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Study on Mine Emergency Mechanism based on TARP and ICS

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Abstract. By analyzing the experiences and practices of mine emergency in China and abroad, especially the United States and Australia, normative principle, risk management principle and adaptability principle of constructing mine emergency mechanism based on Trigger Action Response Plans (TARP) and Incident Command System (ICS) are summarized. Classification method, framework, flow and subject of TARP and ICS which are suitable for the actual situation of domestic mine emergency are proposed. The system dynamics model of TARP and ICS is established. The parameters such as evacuation ratio, response rate, per capita emergency capability and entry rate of rescuers are set up. By simulating the operation process of TARP and ICS, the impact of these parameters on the emergency process are analyzed, which could provide a reference and basis for building emergency capacity, formulating emergency plans and setting up action plans in the emergency process.

1. Introduction

Trigger Action Response Plans (TARP) and Incident Command System (ICS) have been used for many years in Australian mining safety management, which have become effective tools for mining companies, rescue organizations and third parties when dealing with mine accidents. The application of these two emergency models is considered as an important reason for continuous good performance of Australian mine safety. At present, research on TARP mainly concentrates on the basic concepts and principles which were summed up by David Cliff according to years of Australia's mine safety practice and cases [1]. With regard to the research and applications of ICS in mine emergencies, two typical cases are the Incident Command and Control System (ICCS) developed by New South Wales Mine Rescue Service Center [2] and the Mine Emergency Management System (MEMS) developed by Queensland Mine Rescue Center. Chinese researchers also conduct many studies on mine emergency model and mechanism. For instance, Wu zongzhi [3] et al. proposed accident emergency rescue system and plan at the first place. Guo Deyong [4, 5] et al. conducted a research about coal mine gas emergency response mechanism. Zhang Junbo [6] et al. build a coal mine emergency rescue organization model based on the military C2 (Command and Control) system. In summary, researchers in Australia focus on the summary and practical application of emergency models, while researchers in China focus on mathematical modeling and quantitative analysis of emergency models in order to study their mechanism. Therefore, combing the advanced experiences from Australia with the relevant research and actual situation of

China, a modified mine emergency model based on TARP and ICS could be built, and its mechanism would be studied, which could provide a theoretical basis and reference for improving the level of mine emergency response in China.

2. Basic Principles of TARP and ICS

2.1. Normative principle

The principle of normative is the core principle of constructing TARP and ICS. By setting a series of goals, criteria, methods and discourse system covering from the internal response to external intervention, each participant could communicate and cooperate with other participants timely and accurately, which can improve the efficiency of emergency. Normative plans and command structure system could also ensure that the emergency process would not be lack of objectives and necessary procedures, which could improve orderliness and reliability of emergency response. At present, the typical applications of the normative principle are the five major areas (Prevention, Protection, Mitigation, Response, and Recovery) of emergency management established by the Federal Emergency Management Agency [7] (FEMA) and *ISO 22320: Societal security - Emergency management - Requirements for incident response* issued by the International Organization for Standardization. These normative terms and standards have become the prerequisite and basis for building emergency models and studying emergency mechanisms.

2.2. Risk management principle

During the construction and application process of TARP and ICS, many principles and methods of risk management have been adopted such as hazard identification, risk analysis, impact analysis etc. To some extent, risk management during daily operations focuses on preventing the emergence of risk. Risk management in TARP focuses on preventing risks expanding, while risk management in ICS focuses on eliminating the existing risks. Therefore, it is necessary to study and analyze the root of various risks during the emergency process and to adopt and improve different risk control technology according to various task requirements. These risk management methods and technology have become essential tools for building emergency models.

2.3. Adaptation principle

Various types of emergency rescue cases in China and abroad show that inadequate response and over-response may lead to a reduction in emergency response. Therefore, the triggering action response plan and the accident command system should be able to adjust the own organizational structure and process, rationally allocate and make full use of various resources to meet the emergency task requirements according to the severity of the situation and the task requirements of different emergency phases.

3. Mechanism of TARP

3.1. Trigger point setting

In the process of trigger action response, various types of disasters correspond to different trigger points. For example, the trigger points of the fire might be concentration of signature gas, temperature, smoke, etc. The trigger point of flood might be emission quantity, water level, etc. According to the threshold value of trigger point, the trigger response could be divided into TARP 1 (Normal), TARP 2 (Abnormal), TARP 3 (Alarm) and TARP 4 (Evacuation) [8]. Taking the mine fire accident as an example, we could use the percentage of the mixed flammable gas in a certain area and the possibility of the ignition source to set the corresponding trigger point of four TARP levels (shown as in Table 1).
Explosibility of mixed gas could be calculated with following formula.

$$EXP = \frac{V}{N} \times 100\% \tag{1}$$

In the formula above, *V* is the total volume fraction of the mixed gas and *N* is the lower explosion limit (LEL) of mixed gas calculated by the Le Chatelier formula.

3.2. Basic process of TARP

Table 1. Trigger Point of Fire Accident.

Levels of TARP		Explosibility of mixed gas (EXP)			
		0~40%	40%~60%	60%~80%	80%~
Possibility of ignition source	Very likely	3	3	4	4
	Likely	2	3	3	4
	Possible	2	2	3	3
	Impossible	1	2	2	3

TARP is mainly used for internal response process, which involves three main types of the main subjects [9]: workers, control room operators and duty managers. The response procedures of them on different TARP levels are shown in Figure 1.The mine monitoring system is responsible for collecting work environment data. Combining collected data with the pre-set trigger point, the control room operators determine the TARP level which has corresponding subjects and procedures.

3.3. System Dynamics Analysis of TARP

Trigger action response is a dynamic process which involves the operating environment parameters, operator behavior, information transmission and many other variables and processes. Using the theory and method of system dynamics, the system flow of response could be drawn (as shown in Figure 2) [10]. It can not only reflect the variables in the dynamic system, the causal relationship between the subjects, but also quantitatively analyze the different characteristics of system elements, which could show the mechanism of emergency response with higher accuracy [11].

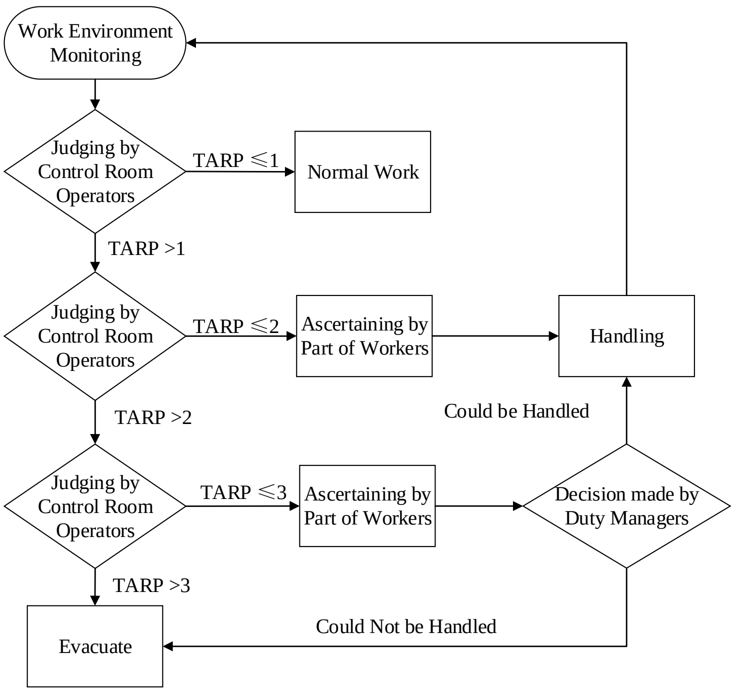


Figure 1. Basic Response Procedure of TARP.

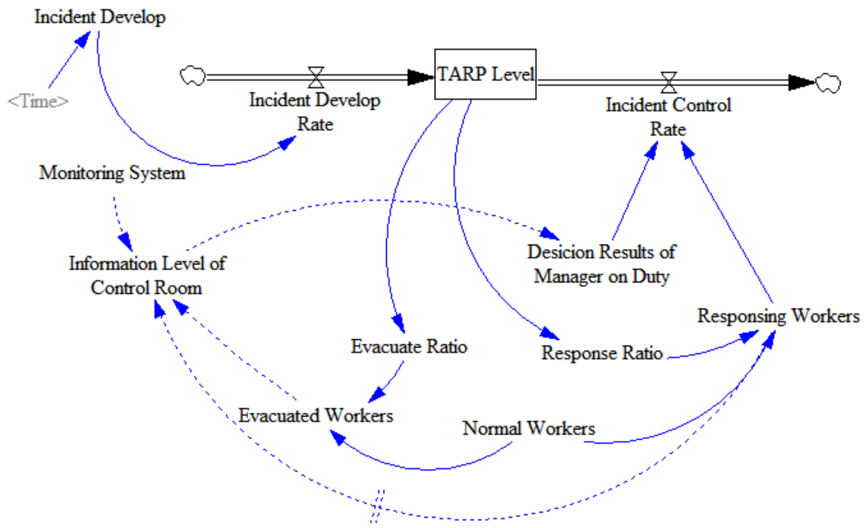


Figure 2. System Flow of TARP.

The TARP level (*TL*) varies with time. At time *t*, *TL(t)* is defined by:

$$TL(t) = \int_{t_0}^{t} (IDR(t) - ICR)\, dt \quad (2)$$

TL(t) determines the operator evacuation ratio(*ER*) and the operator response ratio(*RR*). Since the highest level of response TL_{max} has been determined during the response process, and the development rate is often related to the state of incident development (*ID*), the incident development rate (*IDR*) at time *t* can be determined by the differential equation of logistic model:

$$IDR(t) = \frac{dID(t)}{dt} = rID(t)\left(1 - \frac{ID(t)}{TL_{max}}\right) \quad (3)$$

At the same time, *ID(t)* could be solved, as follows:

$$ID(t) = \frac{TL_{max}}{1+(\frac{TL_{max}}{TL_0}-1)e^{-rt}} \quad (4)$$

TL_{max} represents the highest TARP level of the event. TL_0 represents the initial TARP level of the event, and *r* is the parameter that affects the rate of development.
The incident control rate (*ICR*) is defined by:

$$ICR = aRW \cdot DR \quad (5)$$

In the formula above, the decision result (*DR*) is defined as a dimensionless variable of 0 to 1. 0 represent a complete wrong decision. 1 indicates a complete correct decision. *RW* is the number of respondents. And *a* is the per capita emergency capability, that is, reciprocal of the required number of people for decreasing one TARP level during unit time. The decision result (DR) is defined by:

$$DR = d \cdot lg(IL) \quad (6)$$

In the formula above, the control room information level (*IL*) is defined as a dimensionless variable of 1 to 10. 1 indicates that the situation is completely unknown, 0 indicates that the situation is fully understood, and the decision capability *d* is defined as a constant of 0 to 1.
Control room information level (*IL*) is defined by the following:

$$IL = MS + b \cdot EW + eb \cdot RW \quad (7)$$

In the formula above, *MS* is the monitoring system information, *EW* is the number of evacuees, *RW* is the number of response person, *b* is the per capita information provided, and *e* is the efficiency of emergency information transmission.

Using Vensim PLE to simulate, the initial condition are r = 0.1, a = 0.02, b = 0.02, d = 0.6, e = 0.5, *MS* = 6. The number of operators is 50, and the simulation time is 100 hours. The corresponding relationship between TARP level *ER* and *RR* are shown in Table 2 and Table 3. The simulation results are shown in Figure 3 and Figure 4.

Table 2. Corresponding Relationship of ER, RR and TARP Level (First Simulation)

TARP level	ER	RR
1	0	0
2	0	0.2
3	0.9	0.1
4	1	0

Table 3. Corresponding Relationship of ER, RR and TARP Level (Second Simulation)

TARP level	ER	RR
1	0	0
2	0	0.1
3	1	0.0
4	1	0

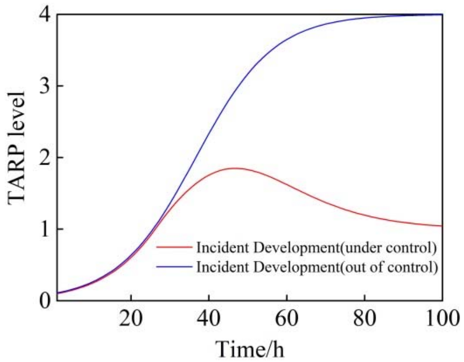


Figure 3. Incident Development (First Simulation).

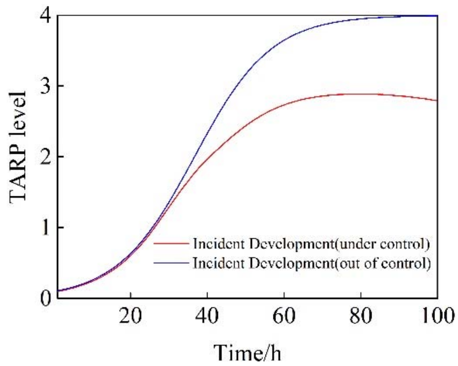


Figure 4. Incident Development (Second Simulation).

The blue curve in Figure 3 and Figure 4 shows the incident development when the state is not controlled. The red curve in Figure 3 indicates that the incident is controlled in time (below TARP level

2 and tends to be normal. The red curve in Figure 4 represents a relatively conservative response, which makes the development of the incident cannot be effectively controlled. Therefore, in the process of making emergency plans, we can set the initial conditions by following the actual situation and the specific type of disaster. With reference to the simulation results, different *ER* and *RR* values could be set, and different emergency strategies would be generated so that the purpose of preventing the expansion of situation could be achieved.

In the case of other initial conditions unchanged, by changing the value of the parameter *a* representing the per capita emergency capability, we examine its impact on the overall TARP level. In Figure 5, the third to sixth simulations were performed, respectively, and the values of *a* were 0.04, 0.06, 0.08 and 0.10, respectively. Moreover, compared with the simulation results of the first time, it can be found that the increase of *a* has a nonlinear relationship with the decrease of TARP level, the early decline is relatively significant, and the later decline is relatively small. Therefore, in the process of building emergency response capacity, referring to the simulation results, a reasonable emergency capacity building goal could be set.

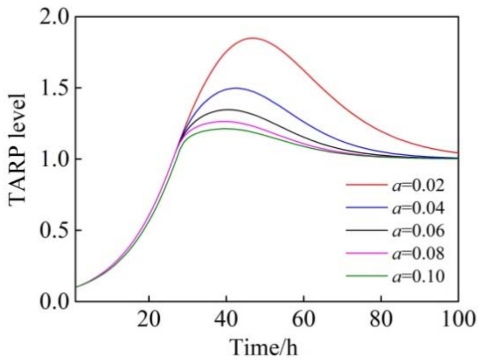


Figure 5. Per capita Emergency Ability and TARP Level.

4. Mechanism of ICS

When the situation is further expanded, especially if there are casualties or personnel trapped, or the development has exceeded emergency response capability of the mine itself requiring the involvement of professional rescue organizations, the introduction of incident command system (ICS) is needed. ICS was originally used to deal with forest fires in California and Arizona, and its main purpose was to address the organization and coordination issues between agencies involved in emergency response. After years of development, ICS has become a critical component of the U.S. National Incident Management System, which has expanded from forest fires to emergency situations such as public safety, hazardous substance handling and natural disasters [12].

4.1. Basic structure and procedure of ICS

The basic ICS structure [2] in the mine emergency process is shown in Figure 6. The Incident Commander, Deputy Commander, Security Officer, Planning Group Leader, Action Group Leader and Logistics Team Leader form Incident Management Team (IMT). Planning group, action group and logistics group have several subgroups. The response process is shown in Figure 7. When the situation is expanded (the casualties or personnel trapped), incident management team would be set according to the emergency plan. The incident management team determines the emergency target and convene the corresponding staff to set up a full ICS. The planning group is responsible for information summary, requirements, preparing media materials and the development of action plans. The incident management team is responsible for review and approval of action plans. The action group is responsible for the implementation of action plans. The logistics group is responsible for the overall resource support and information disclosure.

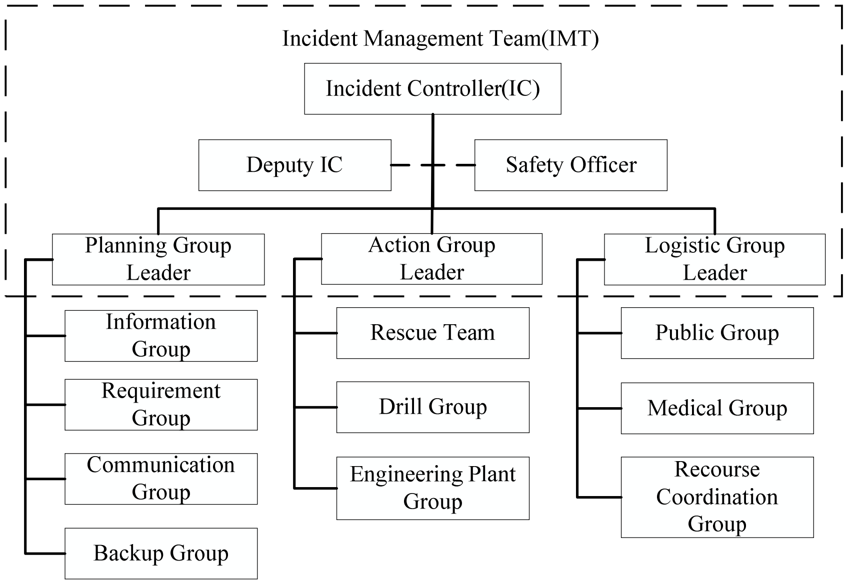


Figure 6. Basic Structure of ICS.

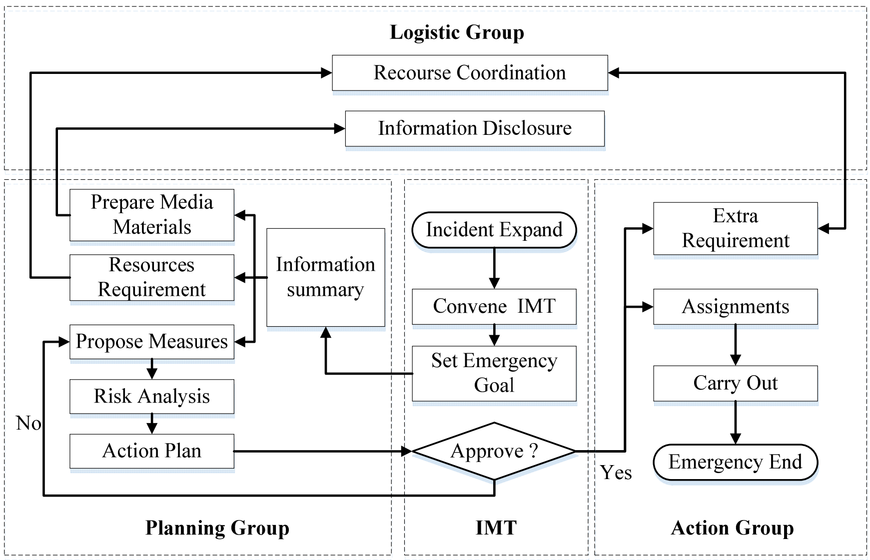


Figure 7. Operation Procedure of ICS.

4.2. System Dynamics Analysis of ICS

Using the system dynamics method described in previous, the system flow of the ICS operation is drawn (see Figure 8), and the corresponding mathematical model is established to analyze its operating mechanism.

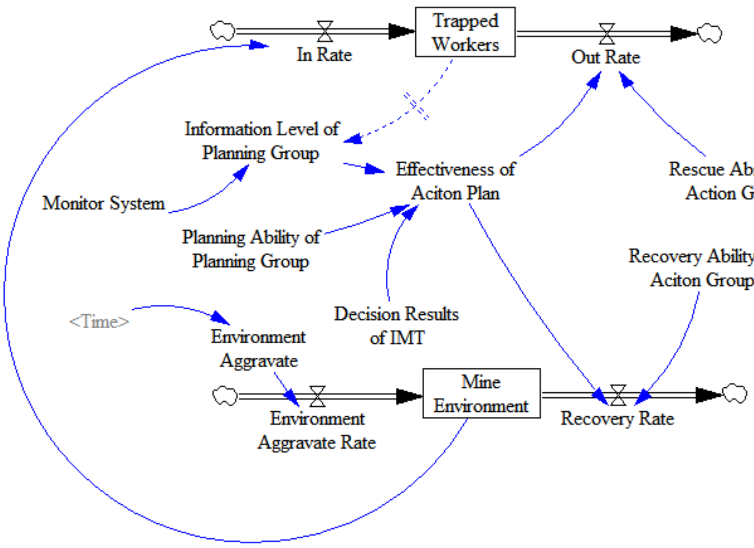


Figure 8. System Flow of Mine Emergency ICS Operation.

In Figure 8, the two objectives of the rescue task are to rescue the trapped personnel and recovery mine environment. The mine environment variable (*ME*) is defined as the percentage of the environmental parameter value to its maximum allowable value (e.g. combustible gas explosion in Table 1).At time *t*, *ME (t)* is defined by:

$$ME(t) = \int_{t_0}^{t} \left(RCR - EAR(t)\right) dt \tag{8}$$

EAR(t) represents the mine environmental degradation rate, which could also be defined by the differential equation of logistic function:

$$EAR(t) = \frac{dEA(t)}{dt} = \frac{EA(t)}{dt} = sEA(t)\left(1 - \frac{EA(t)}{EA_{max}}\right) \tag{9}$$

At the same time, the state quantity of the environment deterioration *EA (t)* can be solved, as follows:

$$EA(t) = \frac{EA_{max}}{1+(\frac{EA_{max}}{EA_0}-1)e^{-st}} \tag{10}$$

And *s* is the parameter that affects the environmental degradation.

The environment recovery variable (*RCR*) is defined by:

$$RCR = E \cdot RCA \tag{11}$$

In the formula, the effectiveness (*E*) of the action plan is defined as a dimensionless variable of 0 to 1, 0 means that the plan is completely invalid and 1 indicates that the plan is fully functional. *RCA* is the mine environmental recovery capability of the action group, i.e. the decrease rate of the mine environment variable *ME*.

The effectiveness of the action plan (*E*) is determined by the planning group information level (*ILP*), the planning group planning capability (*PA*) and the accident management team decision result (*DRI*), as follows.

$$E = \lg(ILP \cdot PA) \cdot DRI \tag{12}$$

Planning Group Information Level (ILP):

$$ILP = MS + e \cdot TW \tag{13}$$

The number of trapped persons changes with time TW (t), defined by:

$$TW(t) = \int_{t_0}^{t} (IR(t) - OR)\, dt \tag{14}$$

Personnel in rate (*IR*), defined as the number of people entering the mine per unit time, are determined by the mine environment (*ME*). Personnel out rate (*OR*) is determined by the following formula:

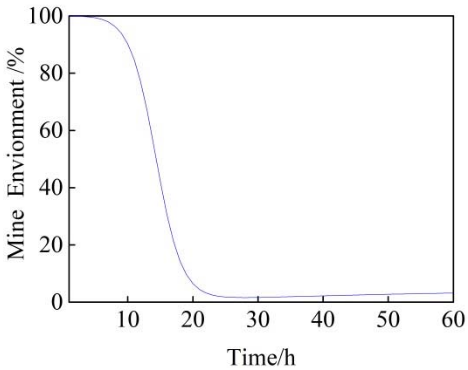
$$OR = E \cdot RSA \tag{15}$$

In the formula above, *RSA* is the rescue team's ability to rescue, that is, the number of people rescued per unit of time (including the rescue workers themselves).

Using Vensim PLE to simulate, the number of initial conditions was TW_0 = 10, *s* = 0.5, *MS* = 5, *e* = 0.5, *PA* = 0.6, *DRI* = 0.6, *RCR* = 0.1, *RSA* = 9. Corresponding Relationship of *IR* and *ME* is shown as Table 4. The simulation time is 60 hours, the simulation results are shown in Figure 9 and Figure 10.

Table 4. Corresponding Relationship of *IR* and *ME*.

ME/%	IR
0~20	4
20~40	3
40~60	2
60~80	1
>80	0



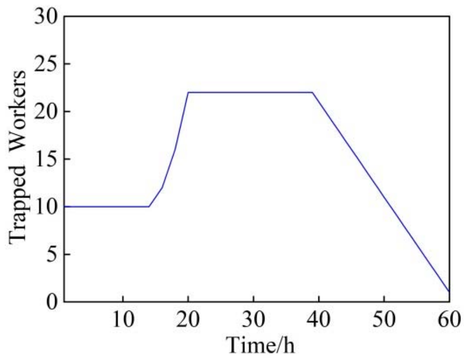


Figure 9. Time-Dependent Mine Environment. **Figure 10.** Time-Dependent Trapped Workers.

It can be seen from Figure 9 and Figure 10, with the implementation of the effective action plan, the mine environment variable *ME* gradually become normal. When *ME* reaches the critical point, the rescuers gradually enter the mine. After a period of search and rescue, rescuers withdraw the mine with the trapped people. In the actual process, the parameters of the ICS system dynamics model can be set according to the specific situation, and the rescue process could be deduced, which will provide reference and basis for the formulation of emergency plans and action plans during the emergency process.

5. Conclusion

Analyzed the experience and practice of mine emergency in China and abroad, three basic principles of constructing mine emergency mechanism based on TARP and ICS are summed up: normative principle, risk management principle and adaptability principle. According to the actual situation of mine emergency response in China, the classification method, basic structure, procedure and subject of TARP and ICS are purposed.

The system dynamics model of TARP and ICS was established, and a series of parameters to construct TARP and ICS emergency mechanism were set up such as parameters such as evacuation ratio(*ER*), response rate (*RR*), per capita emergency capability (*a*), mine environment (*ME*) and

Personnel in rate (*IR*). By simulating the operating process of TARP and ICS, the impact of these parameters on the emergency process are analyzed, which could provide a reference and basis for building emergency capacity, formulating emergency plans and setting up action plans in the emergency process.

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