▨응용논문

원자핵 융합 발전소의 삼중수소 유출 사고 예측*2)

양희중
청주대학교 산업공학과

Predicting the Tritium Release Accident in a Nuclear Fusion Plant

Heejoong Yang
Dept. of Industrial Engineering, Chong Ju University

Abstract

A methodology of the safety analysis on the fusion power plant is introduced. It starts with the understanding of the physics and engineering of the plant followed by the assessment of the tritium inventory and flow rate. We apply the probabilistic risk assessment. An event tree that explains the propagation of the accident is constructed and then it is translated in to an influence diagram, that is statistically equivalent so far as the parameter updating is concerned. We follow the Bayesian approach where model parameters are treated as random variables. We briefly discuss the parameter updating scheme, and finally develop the methodology to obtain the predictive distribution of time to next severe accident.

1. Introduction

During the operation of fusion power plants, ionizing radiation is anticipated to be the most prevalent hazard because it is associated with all aspects of fuel production. Tritium, neutrons and beta-gamma radiation resulting from the decay

---

* 이 논문은 1997학년도 청주대학교 학술연구 조성비에 의하여 연구되었음.

of neutron activation products are the sources of ionizing radiation. Among these we are specifically interested in the analysis of the tritium release accidents.

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 steady state leaks from imperfect fluid system connections, valves and pumps, permeation through pipes and vessel walls, and occasional leaks during routine maintenance and accidents. Only the occasional release will be examined here.

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 rate through the plant. So the assessment of tritium inventory and vulnerability at various locations will be made.

Previous studies have been concentrated on the constructing event trees or fault trees that could explain the tritium accident mitigating systems [3, 6]. As far as we know, there is no explicit parameter updating scheme and thereby no methodology to modify the overall safety factors in a fusion plant. In the case that a particular accident sequence in an event tree or fault tree is reported, it should be utilized to reduce the uncertainties on the safety of a fusion plant. This paper proposes a model and a Bayesian procedure that accomplish updating in real time as possible counts of sub-system failure in an event tree become available through testing or future operational experience. We firstly construct an event tree that leads to various levels of tritium release from abnormal initiating events. Based on the event tree model we construct an influence diagram model which is more useful for the parameter updating and analysis. We explain the way of obtaining posterior distributions on model parameters and predictive distribution of time to next accident.

2. Description of Fuel Cycle System

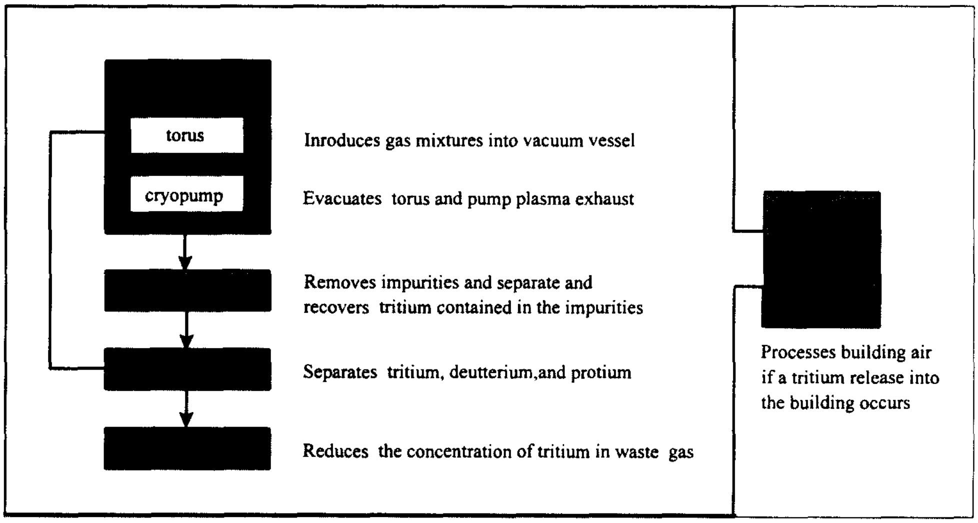
The fuel cycle systems consist of all the sub-systems of the reactor which are needed to process and handle the fuel components. These include the plasma chamber, the vacuum system, the fuel cleanup system, the isotope separation system, fuel storage, fuel injection system, the tritium waste treatment system, the blanket tritium recovery system, and emergency tritium cleanup system.

Burnt gases 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.

The fuel clean up system removes impurities in preparation for the isotope separation system. The gas stream evacuated from the torus include hydrogen 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 not operable.



< Figure 1 > Schematic of Fuel Cycle System

Emergency tritium cleanup system removes airborne tritium from the reactor building, the fuel processing building and all secondary enclosures internal to these buildings. Secondary containment include double-wall piping and components, glove boxes, a large enclosure for enclosing the vacuum system, and integral vacuum jackets around cryogenic components. Emergency tritium cleanup 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 efficiency of the recombiner, the efficiency of the molecular sieve and the leak tightness of the reactor hall.

Effluents from 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 [2, 3].

We introduces the model in <Figure 1> to easily understand the above mentioned sub-systems and roles of those.

3. 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 in the plasma chamber during operation of the reactor is the product of the triton density and the plasma volume. This is 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 inventories in fuel cleanup system, isotope separation system and fuel storage are classified as non-vulnerable because of multiple containment used and/or high reliability of components.

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 liquid metal may drain from the reactor and release its tritium inventory after some accident scenarios.

The blanket structure contains tritium inventory because 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 metals are fairly high, thus possible thermal transients could "bake-out" the tritium in a short period of time. So tritium contained in the structure is designated as vulnerable.

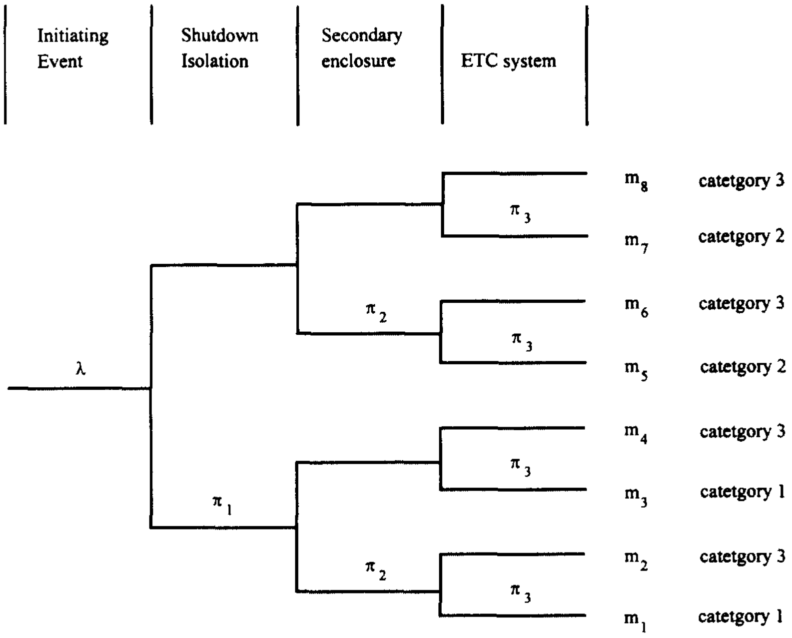
The tritium inventory in the blanket coolant will also be established due to permeation from the plasma and classified as vulnerable.

4. Release of Tritium

Tritium inventories may be released if an abnormal initiating event occurs and safety features that are supposed to mitigate the consequences of initiating events do not operate successfully. The safety features include system shut down or isolation, secondary enclosure, and emergency tritium cleanup system. The amount of tritium release given an initiating event in a specific system depends on the failure or success status of these safety features. We only pay attention to the vulnerable tritium inventories because the probability of release of nonvulnerable tritium is assumed to be negligible.

Previous efforts on Probabilistic Risk Assessment area were devoted to estimate the failure rate of various possible initiators. Therefore there have been difficulties in the assessement of degree of overall safety of the fusion plants from the public point of view. We propose a model and procedure that can estimate the various levels of risks.

<Figure 2> is an event tree that shows the sequences of accidents leading to various levels of tritium release from abnormal initiating events. λ denotes the arrival rate of initiating events, π_1 denotes the probability of failure to isolate or shutdown system, π_2 denotes the probability of secondary enclosure failure, and π_3 denotes the probability of emergency tritium cleanup system failure. m_k denotes the counts of accident of sequence k from an initiating event, which is enumerated from the bottom of the event tree. The incidents of different sequences are classified into three categories depending on the magnitude of the tritium inventory to be released: category 1, 2, 3 denote large, medium, and small portion of release of the tritium inventory in the system.

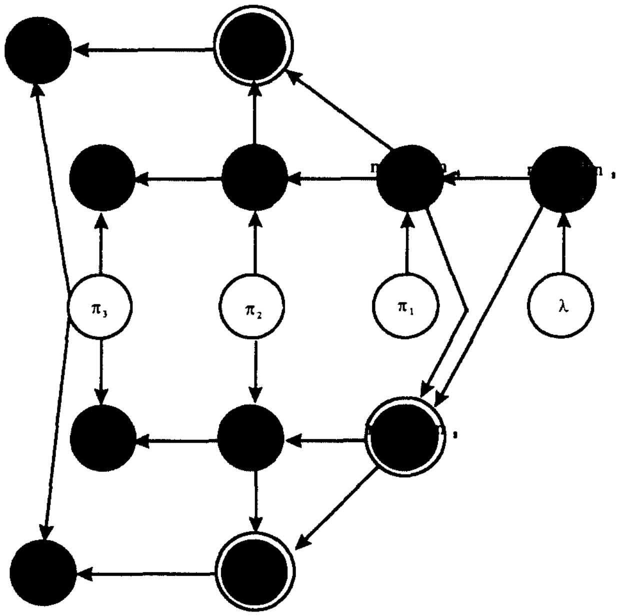


< Figure 2 > Event Tree for Tritium Release Incidents

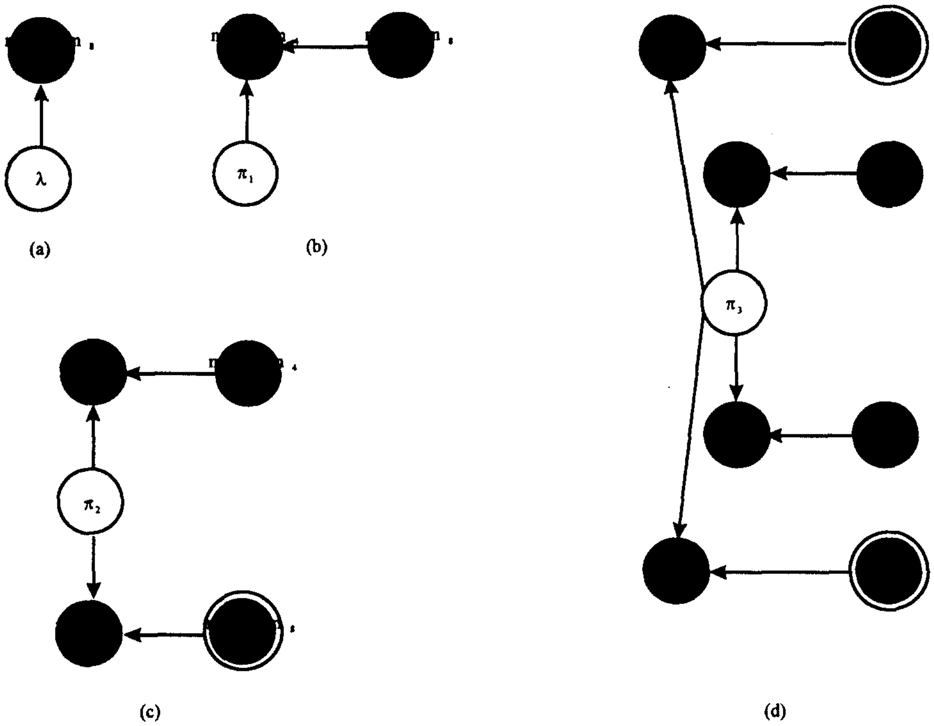
The event tree model in <Figure 2> can be expressed by a statistically equivalent influence diagram as in <Figure 3>.

In the influence diagram nodes denote random variables and directed arcs denote the fact that a conditional probability of the node at the arrowhead need only be assessed in terms of its direct predecessor nodes. We follow a convention that unshaded nodes containing Greek letters denote unobservable parameters that influence the observable counts of events which are denoted by shaded nodes. Deterministic nodes (denoted by double circles) are known exactly given the values of the predecessor nodes since they are simply the sum of counts of subsets of accident sequences passing through the branch of a particular subtree.

On inspection of the influence diagram in <Figure 3>, it can be seen that there is a special structure for each of the random nodes influenced by an unobservable parameter, λ, π_i, l=1,2,3, and a random node corresponding to a count of accident sequences. For example, in <Figure 3>, λ influences $m_1+\ldots+m_8$ and π_1 influences $m_1+\ldots+m_4$. These influences are shown in <Figure 4> where we display the subgraphs that only include direct successors of π's or any other observable nodes which provide us with information needed to update the π's.

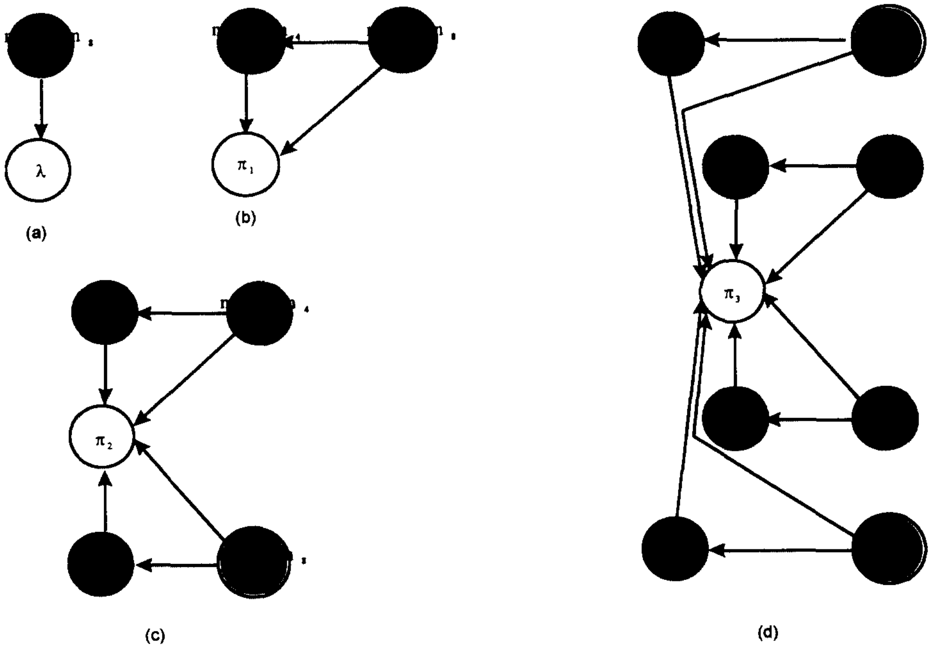


< Figure 3 > An Influence Diagram of the Event Tree in Figure 2



< Figure 4 > Nodes Influenced by Branch Parameters and Counts

By arc reversal we obtain the results in <Figure 5>. The posterior distribution of initiating events is only influenced by the total count and the unshared branch parameters are only influenced by the total count of accident sequences that pass through the lower branch and the sum of total counts of accident sequences that pass through the lower and upper branch, while the shared branch parameters are influenced by the total counts of accident sequences in each of the shared lower branches and the sums of total counts of accident sequences in shared lower and upper branches.



< Figure 5 > Influence Diagrams for Parameter Updating

5. Prediction Model

We conservatively assume that the category 1 incident release all the inventory of the system under consideration. Note that m_3 is classified as category 1 accident because the failure of shutdown and the failure of ETC system is dangerous enough to release almost all the tritium inventory in the system. Let r_2 and r_3 denote the portions of tritium inventory released by category 2 and 3 incidents, respectively (r_1 is assumed to be 1). Also let ϕ_j denote the probability of leading to category j incident given an initiating event. ϕ_j can be easily be obtained from the event tree in <Figure 2> as followings;

$$\phi_1 = \pi_1 \pi_3$$

$$\phi_2 = (1 - \pi_1)\pi_3$$

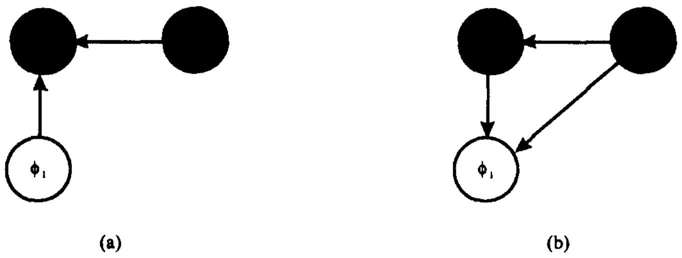
$$\phi_3 = 1 - \pi_3$$

Then the total magnitude of tritium release per unit time, H, can be calculated by the following equation, where I denotes the tritium inventory in system:

$$H = \sum_{j=1}^{j=3} \lambda \phi_j r_j I$$

If we restrict ourselves in predicting the category 1 accident, which is the most severe one, the model can be simplified as <Figure 6(a)>, where $n = n(T) = \sum_{j=1}^{j=8} m_j$ denotes the total number of initiating events during time period T, and $n_1 = n_1(T) = m_1 + m_3$ denotes the total number of category 1 accidents during time period T. Using the arc reversal technique as mentioned above, we obtain <Figure 6(b)>. <Figure 6(b)> shows the procedure that we obtain the posterior distribution of model parameter ϕ_1 by multiplying the prior distribution of ϕ_1 and the likelihood of observed data;

$$p(\phi_1 | n, n_1) \propto p(\phi_1) p(n_1 | \phi_1, n)$$



(a) (b)

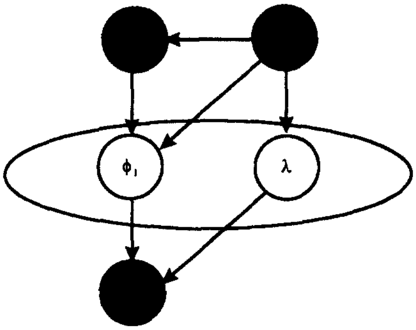
< Figure 6 > Model to Predict Category 1 Accidents

Let τ_1 be the time to the next category 1 accident. The initiating event escalates to the category 1 accident with the probability of ϕ_1, so the rate of category 1 accident is $\lambda\phi_1$. As we can see from <Figure 3>, the arrival rate of initiating events λ influences the total count n and it also does the time to the next initiating event. Therefore we can assume the likelihood on τ_1 conditional on $\lambda\phi_1$. As we acquire data we obtain the posterior distribution on $\lambda\phi_1$. Then the predictive distribution on τ_1 isobtained by integrating out the unobservable parameter λ and ϕ_1 so that the distribution of τ_1 depends only on the observable numbers n and n_1;

$$p(\tau_1|n,n_1) = \int\int p(\tau_1|\lambda,\phi_1)p(\lambda,\phi_1|n,n_1)d\lambda d\phi_1$$

This is depicted in <Figure 7>. When we apply the above mentioned procedure to the real data, the distributional assumption on the prior and the likelihood is very important and difficult job. This paper does not pay much attention to this point since we are more interested in the prediction model building. But we may want to briefly mention about the distributional assumptions. The distribution of ϕ_1 can be assumed as a Beta distribution since the Beta distribution covers almost all forms of distribution covering the range between 0 and 1. The distribution of λ can be assumed as a skewed distribution such as Gamma distribution since the arrival rate of initiating events is usually concentrated to the low probability region while it still has a long tail to the right. The likelihood of $(n_1|\phi_1,n)$ can be assumed as Binomial with the assumption that the accident occurs independent of one another. The arrival of initiating event given parameter λ can be said to be the Poisson process, so $(n|\lambda)$ is assumed to be a Poisson distribution. Similarly, $(\tau_1|\lambda,\phi_1)$ is assumed to be an Exponential distribution with parameter $\lambda\phi_1$. Note that the conjugate prior of Binomial distribution is Beta distribution, and the conjugate prior of Poisson distribution is Gamma distribution. Then the post distribution of ϕ_1 given data is another Beta distribution and the post distribution of λ given data is another Gamma distribution.

But one very important thing we shoul note is that we did not make any distributional assumption on model parameters and likelihood. The influence diagram and the predictive distribution obtained above can be applied to any type of prior and likelihood assumptions.



< Figure 7 > Obtaining the Predictive Distribution

6. Summary

A model for a tritium flow is presented. It explains the components of a fusion reactor and the way of tritium flow through those components. From the view point of mitigating accident propagation to more severe ones, the primary safety features include system shutdown or isolation, secondary enclosure, and emergency tritium clean up system. Depending on the success or failure of the above safety features an initiating accident may or may not escalate to more severe accident. This process is illustrated using an event tree. An influence diagram is presented which is statistically equivalent in parameter updating. This model is simplified to take care of the prediction of the severe accidents. We introduce the way of obtaining predictive distribution of time to next severe accident by absorbing unobservable model parameters.

References

[1] Aitchison, J. and Dunsmore, I.R.(1980), Statistical Prediction Analysis, Cambridge University Press.

[2] Brereton, S.J. and Kazimi, M.S.(1987), "Safety and Economic Comparison of Fusion Fuel Cycles," MIT Plasma Fusion Center.

[3] Bruske, S.Z. and Holland, D.F.(1983), "Risk Assessment Technology for the

Evaluation of Tritium Accident Mitigation," *Nuclear Technology Fusion*, Vol. 4, pp. 539-543.

[4] Holdren, J.P. et.al.(1988), "Exploiting the Competitive Potential of Magnetic Fusion Energy: The Interaction of Economics with Safety and Environmental Characteristics," *Fusion Technology*, Vol. 13, pp. 7-56.

[5] Oliver, R.M. and Yang, Heejoong(1990), "Updating Event Tree Parameters to Predict High Risk Incidents," Influence Diagrams, Belief Nets and Decision Analysis, John Wiley and Sons, pp. 277-296.

[6] Piet, S.J.(1986), "Implication of Probabilistic Risk Assessment for Fusion Decision Making," *Fusion Technology*, Vol. 10, pp. 31-48.

[7] Yang, Heejoong(1990), "An Approximation Method in Bayesian Prediction of Nuclear Power Plant Accidents," Journal of Korean Institute of Industrial Engineers, Vol. 16, No. 2, pp. 135-147.