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Safety Analysis on the Tritium Release Accidents

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Abstract

At the design stage of a plant, the plausible causes and pathways of release of hazardous materials are not clearly known. Thus there exist large amount of uncertainties on the consequences resulting from the operation of a fusion plant. In order to better handle such uncertain circumstances, we utilize the Probabilistic Risk Assessment(PRA) for the safety analyses on fusion power plant.

In this paper, we concentrate on the tritium release accident. We develop a simple model that describes the process and flow of tritium, by which we figure out the locations of tritium inventory and their vulnerability.

We construct event tree models that lead to various levels of tritium release from abnormal initiating events. Branch parameters on the event tree are assessed from the fault tree analysis. Based on the event tree models we construct influence diagram models which are more useful for the parameter updating and analysis. We briefly discuss the parameter updating scheme, and finally develop the methodology to obtain the predictive distribution of consequences resulting from the operating a fusion power plant. We also discuss the way to utilize the results of testing on sub—systems to reduce the uncertainties on over all system.

Introduction

During operation of fusion power plants, the potential for exposure of workers and public to radioac-

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tive hazard will exist. Ionizing radiation is anticipated to be the most prevalent hazard. Sources of ionizing radiation include tritium, and neutron activation products in the structure materials. We are primarily interested in the analyses of the tritium release accidents because, except in the case of extreme accidents involving major structure destruction, tritium poses a dominant hazard.

Fuel cycle activities and handling of tritium contaminated materials could result in release of tritium to the environment. Mechanisms for tritium release have been identified as routine leaks from imperfect fluid system connections, valves and pumps, permeation through pipes and vessel walls, and accidental leaks. Only the accidental leaks will be examined here.

The process of the safety analysis adopted this paper is depicted in Figure 1. Since the safety analysis must be performed with an understanding of the physics and engineering of the fusion plant we firstly describe the fusion plant with a simple model that concentrates on the flow and process of tritium. The potential for tritium release is directly related to the tritium inventory and tritium flow rates through the plant. So the next step is the assessment of tritium inventory and vulnerability at various locations. Third step is the Probabilistic Risk Assessment(PRA). We construct event tree models that lead to various levels of tritium release from abnormal initiating events. Branch parameters on the event tree are assessed from the fault tree analysis. Based on the event tree models we construct influence disagram models which are more useful for the parameter updating and analysis. We briefly discuss the parameter updating scheme, and finally develop the methodology to obtain the predictive distribution of consequences resulting from the operating a fusion power plant.

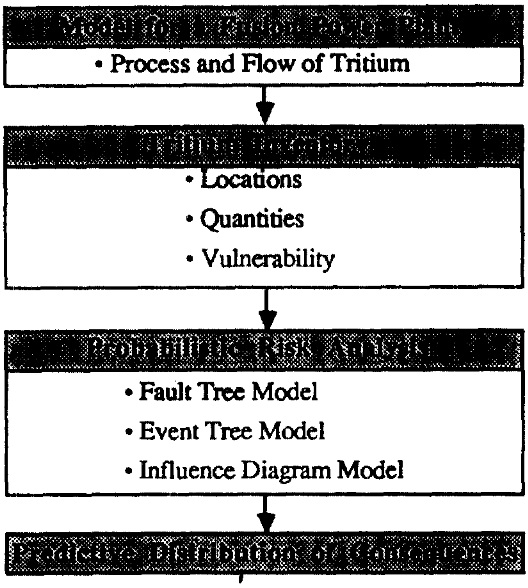
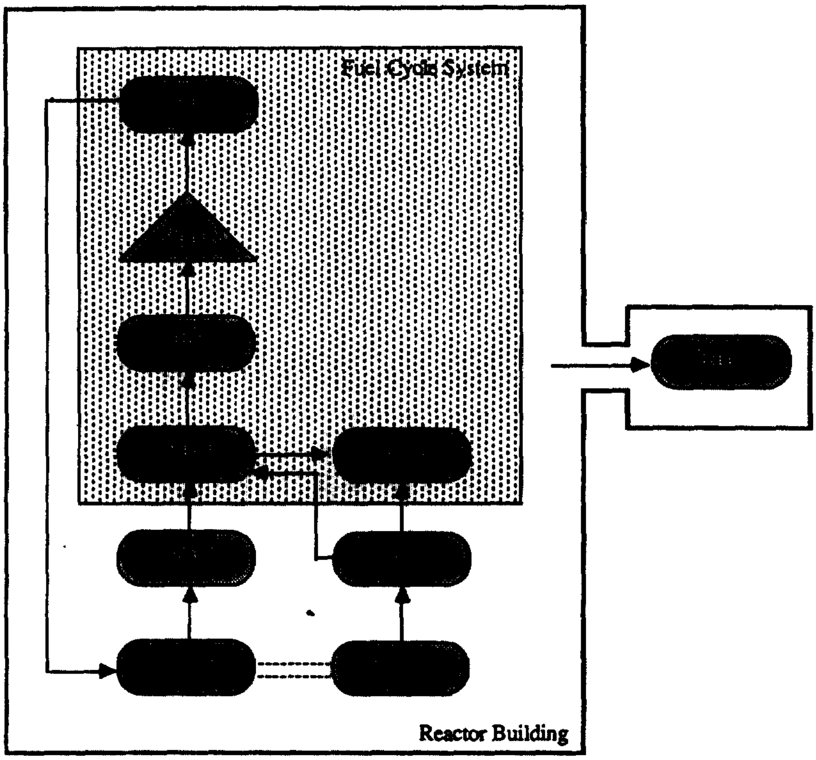


Figure 1 : Process of Safety Analysis on Tritium Release Accident

Model for a Tritium Flow

The fusion reactor consists of the plasma chamber, the vacuum system, the coolant system, the fuel cycle system, blanket tritium recovery system, and emergency tritium cleanup system. The fuel cycle system includes the fuel clenup system, the isotope separation system, fuel storage, fuel injection system, and the tritium waste treatment system. Figure 2 shows the process and flow of tritium.

Burnt agses are removed from the plasma chamber by the vacuum system. This system consists of a large vacuum vessel with associated ducts that lead to the vacuum pump. This system must be capable of reaching and maintaining very low pressure and must offer a very large pumping capacity. Compound cryopumps are well suited to this operation.



VAC : Vacuum pump
BTR : Blanket Tritium Recovery
FCU : Fuel cleanup
ISS : Isotope separation
FIJ : Fuel Injection
TWT : Tritium waste treatment

Figure 2 : Tritium Flow

The fuel clean up system removes impurities in preparation for the isotope separation system. The gas stream evacuated from the torus includes helium, along with gaseous impurities. Helium is initially separated from the other gases at the compound cryopumps. The mixture of hydrogen isotopes and impurities is passed through several chemical processes so that the impurities can be removed. Once the impurities are removed, a relatively pure mixture of hydrogen isotopes is delivered to the isotope separation system.

The isotope separation system separates the hydrogen isotope stream. Cryogenic fractional distillation seems to be well suited for this task.

Once separated, the fuel constituents can be stored until they are needed. Storage is required for both the short term to smooth out supply and demand transients and for the long term to provide fuel for reactor operation in the event that the upstream fuel system is non−operable.

Fuel is provided to the plasma chamber by the fuel injection system such as puffing, pellet injection or a combination of these.

The blanket tritium recovery system recovers the tritium bred in the blanket. For the liquid lithium breeder, a molten salt extraction process is considered to be attractive for removing the tritium.

Effluents form various systems may retain quantities of tritium which are uneconomical to recover, but are too high to release directly to the environment. Tritium waste treatment system provides routine processing of all gaseous effluents generated within the plant to reduce tritium to acceptable levels before they are discharged to the environment.

Emergency tritium cleanup (ETC) system removes airborne tritium from the reactor building, the fuel processing building and all secondary enclosures internal to these buildings. ETC system detritiates room air based on a precious metal catalytic recombiner where hydrogen isotopes are oxidized to water. The water is collected, partly as liquid water and partly by adsorption on molecular sieve beds. The effective tritium removal depends on the effciency of the recombiner, the efficiency of the molecular sieve and the leak tightness of the reactor hall.

Tritium Inventory and Vulnerability

The tritium inventories are classified as vulnerable and nonvulnerable depending on their likelihood of release. If the probability of release of tritium in a system is greater than 10^{-6}per reactor year, we call the tritium is vulnerable.

The quantity of tritium found in the plasma chamber during operation of the reaction is simply the product of the average tritium density and the plasma volume. The amount of tritium contained in the torus at a given time is not large. But this inventory is classified as vulnerable since breach of containment would allow for the immediate release of the tritium inventory.

The tritium inventory in the cryopumps depends on the tritium exhaust rate from the torus and the regeneration period. The tritium in vacuum pumps can be affected by accidents and failures of other components because these pumps are close to the torus. The ingress of air into torus, and hence into vacuum system, or loss of liquid-helium cooling to the pumps would cause tritium release. Thus the tritium inventory in the cryopumps is considered as vulnerable.

The tritium inventory in the breeding blanket is established from neutron interactions with lithium. The inventory in the blanket is considered as vulnerable since the possibility for the liquid metal to drain from the reactor and release its tritium inventory after some accident scenarios exists.

The blanket structure contains tritium inventory becasus of tritium implantation and permeation. Tritium implantation is dependent upon the tritium flux impinging on the first wall and the first wall condition. Tritium permeation is a function of the permeability and thickness of the metal involved. The diffusion rates of tritium in meatls are fairly high, thus possible thermal transients could "bake—out" the tritium in a short period of time. Tritium contained in the structure is designated as vulnerable.

The coolant system presents another potential source for tritium release. Tritium can permeate or leak from the plasma through the first wall or from the blanket into the coolant system. This is also classified as vulnerable.

The tritium inventories in fuel cleanup system, isotope separation system, tritium waste treatment system, and fuel storage are classified as non—vulnerable because of multiple containment used and/or high reliability of components.

We pay attention only to the vulnerable tritium inventories because the probability of release of non—vulnerable tritium is assumed to be negligible. Table 1 summarizes the vulnerable tritium inventory at various locations.

Locations	Amount(g)
Plasma chamber	0.55
VAC	133
breeder/BTR	310
blanket structure/coolant	14
FIJ	90

Total Vulnerable Inventory(g) = 547

Total Vulnerable Inventory (Mci) = 5.25

Table 1 : The Vulnerable Tritium Inventory

If an abnormal initiating event occurs, various amount of tritium inventories may be released depending on success or failure of safety features that are supposed to mitigate the consequences of initiating events. The major safety features include system shut down, secondary enclosure, and ETC system. Secondary enclosures include double-wall piping and components, glove boxes, a large enclosure for enclosing the vacuum system, and integral vacuum jacket around cryogenic components, etc. Reactor building itself can be considered as the final defensive system from the public safety point of view. But only with the failure of the three major safety features mentioned above, the workers will be very severely damaged and it is anticipated that fairly large amount of tritium will be released to the environment. Thus we include only three major safety features in further discussion.

Figure 3 is an event tree that shows the sequences of accidents leading to various levels of tritium release from an initiating event. λ denotes the probability of secondary enclosure failure, and π_3 denotes the probability of failure of system shutdown, π_2 denotes the probability of secondary enclosure failure, and π_1 denotes the probability of ETC system failure. We call these branch parameters and usually estimate them using the fault tree analysis. $m_K = m_K(0, T)$ denotes the counts of accident of sequence k from an initiating event in time period $(0, T)$, which is enumerated from the bottom of the event tree. Possible initiating events and related frequencies are listed in table 2.

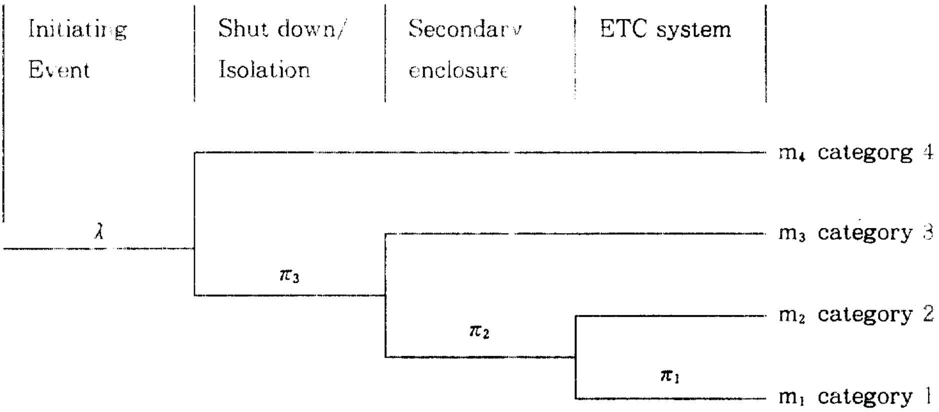


Figure 3: Event Tree for Tritium Release Incidents

The incidents of different sequences are classified into four categories depending on the magnitude of the tritium released; category 1, 2, 3, and 4 are classified according to the descending order of the magnitude of the tritium released. We introduce another classification of incidents: level 1, level 2, level 3, and levle 4. Level 1 incidents consist of category 1 incidents, leve j incidents consist of level $j-1$ incidents and category j incidents, $j=2, 3, 4$. Thus level j incident is a subset of level i incidents for $i>$.

Initiating Events	Frequency(per year)
VAC system cryopump leakage	$7.0 \times 10.^{-1}$
FCU system component leakage/rupture	6.0tan10.−2
FCU system — loss of temperature control	3.0×10^{-1}
FCU system valve incorrectly opened to TWT system	2.0×10^{-3}
ISS process line leadage/rupture into vacuum jacket	2.0×10^{-2}
ISS process line leakage/rupture into glove box	3.0×10^{-1}
ISS uranium bed stainless steel block fails	$6.0 \times 10.^{-5}$
TWT system component leakage/rupture into vacuum jacket	4.0×10^{-2}
LOCA inside/outside vacuum vessel	
LOFA(Loss of Coolant Flow Accident)	

Table 2: Initiating Events

The event tree model in figure 3 can be expressed by a statistically equivalent influence diagram(ID) as in figure 4. Some advantages of using influence diagrams over event trees are demonstrated in R.M. Oliver and H.J.Yang 1990.

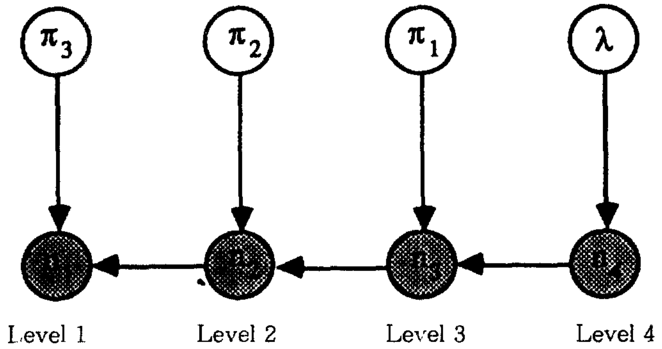


Figure 4: An Influence Diagram of the Event Tree in Figure 3

For the simplicity of notation, we use n_j to denote the count of level j incidents in time interval (0, T), which is obtained by

$$n_j = \sum_{k=1}^{j} m_K$$

In the influence diagrams of this paper nodes denote random variables and directed arcs denote the fact that a conditional probability of the node at the arrow head need only be assessed in terms of its direct predecessor nodes. We follow a convention used earlier:unshaded nodes containing Greek letters denote unobservable parameters that influence the observable counts of events, which are denoted by shaded nodes. Form the influence diagram model in Figure 4, it is clear how an initiating event escalates to more severe incidents. The initiating event occurs with the rate λ. This incident escalates to more severe one if we fail to shutdown system with probability π_3. Similar escalation process is repeated. One important point to note is that the number of level 4 incidents are influenced by λ only and the number of level j incidents are influenced by the number of level j+1 incidents and π_j only, $j=1, 2, 3$. In other words, the number of level j incidents conditional on the counts of level j+1 incidents and corresponding branch parameter are independent of all other parameters and counts. Therefore the escalation process from low severity incidents to high severity accidents, and the dependencies/independencies among random quantities become clear with the use of influence diagram. The information of conditional dependencies simplifies further analysis pretty much, especially parameter updating scheme. We can expand the model in Figure 4 in order to take care of the hazard to the public. Figure 5 is the expanded model. We assume that the amount of tritium release by each category of accident is deterministic so that the amount of tritium release, R, is obtained by

$$R=\sum_{j=1}^{4} h_j m_j \ I$$

where I is the total amount of tritium inventory in a system under consideration, and h_j is the fraction of tritium inventory that will be released by category j accident. The assessment of the amount of tritium release by each category accidents needs more analysis with the consideration of the efficiency of each safety feature. Some random factors, such as weather condition, density of population, location of plant, etc., are involved in assessing the consequences resulting from the tritium release in time period (0, T), C=C(0, T). The node W denotes these random factors.

The predictive distribution of the consequence in future time interval(T, T+$\triangle$T), $\triangle C=\triangle C(T, T+\triangle T)$, can be obtained by integrating out the unobservalbe parameters. Let $\Phi=\{\lambda, \pi_1, \pi_2, \pi_3\}$ be the vector parameter of the branch probabilities and D denote the data available by time T. Then we obtain

$$P(\triangle C \mid D)=\int\cdots\int p(\triangle C \mid w, \Phi)\, p(\Phi, W \mid D)\, d\Phi\, dW \tag{1}$$

Note that the distribution of $\triangle C$ is based on the observable counts only. Also note that we did not make any distributional assumptions on branch parameters and likelihoods. The influence diagram model and the predictive distribution in (1) are applied to any type of prior and likelihood assumptions.

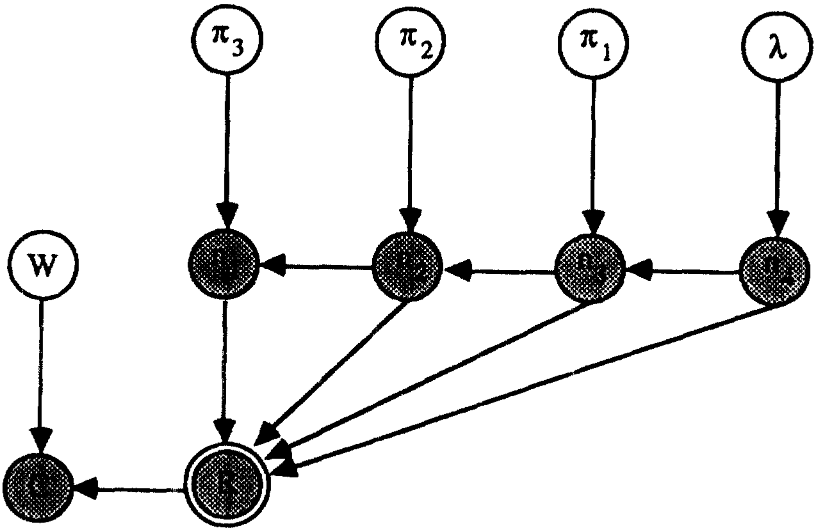


Figure 5 : An Expanded Model for Consequences of Tritium Release

Using expert opinion and engineering knowledge, the parameters are usually estimated from fault trees whose top event yields the desired probability of branch failure. A positive−skewed distribution that has a long tail is usually assumed for the rate of initiating event because a safety system provided with many redundancies tends to bunch up towards the low probability of failure. Lognormal or Gamma distribution with appropriate parameters can be good candidates. For the distributions of π's we may assume beta distributions, which are quite flexible covering almost all forms of distribution on [0, 1]. The likelihood of count of level 4 incident, n_4, given λ is assumed Poisson with parameter λ since it is quite rate incident. The likelihood of n_j given n_{j+1} and π_j is assumed to be Binomial with parameters n_{j+1} and π_j.

From (1), we can see that less uncertainties on branch parameters result in less uncertainties on consequences. We cannot have real operating data at the design stage but fortunately the data from testing can be helpful to sharpen the distributions of branch parameters. With the assumption that branch parameters influence the counts of system failure in testing as they influence the counts of real accidents, the results from testing can be used to update parameters in the same way as we utilize the information obtained from the operating experience. Figure 6 is an example of a model that incorporates the results of testing when we perform testing on the efficiency of secondary enclosure.

U denotes the total number of testing and V denotes the number of failure in testing. Figure 7 is the influence diagram that updates the parameter π_2 with the information available. Note that we can utilize the information U and V even though we do not have any operating data. For the detail of parameter updating scheme, see R.M. Oliver and H.J. Yang [1990].

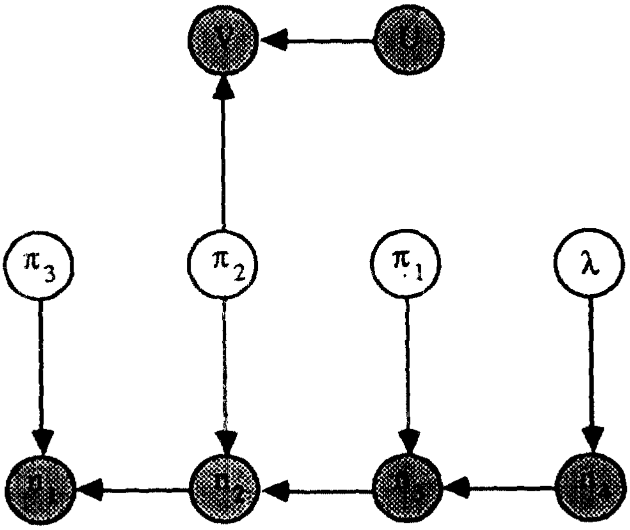


Figure 6: A Model Incorporating the results of Testing

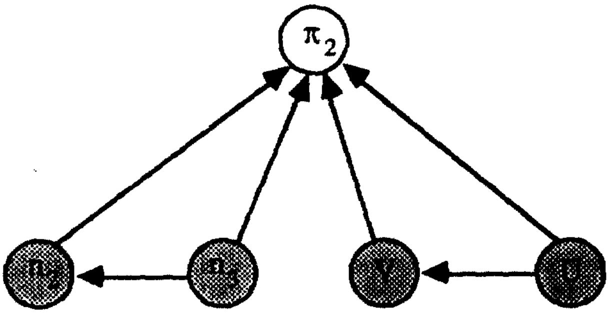


Figure 7: Updating π_2

The prior distribution of π_2 can be assumed as Be(1, 1) if we do not have any iformation about the failure probability of secondary enclosure. And assume that we had no failure on secondary enclosure during 10 times testing under the simulated condition of an initiating event and failure of system shutdown, then the resulting posterior distibution is Be(1, 11). Then we have very much sharpened distribution of π_2 and thus we can estimate the consequences of tritium release accident with less uncertainty. Figure 8 shows how such a testing result influences the degree of uncertainty on a branch parameter. One lesson we can get from Figure 8 is that separate testing on each safety system provides us with valuable information that reduces the uncertainties on overall system.

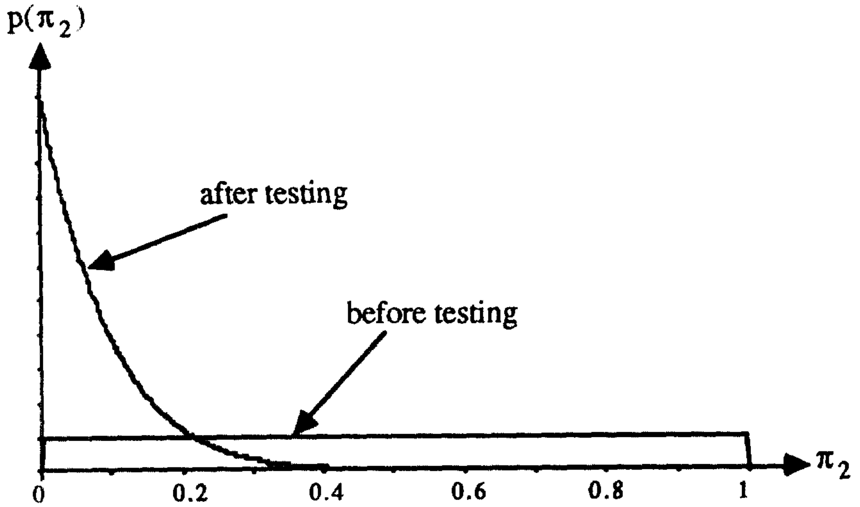


Figure 8: Sharpened Distribution due to Testing

Summary

We construct a model to describe a fusion power plant that concentrates on the flow and process of tritium since tritium can be regarded as a source of dominant hazard from a public safety point of view. To illustrate the accidental sequences of tritium release leading to various levels of hazard, we develop an event tree model and then describe it in terms of an influence diagram which is statistically equivalent so far as branch parameter updating is concerned. We also expand that model to take care of the consequences resulting from the release of tritium, and develop a predictive distribution to predict the consequence from a Bayesian look.

Finally, a model that can utilize information obtained from testing is suggested and show how the information from testing reduces the uncertainties on branch parameters.

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