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ACTIVATION PRODUCT TRANSPORT IN FUSION REACTORS

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Activated corrosion and neutron sputtering products will enter the coolant and/or tritium breeding material of fusion reactor power plants and experiments and cause personnel access problems. Radiation levels around plant components due to these products will cause difficulties with maintenance and repair operations throughout the plant. A computer code, RAPTOR, has been developed to determine the transport of these products in fusion reactor coolant/tritium breeding materials. Without special treatment, it is likely that fusion reactor power plant operators could experience dose rates as high as 8 rem per hour around a number of plant components after only a few years of operation.

1. INTRODUCTION

Radiation exposure to personnel operating future fusion experiments and power plants will need to be considered as these devices are planned and operated. The generation and transport of radioactive corrosion and neutron sputtering products in the heat transfer/tritium breeding fluid of these reactors could be a source of considerable occupational radiation exposure. By keeping the radiation levels around the plant to reasonable levels, it is possible that some of the routine maintenance can be completed in a "hands on" fashion rather than remotely.

Easterly has discussed some of the requirements that fusion reactor designs should meet in order that the occupational radiation exposures could be considered acceptable.[1] The present work involves the estimation of the radiation fields around the fusion reactor plant components due to the corrosion and neutron sputtering products.

2. CALCULATIONAL MODEL

The computer code RAPTOR has been written to assess the transport and activation of corrosion and neutron sputtering products throughout the heat transfer and tritium breeding loops of fusion devices. It determines the amount of mass transfer in a loop based upon the characteristics of the particular system to be modeled and is presently capable of calculating the transport of material in water and liquid lithium-lead eutectics.

A general description of the theory of corrosion product generation, dispersion, and transport was proposed by Bartlett.[2] Such a treatment attempts to include all of the processes involved in the transfer of material in the heat transfer/tritium breeding fluid, and leads to a considerable amount of complexity. However, by imposing reasonable physical constraints, and by estimating some of the transfer processes, it is possible to reduce the difficulty of the problem.

A number of assumptions are included in the RAPTOR computer code. First, it is assumed that the coolant is completely mixed and that variations in the concentration of activation and corrosion products around the loop are negligible. Second, the assumption is made

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that the concentrations are so small as to have no effect on the fluid flow characteristics, neutron fluxes, or the heat transfer properties of the system. Also, only first order nuclear reactions are assumed. Higher order reactions only increase the amount of activation products slightly, and are therefore neglected. In this way, production reactions are modeled individually, necessitating the calculation of each one of the important nuclear reactions independently. Table 1 lists the reactions considered.

After material is released from the various plant components into the coolant/tritium breeding fluid it is subject to a number of transport processes. It is possible that each species in the fluid could deposit on component surfaces throughout the loop, form agglomerates with other particles, or be removed by the purification system. Stable isotopes in the blanket walls, entrained in the fluid, or deposited in the blanket region can undergo a nuclear reaction and become radioactive. Deposits in the system can also be released into the fluid, and the decay of radioactive material will constantly remove material from consideration by the model.

Once all of the processes involved in the transport of the activation products are defined, mass balance equations can be written to describe the concentrations of material in the fluid and deposited throughout the system. The deposits on each component are treated separately and each nuclear reaction requires individual attention. The complete balance equations can be seen in reference 3. The process of corrosion product generation and release, deposition, erosion, activation, decay, particle agglomeration, and removal by the purification system are treated with transfer coefficients. In most cases, and especially during steady state operation, these coefficients will be independent of time. Then, the numerous equations can be combined into a matrix notation of the form

$$\frac{d\vec{M}(t)}{dt} = \underset{\sim}{A}\vec{M}(t) + \vec{S}(t) \qquad (1)$$

where the concentration and deposit vector, $\vec{M}(t)$, includes all of the radioactive and stable concentrations of solubles and particles in the fluid as well as the amounts of radioactive and stable material deposited throughout the system. $\vec{S}(t)$ is a vector containing both the corrosion and neutron sputtering sources of material into the fluid. The transfer matrix, $\underset{\sim}{A}$, includes the various transfer coefficients, i.e. deposition, erosion, activation, decay, and removal by the purification system.

TABLE 1
Activation Products Considered by RAPTOR

Formation Reaction	Activation Product	Half-life	Gamma Energies (MeV)
^{59}Co(n,γ) ^{60}Ni(n,p)	^{60}Co	5.26 y	1.173, 1.332
^{58}Ni(n,p) ^{59}Co(n,2n)	^{58}Co	71.3 d	0.511, 0.81, 0.865, 1.67
^{54}Fe(n,p) ^{55}Mn(n,2n)	^{54}Mn	303 d	0.835
^{50}Cr(n,γ) ^{52}Cr(n,2n) ^{54}Fe(n,α)	^{51}Cr	27.8 d	0.32
^{55}Mn(n,γ)	^{56}Mn	2.6 h	0.847, 1.811 2.11
^{58}Fe(n,γ) ^{59}Co(n,p)	^{59}Fe	45.6 d	0.143, 0.192 1.095, 1.292
^{64}Ni(n,γ)	^{65}Ni	2.6 h	0.368, 1.115 1.481
^{92}Mo(n,γ)	^{93}Mo	6.9 h	0.264, 0.685 1.479
^{98}Mo(n,γ)	^{99}Mo	66.7 h	0.181, 0.372 0.74, 0.78

Data and correlations for the source terms and transfer coefficients have been assembled from a number of sources. The corrosion release source terms for water have been taken from Berry[4] and Cohen.[5] Recent data on the corrosion and weight loss of various reactor structural materials by liquid lithium-lead have been used.[6-8] The coefficients for deposition and erosion processes have been calculated using the work of Beal.[9,10] Additionally, the reaction cross sections were taken from the decay chain data library used in the fusion reactor activation calculations[11] and the decay data is from Lederer.[12]

The matrix equation above is solved using a matrix operator method developed by Lee using the principle of the multiplicative integral.[13] This procedure has been shown to be effective in calculations involving systems of linear differential equations such as equation 1.

After the concentrations and deposits have been determined as a function of time the dose rates around the plant components due to these activation products can be calculated using the MCNP Monte Carlo neutron/photon transport code.[14] This is done by taking the results from RAPTOR and determining the specific gamma radiations emitted from the system at each particular point of interest. This is then imput into MCNP, along with the details of the component geometry, to determine the photon fluxes at various points. These can then be used with photon flux to dose conversion factors to calculate the dose rates.

3. RESULTS

The RAPTOR computer code has been utilized to estimate the effects of activation product transport on fusion reactor designs. Because of the detailed input required, it is necessary that the reactor coolant/tritium breeding system be well defined. Two conceptual reactor designs completed recently meet this criteria, MARS and STARFIRE.[15,16]

For the MARS design, the lithium-lead heat transfer/tritium breeding loop was broken into 15 nodes, each representing a component or portion of the system. Admittedly, such a model cannot accurately treat each separate component, pipe bend, and any other special flow condition which may cause localized depositions, and therefore radiation hot spots. Also, RAPTOR makes no attempt to treat the activation of the LiPb itself. However, it can estimate the global distribution of the corrosion and activation products throughout the plant. Once each system node is described in terms of its specific characteristics, including flow rate, flow velocity, temperature, etc., then the RAPTOR code can be run to determine the activation product transport.

After only 35 months of full power operation the contact dose rates for the uninsulated MARS hot leg pipe are found to be over 7 rem per hour if the LiPb has been drained from the pipe. Such dose rates are too high to allow contact maintenance to be performed close to these pipes. It has also been found that if the LiPb is not drained, then the contact dose rates are one half of the empty pipe values due to shielding by the LiPb. Figure 1 shows the buildup of these radiation levels as a function of the time of operation. These dose rates are very high for such a short time after the initial startup because of the very high corrosion release rates for the ferritic steel HT-9 into the LiPb. The majority of the gamma rays released from the deposits are found to be due to Mn^{54} (0.835 MeV γ, 303 day half-life) which has been formed by $Fe^{54}(n,p)Mn^{54}$ reactions in the blanket. This is then released into the LiPb fluid to be deposited throughout the primary system. Other important radiations emanate from Cr^{51}, Co^{58}, and Co^{60}. It has been found that the fraction of Co^{60} in the system increases significantly over time, and after a number of years could pose a considerable hazard.

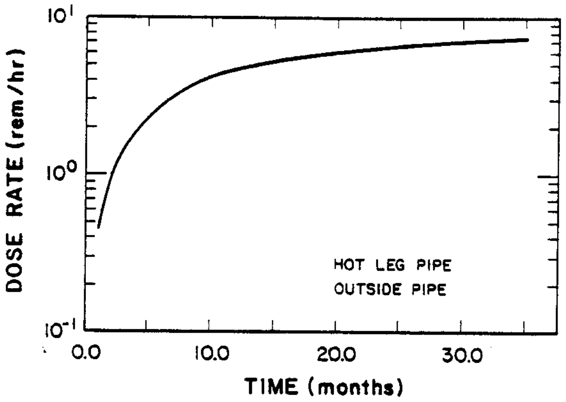

FIGURE 1
MARS Dose Rate vs. Time

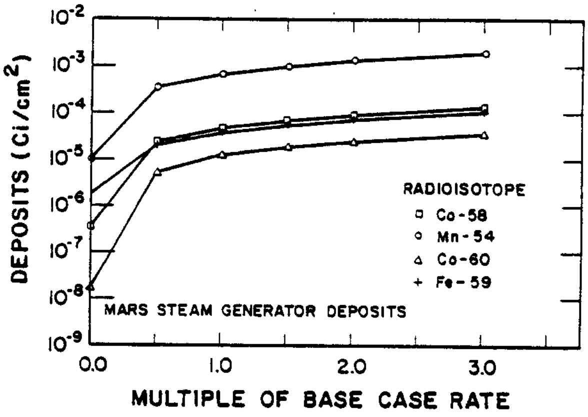

FIGURE 2
Blanket Release Rate Variation

While some of the activation products which deposit throughout the system originate in the base material of components outside of the blanket and first wall which becomes radioactive as it passes through the neutron flux, the majority of these products originate in the blanket and first wall. This can be seen in Figure 2. If no material were to be released from the HT-9 surfaces in the blanket into the LiPb, then at least an order of magnitude decrease in the deposits and therefore the dose rates could be achieved. This provides an incentive for finding methods which will reduce the amount of material transferred from the HT-9 surfaces to the LiPb. It would also be possible to reduce the amount of deposited material by aggressively purifying the LiPb.

The STARFIRE reactor design uses pressurized water as the heat transfer fluid. This loop has been broken into 20 nodes for the RAPTOR calculations. The contact dose rates calculated around the primary system components are found to be comparable with those levels found in present day pressurized water reactors. After roughly 15 months of full power operation it is observed that the dose rates are about 65 mrem/hr outside of the hot leg pipe, about 850 mrem/hr around the steam generators, and the dominant radiations are due to the decay of Co^{58}. This is produced mainly by (n,p) reaction of the Ni^{58} which is released from the Inconel 600 steam generator tubes and deposits in the blanket; it then undergoes the (n,p) reaction and then the Co^{58} is released into the coolant stream to be deposited elsewhere in the system. In contrast, much of the Co^{60} and Mn^{54} which is deposited around the system originates in the blanket piping. Table 2 lists the specific deposits found for a few STARFIRE plant components.

4. CONCLUSIONS

The computer code RAPTOR has been written to assess the buildup of radiation fields around fusion reactor plant components due to the transport and activation of corrosion and neutron sputtering products in the coolant/tritium breeding fluid. It has been tested and applied on the conceptual fusion reactor designs MARS and STARFIRE, and has been benchmarked using data from the Kewaunee Nuclear Power Plant. Because the corrosion release

TABLE 2
Radioactive Deposits in Starfire
Primary System

Component	Deposits (Curies per cm^2) Co^{58}	Co^{60}	Mn^{54}
Steam Generator	1.1-05	2.5-07	2.3-06
Hot Leg Pipe	8.1-06	1.7-07	1.5-06
Cold Leg Pipe	8.0-06	1.6-07	1.5-06
Pipe to Purification System	8.4-07	6.2-08	4.4-07
Blanket	9.1-06	1.7-07	1.5-06
First Wall	1.1-04	8.8-07	4.2-06

rate for HT-9 into the LiPb system of MARS is very high, special treatment will be required to be able to keep the radiation exposure to personnel as low as possible. Results found for STARFIRE indicate similar radiation fields as those found in present PWR systems.

Due to the possibility of high radiation fields around the primary system components in fusion reactors due to activation product transport it may be necessary to consider low activation structural materials, materials which are very corrosion resistant in the blanket regions, or to develop remote maintenance techniques to eliminate the necessity for any hands on maintenance. Any combination of the above methods could greatly reduce the radiation exposure of plant personnel.

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