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KENO-VI: A MONTE CARLO CRITICALITY PROGRAM WITH GENERALIZED QUADRATIC GEOMETRY

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ABSTRACT

KENO-VI is a new version of the KENO Monte Carlo Criticality Safety Code developed at Oak Ridge National Laboratory. The purpose of KENO-VI is to provide a criticality safety code similar to KENO-V.a that possesses a more general and flexible geometry package. KENO-VI constructs and processes geometry data as sets of quadratic equations. A lengthy set of simple, easy-to-use geometric functions, similar to those provided in KENO-V.a, and the ability to build more complex geometric shapes represented by sets of quadratic equations are the heart of the geometry package in KENO-VI. The code's flexibility is increased by allowing intersecting geometry regions, hexagonal as well as cuboidal arrays, and the ability to specify an array boundary that intersects the array.

INTRODUCTION

KENO-V.a[1] is one of the leading Monte Carlo criticality safety codes used throughout the nuclear community. It is a reliable, easy-to-use criticality safety code possessing a significant amount of flexibility and numerous options that can run either as a stand-alone module or as part of the overall SCALE[2] Criticality Safety Analysis Sequence. Restrictions to KENO-V.a geometry modeling include being limited to five basic geometry types and not allowing geometry intersections. KENO-V.a constructs units using nested nonintersecting regions represented by spheres, cylinders, hemispheres, hemicylinders, and cuboids. A new version of KENO, KENO-VI, is being developed to circumvent these restrictions.

KENO-VI maintains the flexibility and options of KENO-V.a, such as nested arrays and holes, supergrouping, and albedos, while permitting the use of more complex geometry shapes. In KENO-VI, units can be constructed using both the simple geometric shapes provided and tailored geometric shapes constructed using quadratic equations. Thus, units can be constructed using regions of any geometric shape that can be described with generalized quadratic equations. In addition, several new features have been included in

KENO-VI such as intersecting regions, triangular-pitched arrays, array boundaries, and the ability to directly put more than one array in a unit.

KENO-VI

Presently, KENO-VI can only be run as a stand-alone module. Eventually KENO-VI will be included as part of the SCALE[2] Criticality Safety Analysis Sequence. SCALE is a modular code system, developed for the U.S. Nuclear Regulatory Commission, used to perform standardized computer analyses for nuclear fuel facility and package licensing evaluation. KENO-VI can use either an ICE[3] mixed cross-section format library or an AMPX[4] working format library for its cross-section data, as is done in KENO-V.a. ICE[3] is a SCALE module used to mix cross-section data used in criticality and shielding modules of SCALE. The AMPX[4] working format is an efficient method for storing multigroup cross-section data used in the SCALE criticality and shielding modules.

Data entry for KENO-VI is similar to that for KENO-V.a. The PARAMETER, BIAS, BOUNDARY, START, MIXT, X1DS, and PLOT data blocks are identical in both KENO-V.a and KENO-VI. From a user's standpoint, the two versions of KENO primarily differ in the GEOMETRY section, where the system's geometry is specified. A minor change is also present in the ARRAY section. Hexagonal (triangular-pitched), as well as cuboidal, arrays can now be specified.

Like KENO-V.a, KENO-VI uses "units" to represent the geometric configuration of a system. Each unit, which is composed of a set of geometry/material regions, has its own independent coordinate system. A primary difference between KENO-V.a and KENO-VI is the methodology used to represent these geometry/material regions. KENO-V.a uses a single geometry record to describe a region which consists of a geometry word, mixture ID, bias ID, dimensions, and optional data. KENO-VI uses two geometry records to describe a region. The first record, called the GEOMETRY record, contains the geometry keyword, region boundary definitions, and geometry modification data, if applicable. The second record, called the MEDIA record, contains the media keyword, the ID number of the material, hole, or array contained in that geometry region, the bias ID if required, and how the region relates to other geometry regions in the unit. Intersecting geometry regions are allowed.

Units with matching faces of the same size can be stacked together to create an array. Arrays can then be placed directly into another unit. More than one array can be directly placed in a given unit. Units and arrays can also be placed within other units using holes. Unlike KENO-V.a, a global unit must be specified in each problem, including single-unit problems. Any number of holes and arrays may be placed in a unit nested to any level.

GEOMETRY

Any geometric shape that can be described using quadratic equations[5] can be represented with the KENO-VI geometry package. The geometry records in the problem contain information describing the shape and location of each geometric region. Geometry data are described for each unit independently. Geometry records are used to describe the geometric shapes contained in the unit. Media records are then used to describe the materials contained in the geometric shapes. The geometry and media records can be combined in any order, but each record type is processed sequentially. This means the first geometry record is geometry region 1, the second geometry record is geometry region 2, and so on when referring to the geometry record numbers in the media records. A boundary geometry record, specified using the keyword BOUNDARY, is required for each unit to define the outermost surface of the unit.

A standard set of simple geometric shapes is available to simplify the geometric input data. Geometry keywords may be input as terse data by using only the first few characters in the keywords needed to uniquely define them. These characters must, however, match the keyword exactly. A list of allowed geometry keywords and a description of the input associated with each keyword are given in Table I.

In addition to the geometry keywords, three geometry modification keywords are available to reposition or modify the geometry keyword description they immediately follow. Any or all modification keywords may follow any geometry keyword. Each of the modification keywords is followed by

TABLE I. Geometry Keyword List

KENO-VI GEOMETRY KEYWORD	DESCRIPTION OF INPUT
CONE	Top and Bottom Radius, Top and Bottom Z-Positions
CUBOID	± X, ± Y, and ± Z Positions
CYLINDER	Radius, Top and Bottom Z-Positions
DODECAHEDRON	Inner Radius
ECYLINDER	X-Radius, Y-Radius, Top and Bottom Z-Positions
ELLIPSOID	X-Radius, Y-Radius, Z-Radius
HEXPRISM	Inner Radius, Top and Bottom Z-Positions
HOPPER	Top Half Length along X & Y axis, Bottom Half length along X & Y axis, Top and Bottom Z-Positions
PARALLELPIPED PPIPED	Distance along X, Y, and Z axis. Angles between the X, Y, and Z faces and axes.
PLANE	Non-Zero Coefficients of the Quadratic
QUADRATIC	Non-Zero Coefficients of the Quadratic
RHOMBOHEDRON	The Length of a Side. The angle between the Y-Edge of the Base and the Y-axis
SPHERE	Radius
WEDGE	Length of triangle base along X-axis. X & Y Coordinate of the triangle top. Length of Wedge along the Z-axis.

input parameters. Each of these parameters is flagged by a subordinate keyword. Only non-zero parameters need to be entered. Table II contains a list of the geometry modification keywords and their subordinate keywords.

TABLE II. Geometry modification keyword list

KENO-VI GEOMETRY MODIFICATION KEYWORD	SUBORDINATE KEYWORDS
CHORD	+X=, -X=, +Y=, -Y=, +Z=, -Z=
ORIGIN	X=, Y=, Z=
ROTATE	A1=, A2=, A3=

The first geometry modification keyword, CHORD, is similar to the same word used in KENO-V.a. It provides a plane that truncates a geometry shape. In KENO-VI, a subordinate keyword specifying the direction of the chord is entered followed by the length of the chord. Unlike KENO-V.a, CHORD may be used with any geometry keyword.

The second geometry modification keyword, ORIGIN, is used to translate the origin (0,0,0) of a geometry region to a specified location relative to the origin of the unit. Only the non-zero coordinates need to be specified. This option allows geometric shapes to be translated anywhere within a unit.

The final geometry modification keyword, ROTATE, rotates a body with respect to the origin of the coordinate system of the unit. The input subordinate keywords correspond to the three angles associated with the Euler angles in the X-convention.[6] Only the non-zero angles need to be entered.

MEDIA

Media records are used to describe the contents of the geometry regions in a unit. Each geometry record must have at least one corresponding media record describing its contents. There are three media keywords used to describe the contents of the regions. Table III contains a list of media keywords and a brief description of the input for each media keyword.

TABLE III. Media keyword list

MEDIA KEYWORD	DESCRIPTION OF INPUT
MEDIA	Mixture Number, Bias ID Number, Geometry Region Numbers
ARRAY	Array Number, Geometry Region Numbers Keyword PLACE followed by the X, Y, Z position of the unit used to position the array and the X, Y, Z coordinates of the unit with respect to the origin of the outer region
HOLE	Unit number, Geometry Region Numbers Keywords ORIGIN and ROTATE as describe in the GEOMETRY section above if desired

The keyword MEDIA is used to specify a material mixture number inside a geometry region. Following the keyword MEDIA, the mixture number, the bias ID number, and the region definition vector are entered. The region definition vector is a series of geometry region numbers used to define the location of the mixture within the regions defined by the GEOMETRY records. A positive value of the geometry region number indicates the mixture is located inside the geometry region, and a negative value indicates the mixture is located outside the geometry region. As many geometry region numbers as is necessary to define the volume occupied by the mixture must be entered in the region definition vector. Consider the following example.

```
MEDIA 2 1 3 -1 -2
```

The above line indicates that mixture 2, with a bias ID of 1, is located inside region 3 and outside regions 1 and 2.

The keyword, ARRAY, is used to specify and position an array inside a geometry region in a unit. Following the keyword ARRAY, the array number, the region definition vector, and the keyword PLACE are entered. The keyword PLACE is followed by six numbers which locate the array within the region. The first three numbers identify a unit in the array. The origin of this unit will be used to locate the array. The last three numbers specify the placement location of the array within the region.

Assume array 1 is a 5 x 5 x 5 array of units existing within the boundaries of region 4. Any portions of the array that extend outside region 4 do not exist in the problem. The origin of the central unit in the array is located at the point X = 7.0, Y = 8.0, Z = 9.0 in region 4. The array specifications would be as follows.

```
ARRAY 1 4  PLACE 3 3 3 7.0 8.0 9.0
```

The geometry region containing the array, the array boundary region, can truncate the array or coincide with the array boundary, but it cannot extend outside the array. A particle enters the array when the region defining the outer boundary of the array is entered. While a particle is inside an array, the code tracks it in the coordinate systems of both the array and the surrounding region. The array is exited when the particle crosses out of the region bounding the array. The ability to specify an array boundary that intersects the array allows KENO-VI to model a problem using only one array that would require multiple arrays and holes in KENO-V.a.

In addition to cuboidal (square-pitched) arrays, hexagonal arrays are available in KENO-VI. Hexagonal (triangular-pitched) arrays are constructed the same way cuboidal arrays are constructed. However, since the X-position, with respect to the origin, changes with respect to the Y-position of the array, care must be taken to ensure the array boundary region is completely inside the array. An array is specified as cuboidal or hexagonal in the ARRAY section of KENO-VI. An array type can be specified using TYP="triangular or cuboidal" immediately after the array number is specified. A default of TYP="cuboidal" is assumed if nothing is specified. The ARRAY section in KENO-VI fills the array in the same manner as KENO-V.a.

The keyword HOLE is used to position a unit within another unit. Following the keyword HOLE, the number of the unit being placed in the hole, the region definition vector, and the optional geometry modification keywords ORIGIN and ROTATE with the applicable parameters, are entered. The geometric region containing the hole must exactly match the outer boundary of the unit being placed in the hole.

Consider the example of placing unit number 3 inside geometry region 2 but outside geometry regions 1 and 3. The origin of the unit in the hole is to be located at position X = 0.0, Y = 26.5, Z = 24.9 with the Euler X-convention rotation angles 45.0, 20.5, 0.0. The HOLE specification would be as follows.

```
HOLE 3 -1 2 -3 ORIGIN X=0.0 Y=26.5 Z=24.9 ROTATE A1=45.0 A2=20.5 A3=0.0
```

Unlike array and unit, HOLE is not a physical entity. Instead, it is a method of transferring from the coordinate system of one unit to the coordinate system of another unit. Any number of holes may be contained in a unit, nested to any level. Arrays may be put into holes indirectly by first putting the array in a unit and then placing the unit in a hole.

RESULTS

To demonstrate the flexibility of KENO-VI, a simple triangular-pitched array consisting of seven fuel cells positioned in a circular pattern with no interstitial moderator and no reflector will be examined. Figure 1 contains a listing of the geometry and array data blocks of KENO-VI used to define the geometry data for this problem. The problem consists of 7 cylinders in a triangular-pitched unreflected array having a pitch of 20.774 cm. Each cylinder consists of a 60-mil-thick aluminum can filled with a highly enriched uranyl fluoride solution 10.312 cm in radius and 18.440 cm in length. A cylinder is placed in a hexagon to create a fuel cell.

As shown in the input data contained in Fig. 1, unit 1 containing a fuel cell and unit 2 containing an empty cell are first constructed. A cylindrical region is then constructed in global unit 3 to the size of the boundary used to contain the triangular-pitched array. Array 1, the triangular-pitched array, is centered in this cylindrical region in the global unit. Only the section of the array contained within the cylindrical boundary is actually present in the problem. The 5 x 5 x 1 array is entirely filled with empty cells and fuel cells so the specified boundary is entirely within the array. The actual array being modeled (i.e., the seven fuel pins) is entirely contained within the specified cylindrical boundary.

```
read geometry
unit 1
com='single cell fuel can in hexprism'
cylinder 10.16  18.288  0.0
cylinder 10.312 18.288 -0.152
boundary hexprism 10.387 18.288 -0.152
media 1 1 1
media 2 1 2 -1
media 0 1 3 -2
unit 2
com='empty cell used to fill array'
boundary hexprism 10.387 18.288 -0.152
media 0 1 1
global unit 3
com='array boundary surrounding triangular pitched array'
boundary cylinder 31.161 18.288 -0.152
array 1 1 place 3 3 1 3*0.0
end geometry
read array
ara=1 typ=triangular nux=5 nuy=5 nuz=1
fill 7*2 2*1 2*2 3*1 2*2 2*1 7*2 end fill
end array
```

Fig. 1. KENO-VI ARRAY and GEOMETRY data blocks for a triangular-pitched array problem.

A hexagonal array does not stack the same way a cuboidal array stacks. Care must be taken to ensure that the array boundary is total inside the defined array. This is achieved by defining the array to be larger than is actually needed and filling the unused array positions with empty cells. Figure 2 shows a 5 x 5 hexagonal array with a circular array boundary inside the array. The array positions totally inside the boundary contain fuel cells. The remaining array positions are empty cells.

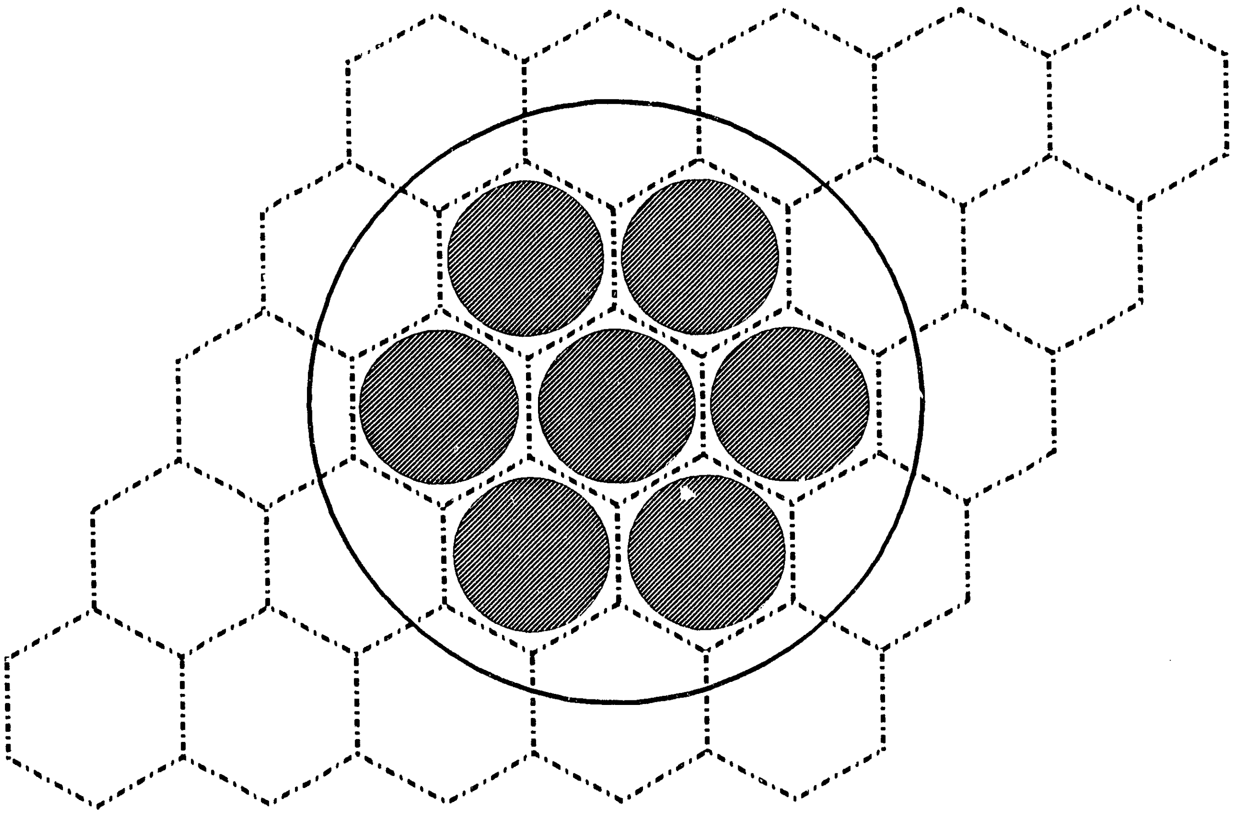

Fig. 2. Triangular-pitched array contained in a cylindrical boundary.

CONCLUSIONS

A new version of KENO, KENO-VI, has been developed which has enhanced geometry capabilities over KENO-V.a. Input specifications for KENO-VI are similar to KENO-V.a with the differences being the method used to model the geometry data. Two records, consisting of a geometry record and a media record, are required in KENO-VI to input a geometry region where only one record was required in KENO-V.a. The standard set of geometry shapes was expanded and the ability to create special geometry regions using quadratic equation was provided. Many systems that could only be approximated in KENO-V.a can now be precisely modelled using the geometry package in KENO-VI.

Using KENO-VI, any system that can be represented by sets of quadratic equations can be exactly modeled. KENO-VI includes the ability to directly model triangular-pitched arrays using hexagonal cells. Although triangular-pitched arrays can be modeled in KENO-V.a using hemicylinders and holes, directly creating a triangular-pitched array greatly simplifies the input. KENO-VI allows an array boundary region to intersect the array, causing the portions of the array that lie outside the boundary to be ignored by the code. The portion of the array contained within the boundary is the only section of the array recognized by the code. The inclusion of a boundary region surrounding an array makes it possible to directly model an array that does not have the same number of units in all rows and columns.

KENO-VI contains the same plotting package currently contained in KENO-V.a. Thought is being given to the creation of a three-dimensional visualization package to be included at a later date.

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