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FISSION PRODUCT PLATEOUT CALCULATIONS
FOR A GAS TURBINE HTGR

by

R. D. Chmielewski and C. G. Hoot

Prepared under Contract AT(04-3)-167
Project Agreement No. 46,
for the
San Francisco Operations Office
U.S. Atomic Energy Commission

Date Published: November 1, 1974

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ABSTRACT

Fission product plateout distributions for a direct cycle gas turbine high-temperature gas-cooled reactor (GT-HTGR) were calculated. This reactor concept uses a helium gas turbine power conversion system with all major components integrated into a prestressed concrete reactor vessel. The magnitude and distribution of fission product contaminants is important in the plant design phase for developing maintenance and handling procedures.

Plateout distributions for ^{137}Cs , ^{140}La , Te , ^{90}Sr , $^{110\text{m}}\text{Ag}$, and ^{131}I have been calculated using a modified version of the computer code PAD. A major uncertainty is lack of adsorption data on the materials of interest. Perfect sink (i.e., no desorption) behavior was assumed for La , Te , Ag , and Sr . A sensitivity calculation was performed on the diffusion coefficient and mass transfer coefficients for Ag . Similarly, a sensitivity analysis for the adsorption isotherms for Cs and I is discussed. Recommendations are made for further work needed to determine design activity levels for the GT-HTGR system.

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I. INTRODUCTION

The principal purpose of the study reported here has been to estimate the distribution of fission product plateout around the power conversion loop of a 3000-MW(t) GT-HTGR. The results provide a preliminary basis for assessing problems and requirements of maintaining the turbomachinery and other components internal to the reactor vessel. Additional goals for the study have been to identify the major uncertainties in the physical data necessary to characterize the distribution, to determine the sensitivity of the calculated distributions to those uncertainties, and to specify those combinations of fission product specie and alloys for which critical sorption data are needed to minimize the plateout distribution uncertainties.

Fission products, neutron-activation products, and radioactive-decay products result from operation of the reactor. A very small fraction of these nuclides are released from the core over the working life of the reactor and enter the helium gas coolant. Fission products released from the core generally result from fuel particles that have defective coatings due to manufacturing or due to a combination of effects resulting from temperature and irradiation during their life in the reactor core. Such defective coatings occur in an extremely small fraction of the fuel particles in the core.

The deposition or plateout of the fission products as they circulate in the closed-loop system is important for questions regarding shielding, safety, and maintenance. The distribution of the plateout nuclides is complex, depending on the physical and chemical properties of the elements of concern, the surface temperature, surface oxidation state (Refs. 1 and 2), surface composition, helium flow hydrodynamics, and circuit geometry. The distribution may also depend on particulates carried around the system.

For the steam cycle HTGR design, the distributions of ^{90}Sr , ^{131}I , ^{137}Cs , ^{140}La , and ^{144}Ce have been calculated with the computer code PAD (Ref. 3), which accounts for the mass transfer to the primary coolant loop surfaces. This code used in the studies reported here does not account for possible transport of the nuclides by circulating dust or by diffusion into the walls. Certain modifications were made to model the GT-HTGR. These modifications to the code are given in the Appendix.

The results shown in this report are for plateout concentrations at the end of 40-year life. The distribution will build up with time for species with long half-lives. Consequently, their contribution to the local dose will vary with the plant age.

2. DIRECT CYCLE GAS TURBINE HTGR

During the period of this study, the configuration of the GT-HTGR was being extensively evaluated; at the end of this evaluation, a configuration involving three power conversion loops containing horizontally oriented turbomachinery was selected. This fission product plateout study utilized an earlier configuration comprising a four-loop design with vertically oriented turbomachines of the same total thermal capacity [3000-MW(t)]. Despite these configurational differences, the distribution of areas within the loops was very similar and the basic cycle conditions were unchanged. Thus, the trends of this study are deemed pertinent to current designs for the plant.

The design considered in this study is illustrated in Fig. 1 and is described as GAC drawing number 0435-SK-118, Issue A. The basic helium flowpath is illustrated in Fig. 2. Each loop shows a gas turbine, a recuperator, a precooler, a compressor, and associated components such as valves, ducts, and plenums. Table 1 gives the design helium pressures and temperatures at several locations in the circuit.

Several manufacturers have prepared design studies for the turbomachinery, and the designs are sufficiently similar that typical geometrical parameters could be used for the turbine and compressor.

The design of the recuperator was specified as type-316 stainless steel tubing which is 12/32-in o.d. by 0.025-inch thick wall. It is 28 ft long with 492 tubes per module and 121 modules per recuperator. The construction of the precooler was specified as being of 1/2% Cr-1/2% Mo steel tubing which is 3/8-inch o.d. by 0.049-inch thick wall. It is 58 ft long with 360 tubes per module and 97 modules per precooler. Cooling water flows inside the precooler tubing, and there is a 13-ft o.d. shroud surrounding the precooler.

Fig. 1. Basic configuration for GT-HTGR plateout calculations

Fig. 2. Pressures and temperatures along the helium flowpath

TABLE 1
NOMINAL OPERATING HELIUM PRESSURE AND TEMPERATURE
FOR A 3000-MW(t) GAS TURBINE HTGR

Location Number (a)	Pressure (psia)	Temperature (°F)
1. Reactor inlet	977	927
2. Reactor outlet	922	1500
3. Turbine inlet	960	1481
4. Turbine outlet	442	1010
5. Recuperator hot inlet	440	998
6. Recuperator hot outlet	432	441
7. Precooler hot inlet	431	441
8. Precooler hot outlet	427	95
9. Compressor inlet	425	95
10. Compressor outlet	1000	350
11. Recuperator cold inlet	993	350
12. Recuperator cold outlet	983	927

(a) See Fig. 2, circled numbers

3. FISSION PRODUCT ACTIVITY LEVELS

The fission product activity levels are based on the "expected" levels for the 1100-MW(e) steam cycle HTGR. These levels are consistent with nuclear and thermal design conditions of the core and are based on current best estimates of fission product release together with operation of the helium purification system. The steam cycle values have been increased by a factor of 3 for metallic fission product activities and by a factor of 1.5 for gaseous fission product levels. This factor was included to account for the reduced retention of fission products within the graphite structure of the fuel elements of the direct-cycle HTGR resulting from its higher average temperature.

The maximum fuel temperatures are essentially equal for the two plants. The average moderator temperatures, however, are approximately 1400°F for the steam plant and 1550°F for the GT-HTGR. This difference is due entirely to the increased reactor inlet temperature in the GT-HTGR.

4. COMPUTER CODE PAD

The computer code PAD (Plateout Activity Distribution) was developed to calculate the plateout activity in the primary circuit such as that in a steam cycle HTGR. It is a transient, one-dimensional, mass-transfer code. A finite difference solution is obtained for the coupled, nonlinear, differential equations describing the mass transfer across a thin boundary layer between an average coolant concentration and a surface concentration. The coolant and surface concentrations are coupled by surface-temperature-dependent sorption process with either Langmuir or Freundlich isotherms. The code allows for production by parent decay, and treats recirculation in a closed loop with fission product removal via the helium purification system.

One drawback to the use of PAD for GT-HTGR calculations is that PAD as developed for the steam cycle HTGR makes the quite reasonable assumption of constant coolant pressure around the loop, using the average pressure as input. The GT-HTGR power conversion loops may be approximated by a low-pressure section at about 430 psia and a high-pressure section at about 980 psia. For example, the mass transfer coefficient depends on (pressure)⁻¹, and a ratio of low pressure to high pressure ($= 430/980 = 1/2.3$) results in a change in the mass transfer coefficient by a factor of 2.3, which should be accounted for in the calculations. The program was therefore modified to allow variation in the coolant gas pressure around the loop.

There were three modifications necessary: one, to the pressure used to calculate the coolant density at each mesh point in the loop; a second for the calculation of fission product concentration; and a third to correct the diffusion coefficient for variation of the coolant pressure. All changes were made in such a way that the program can still be used with the same input as the original, if so desired. The program modifications are included in the Appendix.

Another modification needed for the present application exists in the modeling of the turbine. PAD assumes pipe flow with the surface temperature of the wall dependent only on the axial distance x . In the turbine, a somewhat more realistic model has the blades at one temperature, $T_1(x)$ (the actual temperature does not change greatly from root to tip), while the (cooled) disks are at another temperature, $T_2(x)$, and the outer (cooled) case is at another temperature, $T_3(x)$. In the notation used, the coolant concentration of fission product j at the channel surface $C_{sj}(x,t)$ must be replaced by a perimeter weighted average value for the sides at temperature T_1 , T_2 , and T_3 . This can be written

$$C_{sj}(x,t) = (P_1 C_{s1j}(x,t) + P_2 C_{s2j}(x,t) + P_3 C_{s3j}(x,t))/P \quad (1)$$

where P_i = length of the channel perimeter at temperature $T_i(x)$,

$$P = P_1 + P_2 + P_3 \quad , \quad (2)$$

and $C_{s1j}(x,t)$ = concentration of nuclide j at the surface which is at temperature $T_1(x)$ etc.

Similarly, the surface concentration $S_j(x,t)$ and surface source term $b_j(x)$ for nuclide j become perimeter-weighted averages:

$$S_j(x,t) = (P_1 S_{j1}(x,t) + P_2 S_{j2}(x,t) + P_3 S_{j3}(x,t))/P \quad (3)$$

and

$$b_j(x) = (P_1 b_{j1}(x) + P_2 b_{j2}(x) + P_3 b_{j3}(x))/P \quad (4)$$

if the surface source terms differ on the different temperature boundaries. The surface concentration terms on the right-hand side of Eq. 3 are to be calculated separately by the same methods presently used in PAD to determine the surface concentration.

These modifications to PAD could be made for the turbine section only, and would require the programming of a separate subroutine for that section, some additional core storage for the new variables, and the input of additional initial values and parameters. For the purposes of the present study, these changes were not made, but an effort to approximate their effect was made by using a surface-area-weighted, surface-temperature variation through the turbine. Also, a separate plateout calculation for the blades, disks, and casing can be performed given the component temperatures.

Another problem in using the PAD code is that the correlation of Eq. 5 below for prediction of the mass transfer coefficient is used throughout the reactor circuit:

$$Sh = 0.023 Re^{0.83} Sc^{0.44} \quad (5)$$

where Sh = Sherwood number ,

Re = Reynolds number ,

and

Sc = Schmidt number .

A more appropriate correlation for turbine blades is

$$Sh = 0.4 Re^{0.57} Sc^{0.33} \quad (6)$$

using the analogy to the Ellerbrock (Ref. 4) correlation for heat transfer. The code can be easily modified to accept as input the three numerical coefficients in Eq. 5 and 6 which apply to each section. Using Eq. 6 gives a mass transfer coefficient in the turbine section which is about 60% smaller than that of Eq. 5. This would have decreased the surface concentration at the turbine entrance and would have reduced the change from turbine entrance to exit for the case where there is no desorption. The plateout downstream of the turbine would have changed to maintain the overall mass balance.

The turbine disks are cooled with gas from the compressor outlet, which has a concentration of plateout elements that is several orders of magnitude lower than the flow at the turbine inlet. This, however, is somewhat offset by the lower temperature of the disks, so that there will be less desorption of volatile elements such as Ce.

For volatile elements such as Ce and I, a problem of nonconvergence of the surface concentration occurs for hot surfaces. This is a result of the finite-difference solution of the equations for conservation of mass. The finite mesh size, with the initial zero surface concentration, leads to large initial deposition; then for the next time step at a given mesh point, the desorption is so high that the surface concentration goes negative and an error message is given. This problem has been remedied by further changes to the code. These changes will, if necessary for volatile elements, divide the basic time step into two steps. The first step brings the surface concentration to equilibrium with the coolant concentration. During the second step, the time-rate-of-change of the surface concentration is set equal to zero. The appropriate modification to the equation for the rate of change of the coolant concentration for the second step maintains conservation of mass. Some damping was also included in calculating the equilibrium surface concentration to prevent oscillation about the desired value. The additions to PAD which allow calculation of distributions for volatile elements are included in the Appendix.

5. GAS TURBINE HTGR MODEL

For the GT-HTGR plateout calculations, the model circuit was divided into 12 sections which are listed in Table 2.

The geometrical parameters for the sections listed in Table 2 are the same as those used for the 3000-MW(t) steam cycle HTGR for their common circuit elements; i.e., items 1, 2, 3, and 12. The parameters for the new circuit sections were adjusted to give each section the proper total surface area, transit time, and velocity. Since only one of four loops was calculated, only one-fourth of the core was included in the loop. The total plateout surface area of each loop is $5.52 \times 10^8 \text{ cm}^2$ and the transit time is 4.94 sec as calculated by PAD.

Sorption data are available (Ref. 5) for Ba, Cs, Rb, Sr, and I on graphite, for I on low-chromium steel, and Cs on 304 stainless steel and carbon steel (Ref. 1). No available sorption data were found for any of these elements on such important materials as the type-316 stainless steel of the recuperator (which is more oxidation-resistant than type-304) or on the Nimonic alloys (such as M21LC, Rene 100, 713LC, MM004, MM247, or IN100) under consideration for the turbine blades. Te is another important element for which sorption data were not available. Te is important because the expected release is significant and because of its potential effect on iron, stainless steel, and nickel based alloys. Table 3 contains experimentally derived constants which enter the equation for the coolant concentration at the surface (C_s) in the form

$$C_s = \frac{\exp [ACP + BCP \cdot 10^3/T] S^{(CCP + DCP \cdot 10^3/T)}}{[1 - S/DCP \cdot 10^{23}]} \quad (7)$$

TABLE 2
COOLANT CIRCUIT SECTIONS
GAS TURBINE HTGR MODEL

Section	Name
1	Active core
2	Lower reflector (transitional block)
3	Lower reflector (large coolant holes)
4	Core exit plenum and turbine inlet duct
5	Gas turbine
6	Recuperator (LP side)
7	Precooler
8	Compressor
9	Duct (to recuperator HP)
10	Recuperator (HP side)
11	Duct to core and entrance plenum
12	Upper reflector

TABLE 3
TYPICAL EXPERIMENTAL SORPTION CONSTANTS

System	ACP	BCP	CCP	DCP	CRITSC ($\mu\text{g}/\text{cm}^2$)	UNTFAC ^(a)	Range of Experimental Data ($\mu\text{g}/\text{cm}^2$)
Ba-Graphite ^(b)	6.48	-33.7	-1.304	7.55	--	1.38×10^{-2}	$10^{-2} - 10^0$
Cs-Graphite ^(c)	7.8	-29.84	0.2351	1.873	--	1.33×10^{-2}	$10^{-5} - 10^{-1}$
Rb-Graphite ^(d)	9.33	-31.06	-2.23	6.99	--	8.5×10^{-3}	$10^{-2} - 10^{-1}$
Sr-Graphite ^(b)	8.65	-36.0	-0.57	4.59	--	8.6×10^{-3}	$10^{-3} - 10^0$
I-Graphite ^(e)	7.24	0.012	0.73	1.25	--	0.1	$10^{-5} - 10^{-2}$
I-Low-chromium steel ^(f)	53.69	-53.04	-5.83	6.85	--	1.0	$10^{-1} - 10^2$
Cs-oxidized 304- stainless steel ^(c)	74.84	-100.1	-37.82	43.12	--	1.0	1 - 10

(a) UNTFAC is a code input quantity that converts surface concentration units of experimental study to $\mu\text{g}/\text{cm}^2$.

(b) Data compiled at General Atomic.

(c) Data taken from work by Milstead and Zumwalt (Ref. 2).

(d) Data compiled by Haire (Ref. 6).

(e) Data taken from Salzano (Ref. 7).

(f) Data taken from review study by Hoinkis (Ref. 8).

where T is the absolute temperature of the surface ($^{\circ}\text{K}$)

S is the surface concentration of the sorbed species,

and

ACP , BCP , CCP , and DCP are constants.

For Freundlich-type behavior, all the constants are determined from the experimental data (the denominator will be approximately equal to 1). For Langmuir-type behavior, the constant CCP in Eq. 7 is set equal to 1, the constant DCP is set equal to the product of 10^{-23} , and the saturated surface concentration S_{sat} and constants ACP and BCP are determined from the experimental data. In addition to simple Freundlich or simple Langmuir sorption kinetics, certain systems exhibit Henrian-type behavior at lower concentrations; that is, the gaseous concentration becomes proportional to the surface concentration at the lower surface loadings. The proportionality constant is determined by evaluating the gaseous concentration at the critical surface loading, $CRITSC$, and then dividing by the critical loading. The program PAD automatically makes this change in sorption behavior if a critical surface loading, $CRITSC$, is supplied.

6. PLATEOUT DISTRIBUTIONS

6.1 CESIUM-137 DISTRIBUTION

There are two components of the ^{137}Cs distribution: 1) the daughter component resulting from the decay of ^{137}Xe circulating in the coolant, and 2) as a direct consequence, the release of ^{137}Cs from the core. However, over 99% of the total expected ^{137}Cs is a consequence of direct release so that the daughter component becomes important mainly downstream of the recuperator where the direct-release component has been substantially depleted.

The sorption of Cs on graphite was described by Eq. 7, with appropriate constants from Table 3; the internal surface area, of about $2 \times 10^4 \text{ cm}^2$ per cm^2 of geometric surface area, was allowed for; and the replacement of fuel elements and reflector blocks was taken into account. The sorptivity of the fuel elements was increased by a factor of 10 because 10 sets of elements comprise the 40 year fuel cycle. Similarly, the sorptivity of the replaceable upper and lower reflector blocks was increased by a factor of 5 because of their 8-year life. Therefore, the plateout on the replaceable reflector blocks is the accumulated 40-year value. The effect of substantial quantities of ^{133}Cs and ^{135}Cs on the sorption of ^{137}Cs was accounted for in the calculation.

Because of the lack of sorption data on the alloys planned for the hot duct from the core to the turbine, the Cs on oxidized type-304 stainless steel sorption parameters were used to obtain a conservative upper limit. The effect of assuming these hot surfaces to be oxide free ("reduced") is estimated to lower the surface concentration by about two orders of magnitude. Below a surface temperature of about 400°C , the isotherms become nearly vertical lines (Ref. 2), while flow experiments (Ref. 1) show that very large amounts of Ce are deposited below 400°C . In view of these results, it is

assumed that those metal surfaces below 400°C act as perfect sinks for Ce deposition, i.e., deposition of the Ce is neglected. This occurs about mid-point in the recuperator; therefore, the whole recuperator was treated as a perfect sink to avoid discontinuity. This accounts for the surface concentration of ^{137}Cs shown in Fig. 3 on the order of 2 mCi/cm² at the entrance of the recuperator where the surface temperature is about 520°C. With this assumption it can be seen from Fig. 3 that most (actually about 92%) of the ^{137}Cs deposits in the recuperator, with 72% plated out in the first 20% of the recuperator area. The average surface concentration in the turbine is about twice the uniform distribution in the whole circuit for "oxidized" metal; the surface concentration on the "reduced" metal turbine is about 40 times less than the uniform distribution. The scale factors shown on the figures are those factors which multiply the actual values to bring them into the concentration range shown on the ordinate.

The sensitivity of the ^{137}Cs surface concentration in the hot duct and turbine sections to variation of the sorption constants may be estimated from the sorption constants in Table 3, from the surface temperature, and from the cesium partial pressure. A variation of +10% (-10%) in ACP results in a 0.02 (40) change in the surface concentration of ^{137}Cs on the hot duct. For the turbine, the 10% variation in ACP produces a decrease of about 65% at the entrance and a decrease of about 40% at the exit; the -10% variation increases the surface concentration at the entrance by a factor of 2.9 and at the exit by about 1.7.

A variation of +10% (-10%) in BCP changes the ^{137}Cs activity in the hot duct by about 100 (0.01) and that in the turbine by 4.4 (0.23) at the entrance and 2.4 (0.42) at the exit. A variation of +1% (-1%) in the constant CCP changes the activity in the hot duct by 0.3 (1.5). A +10% (-10%) variation in CCP produces a change in surface activity of 1.26 (0.94) at the turbine entrance and 1.57 (0.77) at the turbine exit. A variation of +1% (-1%) in DCP changes the ^{137}Cs activity by 2.9 (0.18) at the hot duct entrance and 2.0 (0.37) at its exit; a +10% (-10%) DCP variation changes the activity by 0.93 (1.29) at the turbine entrance and 0.76 (1.62) at the turbine exit.

Fig. 3. Expected 40-year plateout distribution of ^{137}Cs in a 4-loop, 3000-MW(t), GT-HTGR

The effect of calculating the plateout separately for the blades, vanes, disks, turbine inlet, outlet, and case--and assuming no mixing of the compressor outlet flow over the disks with the hot gas entering the turbine--indicates that the total ^{137}Cs activity obtained using the surface-area-weighted surface-temperature variation is about 17% high.

6.2 CESIUM-134 DISTRIBUTION

The appearance of ^{134}Cs results from neutron activation of stable ^{133}Cs ; therefore, all ^{134}Cs plateout results from directly released Ce metal. Since most of the ^{137}Cs activity (>99%) is also directly released, the distribution of ^{134}Cs is expected to be essentially the same as that of ^{137}Cs . Therefore, the distribution of ^{134}Cs for those sections where directly released Ce dominates may be estimated from that of ^{137}Cs by using Fig. 3 and the conversion factor of 0.38 Ci ^{134}Cs /Ci ^{137}Cs .

6.3 LANTHANUM-140 DISTRIBUTION

The distribution of ^{140}La results from the decay of circulating ^{140}Xe via the decay chain $^{140}\text{Xe} \xrightarrow{13.6\text{s}} ^{140}\text{Cs} \xrightarrow{63.3\text{s}} ^{140}\text{Ba} \xrightarrow{12.8\text{d}} ^{140}\text{La} \xrightarrow{40.26\text{d}} ^{140}\text{Ce}$, and from the directly released metals. Therefore, sorption effects of the ^{140}Cs precursor will affect the distribution of ^{140}La . This effect was neglected in the calculated distribution for ^{140}La of Fig. 4, and only two sources were considered: namely, the decay of circulating ^{140}Xe , giving about 28% of the total ^{140}La , and a lumped source of directly released ^{140}Cs , ^{140}Ba , and ^{140}La yielding about 72% of the total ^{140}La . These fractions differ from those for the steam cycle HTGR (44% and 56%, respectively) because of the assumed greater increase in directly released metal relative to gaseous release. The direct release is the main component from the exit of the active core to the entrance of the precooler. In the precooler, the daughter component becomes dominant (as indicated in Fig. 4) and accounts for most of the ^{140}La for the remainder of the loop. The effect of including Cs sorption on the ^{140}La distribution would be to

Fig. 4. Expected 40-year plateout distribution of ^{140}La in a 4-loop, 3000-MW(t), GT-HTGR

reduce the ^{140}La surface activity in the hotter parts of the circuit and to increase it in the cooler parts, with most of the increase expected to be at the entrance of the recuperator.

6.4 TELLURIUM DISTRIBUTION

Almost all of the plateout of Te is in the form of stable ^{130}Te , ^{128}Te , and ^{125}Te , and over 99% results from direct release. Since there are no available sorption data for Te, it was assumed that the entire circuit is a perfect sink for Te. The 40-year expected plateout distribution that results is shown in Fig. 5. It is evident that surface concentrations in the hot duct to the turbine and in the turbine may range from 150 to 500 $\mu\text{g}/\text{cm}^2$, which is much higher than the uniform distribution of about 4.4 $\mu\text{m}/\text{cm}^2$ for the whole circuit. The distributions of the radioactive isotopes ^{129}Te and ^{132}Te may be estimated from Fig. 5 by use of the conversion factors $3.8 \times 10^{-7} \text{ Ci } ^{129}\text{Te}/\mu\text{gm Te}$ and $2.8 \times 10^{-6} \text{ Ci } ^{132}\text{Te}/\mu\text{gm Te}$.

From Fig. 5, it is seen that the slope of the distribution in the recuperator (after the turbine) and the precooler becomes less negative (i.e., positive curvature) from entrance to exit, while going through the recuperator in the opposite direction has negative curvature. This effect is due to the decrease of the coolant temperature from entrance to exit of the recuperator and precooler, while in going through the recuperator in the opposite direction the coolant temperature increases. Since the mass transfer coefficient for the correlation of Eq. 5 depends on coolant temperature to about the 1.1 power, this effect is to be expected. Another feature of interest is the higher surface concentration in the compressor, relative to the precooler, and in the duct, relative to the recuperator. This effect results from the higher velocity of the coolant in the compressor. The higher velocity increases the Reynolds number in the compressor, which results in an increased mass transfer coefficient that is determined from Eq. 5.

Fig. 5. Expected 40-year plateout of Te in a 4-loop, 3000-MW(t), GT-HTGR

6.5 SELENIUM DISTRIBUTION

The 40-year expected release of Se, which is chemically similar to Te, is about one-sixth that of Te, and is mainly the direct release of the stable isotopes ^{79}Se , ^{80}Se , and ^{82}Se . An estimate of the Se surface concentration can be made using Fig. 5 and the factor $0.17 \mu\text{gm Se}/\mu\text{gm Te}$.

6.6 IODINE DISTRIBUTION

The majority of iodine release expected is in the form of stable ^{127}I and ^{129}I . The important radioactive isotopes are ^{131}I , ^{133}I , and ^{135}I . For this volatile element, the problem of nonconvergence in the original version of PAD is especially severe. Thus, the addition to the program described in Section 4, and included in the Appendix, was necessary. Using the modified program, it was possible to calculate the distribution of ^{131}I as shown in Figs. 6, 7, 8, and 9 for various changes in the sorption constants of iodine on graphite and low-chromium steel.

Sorption constants for the planned structural materials are likely to be somewhat different than those for the low-chromium steel. Figure 6 shows the effect of a +10% (-10%) variation of ACP for I on graphite; a 0.68 (0.53) change occurs in the activity on the lower reflectors. However, the total activity on the lower reflectors is negligible, so that the change in the rest of the circuit is negligible. Since a volume source term at the last mesh point of the core was used, the plateout shown for the core results from recirculation and may be lower than what would be present in a reactor. The lower reflectors, hot duct, turbine, and about 93% of the recuperator are saturated, so that their surface activity is determined by equilibrium between sorption and desorption. The surface concentration reaches a peak near the end of the recuperator, after which the distribution is determined by the mass transfer coefficient and the concentration in the coolant. The last half of the recuperator and the first 18% of the precooler have concentrations greater than a uniform distribution.

Fig. 6. Sensitivity of the 40-year expected plateout distribution of ^{131}I in a 4-loop, 3000-MW(t), GT-HTGR to +10% variation of the parameter ACP for graphite

Fig. 7. Sensitivity of the 40-year expected plateout distribution of ^{131}I in a 4-loop, 3000-MW(t), GT-HTGR to +25% variation of the parameters CCP and DCP for graphite

Fig. 8. Sensitivity of the 40-year expected plateout distribution of ^{131}I in a 4-loop, 3000-MW(t), GT-HTGR to +10% variation of the parameter ACP for stainless steel

Fig. 9. Sensitivity of the 40-year expected plateout distribution of ^{131}I in a 4-loop, 3000-MW(t), GT-HTGR to $\pm 10\%$ variation of the parameter BCP and $+25\%$ variation of CCP and DCP for steel

The parameter BCP (0.012) for I-graphite is so small that even an increase by a factor of 10 has negligible effect on the distribution, while a factor of 100 makes a 0.93 change in the lower reflectors. Figure 7 illustrates the effect of a +25% variation in CCP and DCP for I-graphite. Again, it is the lower reflectors that are mainly affected, each increasing by about a factor of 5 and 10. The activity in the upper reflector and core is very nearly the same for +25% variation in CCP and DCP.

In Fig. 8, the result of $\pm 10\%$ variation in ACP for I on steel is shown: the hot duct changes by more than 100 (0.01) while the turbine changes by 0.01 (10), the values varying somewhat between turbine entrance and exit.

In the recuperator, the three curves cross, and the activity for a 10% increase in ACP is higher than for a -10% decrease in ACP. The surface activity is saturated throughout the recuperator for the curve of +10% in ACP. From the entrance of the precooler throughout the rest of the loop, the surface activity for a 10% increase in ACP is greater than for a 10% decrease in ACP by more than an order of magnitude.

Figure 9 illustrates the effects on the iodine distribution for a +10% (-10%) variation in BCP and a +25% variation of CCP and DCP for iodine on steel. The activity in the hot duct changes by 100 (0.01) for the BCP variation, while increasing CCP reduces that activity by a 10^{-7} factor and increasing DCP increases the activity by a 10^8 factor. In the turbine, the activity changes by factors of about 30, 5×10^{-3} , 2×10^{-5} , and 4×10^4 for variations in BCP of +10% (-10%), CCP + 25%, and DCP + 25%, respectively. The iodine activity in the recuperator saturates for a 10% decrease in BCP and for a 25% decrease in DCP, while the ^{131}I activity reaches a maximum for BCP + 10%, CCP + 25%, and for nominal parameters in the order listed. The entrance of the precooler is saturated only for BCP - 10%. Sorption effects are also apparent in the duct to the core for BCP - 10% and DCP + 25%.

6.7 SILVER 110m DISTRIBUTION

The 40-year expected plateout distribution of ^{110m}Ag for three values of the diffusion coefficient parameter D_0 are shown in Fig. 10. Since there are no sorption constants available for Ag, and considering its high melting point, it was assumed that the entire circuit acts as a perfect sink. The parameter D_0 in cm^2/sec is the diffusion coefficient for mass number 100 in helium at 1000°C and at 47.6 atm pressure. In Fig. 10, the curves correspond to the GAC standard, a value corresponding to a +21% increase, and a diffusion coefficient that is about 60% of the GAC standard. The variations from the GAC reference value make small changes (less than a factor of 2) in the lower reflectors, hot duct, and turbine. However, the three curves cross in the recuperator, and at the exit there are differences of about an order of magnitude. From about 36% through the recuperator (low-pressure inlet) to the end of the circuit, the distribution for lowest D_0 is greater than that for the GAC reference value, which is greater than that for the highest value. This is to be expected since the lowest value gives the smallest mass transfer coefficient (MTC), and therefore the depletion of the concentration in the coolant flow will be less.

In view of the uncertainty in the MTC for the turbine discussed in Section 4, the plateout of ^{110m}Ag was calculated for changes of -50%, +100%, and +200% in the turbine MTC (Fig. 11). There is a difference of less than an order of magnitude at the turbine entrance for the two extremes, while the rest of the circuit shows much smaller differences. In fact, different scale factors were used in the first part of the recuperator for the different MTC values so that the curves would be distinguishable. Since the activity in the turbine is a small fraction of the total activity in the circuit, it does not change the plateout in the remainder of the loop by more than about a factor of 2 between the extreme MTCs.

Fig. 10. Sensitivity of the 40-year expected plateout distribution of ^{110m}Ag in a 4-loop, 3000-MW(t), GT-HTGR to variation of the diffusion coefficient parameter

Fig. 11. Sensitivity of the 40-year expected plateout distribution of ^{110m}Ag in a 4-loop, 3000-MW(t), GT-HTGR to uncertainty in the mass transfer coefficient in the turbine

6.8 STRONTIUM 90 DISTRIBUTION

The 40-year expected plateout distribution of ^{90}Sr is shown in Fig. 12. Sources of ^{90}Sr include decay of ^{90}Kr in the coolant via ^{90}Rb , and the direct release of $^{90\text{m}}\text{Rb}$, ^{90}Rb , and ^{90}Sr . The effect of stable ^{85}Rb on the plateout of the ^{90}Rb intermediate was estimated by using the Cs-oxidized 304 stainless steel sorption constants. However, about 95% of the total ^{90}Sr results from direct release of ^{90}Sr , so sorption effects on ^{90}Rb are not important. Sorption effects for Sr on graphite were included, while metal surfaces were assumed to act as perfect sinks for Sr.

Fig. 12. The 40-year expected plateout of ^{90}Sr in a 4-loop, 3000-MW(t), GT-HTGR

7. SUMMARY AND CONCLUSIONS

Plateout distributions for ^{137}Cs , ^{140}La , Te , ^{131}I , $^{110\text{m}}\text{Ag}$, and ^{90}Sr have been calculated for a 3000-MW(t) direct cycle GT-HTGR. The plateout distributions reported here are not meant to represent design levels of activities for the GT-HTGR, but were calculated to establish the areas where further experimental data and analytical methods are needed.

Several general conclusions may be drawn from the results presented. With a perfect sink assumption for metallic fission products, the hot recuperator adsorbs the greatest fraction of the overall plateout. The lack of an adsorption isotherm may be exaggerating this trend, although ignoring desorption at the cold portions of the loop is not a severe restriction. It is expected that adsorption data for these elements will result in plateout distribution curves having a less steep slope through the recuperators, resulting in a more uniform surface concentration. For iodine, the relatively high vapor pressure allows the hotter portions of the loop to desorb with higher surface concentrations in the colder portions, i.e., the cold end of the recuperator and precooler. The precooler is significantly colder than any section of the steam plant primary coolant system. The low concentrations shown for the reactor active core occur because of a modeling peculiarity; the PAD code uses the lower reflector as the fission product source location, consequently all of the fission products are introduced into the coolant at this location. Fission product concentrations in the active core reflect deposition from relatively clean helium, having passed around the circuit. In reality the fission products are introduced axially along the active core region. An additional phenomena that is not included in this study is the effect of certain plant transients upon the plateout distribution. Specifically, certain control actions may result in temperature transients in the

system. Specifically, increasing the recuperator temperature can cause fission products to desorb and move down stream, where they plateout again. The effect of such transient processes depends upon the particular gas turbine control mode and the frequency of operation. Effects of the adsorption surface oxidation state have been estimated for ^{137}Cs . Metal surfaces in the entire circuit were assumed to be a perfect sink for Te, $^{110\text{m}}\text{Ag}$, ^{90}Sr , and ^{140}La . This assumption is thought to give an upper limit for plateout distributions lacking data on the adsorption behavior on the surfaces of interest. Uncertainties in the diffusion coefficient, and in the mass transfer coefficient in the turbine, and their effect on the distribution of $^{110\text{m}}\text{Ag}$ have been considered. Fission product source terms were increased to allow for the higher average core temperature of the GT-HTGR.

For the turbine, the calculated ^{137}Cs surface activity is greater than a uniform distribution if sorption on oxidized metal in the turbine is assumed, and the turbine activity is less than the uniform distribution if the turbine surface is a reduced metal. The ^{140}La distribution is dominated by directly released metals to the entrance of the precoolers where ^{140}Xe decay begins to become dominant. For Te, the calculated distribution is greater than a uniform distribution on the lower reflectors, the duct to the turbine, and the first quarter of the recuperator. This indicates that any problems from Te plateout may be expected to be more likely in these sections.

There are several areas where further work is needed on problems related to plateout for the GT-HTGR. These areas include modifications of the PAD code to better model the turbine, experimental measurements of sorption data for the elements of interest on turbine and recuperator alloys, and more detailed calculations for release of plateout fission products from the core under GT-HTGR operating conditions. Finally, the potential fission product transport by dust needs to be evaluated.

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APPENDIX

MODIFICATIONS TO THE PAD CODE

The primary modifications to the PAD code were made to account for changing primary coolant pressure and, consequently, density in the Gas Turbine HTGR. Minor modifications were made to the input and output sections of the code to describe the changing pressure around the circuit.

A.1 CHANGES TO SUBROUTINE INPUT

The primary coolant pressure was input for each section. The code treats the GT-HTGR as a two-pressure system with Sections 1, 2, 3, 4, 9, 10, 11, and 12 at the high pressure and Sections 6 and 7 at low pressure (See Table 2 for model description). Sections 5 and 8 model the turbine and the compressor, respectively.

A.2 CHANGES TO SUBROUTINE PAD2

The pressure change through the turbine and compressor are calculated by a linear expression relating the inlet and outlet pressures.

$$\text{SLOPEP} = (\text{PCI}(\text{KP1}) - \text{PCI}(\text{K})) / \text{DIST}(\text{K})$$

$$\text{PATMJ} = \text{PCI}(\text{K}) + \text{SLOPEP} * \text{DISTAK}$$

where PCI = section pressure level ,

 DIST = axial length through component ,

 DISTAK = fractional length through component ,

and

 PATMJ = coolant pressure at given axial position through component .

The pressure dependence of the diffusion coefficient has been included into the code as

$$DIFC = DIF\emptyset * PATM\emptyset / PATMJ$$

where $DIFC$ = diffusion coefficient (pressure corrected) ,
 $DIF\emptyset$ = temperature corrected diffusion coefficient ,
and
 $PATM\emptyset$ = base pressure for $DIF\emptyset$.

The pressure dependence of the coolant density is also included:

$$DENS(J) = PATMJ * MOLWTC / \{82.06 * [CTEMPC(J) + 273]\} .$$

Finally, the density correction to the convective transport term was included:

$$CONVEC = C(I,J) - DENS(J) / DENS(JM1) * COLD(I)$$

where $C(I,J)$ = concentration of species I at location J ,
 $DENS(JM1)$ = density at location J-1 ,
and
 $CCOLD(I)$ = concentration of species I at location J-1.

For some volatile elements, notably iodine, a non-convergence problem developed in the hot sections of the loop. The following program changes were made:

```

      PEQ=0.0
      SUMC=0.0
      DO 598 L=1,II
      IF(NAMISO(L).NE.ELEMNT(M)) GO TO 598
      PEQ=ADSC(L)*(CTEMPC(J)+273.)*82.08*0E-06/AM(L) +PEQ
      SUMC=SUMC+ADSC(L)
598   CONTINUE
      IF (CRITSC(M,K) .NE. 0. .AND. SSC(M,J) .LE. CRITSC(M,K)) GO TO 5980
      SEQ=ADSC(I)/SUMC*UNTFAC(M,K)*(PEQ*(1.-SSCO)/CONK(M,J))..(1./CONK(M,J))
      . ,J))
      GO TO 5981
5980  Z=DLOG(DBLE(ADSC(I)/SUMC*PEQ*CRITSC(M,K)))-DLOG(CONK(M,J))-CONP(M,
      ,J)*DLOG(DBLE(CRITSC(M,K)/UNTFAC(M,K)))
      IF(Z.LT.-709.) Z=-709.
      IF(Z.GT.709.) Z=709.
      SEQ=DEXP(Z)
5981  CONTINUE
      Z=DABS((SEQ-S(I,J))/(SEQ+S(I,J)))
      IF(S(I,J).E0.0.0) Z=0.0
      SEQ=(SEQ+Z*S(I,J))/(1.+Z)
      DT=(SEQ-S(I,J))/(BS(I,J)+MTC(I,J)*(ADSSC-DESSC)+DECSUR)
      IF(DT.LT.-DBLE(DELTA(T(K)))) DT=-DBLE(DELTA(T(K)))
      IF(DT.GT.DELTA(T(K))) GO TO 599
      SOLD=S(I,J)
      S(I,J)=S(I,J)+DT*(BS(I,J)+MIC(P,J)*(ADSSC-DESSC)+DECSUR)
      DC=C(I,J) +DT*((BC(I,J)-MTC(I,J)*4./DIA(K)*(ADSSC-DESSC)+DECOOL)-
      . CONVEC/DELTA(T(K)))
      COLD(I)=C(I,J)
      C(I,J)=DC+(DELTA(T(K))-OT)*(BC(I,J)+4./DIA(K)*(BS(I,J)+DESCUR)+
      . DECOOL-CONVEC/DELTA(T(K)))
      IF(S(I,J).GE.0.0.AND.C(I,J).GE.00) GO TO 62
      IPATH=1
      GO TO 605
      . . . . .
605   CONTINUE
      WRITE (6,6020) I,J

6020  FORMAT (IHI, 'CALCULATIONS STOPPED BECAUSE NEGATIVE VALUE OF
      SURFACE CONCENTRATION WAS OBTAINED FOR ISOTOPE 'I2' AT LOCATION
      'I4 )

```

The desorption process is evaluated to obtain an updated surface concentration (SEQ). A new time step (DT) is then evaluated by comparing this updated surface concentration with the previous iteration, given the mass transfer rate from the coolant to the surface. The surface concentration is again revised, given the mass transfer rate using the newly defined time step.