Journal of Environmental Sciences Vol.17, No.2, pp.263—267, 2005

ISSN 1001—0742
CN11—2629/X

Article ID: 1001-0742(2005)02-263-05 **CLC number**: X22 **Document code**: A

Risk forecasting and evaluating model of Environmental pollution accident

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Abstract: Environmental risk(ER) factors come from ER source and they are controlled by the primary control mechanism(PCM) of environmental risk, due to the self failures or the effects of external environment risk trigger mechanism, the PCM could not work regularly any more, then, the ER factors will release environmental space, and an ER field is formed up. The forming of ER field does not mean that any environmental pollution accident(EPA) will break out; only the ER receptors are exposed in the ER field and damaged seriously, the potential ER really turns into an actual EPA. Researching on the general laws of evolving from environmental risk to EPA, this paper bring forwards a relevant concept model of risk forecasting and evaluating of EPA. This model provides some scientific methods for risk evaluation, prevention and emergency response of EPA. This model not only enriches and develops the theory system of environment safety and emergency response, but also acts as an instruction for public safety, enterprise's safety management and emergency response of the accident.

Keywords: environmental risk(ER); environmental pollution accident(EPA); ER evaluation; ER field; EPA damage field

Introduction

As the industries develop rapidly, a great deal of combustible, explosive, poisonous and corrosive materials are used in production or processing, which frequently cause many accidents like explosion, fire disaster, toxicosis, radiation during production, storage and handling, and the damage also become more and more ghostly.

How to prevent the happening of such accidents, how to take proper steps to respond the accidents once they break out, and how to reduce the thread to public health and biological environment, etc. become some hot topics for the moment and cause attentions from all circles of the world. As it is, many international organizations and experts have done a great deal of works in researching and studying.

As early as 1988, UNEP IE/PAC brought forward APELL plan, which aims at preventing technical accidents and increasing the public consciousness to deal with environmental accidents and their damage by the support from decision-makers and technicians, even preparing to respond any accident endangered the people's life and properties(Zeng, 2000).

The action plan—21st Century Agenda, adopted by Environment and Development Conference of UN, had overpassed the detailed and specific document to support APELL in order to enhance the project. In the Convention of EN/ECE, it takes APELL as a tool to identify and respond to industry accidents in their trans-boundary effect. Nowadays, INCUEA is organizing strength for Emergency Response to industrial accidents, and plan to establish emergency response program to industrial accident in country-level by the help of APELL(UNEP, 1994).

OEDC had studied all kind of EPA, particularly, it issued the monograph "OECD's guiding principles for chemical accident prevention, preparedness, and response", which summarized the prevention and cure, emergency treatment preparation and emergency response of EPA caused by hazardous chemical production (OEDC, 1999).

United States had made intense and elaborate research on emergency treatment technology for all kind of EPAs, and formed technical code integrative treatment flow and document. Canada Environmental Protection Bureau had a special plan to respond emergency, which was called E2 Plan, and collaborated with United States in most areas. The achievements include "2000 emergency response guidebook", and so on.

Up to now, the research on EPA mainly concentrates on the risk assessment of EPA, precaution measures and emergency response technology etc. However, the general laws from the environmental risk to EPA and the universal ways forecasting and assessment for EPA are still few. Researching on the general laws of evolving from environmental risk to EPA, this paper brings forward a relevant concept model of risk forecasting and evaluating of EPA. This model provides some scientific methods for risk evaluation, prevention and emergency response of EPA. This model not only enriches and develops the theory system of environment safety and emergency response, but also acts as an instruction for public safety, enterprise's safety management and emergency response of the accident.

1 The general laws evolved from ER to EPA

As the potential EPA, all kinds of environmental risks are not isolated, they are interrelated and influenced each other in a certain form, and construct an ER system, instead. Fig. 1 describes the logical figure of the ER System. The ER system is composed of the ER source, the ER factor, the ER field and the ER receptor, and the primary control mechanism(PCM) and trigger mechanism(TM) which control ER factors releasing from an ER source, and the secondary control mechanism(SCM) which control ER receptors touching with the ER fields(Zeng, 2000; Zhu, 1990).

ER factors come from ER source and they are controlled by the primary control mechanism(PCM) of environmental risk(ER); due to the self failures or the effects of external environment risk trigger mechanism, the PCM could not work regularly any more, then, the ER factors will release environmental space, and an ER field is formed up. The forming of ER field does not mean that any EPA will break out; only the ER receptors are exposed in the ER field and damaged seriously, the

Foundation item: The National Natural Science Foundation of China(No. 70273005) and the Hi-Tech Research and Development Program(863) of China(No. 2003AA601010)

potential ER really turns into an actual EPA. This process is controlled by the SCM of the ER. The ER field is controlled by the SCM of the ER, the PCM prevent ER field form evolving and expanding, and avoiding ER field touching with receptors. Once the PCM of the ER does not work well or is disabled absolutely, receptors will be exposed in ER field, causing damage, which means EPA breaks out.

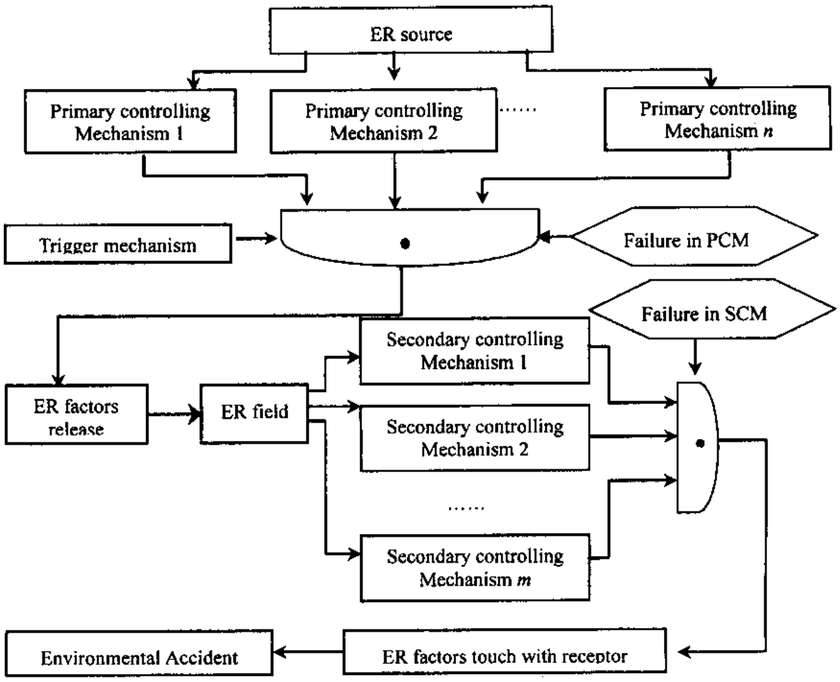

Fig. 1 Logical structure of an environmental risk system

2 Risk forecasting and evaluating model for an EPA

Fig. 1 describes the whole process of ER generating, developing and finally evolving into an EPA. A potential ER evolves into a practical EPA, it takes mainly four steps, i.e., the ER factors are released from the ER source, an ER field is formed in an environmental space, ER receptors are exposed in the ER field, the ER receptors suffer damage or loss in different extents, and an EPA breaks out finally.

In order to consider evolution mechanism of ER and composing structure systemically, Fig. 2 brings forward a concept model of risk forecasting and assessment for an EPA. The risk forecasting and assessment for an EPA is made up by three lines. The main one is the process evolving from an ER to an EPA, and there are two accessorial lines, one is the process for determining the probability of an EPA occurrence, another is intensity of accident corresponding to the probability of the EPA occurrence, and further more harmful results could be determined(Zeng, 2000).

The essential cause for the forming of ER field depends on ER factors released into environmental space. It is the space pattern of the ER factors which are constructed owing to the ER factors diffusing and transferring. During the process ER field are formed, it has no relation with the ER receptors and HP caused by the ER factors to ER receptor under an unit exposure condition; only the ER receptors enter into ER field, the latent thread effect may be translated into practical harm.

The intensity of ER field relates to the released intensity of the ER factors, the condition of environment, environmental media parameters and so on. It is a specific representation of its exposure level when the ER factors are diffused and transferred into some position of the environmental space, it does not relate to the ER receptors. The probability of a certain ER field emergence relates to the frequency of the ER factors releasing and the probability of the condition of environment, but unrelated with the probability of the ER receptors occur in the ER field.

After the ER factors are released, the ER field is established through the ER factors constantly diffuse and run in environmental space. The formation, development and evolution of ER field are called the Operation Mechanism of ER. Once an ER field communicates with an ER receptor, it will be harmful to the ER receptor, and cause ER receptor losing in different extent. Thus it can be seen, the SCM of an ER preventing ER field touching with the ER receptors is the last barrier in order to avoid an ER transforming into an EPA. Once it is disabled, it means EPA will be broken out.

Usually, operation mechanism of ER could be described with some mechanism models, such as the diffusion model of the toxic gas in leaking risk under special meteorological condition and so on. Moreover, the SCM of ER mainly presents as controlling the diffusion and transferring of the ER factors, including measures and installations to prevent ER source touched with ER receptor, such as separating oil equipment in oil leaking risk, evacuating people in toxic gas leaking risk, and so on.

The ultimate aim of analyzing the operation mechanism of ER is to develop simulation model in order to describe the generation, development and evolution of the ER field. It is different approaches to make models for different ER factors and environmental condition. Firstly, it need to make sure the diffusion and movement laws in the environmental space after the ER factors are released, and then determine the mathematical model to describe the law. Secondly, the unknown parameters of the model should be determined. At the end, the model should be validated.

The ultimate aim of analyzing the SCM of the ER is to search practical measures and schemes to prevent the ER field touching with the ER receptors and protect them after ER factors are released. The analysis can be carried through the follow ways, one is considered from the measures to keep within limits of ER field on the basis of analyzing the operation mechanism of the ER, another can be considered from the ER factors, make the ER receptors separated from the ER field as far as possible.

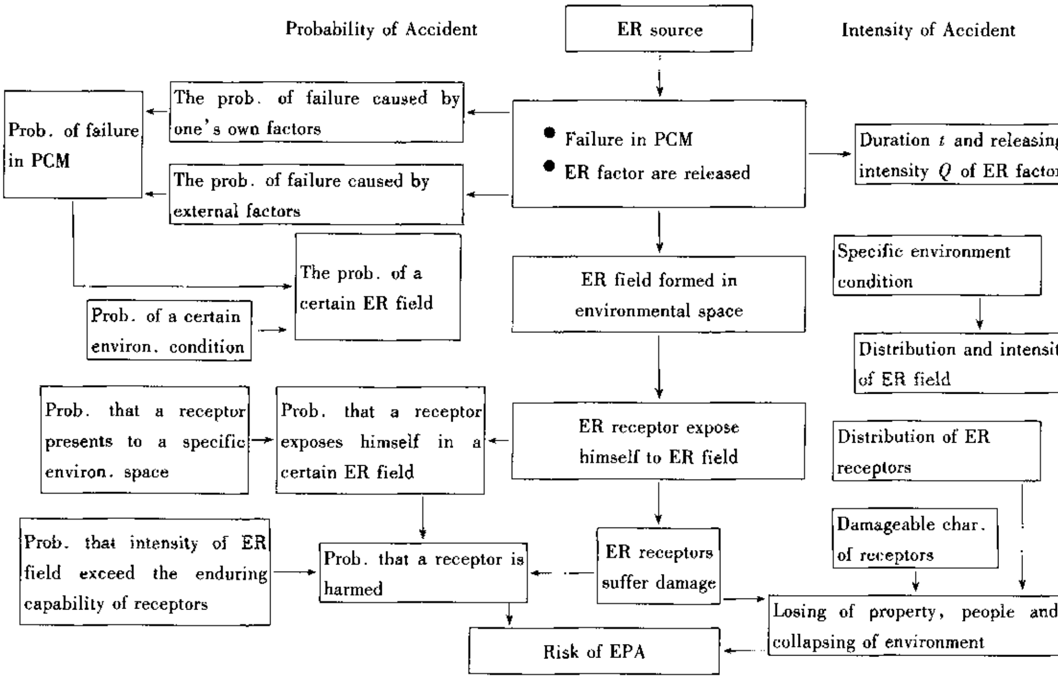

Fig. 2 Concept model of risk forecasting and assessment of EPA

3 Probability of ER factors releasing

3.1 Failure rate of PCM

The failure risk of PCM refers to the probability($F(t)$) which PCM could not fulfill the prospective function(i.e., failure of PCM, and the ER factors are released) while $(0, t)$ for an arbitrary $t > 0$ in a specific condition, i.e.,

$$F(t) = P(\tau \leqslant t) = \int_0^t f(t)\mathrm{d}t. \tag{1}$$

The failure rate of PCM refers to the probability($\lambda(t)$) of failure in a specific time(t), when the PCM runs regularly.

$$\lambda(t) = \lim_{\Delta t \to 0}\left(\frac{P(t < \tau \leqslant t + \Delta t \mid \tau > t)}{\Delta t}\right). \tag{2}$$

On the one hand, the PCM of environmental risk depends on its composition(including human activities) and its reliability. On the other hand, it depends on the environmental pressure coming from outside (such as earthquake, flood and typhoon etc.) and the carrying capacity of the PCM to the outside pressure.

3.1.1 Failure risk of components of PCM

Failure risk of components of the PCM is a function of t. For an un-repairable PCM, it can be expressed as the failure rate. For those repairable PCM, the effective rate should be introduced and described further.

In order to improve the reliability of a PCM of an ER, a parallel connection stock structure(PCSS) is used often in the actual PCM design process. What is called PCSS is a structure which the control component would be replaced immediately when it is failure for the controlling. Take an example for a simple ideal structure, in case of PCM is buildup with $n + 1$ control parts, one part works and the others are on standby, and the life time of all spare parts on standby is invariable, and the failure components would be replaced one by one, and then the control mechanism failure finally until all parts are failed. The failure rate of the PCSS may be defined as,

$$F_s(t) = P(\tau_1 + \tau_2 + \Lambda + \tau_n \leqslant t)$$

$$= \int_{-\infty}^{\infty} \int_{-\infty}^{t-t_1} \Lambda \int_{-\infty}^{t-\sum_{i=1}^{n} t_i} \prod_{i=1}^{n+1} f_{\tau_i}(t_i)\mathrm{d}t_1\mathrm{d}t_2 \Lambda \mathrm{d}t_{n+1}. \tag{3}$$

3.1.2 Failure risk of PCM due to outside pressure

Another factor cause of PCM of ER failure comes from outside pressure, such as natural disaster(earthquake, typhoon and flood etc.) and man-made disaster(traffic accident, shipwreck and air disaster). For a compositive structure of a PCM of an ER, all of its carrying capacity supporting outside pressure and the pressure coming from the outside are stochastic variable. The PCM formed by a compositive structure is considered to be reliability only when the PCM could support an outside pressure under a certain probability condition. By contraries, it is consider being fallibility, namely there are a certain risk.

The probability that carrying capacity of a PCM (C_p) is less than the outside pressure(P_p) is named for failure rate(or risk rate), known as $F_0 = P\ (C_p < P_p)$.

If C_p and P_p are continuous stochastic variables, and their probability density functions are $f_{pc}(c)$ and $f_{pc}(p)$ respectively, and their joint probability density function is $f_{pcp}(c, p)$, F_0 could be computed by integrating the joint probability density function. In the same way, it could be computed by introducing a safe distance function (or named as limiting state function) $M_p = C_p - P_p$. M_p is stochastic variable apparently, its probability density function is $f_{pm}(m_p)$, and the failure rate could be computed as follows:

$$F_0 = \int_{\infty}^{0} f_{pm}(m_p)\mathrm{d}m = F_{pm}(0). \tag{4}$$

3.2 Probability of ER factors releasing

Through analyzing the failure rate of its compositive structure of an PCM, the failure rate $F_S(t)$ of the PCM in$(0, t)$ could be determined, furthermore, the time of the ER factors releasing in certain times could be determined also, namely frequency of the ER factors are releasing. And then the average failure frequency (F_S) of the PCM could be determined further.

For an un-repairable PCM, the average failure frequency is the reciprocal of the average effective work time of a PCM, it could be computed by follow formula,

$$F_S = \frac{1}{E(\tau)} = \frac{1}{\int_0^{\infty}(1 - F_S(t))dt} \quad . \tag{5}$$

For a reparable PCM, the average failure F_S is equal to reciprocal of average work cycle period (T),

$$F_S = 1/E\ (T) \quad . \tag{6}$$

What is called work cycle period here is known as the periods that a PCM fulfill an effective work, failure, overhaul and resume function. In the case that the PCM would be overhaul only after it failure, and resume work only after renovating, and then the cycle period equal to the effective work time(T_W) plus the overhaul time(T_O). Furthermore, the average cycle period equal to the sum of the effective work time(T_W) and the overhaul time(T_O),

$$E(T) = E(T_W) + E(T_O). \tag{7}$$

The Trigger Mechanism of an ER includes natural factors, such as earthquake, typhoon and flood, and man-made factors, such as traffic accident, shipwreck and air disaster. Whether natural or man-made, the probability of the PCM failure could be determined by statistic information.

The releasing of the ER factors depend on three complications as follow, the first is the PCM failure due to the faults for inside reason, the second is the PCM failure for outside reason, such as outside pressure exceed to the carrying capacity of the PCM, and the last one is the PCM failure for the Trigger Mechanism of the ER.

Supposed event E = {an ER factors release}, E_1 = {the PCM failure due to the faults for inside reasons}, E_2 = {the PCM failure for outside reasons}, E_3 = {the PCM failure for the Trigger Mechanism}, and then $E = E_1 \cup E_2 \cup E_3$. Furthermore, the probability (F) of the ER factors releasing could be computed as follows:

$$\begin{aligned} F &= P(E) = P\{E_1 \cup E_2 \cup E_3\} \\ &= P(E_1) + P(E_2) + P(E_3) \\ &= F_S + F_O + F_T. \end{aligned} \tag{8}$$

4 Forecasting the intensity of ER factors releasing

The duration of the ER factors releasing in an EPA depends on the intensity of the EPA to a great extent. For a certain paroxysmal EPA, such as toxic gas leakage or nucleus leakage, once the PCM of the ER is failure, the speed(Q_{ERF}) of the ER factors releasing is stable, and it depends on the specific design size of the ER source.

For the un-reparable of the PCM of ER source, such as toxic gas leakage for traffic accident during the transportation of toxic gas, the releasing time(T_0) of the ER factors(toxic gas) are equal to releasing time that all ER factors are released. It depends on the inside parameters of ER source, such as reserves and intensity of pressure, and the extent of the PCM destroyed and parameters of environmental media. Because all ER factors are released, the releasing process could not be considered, and the stable state distribution of the ER factors(ER field), which is formed, and decline step by step in the environmental media after all of the ER factors release is considered only.

For the reparable PCM of ER source, such as India Bhopal toxic gas leakage, the releasing time(T_O) is the time of renovating time of the PCM, namely, the time that the PCM is failure till it is renovated and run again. Therefore, the intensity of the ER factors releasing could be determined as follows:

$$W = Q_{ERF} \times E_0(T_O) \quad . \tag{9}$$

5 Simulating and forecasting of ER field

It depends on the intermedium action of environmental media that ER factors form the ER field in environmental space. The environmental media refers to the material in environment, which could transfers, the material and energy, such as air, water and soil and so on. The capacity of the ER factors transferring, diffusing, and transforming in different environmental media, it depends on the density and fluidity of the environmental media. By all appearances, the ER factors form an ER field easily in a larger area in air or water, and the space that the ER receptors are influenced in a great extent. But the ER factors form an ER field in a limited area in soil, i.e., the effect to the ER receptors far from the ER sources is very little.

For the paroxysmal ER, the ER factors release in a very short time, the releasing time could be ignored as compared with its action time in the environmental space. Therefore, it could be considered as instantaneous releasing, and the ER field that form in the environmental space is declined step by step.

The probability of ER field forming generally depends on the frequency of the ER factors releasing, velocity of the environmental media and diffusion parameters, and the stochastic fluctuation of outside environmental condition, such as hydrology and weather usually. The methods in common use is that the randomicity of the other parameters besides hydrological an weather parameters are ignored, analytic solution of the simulation model is computed in the hydrological an weather condition of a certain factor of guarantee(P_G), and then the ER field pattern under the factor of guarantee could be determined. Therefore, the probability of ER field forming(P_{ERF}) is as follows:

$$P_{ERF} = P_G \times F \quad . \tag{10}$$

The forming of the ER field does not mean that the receptors will be harmful. Only the receptors are exposed in the ER field and the intensity of the ER field exceeds the carrying capacity of the receptors, the potential danger would transform into an actual disaster. Therefore, the risk-forecasting problem that the receptors suffer loss should be solved.

The risk of the receptors suffering loss depends on the intensity of the ER field in a certain factor of guarantee(P_G), and the carrying capacity of the receptors which relate to the vulnerability of the receptors. The probability that the carrying capacity of the receptors to a ER field C_e is less than the intensity of the ER field P_e refers to the risk rate of receptors suffering loss, which could be represented as $F_{eo} = P(C_e < P_e)$.

If C_e and P_e are continuous stochastic variables, and their probability density function are $f_{ec}(c)$ and $f_{ec}(p)$ respectively, and their joint probability density function is $f_{ecp}(c,\ p)$, then F_e could be computed by integrating the joint probability density function. In the same way, it could be computed by introducing a safe distance function (or named as limiting state function) $M_e = C_e - P_e$. M_e is a stochastic variable apparently, its probability density function is $f_{em}(m_e)$, and the risk rate of receptors suffering loss could be computed as follows:

$$F_e = \int_{-\infty}^{0} f_{Me}(m_e)dm = F_{Me}(0). \tag{11}$$

6 Simulating and forecasting of loss field of an EPA

The loss field of an EPA refers to the space pattern that the receptors suffer loss when the receptors are exposed in an ER field and the intensity of the ER field exceeds the carrying capacity of the receptors. The determinant of the loss field of an EPA includes as follows:

· Distribution and evolution of the ER field;

· Space pattern of the receptors. For the stable receptors, it is the space distribution of the receptors; for the unstable receptors, it can be represented as the space distribution of the receptors in a certain factor of guarantee;

· The vulnerability of the receptors. It depends on the inside structure of the receptors and the type of the ER field.

Being different from the ER fiel, it is very difficult that the distribution of the receptors in the determinant of a loss field of an EPA is represented in a mathematics model. Therefore, the loss value(intensity of the loss field) of a certain position is determined usually only according to the exposure level of the ER factors and the density of the receptors in a specific space position, and the vulnerability of the receptors related to the ER factors. In the process of simulating and forecasting of loss field of an EPA, the Geographic Information System (GIS) is very useful computer aid tools(John, 1993; King, 1995). Fig. 3 is the technical route of simulating and forecasting of the loss field of an EPA with the overlay model of GIS. Thereby, the aim of analyzing of the vulnerability of the receptors is to determine the loss degree of the receptors caused by different intensity of the ER field. The carrying disaster capacity of the receptors, namely, the exposure level which the receptors could suffer, depends on the vulnerability of the receptors. For an EPA, the carrying disaster capacity could be measured with environmental function standard. Obviously, the higher the environmental function is, the lower the carrying capacity is. The environmental function standard is the qualitative standard to judge the loss degree of the receptors.

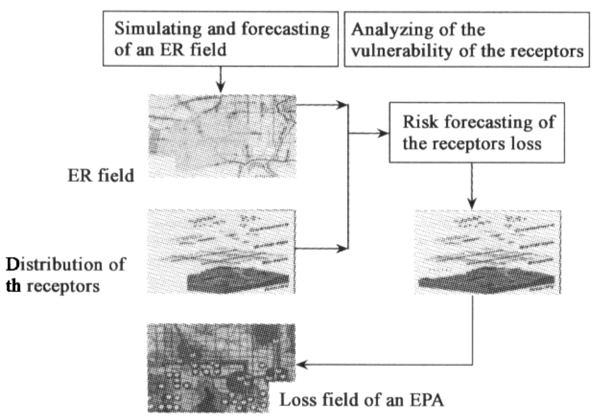

Fig. 3 Technical route of simulating and forecasting of the loss field of an EPA

The loss of the receptors depends on the intensity of the ER factors releasing. Its computer method is very much, such as market value, manpower capital, substitute market, opportunity cost, resume and protection cost and shadow engineering, etc. The expected value of an unit loss of different receptors could be computed as follows:

$$E(LOSS) = \sum_{i=1}^{n} LOSS_i \cdot F_{C_i}, \tag{12}$$

where, $LOSS_i$ is the loss of the No. i receptor; F_{C_i} is the risk that the intensity of the ER field exceed to the carrying capacity of the No. i receptor.

The expected value of an unit loss of every point in a certain receptors space could be determined by risk forecasting that the receptors suffer losing, and the sum of the expected value of the loss of every receptors is the loss value of the receptors in the point.

7 Conclusions

There is a general evolving law in the evolution from the environmental risk to the EPA, i.e., ER factors come from ER source and they are controlled by the PCM; due to the failures or outer environment factors, the PCM could not work regularly any more, the ER factors will release environmental space, then, an ER field is formed up. The forming of ER field does not mean that any EPA will break out; only the ER receptors are exposed in the ER field and are damaged seriously, the potential ER turns into an actual EPA.

The probability of ER factors releasing depends on the probability of failure of PCM, it mainly includes three elements: the first is the failure of PCM caused by the internal errors; the second is the failure of PCM caused by external errors; and the third is the failure caused by the ER triggering mechanism.

The ER factors release into the environmental space to form up an ER field, once the receptors are exposed in the ER field, the EPA will break out. The second control mechanism could prevent the forming of ER field, and the success probability relies on the failure rate of SCM.

The forecasting model of EPA includes two parts: one is happening probability, mainly depends on the failure probability of primary and second control mechanism; the other is happening strength, mainly relies on the strength of accident source and the position of ER receptors. During the process for forecasting the risk of environmental pollutions, the application of 3S(SR, GIS, GPS) technologies benefits to improve the precision and efficiency.

The forecasting model of EPA risk based on the general rules of ER evolving into EPA offers a scientific method for evaluating, preventing and responding the EPAs; on the one hand, it enrich and develop the environmental safety and response theories; on the other hand, it also show some directions for the public safety, enterprise's safety management and response.

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(Received for review April 6, 2004. Accepted August 3, 2004)