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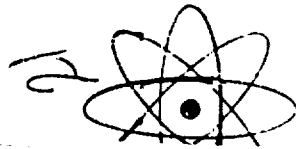
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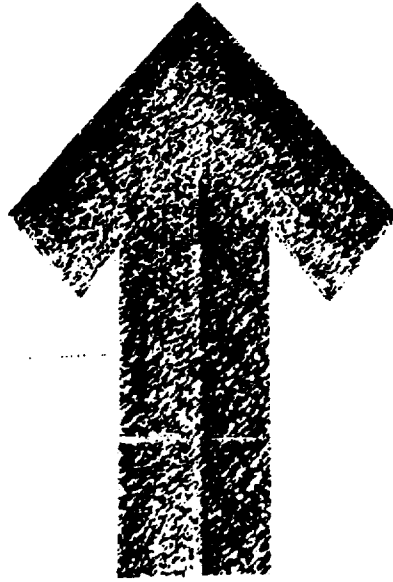
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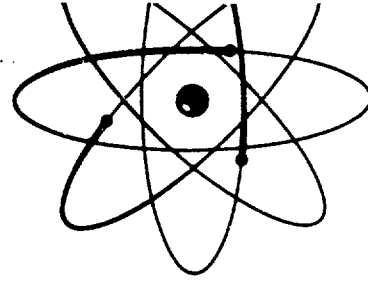
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EFFECT OF AN INCONEL STEAM GENERATOR ON
DEPOSITED ACTIVITY AND WATER TREATMENT
OF THE PM-2A

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1.0 SUMMARY

An analysis was made of the effects of an Inconel steam generator on activity deposition in the MW-2A primary system. Equations were derived for determining amounts of activated corrosion products released from in-flux and out-of-flux surfaces. The results permit comparison of predicted activity from a 50% Inconel-50% stainless steel system with activity from an all stainless steel system. A discussion of the methods of treatment of the primary and secondary waters in contact with an Inconel steam generator was given.

1.1 Conclusions

1. Use of an Inconel steam generator in the MW-2A may result in a radiation level at the end of 1 year 2.34 times that expected from an all-stainless steel primary system. (Based on 0.002% cobalt content for in-flux materials and 0.05% content for out-of-flux materials.) After two years of operation this value would decrease to 1.9 times the compared value. The greater amount of activity from an Inconel steam generator is due to the large amount of nickel in Inconel which transmutes to Co58 upon neutron bombardment. As time increases, the decrease in difference between the two systems is due to greater Co60 activity. If a value of 0.1% cobalt in out-of-flux materials is assumed, an Inconel system would have 76% more activity after two years operation than a stainless system.
2. Calculations for an all-stainless steel system indicate that up to two years, approximately half of total system activity may originate from activation of corrosion products released from out-of-flux regions. (Based on a 0.002% cobalt content in-flux and 0.05% content out-of-flux.)

3. Water treatment with an Inconel steam generator should be the same as that proposed for the PM-2A primary and secondary systems with a stainless steel steam generator. Primary water specifications should be the same for either steam generator. In the secondary system the chloride and total solids concentrations can be increased to 100 ppm and 700 ppm, respectively, with an Inconel steam generator. The other specifications are the same for either steam generator.

3. For a 50% Inconel - 50% stainless steel system, the amount of activity arising from activation of corrosion products released from out-of-flux surfaces may be as much as 4 to 5 times that originating from in-flux surfaces. (Based on a 0.002% cobalt content in-flux and a 0.05% content out-of-flux). The larger amount from out-of-core surfaces is due to the greater amount of nickel in Inconel than in stainless steel.

4. Calculations show that operating the PM-2A purification system at its maximum rate (1.7 gpm) will result in a 30% activity decrease compared to operating at the design rate (1.0 gpm).

5. The use of an Inconel steam generator will not alter the water treatment or purity specifications of the primary system. Because Inconel is not subject to chloride stress corrosion cracking, an increased concentration of up to 100 ppm chloride is permissible in the secondary.

1.2 Recommendations

1. The advantages of an Inconel steam generator should be more fully weighed against its disadvantages. In a study of this short duration, it is not possible to consider all the possible parameters and their ramifications on a reactor system. Rather, the study serves to point out areas that require more evaluation and study. Collaboration should be made with other reactor designers who are using or propose to use Inconel in the primary system.
2. In order to minimize buildup of activity, the purification rate of the PM-2A should be operated at a maximum (1.7 gpm) when possible.

2.0 INTRODUCTION

The second steam generator for the PM-2A reactor will be constructed with Inconel tubes. The buildup of radioactive corrosion products on reactor primary system surfaces has been measured in power reactor systems which contain all stainless steel and those which contain zircaloy and stainless steel. (5,8) However, no reactor system with significant amounts of Inconel exposed to the primary coolant has been operated to date.

Various mechanisms of activity buildup have been proposed and mathematical models for predicting the degree of buildup have been advanced for all-stainless steel and zircaloy-stainless steel systems. Equations have been derived which account for the activity experimentally found on system surfaces. However, all the equations have the disadvantage of requiring evaluation of certain constants which can best be found from experimental data. As a further complication, power reactor systems are generally not operated under controlled research conditions. Because of the many parameters which appear to affect the buildup of activity on system surfaces, it is difficult to extrapolate data and conditions from one system to another. This uncertainty however, does not preclude a broad analysis of what might be expected in a system which contains a considerable amount of Inconel exposed to the coolant.

The purpose of this report is to investigate the possible effects of an Inconel steam generator on the deposited activity of the primary system. The effects of an Inconel steam generator in the PM-2A on the primary and secondary water treatment is also discussed.

3.0 SOURCES OF RADIOACTIVITY

In a pressurized water reactor system, active nuclides can arise from several sources, of which principal sources are:

1. Release of fission products from the nuclear fuel through a defect in the fuel cladding.
2. Recoil of fission products from fissionable impurities in the cladding material.
3. Recoil of induced nuclides from the cladding material.
4. Activation of the coolant and impurities in the coolant (including corrosion products) as they circulate through the core.
5. Activation and subsequent release of corrosion products from out-of-flux surfaces (e.g. steam generator) deposited on the core.
6. Activation and later release as corrosion products of material from the core itself.

In this study, only those long-lived gamma emitting activities arising from the last two sources (5. and 6.) are considered. Other sources are excluded because: (1) Under ordinary conditions the fuel cladding will contain no defects and hence no release of fission products would be expected; (2) If fuel cladding is fabricated under rigid control conditions an insignificant amount of fuel material will be in the cladding; (3) In the case of sources 3. and 4. above, previous work (4.) has shown these contributions to be insignificant for long-lived nuclides.

Several methods of calculating the activities arising from the last two sources have been published (5,10). For all stainless steel reactor systems at neutral pH, it appears the major source of nuclides is the corrosion of in-flux surfaces. However, a sig-

nificant amount of activity may well originate from out-of-flux corrosion products depositing on in-flux surfaces. For a stainless steel-Zircaloy system at pH 9 to 10, calculations have shown that the major activity comes from out-of-flux corrosion products being deposited on in-flux surfaces and subsequently activated and released. In both of these cases, because assumptions were made based on limited data, results could vary by a factor of 2. Sufficient experimental data were not available to define complex mechanisms of nuclide activation, transport and loss, so that simplifying assumptions were made to obtain an order of magnitude of activity buildup. For this study, activity contributions from both out-of-flux and in-flux surfaces are considered.

3.1 Out-of-Flux Contributions

The mathematical expressions used to describe activity buildup in the PM-2A due to out-of-flux corrosion are derived in the Appendix, Section 6.1. The expressions do not reflect all of the probable transport and activation processes occurring in a reactor system, but rather are for the limiting or extreme case. The equations for calculating the activity buildup were based on the following assumed mechanisms:

1. Corrosion products from out-of-flux areas (steam generator plus piping) were assumed to be deposited on the in-flux areas. The rate of deposition was taken equal to the rate of deposition found on metal test coupons inserted in the SK-1 primary blowdown line. The SK-1 data indicates this rate is not constant, but it was felt that within the range of experimental error, it could be assumed constant.
2. As the corrosion products are deposited on the in-flux areas, nuclides are freed by destruction and lost by decay.
3. Subsequently, active nuclides are released to the coolant and either go to out-of-flux surfaces or are lost by decay or through the purification system.

3.2 In-Flux Contributions

The equations for determining activity buildup in the PM-2A due to in-flux corrosion are derived in the Appendix, Section 6.2. Again, not all parameters such as coolant velocity, pH, neutron flux, solubility and physical form of corrosion products were considered. Rather, the equations were based on the limiting case and the following mechanisms were assumed:

1. The active nuclides in the material exposed to a significant neutron flux (fuel elements, thermal shields, pressure vessel, etc.) are produced by the thermal and fast flux. The nuclides are subsequently lost from the core by decay and release into the primary coolant by corrosion.
2. Nuclides in the coolant are lost by decay, by removal through the purification system, and by deposition on the primary system surfaces.

4.0 CALCULATED RADIOACTIVITY

Using the appropriate constants, the equations were solved for intervals of one month. Activity originating from out-of-flux surfaces and in-flux surfaces, as well as the activity expected from an all-stainless steel system and an Inconel-stainless steel system, was calculated.

4.1 Out-of-Flux and In-Flux Contributions

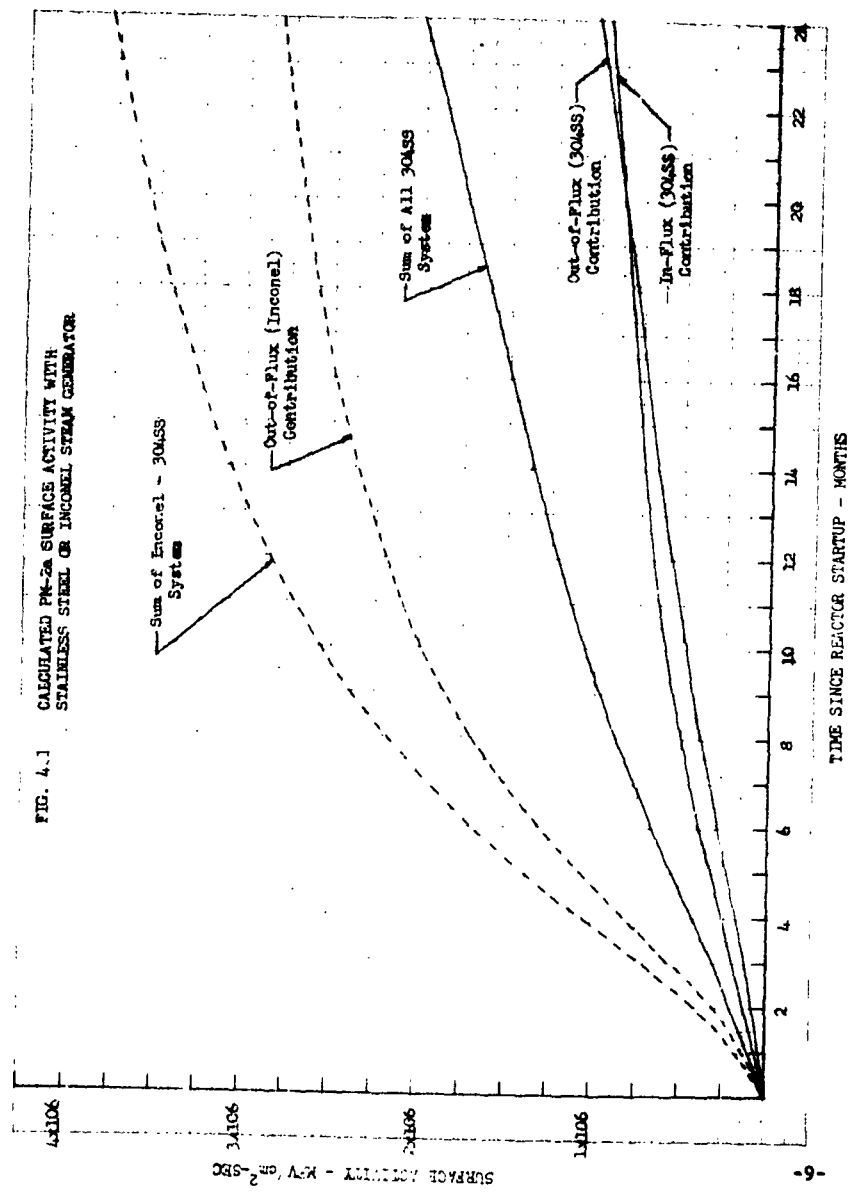
Figure 4.1 shows the activities calculated for the PM-2A with an all-stainless steel system, and with a system having an Inconel steam generator. In the all-stainless system, the contribution from out-of-flux components surpasses the in-flux contribution at 20 months. Up to this period, Co⁵⁸ is the predominant nuclide to the total activity from both in-flux and out-of-flux areas. After 20 months, the contribution of Co⁶⁰ from the out-of-flux surfaces begins to overshadow other nuclides. Since the cobalt content in the steam generator was assumed to be 0.05% and the content in the core is only 0.002%, the greater contribution from out-of-flux is not unexpected.

Comparison of the mathematical expressions for in-flux and out-of-flux contributions (Appendix, Sections 6.1 and 6.2) shows them to be identical except for the constants in front of the brackets. The ratio of out-of-flux to in-flux active atoms is found to be:

$$\frac{N_o}{N_i} = \frac{f_{s0} f_{n0} a g}{f_{s1} f_{n1} C}$$

Where: N_o = active atoms due to out-of-flux surfaces
 N_i = active atoms due to in-flux surfaces
 f_{s0}, f_{n0} = product of fractional abundance of chemical element in system material and fractional abundance of target nuclide in chemical element. In the case of out-of-flux material, the theoretical corrosion product (oxide) of the constituents was calculated and used. Elements were assumed to corrode in the same proportion as found in the base metal.

FIG. 4.1 CALCULATED PM-2a SURFACE ACTIVITY WITH
STAINLESS STEEL OR INCONEL STEAM GENERATOR



Where: a = rate of buildup of crud thickness on core surfaces.
 g = fraction of crud deposited on core that is released to the coolant (assumed equal to one).
 C = release rate of corrosion products of core (assumed equal to corrosion rate).

Substituting the observed experimental values for " a " and " C " and assuming " g " equal to one, gives:

$$\frac{M_0}{M_I} = \frac{0.9 f_{20} f_{20}}{f_{21} f_{21}}$$

For each nuclide, with the exception of cobalt, the average ratio of the atoms available for activation (f_g, f_n) arising from out-of-flux areas to those from in-flux areas is approximately 0.75. (This is due to corrosion of those nuclides out-of-flux before they are deposited on the core.) Thus the average ratio of activity due to uncontrollable elements (iron and nickel) arising from out-of-flux surfaces to that due to in-flux surfaces is 0.675. The ratio of activity from out-of-flux to in-flux for cobalt is 16.8, since the FM-2A stainless in the core contains 0.002% cobalt while stainless out-of-flux was assumed to contain 0.05% cobalt.

Based on 0.002% cobalt in-flux, the cobalt nuclides arising from in-flux areas contribute approximately 1.2% of the total system radiation level, at the end of two years. If a "nominal" value of cobalt (0.1%) is assumed in out-of-flux surfaces, the percentage of total activity due to in-flux cobalt after two years would be reduced to 0.6%. Based on these calculations, specifying a low-level of cobalt in the core cladding is not justified, since the major amount of the total activity is due to out-of-flux cobalt and the in-flux and out-of-flux uncontrollable nuclides. However, when the effects of activity due to in-core surfaces is evaluated over a long period of reactor operation (about 10 years), it may be that levels of cobalt below "nominal" (0.1%) would be justified.

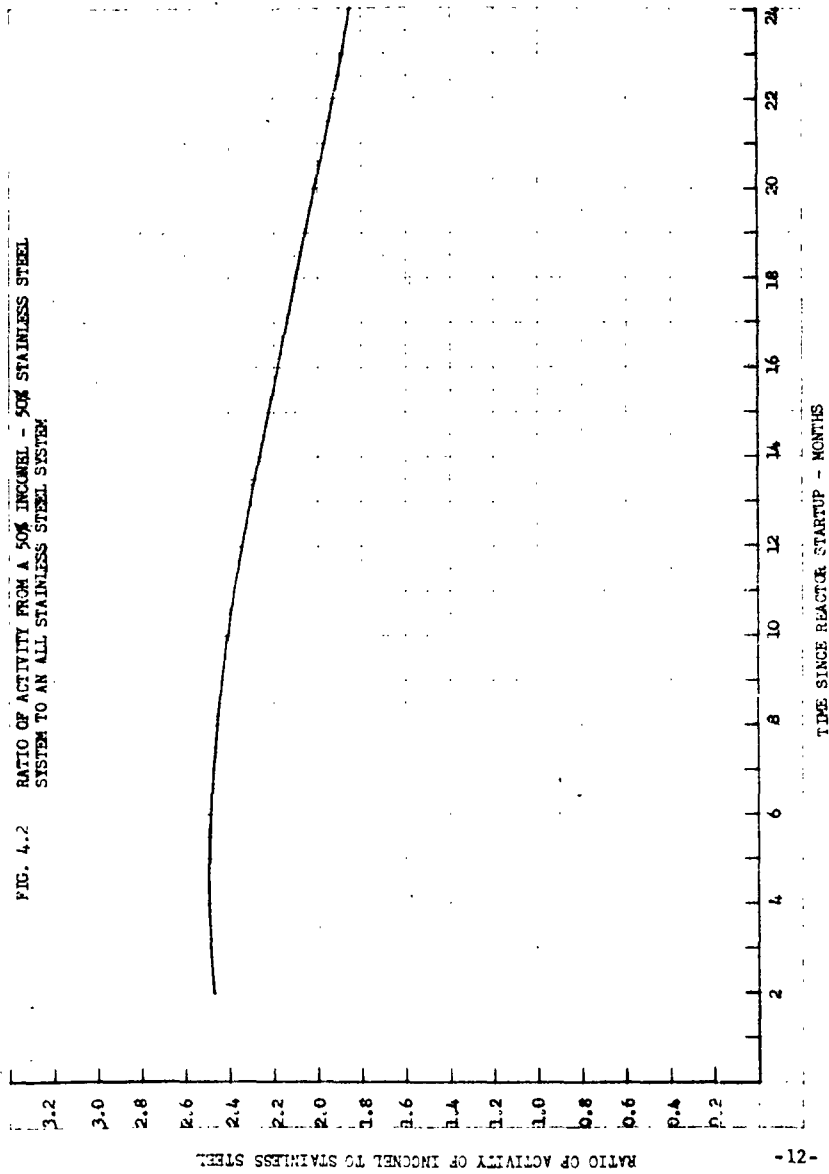
Although 0.1% cobalt in stainless steel is usually considered the "nominal" value, 0.05% was used in this study, because the cobalt content of a heat of Inconel for the FM-2A tubes analyzed 0.05%. To form a basis of comparison, the percent cobalt in the stainless was assumed equal to this value also. A detailed study and experimental work would have to be undertaken before the optimum level of cobalt in the stainless could be determined. Such factors as frequency of decontamination, and the actual transport mechanisms in a reactor would have to be considered.

If the FM-2A utilized an Inconel steam generator, calculated activity due to out-of-flux surfaces is approximately 3 to 4 times greater than that due to in-flux surfaces. In this study the corrosion release rate of Inconel was assumed equal to that of stainless steel. Data available in the literature and those obtained at the SM-1 indicate this assumption is valid for Inconel exposed to conditions expected in the FM-2A (see Appendix, 6.3). The greater out-of-flux activity is due primarily to the large amount of nickel in Inconel, thus producing Co^{58} .

4.2 Comparison of Activity Expected from Inconel-Stainless Steel System to an All-Stainless Steel System

Using the values of activities calculated in Figure 4.1, the ratio of activity from an Inconel-stainless steel system to an all-stainless steel system was found. The results are shown in Figure 4.2. In the FM-2A, approximately 50% of the total surface area is out-of-flux.

The results show that after one year, a 50% Inconel system would be expected to have 134 percent more activity than an all-stainless steel system. After two years of reactor operation this value would decrease to 80 percent more activity. The decrease is due to the increasing predominance of Co^{60} after several years. If a value of 0.1% cobalt is assumed for out-of-flux materials, an



Inconel system would have 76% more activity after two years of operation than a stainless system.

In comparison, work done at Westinghouse indicates that 20% more activity after one year would be expected from a 2/3 Inconel-1/3 stainless system as compared to an all-stainless system. (9) However, the method used to calculate the expected activity was different from that used in this study. The different assumptions made in that work and the different reactor operating conditions prevent any direct comparison of results.

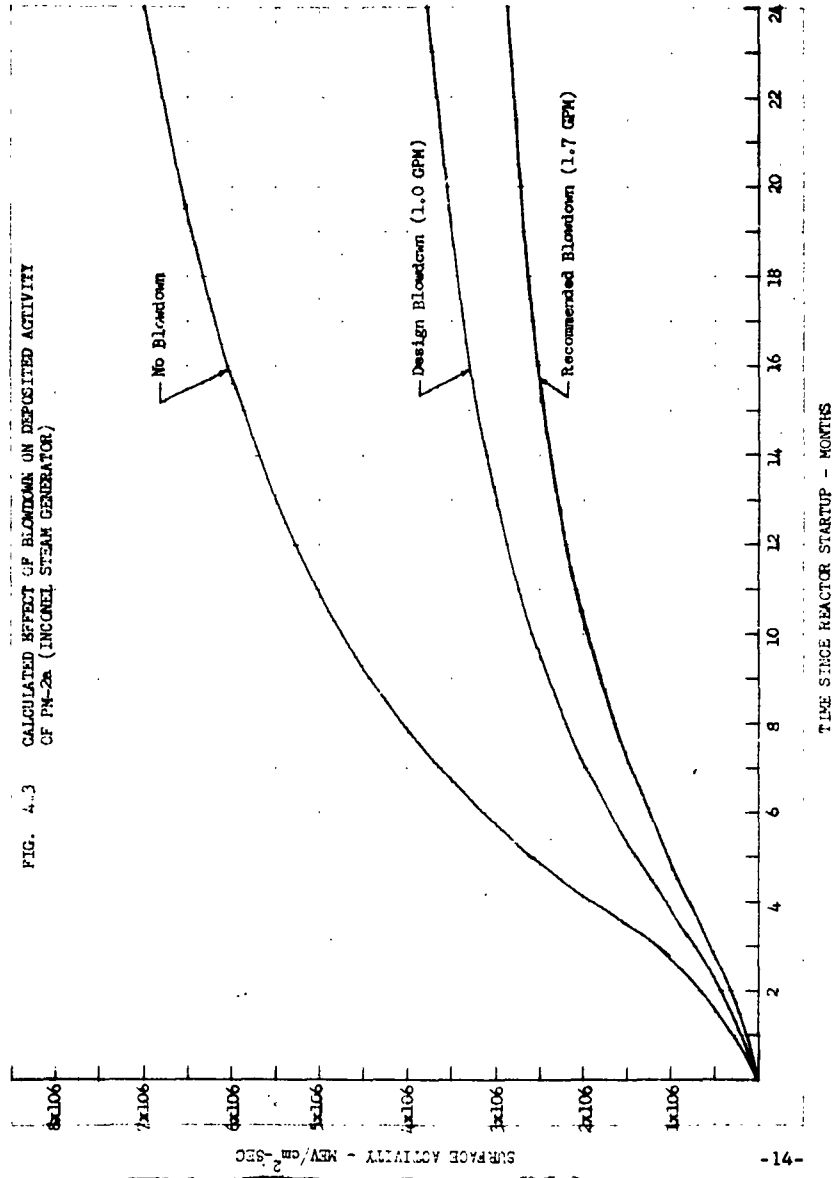
4.3 Effect of Blowdown Rate on Activity Buildup

Calculations were made to determine the effect of the blowdown rate on the expected activity of the system with an Inconel steam generator. The results are shown in Fig. 4.3. The upper curve is the activity expected if there were no blowdown. This assumption represents the limiting case of activity buildup.

From Figure 4.3 it is found that increasing the purification rate to 1.7 gallons per minute causes approximately 32% reduction in activity from that expected at one gallon per minute. The theoretical effect of the purification rate on the deposited activity is seen by inspection of the derived equations (Appendix, Sections 6.1 and 6.2). By using different values of α , the purification rate, it was found that the fraction of activity lost to the purification system was equal to $\frac{\alpha}{\lambda_0 + \alpha}$. For long-lived nuclides, λ is negligible and the ratio reduces to $\frac{\alpha}{\lambda_0}$. Thus, at PM-2A present design conditions (1.0 gpm purification rate) the ratio is equal to:

$$\frac{2.76 \times 10^{-5}}{3.27 \times 10^{-5} + 2.78 \times 10^{-5}} = 0.46$$

Increasing the purification rate to 1.7 gpm gives a ratio of 0.59; or in other terms, the activity remaining in the system has been reduced by approximately 32%.



4.4 Discussion of Results

The calculated activity of the surface deposits of the PM-2A is higher than what would be expected from observations at the SM-1. Since the PM-2A is comparable to the SM-1 in its ratio of out-of-flux area to in-flux area, in water chemistry and neutron flux, similar radiation levels would be expected. The dose rate observed on the steam generator baffle plate of the SM-1 after 17 months of operation was approximately 160 mr/hr (outlet side) and 230 mr/hr (inlet side). In contrast, the calculated dose rate for an all-stainless steel system for the PM-2A, including the out-of-flux and in-flux contributions, is found to be 1.5 R/hr after 17 months of operation. This value was found from Figure 4.1 and is the dose rate corresponding to a surface of infinite area, comparable to the SM-1 baffle plate.

The values for the PM-2A as compared to those observed at the SM-1 could be greater for several reasons. First, the same equations used to calculate the in-core activity for the SM-1 were used for the PM-2A. The calculated and observed values agreed well when using certain constants. One of these constants was the corrosion rate, found to vary from 5 to 1 mg/dm²-mo from start-up to the first year of operation (based on metal coupon data). Additional data obtained later showed the reactor system corrosion rate was several times that of the metal coupon corrosion rate and could be approximated at a constant 4 mg/dm²-mo. This value was used for the PM-2A system corrosion rate. Since the same equation for SM-1 was used for PM-2A in-core contributions, activity levels three to four times greater are not unexpected.

Second, activity lost in crud traps for the PM-2A was not taken into account. A significant amount of activity could conceivably be in these areas. In the SM-1, this activity loss was not considered either. Since the activity due to out-of-flux surfaces was not included in calculations for the SM-1, the net effect

of the above two exclusions may be to cancel each other. Since crud traps were neglected and out-of-core contributions were included, it is not surprising that activity calculated for the PM-2A is another factor of 2, or, eight times that observed in the SM-1. In this study the absolute value of deposited activity was not considered as important as the ratio of the activities originating from a 50% Inconel-50% Stainless system to an all-stainless system. If it can be assumed that Inconel releases at the same rate as stainless, and that nuclides originating from both metals have the same transport properties, then the calculated ratios should be valid.

The equations were derived assuming that only fresh corrosion products are released to the system and that radioactive nuclides are irreversibly deposited. For example, all out-of-flux corrosion products were assumed to originate from fresh surfaces, to be deposited on the core, become activated, and then irreversibly deposited on out-of-flux surfaces. In actuality, a portion of corrosion products being transported from out-of-flux to in-flux surfaces probably have a previous history of activation. Activated nuclides in these corrosion products would subsequently be transported into stable or less energetic nuclides, while inactive atoms would be activated. A similar analogy can be given for nuclides originating from in-flux surfaces. The effect of this transport mechanism on the radiation level, or the ratio of a 50% Inconel-50% stainless steel system to an all-stainless steel system is not definitely known. Modifications to the equations used would have to be made before the effects could be calculated.

5.0 WATER TREATMENT WITH INCONEL STEAM GENERATOR

Treatment of primary and secondary reactor waters is dependent upon their source and the necessary limits of impurities and corrosion control chemicals. Limits of various chemicals and im-

purities are prescribed so as not to cause deleterious effects on the reactor system. These limits for the primary system are usually stringent, since it is desirable to maintain total solids at a low level to avoid induced radioactivity and the possibility of clogging close tolerance parts. Consequently, it has become standard practice in the nuclear industry to specify materials for the primary system known to have low corrosion rates, e.g. stainless steel, Zircaloy and Inconel. Furthermore, water used as the reactor coolant generally is equivalent to that produced by deionization or evaporation, and a portion is continuously removed, purified and returned to the system. The net effect of the above factors is to keep the level of total solids low.

Limits of feedwater for the secondary system are generally determined by the materials of construction of the steam generator (boiler) and other parts of the system. Since the steam generator acts as an evaporator, impurities in the feedwater will concentrate in it. Excessive amounts of suspended and dissolved solids tends to cause carry-over and deposition of scale on the boiler. The concentrations of impurities in the feedwater are dependent upon the percent blowdown of the steam generator. For boilers operating between 400-600 psig, a total solids limit of 2500 ppm and a suspended solids limit of 150 ppm is recommended by the American Boiler Manufacturers' Association (3).

Treatment of primary and secondary waters for the PM-2A with a stainless steel steam generator is similar to that used at the SM-1. In the PM-2A primary system, hydrazine will be added for oxygen scavenging during startup and initial testing. Afterwards, the addition of hydrogen is required to scavenge the oxygen in the presence of a gamma flux. A portion of the water will be continuously withdrawn and passed through a mixed bed demineralizer thus maintaining a specific resistance of 500,000 ohm-cm or greater. Total solids will be kept at 2 ppm and the pH between 6 to 8.

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Chloride concentration will be 0.5 ppm or less and the oxygen concentration is to be maintained at less than 0.03 ppm. In the PM-2A secondary system, sodium sulfite will be added to keep the oxygen level below 0.03 ppm and the pH maintained around 8.5 to 9.5 by addition of morpholine. Chlorides in the steam generator are specified at 0.5 ppm maximum and total solids shall not exceed 80 ppm.

With an Inconel steam generator, primary water treatment would be the same as with a stainless steel steam generator with the exception of hydrazine addition. Since considerable gamma flux would be available from the induced activity in the pressure vessel, core supports, etc., the addition of hydrazine would not have to be continued for the length of time as initial startup. For the secondary system, with an Inconel steam generator, the water treatment would be identical to that used with a stainless steel steam generator. That is, it would consist of the addition of sodium sulfite for oxygen scavenging and morpholine for pH control. However, with an Inconel steam generator, the chloride concentration in the feedwater can be relaxed. At a 1% blowdown rate, a chloride concentration of 1.0 ppm in the feedwater, or 100 ppm in the boiler, would be permissible. Since the feedwater will be melted snow passed through a demineralizer, the chloride content should be well below 1.0 ppm. Thus it may be possible to intermittently blow down the steam generator, when the chlorides exceed 100 ppm or the total solids exceed 1250 ppm. The total solids concentration would be expected to consist primarily of sulfates. The feasibility of running the plant with intermittent blowdown would have to be investigated from the viewpoint of system heat balance before any final recommendations can be made.

The possibility of using the coordinated pH - phosphate treatment for the secondary system was also investigated. This treatment is used in many conventional power plants for water softening.

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ing and corrosion control. Since the PM-2A secondary water is deionized, no hardness would be expected and consequently no softening required. One possible advantage of phosphate treatment is that it can raise the pH of the water to 10-11. A high pH value is thought to inhibit the corrosion of Inconel. However, the data are conflicting and results are not conclusive. (See Appendix, Section 6.3.) Since phosphate does not volatilize, the treatment suffers a major disadvantage in that no pH protection for other parts of the secondary system is afforded. Also close surveillance of water conditions is required, which is not in keeping with process control philosophy of remote reactor plants. Based on the above discussion, the same water treatment is recommended for the PM-2A primary and secondary system with an Inconel steam generator as with a stainless steel steam generator.

A summary of the recommended water treatment and specifications for the PM-2A reactor system with a stainless steel or Inconel steam generator is given in Table 5.1.

TABLE 5.1
SUMMARY OF RECOMMENDED WATER TREATMENT AND SPECIFICATIONS FOR PM-2A

Water Treatment	Stainless Steel Steam Generator		Inconel Steam Generator	
	Primary System	Secondary System	Primary System	Secondary System
Oxygen Control	Hydrazine during startup, hydrogen during operation.	Sodium sulfite	Hydrazine during startup*, hydrogen during operation.	Sodium sulfite
pH Control	maintained around neutral by mixed bed demineralizer	morpholine	maintained around neutral by mixed bed demineralizer	morpholine

Water Specifications		Inconel Steam Generator	
pH	6.0 - 8.0	8.5 - 9.5 in steam generator 8.5 - 9.0 in condenser	8.5 - 9.5 in steam generator 8.5 - 9.5 in condenser
Oxygen	0.03 ppm max.	0.03 ppm max.	0.03 ppm max.
Chloride	0.5 ppm max.	0.5 ppm max. in steam generator	100.0 ppm max. in steam generator
Hydrogen	15 - 30 cc/kg of water		
Total Solids	2 ppm max.	80 ppm max. in steam generator	1250 ppm max. in steam generator

* Since considerable gamma flux will be available from induced activity in the pressure vessel, core supports, etc., hydrazine addition should not have to be continued for the length of time as initial startup with stainless steel steam generator.

6.0 APPENDIX

5.1 Equations for Activity Arising from Out-of-Flux Areas

The following equations describe the mechanism set forth in Section 3.2.

Let:

$$\frac{d\phi}{dt} = a \quad (1)$$

$$\frac{dM_c}{dt} = S a c f_s f_p J_{\phi\phi} - \lambda N_c \quad (2)$$

$$\frac{dN'}{dt} = \frac{S}{V} \frac{dM_c}{dt} - (\lambda + a + D A_0) N' \quad (3)$$

$$\frac{dN''}{dt} = D V N' - \lambda N'' \quad (4)$$

where: S = corrosion product (crud) film thickness on core. (Assumed equal to thickness found on SM-1 out-of-core surfaces), atoms/cm²

M_c = total number of radioactive atoms in crud deposited on core, atoms

N' = number of radioactive atoms in primary coolant, atoms/cm³

N'' = number of radioactive atoms deposited on out-of-core system surfaces, atoms/cm²

A_c = in-core area exposed to neutron flux, cm²

A_o = out-of-core area exposed to primary coolant, cm²

a = rate of buildup of crud thickness on core surfaces found from experimental data and approximated by a constant, atoms/cm²-sec

f_s = fractional abundance of chemical element in system material, weight fraction

f_n = fractional abundance of target nuclide in chemical element, weight fraction

$$\Sigma\phi = \sigma_{th}\phi_{th} + \sigma_{fe}\phi_{fe}$$

where: σ_{th} = thermal cross section

ϕ_{th} = weighted thermal flux

σ_{fe} = effective cross section for effective fast flux (resonance integral)

ϕ_{fe} = weighted effective fast flux

The above applies for (n,γ) reactions. For (n,p) reactions, $\Sigma\phi$ is equal to the product of the fast flux, ϕ_f and the effective cross section, σ_{eff} .

λ = decay constant of N, sec⁻¹

g = fraction of crud deposited on core that is released to the coolant. (Assumed equal to one, since in calculating the activity due to in-core corrosion, the amount released is taken equal to the amount corroded. See Section 6.2.)

V = total volume of primary coolant, cm³

a = purification constant, equals purification rate to demineralizer divided by system volume, sec⁻¹

D = deposition probability that one of the active nuclides carried by the coolant will deposit on a surface, 1/cm² - sec.

Equation (1) describes the crud film thickness buildup on the core. The value of "a" was found from the crud film buildup on metal test specimens inserted in the SM-1 purification system. The buildup on the test specimens agreed well with the buildup found on the steam generator baffle plate. Although the buildup curve is not a straight line, it was assumed to be straight and hence the rate is a constant. It is not known whether the crud film builds up in-core at the same rate as out-of-core, but as an approximation it was so assumed. Equation (2) describes the activation of atoms in the crud and their loss by decay. All areas exposed to neutron

flux were included in the area of the core and a weighted flux corresponding to this area was calculated. The term $\Sigma\phi$ includes the contribution of the effective fast flux for (n, γ) reactions. Thermal cross sections were corrected for Maxwell-Boltzmann distribution and temperature. For (n, p) reactions, the fast flux and the effective cross section, based on experimental measurements was used. (6) The effect of thermal neutron flux for (n, p) reactions is neglected. Equation (3) is the change in concentration of the nuclides in the primary water. The first term is the change in concentration by release of the nuclides activated in the crud film. The second term is the loss by deposition on out-of-core walls, decay and the purification system. Equation (4) describes the increase in concentration of the nuclides deposited on the walls; the first term is the increase by deposition from the cor-lant and the second term is the loss by decay.

The value of D was found in the following manner. Calculated values for the activity observed in the SM-1 were closely dependent upon the value of the ratio (5),

$$\frac{\alpha}{\alpha + DA_0}$$

where: α = purification rate

A_0 = out-of-core area

D = deposition probability.

For the SM-1, a value of 0.46 for the ratio gave values which best agreed with the experimental data. Since the values of α and A_0 are known, a value of D was calculated for the PM-2A.

The solution to the equations are:

$$S = \alpha t$$

$$Nc = \frac{B}{2} (\lambda t - 1 + e^{-\lambda t}) \quad (1a)$$

$$Nc = \frac{B}{2} (\lambda t - 1 + e^{-\lambda t}) \quad (2a)$$

where $B = Ac f_{gn} \Sigma \phi a$

$$N' = \frac{GB}{V\lambda} \left[\frac{1 - e^{-Rt}}{R} + \frac{e^{-Rt} - e^{-\lambda t}}{R - \lambda} \right] \quad (3a)$$

Where: $R = DA_0 + \alpha + \lambda$

$$N'' = \frac{DGB}{\lambda} \left[\frac{1 - e^{-\lambda t}}{R - \lambda} + \frac{e^{-Rt} - e^{-\lambda t}}{(R - \lambda)(\lambda - \alpha)} + \frac{e^{-\lambda t} - e^{-Rt}}{R(\lambda - \alpha)} - \frac{e^{-\lambda t}}{(R - \lambda)} \right] \quad (4a)$$

Values of constants for the PM-2A are listed below:

a	$= 1.56 \times 10^{11}$ atoms/cm ² -sec
A_0	$= 8.04 \times 10^5$ cm ²
Ac	$= 7.0 \times 10^5$ cm ²
D	$= 4.06 \times 10^{-11}$ 1/cm ² -sec
α	$= 2.78 \times 10^{-5}$ sec ⁻¹
V	$= 2.35 \times 10^6$ cm ³
ϕ_{th}	$= 1.90 \times 10^{13}$ neutrons/cm ² -sec
ϕ_f	$= 1.19 \times 10^{14}$ neutrons/cm ² -sec
ϕ_{fe}	$= 7.7 \times 10^{12}$ neutrons/cm ² -sec

Activation reactions considered and their constants are shown in Table 6.1.

TABLE 6.1

ACTIVATION REACTION CONSTANTS

Reaction	λ (sec ⁻¹)	$\phi_{th} \times 10^{24}$	$\phi_f \times 10^{24}$	ϕ_{fe}
Fe ⁵⁸ (n, γ)Fe ⁵⁹	1.74×10^{-7}	0.6	13.0	-
Co ⁵⁹ (n, γ)Co ⁶⁰	4.17×10^{-9}	28.1	49.3	-
Ni ⁵⁸ (n, p)Co ⁵⁸	1.13×10^{-7}	-	-	0.096
Fe ⁵⁴ (n, p)Mn ⁵⁴	2.55×10^{-8}	-	-	0.060

Values for f_{gn} for Inconel and stainless steel are shown in Table 6.2

TABLE 6.2

VALUES FOR PRODUCT OF f_s AND f_n

Reaction	Stainless	Inconel
Fe ⁵⁸ (n,γ)Fe ⁵⁹	1.66×10^{-3}	1.91×10^{-4}
Co ⁵⁹ (n,γ)Co ⁶⁰	3.70×10^{-4}	3.70×10^{-4}
Ni ⁵⁸ (n,p)Co ⁵⁸	5.00×10^{-2}	3.97×10^{-1}
Fe ⁵⁴ (n,p)Mn ⁵⁴	2.97×10^{-2}	3.40×10^{-3}

The expected oxide form for each nuclide was assumed in calculating the product, f_s , f_n . Each nuclide was considered to corrode in the same proportion as that found in the base metal. Data at the SM-1 indicates this is valid for nuclides under consideration. The activation of chromium was not included, since it apparently does not release to any significant degree, and its low gamma energy and type of decay does not produce a principal radiation source.

6.2 Equations for Activity Arising From In-Flux Areas

The following equations, based on the mechanisms proposed in Section 3.3, describe the activity due to in-core corrosion of the PM-2A (ref.).

$$\frac{dN_s}{dt} = PZ\sigma\phi - \lambda N_s \quad (5)$$

$$\frac{dN'}{dt} = \frac{C A_c P Z}{VH} - (DA_0 + \lambda N')N' \quad (6)$$

$$\frac{dN''}{dt} = DVN' - \lambda N'' \quad (7)$$

where: P = atomic concentration of the parent of N in steel, atoms/cm³

H = atomic concentration of all elements in steel, atoms/cm³

N_s = atomic concentration of the active nuclide in steel, atoms/cm³

C = corrosion release rate of stainless steel. The re-

lease rate was assumed equal to the corrosion rate, atoms/cm²-sec. (The corrosion rate was approximated by a constant, based on data obtained at the SM-1).

All other terms are as listed in Section 6.1.

Equation (5) describes the buildup of active nuclides within the steel of the fuel element. The fluxes were weighted over the area exposed to a significant number of neutrons, including thermal shields and pressure vessel walls. Appropriate fluxes and cross sections were used as explained previously. Equation (6) describes the increase in concentration of the nuclide in the primary water. The first term is the increase by corrosion release of the nuclides and the second term describes the loss by deposition on the walls, purification system, and decay. Equation (7) describes the increase in concentration of the deposited nuclides on the walls. The first term is the increase by deposition from the water and the second term is the loss by decay.

The solutions of the equations are:

$$N_s = \frac{PZ\sigma\phi}{\lambda} (1 - e^{-\lambda t}) \quad (5a)$$

$$N' = \frac{C A_c P Z}{VH} \left[\frac{(1 - e^{-\lambda t})}{\lambda} + \frac{(e^{-Rt} - e^{-\lambda t})}{(R - \lambda)} \right] \quad (6a)$$

$$N'' = DQ \left[\frac{(1 - e^{-\lambda t})}{\lambda} + \frac{(e^{-Rt} - e^{-\lambda t})}{(R - \lambda)(\lambda - R)} + \frac{(e^{-\lambda t} - e^{-Rt})}{R(\lambda - R)} - \frac{(e^{-\lambda t})}{(R - \lambda)} \right] \quad (7a)$$

where $R = (DA_0 + \alpha + \lambda)$

$$Q = \frac{A_c C f_s f_n P Z \sigma \phi}{\lambda} \quad (\text{since } \frac{P}{H} = f_s f_n)$$

Activation reactions considered and their constants are the same as those used for out-of-flux activity given in Section 6.1. Values used for the product (f_s , f_n) for the stainless steel core are given in Table 6.3.

TABLE 6.3

VALUES FOR PRODUCT OF f_s AND f_n FOR STAINLESS STEEL

Reaction	Value
Fe58 (n, γ) Fe59	2.29×10^{-3}
Co59 (n, γ) Co60	2.00×10^{-5}
Ni58 (n,p) Co58	6.44×10^{-2}
Fe54 (n,p) Mn54	4.12×10^{-2}

Values for f_s , f_n were obtained by assuming each element is released to the coolant in the same proportion as found in the base metal. Values for the other constants are the same as listed in Section 6.1. The value used for C was 1.73×10^{11} atoms/cm²-sec.

6.3 Inconel Corrosion Data

Data on the corrosion of Inconel in reactor grade water at elevated temperatures and neutral pH is limited. Battelle Memorial Institute reports a corrosion rate of less than 12 mg/dm² per month in 650°F primary water at 25 feet per second, and a corrosion rate of 10 mg/dm² per month in 550°F primary water at 28 feet per second. (1,2) In these tests, the primary water was made up from demineralized water of 750,000 ohm-cm resistivity to which had been added 2 to 4 ppm NH₃, with a resulting pH of 8.9 to 9.5. Hydrogen was maintained between 15 and 50 cc/kg of water and the oxygen content was less than 0.02 ppm. Other investigators (7) report a corrosion rate less than Type 304 SS in 550°F reactor grade lithiated water at a pH of 9.5 to 10.5. No difference was noted between a water velocity of 15 feet per second and 30 feet per second. Oxygen content was maintained at less than 0.1 ppm.

Data obtained from Inconel test specimens inserted in the primary purification line of the SM-1 L. P. is listed in Table 6.4.

TABLE 6.4

DESCALED WEIGHT LOSS OF INCONEL SPECIMENS EXPOSED TO SM-1 PRIMARY COOLANT

Sample No.	Exposure Time (hours)	Weight Loss (mg/dm ²)
I-1-7	493	1.5
I-1-1	857	0.0
I-1-12	1267	7.3
I-1-15	1365	5.8
I-1-3	2730	11.2
I-1-2	4995	14.6

By graphing the descaled weight loss versus time, the corrosion rate at 5000 hours was found to be approximately 2 mg/dm² per month. The Inconel specimens were exposed to reactor grade water at 420°F and pH 7.0 to 8.0. Oxygen content was usually below 0.01 ppm. The apparent lower corrosion rate found from SM-1 data compared to that found by other investigators could be due to several factors: the effect of pH, coolant temperature, coolant velocity, or oxygen content. Also, since the corrosion rates are very low, the difference could be accounted for by statistical error, methods of sampling, or limited number of samples.

The coolant of the PM-2A will be reactor grade water at 510°F and pH 7.0 to 8.0. Because of the higher temperature and the uncertainty of available Inconel corrosion data, it was assumed in this study that Inconel corrodes and is released at the same rate as Type 304 stainless steel.

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