EVALUATION OF THE CLOSED-TYPE SPRINKLER HEAD ACTIVATION TIME

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Abstract : As a predominant active fire suppression method, closed-type sprinkler systems are used for the purpose of fire control and suppression at the nuclear power plants as well as the industrial facilities. It goes without saying that the proper selection of the system guarantees the adequate actuation of the thermal device. Consequently, the appropriate evaluation should be executed for the thermal behavior with the theoretical and empirical approach. For this purpose, the comparison of activation time for the fusible-link type sprinkler head with the simplified fire case and t-square fire growth case was evaluated. At this paper, the comparison output was presented with the tendency of thermal behavior. In addition, we issued some technical comments for the most appropriate equation in case of the estimation of the sprinkler head activation time. We also raised some idea that should be incorporated for the usage of the t-square equation for the realistic application in the field of the performance-base fire protection approach.

Nomenclature

$t_{activation}$	: sprinkler head activation time [sec]	RTI	: response time index [(m-sec)$^{1/2}$]
U_m	: gas velocity [m/sec]	T_m	: gas temperature [℃]
T_o	: ambient temperature [℃]	T_{act}	: activation temperature of head [℃]
t_s	: activation time at modified condition[sec]	Q'_s	: heat release rate at time, t_s
z/H	: height above fire [m]	r	: radial distance from fire [m]
α	: fire intensity coefficient [kW/sec^2]	t_c^p	: critical time factor for t-square [sec]
t^p/t_a	: activation time for t-square [sec]	t_{t2}/t_{DT2}	: activation time for t^2/DETECT-T2 [s]

1. INTRODUCTION

It is predominant that the sprinkler system is preferred for the active fire control and suppression system at the industrial buildings as well as at the residential and commercial areas. At nuclear power plants, the sprinkler systems have been chosen and utilized as an active fire protection facility with specific purposes such as the capability of safe shutdown the reactor and the defense in-depth philosophy. Considering the sprinkler system for the wide application from the onset of design stage and the installation afterwards as an active fire protection system at several fire areas, it must be stressed the importance of reliability of proper actuation at its needs. In this sense, the functioning of the thermal mechanism of the closed-type sprinkler head is a major concern in the research and development field coincident with the adoption of performance-based fire analysis approach.

Recently, with the specific research of thermal behavior of the sprinkler head opening, it came to be utilized computer programs to predict the performance of the thermal detectors and their capability for the design purpose. With the theoretical and empirical approach as well, many sorts of fire evaluation and prediction programs as a zone or field modeling are now available at the fire protection engineering discipline. Some zone models need only a few minutes to get the simulated output and others such as computational fluid dynamics take one or two days to find the final result through the convergence process. Notably, in consideration of much effort and cost, the reliability and validity of the basic theories and empirical equations should be credited for the wide use of computer programs. In this context, we evaluated the basic equation whose purpose is to find the activation time of the closed-type sprinkler head for the two cases, that is, the simplified steady-state fire growth case and the time-square fire growth situation. In addition, the preliminary output was checked by use of the program, "DETACT-T2", which was developed by the National Institute of Standard and Technology in America. Consecutively, the critical time derived from the steady fire growth case was used as an input variable for the validity check of the t-squared fire equation. At conclusion, an insight was issued the proper usage of the equations for the estimation of the sprinkler heads with the proper modification for their application at industrial sites.

2. Estimation of the closed-type sprinkler head activation time

The primary case for the estimation of the sprinkler head is the simplified fire growth that assumes that the heat release rate is steady. Edward K. Budnick, David D. Evans and Harold E. Nelson described the theory. Robert P. Schifiliti, Brian J. Meacham, and RICHARD L.P. Custer developed the second case used for the calculation of the sprinkler head actuation time.

2.1 Steady-state fire growth case

Steady state means that the heat release rate is assumed constant ideally. In case of steady state, the time for the activation of the sprinkler head or the thermal detector is given as follows.

$$t_{activation} = \frac{RTI}{\sqrt{U_m}} \ln\left(\frac{T_m - T_o}{T_m - T_{act}} \right) \qquad \text{------------------------- (1)}$$

At the equation, it is visible that RTI, ambient temperature, and the activation temperature of the thermal device are constant parameters. Others such as the gas temperature presented as T_m, and the gas velocity with the symbol of $U_{m,}$ are defined as below depending on the geometry of fire zone and the location of thermal devices.

$$T_m = T_o + 16.9 \frac{q^{2/3}}{z^{5/3}} \Leftrightarrow \quad for \ \frac{r}{z} \leq 0.18 \qquad \text{---------------------------- (2)}$$

$$T_m = T_o + \frac{5.38}{z}\left(\frac{q}{r}\right)^{2/3} \Leftrightarrow \quad for \ \frac{r}{z} > 0.18 \qquad \text{--------------------------- (3)}$$

$$U_m = 0.96\left(\frac{q}{z}\right)^{1/3} \Leftrightarrow \quad for \ \frac{r}{z} \leq 0.15 \qquad \text{-------------------------- (4)}$$

$$U_m = 0.195 \frac{q^{1/3} z^{1/3}}{r^{5/6}} \Leftrightarrow \quad for \ \frac{r}{z} > 0.15 \qquad \text{------------------------- (5)}$$

At each location of the sprinkler head, the activation time of thermal detector can be calculated at simple manipulation. However, it should be noted that there are some applications and limitations for this equation, that is, the case is valid for the quite large scale of fires from 670 kW to 100 MW with the unconfined ceiling jet flow.

2.2 time squared fire-growing case

In reality, the stages of fire growth have the characteristics of fire incipient stage, slowly growing development process. Then, it grows to the fully developed state after flash over and transfers to the decay status. To figure out the fire phenomenon at the initial developing stage, there are several models to calculate the gas temperature and its velocity at the plume zone and the ceiling jet area. The t-square fire growth approach is one of the realistic power-law analyses to justify the heat release rate and the rapidly increasing fire behavior.

At the t-square fire growth, the activation time can be estimated with the assumption of time t with the iteration manipulation. The modeling for the temperature and velocity of fire gases as a form of non-dimensional format was presented by Heskestad and Delichatsios with the correlation of fire growth rate, that is, the function of critical time to reach at 1055 kW and the variable of non-dimensional time for the activation. The power-law relationship is presented with the equation as below.

$$Q' = \alpha t^{p} = \frac{1055}{t_c^{p}} t^{p} \Leftrightarrow here, \alpha = \frac{1055}{t_c^{p}} (fire \wedge \mathrm{int}\, ensity \wedge coefficien\ t) \quad \text{----------} \ (6)$$

It is noted that α means the fire intensity coefficient. It is the function of the critical time as defined that the time at which a power-law fire would reach a heat release rate of 1055 kW. The numeric value of p at the above equation is 2 for the t-square case. The relative formula given by Heskestad and Delichatsios for the gas temperature and velocity in the fire zone are specifically described at the reference handbook for the closed-type sprinkler heads.

2.3 Evaluation for the sprinkler head activation time with fusible link

At each case, the geometry and the circumstance of the fire area are same. However, the location and fire growth rate are set up for three different situations to verify the fire behavior. Geometrically, the width and the length of the fire area are 12 and 10 meter respectively. The ceiling is flat with the closed opening and the flow type is established as an unconfined state. The fusible link is actuated at the temperature of 74°C at the room temperature of 20°C. The height from the fire source to the sprinkler head is 3.5 meter and the horizontal distances are assumed to locate at the plume zone, ceiling jet zone and the intermediate zone.

The Excel program was used to calculate the sprinkler head activation time for two cases for the easy dealing with the iterative process. For the convenience of the estimation, The response time for the sprinkler head was selected as 130 $(m\cdot sec)^{1/2}$ for the standard response link and 34 $(m\cdot sec)^{1/2}$ for the quick response link. For each fire growth case, the sprinkler head was located at the plume zone with the value of 0.5 meter, the intermediate zone with the value of 0.6 meter, and the ceiling jet area with the value of 1.0 meter respectively.

For the t-square fire growth, it was assumed that critical time for the slow, medium, and fast growth rate was set to be 400, 275, and 150 second. In parallel, for the steady fire growth case, a constant heat release rate of 250, 500, and 1000 kW was given for a small, medium, and large fire. The following tables and figures show the summarized calculation result for the steady heat release case and the t-square fire growth situation.

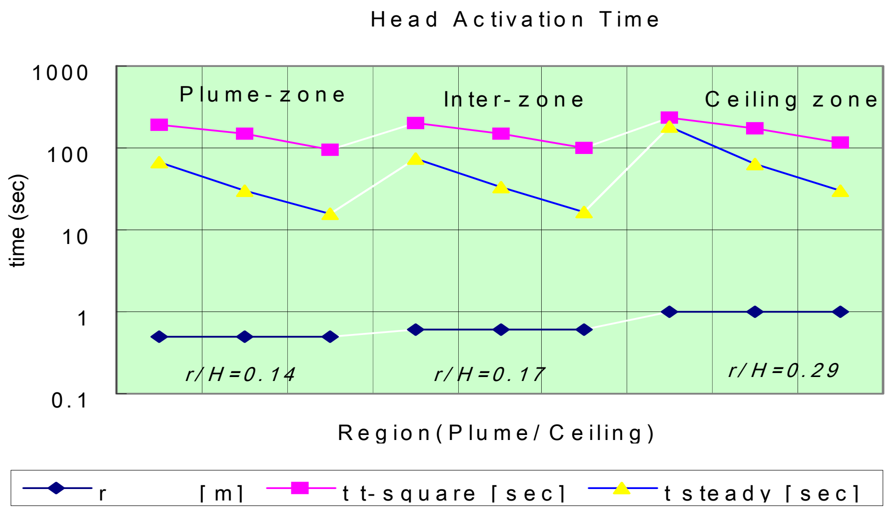
[Table 1. Activation time at steady-state fire growth with RTI=130]

Parameters	**Small Medium Large**	**Small Medium Large**	**Small Medium Large**
Height	3.5 m	3.5 m	3.5 m
Room temperature	20°C	20°C	20°C
RTI Activation	130$(m\cdot sec)^{1/2}$	130$(m\cdot sec)^{1/2}$	130$(m\cdot sec)^{1/2}$
temperature Radius	74°C	74°C	74°C
HRR (kW)	0.5 m	0.6 m	1.0 m
Actuation time(sec)	250 500 1,000	250 500 1,000	250 500 1,000
	68.3 30.5 15.4	**72.7 32.5 16.4**	**185.6 62.3 29.5**

[Table 2. Activation time at t-square fire growth with RTI=130]

Parameters	**Slow**	**Medium**	**Fast**	**Slow**	**Medium**	**Fast**	**Slow**	**Medium**	**Fast**
Height		3.5 m			3.5 m			3.5 m	
Room temperature		20°C			20°C			20°C	
RTI Activation		130$(m\cdot sec)^{1/2}$			130$(m\cdot sec)^{1/2}$			130$(m\cdot sec)^{1/2}$	
temperature Radius		74°C			74°C			74°C	
Critical time(sec)		0.5 m			0.6 m			1.0 m	
Actuation time(sec)	400.0	275.0	150.0	400.0	275.0	150.0	400.0	275.0	150.0
	191.6	**146.5**	**96.50**	**200.0**	**152.5**	**100.5**	**229.5**	**175.5**	**115.5**

The comparison for two cases with the RTI value of 130 is shown at figure 1 for each zone. The slopes for the different location have the similar tendency, but the point values have quite



big difference between the steady heat release rate and the time-squared heat release rate.

[Figure 1. Comparison of computational output for RTI=130]

Table 3 and Table 4 with the Figure 2 represent the evaluation output for the RTI value of 34, which is typical for the quick response sprinkler head.

[Table 3. Activation time at steady-state fire growth with RTI=34]

Parameters	**Small Medium Large**	**Small Medium Large**	**Small Medium Large**
Height	3.5 m	3.5 m	3.5 m
Room temperature	20°C	20°C	20°C
RTI Activation	34(m·sec)$^{1/2}$	34(m·sec)$^{1/2}$	34(m·sec)$^{1/2}$
temperature Radius	74°C	74°C	74°C
HRR (kW)	0.5 m	0.6 m	1.0 m
Actuation time(sec)	250 500 1,000	250 500 1,000	250 500 1,000
	17.9 8.0 4.0	**19.0 8.5 4.3**	**48.6 16.3 7.7**

[Table 4. Activation time at t-square fire growth with RTI=34]

Parameters	**Slow**	**Medium**	**Fast**	**Slow**	**Medium**	**Fast**	**Slow**	**Medium**	**Fast**

Height		3.5 m			3.5 m			3.5 m	
Room temperature		20°C			20°C			20°C	
RTI Activation		$34(m\cdot sec)^{1/2}$			$34(m\cdot sec)^{1/2}$			$34(m\cdot sec)^{1/2}$	
temperature Radius		74°C			74°C			74°C	
Critical time(sec)		0.5 m			0.6 m			1.0 m	
Actuation time(sec)	400.0	275.0	150.0	400.0	275.0	150.0	400.0	275.0	150.0
	156.5	**115.0**	**72.0**	**162.5**	**119.5**	**75.0**	**186.0**	**137.0**	**86.0**

At the figure 2, the similar tendency is projected on the graph with the output shown on

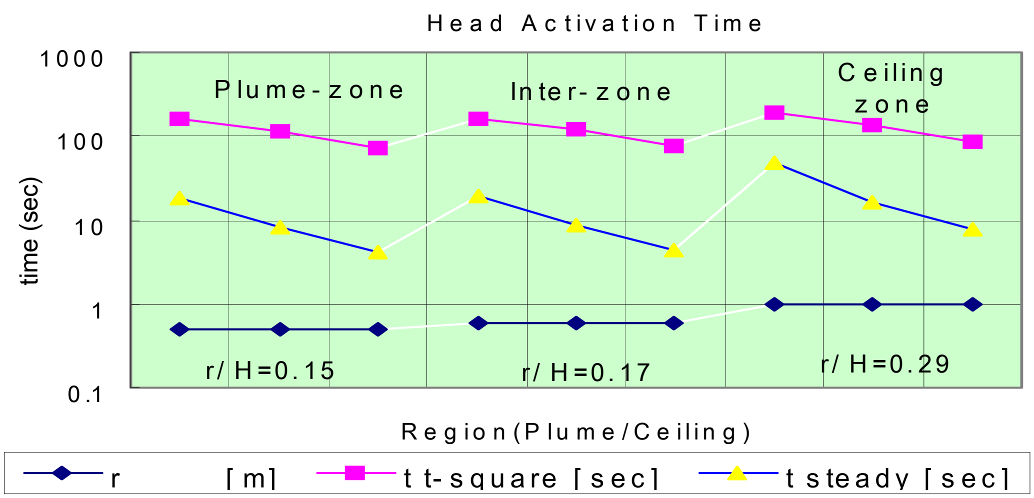


Figure 1.

[Figure 2. Comparison of computational output for RTI=34]

3. Activation time verification by use of DETACT-T2, Computer Program

DETACT-T2 is a program developed by the National Institute of Standard and Technology to predict the actuation time of thermal device such as the constant-temperature heat detector and sprinkler head with unconfined ceilings. The input parameters to utilize the programs are the ambient temperature, the response time index for the head, the activation temperature, and fire growth rate such as slow, medium, and fast with geometric variables. The output of the program shows the heat release rate and the time to activation of the thermal detector.

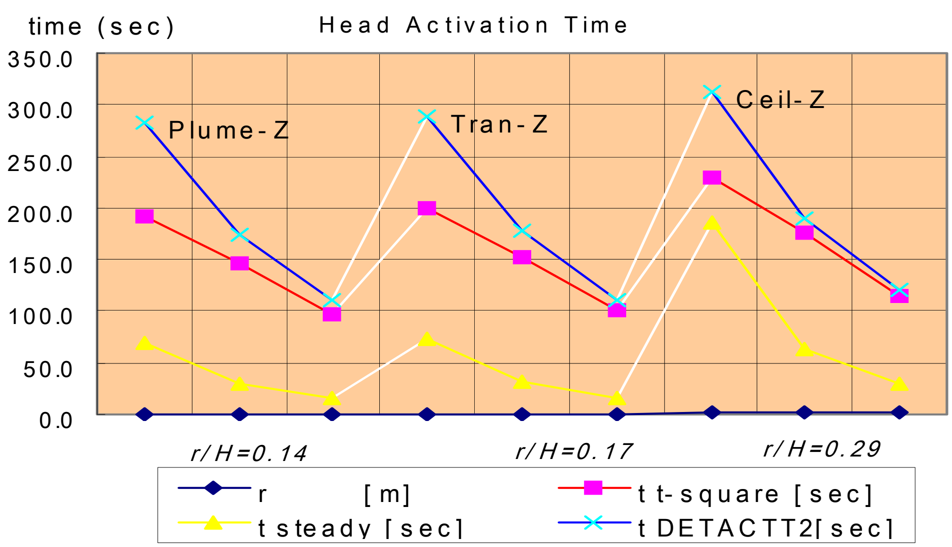
3.1 Comparison of the outputs

The same inputs that are used for the t-square fire growth case are also given to the DETACT-T2. For the direct comparison with the steady fire growth case and the t-square fire growth situation, the calculated results are shown on the tables and figures.

In this evaluation, the thermal conditions are same with the previous analysis. The fire zone is divided into three regions, that are, plume zone, intermediate area, and the ceiling jet boundary depending on the location of the thermal detectors. Table 5 and Figure 3 present the activation time and its trend for the RTI value of 130.

[Table 5. Activation time for each case with RTI=130]

Case	Plume Zone			Inter-Zone			Ceiling Jet Zone		
Radius	0.5 m			0.6 m			1.0 m		
Time : Steady state	**68.3**	**30.5**	**15.4**	**72.7**	**32.5**	**16.4**	**185.6**	**62.3**	**29.5**
Time : time-squared	**191.6**	**146.5**	**96.5**	**200.0**	**152.5**	**100.5**	**229.5**	**175.5**	**115.5**
Time : DETACT-T2	**282.0**	**173.4**	**109.8**	**288.0**	**177.0**	**109.8**	**312.6**	**191.8**	**120.6**

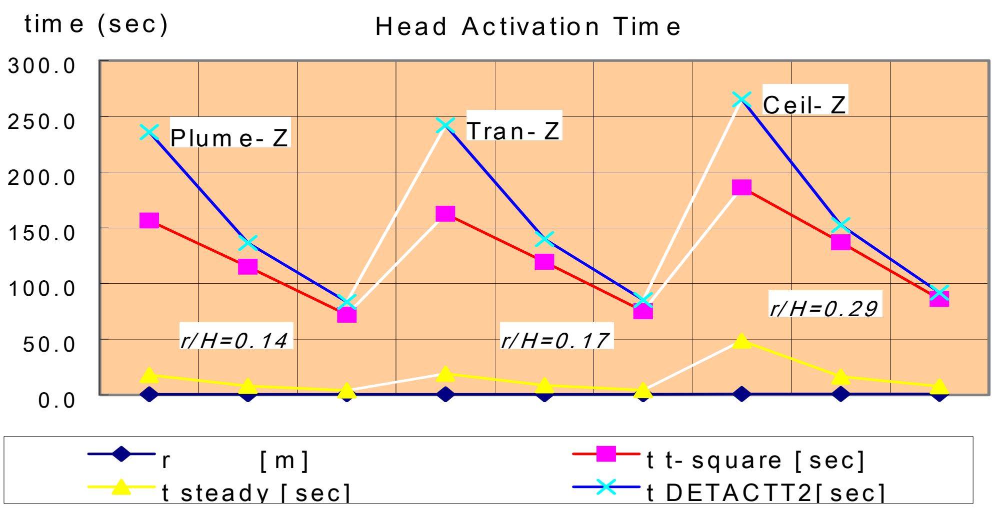


[Figure 3. Trend for the steady, t-squared, and DETACT-T2 Cases]

Table 6 and Figure 4 also present the activation time and its trend for the RTI value of 34.

[Table 6. Activation time for each case with RTI=34]

Case	Plume Zone			Inter-Zone			Ceiling Jet Zone		
Radius	0.5 m			0.6 m			1.0 m		
Time : Steady state	**17.9**	**8.0**	**4.0**	**19.0**	**8.5**	**4.3**	**48.6**	**16.3**	**7.7**
Time : time-squared	**156.5**	**115.0**	**72.0**	**162.5**	**119.5**	**75.0**	**186.0**	**137.0**	**86.0**
Time : DETACT-T2	**235.8**	**136.2**	**83.4**	**241.8**	**139.8**	**85.2**	**265.2**	**152.4**	**91.8**



[Figure 4. Trend for the steady, t-squared, and DETACT-T2 Cases]

3.2 Adequacy Evaluation for the t-square equation

In order to evaluate the adequacy and its validity of the equation for the t-square fire growth rate, the critical time was construed from the equation of the steady fire growth based on the following approach.

$$Q'_s*(t_s)=\frac{1055}{t_c^p}\int t^p dt \Leftrightarrow here\ , p = 2 \quad \text{-- (7)}$$

As a result, critical time is calculated as a modified equation, $t_c = (\frac{1055}{3}*\frac{t_s^2}{Q'_s})^{1/2}$

From the above approach, the critical time that is presented as tc is derived with the function of time at which the sprinkler head is activated. The calculated critical time is used to get the revised activation time for t-square fire growth case. As a result, the original critical time is substituted with the newly calculated one for the modification of the t-squared fire growth case. On the other hand, for DETACT-T2, the calculated critical time should be utilized as a determinant factor for the evaluation of fire intensity ratio, that is to say, if the value is less than 75 seconds, the fire growth rate is judged as a ultra-fast fire growth case. If the value is larger than 75 but less than 150 seconds, it is treated as fast fire growth case and if the value is larger than 275 seconds, the situation is classified as a medium fire growth case.

The table 7 and table 8 and the figure 5 deliver the modified output and its trend for the standard sprinkler head with the RTI value of 130.

[Table 7. Critical time derivation from the steady-state fire growth with RTI=130]

Parameters	**Small**	**Medium**	**Large**	**Small**	**Medium**	**Large**	**Small**	**Medium**	**Large**
RTI	130(m·sec)$^{1/2}$			130(m·sec)$^{1/2}$			130(m·sec)$^{1/2}$		
Radius	0.5 m			0.6 m			1.0 m		
HRR (kW)	250	500	1,000	250	500	1,000	250	500	1,000
Actuation time(sec)	68.3	30.5	15.4	72.7	32.5	16.4	185.6	62.3	29.5
Derived Critical time	**81.0**	**25.6**	**9.1**	**86.2**	**27.3**	**9.7**	**220.1**	**52.2**	**17.5**

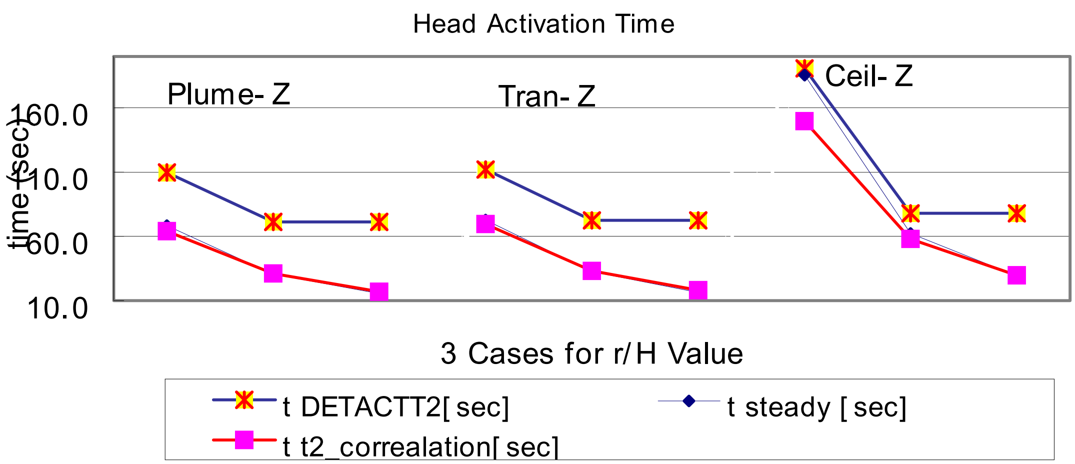
[Table 8. Activation time at t-square fire growth with RTI=130]

Parameters	**Slow**	**Medium**	**Fast**	**Slow**	**Medium**	**Fast**	**Slow**	**Medium**	**Fast**
RTI	130(m·sec)$^{1/2}$			130(m·sec)$^{1/2}$			130(m·sec)$^{1/2}$		
Radius	0.5 m			0.6 m			1.0 m		
Derived Critical time	**81.0**	**25.6**	**9.1**	**86.2**	**27.3**	**9.7**	**220.1**	**52.2**	**17.5**
Actuation time(sec)	**64.2**	**31.2**	**16.8**	**69.7**	**33.0**	**18.2**	**149.8**	**58.1**	**29.6**
Fire Growth Ration	**Fast**	**U-Fast**	**U-fast**	**Fast**	**U-Fast**	**U-fast**	**Medium**	**U-Fast**	**U-fast**

[Table 9. Comparison for Modified Output with RTI=130]

Case	**Plume Zone**	**Inter-Zone**	**Ceiling Jet Zone**

Radius		0.5 m			0.6 m			1.0 m	
Time : Steady state	68.3	30.5	15.4	72.7	32.5	16.4	185.6	62.3	29.5
Time : time-squared	**64.2**	**31.2**	**16.8**	**69.7**	**33.0**	**18.2**	**149.8**	**58.1**	**29.6**
Time : DETACT-T2	**109.8**	**71.4**	**71.4**	**112.2**	**72.6**	**72.6**	**190.8**	**78.0**	**78.0**

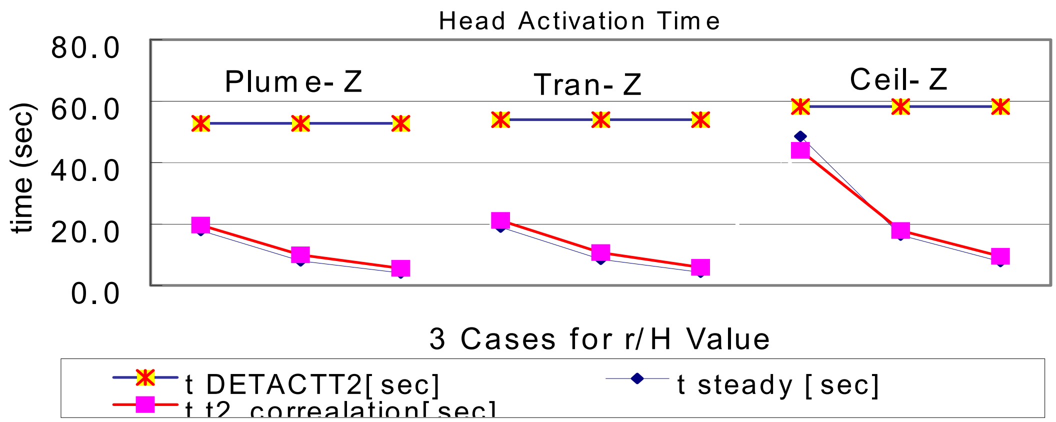


[Figure 5. The trend of the modified Output with RTI=130]

The output and the trend are quite similar for the RTI value of 34 compared to those with RTI value of 130. At table 10, the output is shown and on figure 6, the trend is presented.

[Table 10. Comparison for Modified Output with RTI=34]

Case	Plume Zone			Inter-Zone			Ceiling Jet Zone		
Radius		0.5 m			0.6 m			1.0 m	
Time : Steady state	17.9	8.0	4.0	19.0	8.5	4.3	48.6	16.3	7.7
Time : time-squared	**19.6**	**9.9**	**5.6**	21.1	10.7	**5.9**	**43.9**	**17.9**	**9.5**
Time : DETACT-T2	**52.8**	**52.8**	**52.8**	**54.0**	**54.0**	**54.0**	**58.2**	**58.2**	**58.2**



[Figure 6. The trend of the modified Output with RTI=34]

3.3 Technical evaluation for the activation time of sprinkler head

The prediction for the activation time of the closed-type sprinkler head was performed for two typical types. One is the standard link-type sprinkler head and the other is the quick response sprinkler head. The thermal device was assumed to be located at three zones. Primary zone is the plume region that is directly affected by the hot gas rising from the fire source and the ceiling jet zone is referred to the relatively rapid gas flow zone in a shallow layer beneath the ceiling surface. The interface area is referred to the intermediate zone.

In consideration of the simulated output, some potential remarks can be raised for the evaluation purposes. First of all, activation time of the sprinkler head for the steady heat release rate and the t-square fire growth showed quite big difference in their activation value. While the gap is large, it still needs further research in order to confirm the adequacy of the equivalent comparison between the fire growth rate and the fire size. The other insight is that the activation time of the thermal device for each fire zone reduced simultaneously with the rapid increase of fire growth rate as well as the amount of the fire size. Another finding is that for the t-square fire growth case and the DETACT-T2 program, the basic concept for the prediction of gas velocity and thermal phenomena are similar each other, but the result showed some difference. Consequently, the output from the DETACT-T2 program is more conservative than that from the t-square fire growth case.

One of outstanding results from this research is the output and the trend of the modified simulation. For the proper comparison, the output from the modified activation time at the t-square fire growth case, DETACT-T2 was equivalently calculated on the basis of modifed input parameters. The result showed the proximity tendency for the output between the steady state and the t-squared fire growth unexpectedly, but contrary to the expectation the output of DETACT-T2 was quite conservative and seemed to be impractical in some sense. As a whole, it was judged that the t-square equation is quite reasonable and is available for the applicable model to the performance-based fire behavior analysis.

One important insight is that the critical time to reach at 1044kw is not the input parameter for the t-square fire growth situation but rather the heat release rate is the critical factor. On the contrary, in practice, it is easier to estimate the critical time judging from the features of the combustibles to be fast, medium, and fast fire growth rather than to find out the heat release rate for the fixed and transient combustible load. In this sense the t-square equation seemed to be more reasonable tool if the critical time is incorporated to the equation as a user-input parameter. In addition, if the modified equation is supplemented to the algorithm at the computer-based program, which can supply more convenient and practical estimation as the state-of-the-art technology.

4. CONCLUSIONS

Nowadays, it is able to verify the fire hazard analysis and quantitative evaluation by use of electronic programs. With improvement of uncertainty in design variables and technical development in engineering areas, fire protection techniques for the nuclear power plant as well as in industrial buildings have shown drastic progress in risk evaluation and in assurance of fire protection capabilities. Specifically, the risk-informed and performance-based fire protection technology for the nuclear power plants is under development with implementation guide in U.S. by the regulatory body and the relevant entities. It is notable that more accurate quantitative analysis is possible by the wide variety of computer programs and tools such as FDS, Flow-3D as CFD models and FPEtool, CFAST, FIVE as zone models.

In this situation, it should be raised that the users have to understand not only the appropriate selection of relevant equations but also the limitation and applicability of the computer programs. As one of examples for the user to be accustomed to this kind approach, we focused to the evaluation of the equations for the activation time of the sprinkler head for comparison and obtained some meaningful conclusions. Technically, it is also assured that the equation for the t-square fire growth is quite reasonable and it is required to incorporate some modification at user-friendly input parameters.

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