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PROPOSED ANALYSIS AND INTERPRETATION OF THE FORT ST. VRAIN PLATEOUT PROBES

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1. ABSTRACT

This report discusses the design, analysis, and interpretation of the two replaceable plateout probes to be installed in the Fort St. Vrain reactor circuit. The probes are located at the inlet to two steam generators, one in each coolant loop. Samples of both the core outlet and core inlet coolant streams of each of the two coolant loops are continuously bypassed through the probes. During shutdown for refueling, the plateout probes can be removed through the PCRV penetrations at each probe location and subjected to gamma spectroscopy and radiochemical analysis. The activity profiles on the diffusion tubes and sorption beds located inside the probes are used to determine the amount, distribution, and chemical forms of the Sr^{90} inventory in the reactor circuit. It is anticipated that the Sr^{90} inventory might be composed of three components: a gaseous component, a dust-borne component, and a noble-gas precursor component. Equations to determine each of these components from the plateout probe data are presented.

2. INTRODUCTION

The primary function of the Fort St. Vrain plateout probes is to obtain a measure of the Sr^{90} activity in the reactor circuit. However, the probes have been designed so that it is possible to obtain considerable scientific information about other fission products in the reactor circuit. This report provides the theory necessary to analyze the data obtained from the diffusion tubes and sorption beds located inside the probe. Other, more empirical, information could also be obtained from an analysis of the removable plateout sleeves on the outside of the plateout probe; however, since this information involves a complex mass transport problem, and since this information is not necessary for the analysis of the circuit inventory of Sr^{90} , this report will be restricted to an analysis of the more theoretically founded diffusion tubes.

It is anticipated that each of the plateout probes will be exposed to the Fort St. Vrain reactor coolant for periods of from 1 to 5 years. During this period, the probes will continuously sample a portion of both the core outlet coolant and the core return coolant. Upon shutdown for refueling, the plateout probes can be removed from the PCRV and subjected to gamma spectroscopy and radiochemical analysis. This data will be used to determine the

amount, distribution, and chemical form of the Sr^{90} released into the reactor circuit during the sampling period. The total reactor Sr^{90} activity will, of course, be equal to the sum of this activity plus the initial activity (decayed throughout the sampling period).

It is anticipated that the Sr^{90} inventory might be composed of three components: a gaseous component, a dust-borne component, and a noble-gas precursor component. The amount collected from the noble-gas precursor should be directly proportional to the exposure time of the probe, due to the relatively constant release rate of the 33-sec half-life Kr^{90} precursor of 30-yr half-life Sr^{90} . However, the dust-borne and gaseous components may reflect the previous operating experience of the plant and need not be directly related to the exposure time of the probe. The removal schedule will therefore have to be dictated by the plant operating experience, particularly with regard to periods of abnormal reactor temperatures.

3. MECHANICAL DESIGN

Fig. 1 is a cross-section of the reactor vessel showing the location of the plateout probes. One sample stream is taken from each coolant loop at the inlet to the steam generator and exhausted to the inlet to the circulator. A second sample stream is taken from the return coolant and is also exhausted to the circulator inlet. Fig. 2 shows the details of the plateout probes and their location in the steam generators. These probes are made to be inserted

Fig. 1. Fission Product Plateout Probe Axial Location

Fig. 2. Plateout Probe Details and Radial Locations

through a nozzle in the PCRV and into a penetration through the wall of the steam generator. Thus, they extend into the high-temperature gas at the inlet to the steam generator. The somewhat complex probe design was made necessary by the remote handling requirements and the potential for a relatively large misalignment of the steam generator and PCRV penetrations. This misalignment could result from the initial tolerances on the steam generator mountings, from the thermal strains at refueling temperatures, from the pressure vessel distortions resulting from prestressing and pressurizing, etc.

The probe is clamped into the steam generator penetration with a bayonet-type lock and the handling tool is then removed from the PCRV. Four diffusion tube sample streams are taken from the hot-gas stream inside the steam generator and a fifth is taken from the cold return gas on the outside of the steam generator. All of these flows exhaust into a collection chamber located between the two metal O-ring seals. From there the flow is taken out of the port located on top of the steam generator penetration and routed down through the lower plenum floor to the inlet to the circulators (as indicated in Fig. 1). Thus, the flows are driven by the normal pressure differences of the reactor circuit - approximately 3 psi for the hot-gas samples and 13 psi for the cold-gas sample. The flow is controlled by a porous metal filter located at the exit of each diffusion tube. These metal filters are preceded by fiberfrax filters for removing excess dust particles, and by charcoal filters

for removing all sorbable fission products. The probe has an arrangement of insulation and thermal conductors to maintain the greater part of the diffusion tube length at the return coolant gas temperature. Fig. 3 shows the expected temperature profile.

For ease of identification, the tubes are labeled with a letter indicating their position when the probe is viewed from the locking mechanism end of the probe, that is: Top, Center, Bottom, Left, and Right. Each of these tubes has a slightly different function. The T, B, and R tubes are designed to provide information about the larger dust particles in the reactor circuit. The collection efficiency of the larger dust particles will be influenced by the entrance configuration of the tube in contrast to the smaller dust particles, which will be collected equally by all of the diffusion tubes. The T tube faces upstream and will collect more large particles than the R tube, which faces perpendicular to the flow, and the B tube, which faces downstream.

The C tube processes a sample of the return coolant gas and will provide information about the amount of circulation of fission products around the loop, and thus additional information about the physical form of the different chemical species, e.g., elemental, compounds, dust-borne, etc. The L tube is also a Low flow tube and is specifically designed to help distinguish between dust and noble-gas fission product transport. These points will be discussed in more detail in the following section.

Fig. 3. Diffusion Tube Temperature Profile

The probe is constructed to be potentially reusable. To remove the tubes, the circumferential weld is cut out at the base of the probe tip. This releases both the outer plateout sleeve and the four diffusion tubes connected to the tip. Drilling out the tube welds frees the four diffusion tubes from the tip and the center diffusion tube from the locking nut. The diffusion tubes can then be analyzed as discussed in the following section, and the plateout sleeve retained for possible analysis. It is anticipated that the removal of the plateout sleeve, the tip, and the diffusion tubes will remove the majority of the activity and allow the insertion of new components without an extensive decontamination of the probe. This decontamination could possibly result in damage to the silver coating on the metal O-ring seals.

4. THEORY OF DIFFUSION TUBES

A diffusion tube, as the name implies, is a device for determining the diffusion coefficient of a chemical species. Essentially it consists of a reactive tube through which is passed a laminar flow of gas containing the chemical species to be analyzed. The assumption is made that the gas enters at a uniform concentration and instantaneously establishes a parabolic velocity distribution across the diameter of the tube. Radial and axial concentration distributions are then gradually established due to diffusion of the chemical species to the wall of tube, which is assumed to

behave as a "perfect sink."

Various investigators (Refs. 1-4) have treated this theoretical problem. In terms of the axial surface distribution, the solution can be expressed as

$$A(Z) = \frac{A_T D}{Q} (9.4106e^{-11.489DZ/Q} + 6.8309e^{-70.06DZ/Q} + 5.8198e^{-179.07DZ/Q} + \dots), \quad (1)$$

where $A(Z)$ = the amount on the surface per cm of tube length,

A_T = the total amount that has entered the tube,

D = the diffusion coefficient in cm^2/sec

Q = the volumetric flow rate in cm^3/sec , and

Z = the distance from the entrance of tube in cm.

If the flow rate is sufficiently low, the higher order terms quickly die out and only the first term in the series remains.

4.1 ELEMENTAL SORBABLE FISSION PRODUCTS

Figure 4 is a typical plot showing the profile to be expected at the conditions of the Fort St. Vrain plateout probe. This is the theoretical plot for completely isothermal conditions. However, the Fort St. Vrain diffusion tubes will not be isothermal; they will have a temperature profile similar to that shown in Fig. 3. Consequently, the concentration profile might be expected to be steeper in the higher temperature inlet portions of the tubes.

Fig. 4. Typical Plateout Profile at Reactor Conditions

Unfortunately, past experience has indicated that the "perfect sink" boundary condition is apt to be violated at the higher temperatures. Iodine, in particular, has been known to react with the metal at the inlet temperatures, producing volatile metal iodides that then plate out further downstream. This results in a concentration profile which has a maximum downstream from the entrance. In the cooler portions of the probe, the concentration profile will, however, assume the slope indicated by the first term of Eq. 1. Consequently, the diffusion coefficient can still be determined from this portion of the curve. (Conversely, the flow rate can be determined if the diffusion coefficient is known.)

The total amount, A_T , of gaseous Sr^{90} that has entered the diffusion tube can usually be determined by an analysis of the diffusion tubes and the outlet filters (if there are no dust-borne or noble-gas-borne components). These filter units contain a fiberfrax section, a charcoal trap, and a 1/4-in length of porous metal filters that are typically rated at 98% removal of $> 0.7\mu$ particles. These filter units should remove essentially all of the fission products in the coolant stream because of physical entrapment or increased mass transport. As an alternate (or check) to the filter measurements, the total amount of gaseous material that entered the filter can be estimated by integrating Eq. 1 to get the amount for an infinitely long tube. Assuming that only the first term is important, this results in

$$A_{\infty} = 0.0870 A(L) \frac{Q}{D}, \quad (2)$$

where

A_{∞} = the extra amount which would be collected by an infinitely long tube,

$A(L)$ = the amount per unit length as recorded at the exit end of the tube,

Q = the flow rate in cm^3/sec , and

D = the diffusion coefficient in cm^2/sec .

4.2 DUST-BORNE FISSION PRODUCTS

Some of the fission products in a reactor circuit may be sorbed on dust or other gas-borne particles. The theoretical distribution of these particles in the diffusion tubes will still be given by Eq. 1 if the walls of the tube approximate a "perfect sink". However, the diffusion coefficients for reasonably sized dust particles will be many decades smaller than the diffusion coefficients of elemental species. Thus, the concentration profile along the surface of the tube will be essentially flat at the contemplated flow rates, and no information can be obtained on the diffusion coefficients of these particles. In practice, it is found that the concentration profile is essentially constant, but somewhat erratic, due to nonuniform particle sizes, nonuniform sticking, and low concentration levels.

The majority of the dust particles will remain in the gas stream until they are removed by the filter units. Therefore, the amount of dust entering the diffusion tube can be obtained from an analysis of the filter units. If some amount of fission products in the elemental state are also contained in the tube, the contribution to the amount in the filter unit can be estimated from Eq. 2 and subtracted from the total amount in the filter unit to yield the amount transported by dust particles.

4.3 NOBLE-GAS DAUGHTER PRODUCTS

The source of some fission products of interest may be primarily from short-lived noble-gas precursors, such as 16-sec Xe^{140} , 33-sec Kr^{90} , and 4.2-min Xe^{137} . In this case, the daughter-product concentration profile will be similar to the noble-gas parent profile in the diffusion tubes. With an inside diameter of the diffusion tubes of 0.155 in and a length of 13 in, the tube volume is 4.0 cm^3 giving a transit time of 2 seconds at a flow rate of $2 \text{ cm}^3/\text{sec}$. Thus, there will be negligible decay of the above listed noble gases, and the daughter-product concentration profiles will be relatively flat. However, the L tube is also a Low flow tube and there will be approximately a 66 second transit time for this tube. Thus, there will be significant decay of the noble-gas precursors during transit through the L tube.

The solid line on Fig. 5 illustrates the concentration profile that might be expected for Sr^{90} being deposited from its 33-sec half-life Kr^{90} parent in the L tube. The two dashed lines show (1) the extremely steep profile to be expected if Sr^{90} is present in the elemental form, and (2) the extremely flat profile to be expected if Sr^{90} is present on dust particles that might be deposited in the tube. It should be remembered that, if a dust component is present, the majority of the dust will be found in the outlet filter, while a noble-gas precursor will have essentially no contribution to the filter activity, since there is very little delay time in the filter.

5. ANTICIPATED ANALYSIS TECHNIQUES

It is suggested that the plateout probe be disassembled as quickly as possible so as to obtain data on short-lived fission products, particularly 8.05-day I^{131} . The circumferential weld at the base of the probe tip should be cut first. The plateout sleeve should then be removed undisturbed and saved for possible future analysis. Before removal from the probe tip, all tubes should be checked to verify that they are marked with the appropriate letter at a point 1-3/4 in from the filter unit end of the tubes. The four diffusion tubes should then be separated from the tip by cutting out the installation weld, being careful to minimize disturbance of the diffusion tubes. The fifth diffusion tube should be removed from the probe locking nut in a similar manner. All five

Fig. 5. Typical Plateout Profiles in the Low-Flow Tube

tubes should then be counted with a high-resolution solid-state gamma detector, using depleted uranium as a collimator to obtain a profile of activity along the length of each tube. Particular care should be exercised to obtain good profiles for 8.05-day I^{131} , 12.8-day Ba^{140} , 30-yr Cs^{137} , and any other fission products present in moderate amounts. If the activity of the filter units is high enough to interfere with this profile measurement, then they may be cut off at the weld joint and counted separately.

All of the gamma spectrometer data should be plotted immediately to detect any irregularities in the counting techniques. If no irregularities are detected, then the tubes should be sectioned for chemical analysis to obtain the β -emitting Sr^{90} values. In the initial probes, Sr^{90} profiles will likely be obtained on all five diffusion tubes. However, subsequent probes may require a lesser amount of analysis, depending on the previous data obtained and on the confidence in the accuracy of the data.

From the straight-line portion of the concentration profiles of I^{131} and Cs^{137} and the diffusion coefficients at reactor conditions, a flow rate for each regular flow diffusion tube can be calculated. The flow rate in the L tube can be calculated from the Ba^{140} concentration by assuming that it resulted from the decay of 16-sec Xe^{140} . (Similarly, the Xe^{137}/Cs^{137} or Kr^{90}/Sr^{90} profiles might be used.) These calculated flows should be compared with the manufacturer's calibration data on the diffusion tubes to ascertain whether there

have been any flow irregularities. It should be remembered that the 8.05-day I^{131} and 12.8-day Ba^{140} data will give the average flow during the last few weeks of reactor operation while the 30-yr Cs^{137} data represents the average during the sampling period.

5.1 GAS-BORNE Sr^{90}

Each of the three components of Sr^{90} activity should be calculated from the diffusion tube data, that is, gaseous, dust-borne, and noble-gas precursor. The gaseous component should be calculated from any straight-line portion of the data having a slope of the same order of magnitude as that shown in Fig. 4. The total gaseous component is calculated as consisting of the activity in the first nonisothermal portion of the tube plus the amount indicated by the sloping portion of the profile (plus any additional amount that might have been collected by an infinitely long tube as calculated from Eq. 2).

When the total activity is divided by the diffusion tube flow rate, identical results should be obtained for the T, R, and B diffusion tubes. Also, the amount obtained from either plateout probe should be the same since there should not be any significant difference between the two reactor flow loops. Although there might be preferential release from the older fuel regions, the scattered loading pattern and the changing flux profiles throughout a 1-yr or longer sampling period should damp out any differences. Therefore, if both probes are removed at the same time, the six

normal flow tubes should be used to select one most probable amount of gaseous Sr^{90} per unit flow rate at the entrance to the steam generators. This may involve discarding very high or low values to arrive at a most probable one. As previously stated, unless there are very strong indications to the contrary, there should be very little difference in the amount of gaseous component entering each tube, and any differences are likely because of the complex analysis and interpretation procedures.

The C tube, which is the Center Counterflow tube that samples the return coolant, should be analyzed for a gaseous Sr^{90} component in the same manner as for the T, R, and B tubes. However, calculations indicate that essentially all of this gaseous component will be removed by the steam generator surfaces. It may, therefore, be extremely difficult to detect a gaseous component with a slope equal to that found in the tubes sampling the hot gas entering the steam generators. Again, if both probes are removed at the same time, the data from both probes should be used to arrive at a most probable value. An underestimate of the amount might be selected (perhaps even zero) since this is on the conservative side when the total reactor inventory resulting from the gaseous phase transport is estimated from

$$A_{\text{Gas}/\text{Sr}^{90}} = \left[\left(\frac{A_{\text{TG}}}{f} \right)_{\text{Hot}} - \left(\frac{A_{\text{TG}}}{f} \right)_{\text{Cold}} \right] F, \quad (3)$$

where

$\left(\frac{A_{TG}}{f}\right)_{Hot}$ = the total amount of gaseous Sr^{90} per unit mass flow rate
in the hot gas as determined from the T, R, and
B tubes,

$\left(\frac{A_{TG}}{f}\right)_{Cold}$ = the total amount of gaseous Sr^{90} per unit mass flow rate
in the cold gas as determined from the C tubes, and

F = the total mass flow rate in the reactor circuit.

(This is actually the inventory associated with the steam generators and circulators, but it is the appropriate value needed for consideration of a depressurization incident.)

5.2 Sr^{90} FROM Kr^{90} DECAY

The amount of Sr^{90} resulting from the decay of released Kr^{90} is determined from the Low-flow L tubes. This is accomplished by fitting a straight-line to the data points at the slope indicated by the velocity of the gas in the diffusion tube and the 33-sec half-life of Kr^{90} . Integrating under this line gives the total amount of Sr^{90} in the tube from the decay of Kr^{90} . If both probes are removed at the same time, they should both give the same result. However, if large differences exist, the most likely value should be used since the Kr^{90} activity around the circuit will be essentially constant. The total reactor inventory of Sr^{90} resulting from Kr^{90}

will then be calculated from

$$A_{\text{Kr}/\text{Sr}^{90}} = 0.1M \left[\frac{A_{\text{KL}} \lambda_{\text{Kr}^{90}}}{f_L (1 - e^{-\lambda_{\text{Kr}^{90}} \tau_L})} \right], \quad (4)$$

where

- M = the total mass of helium circulating in the loop in pounds,
- A_{KL} = the integrated Sr^{90} activity in the L tube that resulted from Kr^{90} decay,
- $\lambda_{\text{Kr}^{90}}$ = the decay constant of Kr^{90} in reciprocal sec,
- f_L = the mass flow through the L tube in pounds per sec, and
- τ_L = the transit time through the L diffusion tube in sec (~ 66 sec).

The exponential term is the factor necessary to account for the finite length of the diffusion tube. The term in square brackets is equal to $1 - e^{-\lambda t}$ times the Kr^{90} activity per unit mass of coolant at the entrance to the diffusion tubes, where λ is the decay constant of Sr^{90} and t is the time of operation of the probe.

The amount of Sr^{90} activity resulting from Kr^{90} decay as calculated from Eq. 4 should be equal to one-tenth the amount that would be calculated by assuming that the Kr^{90} R/B value can be estimated from the other measured krypton R/B values (by assuming that the R/B values are proportional to the square root of the fission product half-life.) The one-tenth factor results from mass transport

calculations indicating that more than 90% of the Rb^{90} and Sr^{90} daughters are deposited in the upper plenum, the core components, and the lower plenum, even though the gaseous Kr^{90} activity is approximately constant around the loop. Therefore, it is conservatively assumed that 10% of the Kr^{90} -borne Sr^{90} is associated with the steam generators and circulators.

The physical reason for this preferential plateout is that the majority of the Kr^{90} decay occurs during transport of the cold gas through the lower plenum that houses the steam generators. The mass transport characteristics of this plenum are very low. Therefore, the daughter products remain in the gas stream until they reach the next components, which have much better mass (or heat) transfer characteristics.

5.3 DUST-BORNE Sr^{90}

The amount of dust-borne Sr^{90} in the diffusion tubes is assumed to be equal to the activity not accounted for in the diffusion tubes. That is, the total direct gas-borne activity (assuming an infinitely long tube) and the total noble-gas-transported activity (assuming a finite length tube) is subtracted from the total activity in each tube to yield the dust-borne activity. It should be noted that the L tube noble-gas-transported activity is obtained by integrating under the straight-line portion of the activity profile as

previously described. The other tubes' noble-gas-transported activities are obtained from

$$A_{KX} = \frac{f_X (1 - e^{-\lambda_{Kr^{90}\tau_X})}}{f_L (1 - e^{-\lambda_{Kr^{90}\tau_L})}} A_{KL} , \quad (5)$$

where

A_{KL} = the noble-gas-transported activity in the L tubes,

f_X = the mass flow rate in the T, C, B, or R tubes,

f_L = the mass flow rate in the L tube,

τ_X = the transit time in the T, C, B, or R tubes, and

τ_L = the transit time in the L tube.

After the direct gas-borne and the noble gas-transported activities have been subtracted from the diffusion tube activities, the remaining activities should be divided by the individual tube mass flow rates and compared to see if there are any statistically significant differences between the T, R, B, and L tube values. Both probes, if analyzed, should be used to obtain a most probable value, since there should be no significant differences in the two loops averaged over the minimum contemplated 1-yr sampling period.

The amount of dust-borne activity in the C tube, which is the center tube that samples the return coolant, should be determined in a manner similar to the T, R, B, and L tubes. However, should essentially all of the dust-borne component be removed by the steam generators, this procedure may lead to inconsistent (or even negative) results when the calculated Kr^{90} precursor component is subtracted from the C tube inventory. In this case, a deliberate underestimate of the amount in the C tube might be selected since this is on the conservative side when the total reactor dust-borne Sr^{90} inventory is estimated from

$$A_{\text{Dust}/Sr^{90}} = \left[\left(\frac{A_{TD}}{f} \right)_{\text{Hot}} - \left(\frac{A_{TD}}{f} \right)_{\text{Cold}} \right] F, \quad (6)$$

where

$\left(\frac{A_{TD}}{f} \right)_{\text{Hot}}$ = the total amount of dust-borne Sr^{90} per unit mass flow rate in the hot gas as determined from the T, R, and B tubes,

$\left(\frac{A_{TD}}{f} \right)_{\text{Cold}}$ = the total amount of dust-borne Sr^{90} per unit mass flow rate in the cold gas as determined from the C tubes, and

F = the total mass flow rate of the reactor.

If there is a significantly greater collection of dust-borne Sr^{90} by the upstream-facing T tube, then this extra amount might be used to calculate a large dust particle reactor inventory from

$$A_{\text{Large Dust/Sr}^{90}} = A_{\text{LD}} R, \quad (7)$$

where

A_{LD} = the amount of Sr^{90} in the T tube that is assumed to be on large dust particles, and

R = the ratio of the cross-sectional area of the steam generator entrance to the cross-sectional area of the diffusion tube entrance.

It should be noted that this area ratio is in order of magnitude less than the flow rate ratio (F/f) used in Eq. 6 and this method should, therefore, not be used unless there are very clear-cut indications of its applicability.

6. SUMMARY

It is presently anticipated that the transport of Sr^{90} in the reactor circuit can be described by three processes which result in a gaseous component, a dust-borne component, and a Kr^{90} precursor component. Thus, the reactor inventory of Sr^{90} would be given by

$$A_{\text{Sr}^{90}} = A_{\text{Gas/Sr}^{90}} + A_{\text{Dust/Sr}^{90}} + A_{\text{Kr/Sr}^{90}}. \quad (8)$$

However, in practice it has been found that only the Kr^{90} precursor component is of any importance for most situations. This fact should be considered when interpreting the diffusion tubes. The activity should always be compared to the activity that would be calculated by assuming a Kr^{90} release extrapolated from the other krypton isotopes. This reactor activity would be given by

$$A_{\text{Sr}^{90}} \approx B \left(\frac{R}{B} \right)_{\text{Kr}^{90}} \left(1 - e^{-\lambda_{\text{Sr}^{90}} t} \right), \quad (9)$$

where

- B = the reactor birthrate of Kr^{90} ,
- $(R/B)_{\text{Kr}^{90}}$ = the estimated normalized release rate of Kr^{90} , and
- t = the time of operation of the probe.

Although an attempt has been made to cover all of the major possibilities on Sr^{90} transport, there is a possibility that some interpretation difficulties have been overlooked. Therefore, it is imperative that all the data be given careful consideration, and that imagination be used in the interpretation rather than a mechanical following of the listed procedures. A perusal of past performance should be helpful. Fortunately, the buildup of 30-yr Sr^{90} is a slow process, and time should be available so that one might rely on future clarification or correction of a tentative interpretation.

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