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**Automated Determination of Irradiated
Fuel Pin Centerlines for Gamma Scanning**

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AUTOMATED DETERMINATION OF IRRADIATED FUEL PIN CENTERLINES FOR GAMMA SCANNING

B. K. Barnes, J. N. Quintana, and A. S. Murray

ABSTRACT

We describe a method for calculating the centerlines of irradiated fuel pins to be analyzed by gamma scanning. Fuel pin centering has been automated by computer control through a CAMAC link to the scanning mechanism. Rapidity and accuracy of the gamma scanning process have been improved by replacing the former trial and error method with this automated technique.

INTRODUCTION

Gamma scanning is an important nondestructive technique for analysis of fuel pins. It can be applied to research and development in fuel pin technology and to materials control by manufacturers of commercial fuel pins. A destructive examination, which can determine more accurately the amounts of fission products and fissionable materials in an irradiated fuel pin, is extremely expensive and, in many cases, not feasible. Thus the highest possible degree of accuracy is demanded of a nondestructive analysis technique. The possible advent of commercial fast breeder reactors will increase the importance of high accuracy techniques because large amounts of fissionable materials and much reprocessing are associated with such reactors.

THE PROBLEM

Axial gamma scanning of an irradiated fuel pin requires an accurate determination of the fuel pin centerline. To avoid variation of the gamma-ray intensity with axial position, the fuel pin must remain centered in the volume-defining collimators as it is moved past them. Any significant deviation of the fuel pin centerline from the centerline of the collimators produces a decrease in the measured

gamma-ray intensity because of the collimator geometry and the nonuniform response of the detector across its face.

Most irradiated fuel pins exhibit a degree of mechanical bowing greater than the amount (approximately 1 mm from end to end) that does not affect significantly the gamma-ray intensity.¹ A mechanical device has been used to hold the fuel pin centered in the collimators. Use of such a device, however, requires that the fuel pin be handled bare—a situation that, in the event of fission product leakage from the fuel pin, could lead to contamination of the scanning mechanism and the hot cell. Also, malfunction of the centering mechanism could cause damage to the fuel pin. To avoid the possibility of contamination or damage, fuel pins are scanned inside an alpha-particle containment canister, a thin-walled stainless steel tube sealed at both ends. A canister small enough to hold the fuel pin straight could be used, but loading a bowed fuel pin into such a tight container by manipulators inside a hot cell would be difficult and time-consuming. Therefore, we use a more loosely fitting canister and the bow remains. The customary procedure for eliminating the effects of the bow has been to locate by trial and error a rotation and tilt of the canister such that the fuel pin remains on the centerline of the collimators as it is being axially scanned.

THE SOLUTION

In most cases, it is possible to determine a single rotation and tilt such that, for all axial positions, the fuel pin is centered in the collimators. Most fuel pins must therefore have a simple plane bow, as opposed to a spiral bow. For a simple plane bow, the required rotation and tilt can be calculated from a set of initial measurements in the following manner.

Six diametral scans are made across the fuel pin, two at each of three axial positions corresponding to the approximate beginning, middle, and end of that portion of the fuel pin containing the enriched fuel. The fuel pin is rotated 90° between the two scans at each axial position. From analysis of these six diametral scans, we can determine the three-dimensional coordinates of the fuel pin centerline at three points (x_1, y_1, z_1) , (x_2, y_2, z_2) , and (x_3, y_3, z_3) where z denotes the axial position of the centerline and x and y denote the diametral positions of the centerline for the two rotations (90° relative to each other).

Assuming a simple plane bow of the fuel pin, these three points determine a plane, namely the plane of the fuel pin bow. If the equation of this plane is given by

$$x + by + cz + d = 0,$$

where b , c , and d are constants determined from the coordinates of the three points, then the direction angles α , β , and γ of the line P normal to the bow plane are given² by

$$\cos \alpha = 1/(1 + b^2 + c^2)^{1/2},$$

$$\cos \beta = b/(1 + b^2 + c^2)^{1/2},$$

and

$$\cos \gamma = c/(1 + b^2 + c^2)^{1/2}.$$

The direction angles α_z , β_z , and γ_z of the directed line segment $+Z$ (the axis of rotation of the fuel pin) are given by

$$\cos \alpha_z = \cos \pi/2 = 0,$$

$$\cos \beta_z = \cos \pi/2 = 0,$$

and

$$\cos \gamma_z = \cos 0 = 1.$$

The cosine of the angle ϕ between P and $+Z$ is given by the sum of the products of the respective direction cosines.³

$$\begin{aligned} \cos \phi &= \cos \alpha \cos \alpha_z + \cos \beta \cos \beta_z + \cos \gamma \cos \gamma_z \\ &= \cos \gamma. \end{aligned}$$

By tilting the bow plane an amount such that P and $+Z$ are perpendicular, the bow plane becomes parallel to the X axis. So, first we tilt the fuel pin by an angle of $90^\circ - \gamma$.

Next, we rotate P so that it is parallel to the axis of the diametral scans (in our case, the X axis). From Fig. 1, we see that the angle δ between the Y axis and the projection of P on the X - Y plane is given by

$$\cos \delta = \cos \beta / \sin \gamma.$$

Fig. 1.
Geometry of the scanning mechanism.

Therefore by rotating the bow plane by an angle of $90^\circ - \delta$ (where $\delta = \cos^{-1} [(\cos \beta)/(\sin \gamma)]$), the bow plane becomes perpendicular to the X axis.

CONCLUSIONS

In summary, having determined the direction angles of the normal to the fuel pin bow plane to be α , β , and γ , we can make the bow plane perpendicular to the diametral scan direction by (a) tilting the fuel pin by $90^\circ - \gamma$ and (b) rotating the fuel pin by $90^\circ - \cos^{-1} [(\cos \beta)/(\sin \gamma)]$. With this tilt and rotation, the fuel pin remains centered in the collimators during an axial scan. A computer program for the necessary calculations has been written and used on an HP-9820 calculator (Hewlett-Packard Co.), a PDP-8 computer (Digital Equipment Corp.), a CDC-7600 computer (Control Data Corp.) and an ND6620 multichannel analyzer (Nuclear Data, Inc.). A FORTRAN version of this program is given in the Appendix.

A program to automate centering of the fuel pins has been written for the ND6620 multichannel analyzer. Computer control of the five degrees of freedom of the scanning mechanism (rotation, tilt, and motion along the X, Y, and Z axes) is achieved

by a CAMAC link to the scanning mechanism. The program takes the required diametral scans, calculates the centerline coordinates and the required rotation and tilt, moves the fuel pin, and checks the centerline. If necessary, the process is repeated until a satisfactory centerline is located.

Automation of fuel pin centering reduces the time required for gamma scanning by typically one to two hours per fuel pin. Accuracy of the centerline so determined is greater; therefore, error in the data is reduced.

REFERENCES

1. J. R. Phillips, "New Techniques in Precision Gamma Scanning: Applications to Fast-Breeder Reactor Fuel Pins," Los Alamos Scientific Laboratory report LA-5260-T (July 1973).
2. J. M. H. Olmsted, *Solid Analytic Geometry* (Appleton-Century Crofts, New York, 1947), p. 15.
3. J. H. Kindle, *Analytic Geometry* (McGraw-Hill Book Co., New York, 1950), p. 105.

APPENDIX

FORTTRAN VERSION OF THE PROGRAM ACL

LASL Identification No. LP-2024

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C      SOURCE ACL (AUTOMATIC CENTER LINE)
      INTEGER DKS, SVAR, TITLE, AX, FIRST, TAPE, TN, CURR, BLANK, RVAR,
1     AXT, DIT, DT, AM, TOP(2), BOT(2), ZERO(240), ARRAY(720)
      LOGICAL *1AADC, YN, YES, ERASE(7)
      DIMENSION TITLE(12), AADC(25), TAPE(5), TN(2), AR(360), ITITLE(12)
1     , ITN(2), ROT(6), ZPOS(6), IADCTX(32), X(6), DATA(240), START(6),
2     STOP(6)
      EQUIVALENCE (TAPE(4),TN), (IADCTX(29),SLOPE), (IADCTX(31),OFFSET),
1     (AR,ARRAY)
      DATA AADC /1H:,1HA,1HA,1HD,1HG,1H,1H1,1H,,1H1,1H,,1H4,1H0,1H9,1H6
1     ,1H,,1H2,1H0,1H,,1H1,1H1,1H1,1H1,1H1,1H1,1H:/
      DATA TAPE /2HJP,2HC0,2H1-,2HXX,2HX /, AXT /"AX"/, DIT /"DI"/, YES
1     /"Y"/, BLANK /"/, ZERO /240*0/, TITLE /2HLA,2HSL,2H -,9*2H**/,
2     ERASE /1WL,1HE,1HR,1HA,1HS,1HE,1H/
      DIFMIN=1000000.
      TUL=7.120
      TLL=3.915
C      TUL=TILT UPPER LIMIT > TLL=TILT LOWER LIMIT
      WRITE (7,500)
      WRITE (7,490)
      WRITE (7,500)
      WRITE (7,230)
      WRITE (7,490)
      WRITE (7,500)
10     WRITE (7,240)
      WRITE (7,290) ZL
      WRITE (7,270)
      READ (5,250) AZL
      IF (AZL.NE.0.) ZL=AZL
      PP=(60.-ZL)+0.3
C      PP IS POSITION OF PIVOT POINT, USED TO CALCULATE
C      NEW START AND STOP POSITIONS AFTER TILTING.
20     WRITE (7,260)
      WRITE (7,290) TOPF
      WRITE (7,270)
      READ (5,280) ATOPF
      IF (ATOPF.NE.0) TOPF=ATOPF
      WRITE (7,300)
      WRITE (7,290) BOTF
      WRITE (7,270)
      READ (5,280) ABOTF
      IF (ABOTF.NE.0.) BOTF=ABOTF
      STEP=.025
      TIME=.2
      NDIA=6
      ZPOS(1)=TOPF
      ZPOS(2)=(TOPF+BOTF)/2.
      ZPOS(3)=BOTF
      ZPOS(4)=BOTF
      ZPOS(5)=ZPOS(2)
      ZPOS(6)=TOPF
      CALL RDPOS (4,R0)
      CALL RDPOS (5,T0)

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C      R0 IS PRESET ROTATION, T0 IS PRESET TILT
      ROT(3)=R0
      ROT(1)=ROT(3)
      ROT(2)=ROT(3)
      ROT(6)=R0-.050
      ROT(5)=ROT(6)
      ROT(4)=ROT(5)
      WRITE (7,310)
      WRITE (7,270)
      READ (5,360) YN
      IF (YN.NE.YES) GO TO 30
      WRITE (7,320)
      GO TO 10
30     CALL SETPOS (2,32.5)
      IF (T0.EQ.5.00) GO TO 40
      WRITE (7,330) T0
      READ (5,360) YN
      IF (YN.NE.YES) GO TO 40
      CALL SETPOS (5,5.080)
      T0=5.080
40     CONTINUE
C      CALCULATE TAN OF ANGLE OF TILT FROM VERTICAL
C      USE TO CORRECT START AND STOP POSITIONS
      TA=((T0-5.080)/2.)*1.25/ZL
      DO 50 L=1,NDIA
      START(L)=1.80+(ZPOS(L)-PP)*TA
      STOP(L)=START(L)+1.4
50     CONTINUE
C      CHANGE ENERGY CAL TO READ MARKER IN INCHES.
      CALL DECP (1,STEP,START(1),IERR)
      NPTS=NDIA*((STOP(1)-START(1))/STEP+1)
      IF (NPTS.LE.4096) GO TO 60
      WRITE (7,340) NPTS
      GO TO 20
60     CONTINUE
      CALL MCLI (AADC,ISTAT)
C      EXPAND DISPLAY TO 10K X NPTS
      TOP(1)=0
      TOP(2)=1000
      IST=1
      CALL ASPP (1,IST,NPTS,BOT,TOP,IERR)
      IF (ISTAT.EQ.1) GO TO 70
      WRITE (7,350)
      WRITE (7,270)
      READ (5,360) YN
      IF (YN.NE.YES) GO TO 70
      CALL EXIT
70     CONTINUE
      NPT=(STOP(1)-START(1))/STEP+1
      NTPT=NDIA*NPT
80     CALL MCLI (ERASE,IERR)
      DO 100 L=1,NDIA

```

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C      SETPOS(N,A) SETS STEPPING MOTOR N TO POSITION A
C      N=1 IS X AXIS
C      N=2 IS Y AXIS
C      N=3 IS Z AXIS
C      N=4 IS ROTATION
C      N=5 IS TILT
      CALL RDPOS (3,ZPRES)
      STEPS=ZPOS(L)-ZPRES
      IF (ABS(STEPS).GT.0.1) CALL SETPOQ (3,STEPS)
      CALL SETPOS (4,ROT(L))
      CALL SETPOS (1,START(L))
      CALL SETPOS (3,ZPOS(L))
      TIME=.3
      CALL CROSS (START(L),STOP(L),STEP,TIME,AX)
C      SAVE DATA TO BE ABLE TO ERASE
      CALL GADC (AR,1,NTPT,1,1,IERR)
      SUM=0.
C      FIND CENTER LINE OF DATA JUST TAKEN
      DO 90 M=1,NPT
      MT=2*M-1
      CALL CHOP (ARRAY(MD),ARRAY(MD))
      CALL SFLOAT (ARRAY(MD),DATA(M))
      SUM=SUM+DATA(M)
90    CONTINUE
      AVG=SUM/NPT
      DO 100 M=1,NPT
      IF (DATA(M).GT.AVG.AND.DATA(M+1).GT.AVG.AND.DATA(M+2).GT.AVG) GO
1    TO 110
100  CONTINUE
      WRITE (6,370) ZPOS(L)
      M=1
      ALS=START(L)
      GO TO 120
110  ALS=START(L)+(M-1)*STEP
120  DO 130 LM=1,NPT
      MM=NPT+1-LM
      IF (DATA(MM).GT.AVG.AND.DATA(MM-1).GT.AVG.AND.DATA(MM-2).GT.AVG)
1    GO TO 140
130  CONTINUE
      WRITE (6,380) ZPOS(L)
      MM=NPTS
      ARS=STOP(L)
      GO TO 150
140  ARS=START(L)+MM*STEP
150  JLS=L
      IF (L.EQ.4) JLS=6
      IF (L.EQ.6) JLS=4
      X(JLS)=(ARS+ALS)/2.
      M=(M+MD)/2
      CALL BITS (AR(M),31,AR(M))
      CALL MCLI (ERASE,IERR)
      CALL PADC (AR,1,NTPT,1,1,IERR)

```



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C      IF (L.EQ.NDIA) GO TO 160
C      MOVE DIA JUST TAKEN UP
C      GADA(AR,1,NPT,1,1,IERR)

      ISC=(NDIA-L)*NPT+1
      IEC=(NDIA-L+1)*NPT
C      CALL PADC (AR,ISC,IEC,1,1,IERR)
      ZERO OUT LOWER AREA
C      CALL PADC (ZERO,1,NPT,1,1,IERR)
      DIFF=AMAX1(X(1),X(2),X(3))-AMIN1(X(1),X(2),X(3))
      IF (L.EQ.3.AND.DIFF.LT.0.03) GO TO 220
160  CONTINUE
C  PROGRAM CETERLINE (SOURCE,CL)
      W=57.29578
      CM=1.6
      C0=(X(2)-X(3))-(X(1)-X(3))*((X(5)-X(6))/(X(4)-X(6)))
      C1=(ZPOS(2)-ZPOS(3))-(ZPOS(1)-ZPOS(3))*((X(5)-X(6))/(X(4)-X(6)))
      C=-C0/C1
      B=(-C*(ZPOS(2)-ZPOS(3))-(X(2)-X(3)))/(X(5)-X(6))
      A=-X(3)-B*X(6)-C*ZPOS(3)
      AB1=1+B*B+C*C
      IF (AB1.LT.0) AB1=-AB1
      XD=SQRT(AB1)
      AB=1./XD
      BB=B/XD
      CB=C/XD
      ACA=1.-CB*CB
      IF (ACA.LT.0) ACA=-ACA
      ACB=SQRT(ACA)
      ABC=ACB/CB
      CC=ATAN(ABC)
      IF (CC.LT.0.) CC=CC+3.14159
      CC=CC*W
      ZD=BB/SIN(CC/W)
      ABB=1.-ZD*ZD
      IF (ABB.LT.0.) ABB=-ABB
      BBB=SQRT(ABB)
      BBC=BBB/ZD
      D=ATAN(BBC)
      IF (D.LT.0.) D=D+3.14159
      D=D*W
      ZE=-90.+D
      C4=90.-CC
      RF=R0+ZE/1800
      TA=SIN(C4/W)/COS(C4/W)
      TO PRESET TILT POSITION
C      TF=(ZL*CM*TA+T0)
      WRITE (6,490)
      IF (TF.LT.TUL) GO TO 170
      WRITE (6,390) TF,TUL
      TF=TUL
      GO TO 180

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170 IF (TF.GT.TLL) GO TO 180
    WRITE (6,400) TF,TLL
    DF=DF-.100
    TF=TUL
C   ROTATE -180 DEG. SINCE LIMIT IS GREATER THERE
180 CONTINUE
    WRITE (6,270)
    WRITE (6,410) (X(L),L=1,6)
    CL1=(X(1)+X(2)+X(3))/3.
    CL2=(X(4)+X(5)+X(6))/3.
    WRITE (6,420) CL1,CL2
    DIF1=AMAX1(X(1),X(2),X(3))-AMIN1(X(1),X(2),X(3))
    DIF2=AMAX1(X(4),X(5),X(6))-AMIN1(X(4),X(5),X(6))
    IF (DIFMIN.LE.DIF1) GO TO 190
    DIFMIN=DIF1
    ROTMIN=ROT(1)
    TLTMIN=T0
    CLMIN=CL1
190 IF (DIFMIN.LE.DIF2) GO TO 200
    DIFMIN=DIF2
    FORMIN=ROT(4)
    TLTMIN=T0
    CLMIN=CL2
200 CONTINUE
    WRITE (6,430) DIF1,DIF2,DIFMIN,ROTMIN,TLTMIN,CLMIN
    WRITE (6,440) (ROT(L),L=1,6)
    WRITE (6,450) (ZPOS(L),L=1,3),ZPOS(6),ZPOS(5),ZPOS(4)
    WRITE (6,460) T0,T0,T0,T0,T0,T0
    WRITE (6,270)
    WRITE (6,470) R0,RF
    WRITE (6,480) T0,TF
    WRITE (6,270)
    WRITE (6,490)
    WRITE (6,500)
    CALL SETPOS (3,TF)
    CALL SETPOS (4,RF)
C   CALCULATE NEW TANGENT OF THE TITLE ANGLE
C   FROM 2000 STEPS=1.258 AT END OF CAPSULE
    TA=((TF-T0)/2.)*1.25/ZL
C   USE THIS TANGENT TO CORRECT SCAN POS FOR TILT
    T0=TF
    R0=RF
    ROT(3)=RF
    ROT(1)=ROT(3)
    ROT(2)=ROT(3)
    ROT(6)=RF-.050
    ROT(4)=ROT(6)
    ROT(5)=ROT(6)
    DO 210 L=1,NDIA
    START(L)=X(L)+(ZPOS(L)-PP)*TA-.4
    COR=(ZPOS(L)-PP)*TA
    STOP(L)=START(L)+.8
210 CONTINUE

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      GO TO 80
220 CONTINUE
      WRITE (6,510) X(1),X(2),X(3),DIFF
      WRITE (6,520) ZPOS(1),ZPOS(2),ZPOS(3)
      WRITE (6,530) R0
      CALL RDPOS (5,T0)
      WRITE (6,540) T0
      CL=(X(1)+X(2)+X(3))/3.
      WRITE (6,550) CL
      CALL SETPOS (1,CL)
      STOP

230 FORMAT (" ARE COLLIMATORS VERTICAL?")
240 FORMAT (" LENGTH OF THE ALPHA CAN ")
250 FORMAT (F10.0)
260 FORMAT (" Z FOR DIA AT FUEL START (F10.0)?")
270 FORMAT (2H )
280 FORMAT (F10.0)
290 FORMAT (F10.3)
300 FORMAT (" Z FOR DIA AT FUEL STOP (F10.0)?")
310 FORMAT (" DO YOU WISH TO CHANGE ANY INPUT (Y/N)?")
320 FORMAT (" TYPE RETURN TO LEAVE ANY INPUT UNCHANGED.")
330 FORMAT (" PRESENT TILT=",F8.3," CHANGE TO 5.000 ?(Y/N)")
340 FORMAT (" THAT IS ",I6,"POINTS. 4096 MAXIMUM.")
350 FORMAT (" ERROR ON AADC, DO YOU WISH TO CALL EXIT (Y/N)?")
360 FORMAT (A1)
370 FORMAT (" LEFT SIDE NOT LOCATED AT ",F10.3)
380 FORMAT (" RIGHT SIDE NOT LOCATED AT ",F10.3)
390 FORMAT (" CALCULATED TILT OF ",F10.3," IS GREATER THAN ",
1"THE UPPER LIMIT ",F6.3)
400 FORMAT (" CALCULATED TILT ",F10.3," IS LESS THAN THE LOWER LIMIT",
. 1F6.3)
410 FORMAT (" CENTERS ",6F8.3)
420 FORMAT (" AVERAGE ",8X,F8.3,16X,F8.3)
430 FORMAT (" MAX DIF ",8X,F8.3,16X,F8.3,/, " MIN TO NOW ",F8.3,
1" FOR ROT= ",F8.3," TILT= ",F8.3," CL= ",F8.3)
440 FORMAT (" ROTATIONS ",6F8.3)
450 FORMAT (" POSITIONS ",6F8.3)
460 FORMAT (" TILTS ",6F8.3)
470 FORMAT (/, " ROTATE FROM ",F10.3," TO ",F10.3)
480 FORMAT (" TILT FROM ",F10.3," TO ",F10.3)
490 FORMAT (20(1HX))
500 FORMAT ("")
510 FORMAT (" CL O.K. ",3F10.3," MAX DIF",F10.3)
520 FORMAT (" AT ZPOS",3F10.3)
530 FORMAT (" ROTATION=",F10.3)
540 FORMAT (" TILT=",F10.3)
550 FORMAT (" CENTERLINE=",F10.3)
      END

```