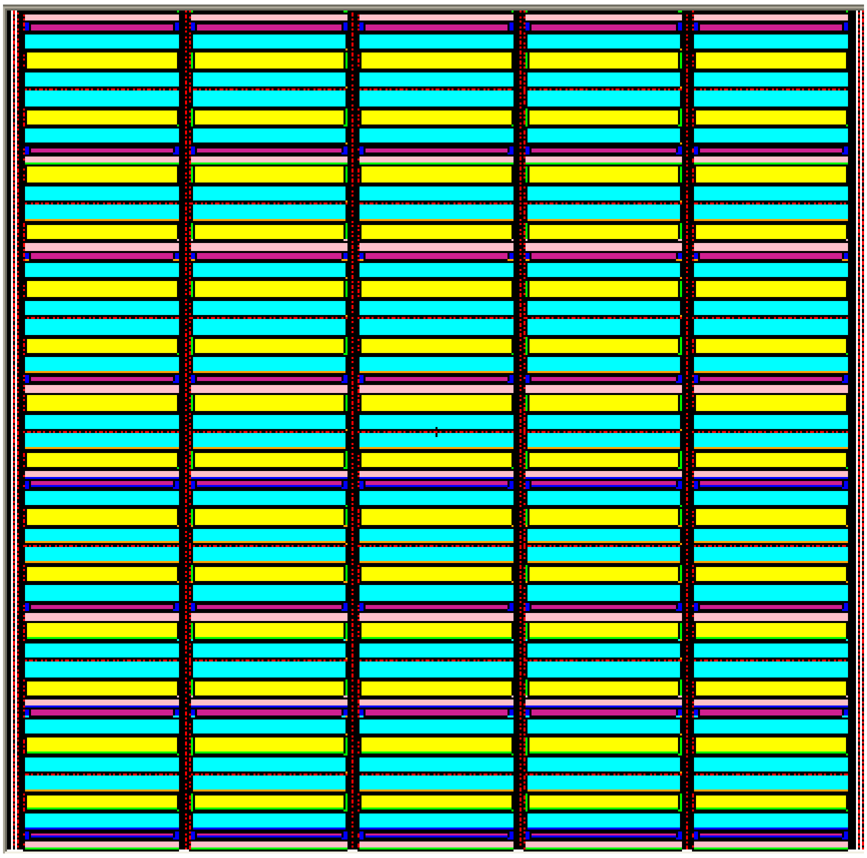

Fig. 2. Cross-section of the plates in 5 core elements within the superlattice grid spaces.

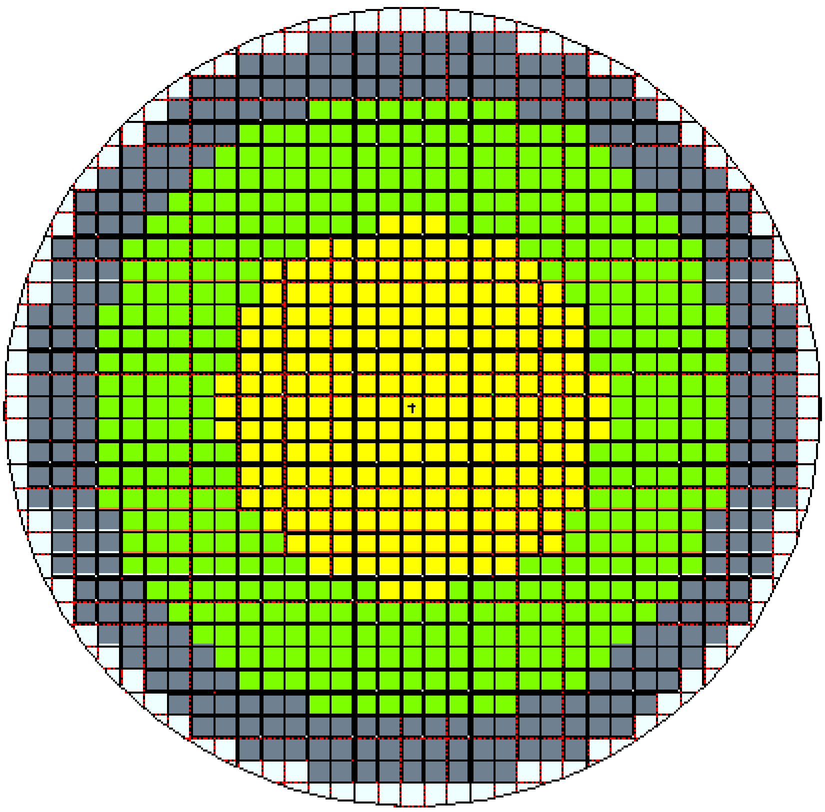

Fig. 3. Plan of the Zebra 22 assembly showing the Core, Natural Uranium Radial Blanket and Steel Reflector Regions.
The Blanket and the Reflector Elements, and the outer boundaries of these regions, are the same in the four Cadenza Cores, Zebra 22 to Zebra 25.

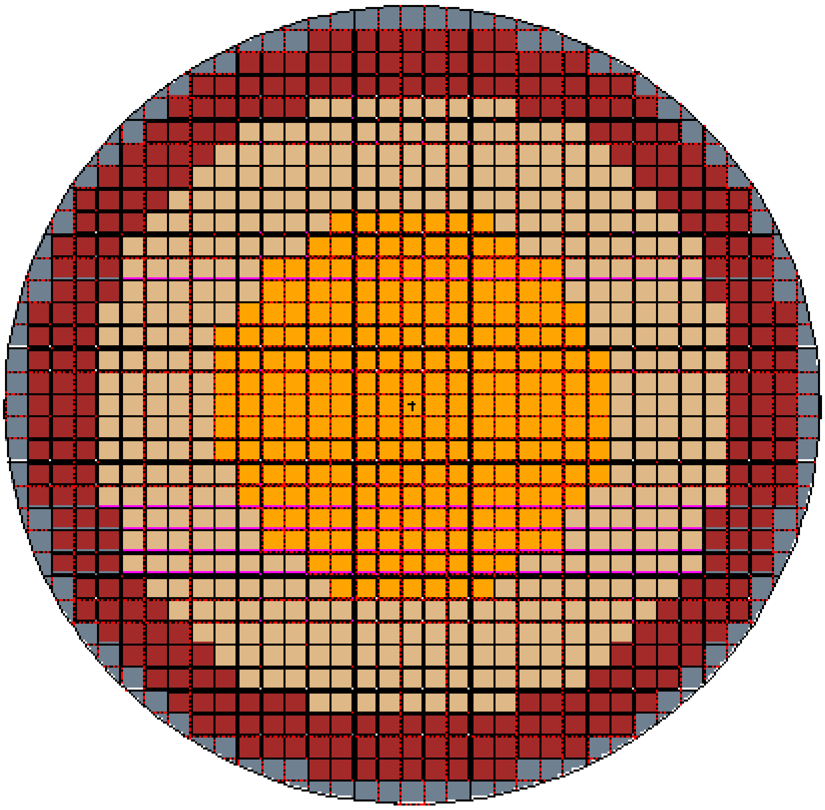

Fig.4. Core Plan of the Zebra 24 assembly.

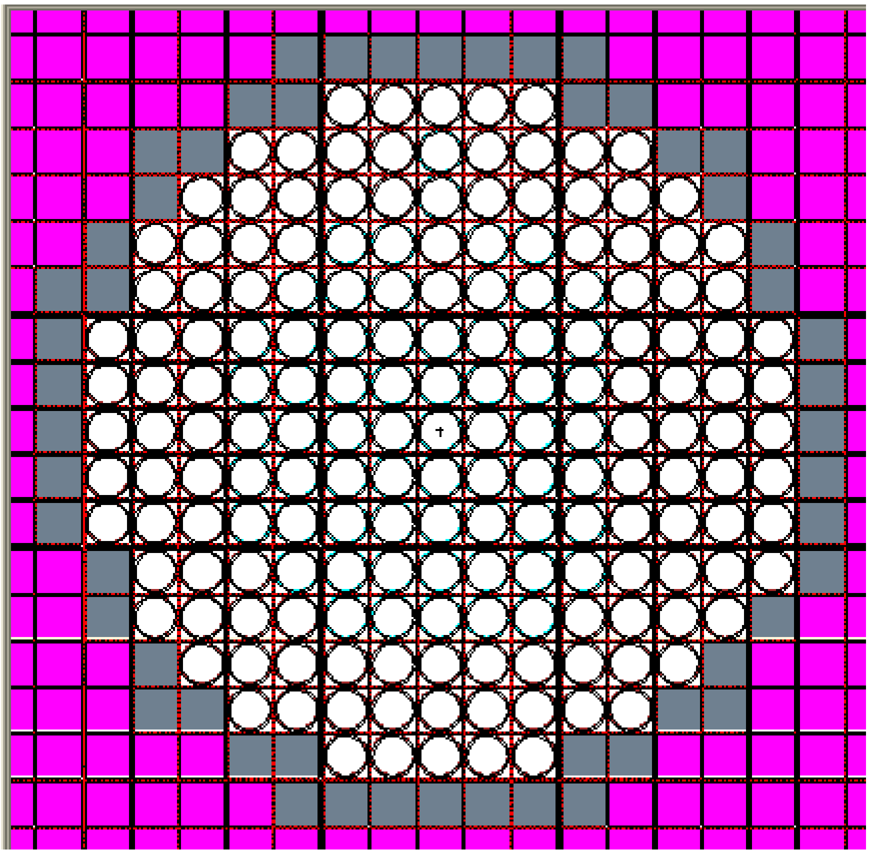

Fig. 5. Zebra 24 core plan showing the positions of the elements containing the two types of ring shaped “dummy” plates (which replace the sodium plates of Zebra 22) surrounded by the ring of elements containing the “honeycomb shaped” “dummy” plates.

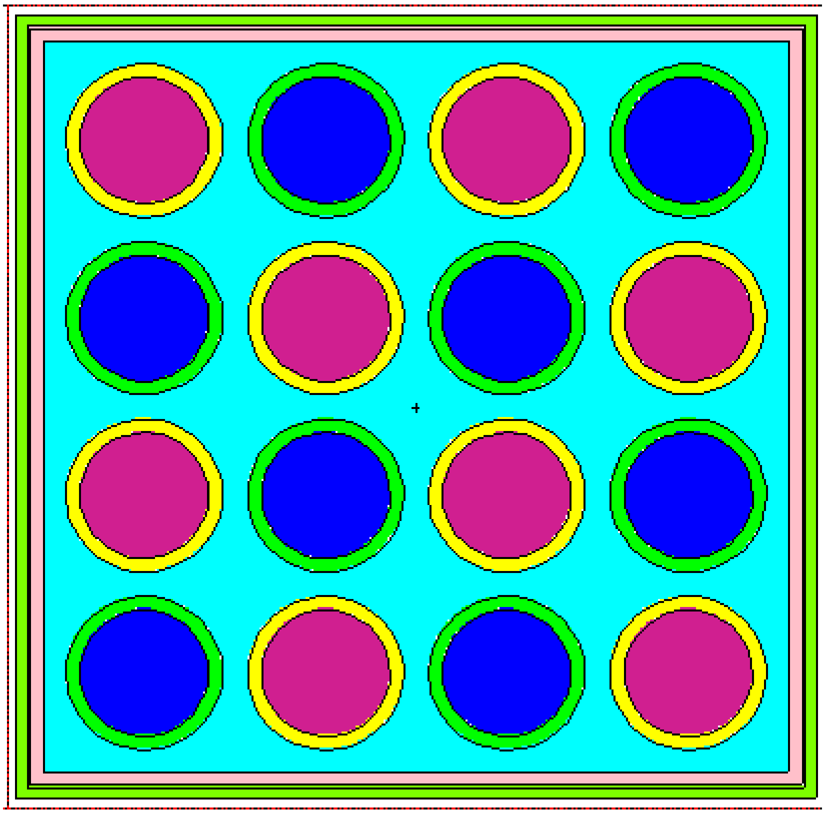

Fig. 6. 4 x 4 array of pins in the calandria which form the core cells of Zebra 23 and Zebra 25. Note: in this model the fuel pin canning has been merged with the calandria tubes.

There are three calandria in the core region of each element, one above the other.
In the Zebra 23 elements the calandria contain sodium and in Zebra 25 they are without sodium.

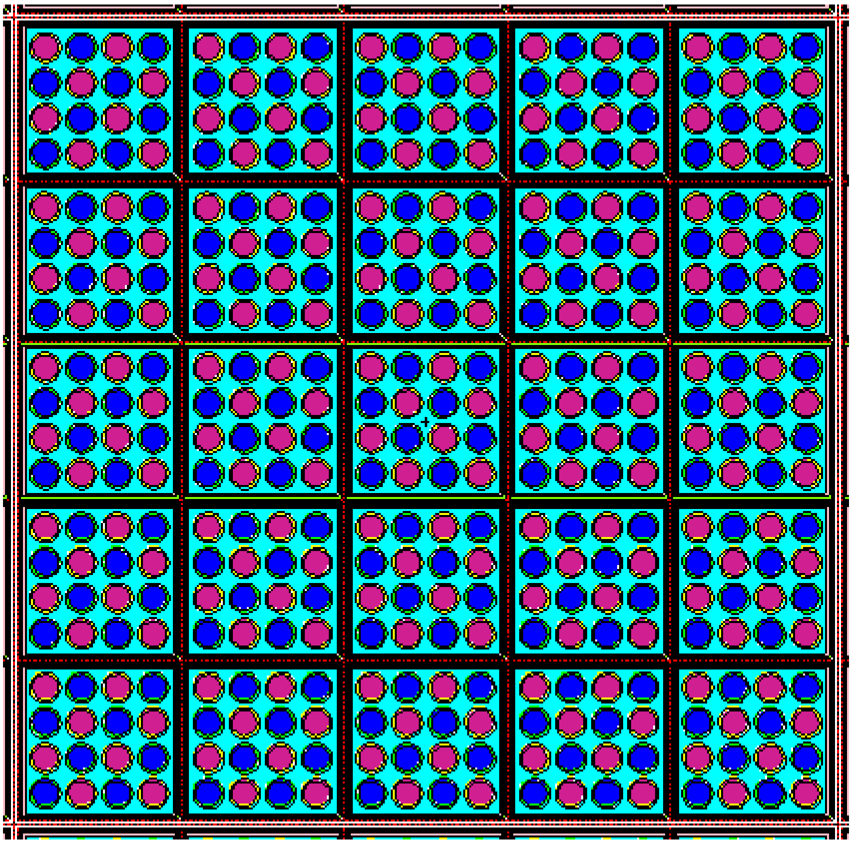

Fig. 7. Array of 5x5 pin geometry elements within the central superlattice grid.

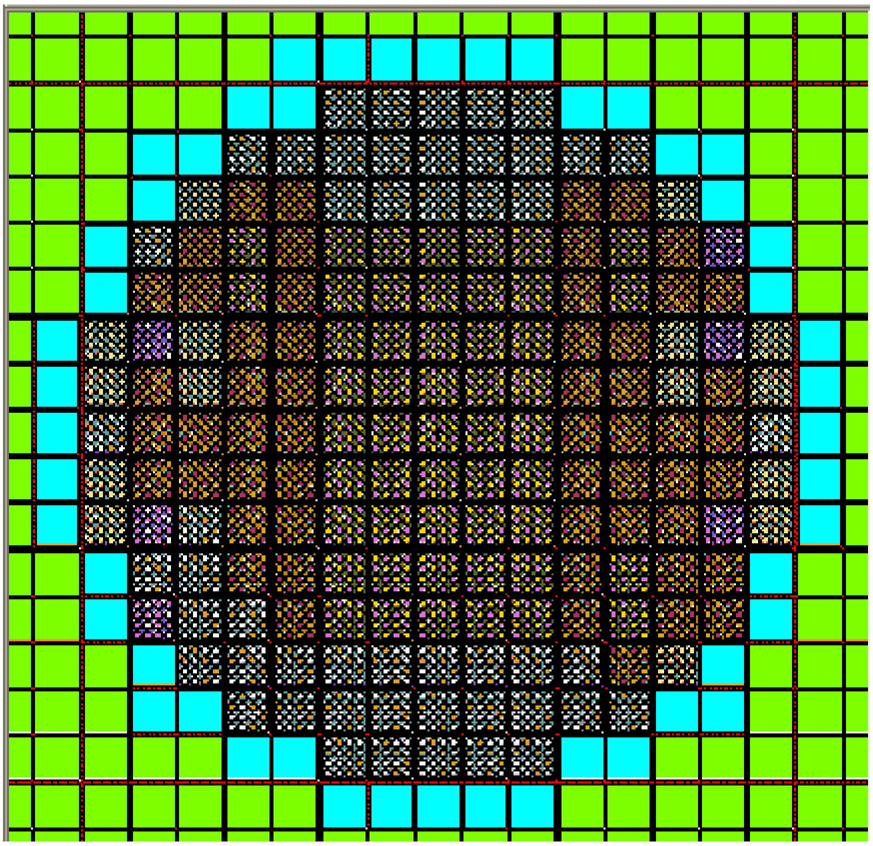

Fig. 8. Plan of the Zebra 23 core showing the outer ring of plate geometry elements and the different pin geometry elements.
(Note: the view is reflected about the Y axis relative to that given in the detailed documentation)

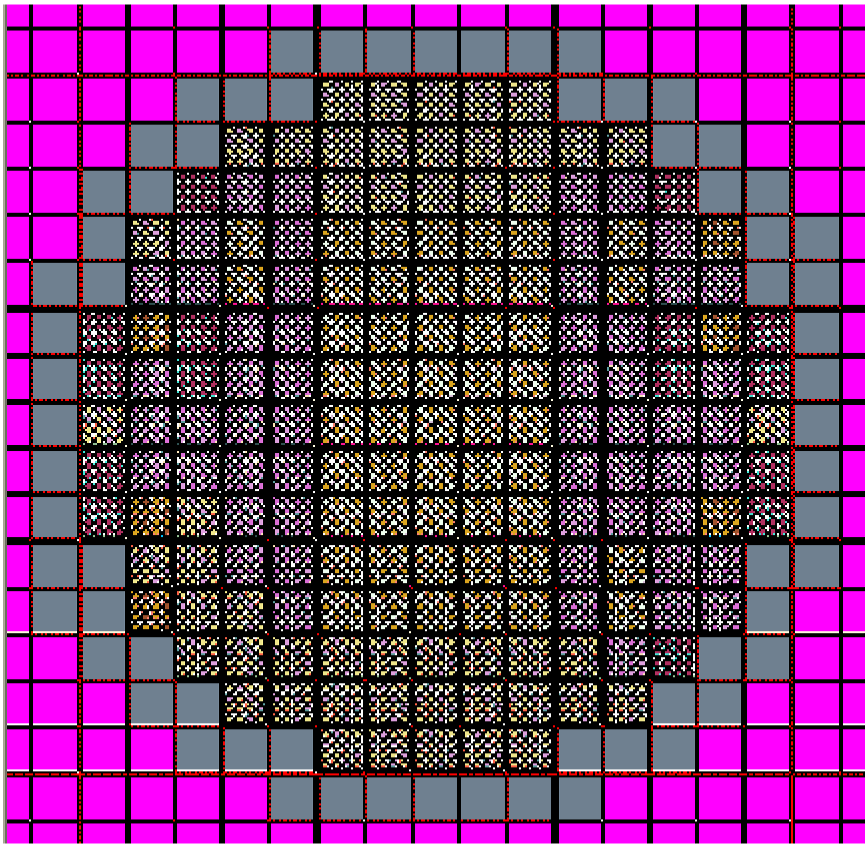

Fig. 9. Plan of Zebra 25 showing the positions of the ring of plate geometry elements at the core radial boundary and the different pin geometry elements in the core.

The array of pin geometry elements in Zebra 25 is the same as in Zebra 23 but the calandria are voided of sodium. The plate geometry elements at the radial boundary of the core are the same elements, voided of sodium, as those used in Core 24.
There are more radial boundary plate geometry elements than in Zebra 23.

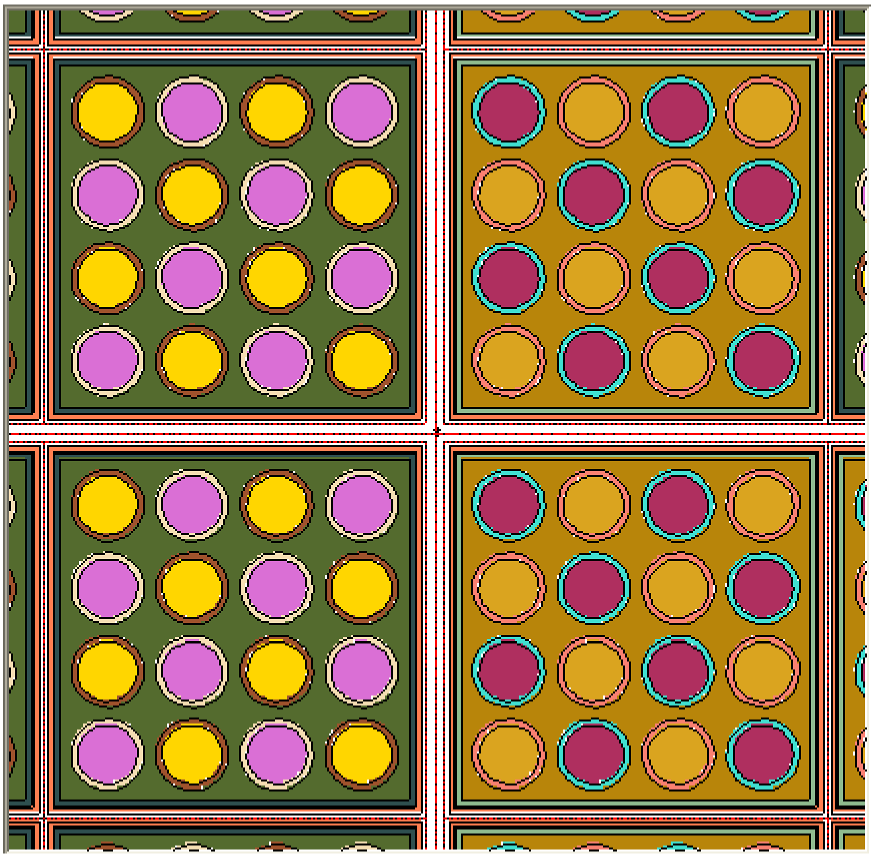

Fig. 10. A section of the detailed MCNP model of Zebra 23 showing the superlattice structure and the different types of pin geometry element on either side of the superlattice grid regions.

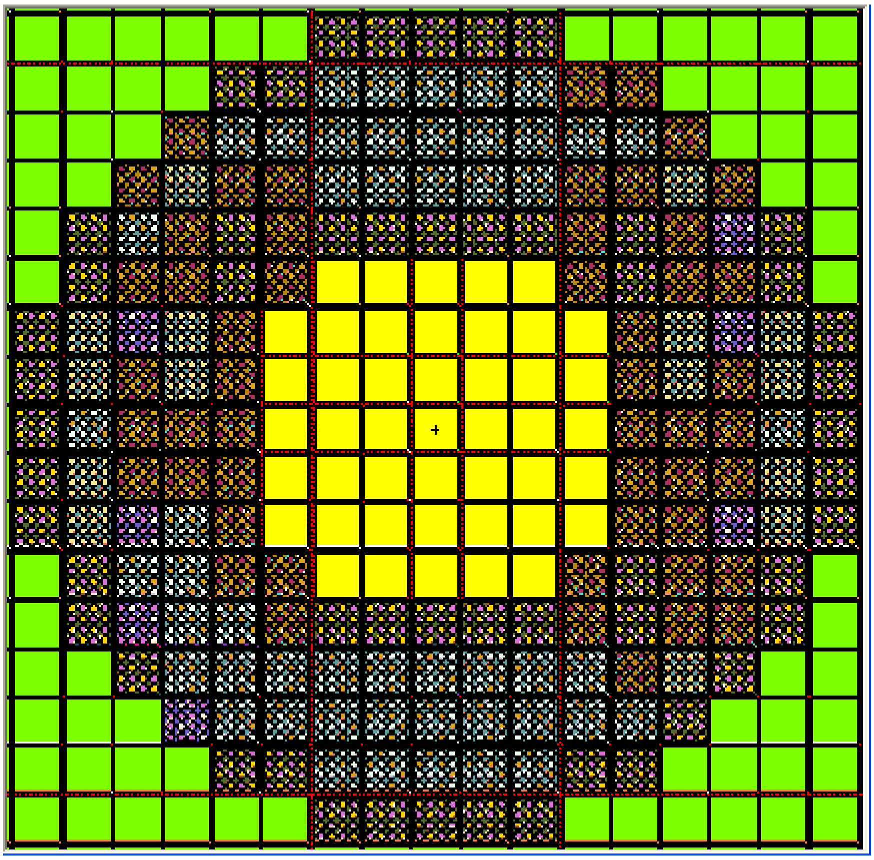

Fig. 11. The version of Zebra 23 with a central plate zone.

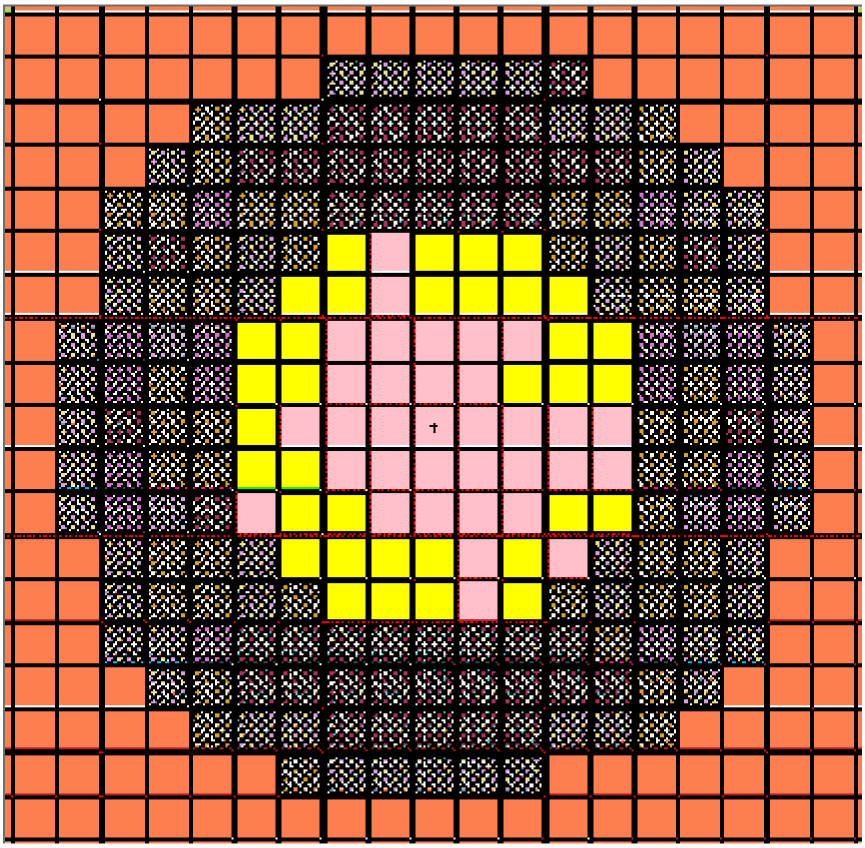

Fig. 12. The version of Zebra 25 containing a central plate zone, showing the Y and Z type plate elements, the central region being predominantly type Y.

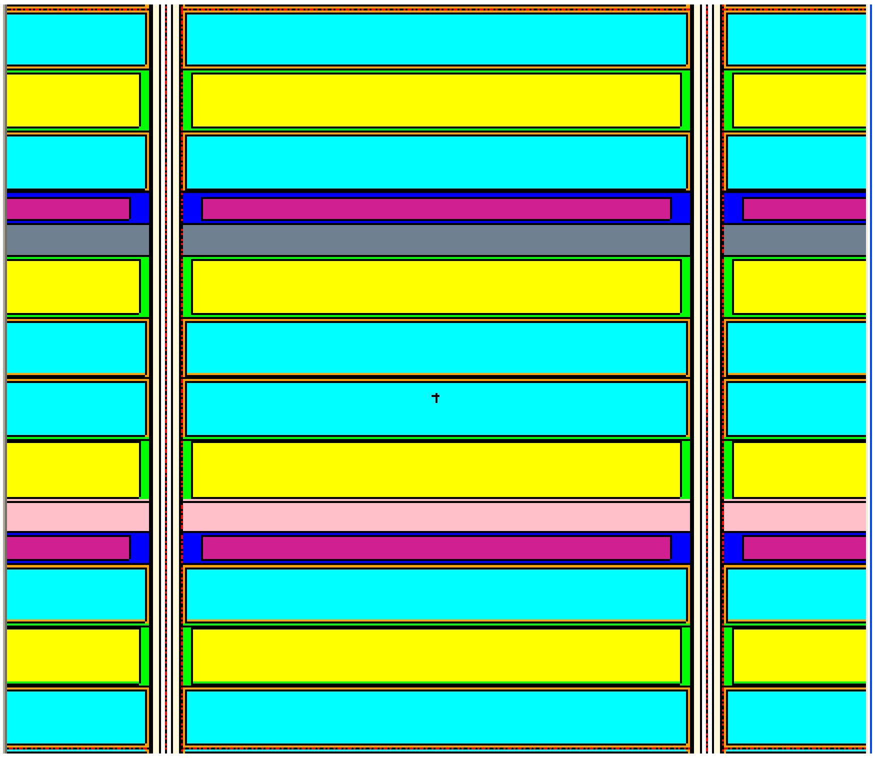

Fig.13. Core region cell pattern of MZA.
Also the Outer Core region cell of MZB.

Cell Pattern:
Na; UO2; Na; Pu; SS; UO2; Na; Na; UO2; C; PU; Na; UO2; Na;

There are 12 core cells in each core element with 4 axial blanket cells above and below.

There are four versions of the MZA core cell, denoted by A, B, C and D.
They differ in the plutonium metal plates used and also in the sodium plates.
The plutonium plates are respectively:PUV8, PUVI8, PUVII8 and PUVIII8.
The sodium plate used in cell A is NASTBR4 and in cells B, Cand D is NASTDL4.

The elements containing these four versions of the core cell are similarly named A, B, C and D

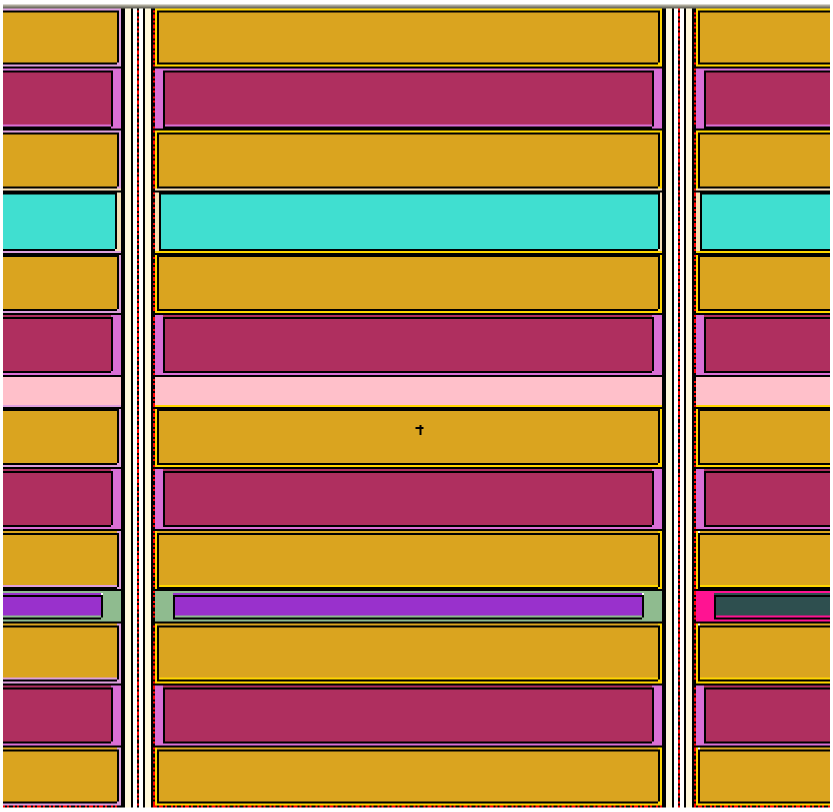

Fig. 14. The MZB Inner Core Cell.

Cell Pattern:
Na; UO2; Na; Pu; Na; UO2; Na; SS; UO2; Na; MOX; Na; UO2; Na;

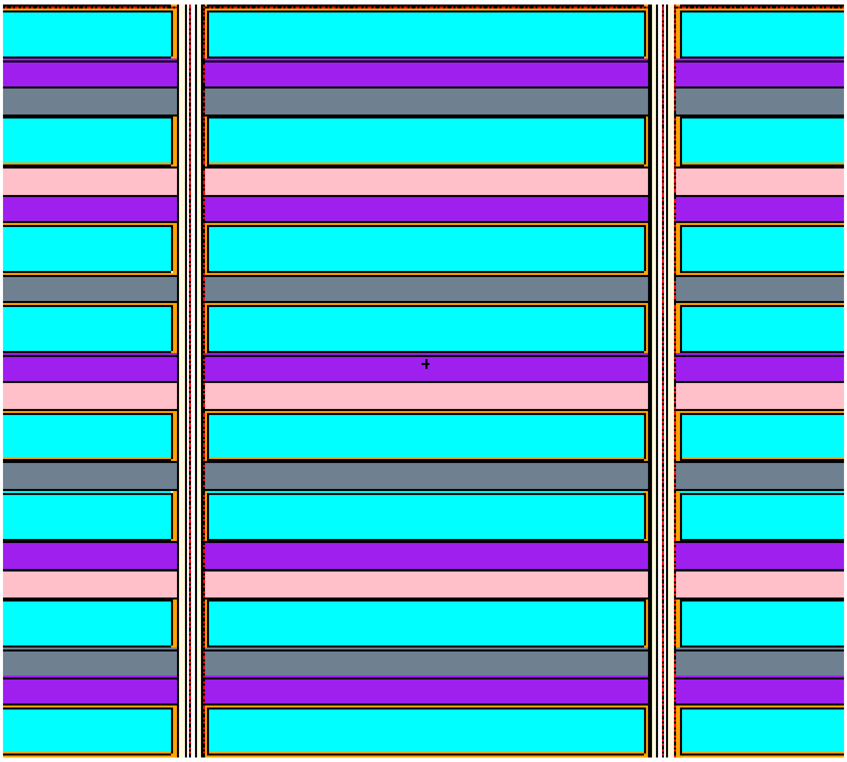

Fig. 15. The MZA and MZB Axial Blanket Cell.

Cell Pattern:
Na; U8; C; Na; SS; U8; Na; C; Na; SS; U8; Na; C; Na; U8; SS; Na; C; U8; Na

There are 4 cells in the lower axial blanket and 4 in the upper axial blanket region of each core element. Outside these regions are the plenum regions containing aluminium and mild steel plates.

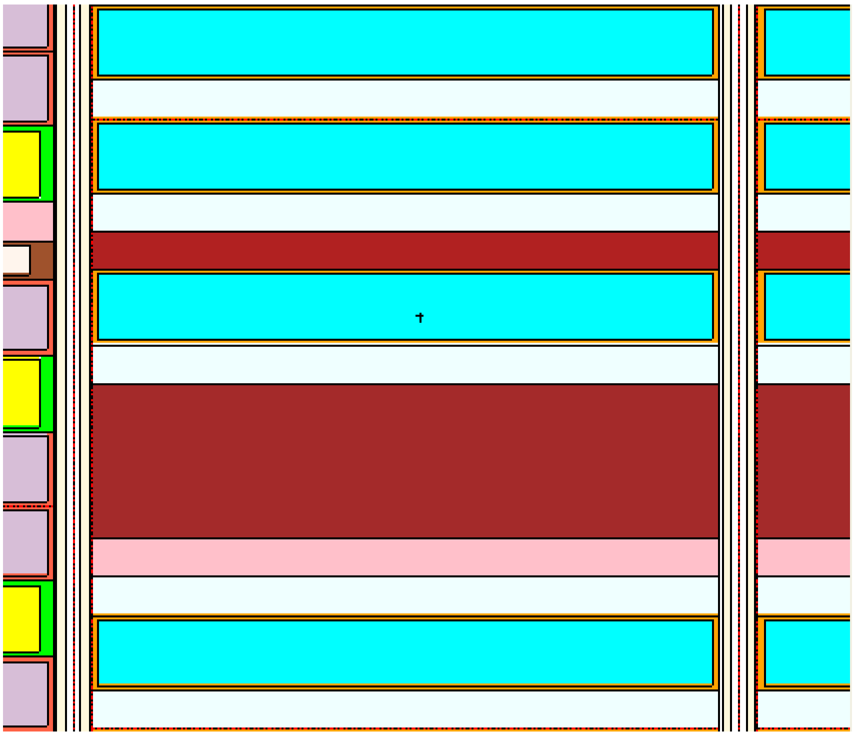

Fig.16. MZA and MZB Radial Blanket Central Section Cell.

Cell Pattern:
C; Na; C; SS; U2; C; Na; MS; C; Na

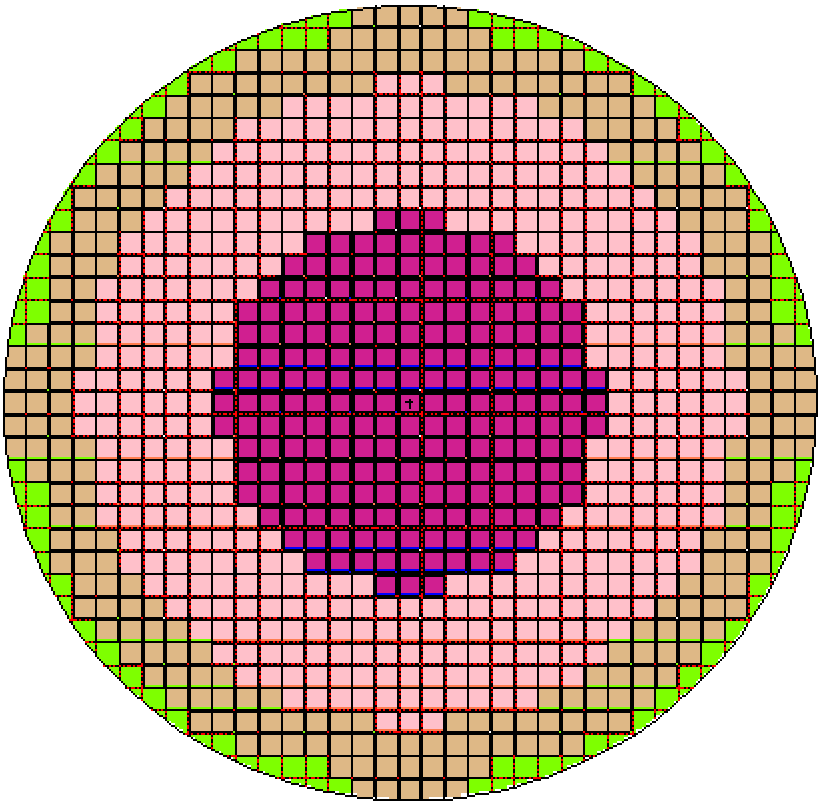

Fig. 17. Plan of MZA showing the Core, Radial Blanket and Reflector elements.

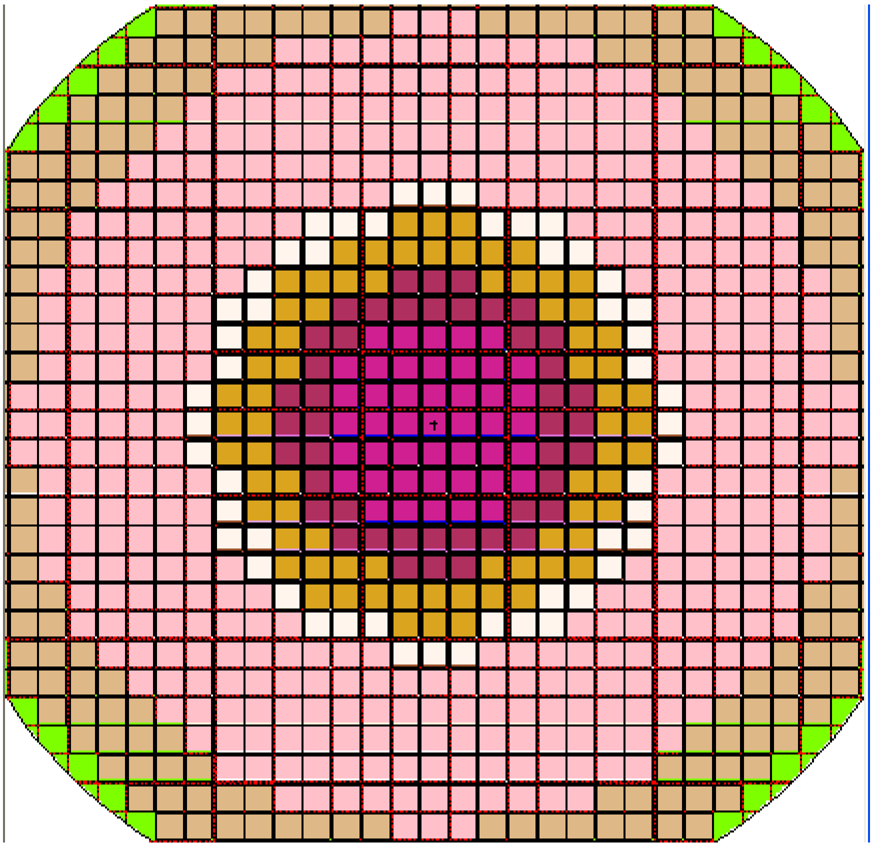

Fig. 18 . Plan view showing the disposition of the four different types of element in the core of MZA, denoted by A, B, C and D.

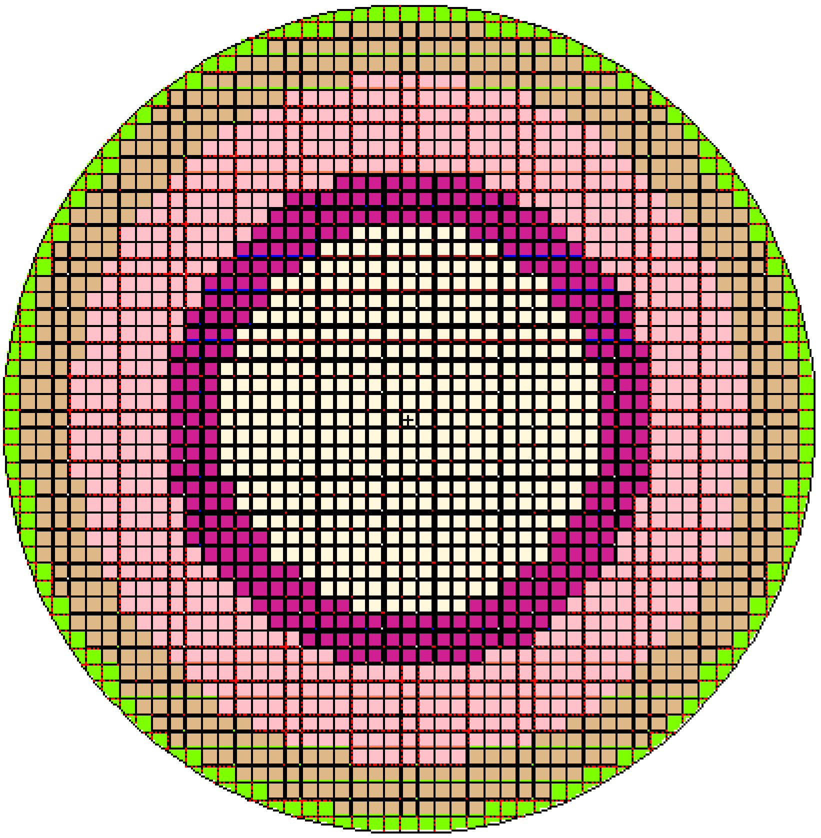

Fig. 19. Core plan of MZB showing the Inner Core, Outer Core, Radial Blanket and Reflector regions. (See Fig. 22 for detailes of the steel and graphite reflector elements not represented in this simplified model).

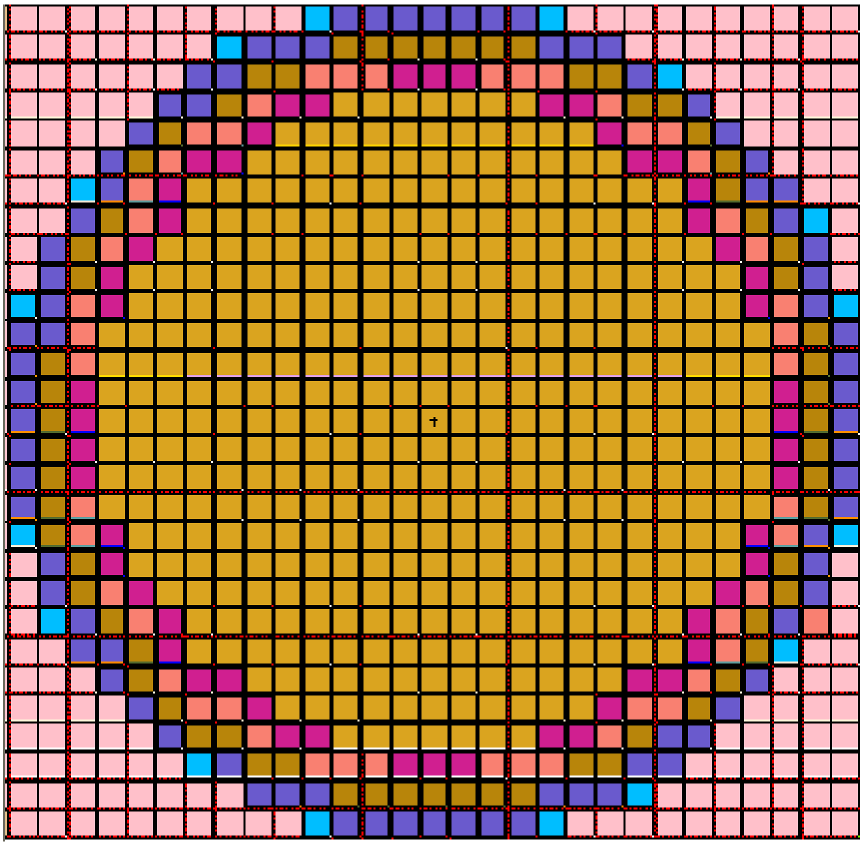

Fig. 20. MZB core plan showing positions of the different outer core elements, Types A, B, C, D and G containing the different plutonium metal plates. There are two different versions of the B and D elements associated with the different sodium plates.

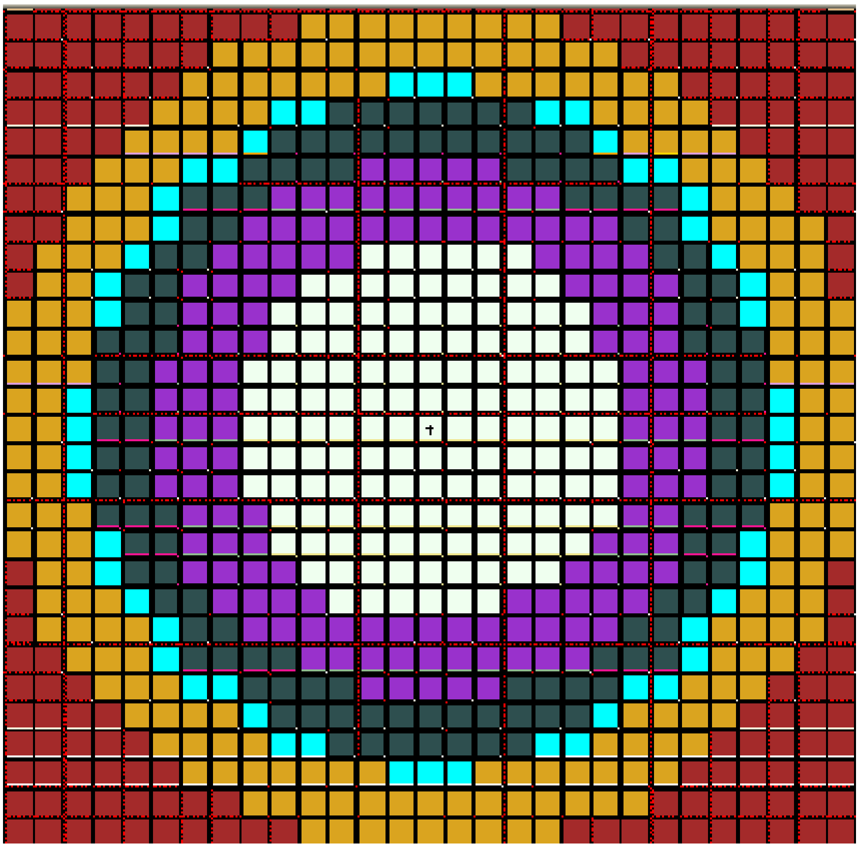

Fig. 21. MZB core plan showing the positions of the inner core elements containing different plutonium metal plates.

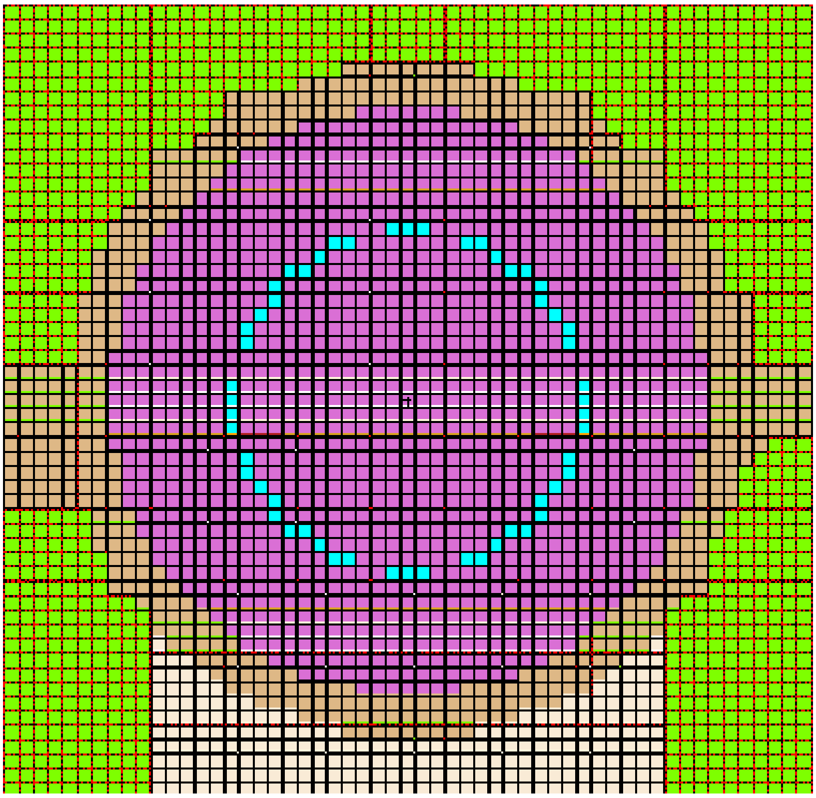

Fig. 22. Plan of MZB showing the steel reflector or shield rods and the graphite reflector region at the bottom of the diagram.