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GRESS Translation of the ORIGEN2 Code

Francois G. Pin
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GRESS TRANSLATION OF THE ORIGEN2 CODE

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ABSTRACT

ORIGEN2 is a widely used point-depletion and radioactive-decay computer code for use in simulating nuclear fuel cycles and/or spent fuel characteristics. In typical applications the code calculates chain buildup and decay of more than 1600 radionuclides and elements. This report describes the addition to the ORIGEN2 code of an automated sensitivity calculation capability by means of the GRESS precompiler. The GRESS precompiler uses computer calculus to automatically enhance FORTRAN computer codes with derivative-taking capabilities. From these derivatives generated concurrently with the normal results, sensitivities of any variable used in the code with respect to any other variable or input parameter can readily be obtained. The added sensitivity calculation capability is verified on a sample problem involving fuel burnup under specified power, radioactive decay, and material irradiation under specified flux. The accuracy of the GRESS results is demonstrated using comparisons with the results of perturbation analyses.

I. INTRODUCTION

ORIGEN2[1] is a point-depletion and radioactive-decay computer code for use in simulating nuclear fuel cycles and calculating the nuclide compositions and characteristics of materials contained therein. It is a revised version of the original ORIGEN computer code[2-5] which was developed at the Oak Ridge National Laboratory in the early 1970's. The revisions include updates of the reactor models, cross sections, fission product yields, decay data, and decay photon data. The list of reactors that can be simulated includes pressurized water reactors, boiling water reactors, liquid-metal fast breeder reactors, and Canada deuterium uranium reactors.

The code uses a matrix exponential method to solve a large system of coupled, linear, first order ordinary differential equations with constant coefficients. It has been variably dimensioned to allow the user to tailor the size of the executable module to the problem size and/or the available computer space. The data used by the code is of two types, generic data which is part of the code package and is read from a series of library files describing the nuclide chain characteristics, cross sections, fission product yields, decay data and decay photon data; and problem specific data including the composition of the materials in the reactor and a series of commands describing, step by step, the nuclear fuel cycle scenarios considered in the problem. The output of the code consists of vectors that contain the amount of each radionuclide being considered in the problem. A vector in ORIGEN2 is a one-dimensional array which is printed as a single column of numbers in the output. Within the vectors, the nuclides are grouped into three segments as follows:

1. Activation products, which consist of nearly all naturally occuring nuclides, their neutron absorption products, and the decay daughters of these products. This segment is principally used to handle structural materials (e.g. Zircaloy) and fuel impurities.

2. Actinides, which contain the isotopes of the elements thorium (atomic number 90) through einsteinium (atomic number 99) that appear in significant amounts in discharged reactor fuels plus their decay daughters.

3. Fission products, which consist of nuclides produced by actinides fission plus their decay and capture products.

For the cases considered here, each vector contained concentration values for 688 activation products, 129 actinides and daughters, and 879 fission products.

II. CODE PREPARATION

The GRESS precompiler and its capabilities have been described in details in several other publications.[6-8] In essence, GRESS reads and analyzes every statement in the FORTRAN source code to be translated and automatically adds the lines of coding that are necessary to calculate the derivatives of the stored quantity with respect to the variables used in its computation. It is, therefore, essential that the source code be written using a format compatible with that recognizable by GRESS. This is the case, in general, if the code has been written using regular FORTRAN syntax. In the case of ORIGEN2, only minor changes were required to make the code compatible with the GRESS precompiler.[6]
These changes are described below:

1. In its present form, the GRESS precompiler does not recognize subscripts that are indexed variables or expressions. This was easily remedied by replacing statements of the form:

```
A = B (C(D))
by
INDEX = C(D)
A = B (INDEX)
```

   and replacing statements of the form:

```
A = B (C+D)
by
INDEX = C+D
A = B (INDEX)
```

2. All DOUBLE PRECISION definition statements were replaced by REAL *8 definition statements.

3. All INTEGER *2 definition statements were replaced by INTEGER definition statements.

4. Colons and semicolons were replaced by blank characters.

5. Arrays with 3 (or more) subscripts were replaced by arrays with 1 subscript coupled with a statement to compute the index. In ORIGEN2 only one such array was encountered (XCUM in the subroutine OUTPUT).

6. Statements using an expression in the argument list of a call to a subroutine were modified by calculating and storing the expression in a variable, then using the variable in the argument list. An example of this modification occurs at card #3437 in ORIGEN2 where JTYP +2 was used as an argument. The statement JTYP2 = JTYP+2 was inserted before the call to the subroutine and JTYP2 was used in the argument list.

7. Arithmetic statement function were replaced by a call to a function subprogram and an insert of the function subprogram.

These changes involved FORTRAN language optimization only and had no effect on the results of the code. This was verified by checking that the results of the code before and after the modifications were made were identical.

In addition to the modifications described above, minor modifications were made in the code output routines to facilitate the sensitivity calculation verification studies. The output formats were changed to include 6 significant digits and allow printing of normalized sensitivity coefficients concurrently with the printing of regular output. Software was also developed to automatically calculate, store, and print sensitivities derived from perturbation runs.

A more serious problem necessitating code modification was encountered with the ORIGEN2 code during the verification phase. This problem does not relate to GRESS compatibility and deals with a loss of precision caused by truncation errors in the calculation of the concentration of certain nuclides. The loss of precision was found to occur in a nested series of DO loops in the subroutine MATREX. To remedy the problem, the variables CIMO, CIMB, CIMNI, TON, AP and T were changed locally to REAL *8 variables. Much better results were obtained with this configuration and it is suggested that this modification be proposed to the ORIGEN2 code authors.

III. AUTOMATED SENSITIVITY CALCULATIONS

With the modifications described previously, the ORIGEN2 was successfully translated through the GRESS precompiler. The double precision GRESS library was used for this translation allowing propagation of derivatives through mixed single and double precision variables. A sample problem involving burnup of one metric ton of fuel under specified power, radioactive decay, and irradiation of Zircaloy under specified flux was used for the sensitivity calculation and verification study. A listing of the command input file including fuel and Zircaloy composition is given in Exhibit 1. Six parameters, representative of the various data types used by ORIGEN2 were selected for calculation of sensitivities. Three parameters, the cross-sections for ^{235}U fission (P1), ^{238}U capture (P2), and ^{239}Pu (P3) fission, are input from cross-section libraries that are part of the ORIGEN2 code package, and three parameters, the Zircaloy irradiation flux (P4), the fuel burnup power (P5), and the ^{235}U assay (P6) are input from the command and material composition input file shown in Exhibit 1. Normalized sensitivity coefficients of all radionuclide concentrations representing discharge characteristics after irradiation of Zircaloy (V1) and fuel burnup (V2) to the 6 parameters mentioned above were calculated using the GRESS procedure. Examples of printout of these sensitivities for the first 104 activation products (a total of about 20352 sensitivities were calculated) are shown in Exhibits 2 and 3. The first two columns give the results of the ORIGEN2 code for the performance measures V1 and V2. The next six columns with headings of the type ViP_j give the normalized sensitivity coefficients

```
LISTING OF INPUT DATA ON UNIT = 5

INPUT   WRITE   CARD                                        CARD IMAGE
UNIT    UNIT    NUMBER
  5      50        1     -1
  5      50        2     -1
  5      50        3     -1
  5      50        4       BAS    ONE METRIC TON OF PWRU FUEL
  5      50        5       RDA    -1 = FRESH U FUEL WITH IMPURITIES (1 MT)
  5      50        6       RDA    -2 = FRESH ZIRCALOY COMPOSITION (1 KG)
  5      50        7       RDA    -3 = FRESH SS 304 COMPOSITION (1 KG)
  5      50        8       RDA    -4 = FRESH SS 302 COMPOSITION (1 KG)
  5      50        9       RDA    -5 = FRESH INCONEL COMPOSITION (1 KG)
  5      50       10       RDA    -6 = FRESH NICROBRAZE COMPOSITION (1 KG)
  5      50       11       RDA    WARNING:  VECTORS ARE OFTEN CHANGED WITH RESPECT TO THEIR CONTENT.
  5      50       12       RDA              THESE CHANGES WILL BE NOTED ON RDA CARDS.
  5      50       13       CUT    -1
  5      50       14       LIP    0 0 0
  5      50       15       LIB    0  1 2 3  204  205  206   9   3   0  1   1
  5      50       16       PHO    0  0  0   10
  5      50       17       TIT    INITIAL COMPOSITIONS OF UNIT AMOUNTS OF FUEL AND STRUCT MAT'LS
  5      50       18       RDA    READ FUEL COMPOSITION INCLUDING IMPURITIES (1000 KG)
  5      50       19       INP    -1   1  -1  -1  1  1
  5      50       20       RDA    READ ZIRCALOY COMPOSITION (1.0 KG)
  5      50       21       INP    -2   1  -1  -1  1  1
  5      50       22       RDA    READ SS304 COMPOSITION (1.0 KG)
  5      50       23       INP    -3   1  -1  -1  1  1
  5      50       24       RDA    READ SS302 COMPOSITION (1.0 KG)
  5      50       25       INP    -4   1  -1  -1  1  1
  5      50       26       RDA    READ INCONEL 718 COMPOSITION (1.0 KG)
  5      50       27       INP    -5   1  -1  -1  1  1
  5      50       28       RDA    READ NICROBRAZE 50 COMPOSITION (1.0 KG)
  5      50       29       INP    -6   1  -1  -1  1  1
  5      50       30       TIT    IRRADIATION OF ONE METRIC TON OF PWRU FUEL
  5      50       31       MOV    -1   1    0    1.0
  5      50       32       PCH     1   1    1
  5      50       33       HED     1                                                  CHARGE
  5      50       34       BUP
  5      50       35       IRP      26.0    38.40   1   2   4  2   END OF THIS STEP= 1,000 MWD/MTIHM
  5      50       36       IRP      65.1    38.40   2   3   4  0   END OF THIS STEP= 2,500 MWD/MTIHM
  5      50       37       IRP     130.2    38.40   3   4   4  0   END OF THIS STEP= 5,000 MWD/MTIHM
  5      50       38       IRP     284.0    38.40   4   5   4  0   END OF THIS STEP=10,906 MWD/MTIHM
  5      50       39       DEC     390.0            5   6   4  0   DECAY FOR 106 DAYS
  5      50       40       IRP     496.6    38.40   6   7   4  0   END OF THIS STEP=15,000 MWD/MTIHM
  5      50       41       IRP     535.7    38.40   7   8   4  0   END OF THIS STEP=16,500 MWD/MTIHM
  5      50       42       IRP     674.0    38.40   8   9   4  0   END OF THIS STEP=21,811 MWD/MTIHM
  5      50       43       DEC     780.0            9  10   4  0   DECAY FOR 106 DAYS
  5      50       44       IRP     863.0    38.40  10  11   4  0   END OF THIS STEP=25,000 MWD/MTIHM
  5      50       45       IRP     928.1    38.40  11  12   4  0   END OF THIS STEP=27,500 MWD/MTIHM
  5      50       46       IRP     993.3    38.40  12   1   4  0   END OF THIS STEP=30,000 MWD/MTIHM
  5      50       47       IRP    1064.0    38.40   1  12   4  0   END OF THIS STEP=32,717 MWD/MTIHM
  5      50       48       BUP
  5      50       49       RDA    -10 = IRRADIATED U FUEL AT DISCHARGE
```

Exhibit 1. Command and material composition input file for sample problem.

```
LISTING OF INPUT DATA ON UNIT = 5

INPUT   WRITE   CARD                                    CARD IMAGE
UNIT    UNIT    NUMBER
  5      50       50    MOV     12    -10      0      1.0
  5      50       51    PCH    -10    -10    -10
  5      50       52    RDA    IRRADIATION OF ZIRCALOY AT 1.000 FLUX
  5      50       53    TIT    IRRADIATION OF ZIRCALOY AT 1.000 FLUX
  5      50       54    MOV    -2      1       0    223.0        ZIRCALOY
  5      50       55    PCH     1      1       1
  5      50       56    HED     1                                                  CHARGE
  5      50       57    IRF    26.0      -1.0    1    2    4  2   END OF THIS STEP= 1,000 MWD/MTIHM
  5      50       58    IRF    65.1      -1.0    2    3    4  0   END OF THIS STEP= 2,500 MWD/MTIHM
  5      50       59    IRF    130.2     -1.0    3    4    4  0   END OF THIS STEP= 5,000 MWD/MTIHM
  5      50       60    IRF    284.0     -1.0    4    5    4  0   END OF THIS STEP=10,906 MWD/MTIHM
  5      50       61    DEC    390.0             5    6    4  0   DECAY FOR 106 DAYS
  5      50       62    IRF    496.6     -1.0    6    7    4  0   END OF THIS STEP=15,000 MWD/MTIHM
  5      50       63    IRF    535.7     -1.0    7    8    4  0   END OF THIS STEP=16,500 MWD/MTIHM
  5      50       64    IRF    674.0     -1.0    8    9    4  0   END OF THIS STEP=21,811 MWD/MTIHM
  5      50       65    DEC    780.0             9   10    4  0   DECAY FOR 106 DAYS
  5      50       66    IRF    863.0     -1.0   10   11    4  0   END OF THIS STEP=25,000 MWD/MTIHM
  5      50       67    IRF    928.1     -1.0   11   12    4  0   END OF THIS STEP=27,500 MWD/MTIHM
  5      50       68    IRF    993.3     -1.0   12    1    4  0   END OF THIS STEP=30,000 MWD/MTIHM
  5      50       69    IRF   1064.0     -1.0    1   12    4  0   END OF THIS STEP=32,717 MWD/MTIHM
  5      50       70    RDA   -9 = IRRADIATED ZIRCALOY
  5      50       71    MOV     12    -9      0      1.0
  5      50       72    PCH    -9    -9    -9
  5      50       73    RDA     SUMMARY OF DISCHARGE CHARACTERISTICS
  5      50       74    TIT     SUMMARY OF DISCHARGE CHARACTERISTICS
  5      50       75    HED    -9     ZIRC-100%
  5      50       76    HED    -10     FUEL DIS
  5      50       77    MOV    -9      1     0    1.0
  5      50       78    MOV    -10     2     0    1.0
  5      50       79    OPTL     4*8     7 8 2    17*8
  5      50       80    OPTA     4*8     7 8 2    17*8
  5      50       81    OPTF     4*8     7 8 2    17*8
  5      50       82    OUT    -2       1      -1      0
  5      50       83    END
  5      50       84    2   922340  290.0   922350  32000   922380  967710.        0    0.0      FUEL 3.2%
  5      50       85    4   030000  1.0     050000  1.0     060000  89.4     070000  25.0      FUEL IMPU
  5      50       86    4   080000 134454.  090000  10.7    110000  15.0     120000  2.0       FUEL IMPU
  5      50       87    4   130000  16.7    140000  12.1    150000  35.0     170000  5.3       FUEL IMPU
  5      50       88    4   200000  2.0     220000  1.0     230000  3.0      240000  4.0       FUEL IMPU
  5      50       89    4   250000  1.7     260000  18.0    270000  1.0      280000  24.0      FUEL IMPU
  5      50       90    4   290000  1.0     300000  40.3    420000  10.0     470000  0.1       FUEL IMPU
  5      50       91    4   480000  25.0    490000  2.0     500000  4.0      640000  2.5       FUEL IMPU
  5      50       92    4   740000  2.0     820000  1.0     830000  0.4      0       0.0       FUEL IMPU
  5      50       93    0
  5      50       94    4   400000  979.11  500000  16.0    260000  2.25     240000  1.25        ZIRC-4
  5      50       95    4   280000  0.02    130000  0.024   050000  0.00033  480000  0.00025     ZIRC-4
  5      50       96    4   060000  0.120   270000  0.010   290000  0.020    720000  0.078       ZIRC-4
  5      50       97    4   010000  0.013   250000  0.020   070000  0.080    080000  0.950       ZIRC-4
  5      50       98    4   160000  0.035   220000  0.020   740000  0.020    230000  0.020       ZIRC-4
  5      50       99    5   920000  0.0002       0  0.0                                         ZIRC-4
```

Exhibit 1. (Cont'd.)

• SUMMARY OF DISCHARGE CHARACTERISTICS

ACTIVATION PRODUCTS

POWER= 3.83999E+01 MW, BURNUP= 3.27168E+04 MWD, FLUX= 3.31E+14 N/CM**2-SEC

7 NUCLIDE TABLE RADIOACTIVITY, CURIES

ONE METRIC TON OF PWRU FUEL

		ZIRC-100%	FUEL DIS	V1P1	V1P2	V1P3	V2P1	V2P2	V2P3
1	H 1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	H 2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3	H 3	1.77958E-04	2.67142E+02	-9.00460E-01	-9.77770E-01	-4.08757E-01	-1.17192E-01	-1.33099E-01	-5.47921E-02
4	H 4	6.78586E-02	7.57450E+00	-9.64400E-02	-6.87461E-01	-1.84388E-01	-9.62556E-02	-6.87261E-01	-1.84303E-01
5	HE 3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
6	HE 4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7	HE 6	5.02687E-03	2.82431E-02	-4.80644E-01	-1.10223E+00	-3.58166E-01	-9.38528E-03	-5.93482E-01	-1.45011E-01
8	LI 6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9	LI 7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
10	LI 8	2.72673E-02	3.03280E+00	-9.66444E-02	-6.87678E-01	-1.84478E-01	-9.62626E-02	-6.87266E-01	-1.84304E-01
11	BE 8	3.59357E-02	3.06176E+00	-1.89273E-01	-7.87676E-01	-2.26375E-01	-9.98983E-02	-6.91191E-01	-1.85949E-01
12	BE 9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
13	BE 10	1.11243E-07	1.59293E-06	-3.85168E-01	-4.15812E-01	-1.74217E-01	-6.70591E-01	-7.23943E-01	-3.03318E-01
14	BE 11	2.88313E-07	4.12851E-06	-4.81499E-01	-1.10316E+00	-3.58554E-01	-7.66924E-01	-1.41129E+00	-4.87654E-01
15	B 10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
16	B 11	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
17	B 12	2.12312E-02	2.53702E-01	-1.45837E-01	-7.40706E-01	-2.06729E-01	-1.02141E-01	-6.93615E-01	-1.86965E-01
18	C 12	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
19	C 13	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
20	C 14	3.49140E-01	5.93968E-01	-3.83775E-01	-4.14353E-01	-1.73601E-01	-3.84000E-01	-4.14596E-01	-1.73702E-01
21	C 15	7.82164E-02	4.96277E+01	-9.63473E-02	-6.87361E-01	-1.84345E-01	-9.63279E-02	-6.87339E-01	-1.84336E-01
22	N 13	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
23	N 14	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
24	N 15	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
25	N 16	4.60458E-01	3.10817E+02	-9.63095E-02	-6.87320E-01	-1.84326E-01	-9.63053E-02	-6.87316E-01	-1.84325E-01
26	O 16	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
27	O 17	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
28	O 18	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
29	O 19	5.59125E-03	5.25647E+00	-9.63319E-02	-6.87343E-01	-1.84338E-01	-9.63130E-02	-6.87323E-01	-1.84329E-01
30	F 19	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
31	F 20	1.63793E-07	4.96953E+00	-4.81101E-01	-1.10272E+00	-3.58374E-01	-9.61674E-02	-6.87167E-01	-1.84262E-01
32	NE 20	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
33	NE 21	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
34	NE 22	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
35	NE 23	3.63041E-09	1.99265E+00	-8.65956E-01	-1.51820E+00	-5.32449E-01	-9.55100E-02	-6.86456E-01	-1.83966E-01
36	NA 22	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
37	NA 23	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
38	NA 24	2.48099E-01	3.73848E+02	-9.61272E-02	-6.87121E-01	-1.84244E-01	-9.54856E-02	-6.86430E-01	-1.83954E-01
39	NA 24M	1.12431E-12	1.56345E+02	-1.25054E+00	-1.93337E+00	-7.06400E-01	-9.54782E-02	-6.86422E-01	-1.83951E-01
40	NA 25	1.39331E-09	3.16999E-02	-8.65761E-01	-1.51797E+00	-5.32356E-01	-9.65907E-02	-6.87631E-01	-1.84458E-01
41	MG 24	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
42	MG 25	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
43	MG 26	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
44	MG 27	1.18621E+00	3.91537E+00	-9.61168E-02	-6.87112E-01	-1.84239E-01	-9.61373E-02	-6.87134E-01	-1.84248E-01
45	MG 28	1.38277E-09	4.56418E-09	-1.92453E-01	-1.37446E+00	-3.68578E-01	-1.92473E-01	-1.37448E+00	-3.68587E-01
46	AL 27	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
47	AL 28	2.84424E-01	9.46310E+01	-9.61282E-02	-6.87124E-01	-1.84245E-01	-9.61326E-02	-6.87129E-01	-1.84246E-01
48	AL 29	1.36843E-04	1.05640E-01	-4.81061E-01	-1.10268E+00	-3.58355E-01	-9.89580E-02	-6.90178E-01	-1.85525E-01
49	AL 30	4.75825E-09	1.01869E-04	-5.12656E-01	-1.13679E+00	-3.72647E-01	-9.65931E-02	-6.87626E-01	-1.84456E-01
50	SI 28	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
51	SI 29	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
52	SI 30	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

OUTPUT UNIT = 11

PAGE 5

Exhibit 2. ORIGEN2 output and sensitivities to parameters 1, 2, 3 for sample problem.

SUMMARY OF DISCHARGE CHARACTERISTICS

ACTIVATION PRODUCTS

POWER= 3.83999E+01 MW, BURNUP= 3.27168E+04 MWD, FLUX= 3.31E+14 N/CM**2-SEC

NUCLIDE TABLE RADIOACTIVITY, CURIES

ONE METRIC TON OF P-RU FUEL

		ZIRC-200%	FUEL DIS	V1P1	V1P2	V1P3	V2P1	V2P2	V2P3
53	SI 31	4.95083E-02	6.85214E+01	-9.65785E-02	-6.87611E-01	-1.84450E-01	-9.61803E-02	-6.87181E-01	-1.84269E-01
54	SI 32	2.11015E-11	2.92192E-08	-7.31199E-01	-8.65319E-01	-3.52617E-01	-7.31060E-01	-8.65049E-01	-3.52419E-01
55	P 31	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
56	P 32	2.67094E+01	1.18606E+02	-9.71927E-02	-6.85412E-01	-1.84327E-01	-9.73320E-02	-6.85559E-01	-1.84385E-01
57	P 33	2.40148E-03	2.73229E-07	-1.52754E-01	-7.30699E-01	-2.06987E-01	-9.01504E-01	-1.46363E+00	-5.31570E-01
58	P 34	1.24372E-07	8.40375E-02	-9.61262E-02	-6.87119E-01	-1.84243E-01	-9.83741E-02	-6.89544E-01	-1.85261E-01
59	S 32	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
60	S 33	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
61	S 34	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
62	S 35	1.28927E+00	3.19146E+01	-1.41798E-01	-6.40523E-01	-1.89881E-01	-1.07472E-01	-6.60027E-01	-1.75767E-01
63	S 36	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
64	S 37	3.59297E-03	1.68865E-02	-9.62034E-02	-6.87206E-01	-1.84279E-01	-1.00343E-01	-6.91671E-01	-1.86150E-01
65	CL 35	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
66	CL 36	2.36579E-07	1.20447E-02	-7.66486E-01	-8.07062E-01	-3.39501E-01	-3.62331E-01	-3.91147E-01	-1.03084E-01
67	CL 37	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
68	CL 38	4.06664E-06	9.65421E+00	-5.47197E-01	-1.17800E+00	-3.89467E-01	-9.83724E-02	-6.89545E-01	-1.85259E-01
69	CL 38M	4.84018E-08	1.14906E-01	-5.47195E-01	-1.17679E+00	-3.89467E-01	-9.83711E-02	-6.89542E-01	-1.85260E-01
70	AR 36	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
71	AR 37	8.63354E-10	6.86266E-01	-1.08730E+00	-1.29811E+00	-5.04815E-01	-1.00972E-01	-6.73306E-01	-1.86051E-01
72	AR 38	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
73	AR 39	4.36378E-12	7.21327E-05	-1.06752E+00	-1.15765E+00	-4.84382E-01	-3.69468E-01	-3.99723E-01	-1.67361E-01
74	AR 40	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
75	AR 41	1.96869E-08	1.19275E-04	-4.89780E-01	-1.11209E+00	-3.62299E-01	-4.02532E-01	-1.01793E+00	-3.22645E-01
76	AR 42	6.16770E-17	5.26476E-13	-9.96683E-01	-1.39817E+00	-5.43996E-01	-8.43642E-01	-1.06732E+00	-4.25763E-01
77	K 39	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
78	K 40	1.60341E-24	4.55695E-09	-1.64116E+00	-1.43826E+00	-6.30760E-01	-3.69736E-01	-3.99151E-01	-1.67236E-01
79	K 41	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
80	K 42	3.40993E-10	1.35903E-02	-5.92475E-01	-1.09264E+00	-3.73698E-01	-1.25638E-01	-7.18971E-01	-1.97590E-01
81	K 43	2.46672E-07	4.21567E-04	-4.77873E-01	-1.09925E+00	-3.56914E-01	-9.31919E-02	-6.83971E-01	-1.82921E-01
82	K 44	4.39116E-08	1.60609E-04	-4.80561E-01	-1.10214E+00	-3.56129E-01	-9.58388E-02	-6.86111E-01	-1.84114E-01
83	CA 40	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
84	CA 41	0.0	1.91227E-04	0.0	0.0	0.0	-3.84551E-01	-4.15148E-01	-1.73938E-01
85	CA 42	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
86	CA 43	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
87	CA 44	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
88	CA 45	1.27434E-03	5.01804E-01	-2.15946E-01	-6.24571E-01	-2.03234E-01	-1.85428E-01	-5.96297E-01	-1.90051E-01
89	CA 46	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
90	CA 47	1.75640E-05	7.11840E-04	-4.29732E-01	-1.04727E+00	-3.35139E-01	-9.75785E-02	-6.88694E-01	-1.84902E-01
91	CA 48	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
92	CA 49	0.0	6.02392E-02	0.0	0.0	0.0	-9.53845E-02	-6.66320E-01	-1.63909E-01
93	SC 45	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
94	SC 46	1.72912E-01	5.95902E-02	-1.38298E-01	-6.41140E-01	-1.69004E-01	-3.03463E-01	-7.53007E-01	-2.44777E-01
95	SC 46M	2.34413E-05	9.57252E-03	-5.59135E-01	-1.04107E+00	-3.54427E-01	-5.42354E-01	-1.02841E+00	-3.47712E-01
96	SC 47	2.94283E-01	6.67447E-02	-9.55525E-02	-6.87394E-01	-1.84215E-01	-9.60795E-02	-6.88236E-01	-1.84518E-01
97	SC 48	2.79692E-02	6.52435E-03	-9.05465E-02	-6.81075E-01	-1.81713E-01	-8.99352E-02	-6.80471E-01	-1.81451E-01
98	SC 49	2.75302E-02	6.64101E-02	-1.68185E-01	-7.64913E-01	-2.16838E-01	-1.02142E-01	-6.93517E-01	-1.86966E-01
99	SC 50	4.70834E-04	1.05335E-04	-9.96591E-02	-6.90935E-01	-1.85842E-01	-9.87960E-02	-6.90004E-01	-1.85452E-01
100	TI 46	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
101	TI 47	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
102	TI 48	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
103	TI 49	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
104	TI 50	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

OUTPUT UNIT = 11 PAGE 6

Exhibit 2. (Cont'd.)

• SUMMARY OF DISCHARGE CHARACTERISTICS

ACTIVATION PRODUCTS

POWER= 3.83999E+01 MW, BURNUP= 3.27168E+04 MWD, FLUX= 3.31E+14 N/CM**2-SEC

7 NUCLIDE TABLE RADIOACTIVITY, CURIES

ONE METRIC TON OF PWRU FUEL

		ZIRC-100%	FUEL DIS	V1P4	V1P5	V1P6	V2P4	V2P5	V2P6
1	H 1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	H 2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3	H 3	1.77958E-04	2.67142E+02	2.34741E+00	2.78536E+00	-1.59899E+00	0.0	3.73253E-01	-2.12038E-01
4	H 4	6.78586E-02	7.57450E+00	1.00028E+00	1.34813E+00	-5.48151E-01	0.0	1.34756E+00	-5.47825E-01
5	HE 3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
6	HE 4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7	HE 6	5.02687E-03	2.82031E-02	1.99872E+00	2.53212E+00	-1.22879E+00	0.0	1.07986E+00	-3.93931E-01
8	LI 6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9	LI 7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
10	LI 8	2.72673E-02	3.03280E+00	1.00079E+00	1.34874E+00	-5.48512E-01	0.0	1.34757E+00	-5.47836E-01
11	BE 8	3.59357E-02	3.06176E+00	1.24151E+00	1.63420E+00	-7.12608E-01	0.0	1.35877E+00	-5.54277E-01
12	BE 9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
13	BE 10	1.11243E-07	1.59293E-06	1.00095E+00	1.18698E+00	-6.82349E-01	0.0	2.06657E+00	-1.18799E+00
14	BE 11	2.88313E-07	4.12851E-06	2.00095E+00	2.53478E+00	-1.23031E+00	0.0	3.41437E+00	-1.73596E+00
15	B 10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
16	B 11	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
17	B 12	2.12312E-02	2.53702E-01	1.12865E+00	1.50036E+00	-6.35661E-01	0.0	1.36570E+00	-5.58252E-01
18	C 12	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
19	C 13	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
20	C 14	3.49140E-01	5.93968E-01	9.97389E-01	1.18277E+00	-6.79913E-01	0.0	1.18346E+00	-6.80309E-01
21	C 15	7.82164E-02	4.96277E+01	1.00004E+00	1.34785E+00	-5.47989E-01	0.0	1.34778E+00	-5.47953E-01
22	N 13	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
23	N 14	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
24	N 15	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
25	N 16	4.60058E-01	3.10817E+02	9.99941E-01	1.34773E+00	-5.47922E-01	0.0	1.34771E+00	-5.47915E-01
26	O 16	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
27	O 17	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
28	O 18	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
29	O 19	5.59125E-03	5.25647E+00	9.99999E-01	1.34780E+00	-5.47962E-01	0.0	1.34774E+00	-5.47927E-01
30	F 19	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
31	F 20	1.63793E-07	4.96953E+00	1.99991E+00	2.53355E+00	-1.22960E+00	0.0	1.34729E+00	-5.47670E-01
32	NE 20	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
33	NE 21	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
34	NE 22	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
35	NE 23	3.63041E-09	1.99265E+00	3.00000E+00	3.71955E+00	-1.91139E+00	0.0	1.34526E+00	-5.46505E-01
36	NA 22	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
37	NA 23	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
38	NA 24	2.48099E-01	3.73848E+02	9.99450E-01	1.34715E+00	-5.47597E-01	0.0	1.34518E+00	-5.46463E-01
39	NA 24M	1.12431E-12	1.56345E+02	3.99946E+00	4.90471E+00	-2.59270E+00	0.0	1.34516E+00	-5.46449E-01
40	NA 25	1.39331E-09	3.16999E-02	2.99950E+00	3.71891E+00	-1.91104E+00	0.0	1.34862E+00	-5.48433E-01
41	MG 24	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
42	MG 25	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
43	MG 26	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
44	MG 27	1.18621E+00	3.91537E+00	9.99439E-01	1.34713E+00	-5.47580E-01	0.0	1.34720E+00	-5.47616E-01
45	MG 28	1.38277E-09	4.56418E-09	1.99944E+00	2.69493E+00	-1.09555E+00	0.0	2.69500E+00	-1.09558E+00
46	AL 27	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
47	AL 28	2.84424E+01	9.46310E+01	9.99470E-01	1.34717E+00	-5.47601E-01	0.0	1.34718E+00	-5.47608E-01
48	AL 29	1.36843E-06	1.05640E-01	1.99979E+00	2.53340E+00	-1.22953E+00	0.0	1.35589E+00	-5.52613E-01
49	AL 30	4.75825E-09	1.01869E-04	2.08191E+00	2.63078E+00	-1.28550E+00	0.0	1.34860E+00	-5.48423E-01
50	SI 28	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
51	SI 29	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
52	SI 30	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

OUTPUT UNIT = 11 PAGE 5

Exhibit 3. ORIGEN2 output and sensitivities to parameters 4, 5, 6 for sample problem.

• SUMMARY OF DISCHARGE CHARACTERISTICS ACTIVATION PRODUCTS

POWER= 3.03999E+01 MW, BURNUP= 3.27168E+04 MWD, FLUX= 3.31E+14 N/CM**2-SEC

7 NUCLIDE TABLE RADIOACTIVITY, CURIES

ONE METRIC TON OF PWRU FUEL

		ZIRC-100*	FUEL DIS	V1P4	V1P5	V1P6	V2P4	V2P5	V2P6
53	SI 31	4.95083E-02	6.85214E+01	1.00064E+00	1.34856E+00	-5.48399E-01	0.0	1.34733E+00	-5.47693E-01
54	SI 32	2.11015E-11	2.92192E-08	2.00031E+00	2.39470E+00	-1.34766E+00	0.0	2.39405E+00	-1.34733E+00
55	P 31	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
56	P 32	2.67094E+01	1.18666E+02	9.98722E-01	1.34675E+00	-5.48161E-01	0.0	1.34716E+00	-5.48405E-01
57	P 33	2.40148E-03	2.73229E-07	1.12485E+00	1.49711E+00	-6.38952E-01	0.0	3.70216E+00	-1.92854E+00
58	P 34	1.24372E-02	8.40375E-02	9.99446E-01	1.34714E+00	-5.47595E-01	0.0	1.35408E+00	-5.51576E-01
59	S 32	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
60	S 33	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
61	S 34	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
62	S 35	1.28927E+00	3.19146E+01	1.00040E+00	1.33693E+00	-5.77059E-01	0.0	1.24075E+00	-5.19785E-01
63	S 36	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
64	S 37	3.59297E-03	1.68865E-02	9.99666E-01	1.34740E+00	-5.47730E-01	0.0	1.36015E+00	-5.55066E-01
65	CL 35	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
66	CL 36	2.36579E-07	1.20447E-02	1.96400E+00	2.32326E+00	-1.34315E+00	0.0	1.11658E+00	-6.41881E-01
67	CL 37	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
68	CL 38	4.06664E-06	9.65421E+00	2.17778E+00	2.74592E+00	-1.34991E+00	0.0	1.35408E+00	-5.51575E-01
69	CL 38M	4.84018E-08	1.14906E-01	2.17777E+00	2.74592E+00	-1.34990E+00	0.0	1.35408E+00	-5.51571E-01
70	AR 36	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
71	AR 37	8.63354E-10	6.86266E-01	2.97282E+00	3.56101E+00	-1.99263E+00	0.0	1.34974E+00	-5.56896E-01
72	AR 38	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
73	AR 39	4.36378E-12	7.21327E-05	2.78106E+00	3.29942E+00	-1.89478E+00	0.0	1.14018E+00	-6.55124E-01
74	AR 40	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
75	AR 41	1.96869E-08	1.19275E-04	2.02246E+00	2.56029E+00	-1.24498E+00	0.0	2.29146E+00	-1.09043E+00
76	AR 42	6.16770E-17	5.26476E-13	3.01540E+00	3.67032E+00	-1.98752E+00	0.0	2.89080E+00	-1.60188E+00
77	K 39	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
78	K 40	1.60341E-24	4.55695E-09	3.81938E+00	4.43697E+00	-2.67208E+00	0.0	1.13941E+00	-6.55009E-01
79	K 41	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
80	K 42	3.40993E-10	1.35903E-02	2.11932E+00	2.63561E+00	-1.33865E+00	0.0	1.43809E+00	-5.99870E-01
81	K 43	2.46672E-07	4.21567E-04	1.99152E+00	2.52361E+00	-1.22389E+00	0.0	1.33815E+00	-5.42411E-01
82	K 44	4.39116E-08	1.60609E-04	1.99850E+00	2.53107E+00	-1.22864E+00	0.0	1.34627E+00	-5.47085E-01
83	CA 40	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
84	CA 41	0.0	1.91227E-04	0.0	0.0	0.0	0.0	1.18508E+00	-6.81255E-01
85	CA 42	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
86	CA 43	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
87	CA 44	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
88	CA 45	1.27434E-03	5.01864E-01	1.07208E+00	1.38993E+00	-6.47801E-01	0.0	1.30458E+00	-5.97012E-01
89	CA 46	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
90	CA 47	1.75640E-05	7.11840E-04	1.86641E+00	2.37523E+00	-1.13860E+00	0.0	1.35164E+00	-5.50172E-01
91	CA 48	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
92	CA 49	0.0	6.02392E-02	0.0	0.0	0.0	0.0	1.34487E+00	-5.46281E-01
93	SC 45	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
94	SC 46	1.72912E-01	5.95902E-02	9.96679E-01	1.33395E+00	-5.73398E-01	0.0	1.71926E+00	-8.20085E-01
95	SC 46M	2.34413E-05	9.57252E-03	2.01235E+00	2.50403E+00	-1.26904E+00	0.0	2.45870E+00	-1.24161E+00
96	SC 47	2.94283E-01	6.67447E-02	9.99129E-01	1.34704E+00	-5.47175E-01	0.0	1.34916E+00	-5.48286E-01
97	SC 48	2.79692E-02	6.52435E-03	9.84934E-01	1.32992E+00	-5.37697E-01	0.0	1.32814E+00	-5.36651E-01
98	SC 49	2.75302E-02	6.64101E-02	1.18673E+00	1.56923E+00	-6.75254E-01	0.0	1.36570E+00	-5.58253E-01
99	SC 50	4.70834E-04	1.05335E-04	1.00864E+00	1.35804E+00	-5.53853E-01	0.0	1.35538E+00	-5.52325E-01
100	TI 46	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
101	TI 47	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
102	TI 48	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
103	TI 49	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
104	TI 50	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

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Exhibit 3. (Cont'd.)

$\frac{P_j}{V_i}\frac{\partial V_i}{\partial P_j}$ of the performance measure Vi with respect to the parameter P_j. Sensitivity coefficients were found either identically zero, indicating no influence of the parameter on the nuclide concentration, or with magnitude ranging from 10^{-2} to 2.0×10^1. In general, sensitivity coefficients to the specified power and the specified flux were found to be the largest, indicating that these parameters should be carefully selected for a simulation study since they are the most likely to propagate large uncertainties to the model results.

IV. SENSITIVITY VERIFICATION STUDY

Since analytical solutions are not feasible or practical for problems such as those treated by the ORIGEN2 code, the verification of the GRESS sensitivity calculations was performed using perturbation analysis methods. It should be noted, however, that for codes involving decay and buildup of large chains of radionuclides, perturbation analysis using forward (positive) parameter perturbations or large parameter perturbation values provide only a poor approximation of the gradients at the solution point. This problem was overcome here by using small parameter perturbation values (-1% to 1%) and, when necessary, approximating the gradients at the solution point by using forward (positive) and backward (negative) parameter perturbation values. Software was designed to automate the calculations of the approximate sensitivity coefficients from forward perturbation results. Examples of the results printout for the first 104 activation products are shown in Exhibits 4 to 9 for a forward perturbation of parameters 1 to 6, respectively. In cases where the results of the forward perturbation analysis were thought to provide a poor approximation of the local gradients, check calculations were performed using the results of forward and backward perturbation runs. For all calculated normalized sensitivity coefficients, perfect agreement was found between GRESS and perturbation analysis results with maximum differences well within the range of the expected precision obtainable from perturbation analysis using results printed with six significant digits. The method of determination of expected precision intervals is outlined in the Appendix.

7 NUCLIDE TABLE RADIOACTIVITY, CURIES ACTIVATION PRODUCTS
PERTURBATION IS A 0.1% INCREASE IN U-235 FISSION

	ZIRC	PERT(P1)	SENS(P1)	FUEL	PERT(P1)	SENS(P1)
H 1	0.0	0.0	0.0	0.0	0.0	0.0
H 2	0.0	0.0	0.0	0.0	0.0	0.0
H 3	1.77959E-04	1.77799E-04	-8.99074E-01	2.67142E+02	2.67111E+02	-1.16065E-01
H 4	6.76590E-02	6.76524E-02	-9.74979E-02	7.57453E+00	7.57378E+00	-9.89617E-02
HE 3	0.0	0.0	0.0	0.0	0.0	0.0
HE 4	0.0	0.0	0.0	0.0	0.0	0.0
HE 6	5.02690E-03	5.02446E-03	-4.85402E-01	2.82432E-02	2.82429E-02	-1.05520E-02
LI 6	0.0	0.0	0.0	0.0	0.0	0.0
LI 7	0.0	0.0	0.0	0.0	0.0	0.0
LI 8	2.72675E-02	2.72649E-02	-9.53608E-02	3.03281E+00	3.03251E+00	-9.90524E-02
BE 8	3.59360E-02	3.59292E-02	-1.89291E-01	3.06177E+00	3.06146E+00	-1.01542E-01
BE 9	0.0	0.0	0.0	0.0	0.0	0.0
BE 10	1.11243E-07	1.11200E-07	-3.86815E-01	1.59294E-06	1.59187E-06	-6.71441E-01
BE 11	2.86315E-07	2.86176E-07	-4.82050E-01	4.12854E-06	4.12537E-06	-7.67946E-01
B 10	0.0	0.0	0.0	0.0	0.0	0.0
B 11	0.0	0.0	0.0	0.0	0.0	0.0
B 12	2.12312E-02	2.12281E-02	-1.45985E-01	2.53703E-01	2.53677E-01	-1.02433E-01
C 12	0.0	0.0	0.0	0.0	0.0	0.0
C 13	0.0	0.0	0.0	0.0	0.0	0.0
C 14	3.49141E-01	3.49007E-01	-3.83774E-01	5.93969E-01	5.93741E-01	-3.83838E-01
C 15	7.82166E-02	7.82089E-02	-9.83039E-02	4.96278E+01	4.96230E+01	-9.66513E-02
N 13	0.0	0.0	0.0	0.0	0.0	0.0
N 14	0.0	0.0	0.0	0.0	0.0	0.0
N 15	0.0	0.0	0.0	0.0	0.0	0.0
N 16	4.60460E-01	4.60415E-01	-9.77316E-02	3.10818E+02	3.10788E+02	-9.66137E-02
O 16	0.0	0.0	0.0	0.0	0.0	0.0
O 17	0.0	0.0	0.0	0.0	0.0	0.0
O 18	0.0	0.0	0.0	0.0	0.0	0.0
O 19	5.59127E-03	5.59072E-03	-9.86078E-02	5.25648E+00	5.25597E+00	-9.70641E-02
F 19	0.0	0.0	0.0	0.0	0.0	0.0
F 20	1.63794E-07	1.63715E-07	-4.82388E-01	4.96954E+00	4.96906E+00	-9.65276E-02
NE 20	0.0	0.0	0.0	0.0	0.0	0.0
NE 21	0.0	0.0	0.0	0.0	0.0	0.0
NE 22	0.0	0.0	0.0	0.0	0.0	0.0
NE 23	3.63044E-09	3.62728E-09	-8.70395E-01	1.99266E+00	1.99247E+00	-9.52401E-02
NA 22	0.0	0.0	0.0	0.0	0.0	0.0
NA 23	0.0	0.0	0.0	0.0	0.0	0.0
NA 24	2.48100E-01	2.48076E-01	-9.65782E-02	3.73849E+02	3.73813E+02	-9.66508E-02
NA 24M	1.12432E-12	1.12291E-12	-1.25438E+00	1.56345E+02	1.56330E+02	-9.59377E-02
NA 25	1.39332E-09	1.39211E-09	-8.68373E-01	3.17000E-02	3.16969E-02	-9.77741E-02
MG 24	0.0	0.0	0.0	0.0	0.0	0.0
MG 25	0.0	0.0	0.0	0.0	0.0	0.0
MG 26	0.0	0.0	0.0	0.0	0.0	0.0
MG 27	1.18621E+00	1.18610E+00	-9.24562E-02	3.91538E+00	3.91500E+00	-9.69414E-02
MG 28	1.38278E-09	1.38250E-09	-2.02469E-01	4.56421E-09	4.56332E-09	-1.95375E-01
AL 27	0.0	0.0	0.0	0.0	0.0	0.0
AL 28	2.84426E+01	2.84398E+01	-9.81752E-02	9.46313E+01	9.46221E+01	-9.72305E-02
AL 29	1.36844E-04	1.36777E-04	-4.89587E-01	1.05641E-01	1.05630E-01	-1.04380E-01
AL 30	4.75627E-09	4.75562E-09	-5.15161E-01	1.01870E-04	1.01860E-04	-9.81365E-02
SI 28	0.0	0.0	0.0	0.0	0.0	0.0
SI 29	0.0	0.0	0.0	0.0	0.0	0.0
SI 30	0.0	0.0	0.0	0.0	0.0	0.0

Exhibit 4. Sensitivities to parameter 1 approximated from forward perturbation analysis.

7 NUCLIDE TABLE RADIOACTIVITY, CURIES ACTIVATION PRODUCTS
PERTURBATION IS A 0.1% INCREASE IN U-235 FISSION

	ZIRC	PERT(P1)	SENS(P1)	FUEL	PERT(P1)	SENS(P1)
SI 31	4.95085E-02	4.95036E-02	-9.90230E-02	6.85217E+01	6.85150E+01	-9.77569E-02
SI 32	2.11015E-11	2.10861E-11	-7.29354E-01	2.92192E-08	2.91979E-08	-7.29043E-01
P 31	0.0	0.0	0.0	0.0	0.0	0.0
P 32	2.67094E+01	2.67068E+01	-9.71191E-02	1.18666E+02	1.18654E+02	-1.01069E-01
P 33	2.40149E-03	2.40111E-03	-1.58227E-01	2.73226E-07	2.72979E-07	-9.04165E-01
P 34	1.24373E-02	1.24361E-02	-9.64472E-02	8.40377E-02	8.40293E-02	-1.00006E-01
S 32	0.0	0.0	0.0	0.0	0.0	0.0
S 33	0.0	0.0	0.0	0.0	0.0	0.0
S 34	0.0	0.0	0.0	0.0	0.0	0.0
S 35	1.26927E+00	1.26909E+00	-1.39803E-01	3.19146E+01	3.19112E+01	-1.06619E-01
S 36	0.0	0.0	0.0	0.0	0.0	0.0
S 37	3.59298E-03	3.59263E-03	-9.74615E-02	1.66866E-02	1.66849E-02	-1.00596E-01
CL 35	0.0	0.0	0.0	0.0	0.0	0.0
CL 36	2.36580E-07	2.36399E-07	-7.65024E-01	1.20447E-02	1.20404E-02	-3.57228E-01
CL 37	0.0	0.0	0.0	0.0	0.0	0.0
CL 38	4.06667E-06	4.06443E-06	-5.50840E-01	9.65424E+00	9.65329E+00	-9.63878E-02
CL 38M	4.64021E-06	4.63754E-06	-5.51601E-01	1.14906E-01	1.14895E-01	-9.59641E-02
AR 36	0.0	0.0	0.0	0.0	0.0	0.0
AR 37	8.63360E-10	8.62421E-10	-1.08764E+00	6.86268E-01	6.86193E-01	-1.09261E-01
AR 38	0.0	0.0	0.0	0.0	0.0	0.0
AR 39	4.36381E-12	4.35914E-12	-1.07014E+00	7.21328E-05	7.21064E-05	-3.65952E-01
AR 40	0.0	0.0	0.0	0.0	0.0	0.0
AR 41	1.96871E-08	1.96773E-08	-4.97706E-01	1.19276E-04	1.19228E-04	-4.02363E-01
AR 42	6.16775E-17	6.16158E-17	-1.00038E+00	5.26476E-13	5.26035E-13	-8.41450E-01
K 39	0.0	0.0	0.0	0.0	0.0	0.0
K 40	1.60342E-24	1.60080E-24	-1.63389E+00	4.55695E-09	4.55527E-09	-3.67983E-01
K 41	0.0	0.0	0.0	0.0	0.0	0.0
K 42	3.40995E-10	3.40792E-10	-5.95166E-01	1.35903E-02	1.35886E-02	-1.24996E-01
K 43	2.46674E-07	2.46555E-07	-4.82540E-01	4.21568E-04	4.21528E-04	-9.49950E-02
K 44	4.39119E-08	4.38907E-08	-4.82763E-01	1.60610E-04	1.60594E-04	-9.95738E-02
CA 40	0.0	0.0	0.0	0.0	0.0	0.0
CA 41	0.0	0.0	0.0	1.91228E-04	1.91154E-04	-3.86954E-01
CA 42	0.0	0.0	0.0	0.0	0.0	0.0
CA 43	0.0	0.0	0.0	0.0	0.0	0.0
CA 44	0.0	0.0	0.0	0.0	0.0	0.0
CA 45	1.27434E-03	1.27407E-03	-2.11940E-01	5.01865E-01	5.01772E-01	-1.85394E-01
CA 46	0.0	0.0	0.0	0.0	0.0	0.0
CA 47	1.75640E-05	1.75565E-05	-4.27510E-01	7.11841E-04	7.11771E-04	-9.84517E-02
CA 48	0.0	0.0	0.0	0.0	0.0	0.0
CA 49	0.0	0.0	0.0	6.02394E-02	6.02336E-02	-9.62871E-02
SC 45	0.0	0.0	0.0	0.0	0.0	0.0
SC 46	1.72913E-01	1.72888E-01	-1.44778E-01	5.95904E-02	5.95722E-02	-3.05385E-01
SC 46M	2.34414E-05	2.34283E-05	-5.58700E-01	9.57256E-03	9.56738E-03	-5.41326E-01
SC 47	2.94284E-01	2.94255E-01	-9.84350E-02	6.67449E-02	6.67384E-02	-9.73393E-02
SC 48	2.79693E-02	2.79667E-02	-9.29680E-02	6.52438E-03	6.52378E-03	-9.19277E-02
SC 49	2.75304E-02	2.75256E-02	-1.74286E-01	6.64104E-02	6.64035E-02	-1.04112E-01
SC 50	4.70835E-04	4.70788E-04	-9.98901E-02	1.05335E-04	1.05325E-04	-9.49082E-02
TI 46	0.0	0.0	0.0	0.0	0.0	0.0
TI 47	0.0	0.0	0.0	0.0	0.0	0.0
TI 48	0.0	0.0	0.0	0.0	0.0	0.0
TI 49	0.0	0.0	0.0	0.0	0.0	0.0
TI 50	0.0	0.0	0.0	0.0	0.0	0.0

Exhibit 4. (Cont'd.)

7 NUCLIDE TABLE RADIOACTIVITY, CURIES ACTIVATION PRODUCTS
PERTURBATION IS A 0.1% INCREASE IN U-238 CAPTURE

	ZIRC	PERT(P2)	SENS(P2)	FUEL	PERT(P2)	SENS(P2)
H 1	0.0	0.0	0.0	0.0	0.0	0.0
H 2	0.0	0.0	0.0	0.0	0.0	0.0
H 3	1.77959E-04	1.77784E-04	-9.83380E-01	2.67142E+02	2.67106E+02	-1.35257E-01
H 4	6.76590E-02	6.76122E-02	-6.89513E-01	7.57453E+00	7.56932E+00	-6.87821E-01
HE 3	0.0	0.0	0.0	0.0	0.0	0.0
HE 4	0.0	0.0	0.0	0.0	0.0	0.0
HE 6	5.02690E-03	5.02134E-03	-1.10568E+00	2.82432E-02	2.82264E-02	-5.94739E-01
LI 6	0.0	0.0	0.0	0.0	0.0	0.0
LI 7	0.0	0.0	0.0	0.0	0.0	0.0
LI 8	2.72675E-02	2.72487E-02	-6.89522E-01	3.03281E+00	3.03072E+00	-6.89279E-01
BE 8	3.59369E-02	3.59076E-02	-7.90338E-01	3.06177E+00	3.05965E+00	-6.92415E-01
BE 9	0.0	0.0	0.0	0.0	0.0	0.0
BE 10	1.11243E-07	1.11196E-07	-4.22584E-01	1.59294E-06	1.59179E-06	-7.21685E-01
BE 11	2.68315E-07	2.67997E-07	-1.10290E+00	4.12854E-06	4.12271E-06	-1.41209E+00
B 10	0.0	0.0	0.0	0.0	0.0	0.0
B 11	0.0	0.0	0.0	0.0	0.0	0.0
B 12	2.12312E-02	2.12155E-02	-7.39577E-01	2.53705E-01	2.53526E-01	-6.97768E-01
C 12	0.0	0.0	0.0	0.0	0.0	0.0
C 13	0.0	0.0	0.0	0.0	0.0	0.0
C 14	3.49141E-01	3.46996E-01	-4.15357E-01	5.93969E-01	5.93723E-01	-4.14143E-01
C 15	7.82166E-02	7.81628E-02	-6.88127E-01	4.96278E+01	4.95937E+01	-6.87163E-01
N 13	0.0	0.0	0.0	0.0	0.0	0.0
N 14	0.0	0.0	0.0	0.0	0.0	0.0
N 15	0.0	0.0	0.0	0.0	0.0	0.0
N 16	4.60460E-01	4.60143E-01	-6.88393E-01	3.10818E+02	3.10604E+02	-6.88864E-01
O 16	0.0	0.0	0.0	0.0	0.0	0.0
O 17	0.0	0.0	0.0	0.0	0.0	0.0
O 18	0.0	0.0	0.0	0.0	0.0	0.0
O 19	5.59127E-03	5.58742E-03	-6.88256E-01	5.25648E+00	5.25287E+00	-6.86887E-01
F 19	0.0	0.0	0.0	0.0	0.0	0.0
F 20	1.63794E-07	1.63613E-07	-1.10533E+00	4.96954E+00	4.96612E+00	-6.88168E-01
NE 20	0.0	0.0	0.0	0.0	0.0	0.0
NE 21	0.0	0.0	0.0	0.0	0.0	0.0
NE 22	0.0	0.0	0.0	0.0	0.0	0.0
NE 23	3.63044E-09	3.62491E-09	-1.52324E+00	1.99266E+00	1.99124E+00	-6.87260E-01
NA 22	0.0	0.0	0.0	0.0	0.0	0.0
NA 23	0.0	0.0	0.0	0.0	0.0	0.0
NA 24	2.48100E-01	2.47929E-01	-6.89261E-01	3.73849E+02	3.73593E+02	-6.85045E-01
NA 24M	1.12432E-12	1.12214E-12	-1.93944E+00	1.56345E+02	1.56238E+02	-6.84349E-01
NA 25	1.39332E-09	1.39120E-09	-1.52144E+00	3.17000E-02	3.16781E-02	-6.90883E-01
MG 24	0.0	0.0	0.0	0.0	0.0	0.0
MG 25	0.0	0.0	0.0	0.0	0.0	0.0
MG 26	0.0	0.0	0.0	0.0	0.0	0.0
MG 27	1.16621E+00	1.16540E+00	-6.82568E-01	3.91538E+00	3.91269E+00	-6.86871E-01
MG 28	1.38278E-09	1.38087E-09	-1.38113E+00	4.56421E-09	4.55793E-09	-1.37618E+00
AL 27	0.0	0.0	0.0	0.0	0.0	0.0
AL 28	2.84426E+01	2.84230E+01	-6.88836E-01	9.46313E+01	9.45662E+01	-6.88031E-01
AL 29	1.36844E-04	1.36692E-04	-1.11071E+00	1.05641E-01	1.05568E-01	-6.91168E-01
AL 30	4.75827E-09	4.75265E-09	-1.13937E+00	1.01870E-04	1.01800E-04	-6.87098E-01
SI 28	0.0	0.0	0.0	0.0	0.0	0.0
SI 29	0.0	0.0	0.0	0.0	0.0	0.0
SI 30	0.0	0.0	0.0	0.0	0.0	0.0

Exhibit 5. Sensitivities to parameter 2 approximated from forward perturbation analysis.

7 NUCLIDE TABLE RADIOACTIVITY, CURIES ACTIVATION PRODUCTS
PERTURBATION IS A 0.1% INCREASE IN U-238 CAPTURE

	ZIRC	PERT(P2)	SENS(P2)	FUEL	PERT(P2)	SENS(P2)
SI 31	4.95065E-02	4.94744E-02	-6.68797E-01	6.65217E+01	6.64746E+01	-6.67430E-01
SI 32	2.11015E-11	2.10632E-11	-8.66807E-01	2.92192E-08	2.91940E-08	-8.62547E-01
P 31	0.0	0.0	0.0	0.0	0.0	0.0
P 32	2.67094E+01	2.66911E+01	-6.84976E-01	1.18666E+02	1.18585E+02	-6.82534E-01
P 33	2.40149E-03	2.39973E-03	-7.32864E-01	2.73226E-07	2.72823E-07	-1.47504E+00
P 34	1.24373E-02	1.24287E-02	-6.91305E-01	8.40377E-02	8.39796E-02	-6.91529E-01
S 32	0.0	0.0	0.0	0.0	0.0	0.0
S 33	0.0	0.0	0.0	0.0	0.0	0.0
S 34	0.0	0.0	0.0	0.0	0.0	0.0
S 35	1.28927E+00	1.28844E+00	-6.44279E-01	3.19146E+01	3.18951E+01	-6.11029E-01
S 36	0.0	0.0	0.0	0.0	0.0	0.0
S 37	3.59296E-03	3.59051E-03	-6.87479E-01	1.68866E-02	1.68749E-02	-6.92924E-01
CL 35	0.0	0.0	0.0	0.0	0.0	0.0
CL 36	2.36580E-07	2.36389E-07	-8.07312E-01	1.20447E-02	1.20400E-02	-3.90322E-01
CL 37	0.0	0.0	0.0	0.0	0.0	0.0
CL 38	4.06667E-06	4.06188E-06	-1.17794E+00	9.65424E+00	9.64759E+00	-6.88813E-01
CL 38M	4.84021E-08	4.83450E-08	-1.17968E+00	1.14906E-01	1.14827E-01	-6.87829E-01
AR 36	0.0	0.0	0.0	0.0	0.0	0.0
AR 37	8.63360E-10	8.62238E-10	-1.29956E+00	6.86266E-01	6.85806E-01	-6.73200E-01
AR 38	0.0	0.0	0.0	0.0	0.0	0.0
AR 39	4.36381E-12	4.35875E-12	-1.15938E+00	7.21328E-05	7.21040E-05	-3.99239E-01
AR 40	0.0	0.0	0.0	0.0	0.0	0.0
AR 41	1.96871E-08	1.96651E-08	-1.11740E+00	1.19276E-04	1.19154E-04	-1.02274E+00
AR 42	6.16775E-17	6.15909E-17	-1.40401E+00	5.26478E-13	5.25916E-13	-1.06746E+00
K 39	0.0	0.0	0.0	0.0	0.0	0.0
K 40	1.60342E-24	1.60112E-24	-1.43414E+00	4.55695E-09	4.55514E-09	-3.96829E-01
K 41	0.0	0.0	0.0	0.0	0.0	0.0
K 42	3.40995E-10	3.40622E-10	-1.09396E+00	1.35903E-02	1.35805E-02	-7.20920E-01
K 43	2.46674E-07	2.46403E-07	-1.09873E+00	4.21568E-04	4.21280E-04	-6.83191E-01
K 44	4.39119E-08	4.38634E-08	-1.10452E+00	1.60610E-04	1.60500E-04	-6.84876E-01
CA 40	0.0	0.0	0.0	0.0	0.0	0.0
CA 41	0.0	0.0	0.0	1.91228E-04	1.91148E-04	-4.18306E-01
CA 42	0.0	0.0	0.0	0.0	0.0	0.0
CA 43	0.0	0.0	0.0	0.0	0.0	0.0
CA 44	0.0	0.0	0.0	0.0	0.0	0.0
CA 45	1.27434E-03	1.27354E-03	-6.27781E-01	5.01865E-01	5.01566E-01	-5.95650E-01
CA 46	0.0	0.0	0.0	0.0	0.0	0.0
CA 47	1.75640E-05	1.75456E-05	-1.04806E+00	7.11841E-04	7.11351E-04	-6.88508E-01
CA 48	0.0	0.0	0.0	0.0	0.0	0.0
CA 49	0.0	0.0	0.0	6.02394E-02	6.01981E-02	-6.85636E-01
SC 45	0.0	0.0	0.0	0.0	0.0	0.0
SC 46	1.72913E-01	1.72802E-01	-6.42193E-01	5.95904E-02	5.95455E-02	-7.53493E-01
SC 46M	2.34414E-05	2.34170E-05	-1.04104E+00	9.57256E-03	9.56276E-03	-1.02389E+00
SC 47	2.94284E-01	2.94081E-01	-6.89855E-01	6.67449E-02	6.66990E-02	-6.87826E-01
SC 48	2.79693E-02	2.79502E-02	-6.82876E-01	6.52438E-03	6.51993E-03	-6.82321E-01
SC 49	2.75304E-02	2.75092E-02	-7.69945E-01	6.64104E-02	6.63643E-02	-6.94680E-01
SC 50	4.70635E-04	4.70509E-04	-6.92308E-01	1.05335E-04	1.05263E-04	-6.83561E-01
TI 46	0.0	0.0	0.0	0.0	0.0	0.0
TI 47	0.0	0.0	0.0	0.0	0.0	0.0
TI 48	0.0	0.0	0.0	0.0	0.0	0.0
TI 49	0.0	0.0	0.0	0.0	0.0	0.0
TI 50	0.0	0.0	0.0	0.0	0.0	0.0

Exhibit 5. (Cont'd.)

7 NUCLIDE TABLE RADIOACTIVITY, CURIES ACTIVATION PRODUCTS
PERTURBATION IS A 0.1% INCREASE IN PU-239 FISSION

	ZIRC	PERT(P3)	SENS(P3)	FUEL	PERT(P3)	SENS(P3)
H 1	0.0	0.0	0.0	0.0	0.0	0.0
H 2	0.0	0.0	0.0	0.0	0.0	0.0
H 3	1.77959E-04	1.77887E-04	-4.04522E-01	2.67142E+02	2.67128E+02	-5.30061E-02
H 4	6.78590E-02	6.78466E-02	-1.82699E-01	7.57453E+00	7.57313E+00	-1.84829E-01
HE 3	0.0	0.0	0.0	0.0	0.0	0.0
HE 4	0.0	0.0	0.0	0.0	0.0	0.0
HE 6	5.02690E-03	5.02510E-03	-3.57937E-01	2.82432E-02	2.82391E-02	-1.45090E-01
LI 6	0.0	0.0	0.0	0.0	0.0	0.0
LI 7	0.0	0.0	0.0	0.0	0.0	0.0
LI 8	2.72675E-02	2.72625E-02	-1.83344E-01	3.03281E+00	3.03225E+00	-1.84583E-01
BE 8	3.59360E-02	3.59279E-02	-2.25470E-01	3.06177E+00	3.06120E+00	-1.86264E-01
BE 9	0.0	0.0	0.0	0.0	0.0	0.0
BE 10	1.11243E-07	1.11224E-07	-1.71180E-01	1.59294E-06	1.59246E-06	-3.01463E-01
BE 11	2.88315E-07	2.88213E-07	-3.53700E-01	4.12854E-06	4.12654E-06	-4.84427E-01
B 10	0.0	0.0	0.0	0.0	0.0	0.0
B 11	0.0	0.0	0.0	0.0	0.0	0.0
B 12	2.12312E-02	2.12269E-02	-2.02484E-01	2.53703E-01	2.53655E-01	-1.89126E-01
C 12	0.0	0.0	0.0	0.0	0.0	0.0
C 13	0.0	0.0	0.0	0.0	0.0	0.0
C 14	3.49141E-01	3.49081E-01	-1.71913E-01	5.93969E-01	5.93866E-01	-1.73404E-01
C 15	7.82166E-02	7.82024E-02	-1.81367E-01	4.96278E+01	4.96187E+01	-1.83556E-01
N 13	0.0	0.0	0.0	0.0	0.0	0.0
N 14	0.0	0.0	0.0	0.0	0.0	0.0
N 15	0.0	0.0	0.0	0.0	0.0	0.0
N 16	4.60460E-01	4.60376E-01	-1.82389E-01	3.10818E+02	3.10761E+02	-1.83802E-01
O 16	0.0	0.0	0.0	0.0	0.0	0.0
O 17	0.0	0.0	0.0	0.0	0.0	0.0
O 18	0.0	0.0	0.0	0.0	0.0	0.0
O 19	5.59127E-03	5.59025E-03	-1.82558E-01	5.25648E+00	5.25552E+00	-1.82698E-01
F 19	0.0	0.0	0.0	0.0	0.0	0.0
F 20	1.63794E-07	1.63736E-07	-3.54330E-01	4.96954E+00	4.96863E+00	-1.83076E-01
NE 20	0.0	0.0	0.0	0.0	0.0	0.0
NE 21	0.0	0.0	0.0	0.0	0.0	0.0
NE 22	0.0	0.0	0.0	0.0	0.0	0.0
NE 23	3.63044E-09	3.62851E-09	-5.31619E-01	1.99266E+00	1.99229E+00	-1.85694E-01
NA 22	0.0	0.0	0.0	0.0	0.0	0.0
NA 23	0.0	0.0	0.0	0.0	0.0	0.0
NA 24	2.48100E-01	2.48056E-01	-1.77300E-01	3.73849E+02	3.73781E+02	-1.82200E-01
NA 24M	1.12432E-12	1.12353E-12	-7.02795E-01	1.56345E+02	1.56317E+02	-1.79090E-01
NA 25	1.39332E-09	1.39259E-09	-5.23828E-01	3.17000E-02	3.16941E-02	-1.86147E-01
MG 24	0.0	0.0	0.0	0.0	0.0	0.0
MG 25	0.0	0.0	0.0	0.0	0.0	0.0
MG 26	0.0	0.0	0.0	0.0	0.0	0.0
MG 27	1.18621E+00	1.18600E+00	-1.76873E-01	3.91538E+00	3.91466E+00	-1.83653E-01
MG 28	1.38278E-09	1.38227E-09	-3.68688E-01	4.56421E-09	4.56253E-09	-3.68176E-01
AL 27	0.0	0.0	0.0	0.0	0.0	0.0
AL 28	2.84426E+01	2.84374E+01	-1.82939E-01	9.46313E+01	9.46139E+01	-1.83819E-01
AL 29	1.36844E-04	1.36795E-04	-3.58045E-01	1.05641E-01	1.05621E-01	-1.89578E-01
AL 30	4.75827E-09	4.75651E-09	-3.69586E-01	1.01870E-04	1.01851E-04	-1.86559E-01
SI 28	0.0	0.0	0.0	0.0	0.0	0.0
SI 29	0.0	0.0	0.0	0.0	0.0	0.0
SI 30	0.0	0.0	0.0	0.0	0.0	0.0

Exhibit 6. Sensitivities to parameter 3 approximated from forward perturbation analysis.

7 NUCLIDE TABLE RADIOACTIVITY, CURIES ACTIVATION PRODUCTS
PERTURBATION IS A 0.1% INCREASE IN PU-239 FISSION

	ZIRC	PERT(P3)	SENS(P3)	FUEL	PERT(P3)	SENS(P3)
SI 31	4.95085E-02	4.94994E-02	-1.83825E-01	6.85217E+01	6.85091E+01	-1.83938E-01
SI 32	2.11015E-11	2.10941E-11	-3.50537E-01	2.92192E-08	2.92090E-08	-3.49080E-01
P 31	0.0	0.0	0.0	0.0	0.0	0.0
P 32	2.67094E+01	2.67046E+01	-1.79385E-01	1.18666E+02	1.18644E+02	-1.85421E-01
P 33	2.40149E-03	2.40099E-03	-2.08157E-01	2.73226E-07	2.73082E-07	-5.27187E-01
P 34	1.24373E-02	1.24350E-02	-1.84807E-01	8.40377E-02	8.40222E-02	-1.84408E-01
S 32	0.0	0.0	0.0	0.0	0.0	0.0
S 33	0.0	0.0	0.0	0.0	0.0	0.0
S 34	0.0	0.0	0.0	0.0	0.0	0.0
S 35	1.28927E+00	1.28903E+00	-1.86405E-01	3.19146E+01	3.19090E+01	-1.75467E-01
S 36	0.0	0.0	0.0	0.0	0.0	0.0
S 37	3.59298E-03	3.59233E-03	-1.80926E-01	1.68866E-02	1.68835E-02	-1.83544E-01
CL 35	0.0	0.0	0.0	0.0	0.0	0.0
CL 36	2.36580E-07	2.36501E-07	-3.33737E-01	1.20447E-02	1.20428E-02	-1.57737E-01
CL 37	0.0	0.0	0.0	0.0	0.0	0.0
CL 38	4.06667E-06	4.06511E-06	-3.83553E-01	9.65424E+00	9.65247E+00	-1.83341E-01
CL 38M	4.84021E-08	4.83834E-08	-3.86377E-01	1.14906E-01	1.14885E-01	-1.83110E-01
AR 36	0.0	0.0	0.0	0.0	0.0	0.0
AR 37	8.63360E-10	8.62928E-10	-5.00485E-01	6.86268E-01	6.86141E-01	-1.84997E-01
AR 38	0.0	0.0	0.0	0.0	0.0	0.0
AR 39	4.36381E-12	4.36171E-12	-4.81204E-01	7.21328E-05	7.21209E-05	-1.64820E-01
AR 40	0.0	0.0	0.0	0.0	0.0	0.0
AR 41	1.96871E-08	1.96800E-08	-3.60557E-01	1.19276E-04	1.19237E-04	-3.26965E-01
AR 42	6.16775E-17	6.16440E-17	-5.43107E-01	5.26478E-13	5.26255E-13	-4.23608E-01
K 39	0.0	0.0	0.0	0.0	0.0	0.0
K 40	1.60342E-24	1.60241E-24	-6.29743E-01	4.55695E-09	4.55620E-09	-1.64501E-01
K 41	0.0	0.0	0.0	0.0	0.0	0.0
K 42	3.40995E-10	3.40869E-10	-3.69211E-01	1.35903E-02	1.35876E-02	-1.98458E-01
K 43	2.46674E-07	2.46587E-07	-3.52803E-01	4.21568E-04	4.21491E-04	-1.82810E-01
K 44	4.39119E-08	4.38963E-08	-3.55256E-01	1.60610E-04	1.60581E-04	-1.80574E-01
CA 40	0.0	0.0	0.0	0.0	0.0	0.0
CA 41	0.0	0.0	0.0	1.91228E-04	1.91195E-04	-1.72588E-01
CA 42	0.0	0.0	0.0	0.0	0.0	0.0
CA 43	0.0	0.0	0.0	0.0	0.0	0.0
CA 44	0.0	0.0	0.0	0.0	0.0	0.0
CA 45	1.27434E-03	1.27409E-03	-1.96227E-01	5.01865E-01	5.01770E-01	-1.89313E-01
CA 46	0.0	0.0	0.0	0.0	0.0	0.0
CA 47	1.75640E-05	1.75582E-05	-3.30575E-01	7.11841E-04	7.11710E-04	-1.84147E-01
CA 48	0.0	0.0	0.0	0.0	0.0	0.0
CA 49	0.0	0.0	0.0	6.02394E-02	6.02284E-02	-1.82618E-01
SC 45	0.0	0.0	0.0	0.0	0.0	0.0
SC 46	1.72913E-01	1.72880E-01	-1.90969E-01	5.95904E-02	5.95758E-02	-2.44996E-01
SC 46M	2.34414E-05	2.34332E-05	-3.50119E-01	9.57256E-03	9.56928E-03	-3.42853E-01
SC 47	2.94284E-01	2.94230E-01	-1.83502E-01	6.67449E-02	6.67327E-02	-1.83069E-01
SC 48	2.79693E-02	2.79643E-02	-1.78744E-01	6.52438E-03	6.52320E-03	-1.81001E-01
SC 49	2.75304E-02	2.75244E-02	-2.17858E-01	6.64104E-02	6.63980E-02	-1.86684E-01
SC 50	4.70835E-04	4.70749E-04	-1.82473E-01	1.05335E-04	1.05316E-04	-1.80422E-01
TI 46	0.0	0.0	0.0	0.0	0.0	0.0
TI 47	0.0	0.0	0.0	0.0	0.0	0.0
TI 48	0.0	0.0	0.0	0.0	0.0	0.0
TI 49	0.0	0.0	0.0	0.0	0.0	0.0
TI 50	0.0	0.0	0.0	0.0	0.0	0.0

Exhibit 6. (Cont'd.)

7 NUCLIDE TABLE RADIOACTIVITY, CURIES ACTIVATION PRODUCTS
PERTURBATION IS A 0.1% INCREASE IN ZIRCALOY FLUX

	ZIRC	PERT(P4)	SENS(P4)	FUEL	PERT(P4)	SENS(P4)
H 1	0.0	0.0	0.0	0.0	0.0	0.0
H 2	0.0	0.0	0.0	0.0	0.0	0.0
H 3	1.77959E-04	1.78377E-04	2.34888E+00	2.67142E+02	2.67142E+02	0.0
H 4	6.78590E-02	6.79268E-02	9.99574E-01	7.57453E+00	7.57453E+00	0.0
HE 3	0.0	0.0	0.0	0.0	0.0	0.0
HE 4	0.0	0.0	0.0	0.0	0.0	0.0
HE 6	5.02690E-03	5.03694E-03	1.99719E+00	2.82432E-02	2.82432E-02	0.0
LI 6	0.0	0.0	0.0	0.0	0.0	0.0
LI 7	0.0	0.0	0.0	0.0	0.0	0.0
LI 8	2.72675E-02	2.72948E-02	1.00115E+00	3.03281E+00	3.03281E+00	0.0
BE 8	3.59360E-02	3.59806E-02	1.24107E+00	3.06177E+00	3.06177E+00	0.0
BE 9	0.0	0.0	0.0	0.0	0.0	0.0
BE 10	1.11243E-07	1.11354E-07	9.97441E-01	1.59294E-06	1.59294E-06	0.0
BE 11	2.88315E-07	2.88892E-07	2.00134E+00	4.12854E-06	4.12854E-06	0.0
B 10	0.0	0.0	0.0	0.0	0.0	0.0
B 11	0.0	0.0	0.0	0.0	0.0	0.0
B 12	2.12312E-02	2.12552E-02	1.13033E+00	2.53703E-01	2.53703E-01	0.0
C 12	0.0	0.0	0.0	0.0	0.0	0.0
C 13	0.0	0.0	0.0	0.0	0.0	0.0
C 14	3.49141E-01	3.49489E-01	9.96651E-01	5.93969E-01	5.93969E-01	0.0
C 15	7.82166E-02	7.82948E-02	9.99804E-01	4.96278E+01	4.96278E+01	0.0
N 13	0.0	0.0	0.0	0.0	0.0	0.0
N 14	0.0	0.0	0.0	0.0	0.0	0.0
N 15	0.0	0.0	0.0	0.0	0.0	0.0
N 16	4.60460E-01	4.60920E-01	9.98934E-01	3.10818E+02	3.10818E+02	0.0
O 16	0.0	0.0	0.0	0.0	0.0	0.0
O 17	0.0	0.0	0.0	0.0	0.0	0.0
O 18	0.0	0.0	0.0	0.0	0.0	0.0
O 19	5.59127E-03	5.59685E-03	9.98071E-01	5.25648E+00	5.25648E+00	0.0
F 19	0.0	0.0	0.0	0.0	0.0	0.0
F 20	1.63794E-07	1.64121E-07	1.99619E+00	4.96954E+00	4.96954E+00	0.0
NE 20	0.0	0.0	0.0	0.0	0.0	0.0
NE 21	0.0	0.0	0.0	0.0	0.0	0.0
NE 22	0.0	0.0	0.0	0.0	0.0	0.0
NE 23	3.63044E-09	3.64134E-09	3.00238E+00	1.99266E+00	1.99266E+00	0.0
NA 22	0.0	0.0	0.0	0.0	0.0	0.0
NA 23	0.0	0.0	0.0	0.0	0.0	0.0
NA 24	2.48100E-01	2.48348E-01	9.99657E-01	3.73849E+02	3.73849E+02	0.0
NA 24M	1.12432E-12	1.12882E-12	4.00230E+00	1.56345E+02	1.56345E+02	0.0
NA 25	1.39332E-09	1.39751E-09	3.00735E+00	3.17000E-02	3.17000E-02	0.0
MG 24	0.0	0.0	0.0	0.0	0.0	0.0
MG 25	0.0	0.0	0.0	0.0	0.0	0.0
MG 26	0.0	0.0	0.0	0.0	0.0	0.0
MG 27	1.18621E+00	1.18740E+00	1.00335E+00	3.91538E+00	3.91538E+00	0.0
MG 28	1.38278E-09	1.38554E-09	1.99599E+00	4.56421E-09	4.56421E-09	0.0
AL 27	0.0	0.0	0.0	0.0	0.0	0.0
AL 28	2.84426E+01	2.84710E+01	9.98383E-01	9.46313E+01	9.46313E+01	0.0
AL 29	1.36844E-04	1.37117E-04	1.99493E+00	1.05641E-01	1.05641E-01	0.0
AL 30	4.75827E-09	4.76817E-09	2.08088E+00	1.01870E-04	1.01870E-04	0.0
SI 28	0.0	0.0	0.0	0.0	0.0	0.0
SI 29	0.0	0.0	0.0	0.0	0.0	0.0
SI 30	0.0	0.0	0.0	0.0	0.0	0.0

Exhibit 7. Sensitivities to parameter 4 approximated from forward perturbation analysis.

7 NUCLIDE TABLE RADIOACTIVITY, CURIES ACTIVATION PRODUCTS
PERTURBATION IS A 0.1% INCREASE IN ZIRCALOY FLUX

	ZIRC	PERT(P4)	SENS(P4)	FUEL	PERT(P4)	SENS(P4)
SI 31	4.95085E-02	4.95580E-02	9.99786E-01	6.85217E+01	6.85217E+01	0.0
SI 32	2.11015E-11	2.11437E-11	1.99997E+00	2.92192E-08	2.92192E-08	0.0
P 31	0.0	0.0	0.0	0.0	0.0	0.0
P 32	2.67094E+01	2.67361E+01	9.99756E-01	1.18666E+02	1.18666E+02	0.0
P 33	2.40149E-03	2.40419E-03	1.12426E+00	2.73226E-07	2.73226E-07	0.0
P 34	1.24373E-02	1.24497E-02	9.97121E-01	8.40377E-02	8.40377E-02	0.0
S 32	0.0	0.0	0.0	0.0	0.0	0.0
S 33	0.0	0.0	0.0	0.0	0.0	0.0
S 34	0.0	0.0	0.0	0.0	0.0	0.0
S 35	1.28927E+00	1.29056E+00	1.00008E+00	3.19146E+01	3.19146E+01	0.0
S 36	0.0	0.0	0.0	0.0	0.0	0.0
S 37	3.59298E-03	3.59658E-03	1.00190E+00	1.68866E-02	1.68866E-02	0.0
CL 35	0.0	0.0	0.0	0.0	0.0	0.0
CL 36	2.36580E-07	2.37045E-07	1.96566E+00	1.20447E-02	1.20447E-02	0.0
CL 37	0.0	0.0	0.0	0.0	0.0	0.0
CL 38	4.06667E-06	4.07552E-06	2.17630E+00	9.65424E+00	9.65424E+00	0.0
CL 38M	4.84021E-08	4.85075E-08	2.17756E+00	1.14906E-01	1.14906E-01	0.0
AR 36	0.0	0.0	0.0	0.0	0.0	0.0
AR 37	8.63360E-10	8.65928E-10	2.97436E+00	6.86268E-01	6.86268E-01	0.0
AR 38	0.0	0.0	0.0	0.0	0.0	0.0
AR 39	4.36381E-12	4.37595E-12	2.78208E+00	7.21328E-05	7.21328E-05	0.0
AR 40	0.0	0.0	0.0	0.0	0.0	0.0
AR 41	1.96071E-08	1.97269E-08	2.02168E+00	1.19276E-04	1.19276E-04	0.0
AR 42	6.16775E-17	6.18636E-17	3.01724E+00	5.26478E-13	5.26478E-13	0.0
K 39	0.0	0.0	0.0	0.0	0.0	0.0
K 40	1.60342E-24	1.60956E-24	3.82962E+00	4.55695E-09	4.55695E-09	0.0
K 41	0.0	0.0	0.0	0.0	0.0	0.0
K 42	3.40995E-10	3.41718E-10	2.12020E+00	1.35903E-02	1.35903E-02	0.0
K 43	2.46674E-07	2.47165E-07	1.99054E+00	4.21568E-04	4.21568E-04	0.0
K 44	4.39119E-08	4.39997E-08	1.99950E+00	1.60610E-04	1.60610E-04	0.0
CA 40	0.0	0.0	0.0	0.0	0.0	0.0
CA 41	0.0	0.0	0.0	1.91228E-04	1.91228E-04	0.0
CA 42	0.0	0.0	0.0	0.0	0.0	0.0
CA 43	0.0	0.0	0.0	0.0	0.0	0.0
CA 44	0.0	0.0	0.0	0.0	0.0	0.0
CA 45	1.27434E-03	1.27571E-03	1.07505E+00	5.01865E-01	5.01865E-01	0.0
CA 46	0.0	0.0	0.0	0.0	0.0	0.0
CA 47	1.75640E-05	1.75968E-05	1.86746E+00	7.11841E-04	7.11841E-04	0.0
CA 48	0.0	0.0	0.0	0.0	0.0	0.0
CA 49	0.0	0.0	0.0	6.02394E-02	6.02394E-02	0.0
SC 45	0.0	0.0	0.0	0.0	0.0	0.0
SC 46	1.72913E-01	1.73085E-01	9.94485E-01	5.95904E-02	5.95904E-02	0.0
SC 46M	2.34414E-05	2.34886E-05	2.01318E+00	9.57256E-03	9.57256E-03	0.0
SC 47	2.94284E-01	2.94578E-01	9.99136E-01	6.67449E-02	6.67449E-02	0.0
SC 48	2.79693E-02	2.79968E-02	9.83224E-01	6.52438E-03	6.52438E-03	0.0
SC 49	2.75304E-02	2.75630E-02	1.18415E+00	6.64104E-02	6.64104E-02	0.0
SC 50	4.70835E-04	4.71311E-04	1.01077E+00	1.05335E-04	1.05335E-04	0.0
TI 46	0.0	0.0	0.0	0.0	0.0	0.0
TI 47	0.0	0.0	0.0	0.0	0.0	0.0
TI 48	0.0	0.0	0.0	0.0	0.0	0.0
TI 49	0.0	0.0	0.0	0.0	0.0	0.0
TI 50	0.0	0.0	0.0	0.0	0.0	0.0

Exhibit 7. (Cont'd.)

7 NUCLIDE TABLE RADIOACTIVITY, CURIES ACTIVATION PRODUCTS
PERTURBATION IS A 0.1% INCREASE IN SPECIFIC POWER

	ZIRC	PERT(PS)	SENS(PS)	FUEL	PERT(PS)	SENS(PS)
H 1	0.0	0.0	0.0	0.0	0.0	0.0
H 2	0.0	0.0	0.0	0.0	0.0	0.0
H 3	1.77959E-04	1.78455E-04	2.78717E+00	2.67142E+02	2.67242E+02	3.73784E-01
H 4	6.78590E-02	6.79501E-02	1.34301E+00	7.57453E+00	7.58472E+00	1.34530E+00
HE 3	0.0	0.0	0.0	0.0	0.0	0.0
HE 4	0.0	0.0	0.0	0.0	0.0	0.0
HE 6	5.02690E-03	5.03961E-03	2.52853E+00	2.82432E-02	2.82736E-02	1.07644E+00
LI 6	0.0	0.0	0.0	0.0	0.0	0.0
LI 7	0.0	0.0	0.0	0.0	0.0	0.0
LI 8	2.72675E-02	2.73042E-02	1.34584E+00	3.03281E+00	3.03689E+00	1.34523E+00
BE 8	3.59360E-02	3.59946E-02	1.63064E+00	3.06177E+00	3.06592E+00	1.35524E+00
BE 9	0.0	0.0	0.0	0.0	0.0	0.0
BE 10	1.11243E-07	1.11375E-07	1.18650E+00	1.59294E-06	1.59623E-06	2.06514E+00
BE 11	2.88315E-07	2.89045E-07	2.53169E+00	4.12854E-06	4.14265E-06	3.41765E+00
B 10	0.0	0.0	0.0	0.0	0.0	0.0
B 11	0.0	0.0	0.0	0.0	0.0	0.0
B 12	2.12312E-02	2.12631E-02	1.50249E+00	2.53703E-01	2.54049E-01	1.36382E+00
C 12	0.0	0.0	0.0	0.0	0.0	0.0
C 13	0.0	0.0	0.0	0.0	0.0	0.0
C 14	3.49141E-01	3.49554E-01	1.18290E+00	5.93969E-01	5.94671E-01	1.18192E+00
C 15	7.82166E-02	7.83216E-02	1.34501E+00	4.96278E+01	4.96946E+01	1.34577E+00
N 13	0.0	0.0	0.0	0.0	0.0	0.0
N 14	0.0	0.0	0.0	0.0	0.0	0.0
N 15	0.0	0.0	0.0	0.0	0.0	0.0
N 16	4.60460E-01	4.61079E-01	1.34429E+00	3.10818E+02	3.11236E+02	1.34474E+00
O 16	0.0	0.0	0.0	0.0	0.0	0.0
O 17	0.0	0.0	0.0	0.0	0.0	0.0
O 18	0.0	0.0	0.0	0.0	0.0	0.0
O 19	5.59127E-03	5.59876E-03	1.34320E+00	5.25648E+00	5.26356E+00	1.34692E+00
F 19	0.0	0.0	0.0	0.0	0.0	0.0
F 20	1.63794E-07	1.64208E-07	2.52751E+00	4.96954E+00	4.97623E+00	1.34621E+00
NE 20	0.0	0.0	0.0	0.0	0.0	0.0
NE 21	0.0	0.0	0.0	0.0	0.0	0.0
NE 22	0.0	0.0	0.0	0.0	0.0	0.0
NE 23	3.63044E-09	3.64394E-09	3.71858E+00	1.99266E+00	1.99534E+00	1.34533E+00
NA 22	0.0	0.0	0.0	0.0	0.0	0.0
NA 23	0.0	0.0	0.0	0.0	0.0	0.0
NA 24	2.48100E-01	2.48433E-01	1.34225E+00	3.73849E+02	3.74351E+02	1.34266E+00
NA 24M	1.12432E-12	1.12983E-12	4.90028E+00	1.56345E+02	1.56555E+02	1.34313E+00
NA 25	1.39332E-09	1.39851E-09	3.72497E+00	3.17000E-02	3.17426E-02	1.34381E+00
MG 24	0.0	0.0	0.0	0.0	0.0	0.0
MG 25	0.0	0.0	0.0	0.0	0.0	0.0
MG 26	0.0	0.0	0.0	0.0	0.0	0.0
MG 27	1.18621E+00	1.18781E+00	1.34906E+00	3.91538E+00	3.92065E+00	1.34597E+00
MG 28	1.38278E-09	1.38650E-09	2.69033E+00	4.56421E-09	4.57650E-09	2.69243E+00
AL 27	0.0	0.0	0.0	0.0	0.0	0.0
AL 28	2.84426E+01	2.84808E+01	1.34334E+00	9.46313E+01	9.47586E+01	1.34526E+00
AL 29	1.36844E-04	1.37190E-04	2.52843E+00	1.05641E-01	1.05784E-01	1.35356E+00
AL 30	4.75627E-09	4.77077E-09	2.62668E+00	1.01870E-04	1.02007E-04	1.34491E+00
SI 28	0.0	0.0	0.0	0.0	0.0	0.0
SI 29	0.0	0.0	0.0	0.0	0.0	0.0
SI 30	0.0	0.0	0.0	0.0	0.0	0.0

Exhibit 8. Sensitivities to parameter 5 approximated from forward perturbation analysis.

7 NUCLIDE TABLE   RADIOACTIVITY, CURIES   ACTIVATION PRODUCTS
PERTURBATION IS A 0.1% INCREASE IN SPECIFIC POWER

	ZIRC	PERT(PS)	SENS(PS)	FUEL	PERT(PS)	SENS(PS)
SI 31	4.95085E-02	4.95750E-02	1.34321E+00	6.85217E+01	6.86139E+01	1.34569E+00
SI 32	2.11015E-11	2.11520E-11	2.39326E+00	2.92192E-08	2.92892E-08	2.39565E+00
P 31	0.0	0.0	0.0	0.0	0.0	0.0
P 32	2.67094E+01	2.67453E+01	1.34424E+00	1.18666E+02	1.18826E+02	1.34835E+00
P 33	2.40149E-03	2.40508E-03	1.49491E+00	2.73226E-07	2.74240E-07	3.71111E+00
P 34	1.24373E-02	1.24540E-02	1.34277E+00	8.40377E-02	8.41514E-02	1.35256E+00
S 32	0.0	0.0	0.0	0.0	0.0	0.0
S 33	0.0	0.0	0.0	0.0	0.0	0.0
S 34	0.0	0.0	0.0	0.0	0.0	0.0
S 35	1.28927E+00	1.29099E+00	1.33368E+00	3.19146E+01	3.19541E+01	1.23783E+00
S 36	0.0	0.0	0.0	0.0	0.0	0.0
S 37	3.59298E-03	3.59781E-03	1.34424E+00	1.68866E-02	1.69095E-02	1.35607E+00
CL 35	0.0	0.0	0.0	0.0	0.0	0.0
CL 36	2.36580E-07	2.37130E-07	2.32487E+00	1.20447E-02	1.20582E-02	1.12055E+00
CL 37	0.0	0.0	0.0	0.0	0.0	0.0
CL 38	4.06667E-06	4.07783E-06	2.74436E+00	9.65424E+00	9.66730E+00	1.35283E+00
CL 38M	4.84021E-08	4.85350E-08	2.74575E+00	1.14906E-01	1.15061E-01	1.34869E+00
AR 36	0.0	0.0	0.0	0.0	0.0	0.0
AR 37	8.63360E-10	8.66436E-10	3.56281E+00	6.86268E-01	6.87194E-01	1.34935E+00
AR 38	0.0	0.0	0.0	0.0	0.0	0.0
AR 39	4.36381E-12	4.37822E-12	3.30224E+00	7.21328E-05	7.22151E-05	1.14103E+00
AR 40	0.0	0.0	0.0	0.0	0.0	0.0
AR 41	1.96871E-08	1.97374E-08	2.55494E+00	1.19276E-04	1.19549E-04	2.28888E+00
AR 42	6.16775E-17	6.19040E-17	3.67236E+00	5.26478E-13	5.28002E-13	2.89472E+00
K 39	0.0	0.0	0.0	0.0	0.0	0.0
K 40	1.60342E-24	1.61055E-24	4.44706E+00	4.55695E-09	4.56215E-09	1.14137E+00
K 41	0.0	0.0	0.0	0.0	0.0	0.0
K 42	3.40995E-10	3.41893E-10	2.63332E+00	1.35903E-02	1.36098E-02	1.43499E+00
K 43	2.46674E-07	2.47296E-07	2.52147E+00	4.21566E-04	4.22132E-04	1.33766E+00
K 44	4.39119E-08	4.40230E-08	2.53008E+00	1.60610E-04	1.60826E-04	1.34493E+00
CA 40	0.0	0.0	0.0	0.0	0.0	0.0
CA 41	0.0	0.0	0.0	1.91228E-04	1.91454E-04	1.18186E+00
CA 42	0.0	0.0	0.0	0.0	0.0	0.0
CA 43	0.0	0.0	0.0	0.0	0.0	0.0
CA 44	0.0	0.0	0.0	0.0	0.0	0.0
CA 45	1.27434E-03	1.27611E-03	1.38894E+00	5.01865E-01	5.02519E-01	1.30310E+00
CA 46	0.0	0.0	0.0	0.0	0.0	0.0
CA 47	1.75640E-05	1.76058E-05	2.37947E+00	7.11841E-04	7.12803E-04	1.35150E+00
CA 48	0.0	0.0	0.0	0.0	0.0	0.0
CA 49	0.0	0.0	0.0	6.02394E-02	6.03203E-02	1.34295E+00
SC 45	0.0	0.0	0.0	0.0	0.0	0.0
SC 46	1.72913E-01	1.73143E-01	1.33023E+00	5.95904E-02	5.96929E-02	1.72010E+00
SC 46M	2.34414E-05	2.35000E-05	2.49987E+00	9.57256E-03	9.59611E-03	2.45990E+00
SC 47	2.94284E-01	2.94679E-01	1.34224E+00	6.67449E-02	6.68348E-02	1.34668E+00
SC 48	2.79693E-02	2.80064E-02	1.32646E+00	6.52438E-03	6.53303E-03	1.32582E+00
SC 49	2.75304E-02	2.75734E-02	1.56195E+00	6.64104E-02	6.65010E-02	1.36423E+00
SC 50	4.70835E-04	4.71475E-04	1.35940E+00	1.05335E-04	1.05478E-04	1.35759E+00
TI 46	0.0	0.0	0.0	0.0	0.0	0.0
TI 47	0.0	0.0	0.0	0.0	0.0	0.0
TI 48	0.0	0.0	0.0	0.0	0.0	0.0
TI 49	0.0	0.0	0.0	0.0	0.0	0.0
TI 50	0.0	0.0	0.0	0.0	0.0	0.0

Exhibit 8. (Cont'd.)

7 NUCLIDE TABLE   RADIOACTIVITY, CURIES   ACTIVATION PRODUCTS
PERTURBATION IS A 0.5% INCREASE IN U-235 DENSITY

	ZIRC	PERT(P6)	SENS(P6)	FUEL	PERT(P6)	SENS(P6)
H 1	0.0	0.0	0.0	0.0	0.0	0.0
H 2	0.0	0.0	0.0	0.0	0.0	0.0
H 3	1.77959E-04	1.76543E-04	-1.59136E+00	2.67142E+02	2.66859E+02	-2.12024E-01
H 4	6.78590E-02	6.76731E-02	-5.47921E-01	7.57453E+00	7.55379E+00	-5.47613E-01
HE 3	0.0	0.0	0.0	0.0	0.0	0.0
HE 4	0.0	0.0	0.0	0.0	0.0	0.0
HE 6	5.02690E-03	4.99609E-03	-1.22573E+00	2.82432E-02	2.81678E-02	-3.92298E-01
LI 6	0.0	0.0	0.0	0.0	0.0	0.0
LI 7	0.0	0.0	0.0	0.0	0.0	0.0
LI 8	2.72675E-02	2.71928E-02	-5.47901E-01	3.03281E+00	3.02450E+00	-5.48028E-01
BE 8	3.59360E-02	3.58082E-02	-7.11284E-01	3.06177E+00	3.05329E+00	-5.53933E-01
BE 9	0.0	0.0	0.0	0.0	0.0	0.0
BE 10	1.11243E-07	1.10864E-07	-6.81448E-01	1.59294E-06	1.58351E-06	-1.18393E+00
BE 11	2.88315E-07	2.86547E-07	-1.22644E+00	4.12854E-06	4.09287E-06	-1.72799E+00
B 10	0.0	0.0	0.0	0.0	0.0	0.0
B 11	0.0	0.0	0.0	0.0	0.0	0.0
B 12	2.12312E-02	2.11639E-02	-6.33963E-01	2.53703E-01	2.52995E-01	-5.58120E-01
C 12	0.0	0.0	0.0	0.0	0.0	0.0
C 13	0.0	0.0	0.0	0.0	0.0	0.0
C 14	3.49141E-01	3.47957E-01	-6.78228E-01	5.93969E-01	5.91953E-01	-6.78826E-01
C 15	7.82166E-02	7.80024E-02	-5.47759E-01	4.96278E+01	4.94919E+01	-5.47717E-01
N 13	0.0	0.0	0.0	0.0	0.0	0.0
N 14	0.0	0.0	0.0	0.0	0.0	0.0
N 15	0.0	0.0	0.0	0.0	0.0	0.0
N 16	4.60460E-01	4.59199E-01	-5.47711E-01	3.10818E+02	3.09967E+02	-5.47635E-01
O 16	0.0	0.0	0.0	0.0	0.0	0.0
O 17	0.0	0.0	0.0	0.0	0.0	0.0
O 18	0.0	0.0	0.0	0.0	0.0	0.0
O 19	5.59127E-03	5.57595E-03	-5.47940E-01	5.25648E+00	5.24209E+00	-5.47514E-01
F 19	0.0	0.0	0.0	0.0	0.0	0.0
F 20	1.63794E-07	1.62790E-07	-1.22596E+00	4.96954E+00	4.95594E+00	-5.47310E-01
NE 20	0.0	0.0	0.0	0.0	0.0	0.0
NE 21	0.0	0.0	0.0	0.0	0.0	0.0
NE 22	0.0	0.0	0.0	0.0	0.0	0.0
NE 23	3.63044E-09	3.59592E-09	-1.90169E+00	1.99266E+00	1.98722E+00	-5.45980E-01
NA 22	0.0	0.0	0.0	0.0	0.0	0.0
NA 23	0.0	0.0	0.0	0.0	0.0	0.0
NA 24	2.48100E-01	2.47421E-01	-5.47325E-01	3.73849E+02	3.72828E+02	-5.46338E-01
NA 24M	1.12432E-12	1.10984E-12	-2.57568E+00	1.56345E+02	1.55918E+02	-5.46230E-01
NA 25	1.39332E-09	1.38007E-09	-1.90191E+00	3.17000E-02	3.16131E-02	-5.48264E-01
MG 24	0.0	0.0	0.0	0.0	0.0	0.0
MG 25	0.0	0.0	0.0	0.0	0.0	0.0
MG 26	0.0	0.0	0.0	0.0	0.0	0.0
MG 27	1.18621E+00	1.18297E+00	-5.46216E-01	3.91538E+00	3.90467E+00	-5.47061E-01
MG 28	1.38278E-09	1.37521E-09	-1.09489E+00	4.56421E-09	4.53926E-09	-1.09332E+00
AL 27	0.0	0.0	0.0	0.0	0.0	0.0
AL 28	2.84426E+01	2.83647E+01	-5.47743E-01	9.46313E+01	9.43724E+01	-5.47167E-01
AL 29	1.36844E-04	1.36005E-04	-1.22622E+00	1.05641E-01	1.05349E-01	-5.52822E-01
AL 30	4.75827E-09	4.72778E-09	-1.28153E+00	1.01870E-04	1.01591E-04	-5.47765E-01
SI 28	0.0	0.0	0.0	0.0	0.0	0.0
SI 29	0.0	0.0	0.0	0.0	0.0	0.0
SI 30	0.0	0.0	0.0	0.0	0.0	0.0

Exhibit 9. Sensitivities to parameter 6 approximated from forward perturbation analysis.

7 NUCLIDE TABLE RADIOACTIVITY, CURIES ACTIVATION PRODUCTS
PERTURBATION IS A 0.5% INCREASE IN U-235 DENSITY

	ZIRC	PERT(P5)	SENS(P5)	FUEL	PERT(P5)	SENS(P5)
SI 31	4.95085E-02	4.93727E-02	-5.48600E-01	6.85217E+01	6.83343E+01	-5.46960E-01
SI 32	2.11015E-11	2.09599E-11	-1.34204E+00	2.92192E-08	2.90232E-08	-1.34158E+00
P 31	0.0	0.0	0.0	0.0	0.0	0.0
P 32	2.67094E+01	2.66363E+01	-5.47295E-01	1.18666E+02	1.18341E+02	-5.47751E-01
P 33	2.40149E-03	2.39382E-03	-6.38762E-01	2.73226E-07	2.70609E-07	-1.91564E+00
P 34	1.24373E-02	1.24033E-02	-5.46754E-01	8.40377E-02	8.38061E-02	-5.51237E-01
S 32	0.0	0.0	0.0	0.0	0.0	0.0
S 33	0.0	0.0	0.0	0.0	0.0	0.0
S 34	0.0	0.0	0.0	0.0	0.0	0.0
S 35	1.28927E+00	1.28555E+00	-5.77115E-01	3.19146E+01	3.18317E+01	-5.19518E-01
S 36	0.0	0.0	0.0	0.0	0.0	0.0
S 37	3.59298E-03	3.58315E-03	-5.47184E-01	1.68866E-02	1.68398E-02	-5.54295E-01
CL 35	0.0	0.0	0.0	0.0	0.0	0.0
CL 36	2.36580E-07	2.34997E-07	-1.33822E+00	1.20447E-02	1.20062E-02	-6.39300E-01
CL 37	0.0	0.0	0.0	0.0	0.0	0.0
CL 38	4.06667E-06	4.03932E-06	-1.34510E+00	9.65424E+00	9.62764E+00	-5.51051E-01
CL 38M	4.84021E-08	4.80766E-08	-1.34498E+00	1.14906E-01	1.14589E-01	-5.51820E-01
AR 36	0.0	0.0	0.0	0.0	0.0	0.0
AR 37	8.63360E-10	8.54805E-10	-1.98183E+00	6.86268E-01	6.84359E-01	-5.56330E-01
AR 38	0.0	0.0	0.0	0.0	0.0	0.0
AR 39	4.36381E-12	4.32269E-12	-1.88459E+00	7.21328E-05	7.18971E-05	-6.53510E-01
AR 40	0.0	0.0	0.0	0.0	0.0	0.0
AR 41	1.96871E-08	1.95649E-08	-1.24141E+00	1.19276E-04	1.18628E-04	-1.08655E+00
AR 42	6.16775E-17	6.10678E-17	-1.97703E+00	5.26478E-13	5.22282E-13	-1.59400E+00
K 39	0.0	0.0	0.0	0.0	0.0	0.0
K 40	1.60342E-24	1.58216E-24	-2.65181E+00	4.55695E-09	4.54207E-09	-6.53014E-01
K 41	0.0	0.0	0.0	0.0	0.0	0.0
K 42	3.40995E-10	3.38721E-10	-1.33372E+00	1.35903E-02	1.35496E-02	-5.98939E-01
K 43	2.46674E-07	2.45169E-07	-1.22022E+00	4.21568E-04	4.20425E-04	-5.42245E-01
K 44	4.39119E-08	4.36430E-08	-1.22473E+00	1.60610E-04	1.60171E-04	-5.46668E-01
CA 40	0.0	0.0	0.0	0.0	0.0	0.0
CA 41	0.0	0.0	0.0	1.91228E-04	1.90578E-04	-6.79822E-01
CA 42	0.0	0.0	0.0	0.0	0.0	0.0
CA 43	0.0	0.0	0.0	0.0	0.0	0.0
CA 44	0.0	0.0	0.0	0.0	0.0	0.0
CA 45	1.27434E-03	1.27022E-03	-6.46636E-01	5.01865E-01	5.00368E-01	-5.96587E-01
CA 46	0.0	0.0	0.0	0.0	0.0	0.0
CA 47	1.75640E-05	1.74644E-05	-1.13423E+00	7.11841E-04	7.09884E-04	-5.49825E-01
CA 48	0.0	0.0	0.0	0.0	0.0	0.0
CA 49	0.0	0.0	0.0	6.02394E-02	6.00750E-02	-5.45825E-01
SC 45	0.0	0.0	0.0	0.0	0.0	0.0
SC 46	1.72913E-01	1.72417E-01	-5.73733E-01	5.95904E-02	5.93465E-02	-8.18583E-01
SC 46M	2.34414E-05	2.32933E-05	-1.26366E+00	9.57256E-03	9.51336E-03	-1.23692E+00
SC 47	2.94284E-01	2.93479E-01	-5.47064E-01	6.67449E-02	6.65620E-02	-5.48136E-01
SC 48	2.79693E-02	2.78942E-02	-5.37031E-01	6.52438E-03	6.50688E-03	-5.36493E-01
SC 49	2.75304E-02	2.74375E-02	-6.74873E-01	6.64104E-02	6.62252E-02	-5.57898E-01
SC 50	4.70835E-04	4.69533E-04	-5.53055E-01	1.05335E-04	1.05045E-04	-5.50634E-01
TI 46	0.0	0.0	0.0	0.0	0.0	0.0
TI 47	0.0	0.0	0.0	0.0	0.0	0.0
TI 48	0.0	0.0	0.0	0.0	0.0	0.0
TI 49	0.0	0.0	0.0	0.0	0.0	0.0
TI 50	0.0	0.0	0.0	0.0	0.0	0.0

Exhibit 9. (Cont'd.)

V. CONCLUSIONS

The GRESS automated procedure was successfully applied and verified on ORIGEN2, a large code (more than 5K cards) using complex coding and resolution methods to calculate chain buildup and decay of large numbers of nuclides and elements (more than 1600) in nuclear reactors. The double precision GRESS library allowing calculation of sensitivities for mixed single and double precision variables was used in conjunction with the GRESS precompiler. A sample problem involving fuel burnup under specified power, radioactive decay, and material irradiation under specified flux was used for the sensitivity calculation and verification analysis. Sensitivities were calculated for all printed nuclide concentrations (more than 1600) in two ORIGEN2 vectors with respect to six parameters. The accuracy of the GRESS results was verified using perturbation analysis methods. Together with preceding validation studies using the SWENT code[7] and the UCBNE-10.2 code,[8] this analysis demonstrates the efficiency of the GRESS automated procedure in calculating model sensitivities and further illustrates its applicability to a wide variety of numerical codes.

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APPENDIX

Method of Determination of Precision Intervals

This attachment briefly describes a method to determine expected precision intervals when approximating gradients and sensitivities from results of perturbation analysis printed with n significant digits.

Let V, F and B be the results of a calculation corresponding to an unperturbed case, a forward perturbed case (i.e. the calculation is performed with a positive parameter perturbation) and a backward perturbed case (i.e. the calculation is performed with a negative parameter perturbation), respectively. Assume that the perturbed cases involve p% perturbation (positive or negative) in the value of the parameters of interest. Then,

$$SF = \frac{F-V}{V} \times \frac{100}{p}$$

and

$$SC = \frac{F-B}{V} \times \frac{100}{2\ p}$$

represent normalized sensitivity coefficients of the variable V with respect to the parameter of interest approximated from forward perturbation analysis and centered (forward and backward) perturbation analysis, respectively. These sensitivity coefficients are exact only when the variable V behaves linearly in the interval [B, F]. This is not generally the case and therefore, SF and SC constitute only approximations of the sensitivity coefficient at the solution point V. In a majority of problems, the assumption of linearity can be made a reasonably close one if the interval [B, F] is small. This is generally achieved by selecting a small value of the parameter perturbation p.

However, in all cases (including linear cases), due to truncation errors in the printed values of the variables V, F and B, SF and SC are calculated within a certain error range which depends on the number of digits with which the variables are printed.

Assume the results are printed with n significant digits in the form

VxEa

BxEb

FxEc

where V, B and F are now n digits real numbers with decimal point to the right of the first digit, and $Ea = 10^a$. For small perturbations a, b and c do not differ by more than 1, i.e., $|a-b| < 1$, $|a-c| < 1$ and $|b-c| \leq 1$.

Then SF and SC are calculated within an error range such that

$$SF = \left(\frac{FEc\text{-}a - V}{V}\right)\frac{100}{P} \pm \left(\frac{5 \times 10^{-n}\ (1 + Ec\text{-}a)}{V}\right)\frac{100}{P}$$

and

$$SC = \left(\frac{FEc\text{-}a - BEb\text{-}a}{V}\right)\frac{100}{2P} \pm \left(\frac{5 \times 10^{-n}\ (Eb\text{-}a + Ec\text{-}a)}{V}\right)\frac{100}{2P} \ .$$

The error ranges define the expected precision intervals within which SF and SC approximate the exact sensitivities at the point solution V. The expected precision intervals can be large depending on the relative values of a, b, c, n, V and p and should be taken into account when comparing approximate sensitivities such as SF and SC to exact local sensitivities such as those calculated by GRESS. This is exemplified below.

A code such as ORIGEN2 calculates variables in single precision, hence 6 significant digits accuracy is well within the truncation error range of the calculations. The code, originally designed to print results with 4 significant digits was modified to print 6 significant digits. Small parameter perturbation values of 0.1% (p = 0.1) were used.

Assume the results of the code are

$$V = 1.00014 \text{ Ea}$$

$$F = 1.00025 \text{ Ea}$$

$$B = 1.00003 \text{ Ea}$$

then the values of SF and SC in this case are:

$$0.99986 \times 10^{-1} < SF < 1.19983 \times 10^{-1}$$

$$1.05000 \times 10^{-1} < SC < 1.14984 \times 10^{-1}$$

or

$$SF = 1.09985 \times 10^{-1} \pm 9.99850 \times 10^{-3}$$

$$SC = 1.09992 \times 10^{-1} \pm 4.99200 \times 10^{-3}$$

or

$$SF = 1.09985 \times 10^{-1} \pm 9.1\%$$

$$SC = 1.09992 \times 10^{-1} \pm 4.5\%.$$

Thus, for this example, the best precision expected on the values of SF and SC are 9.1% and 4.5% respectively.

In the GRESS sensitivities verification study, expected precision intervals were calculated whenever differences of more than 1% were observed between the GRESS and perturbation analysis results. In all cases, GRESS results and perturbation analysis results agreed with precisions much better than the expected precision.

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