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AEC RESEARCH AND
DEVELOPMENT REPORT

GA-5418

CAP

A COLLIMATOR ANALYSIS PROGRAM

Prepared under
Contract AT(04-3)-167
Project Agreement No. 2
for the
San Francisco Operations Office
U. S. Atomic Energy Commission

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July 16, 1964

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GENERAL ATOMIC
DIVISION OF
GENERAL DYNAMICS

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by
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Upton, New York.

July 16, 1964

The CAP computer code is described herein as it existed on July 16, 1964. The code has been in continuous development for 1 year~~s~~ and in its presented form has been applied successfully by General Atomic to the kind of problems discussed later in this report. However, the development and improvement of the code are being continued, so that duplication of results (or even close agreement) between problems run with the code as published and the code as it existed either before or after this time is not necessarily to be expected.

General Atomic has exercised due care in preparation, but does not warrant the merchantability, accuracy, and completeness of the code or of its description contained herein. The complexity of this kind of program precludes any guarantee to that effect. Therefore, any user must make his own determination of the suitability of the code for any specific use, and of the validity of the information produced by use of the code.

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1. INTRODUCTION

The Collimator Analysis Program, CAP, is a FORTRAN program designed to compute the fraction of particles which pass through a collimator system, denoted by the term "efficiency", and provide information as to which collimators are limiting the beam. The source, collimators, and detector may be of either rectangular or circular shape with arbitrary alignment. The efficiency is computed for each point on the source and is integrated to provide the average efficiency for the source.

2. THEORY

We consider a collimator system made up of a source, collimators, and a detector. Since the actual collimators have finite thickness, we split each collimator into two separate zero-thickness collimators, one representing the front face and the other the back face of the actual collimator. Since the detector is allowed to have the same shapes as the collimators, and since it acts like a final collimator, it is not considered separately. Rather, an extra collimator (very thin) is added to represent the detector.

2.1. Collimator Efficiency

We define the efficiency, E , of a collimator system as the ratio of the number of particles incident on the detector with the collimators in place to that without the collimators in place. If there is a point source at (x_1, y_1) the efficiency is given by

$$E(x_1, y_1) = \frac{L^2}{A_d} \int_{\phi_{\min}}^{\phi_{\max}} d\phi [\theta_{\max}(\phi) - \theta_{\min}(\phi)] , \quad (1)$$

where the angles are as defined in Fig. 1; L is the distance between the source and the detector, and A_d is the area of the detector. The problem is to determine the quantities $\theta_{\max}(\phi)$, $\theta_{\min}(\phi)$, $\phi_{\min}$, and $\phi_{\max}$ for a given collimator system and point (x_1, y_1) . The calculation is then repeated for all other source points and an average efficiency is computed,

$$\bar{E} = \frac{1}{A_s} \int dx_1 \int dy_1 E(x_1, y_1) , \quad (2)$$

where A_s is the area of the source.

Fig. 1--Coordinate system

Two basic formulas are easily obtained from Fig. 1 and will frequently be used:

$$y_2 = y_1 + \ell \tan \phi$$

or

$$\phi = \tan^{-1} \left(\frac{y_2 - y_1}{\ell} \right); \quad (3)$$

$$x_2 = x_1 + \ell \tan \theta$$

or

$$\theta = \tan^{-1} \left(\frac{x_2 - x_1}{\ell} \right). \quad (4)$$

2.2. Rectangular Collimator

A rectangular collimator of width a and height b centered at (x_o, y_o) is shown in Fig. 2. The collimator is a distance ℓ from the source. Let

$$\phi_3 = \tan^{-1} \left(\frac{y_o - y_1 - b/2}{\ell} \right), \quad (5)$$

and

$$\phi_4 = \tan^{-1} \left(\frac{y_o - y_1 + b/2}{\ell} \right). \quad (6)$$

Then if $\phi > \phi_4$ or $\phi < \phi_3$, no particles pass through the slit. For $\phi_4 > \phi > \phi_3$, the extreme values of θ are

$$\theta_3 = \tan^{-1} \left(\frac{x_o - x_1 - a/2}{\ell} \right), \quad (7)$$

$$\theta_4 = \tan^{-1} \left(\frac{x_o - x_1 + a/2}{\ell} \right). \quad (8)$$

2.3. Circular Collimator

A circular collimator of radius R centered at (x_o, y_o) is shown in Fig. 3. The collimator is a distance ℓ from the source. Let

$$\phi_3 = \tan^{-1} \left(\frac{y_o - y_1 - R}{\ell} \right), \quad (9)$$

Fig. 2--Schematic of a rectangular collimator

Fig. 3--Schematic of a circular collimator

$$\phi_4 = \tan^{-1} \left(\frac{y_o - y_1 + R}{\ell} \right). \quad (10)$$

Then if $\phi > \phi_4$ or $\phi < \phi_3$, no particles pass through the hole. For $\phi_4 > \phi > \phi_3$, the extreme values of θ are

$$\theta_3 = \tan^{-1} \left(\frac{x_o - x_1 - v}{\ell} \right), \quad (11)$$

$$\theta_4 = \tan^{-1} \left(\frac{x_o - x_1 + v}{\ell} \right), \quad (12)$$

where

$$v = \sqrt{R^2 - (y - y_o)^2}, \quad (13)$$

$$y = y_1 + \ell \tan \phi. \quad (14)$$

2. 4. Summary of Conditions

The limiting values of θ and ϕ given in the preceding sections are summarized in the following tables:

ϕ	θ_3	θ_4
$\phi < \phi_3$	+10	-10
$\phi_3 < \phi < \phi_4$	$\tan^{-1} \left(\frac{x_o - x_1 - v}{\ell} \right)$	$\tan^{-1} \left(\frac{x_o - x_1 + v}{\ell} \right)$
$\phi_4 < \phi$	+10	-10

$$\phi_3 = \tan^{-1} \left(\frac{y_o - y_1 - \alpha}{\ell} \right)$$

$$\phi_4 = \tan^{-1} \left(\frac{y_o - y_1 + \alpha}{\ell} \right)$$

	Rectangular Collimator	Circular Collimator
α	$b/2$	R
v	$a/2$	$\sqrt{R^2 - (y - y_o)^2}$

$$y = y_1 + \ell \tan \phi$$

2.5. Calculation Procedure

From the above conditions we can evaluate ϕ_3 and ϕ_4 for each collimator. If we denote these collimators by index i , then the quantities $\phi_{\min}$ and $\phi_{\max}$ in Eq. (1) are given by

$$\phi_{\min} = \max_i \{\phi_{3i}\} , \quad (15)$$

$$\phi_{\max} = \min_i \{\phi_{4i}\} , \quad (16)$$

which means that $\phi_{\min}$ is the largest of the values of ϕ_3 and $\phi_{\max}$ is the smallest of the values of ϕ_4 .

The integral in Eq. (1) is performed by Simpson's rule. The interval from $\phi_{\min}$ to $\phi_{\max}$ is divided into $(N_\phi - 1)$ equally spaced intervals of width

$$\Delta\phi = \frac{\phi_{\max} - \phi_{\min}}{N_\phi - 1} . \quad (17)$$

The integer N_ϕ must be odd. The N_ϕ values of ϕ are then given by

$$\phi_n = (n - 1) \Delta\phi + \phi_{\min} . \quad (18)$$

At each ϕ_n the values of θ_3 and θ_4 are computed for each collimator. The limiting values $\theta_{\min}(\phi_n)$ and $\theta_{\max}(\phi_n)$ are then given by

$$\theta_{\min}(\phi_n) = \max_i \{\theta_{3i}(\phi_n)\} , \quad (19)$$

$$\theta_{\max}(\phi_n) = \min_i \{\theta_{4i}(\phi_n)\} . \quad (20)$$

The index i corresponding to the maximum or minimum is saved so that information about which collimators limit the beam can be obtained. We define

$$\Delta\theta_n = \theta_{\max}(\phi_n) - \theta_{\min}(\phi_n) . \quad (21)$$

The integral in Eq. (1) is then given by

$$\frac{1}{3} \Delta\phi [\Delta\theta_1 + \Delta\theta_{N_\phi} + 4(\Delta\theta_2 + \Delta\theta_4 \dots) + 2(\Delta\theta_3 + \Delta\theta_5 \dots)] . \quad (22)$$

2.6. Source Configurations

The source may be of either rectangular or circular shape. If a rectangular shape is used (Fig. 4), the required input data are the height and width and the number of evenly spaced source points to be used in each dimension. The positions of the points (x_1, y_1) are computed by the program and a trapezoidal rule integration is used to compute the average efficiency.

If a circular source is used (Fig. 5), the required input data are the source radius and the number of evenly spaced radial points to be used. The program then selects the points (x_1, y_1) so that they uniformly cover the source. For example, if R is the source radius and K is the number of radial points, the spacing between radial points is

$$\Delta R = \frac{R}{K - 1} \quad (23)$$

and the r values are given by

$$r_k = \Delta R (k - 1) \quad (24)$$

Let ω be the azimuthal angle on the source measured from the x axis. The k^{th} annular shell is divided into a sufficient number of intervals that the resulting area elements are roughly square. Thus, the number of intervals in the k^{th} shell is

$$\begin{aligned} K_{\omega k} &= \frac{2\pi r_k}{\Delta R} + 1 \\ &= 1 + 2\pi (k - 1) \end{aligned} \quad (25)$$

and the angular interval is

$$\Delta\omega = \frac{2\pi}{K_{\omega k}} \quad (26)$$

The values of ω are then given by

$$\omega = \Delta\omega (k_{\omega} - 1) \quad (27)$$

and, finally, the coordinates of the source point are

$$x_1 = R \cos \omega \quad (28)$$

Fig. 4--Schematic of a rectangular source. Each point shown is an (x_1, y_1) point. In this illustration, $NXX = 9$, $NYX = 13$.

Fig. 5--Schematic diagram of a circular source. Each point shown is an (x_1, y_1) point. In this illustration, $NRX = 4$.

$$y_1 = R \sin \omega \quad (29)$$

The above procedure leads to 1, 7, 13, 19, 26, etc., azimuthal intervals in the 1st, 2nd, 3rd, 4th, 5th annular shells, respectively. Trapezoidal rule integration is used to compute the average efficiency.

3. CODE DESCRIPTION

In the following sections, a description of the input and output of the CAP program is given. The code is written in FORTRAN and is a single program requiring only the usual input-output subroutines.

Since the angles θ and ϕ are quite small, the following approximations are used:

$$\tan^{-1} x = x - \frac{1}{3} x^3 + \frac{1}{5} x^5,$$

$$\tan x = x + \frac{1}{3} x^3 + \frac{2}{15} x^5.$$

3.1. Input Data

The following table describes the CAP input data:

<u>Card</u>	<u>Cols.</u>	<u>Format</u>	<u>Symbol</u>	<u>Description</u>
1	1-72	12A6	HØL	Title card.
2	1-5	I5	IDENT	Identification number > 0.
	6-10	I5	IX	Number of collimators ≤ 50 . Include the detector as the last collimator.
	11-15	I5	NPHI	N_ϕ , number of intervals in $\phi \leq 100$; N_ϕ must be odd.
	16-20	I5	NPTST	If > 0, print limiting collimator Nos. If ≤ 0 , omit print.
3	1-10	E10.5	ZRT	Reentrant tube length.
	11-20	E10.5	ST	Source test. If ≤ 0 , circular source. If > 0, rectangular source.
	21-30	E10.5	THKX	Width of rectangular source or radius of circular source.
	31-40	E10.5	THKY	Height of rectangular source.

<u>Card</u>	<u>Cols.</u>	<u>Format</u>	<u>Symbol</u>	<u>Description</u>
	41-45	I5	KXX	No. of evenly spaced source points on width of rectangular source or radius of circular source.
	46-50	I5	KYX	No. of evenly spaced source points on height of rectangular source.
4	1-10	E10.5	CP(N, 1)	Collimator position, z (to front edge).
	11-20	E10.5	CP(N, 2)	Collimator center, x_o .
	21-30	E10.5	CP(N, 3)	Collimator center, y_o .
	31-40	E10.5	CP(N, 4)	Collimator height, b.
	41-50	E10.5	CP(N, 5)	Collimator width, a.
	51-60	E10.5	CP(N, 6)	Collimator thickness.
			N = 1, IX	

NOTES:

1. Repeat card 4 for each of the IX collimators.
2. Units are arbitrary, but all quantities must have the same units.
3. Cases may be stacked. End deck with 2 blank cards.
4. The origin of the Z axis is taken to be the face of an experiment with a reentrant tube of length ZRT. The distance between the source and the collimator is $ZRT + CP(N, 1)$.

3.2. Output

The input data are printed and clearly labeled, so no further explanation is necessary.

The efficiency is printed in a line that looks like

X = 5.20396-01 Y = 6.63123-01 E = 4.33038-01

Here, X is the value of x_1 , Y is the value of y_1 , and E is the value of $E(x_1, y_1)$.

If the print test $NPTST > 0$, the following type lines are also printed:

2 -3.43363-02 6 1.27419-03
 2-2 5-6 3-4 2-2 etc.

The first line states that collimator 2 determines $\phi_{\min}$ and the value is -3.43363×10^{-2} , and collimator 6 determines $\phi_{\max}$ and the value is 1.27419×10^{-3} . The remaining lines contain NPHI pairs of numbers, each pair corresponding to one value of ϕ starting at $\phi_{\min}$. The pair of integers denote which collimators determine $\theta_{\min}$ and $\theta_{\max}$. For example, for the second value of ϕ , collimator 5 determines $\theta_{\min}$ and collimator 6 determines $\theta_{\max}$. The collimator numbers are to be read that 1 means the front face of the first collimator, 2 means the back face of the first collimator, 3 means the front face of the second collimator, etc. The last collimator is the detector.

3.3. Program Symbols

The following table gives the symbols used in the FORTRAN program and the corresponding symbols in the text:

<u>Text</u>	<u>Program</u>	<u>Text</u>	<u>Program</u>
N_{ϕ}	NPHI	$\phi_{\min}$	PHN
A	THKX	$\phi_{\max}$	PHX
B	THKY	ϕ	PHI
ΔX	DELX	θ_{3i}	TH3T (I)
ΔY	DELY	θ_{4i}	TH4T (I)
ΔR	DELR	$\theta_{\min}$	THN
l	CP (J, 1)	$\theta_{\max}$	THX
x_o	CP (J, 2)	$\Delta\theta (\phi)$	DTH (N)
y_o	CP (J, 3)	$\Delta\phi$	DPHI
b	CP (J, 4)	ν	GNU
a	CP (J, 5)	$E(x_1, y_1)$	ANS
r	R	$\overline{E}$	AVE
x_1	X1	K_{ω}	KWX
y_1	Y1	k_{ω}	KW
k	KR	ω	W
K	KRX		

3.4. Program Listing

A listing of the FORTRAN source deck of the CAP program is given on the following pages:

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C=====COLLIMATOR ANALYSIS PROGRAM=====
CCAP
$IBFTC
  DIMENSION RTBL(50),TTBL(50),XTBL(50),YTBL(50),CP(50,6),C(100,5),
  1TH3T(100),TH4T(100),IMN(100),IMX(100),DTH(100),HOL(12)
  ARCF(X)=X*(1.+X*X*(-0.3333333+0.2*X*X))
  TANF(X)=X*(1.+X*X*(0.3333333+0.1333333*X*X))
  10 READ(5,20)(HOL(N),N=1,12),IDENT,IX,NPHI,NPTST
  20 FORMAT(12A6/4I5)
  IF(IDENT)2000,2000,30
  30 CONTINUE
C=====SOURCE INPUT DATA=====
  READ(5,150)ZRT,ST,THKX,THKY,KXX,KYX
  150 FORMAT(4E10.5,2I5)
  IF(ST)170,170,160
  160 DELX= THKX/FLOAT(KXX-1)
  DELY= THKY/FLOAT(KYX-1)
  THKX=0.5*THKX
  THKY=0.5*THKY
  GO TO 205
  170 DELR=THKX/FLOAT(KXX-1)
  KRX=KXX
  THKR=THKX
C=====COLLIMATOR DATA INPUT=====
  200 FORMAT(6E10.5)
  205 READ(5,200)((CP(I,L),L=1,6),I=1,IX)
  IXP=2*IX
  DO 230 I=1,IXP,2
  J=(I+1)/2
  C(I,1)=CP(J,1)+ZRT
  C(I+1,1)=C(I,1)+CP(J,6)
  C(I,2)=CP(J,2)
  C(I+1,2)=CP(J,2)
  C(I,3)=CP(J,3)
  C(I+1,3)=CP(J,3)
  IF(CP(J,5))210,210,220
  210 C(I,4)=CP(J,4)
  C(I+1,4)=CP(J,4)
  C(I,5)=0.
  C(I+1,5)=0.
  GO TO 230
  220 C(I,4)=CP(J,4)/2.
  C(I+1,4)=C(I,4)
  C(I,5)=CP(J,5)/2.
  C(I+1,5)=C(I,5)
  230 CONTINUE
C=====PRINT INPUT DATA=====
  300 WRITE(6,310)(HOL(N),N=1,12),IDENT,IX,ZRT,NPHI
  310 FORMAT(1H12A6,6H CASE15/15,12H COLLIMATORS/24H REENTRANT TUBE L
  1LENGTH=1PE12.5/15,11H PHI ANGLES)

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      IF(ST)340,340,320
320  WRITE(6,330)THKX,KXX,THKY,KYX
330  FORMAT(19H RECTANGULAR SOURCE/15H      HALF WIDTH=1PE12.5,I10,7H POI
      INTS/16H      HALF HEIGHT=1PE12.5,I10,7H POINTS)
      GO TO 360
340  WRITE(6,350)THKR,KRX
350  FORMAT(16H CIRCULAR SOURCE/11H      RADIUS=1PE12.5,I10,7H POINTS)
360  WRITE(6,370)((CP(N,L),L=1,6),N=1,IX)
370  FORMAT(12HOCOLLIMATORS/(3H Z=1PE12.5,6H      XO=E12.5,
      16H      YO=E12.5,5H      H=E12.5,5H      A=E12.5,5H      T=E12.5))
      AVE=0.0
      IF(ST)600,600,500
C=====SOURCE POSITION LOOP, RECTANGLE=====
500  KX=1
510  X1=-THKX+DELX*FLOAT(KX-1)
      KY=1
520  Y1=-THKY+DELY*FLOAT(KY-1)
      GO TO 1000
C=====SOURCE POSITION LOOP, CIRCLE=====
600  KR=1
610  R=DELR*FLOAT(KR-1)
      KW=1
      IF(R)620,620,630
620  KWX=1
      X1=0.0
      Y1=0.0
      GO TO 1000
630  KWX=(2.*3.1415927*R/DELR)+1.0
      DW=2.*3.1415927/FLOAT(KWX)
      W=0.0
640  X1=R*COS(W)
      Y1=R*SIN(W)
      GO TO 1000
C=====FIND PHI(MIN)=PHN AND PHI(MAX)=PHX =====
1000 PHN=-10.
      DO 1020 I=1,IXP
      PHI=ARCF((-C(I,4)+C(I,3)-Y1)/C(I,1))
      IF(PHI-PHN)1020,1020,1010
1010 PHN=PHI
      LPHN=I
1020 CONTINUE
      PHX=10.
      DO 1040 I=1,IXP
      PHI=ARCF((C(I,4)+C(I,3)-Y1)/C(I,1))
      IF(PHI-PHX)1030,1040,1040
1030 PHX=PHI
      LPHX=I
1040 CONTINUE
      DPHI=(PHX-PHN)/FLOAT(NPHI-1)
C=====GET THETA(MAX)=THX AND THETA(MIN)=THN FOR EACH PHI=====

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```

PHE=PHN
DO 1210 N=1,NPHI
PHI=PHE
IF(N-1)1050,1050,1060
1050 PHI=PHI+0.01*DPHI
GO TO 1080
1060 IF(N-NPHI)1080,1070,1070
1070 PHI=PHI-0.01*DPHI
1080 DO 1150 I=1,IXP
Y=Y1+C(I,1)*TANF(PHI)
IF(Y-C(I,4)-C(I,3))1100,1090,1090
1090 TH3T(I)=10.
TH4T(I)=-10.
GO TO 1150
1100 IF(Y+C(I,4)-C(I,3))1090,1090,1110
1110 IF(C(I,5))1120,1120,1130
1120 GNU=SQRT(C(I,4)*C(I,4)-(Y-C(I,3))**2)
GO TO 1140
1130 GNU=C(I,5)
1140 TH3T(I)=ARCF((C(I,2)-X1-GNU)/C(I,1))
TH4T(I)=ARCF((C(I,2)-X1+GNU)/C(I,1))
1150 CONTINUE
THN=-20.
DO 1170 I=1,IXP
IF(THN-TH3T(I))1160,1170,1170
1160 THN=TH3T(I)
IMN(N)=I
1170 CONTINUE
THX=20.
DO 1190 I=1,IXP
IF(THX-TH4T(I))1190,1190,1180
1180 THX=TH4T(I)
IMX(N)=I
1190 CONTINUE
DTH(N)=THX-THN
IF(DTH(N))1200,1210,1210
1200 DTH(N)=0.
1210 PHE=PHE+DPHI
C=====INTEGRATE OVER PHI=====
ANS=DTH(1)+DTH(NPHI)
NPHIP=NPHI-1
DO 1220 N=2,NPHIP,2
1220 ANS=ANS+4.*DTH(N)
DO 1230 N=3,NPHIP,2
1230 ANS=ANS+2.*DTH(N)
ANS=ANS*DPHI/3.
IF(C(IXP,5))1240,1240,1250
1240 ANS=ANS*((C(IXP,1)/C(IXP,4))**2)/3.14159
GO TO 1260
1250 ANS=ANS*C(IXP,1)*C(IXP,1)/(C(IXP,4)*C(IXP,5)*4.)

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```

1260 WRITE(6,1270)X1,Y1,ANS
1270 FORMAT(1H /3H X=1PE12.5,6H      Y=E12.5,6H      E=E12.5)
      IF(NPTST)1300,1300,1280
1280 WRITE(6,1285)LPHN,PHN,LPHX,PHX
1285 FORMAT(1H /17,1PE12.5,17,E12.5)
      WRITE(6,1290)((IMN(N),IMX(N),N=1,NPHI))
1290 FORMAT(16(14,1H-12))
1300 CONTINUE
      IF(ST)1500,1500,1400
C====END SOURCE LOOP, RECTANGLE=====
1400 IF(KY-1)1410,1410,1420
1410 ANS=0.5*ANS
      GO TO 1440
1420 IF(KY-KYX)1440,1430,1430
1430 ANS=0.5*ANS
1440 IF(KX-1)1450,1450,1460
1450 ANS=0.5*ANS
      GO TO 1480
1460 IF(KX-KXX)1480,1470,1470
1470 ANS=0.5*ANS
1480 AVE=AVE+ANS*DELX*DELY/(4.*THKX*THKY)
      KY=KY+1
      IF(KY-KYX)520,520,1490
1490 KX=KX+1
      IF(KX-KXX)510,510,1600
C====END SOURCE LOOP, CIRCLE=====
1500 IF(KR-1)1510,1510,1520
1510 ANS=0.5*ANS
      GO TO 1540
1520 IF(KR-KRX)1540,1530,1530
1530 ANS=0.5*ANS
1540 AVE=AVE+ANS*2.*R*DELR/(THKR*THKR*FLOAT(KWX))
      KW=KW+1
      W=W+DW
      IF(KW-KWX)640,640,1550
1550 KR=KR+1
      IF(KR-KRX)610,610,1600
C====FINAL PRINT=====
1600 WRITE(6,1610)AVE
1610 FORMAT(13HOAVERAGE EFF=1PE12.5)
      GO TO 10
2000 CALL EXIT
      END

```