



Probability of Burn Victim Survival from BLEVE Fireball Impact during LPG Transportation Accident

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Abstract

The probability of burn victim survival from BLEVE fireball impacts during an LPG transportation accident can be estimated by understanding the thermal radiation model and the consequences of a BLEVE. The sequence of a BLEVE fireball event is reviewed as guidance in collecting sufficient data and elements to be used throughout this study. The differences between two thermal radiation models which are solid-flame and point-source model have also been distinguished theoretically. Malaysia LPG specification is used to simulate this case study. Thermal radiation by solid-flame model is taken as the main parameter to be compared with few tables, charts and models in determining the consequences of a BLEVE event. Different chances of survival probability are discussed based on a few elements; such as distance, time, age and total burn body surface area.

Keywords: Burn Injury; BLEVE Fireball; Liquefied Petroleum Gas; Simulation; Thermal Radiation.

1. Introduction

For the past few years, many fatalities and injuries have been recorded which involved boiling liquid expanding vapour explosion (BLEVE) fireball accident which resulted from the failure of LPG storage vessels or tank trucks. On 28th of August 2012, a leakage from LPG truck tanker triggered a massive explosion in India causing severe burns on 12 people, 6 of them are seriously injured. The explosion also destroyed several buildings within the area of explosion. Meanwhile in Malaysia, Sabah on 31st of October 2011, a commuter train collided with a Shell LPG truck carrying 27,000 liters of fuel, which caused a huge explosion and 12 people were seriously injured in the explosion. BLEVE produces a large amount of heat energy [1], which is also known as thermal impact and it is one of the most lethal aftermaths putting aside the overpressure produced by a BLEVE.

In order to prevent BLEVE accident, more attention is given to qualitative analysis in order to evaluate the possibilities of an LPG truck accident [7]. The countries such as United States of America, United Kingdom, Switzerland, Italy, and several others, have come up with a new policy to improve and ensure the safety of hazardous chemical transportation [2]. Many research and investigations have been done in choosing the safest route for chemical transportation to travel from one location to another. Apart from that, the application of quantitative analysis should also be done in order to fully understand the effects and severities of a BLEVE event.

There are a few models [1-5, 7, 11, 12] that have been developed and used all over the world to calculate or simulate a BLEVE event and its consequences. The BLEVE blast approaches can be classified into the following several categories: i) empirical correlations by comparing the BLEVE blast wave characteristics

(overpressure, impulse) with those of high explosives (TNT equivalence approach) [12, 13, 14, 15,16]; ii) models focusing on the processes of liquid boil-up, superheat temperature limit, nucleation in superheated liquid, bubble growth etc. [17,18]; iii) gas-dynamical models focusing on blast wave propagation in the atmosphere[13]. However, potential thermal impact resulted from a BLEVE event yet to be investigated further to ensure full safety of LPG transportation and the ability to predict the casualties and injuries that might occur during a BLEVE event. The severity resulted from a BLEVE thermal radiation affects the survival rate of a victim. However, existing research still contain many loopholes as few factors are not put into consideration. This explains why death records increase few days of the actual incident event. BLEVE thermal impacts are directly affected by the distance between the victim and the BLEVE fireball. The absence of human physiological factor reduces the accuracy of a risk analysis during and LPG transportation. In analyzing a BLEVE event, factors such as age, total burn body surface, clothing and etc should be included. Lack of concerns regarding this matter will affect the public since transportation of chemical substance use the same route taken by the public.

2. Methodology

2.1. Case study description

This study is simulated using a truck tanker carrying 13,000 kg of LPG, which was on its way to deliver LPG to several petrol pumps and shopping malls. The accident took place on 21st March 2013 around 10.30 a.m near the Jalan Bakar Sampah, Port Dickson, Negeri Sembilan (Malaysia). The LPG tanker lost the control due to running over a really big hole which causes one of the front tires burst. The tanker overturned by the road side, hit a divider thus which caused a little crack on its tank surface,

creating a minor leak area. Sparks from the engine tanker ignite the LPG vapor which has leaked from the tank containment. Few minutes later, the leakage formed a pool fire which heated up the affected LPG tanker. Due to the extreme heat produced, the truck tires also engulfed in flames producing black smokes. Approximately, 15 minutes after the accident, a minor explosion took place; producing a hissing sound due to the massive amount of LPG vapour which escaped from the tanker. Few seconds later, a huge explosion occurred producing a fireball filled with tremendous amount of heat radiation. Specification of LPG that will be used throughout this study is listed below:-

Table 1: Relative Occurrence of Installation Types in Primary and Secondary Accidents⁵

Specific Volume (m ³ /kg)	0.552
Density of Liquid at atmospheric pressure (kg/m ³)	580
Vapor pressure at 25°C (MN/m ²)	0.936
Specific Heat, Cp (J/kg.K)	1630
Specific heat ratio, Cp/Cv	1.2
Gas constant, R (J/kg.C)	188
Boiling Point at 1 atm (°C)	-42.2
Latent Heat of Evaporation at boiling point (J/kg)	428000
Freezing or melting point at 1 atm (°C)	-189.9
Latent Heat of Fusion (J/kg)	44400
Flammable	Yes
Heat of combustion (kJ/kg)	50340
Heat of combustion (MJ/m ³)	91.19565

Fig. 1 shows the route taken from point A to a pump station at point B in order to deliver the LPG. The red arrow shows the location where the accident took place. The red circle represents the possible area of an accident prone BLEVE explosion. Population density within the plot area is around 300 peoples during the time of accident. The population age distribution is between 15 to 75 years old.



Fig. 1: Sequence model analysis on the 179 domino effect-related case studies via event tree analysis.

2.2. Thermal dosage prediction on human

The first step in analyzing thermal effects on human is to determine the combustion duration for the fireball, t_d [10]. Mass of fireball is taken from the process description, therefore:

$$t_d = 0.9(13000)^{\frac{1}{4}} = 9.61s \quad (1)$$

$$\frac{1}{3}t_d = \frac{9.61}{3} = 3.2s \quad (2)$$

Fireball diameter is time-dependent $D(t)$; it changes its diameter during the whole combustion process [3].

$$D(t) = 8.664(13000)^{\frac{1}{4}}t^{\frac{1}{3}} \text{ for } 0 \leq t \leq 3.2s \quad (3)$$

Maximum fireball diameter (D_{max}) is determined by:

$$D_{max} = 5.8(13000)^{\frac{1}{3}} \text{ for } 3.2 \leq t \leq 9.61s \quad (4)$$

$$D_{max} = 136m \text{ for } 3.2 \leq t \leq 9.61s \quad (5)$$

Ground flash radius (R_{flash}) associated with the BLEVE fireball is calculated by:

$$R_{flash} = 0.65(136m) = 88.4m \quad (6)$$

The height of the centre of fireball is time-dependent as well, $H_{fb}(t)$ [4]. The fireball growth and post growth phase are calculated respectively:

$$H_{fb}(t) = 46.41t^{\frac{1}{3}} \text{ for } 0 \leq t \leq 3.2s \quad (7)$$

$$H_{fb}(t) = \frac{3(136m)t}{2(9.61s)} \text{ for } 3.2 \leq t \leq 9.61s \quad (8)$$

$$H_{fb}(t) = 21.23t \text{ for } 3.2 \leq t \leq 9.61s \quad (9)$$

f is the radiant heat fraction for the BLEVE fireball. In order to determine the value of the vessel burst pressure is assumed to be at 2.21 MPa [6]. The calculation is as follow:

$$f = 0.27(2.21 \text{ MPa})^{0.32} = 0.348 \quad (10)$$

Maximum surface emitted thermal flux (E_{max}) is given by the calculation below:

$$E_{max} = 0.0133(0.348) \left(50340 \frac{\text{kJ}}{\text{kg}} \right) (13000\text{kg})^{\frac{1}{12}} \text{ for } 0 \leq t \leq 3.2s \quad (11)$$

$$E_{max} = 513 \frac{\text{kW}}{\text{m}^2} \text{ for } 0 \leq t \leq 3.2s \quad (12)$$

Calculation above estimates that E_{max} is greater than 400 kW/m², therefore it is assumed to be limited to 400 kW/m² [9]. Surface emitted flux [$E_s(t)$] during the growth phase of the fireball is determined:

$$E_s(t) = 400 \frac{\text{kW}}{\text{m}^2} \left[\frac{3}{2} \left(1 - \frac{t}{9.61s} \right) \right] \text{ for } 3.2 \leq t \leq 9.61s \quad (13)$$

$$E_s(t) = 600 - 62.24t \text{ for } 3.2 \leq t \leq 9.61s \quad (14)$$

$$F(x,t) = \frac{2153.9t^{\frac{2}{3}}}{(2153.9t^{\frac{2}{3}} + x^2)} \text{ for } 0 \leq t \leq 3.2s \quad (15)$$

$$F(x,t) = \frac{4692}{(454.5t^2 + x^2)} \text{ for } 3.2 \leq t \leq 9.61s \quad (16)$$

By substituting suitable value of $F(x,t)$, $D(t)$ and $H_{fb}(t)$ into the model reviewed earlier; the time- and distance-dependent atmospheric transmissivity can be determined.

$$\tau(x,t) = 1.03 \left[\sqrt{2153.9t^{\frac{2}{3}} + x^2} - 46.41t^{\frac{1}{3}} \right]^{-0.09} \text{ for } 0 \leq t \leq 3.2s \quad (17)$$

$$\tau(x,t) = 1.03 \left[\sqrt{454.5t^2 + x^2} - 68.5 \right]^{-0.09} \text{ for } 3.2 \leq t \leq 9.61s \quad (18)$$

By taking all of the values and combining them into thermal flux model, thermal dose inflicted on victim can be calculated.

$$E_t = \tau_a E F_{21} \quad (19)$$

Severity of BLEVE fireball thermal exposure is highly dependent on the thermal dose received by a target in certain duration. This can be calculated using the integral of the E_t , radiative flux over the duration of the fireball.

$$E_{dose} = \int_0^{t_{BLEVE}} E_t dt \quad (20)$$

Thermal impacts on human survivability can be measured using all the available data [19] and sources. By providing the thermal dose calculation above, the probability of human survivability will

be measured using a few parameters which are age distribution, total body surface area (TBSA) burned, probit calculation and probability of death model [8]. Probit equations for human thermal radiation impacts:-

$$1^{st} \text{ degree burns: } Y = -39.83 + 3.02 \ln(Q_{dose}^{4/3} t) \quad (21)$$

$$2^{nd} \text{ degree burns: } Y = -43.14 + 3.02 \ln(Q_{dose}^{4/3} t) \quad (22)$$

$$\text{Lethality, } Y = -36.38 + 2.56 \ln(Q_{dose}^{4/3} t) \quad (23)$$

$$\text{Protected, } Y = -37.23 + 2.56 \ln(Q_{dose}^{4/3} t) \quad (24)$$

The probability of fatality was calculated using binary logistic regression as below:

$$\text{POD (Probability of Dying)} = [e^X / 1] + e^X \quad (25)$$

$$\text{where, } X = B_0 + B_1 (\text{age}) + B_2 (\% \text{TBS burn}) + B_3 (\text{age})^2 \quad (26)$$

and the coefficients; $B_0 = -5.22$; $B_1 = -0.1041$; $B_2 = 0.09843$ and $B_3 = 0.002296$

Equations (25) and (26) are used to calculate the probability of a person surviving from second degree burn in the thermal radiation impact depending on the percentage of TBS and of the age of the person.

3. Results and discussion

3.1. Thermal Dosage

Fig. 2 shows the amount of thermal dose received in relation to the distance. Generally, the thermal dose graph curve received by the victim as a result of the BLEVE fireball incident that occurred for 9 s shows similar trendline. However, in truth, the victim located nearest to the source of incident will receive higher maximum thermal dose, for example, at a distance of 50 m, the victim will receive a thermal dose as much as $12 \times 10^6 \text{ kW/m}^2$ compared to $1.9 \times 10^6 \text{ kW/m}^2$ at a distance of 400 m at 3.6 s. In conclusion, the thermal dose graph at Fig. 2 showed a gradual decrement in thermal dose inflicted on a victim as the distance increases. The thermal dose decreases due to the loss of energy as heat are travelling through the atmosphere. The further the distance the lower is the thermal dose inflicted. This phenomenon of loss of energy as heat travels through the atmosphere is called atmospheric transmissivity.

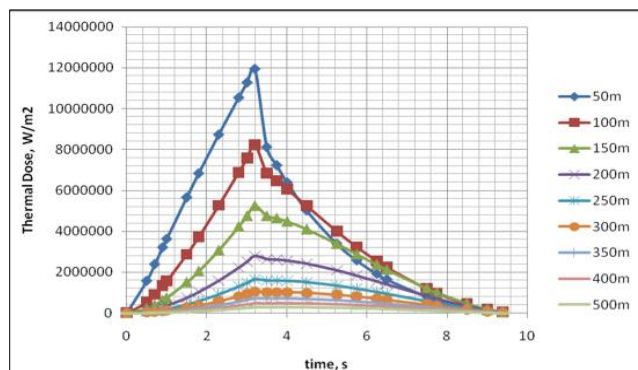


Fig. 2: The amount of thermal dose received in relation to the distance.

Atmospheric transmissivity determines the potential loss of energy when it travels through the atmosphere. Calculation proves that as the distance increases; the atmospheric transmissivity will decrease thus reducing the amount of thermal dose inflicted on victims. Components and small particles in the air absorbs a little amount of the thermal radiation produced by the BLEVE fireball; however, this parameter varies according to weather condition as

well as the environmental object. Therefore, more simplified model has to be developed in order to obtain a more consistent value at varies weather condition in determining the actual thermal radiation.

3.2. Effect of Fireball Thermal Radiation to the Probability of Burn Victim Survival in Relation with Distance and Time

Distance does play an important part in obtaining the most accurate result. It is proven in Fig. 3 where there is a large correlation difference between the percentages of first degree burn injury as the distance increases.

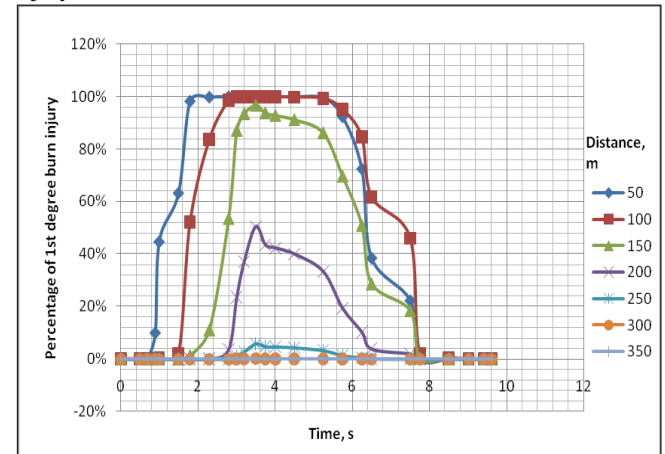


Fig. 3: Probability of 1st degree burn injury in relation with time at a distance of 50 m, 100 m, 150 m, 200 m, 250 m, 300 m, and 350 m.

These data must be interpreted with caution because fireball produces maximum amount of thermal radiation only during its peak condition where it happens in just a split second. In the Fig. 3, the peak condition is observed to be at approximately 3.6 seconds of its growing phase. Contrary to expectations, this data does not show constant thermal radiation once it passed its peak condition but a decreasing trend of thermal impact to human. Therefore, it is possible for a much less injury to be subjected on human that were exposed to the fireball after 3.6 seconds of its formation.

As for a second degree burn injury, almost the same trend can be observed in the percentage value as compared in the first degree burn data. The observed correlation between the probability of burn injury and time can be explained in this way; as when time increases the probability of injury increases but this happens only fireball is reaches its peak condition.

Firstly, note that mass of the fireball is around 13,000 kg equivalent to 13 tonnes. In real life cases, a fireball produced by this large amount of LPG can be very large. This is consistent with the calculation result discussed earlier in this paper. It produced a very high thermal radiation during its growing phase while the thermal radiation required for human to feel pain is only 4 kW/m^2 [8]. However, the data provided does not include the distance between the source of fireball and victims; this parameter can create a big difference in the result obtained when it is taken into consideration. As shown in Fig. 2, during the end phase of the fireball formation, larger distance shows that longer time of exposure is required for the human to feel pain. It is possible for the data provided in the paper[8] to be applicable to a variety of distance; if there is no presence of atmospheric transmissivity as this element reduces the amount of radiation intensity as it travels through the atmosphere.

3.3. Effect of Fireball Thermal Radiation to the Probability of Burn Victim Survival in Relation with Protection

The most interesting finding was that the reduction of probability of lethality of unprotected victim is reduced approximately by half when protection element is added into the model.

As the distance increases, the probability of lethality reduces significantly. A large margin is observed between 50 m radius and 150 m radius. The same modus operandi can be used for further investigation on the probability of first degree and second degree burn by adding the protection elements into an existing model thus creating a more accurate result as well as closing the existing loopholes existed in current research. The observed correlation between the protected and unprotected victims might be explained in this way. Protection reduces the percentage of lethality by absorbing the thermal radiation which in return will damage the protection itself. However, this figure is limited to thermal radiation impact since BLEVE fireball often comes with overpressure as well as missile effect; if these elements are added into the calculation, the model will most likely produce a different result.

3.4. Effect of Fireball Thermal Radiation to the Probability of Burn Victim Survival in Relation with Total Burn Body Surface and Age of Victim

Thermal radiation main consequence is the burn effect whether it is of high level burn injury or low-level burn injury. Human skin is highly sensitive to heat radiation. A specific amount of thermal dose can cause harm to human skin. A variation on the age of victim does affect the finding significantly. One anticipated finding was that the potential of second degree burn victim to survive decreases as the age increases. Many medical researches have been done to determine the probability of burn victims to survive with respect to age. For instance, Bull [20] has reviewed his mortality analyses several times since 1949 and he has come up with a chart called ‘Mortality Probability Chart’.

The Bull chart [8, 19, 20] is based on probability of patients suffering from burn injury in a hospital to survive. In this study, the results observed are compared with the mortality chart produced by Bull since there are quite a few similarities between the variable applied in this study and the mortality chart; such as total burn area and age are taken as the parameters used to determine the probability of lethality. At the age of 35 with total burn body surface of 30%, mortality chart shows the chance of lethality is 10% while the findings for this research shows a different figure; which is approximately 99.92% chance of survival at 200m from BLEVE fireball incident (Fig. 4). Percentage of survival at age 35 years (TBSA 30%) will drop should the victim is situated at 50 m from the starting point of the incident, that is 70.73%. This rather contradictory result may be due to the distance and time frame of the victim suffering from the burn injury itself. However, both findings show the same result; as the age increases the chance of the victim to survive decreases. A possible explanation is that with regards to extent of the burn injury, the depth of injury has an influence on the victims’ chances of recovery. People who are in the age group of 65 – 75 has the lowest chance in surviving which in most cases, these group of victims often died on the spot or on the way to the nearest medical treatment centre. Lack of antibody and weak body can be the factors of lethality instead of the burn injury itself. It is important to note that most of the findings show the same result in which elders have the lowest chance of survival. However, further study can be made by integrating the probability of second degree burn injury with the ability of regeneration at a certain age to enhance the findings in determining the potential survival during a BLEVE accident.

Second degree burn injury often relates with the total burn body surface (TBS). The survival rate of second degree burn injury

victim mostly is different according to TBS percentage. For example, victim with 20% of TBS has higher chance of survival compared to 30% and above TBS, if the ability to treat the victim is at TBS status of 30% and below as in Fig. 5.

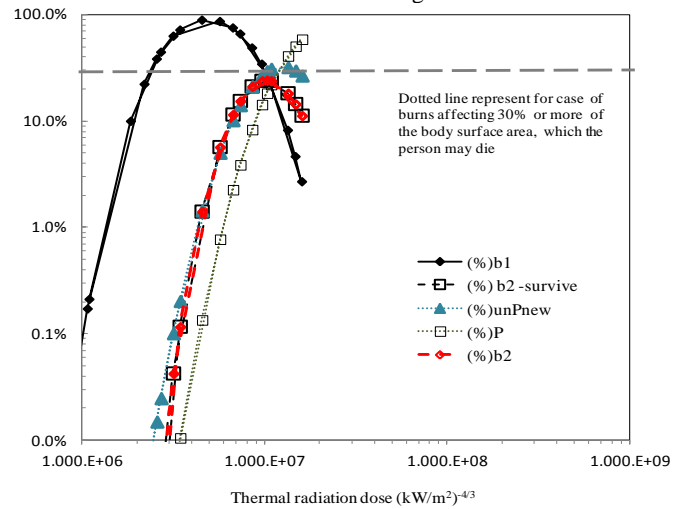


Fig. 4 Probability of 1st degree burn, 2nd degree burn to survive, lethality of unprotected, lethality of protected and 2nd degree burn injury with respect to TBS = 30% at the age of 35 at 50 m

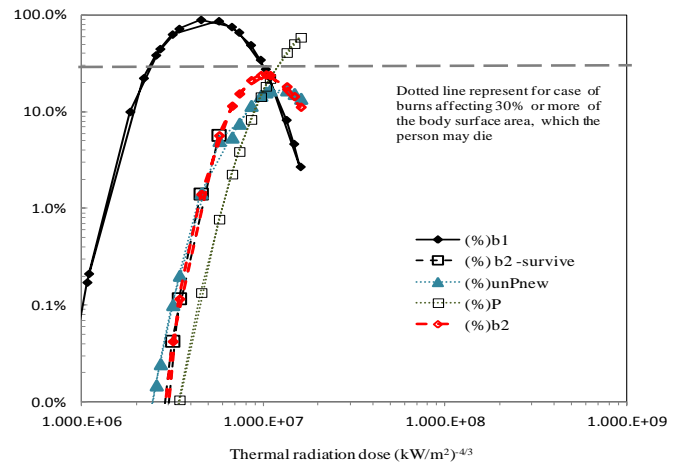


Fig. 5: Probability of 1st degree burn, 2nd degree burn to survive, lethality of unprotected, lethality of protected and 2nd degree burn injury with respect to TBS = 10% at the age of 35 at 50 m from incident

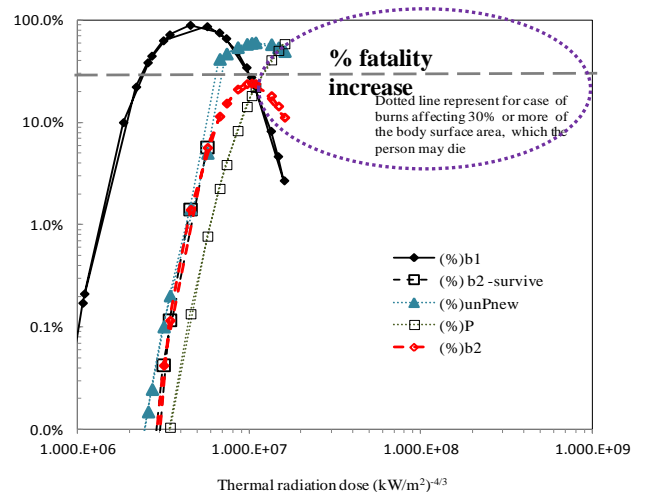


Fig. 6: Probability of 1st degree burn, 2nd degree burn to survive, lethality of unprotected, lethality of protected and 2nd degree burn injury with respect to TBS = 10% at the age of 75 within 50 m radius (the blue curve shows the increment of fatality percentage at the age 75 because some 2nd degree burn injury victim did not survive after the incident had occurred)

Fig. 5 showed the result at which the TBS% of victim is 10%, as compared to that of 30% TBS in Fig. 6 while the result in Fig. 6 demonstrated the survival effects of 70-year-old victim at 10% TBS. No difference is observed in the percentage of first degree burn, second degree burn and lethality but there are a few slight changes between these three figures on the chances of second degree burn victim to survive. It is important to note that the chances of survival get slimmer as the TBS increases. However, these findings cannot be extrapolated to all victims as the term 'area burned' component of the lethality model is independent of depth of the burn injury.

4. Conclusion

This present study determines the probability of burn victim survival from BLEVE fireball impacts during LPG transportation. This study provides the possible effects caused by a fireball thermal radiation. The following conclusion may be drawn from this study:

1. The solid plume model method has been successfully used to study the probability of burn victim survival from BLEVE fireball thermal radiation.
2. Increment in distance between the victims and the source of thermal radiation reduce the thermal dosage inflicted on victims.
3. Thermal radiation produced by the fireball differs every second during its growing phase. It increases when it reaches its peak condition but decreases gradually as it achieved its maximum diameter.
4. Atmospheric transmissivity is affected by both distance as well as element of protection thus the thermal radiation inflicted varies according to the surrounding condition
5. For an explosion produced by LPG with the mass of 13,000 kg; at a distance of 50 m (with the ability to treat patients or victims within 30% exposure TBS) approximately 38.19% of the victims were exposed with the chance of fatality. Nevertheless, the survivor status that can survive secondary injury is low if the level of functional medical abilities is only able to treat exposed patients below 30% TBS level.
6. Protection can reduce the probability of lethality approximately by half.
7. Survival from burn injury victim tends to be an age factor. The chances of survival increase towards the younger age group. Therefore, the probability of lethality does not depend only on burn injury but also the ability of regeneration and healing of a certain body.
8. Total burn body surface affects the potential fatality but does not cover for all victims as it is independent of depth of burn injury. It can be classified as less severe as long as long as it is not greater than third degree burn injury.

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