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ANS54: A Computer Subroutine for Predicting Fission Gas Release

**W. N. Rausch
F. E. Panisko**

August 1979

**Prepared for the
Core Performance Branch
Nuclear Regulatory Commission**

**Pacific Northwest Laboratory
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PREDICTING FISSION GAS RELEASE

by
W. N. Rausch
F. E. Panisko

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Pacific Northwest Laboratory
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UNITED STATES GOVERNMENT
DEPARTMENT OF THE INTERIOR
BUREAU OF LAND MANAGEMENT

W. H. HARRIS
1952

1952

Received from the
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the study of the
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W. H. HARRIS
1952

PREFACE

Pacific Northwest Laboratory(PNL) and Idaho National Engineering Laboratory are collaborating on the development of a new steady-state fuel performance computer code, FRAPCON-2. The Core Performance Branch of the U.S. Nuclear Regulatory Commission requested that the fission gas release model proposed by the Working Group ANS-5.4 of the American Nuclear Society be included in the code. PNL, operated for the Department of Energy by Battelle Memorial Institute, has programmed the new gas release model(ANS54) and it will be included in FRAPCON-2.

This report summarizes the model developed by the ANS committee. It also shows a comparison of model predictions with the light water reactor(LWR) low burnup data and liquid metal fast breeder reactor(LMFBR) high burnup data that were used in the model development. A listing of the ANS54 subroutine is included.

ACKNOWLEDGMENT

We wish to thank the Core Performance Branch of the Nuclear Regulatory Commission, Division of Systems Safety, for their support of this work. Mr. J. C. Voglewede and Dr. R. O. Meyer of that branch were helpful in supplying source material and in reviewing the draft. Mr. C. R. Hann of PNL also made instructive comments on the draft.

ANS54: A COMPUTER SUBROUTINE FOR PREDICTING FISSION GAS RELEASE

(W. N. Rausch, F. E. Panisko)

During the irradiation of reactor fuel rods, gaseous fission products are produced in the fuel. A fraction of these fission gases is released to the gap, i.e., outside of the fuel pellets yet inside the fuel rod cladding. This report presents a FORTRAN subroutine (ANS54) which calculates the fractions of fission gas (both stable and radioactive isotopes) released by the fuel. The routine is based on the model described in a proposed ANS-5.4 fission product release standard.^(a) The subroutine is the gas release model for FRAPCON-2, but may, of course, be used with any steady-state fuel performance code. ^(b,c)

1. Model Summary

The fractional fission gas release is calculated (on a local basis only), as a function of temperature, time, and burnup. The fuel is divided into radial and axial nodes according to the ANS standard. A user requirement is that the time step sizes be such that the burnup increments do not exceed 2000 MWd/MTM.

The routine is divided into two main sections, one to model release of the stable isotopes and the other to model release of the short-lived isotopes. There are high and low temperature models for both the stable and radioactive fission products. The code always calculates the release using both high and low temperature models and then uses the larger release.

I.

The stable fission gas (high temperature model) cumulative total release fraction for a fuel volume after step K is defined as:

(a) R. O. Meyer, "Proposed ANS-5.4 Standard", ANS 5.4 Committee Correspondence, (August 30, 1979).

(b) F. E. Panisko, letter report to J. C. Voglewede (April 12, 1979).

(c) W. N. Rausch, letter report to J. C. Voglewede (May 25, 1979).

$$F_K = 1 - \frac{\sum_{i=1}^{K-1} [B_i (\tau_i g_i - \tau_{i+1} g_{i+1}) / D_i'] + B_K \Delta t_K g_K}{\sum_{i=1}^K B_i \Delta t_i} \quad (1)$$

with

$$\tau_i = \sum_{j=i}^K D_j' \Delta t_j \quad (2)$$

$$g_i = g(\tau_i) = 1 - 4\sqrt{\tau_i/\pi} + 3\tau_i/2 \quad \text{for } \tau_i \leq 0.1 \quad (3a)$$

$$g_i = g(\tau_i) = \frac{1}{15\tau_i} - \frac{6}{\tau_i} \left(\sum_{n=1}^3 \frac{\exp(-n^2 \pi^2 \tau_i)}{n^4 \pi^4} \right) \quad \text{for } \tau_i > 0.1 \quad (3b)$$

$$D_i' = [(D_0/a^2) \exp(-Q/RT_i)] \times 100^{Bu_i/28000} \quad (4)$$

Where

F_K = local cumulative fractional gas release through time step K

B_i = local fission gas production rate during the i^{th} time step

Δt_i = length of i^{th} time step (seconds)

$Q = 72,300$ cal/mol

$R = 1.987$ cal/mol - °K

T_i = temperature (°K) during the i^{th} time step

Bu_i = accumulated local burnup (MWd/MTM) at the midpoint of the i^{th} time step

$D_0/a^2 = 0.61$ sec⁻¹

K = current time step

Equation 1 is rewritten in the code as:

$$F_K = 1 - \frac{\sum_{i=2}^K \left(\frac{B_i}{D_i'} (\tau_i g_i - \tau_{i+1} g_{i+1}) \right)}{\sum_{i=2}^K B_i \Delta t_i} \quad (5)$$

with

$$\tau_{K+1} = g_{K+1} = 0 \quad (6)$$

The FORTRAN coding uses only a $\tau_1(g_1)$ and $\tau_2(g_2)$, but these are updated for each time step. τ_1 always represents τ_i and τ_2 always represents τ_{i+1} . The summations begin at $i=2$, because the first time step is assumed to be very small. (Most fuel codes require a very short, low power time step as the first "warm-up" step. FRAPCON's is built into the code and does not appear as output.)

II.

The low temperature model for the stable fission gas release is dependent only on burnup. The fraction fission gas released is:

$$F = 1 \times 10^{-7} \text{ Bu} \quad (7)$$

where

Bu = rod average accumulated burnup (MWd/MTM)

III.

The radioactive fission gas release high temperature model assumes that power and temperature have remained constant for several half-lives. The fraction released is a function of time, temperature and burnup, and is also dependent on half-life. The release fraction for isotope i is:

$$F_i = \frac{3}{1 - \exp(-\mu_i \tau_i)} \left[\frac{1}{\sqrt{\mu_i}} [\text{erf}(\sqrt{\mu_i \tau_i}) - 2 \sqrt{\mu_i \tau_i / \pi} \exp(-\mu_i \tau_i)] - \frac{1 - (1 + \mu_i \tau_i) \exp(-\mu_i \tau_i)}{\mu_i} \right] \quad \text{for } \tau_i \leq 0.1 \quad (8)$$

and

$$F_i = 3 \left[\frac{1}{\sqrt{\mu_i}} \coth(\sqrt{\mu_i}) - \frac{1}{\mu_i} \right] - \frac{6\mu_i}{\exp(\mu_i \tau_i) - 1} \left(\sum_{n=1}^3 \frac{1 - \exp(-n^2 \pi^2 \tau_i)}{n^2 \pi^2 (n^2 \pi^2 + \mu_i)} \right) \quad \text{for } \tau_i > 0.1 \quad (9)$$

with

$$\mu_i = \lambda_i / D'$$

$$\tau_i = D' t$$

where

λ_i = decay constant for isotope i (sec^{-1})

t = total accumulated irradiation time (seconds)

$D' = [(D_0/a^2) \exp(-Q/RT)] \times 100 \text{ Bu}/2800$

erf = error function

Bu = total accumulated burnup (MWd/MTM)

T = temperature ($^{\circ}\text{K}$) constant for previous four half-lives

IV.

The low temperature radioactive fission gas release for isotope i is defined by:

$$F_i = (1/\lambda_i) [1 \times 10^{-7} \sqrt{\lambda_i} + 2 \times 10^{-12} P] \quad (10)$$

where

P = specific power (megawatts per metric ton heavy metal)

λ_i = decay constant (sec^{-1})

The radioactive fission gas release fraction is not needed in predicting the steady state fuel rod behavior in FRAPCON-2; it is calculated for informational purposes only. The results are output as a table and a plot of fractional release versus half life for each time step. The output subroutine, GASPLT, can be called from the ANS54 subroutine or from the main program.

2. Model Development

The model was developed by the ANS-5.4 working group on fission gas release. 1,2,3

3. Comparison with Data

Although FRAPCON-2 is not yet sufficiently developed to check the entire code against experimental results, the ANS-5.4 high temperature stable fission gas release model was compared to the data base from which the model was developed. This data base included all the rods used to develop the Beyer-Hann

fission gas release model plus 19 Hanford Engineering Development Laboratory (HEDL) LMFBR pins irradiated in Experimental Breeder Reactor (EBR) II.

The predicted and reported values are given in Tables 1 and 2 for the Beyer-Hann (LWR) and HEDL (LMFBR) data² respectively. These tables give the pin identification and reported power, burnup, fuel surface and centerline temperatures, and gas release. The predicted fuel temperatures used by the ANS model were calculated utilizing reported power, fuel surface temperature, fuel diameter, and enrichment. The centerline temperatures calculated for use by the model appear as CL*.

Figure 1 presents the fission gas release predictions plotted against the reported values for the Beyer-Hann data set. Figure 2 plots the same information for the EBR-II pins. The ANS-5.4 model generally overpredicts the releases of the LWR pins, but tends to underpredict the high (over 40,000 MWd/MTM) burnup LMFBR data.

A comparison with other data is necessary to properly evaluate the model, but the information presented here should help the user to evaluate the predictions made by the ANS-5.4 stable high temperature gas release model.

4. Fission Gas Release Subcode ANS54 Listing

A listing of the computer subcode ANS54 is presented in Table 3. A listing of the output subroutine GASPLT is included in Table 4.

5. References

1. R. A. Lorenz, "ANS-5.4 Fission Gas Release Model III. Low Temperature Release", ANS Topical Meeting on Light Water Reactor Fuel Performance, (April 1979) pp 336-345
2. L. D. Noble, "ANS-5.4 Fission Gas Model I. Noble Gases at High Temperature", ANS Topical Meeting on Light Water Reactor Fuel Performance, (April 1979) pp 321-327
3. "Status Report: ANS5.4 Fuel Plenum Gas Activity (N218) (Fission Product Release From UO₂ Fuel)", (April 1977), (Available from S. E. Turner, Southern Science Applications, P.O. Box 10, Dunedin, Florida 33528)

FIGURE 1. Comparison of ANS-5.4 With Low Burnup Data

FIGURE 2. Comparison of ANS-5.4 With EBR-II Data

TABLE 1.

COMPARISON OF ANS-5.4 WITH LOW BURNUP DATA

	Rod	Burnup Mwd/MTM	Power kw/m	Temperature °K			% Gas Release	
				Surface	CL	CL*	Measured	Predicted
1	CYRANO-II	1033	45.6	1031	2344	2399	15.0	17.0
2	CYRANO-VIII	1409	38.0	1116	2243	2296	13.0	19.7
3	116-5	4579	62.0	782	2580	2635	27.5	30.8
4	117-1	8713	64.9	822	2553	2613	25.4	36.0
5	ELP-4	11348	40.3	870	2046	2042	10.8	16.2
6	ELP-5	3870	44.3	763	1992	1985	4.9	4.7
7	ELP-6	13913	49.5	935	2462	2465	23.7	37.1
8	ELP-9	18804	48.9	859	2325	2319	25.8	34.0
9	ELP-10	9348	48.9	879	2357	2353	20.3	26.5
10	ELP-12	8424	43.6	934	2264	2262	19.7	23.9
11	LFL	2230	51.2	728	1935	2003	5.7	7.5
12	LFF	2230	50.8	833	2175	2249	17.3	18.4
13	LFB	2230	49.5	915	2321	2405	23.4	26.6
14	LFS	3120	71.8	834	2726	2819	37.9	37.5
15	LFW	3290	75.8	705	2615	2712	24.8	31.1
16	LFT	3290	72.8	827	2884	2983	49.6	41.5
17	LFX	3290	75.4	792	2826	2927	36.8	39.2
18	LFM	3030	69.9	714	2465	2558	15.5	27.1
19	LFH	3030	69.2	806	2678	2774	31.1	35.6
20	LFD	3030	67.9	893	2846	2939	45.8	42.3
21	CBN	2650	56.1	728	2095	2135	12.3	11.1
22	CBO	2670	56.7	735	2130	2177	14.9	12.6
23	CBP	2610	55.1	730	2087	2133	14.1	10.9
24	CBR	2710	57.1	769	2224	2273	15.7	17.0
25	CBT	2620	54.4	767	2163	2213	15.3	14.4
26	CBV	2760	50.8	741	2216	2265	16.5	16.2
27	CBY	2630	54.4	790	2232	2289	16.9	17.9
28	CBX	2710	56.1	796	2295	2347	18.8	20.4
29	DFE	794	114.8	689	3499	3596	38.8	42.9
30	DFH	648	94.8	712	3114	3209	31.1	34.9
31	DFD	658	95.4	747	3180	3274	31.7	37.3
32	DFB	528	78.4	735	2742	2834	16.9	25.3
33	DFA	386	57.1	675	2003	2078	4.6	3.5
34	4110-AE1	7051	59.4	887	2571	2636	21.6	37.3
35	4110-AE2	6860	57.7	843	2450	2504	22.1	32.1
36	4110-BE1	5738	49.5	821	2151	2199	13.9	19.7
37	4110-BE2	7215	58.4	759	2322	2377	15.9	26.0
38	4112-AE1	3795	64.0	692	2401	2458	12.6	22.1
39	4112-AE2	3549	58.1	755	2333	2385	11.2	21.1
40	4112-BE1	3073	50.5	698	1974	2023	7.9	6.7
41	4112-BE2	3313	54.4	735	2177	2230	12.6	14.4
42	4113-AE1	3418	56.1	1027	2698	2755	26.7	40.0
43	4113-AE2	3116	51.2	1001	2551	2567	28.0	33.0
44	4113-BE1	3124	52.5	804	2240	2299	17.0	17.9
45	4113-BE2	3181	52.2	956	2479	2533	21.0	30.7

*Center-line temperature predicted by code

TABLE 2.

COMPARISON OF ANS-5.4 WITH EBR-II DATA

Pin	Burnup MWd/MTM	Power kW/m	Temperature °K			% Gas Release	
			Surface	CL	CL*	Measured	Predicted
1 PNL 1-6	8070	26.8	1042	1976	1866	12.9	6.8
2 PNL 1-14	8180	27.7	1035	1996	2001	8.2	11.5
3 PNL 1-17	8680	29.4	1042	2056	2019	15.1	12.8
4 PNL 1-18	8950	30.3	1039	2060	1990	18.1	11.7
5 PNL 1-19	9090	30.3	1128	2111	2030	29.9	15.7
6 PNL 3-8	26340	15.9	1198	1748	1723	10.7	28.3
7 PNL 3-27	26740	15.4	1096	1626	1638	12.5	16.1
8 PNL 3-33	26710	15.6	1124	1659	1635	13.1	16.9
9 PNL 4-1	42140	28.0	1124	2024	2043	62.2	58.1
10 PNL 4-26	40980	26.4	1119	2040	1913	64.5	52.1
11 PNL 4-34	39570	25.4	1240	2124	2082	65.4	66.5
12 PNL 7-10	24250	27.7	1135	1995	2030	30.1	38.9
13 PNL 8-11	58200	39.9	1143	2351	2375	92.2	76.5
14 PNL 8-25	57180	38.1	1126	2272	2298	94.3	73.9
15 PNL 8-37	55720	35.3	1091	2143	2184	65.2	68.7
16 PNL 8-38	27760	37.6	1070	2194	2275	53.6	47.3
17 PNL 10-15	60550	28.6	1139	2061	2184	78.7	76.1
18 PNL 10-23	49820	27.4	1150	2090	2099	67.5	67.5
19 PNL 10-63	51960	27.3	1120	2070	2010	71.5	64.9

*Center-line temperature predicted by code.

TABLE 3. Listing of the ANS54 Subcode.

```

SUBROUTINE ANS54( NT,      BURNUP,  DFS,      JPOW,      NPOW,
+      NTIME,  RV,      DV,      NF,      TIME,      B,
+      Q,      RC,      RDOT,      NA,
+      QMPY,  JST,      RELEAS,  DEN,      DCU)

C
C
C   THIS SUBROUTINE CODED BY F E PANISKO AND W N RAUSCH OF BATTTELLE
C   PACIFIC NORTHWEST LABORATORIES, AUGUST 1979                PNL-3077
C
C
C   THE FISSION GAS RELEASE IS CALCULATED INSIDE THE TIME STEP AND
C   GAS PRESSURE LOOPS FOR EACH AXIAL REGION
C   THE FUEL TEMPERATURES ARE CALCULATED INSIDE THE AXIAL LOOP.
C   ONLY THE DIFFUSION PARAMETER, ANSD, NEED BE SAVED FOR EACH RADIAL
C   AND AXIAL REGION EVERY TIME STEP
C   BUT INSTEAD OF MAKING ANSD TRI-DIMENSIONED (TIMESTEP,RADIAL,AXIAL)
C   FOR EXAMPLE ANSD(50,10,10) IT IS SINGLY DIMENSIONED ANSD(5000).
C   A CODE INTERNAL POINTER KEEPS PROPER IDENTIFICATION OF EACH TIME STEP
C   VALUE FOR EACH RADIAL AND AXIAL REGION.
C   ALTHOUGH THE LOCAL GAS PRODUCTION RATE AND BURNUP ARE ALSO
C   NEEDED THEY ARE CALCULATED AS THEY ARE NEEDED.
C
C ***   ANS54 IS CALLED FROM FGASRE   ***
C
C   THE ANS STANDARD CALLS FOR AT LEAST SIX RADIAL REGIONS AND TEN OR
C   MORE AXIAL REGIONS.  THE SUBROUTINE ESTABLISHES THE RADIAL
C   DIVISIONS BUT THE NUMBER OF AXIAL REGIONS IS A USER INPUT.  ALSO,
C   THE TIME STEP SIZE SHOULD BE 2000 MWD/MTM BURNUP OR SHORTER.
C
C   THE DIFFUSION PARAMETERS FOR IODINE, CESIUM, AND TELLURIUM ARE
C   NOT CALCULATED BY THE CODE.
C
C ***   ***   ***   ***   ***   ***   ***   ***   ***   ***
C
C   INPUT ARGUMENTS
C
C   NT IS THE CURRENT TIME STEP NUMBER
C   BURNUP IS THE AXIAL LOCAL MID STEP VALUE IN MWD/MTM
C   DCO IS THE FABRICATED CLAD OD, INCHES
C   DFS IS THE FABRICATED FUEL DIA., INCHES
C   DV IS THE DIAMETER ARRAY ASSOCIATED WITH RV
C   FLOW IS THE FRACTION RELEASE PREDICTED BY THE LOW TEMP STABLE MODEL
C   FLOWR IS THE FRACTION RELEASE PREDICTED BY THE LOW TEMP RADIOACTIVE
C   MODEL
C   FRODEN IS THE FRACTION OF THEORETICAL DENSITY
C   J IS AXIAL REGION COUNTER FOR FRAPCON
C   JPOW IS AXIAL REGION COUNTER FOR ANS54
C   JST IS POINTER FOR TIME DEPENDENT AXIAL PROFILE
C   NA IS THE TOTAL NUMBER OF AXIAL NODES
C   NPOW IS THE TOTAL NO. OF AXIAL REGIONS
C   NTIME IS THE TOTAL NO. OF STEPS
C   RV IS THE FUEL FLUX DEPRESSION ARRAY
C   NF IS THE NUMBER OF FLUX DEPRESSION REGIONS IN THE FUEL
C   TIME IS THE TIME HISTORY ARRAY, CUMULATIVE IN SFCONDS
C   Q IS AXIAL POWER PROFILE ARRAY
C   QMPY IS TIME DEPENDENT POWER ARRAY
C   SP IS THE SPECIFIC POWER(MEGAWATTS PER METRIC TON OF FUEL)

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C B IS ARRAY OF COEFFICIENTS FROM DDLF
C POWR(QC) IS THE FUEL SURFACE HEAT FLUX FOR AN AXIAL REGION
C PF IS THE PRODUCTION FACTOR FOR FISSION GAS
C RC IS THE RADIUS OF THE ANNULUS
C TT AND TS ARE THE FUEL RADIAL TEMP(F) AND DIMENSION (IN) ARRAYS
C WF IS THE WEIGHTING FACTOR FOR THE RADIOACTIVE GAS RELEASE FRACTION
C   TO COMPENSATE FOR DIFFERENT PRODUCTION RATES IN DIFFERENT REGIONS
C
C   OUTPUT ARGUMENTS
C
C ROOT IS THE GAS RELEASE FRACTION PER AXIAL NODE PER CUMULATIVE TIME
C RELEAS IS THE FRACTION RELEASED FOR THE RADIOACTIVE GASES
C
C   ***   ***   ***   ***   ***   ***   ***   ***   ***   ***
C
C   DIMENSION QMPY(NTIME), Q(1), JST(NTIME)
C   DIMENSION TIME(NTIME)
C   DIMENSION RV(NF), DV(NF)
C   DIMENSION B(6)
C   DIMENSION TAU(2), GTAU(2)
C   DIMENSION ANSR(50), F(50), DT( 50), FLXFAC(50), ANSD(5000)
C   DIMENSION DECAY(11), RELEAS(11), HALF(11)
C   DIMENSION PF(20,17)
C
C   DATA PI/3.141592654/
C   FRDEN = DEN/100.
C
C   RFS = DFS/2.
C   DVOIDZ = 2.*RC
C
C THE FOLLOWING CALCULATIONS NEED BE DONE ONLY ONCE
C   IF(NT.GT.1) GO TO 149
C   IF(JPDW.GT.1) GO TO 149
C   IF(NPDW.LT.10) WRITE(6,99) NPDW
C   PI2=PI*PI
C   PI4=PI2*PI2
C   NREG = NUMBER OF FUEL RADIAL GAS RELEASES
C   NREG=20
C   ISTOP=5000/(NREG*NPDW)
C   FNREG=FLOAT(NREG)
C   FLXTOT=0.
C   ANSDA=(DFS*DFS-DVOIDZ*DVOIDZ)/4./FNREG
C   ROUTR=DFS/2.
C CALCULATE RELATIVE PRODUCTION RATES IN EACH NREG FUEL REGION
C
C   ALL THE RADIAL REGIONS FORMED HERE HAVE EQUAL AREAS, NOT
C   EQUAL WIDTHS.
C   ANSR = RADIUS TERM
C   ANSDIA = DIAMETER TERM
C   ANSDA = AREA TERM
C   ROUTR = RADIUS TERM
C   ROUTR2 = AREA TERM
C   DO 151 I1=1,NREG
C   ROUTR2=ROUTR*ROUTR
C   ANSR(I1)=SQRT(ROUTR2-ANSDA/2.)
C   ANSDIA=ANSR(I1)*2.
C   FLXFAC(I1) = TERP(ANSDIA,DV,RV,NF)

```



```

      IF(I1.EQ.NREG) GO TO 151
      ROUTR=SQRT(ROUTR2-ANSDA)
151 FLXTOT=FLXTOT+FLXFAC(I1)
C
C NORMALIZE THE PRODUCTION RATE SO THEIR SUM EQUALS 1
  DO 152 I1=1,NREG
152 FLXFAC(I1)=FLXFAC(I1)/FLXTOT
  DT(1)=0.
  DO 156 N1=2,NTIME
C
C DT(N1) IS THE TIME INCREMENT FOR STEP N1 UNITS ARE SECONDS
  DT(N1) = TIME(N1)-TIME(N1-1)
156 CONTINUE
149 CONTINUE
C
C JPOW AND NOW I1 ARE THE LOCAL AXIAL REGION NUMBERS
  I1=JPOW
C
C ROOT(NT,I1) IS THE RELEASE FRACTION FOR AXIAL REGION I1 THRU STEP NT
  ROOT = 0.0
C
C CHECK ON THE SIZE OF PROBLEM
  IF(NT.GT.ISTOP) GO TO 180
C
C ***** TOP OF THE RADIAL REGION GAS RELEASE LOOP *****
  DO 155 I2=1,NREG
  PROCT=FLXFAC(I2)*FNREG
C
C J1 IS THE POINTER FOR RADIAL REGION I2 FOR AXIAL REGION I1 FOR STEP NT
  J1=I2+NREG*(I1-1)+NPOW*(NT-1)*NREG
  X = ANSR(I2)/RFS
  TEMPK = B(1)+X*B(2)+X*X*B(3)+X**3*B(4)+X**4*B(5)+X**5*B(6)
  TEMPK = TEMPK + 273.
C
C ANSD AT 1400 DEG.C =2.2E-10=D*EXP(-72300./(1673R))
C SOLVING FOR D GIVES 0.61377
C SO ANSD(J1) = 0.61377*EXP(-72300./(1.987*TEMPK))
  ANSD(J1)=0.61377*EXP(-72300./TEMPK)
  BUP = BURNUP * PROCT
C
C CALCULATE DIFFUSION COEFFICIENT FOR LOCAL BURNUP
  ANSD(J1)=ANSD(J1)*100.**(BUP/26000.)
  A=0.
  PREEX=0.
  F(I2) = 0.0
C
C WHEN NT EQ 1 TIME IS ASSUMED TO BE ZERO SO SKIP GAS RELEASE
  IF(NT.EQ.1) GO TO 153
C
C ***** TOP OF THE TIME STEP LOOP *****
  IF(DT(NT).LT.86400.) GO TO 163
  DO 157 I3=2,NT
  IF(DT(I3).LT.86400.) GO TO 157
C
C CONVERT SURFACE HEAT FLUX TO K/FT
  POWR = QMPY(I3) * Q(JPOW+(JST(NT)-1)*NA) * DCO / 13037.
  TAU(1)=0.
  DO 158 I4=I3,NT

```

```

      JZ=I2+NREG*(I1-1)+NPOW*(I4-1)*NREG
158  TAU(1)=TAU(1)+ANSO(JZ)*DT(I4)
      TAU(2)=0.
      JY=I2+NREG*(I1-1)+NPOW*(I3-1)*NREG
      TAU(2)=TAU(1)-ANSO(JY)*DT(I3)
159  A1=0.
C
C THE FOLLOWING CARDS ARE FOR THE FINITE SUM
      DO 170 I5=1,2
      GTAU(I5)=0.
      IF(I5.EQ.2.AND.I3.EQ.NT) GO TO 170
      IF(TAU(I5).GT.0.1 ) GO TO 171
      GTAU(I5)=1.-4.*SQRT(TAU(I5)/PI)+1.5*TAU(I5)
      GO TO 170
171  SUMM=0.
      DO 172 I6=1,3
      X=FLOAT(I6)
      X=X*X
      Y=(X*PI2*TAU(I5))
      IF(Y.LT.-200. ) GO TO 172
      SUMM=SUMM+EXP(Y)/(X*X*PI4)
172  CONTINUE
      GTAU(I5)=(1./(15.*TAU(I5))-(6.*SUMM/TAU(I5)))
170  CONTINUE
      A1=TAU(1)*GTAU(1)-TAU(2)*GTAU(2)
      JW=I2+NREG*(I1-1)+NPOW*(I3-1)*NREG
      A5=A1*PROCT*POWR/ANSO(JW)
      DELEX = PROCT * DT(I3) * POWR
C THE FOLLOWING CARD IS TO OBLVIATE THE NEED FOR DOUBLE PRECISION
      IF(A5.GT.DELEX) A5 = DELEX
      A6=A6+A5
      PREEX = PREEX + DELEX
157  CONTINUE
C ***** BOTTOM OF THE TIME STEP LOOP *****
C
      F(I2)=1.-A6/PREEX
      ROOT = ROOT+F(I2)*FLXFAC(I2)
163  CONTINUE
155  CONTINUE
C*****BOTTOM OF THE RADIAL REGION GAS RELEASE LOOP *****
C LOW TEMPERATURE RELEASE
      FLOW = 1.E-7*RUENUP
      IF(FLOW.GT.ROOT) ROOT = FLOW
C
153  CONTINUE
C*****
C**
C** THE REMAINDER OF THE SUBROUTINE IS FOR THE CALCULATION OF THE
C** RADIOACTIVE GAS RELEASE FRACTION
C** FOR A SERIES OF DIFFERENT HALF-LIVES
C** THE STATEMENTS CALCULATE THE RELEASE AVERAGED OVER THE WHOLE ROD
C**
C** THE AHS SHORT HALF-LIVED RELEASE STANDARD IS VALID ONLY FOR WHEN
C** NO PREVIOUS BUILDUP IS PRESENT. THIS REQUIRES A SHUTDOWN OF A
C** 4*HALF-LIFE PERIOD OF TIME. THE SUBROUTINE DOES NOT CONSIDER THIS
C** PROBLEM.
C**

```

```

      IF(JPOW.NE.1) GO TO 41
      IF(NT.GT.1.AND.JST(NT).EQ.1) GO TO 102
C*** CALCULATE GAS PRODUCTION FACTORS TO USE AS WEIGHTING FACTORS FOR
C*** AVERAGE RELEASE FRACTION FOR THE ROD
      PFTOT = 0.0
      DO 101 JJ=1,NPOW
      DO 100 I =1,NREG
      PF(I,JJ) = G(JJ-1+(JST(NT)-1)*NA)*FLXFAC(I)
      PFTOT = PFTOT + PF(I,JJ)
100  CONTINUE
101  CONTINUE
      PFAVE = PFTOT/(NPOW*NREG)
102  CONTINUE
C***
      DELTIM = 0.5
      DO 40 I=1,11
      RTIME = 1. + (I-1) * DELTIM
C*** HALF IS THE HALF LIVES OF THE ISOTOPES RANGING ON A LOG SCALE FROM
C*** 10 TO 1000000 SECONDS
      HALF(I) = 10. ** RTIME
      DECAY(I) = 1./HALF(I)
      RELEAS(I) = 0.0
40  CONTINUE
41  CONTINUE
      IF(TIME(NT).LT.86400.) RETURN
      DO 50 I=1,NREG
      J1 = I + NREG * (JPOW - 1) + NPOW * (NT - 1) * NREG
      WF = PF(I,JPOW)/PFAVE
      DO 45 JX=1,11
      XMU = DECAY(JX)/ANSO(J1)
      TAUT = ANSO(J1)*TIME(NT)
      ARG = TAUT * XMU
      IF(ARG.GT.675.) ARG = 675.
      IF(TAUT=0.1) 414,414,415
414  CONTINUE
C*** IF TAU IS LESS THAN OR EQUAL TO 0.1
      A = 3./(1.-EXP(-ARG))
      Z = ERF(SQRT(XMU*TAUT))
      C = 2.*(SQRT(XMU*TAUT/PI))*EXP(-ARG)
      P = (Z-C)/SQRT(XMU)
      E = (1.+XMU*TAUT)*EXP(-ARG)
      G = (1.-E)/XMU
      FRAC = A*(P-G)
      GO TO 430
415  CONTINUE
C*** IF TAU IS GREATER THAN 0.1
      A = 1./TANH(SQRT(XMU))
      Z = 3.*(A/SQRT(XMU)-1/XMU)
      C = 6.*(XMU/(EXP(ARG)-1.))
      P = 0.0
      DO 422 IN=1,3
      N2 = IN*IN
      ARG2 = N2*PI2*TAUT
      IF(ARG2.GT.675.) ARG2 = 675.
      H = 1.-EXP(-ARG2)
      O = N2 *PI2 *(N2 *PI2 +XMU)
      P = P+H/O

```


TABLE 4. Listing of Subroutine GASPLT

```

      SUBROUTINE GASPLT(Y,N,T)
C
C   CALLED FROM MAIN
C
C
C*** OUTPUT BOTH TABLE AND PLOT
C
C*** H = HALF-LIFE ARRAY
C*** Y = RELEASE ARRAY
C*** N = CURRENT TIME STEP NUMBER
C*** T = CURRENT TIME
C
      DIMENSION Y(11),H(11),S(11),R(11)
      DELTIM = 0.5
      DO 40 I=1,11
        RTIME = 1. + (I-1) * DELTIM
        H(I) = 10. ** RTIME
40    CONTINUE
      T = T/86400.
      WRITE(6,90000) N,T
      WRITE(6,90008)
C*** OUTPUT TABLE OF HALF-LIVES VS FRACTION RELEASED
      WRITE(6,90001)(H(I),I=1,11),(Y(I),I=1,11)
      WRITE(6,90002)
C*** INITIALIZE PLOT TO BLANKS
C*** R WILL BE USED TO SAVE VALUES OF S(SYMBOL)
      DIF = 1./40.
      DO 10 I=2,10
        S(I) = 5H
        R(I) = S(I)
10    CONTINUE
      S(1) = 5H.
      S(11) = 5H.
      R(1) = S(1)
      R(11) = S(11)
C
C*** BEGIN PLOT CALCULATIONS ONE LINE AT A TIME
      DO 20 I=1,39
        P = 1. + I * DIF
        DO 15 J=1,11
          IF(Y(J).GE.P) S(J) = 5H*
15    CONTINUE
          IF(I.NE.20) GO TO 13
C
C*** PRINT LABEL FOR VERTICAL AXIS
      WRITE(6,90004)(S(K),K=1,11)
      GO TO 14
13    CONTINUE
      WRITE(6,90003) (S(K),K=1,11)
14    CONTINUE
      DO 16 J=1,11
        S(J) = R(J)
16    CONTINUE
20    CONTINUE
      DO 25 J=1,10
C*** PRINT BOTTOM AXIS OF PLOT
        S(J) = 5H.....
      25 CONTINUE

```

```

422  CONTINUE
      FRAC = Z-C*P
C***FRAC IS THE RELEASE FRACTION AT ANY ONE NODE(RADIAL,AXIAL,TIME STEP)
430  CONTINUE
      FRAC = FRAC*WF
C*** RELEASE SUMS THE FRACTION RELEASED FOR EACH AXIAL NODE DURING A
C*** TIME STEP
      RELEAS(JX) = RELEAS(JX) + FRAC
45   CONTINUE
50   CONTINUE
      IF(JPOW.NE.NPOW) RETURN
C*** THE FOLLOWING STATEMENTS WILL BE EXECUTED ONLY ONCE EACH TIME STEP
      TOTAL = NREG * NPOW
      DO 40 I=1,11
        RELEAS(I) = RELEAS(I)/TOTAL
C   CONVERT SURFACE HEAT FLUX TO KW/FT
        POAR = GMPY(NT) * DCO / 13037.
C   CONVERT KW/FT TO MW/MTM (SPECIFIC POWER)
        SP = POWR * 0.001 * (1./((DFS/2.)**2*PI)) * 1./((FRDEN*10.96))
        $ *1.E6*6.102E-2
        FLOWR = (1.E-7*SQRT(DECAY(I))+2.E-12*SP) / DECAY(I)
        IF(FLOWR.GT.RELEAS(I)) RELEAS(I) = FLOWR
60   CONTINUE
C*** THE RESULTS ARE OUTPUT BY A CALL TO GASPLT
C*****
C   RETURN
C
180  WRITE(6,181)
      STOP ' THIS STOP IS IN ANS54'
99   FORMAT(1X,100(1H*)) / 5X, 'PROBLEM MAY NOT SATISFY CONDITIONS FOR ANS-
+5.4 FISSION GAS RELEASE STANDARD' / 5X, 'NUMBER OF AXIAL REGIONS ONLY
+1, I3/1X,100(1H*))
148  FORMAT(1H, 'ANS5.4 REGION DELTA TEMP RECOMMENDATION EXCEEDED AT AX
+IAL REGION', I3, ', AT THE RADIAL REGION', I3, '2F10.3)
181  FORMAT(1H, 'THE PRODUCT OF NREG, NPOW, AND NTIME IS .GT. 5000. ')
      END

```

```

      S(J) = SH*....
25    CONTINUE
      S(11) = SH*
      WRITE(6,90005) (S(J), J=1,11)
C*** PRINT LABEL FOR HORIZONTAL AXIS
      WRITE(6,90006) (H(J), J=1,11,2)
      WRITE(6,90007)
90000 FORMAT(1H1, / 50X, #FRACTION RADIOACTIVE GASES RELEASED#//55X,
+TIME STEP = #, I3/55X, #TIME AT END OF STEP =#, F6.1, # DAYS#/)
90001 FORMAT( /10X, #HALF-LIFE(SEC)#, 5X, 11(IPE 9.1), /10X, #FRACTION# /
+10X, #RELEASED#, 11X, 11(IPE 9.1))
90002 FORMAT(/135(1H*)//40X, #1.0.#, 51(1H.))
90003 FORMAT(44X, 11A5)
90004 FORMAT(16X, #FRACTION RELEASED#, 7X, #0.5.#, 11A5)
90005 FORMAT(40X, #0.0.#, 11A5)
90006 FORMAT(44X, 6(1H., 9X)/37X, 3F10.0, 2X, 3F10.0)
90007 FORMAT(/62X, #HALF-LIFE(SEC)#////)
90008 FORMAT(29X, #RELEASE FRACTION = FRACTION OF NON-DECAYED INVENTORY T
+HAT RESIDES IN THE GAP#//135(1H*))
      RETURN
      END

```

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