METHODS FOR JUDGING TEMPERATURES OF BUILDING STUCTURES IN FIRE

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I、ABSTRACT

After a building catches a fire, the fire tempterature and the combustion time affect directly the capacities of building structures (reinforced concrete structures, brick block structures, steel structures, wood structures and so on). It's extremly important to judge the fire tempteratures correctly during estimating the damage degree of the building. Because the happening of fire is unexpected, it is impossible to test its real developing process. Generally the temperatures of fire can only be judged according to the performance changes of the building elements and materials, the damage characteristics of the articles on the fire sites, and also the fire remains, etc. The fire temperatures of building structures refer to the temperatures directly on the surfaces of the building elements. There is difference of damage degrees even on the same building element, this is affected by the different temperatures on different parts of the building element surfaces, and the fire temperatures are direcly related to the kinds and amount of the combustible articles and the fire spread. Therefore, the fire temperature zones must be determined in the light of the amount and kinds of the combustible articles, combined with the fire damage degrees of building structures and elements during judging the fire temperatures on the fire sites. In the recent four years, we have done the experimental research of the performance changes of building structures after fire, and conducted the pilot projects of damage degree estimation of structures. In the pilot projects, we have done research on judging methods of fire temperatures and their processes. The following are the methods to judge the fire temperatures:

I、TO CACULATE FIRE TEMPTERATURES BY INVESTIGATING FIRE COMBUSTION TIME

The developing process of building fire can be generally divided into threephases: the growing phase, the roaring phase and the decreasing phase. According to this law, the international ISO834 Standard Temperature Rising Curve has been editted to imitate the real fire temperature conditions of building engineering and to carry out the fire tests of building structures. The standard temperature rising curve used in the fire tests to the building elements in our country is the same as the international standard one. The apparant fire is adopted as the fire source. Figure 1 demonstrates the comparison between the building fire characteristic cure in projects and the ISO Standard Time—Temperature Curve.

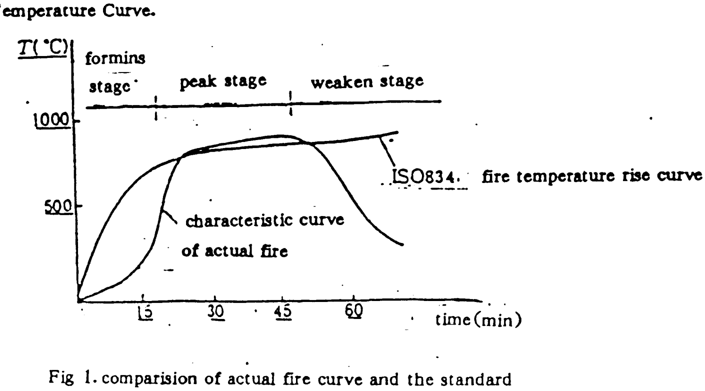

Fig 1. comparision of actual fire curve and the standard fire temperature rise curve

From the real fire performance curve in Figure 1, you can see that there are three phases from the beginning of fire to the period when the fire is distinguishedor dies out naturally. The following is the introduction about the flaming mechanism of the three phases:

Phase 1: Fire Growing Phase. This is the period of fire growing. When the combustible articles are the ordinary fire materials and about 5——20 minutes later, the apparant fire appears on part of the articles and spreads out. The flame is unstable and only on some parts, the fire temperature rises up slowly. When the combustible articles are alcohol, banana oil, foamed plastics, or some other combustible materials, the fire temptерature will rise up very quickly, and the period of this phase will be very short.

Phase 2: At this phase, the fire's spread out to all combustible articles nearby, and the articles are fully on fire, the interior temperature rises up very rapidly, it can amount to about 800℃——1000℃; the flame is relatively stable, and this is the most serious phase when the building elements are damaged or destroyed. The length of this flaming period at this phase is determined by the kinds and quantity of the combustible articles. The more the articles, the longer the flaming time, the more the combustible articles with high heat—releasing rate per unit, the higher the fire temperature will be. Also, the length of the flaming period is related to the combustible conditions: the fire period will be short and the fire temperature will be high if the ventilation conditions are good; on the contrary, the length will be long and the temperature will be low if the conditions are bad.

Phase 3: Fire Decreasing Phase. The combustible articles in this phase basically disappear, the area of the apparant fire begins to decrease, the flame subsides or dies out voluntarily, the interior temperature begins to decrease. In Figure 1, there is the ISO 834 Fire Time—Temperature Standard Curve, this curve indicates that the fire temperature will rise up constantly along with the time of combustion. The temperature is determined by the following function formula:

$$T - T = 345\ \mathrm{Lg}\ (8t + 1)$$

where T ——— Standard temperature (℃)

T ——— Natural temperature (℃)

t ——— Length of fire period (m)

We can see in Fig. 1 that there is difference between the Standard TemperatureRising Curve and Building Fire Temperature Curve. However, the Standard Curve'sone which has been got through the statistics and analyses of many building fires home and abroad and can meet the law of most fires. Therefore, when judging the fire temperatures, the Standard Curve can also be adopted to caculate the fire temperatures.

The method to caculate the fire temperatures is: $T - T = 345\ \mathrm{Lg}(8t + 1)$; where T ——— Natural temperature when fire happens (℃) t ——— Whole fire period fromits growing phase to decreasing phase which can be got through investigation (it can also be got through caculation if the investigation is not available, and there won't be any detailed introduction here), (m). The example of caculating the fire temperatures is as follows: a fire happens on the second floor of a department store, the combustion time (t) is 13 minutes, the natural temperature of that day (T) is 20℃, so the fire temperature is $T = 345\mathrm{Lg}(8 \times 13 + 1) + 20 = 715$ ℃.

Ⅱ、TO JUDGE FIRE TEMPERATURES ACCORDING TO DAMAGE CHARACTERISTICS OF REMAINS ON FIRE SITES

The happening of fire is due to flaming of the combustible articles, and it iseasy to learn the fire characteristics of the articles. We grasp these to serve for judging the fire temperatures.

A). Table 1——5 indicate the information of metal or nonmental materials such as fire points、melting、deformation、fire damages, etc.

Deformation Temperatures of Metal Materials　　　　Table 1

MATERIALS	PRACTICAL EXAMPLES	STATE	TEMPERATURE (℃)
Aluminium, Aluminium alloy	Daily life articles, parts for windows and doors, mechanical parts, decorative materials, etc	Melting into drops	650
Cast iron	Pipes, heat radiators, machines	Getting into drops	1100～1200
Hot-rolled steel	drop hangers, supporting frame steel windows	Deforming & bending	/ 750
Lead	Lead pipes, accumulators, toys	Melting into drops	300～500
Brass	iron mongeries, door handles, windows, machines	Melting	900～1000
Bronze	Electric wires, cables,	Melting	1000～1100
Zinc	Daily life articles, interior water pipes, iron mongeries	Melting	400～430

Deformation Temperatures of Glass　　　　Table 2

MATERIAL	PRACTICAL EXAMPLES	STATE	TEMPERATURE (℃)
Glass	Glass windows and plates	Melting	800～850
	Ash-trays, bottoms cups	Softening	700～750
	Decorative articles	Getting smooth	750

Fire Points of Materials — Table 3

MATERIALS	FIRE POINTS ℃	MATERIALS	FIRE POINTS ℃
ETHENE	450	PHENOL	754
ACETYLENE	299	PAPER	130
ETHANE	515	COTTON	150
BUTYLEN	210	COTTON CLOTH	200
BUTANE	405	NYLON	424
PLYETHYLENE	342	RESIN	300
POLYTETRA-FLUOROETHY-LENE	550	ARTIFICIAL FIBER	235
POLYVINYL CHLORIDE	454	POLYESTER FIBRE	390
VINY PROPY BENZY COPOLYMER	454	RUBBER	130
		FLAX	150
WOOD	250-300: a slight indication of carbonization along the direction of thickness; 400-600: carbon with large holes appearing; 600-800: carbon with small holes burned out; 800-1000: whole wood burned out; 〉1000: structures completely destroyed		

Fire Damage Indications of Paints — Table 4

TEMPERATURE		〈100 ℃	100-300 ℃	300-600℃	〉600℃
Indications after fire	ordinary ready mixed paints	smoke on the surface and the paints can be seen	cracks and decortication can be seen	darkening and dropping down	burning out
	anticorrosion paints	no damage	no damage	changing colours	burning out

B). Requirements for the sampling of the fire damaged or destoryed remains on fire sites

a). To take the samples which are not damaged as the starting point of judging the fire temperatures and the surface temperatures of the structures.

If there is a fire on a building in use, the temperatures of the will be comparatively low in the dead corners where the air is not ventilated, it is an important starting point to determine the surface temperatures of the structures nearby by using the fire points of the articles to judge the lowest temperatures of the whole fire site.

b). To take the remains of the articles damaged by fire and the deformation temperatures of metals as the starting point of determining the lowest and the highest temperatures of fire.

The lowest fire temperature can be known according to the fire points of the fire remains, while the highest fire temperature could be known according to the articles which aren't on fire or damaged or deformed by fire. For example, during a fire site inspection, the aluminum alloy windows have been melted, therefore, the fire temperature can be estimated to be higher than 650℃; the angle bar frame has been bent and distorted, so the fire temperature may be 750℃; the fire temperature may be 800℃ because the glass plates have been melted; the estimated fire temperature may amount to 950℃ because the brass door knobs have been damaged. Therefore, the fire temperatures of this site can be judged according to the axis locations, the fire temperature zones are: 650~800℃, 800~950℃.

c). Sampling of the remains in special locations.

During a fire, the fire temperatures vary upwards in a angle of 60℃, the temperatures on the floors or floor plates are the lowest, while the temperatures are the highest on the bottoms of floor plates; beams. Special attention should be paid to the damage conditions of these areas when sampling the remains, and the damaged areas of the main structures could be learned.

Ⅳ. JUDGING FIRE TEMPERATURES ACCORDING TO SURFACE COLORS AND EXTERIOR CHARACTERISTICS OF CONCRET STRUCTURES AFTER FIRE

To undertake the modelling tests of the concrete surface colors and exteriorcharacteristics of the concrete experimental blocks, mortar experimental blocks, clay bricks and reinforced concrete beams and plates.

After the apparant combustion experiments (which adopts the ISO 834 Standard Temperature Rising Curve) of 8 furnaces of concrete experimental blocks, mortar experimental blocks, clay bricks(8 kinds of temperature)and 2 furnaces of reinforced concrete beams and plates (2 kinds of temperature) to observe the surface colors of the experimental articles, and getting them out quickly from the high temperature furnaces after fire and spraying water to cool down to observe the colors of the surface concrete of the articles, mortar and clay bricks. Table 6 indicates the surface colors and exterior characteristics of concrete experimental blocks; Table 7 indicates the fire temperatures, the concrete surface colors and the exterior characteristics; Table 8 indicates the surface colors of bricks and cement mortar.

Surface Colors of Concrete Experimental Blocks
After Fire Tests

Table 6

Combustion time (m)	Temperature in furnace (℃)	Exterior Characteristics			
		Colors	Surface cracks	Bursting loosening	Indications of cooling down by water
5	536	same with ordinary concrete	no	no	steam going upwards
15	719	shallow blue with slight pink	slightly cracked the widest crack is 0.1~0.2mm	initially cracking appearing	steam in the shape of fog
20	761	pink with slight grey	cracks adding more the widest is 0.2~0.3mm	cracking appearing more	sound can be heard
25	795	pink with obvious grey	cracks lengthening the widest is 0.3~0.5mm	cracking appearing	slight sound of busrting
30	822	mainly grey with slight pink	cracks adding more & lengthening	partially bursting & carcking appearing	sound of bursting can be heard
38	857	shallow grey	cracks adding more & lengthening	partially bursting & cracking appearing	sound of bursting can be heard
45	832	grey	cracks adding more & lengthening	partially bursting & cracking appearing	sound of bursting can be heard and partial concrete dropping down
50	892	grey area becoming large	large amount of cracks appearing the widest is about 0.8mm	partially bursting	sound of bursting can be heard and partial concrete dropping down
60	925	slight shallow yellow	large amount of cracks appearing	partially bursting & loosening	sound of bursting can be heard and partial concrete dropping down
90	986	shallow yellow	horizontal cracks adding more the widest is 1.0mm	partially bursting & loosening	sound of bursting can be heard and partial concrete dropping down

Surface Colors And Exterior Characteristics of Reinforced Concrete Structures After Fire

Table 7

Temperature of Fire(°C)	Concret Colors	Surface Cracks	Loosening & dropping indications	Revealed indications of steel reinforced bars	Sound when hit by a hammer
below 200	grey and blue	no	no	no	sound
300~500	slight pink	no	no	no	sound
719~795	pink and grey with initial shallow yellow	cracks beginning to appear on corners of the elements	no	no	pretty sound
795~857	grey with more cracks slight yellow	more cracks appearing on the surfaces	corners beginning to peel off	no	muffled sound appearing
857~892	mainly grey, slight yellow	penetrating cracks appearing on the surfaces	corners peeling off, surfaces swelling, concrete becoming loose	bars revealed at corners & bottom of plates	muffled
892~986	shallow yellow	more penetrating cracks appearing on the surfaces	surfaces swelling, powder can be touched by hand, corners peeling off seriously	bars revealed	dumb
986-1000	shallow yellow with white	countless cracks	surfaces becoming loose, big parts peeling off	bars revealed seriously	dumb
1000-1100	shallow yellow with white	countless cracks	surfaces becoming loose, big parts peeling off	bars revealed seriously	

Surface Colors of Bricks & Cement Mortar After Fire

Table 8

Temperature of Fire(℃)	Exterior Characteristics							
	Concrete Blocks & Bricks		Clay Bricks		Cement Mortar Coat		Lime Coat	
	Colors	Cracks	Colors	Cracks	Colors	Cracks	Colors	Cracks
below 200	no change	no	no change	no	no change	no	no change	no
300--500	shallow pink	no	no change	no	no change	no	no change	no
719--795	pink with grey	cracks appearing	no change	small ones appearing	rose	small ones appearing	grey & yellow	?--
795--857	grey	more cracks appearing	no change	more surface cracks appearing	shallow grey	cracks appearing	shallow yellow	cracks appearing
857--892	shallow yellow	more cracks appearing & enlarging	no change	more surface cracks appearing	shallow grey	more cracks appearing	shallow yellow	more cracks appearing
892--986	shallow yellow	penetrating cracks appearing	getting shallow	more surface cracks appearing	shallow yellow	surfaces peeling off	shallow grey	peeling off
986-1000	white	more penetrating cracks appearing	getting shallow	serious cracks appearing	white	surfaces peeling off	white	peeling off
1000--1100	white	more penetrating cracks appearing	getting shallow	serious cracks appearing	white	surfaces peeling off	white	peeling off

V. JUDGING FIRE TEMPERATURES BY MEASURING THE THICKNESS OF DAMAGED LAYERS OF CONCRETE STRUCTURES AFTER FIRE

By modelling 10 kinds of temperatures to act on the experimental blocks, the damaged layers of concret can be seperatedly measured when the blocks are hammered into parts after combustion. The measuring method is: the measurements from the surfaces of the elements to their interior layers should be conducted and no less than three testing points should be measured and then the average values should be got. Table 9 indicates the total testing results of the thicknesses of the surface damaged layers of concrete in seven pilot projects.

Table 9

Temperature of Fire(℃)	Damaged Thickness (mm)	Damaged Thickness After Cooling down by spraying water (mm)	Remarks
556	1.3--1.4	1.3--1.4	The values of damaged thickness in this table are the comprehensive values got through the tests to the elements with their trible sides and single side against fire
719	2.5--3.5	2.5--3.5	
761	4.0--5.0	4.5--6.0	
795	4.3--5.5	6.5--8.0	
822	5.1--6.0	7.0--10	
857	6--9	10--14	
882	7--10	11--15	
898	10--11	12--16	the pilot projects prove that the tolerances are ∓ 10 %
925	11--16	13--18	
986	20--26	23--28	
1030	26--30	28--33	

VI. JUDGING FIRE TEMPERATURES ACCORDING TO STRENGTHS OF REINFORCED BARS OF CONCRETE STRUCTURES AFTER FIRE

The fire tests have been undertaken to the beams and the plates with the spans of 4.5m. The main bars are the hot—rolled reinforced bars and cold—draw mild steel wires, the beams have the 1.0——3.5cm protective layers and will undertake trible side fire, the plates have the 0.85——1.5cm protective layers and will undertake the single side fire. The relation between the thicknesses of the protective layrs and the fire temperatures is illustrated in Fig. 2, Fig. 3 and Fig. 4. The elements which are seriously damaged and need to be strengthened can be used when examining or judging the fire temperatures. The protective layers of the steel bars should be chiseled away, and their thicknesses should be measured; the steel bars and wires need to be get out and the tention and limit strength tests should be done. According to the strengths of bas and steel wires, the thicknesses of protective layers, the fire temperatures can be be determined from Fig. 2, Fig. 3, and Fig. 4. This method can cause damages to the elements, and usually it is not used.

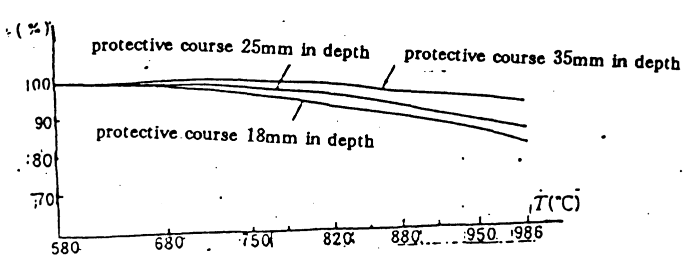

Fig 2. The relationship between strength reductoin factor of hot—rolled main bar and fire temperature of the girder sufferred three sides fire

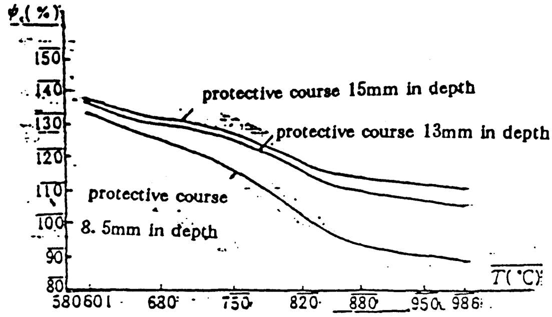

Fig 3. The relationship between the reduction factor of cold—drawn and fire temperature of prestressed hollow slab, botton fired low—carbon wire

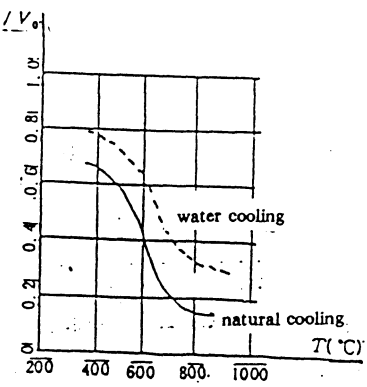

Fig 5. The relationship between impluse velocity and fire temperature

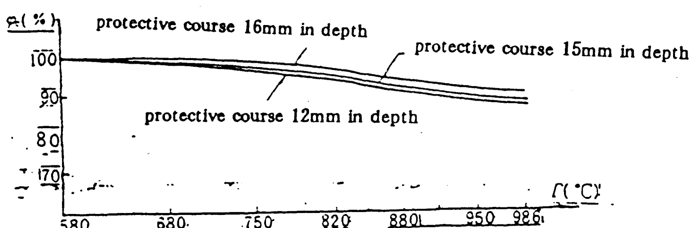

Fig 4. The relationship between the reduction factor of hot—rolled main bar and fire temperature of concrete slab, botton fired

VI. DETERMINING FIRE TEMPERATURES THROUGH MEARING PULSE SPEEDS OF CONCRETE STRUCTURES AFTER BY ULTRASOUND

The basic theory to use ultrasound method to test the elements of concrete structures after fire to determine the fire temperatures of the elements or the zones where the elements are is: the fire temperatures can be possibly determined by comparision between the pulse speeds of the elements which are not damaged and near the fire zones and the ones of the same elements damaged by fire. Some regulations have been found through testing of concrete experimental blocks and reinforced beams and plates, and through the pilot projects. The following is the introduction of the method to caculate fire temperatures by using the relation between the pulse speeds and fire temperatures combined with the ultrasound testing introduction of the non—destructive testing after high temperature in March, 1987:

Supposing V —— the pulse speed of damaged elements after fire; V —— the pulse speed of the same elements which aren't damaged by fire; V can be got through the fire standard temperature curve, the relation curve between it and the fire temperature can be found in Fig. 5, and the fire temperature can be available through this figure. Fig. 5 can be only used for the elements smaller than 150mm. Although this kind of temperatures is only the approximate values, it is helpful to grasp the fire temperature zones so that the damage degrees of structures can be judged.

VII. JUDGING FIRE TEMPERATURES THROUGH ANALYSES OF ELECTRICAL MICROSCOPES TO DAMAGED SURFACE CONCRETE OF STRUCTURES ON FIRE SITES

Judging Fire Temperatures Through Observation To The Structural Characteristics Shown By Electrical Microscope After High Temperature

Table 10

Number	Structural Characteristics Through Electrical Microscope	Caculated Fire Temperature (℃)
1	smooth calcite surface, dense & continuous cement	280--330
2	complete quartz crystals, cement beginning to loosen, cracks on CH crystals,	550--600
3	cement dewatering & shrinking into loosening ones. CH dewatering and decomposing, little CaO appearing and absorbing water in the air and beginning to expand	650--700
4	cement dewatering & shrinking into parts and plates, and CaO appearing, which absorbing water in the air, interior structures destroyed	760
5	cement dewatering & loosening with large opening	780
6	cement becoming the loosening parts	820
7	cement growing into not continuous parts with large opening, more CaO appearing	850
8	cement growing into not continuous parts with large opening, the quartz crystals still complete	880
9	calcite decomposing, small irregular crystals appearing	900
10	calcite decomposing into rectanglar columns, cement de-watering and with pretty large opening after shrinking	930
11	calcite decomposing into columns, cement dewatering and with larger opening after shrinking	980

Fire temperatures can be precisely judged if we conduct analyses to the damaged concrete samples, and make comparision between the results got from the analyses and the testing results under the standard temperatures or the electrical microscope photographs. Many new materials appear through hydration, carbonization, mineral decomposition under the fire temperatures, and the appearing of these materials is just the circumstantial evidence of fire temperatures. Table 10 shows the caculated fire temperatures according to the mineral changes of the damaged concrete after fire.

Ⅸ. APPLICATION OF FIRE TEMPERATURE JUDGING METHODS

The methods of judging fire temperatures should be chosen according to the structural damaged conditions and the actural flammable materials. The following is the introduction about a specific examples:

A hotel in Nanjing is a 7—story frame structure with the building area of 2707m. There was a fire on it in the early morning of Dec. 15, 1991 and lasting 50 minutes. The way of judging the fire temperature is:

(1). To determine the fire beginning location and its flamingdirection.

The fire beginning location and its flamingdirectionul was found to be the same as the investigated information by the ultrasound testing results of the damaged beams and columns.

(2). Analysis on fire lasting period.

It was about 50 minutes from fire beginning to the end. The structures in fire were less than 50 minutes. The suspended angle bars on the fire site were foundto be deformed, the beams, columns and plates nearby had undertaken the temperature about 750℃, the fire lasting period was more than 14 minutes.

(3). To conduct the electrical analyses on the damaged concrete samples on fire site.

The seriously, pretty seriously, and ordinarily damaged samples should be chosen to conduct eletrical microscope analyses according to the structure damaged conditions on the fire site, the quantity and flammability, while considering the types and locations of the elements. The highest temperature of the samples was determined as 850℃, and the less highest was about 750℃ in the light of concrete hydration, carbonization and mineral decomposition.

(4). To conduct analyses on the damaged depths and surface color changes of concrete elements on the fire site.

After measuring the damaged layers of the beams, plates and columns after fire, the depths were generally 2mm, and some serious ones were 7mm, therefore, the fire temperature could be determined as about 800℃. Because the colors of theseriously damaged parts were grey with slight pink through observation, the firetemperature could be 450℃——650℃. Fig. 6 indicates the bottom fire temperature zones comprehensively estimated by the analysis results and the surface temperatures of the remains.

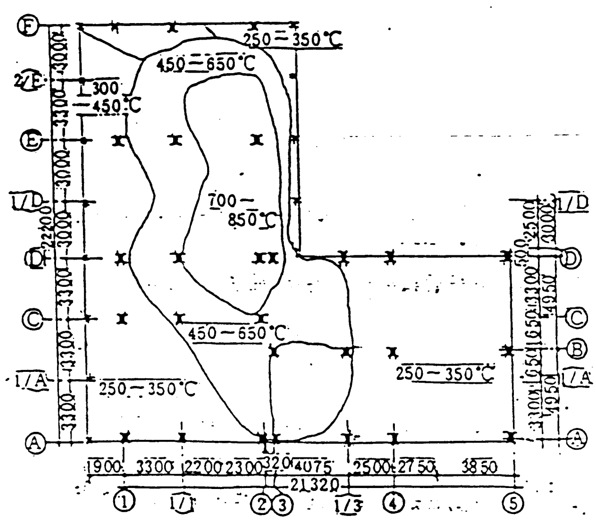

Fig 6. fire temperature distribution