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Application of Thermography Technique for Assessment and Monitoring of Coal Mine Fire: A Special Reference to Jharia Coal Field, Jharkhand, India

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Abstract Coal mine fire problem occurs globally and endangering miners' life. It leads to environmental pollution as well as economic loss to the local and regional governance. Surface coal mine fire affected areas are generally detected by thermal survey of an area. Temperature observations through thermometer or thermocouple are used in most cases as traditional monitoring of coal fire. Infrared thermograph technique combination with GPS topography has more advantage over traditional monitoring in terms of efficiency, precision and less costly. A large surface area can be seen, captured, and presented in thermal and visual form in very short interval of time. This paper describes basic principle, monitoring procedure and application of thermography in Jharia Coalfields (JCF) to assess coal mine fire affected areas and strategy to control it.
Keywords *Thermography, Coal Mine Fire, Emissivity, Thermal Image Analysis, IR Scanning*

1. Introduction

Coal is a prime source of energy that fulfils about 70 % fuel requirements in our day to day life [1]. Fire occurrence in this non-renewable natural fuel is posing serious threat to environment in terms of pollution, global warming and economic loss to the industry. Globally, coal fires are reported in USA, Australia, Germany, Spain, Poland, Czech Republic, India, Pakistan, Indonesia, Venezuela and China [2]. However, this problem is more severe in China, USA and India. In India, surface and subsurface fire throughout Jharia Coal Field (JCF) comprises one of the largest mine fire complex in the world [3]. JCF fire is of specific interest and needs attention for safe production of coal and safety of miners. The incidences of coal fire that occur in JCF are mainly due to spontaneous combustion [4].

Detecting coal mine fire is the most important step to decide measures for mitigating and controlling coal fire. Thermal survey is the most common technique used worldwide for several decades. This technique is used for detecting and evaluating, the status and extent of surface and subsurface coal fire. Until 1960s, researchers have used thermocouples and thermometers to assess the coal mine fire with an advantage of temperature measurements in close proximity. But this method does not produce sufficient data to cover larger area in synoptic view [5]. In case of progress of fire for a larger, unapproachable and unstable area, monitoring by this traditional method becomes very difficult, some time impossible, time consuming and costly.

In view of the above facts, most of researchers prefer the air borne and satellite borne thermal data produced from aerial survey/remote sensing images which make the detection, delineation and monitoring of coal fire easier [6]. The temperature limitation of satellite Landsat-5 TM Band-6 data is 270 K-350K in spectral band 8-14 µm [7]. The spatial resolution of Landsat -5 TM Band 6 and Landsat-7 ETM+ are 120x120m and 60x60m respectively [8]. The Thermal sensor TM band 6 gets saturated (maximum DN value 255 of 8-bit data) at approximately 343-350 K and gives pixel-integrated temperature of about 70^0C only, which is much lower than observed from the field measurement (>500^0C) [9]. However, hot spots observed using this technique is unable to distinguish actual coal fires from forest fires, fire in bushes, and fire in soft coal generated by the people residing in the vicinity of the coal field. This often leads to undercounting over a significant amount [1] and [9]. The infrared thermograph, compared to traditional technique has an advantage of good coverage area, non contact type, more-efficient with high precision of temperature measurement [10]. In an electromagnetic spectrum the infrared region varies from 2µm to 13µm wavelength (Figure 1). This wavelength of infrared spectrum is more than that of a visible spectrum [11].

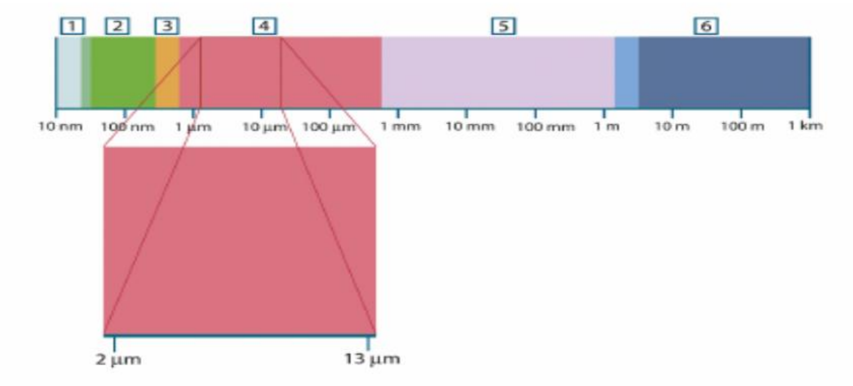

Figure 1: *Electromagnetic Spectrum. 1: X Ray, 2: UV, 3: Visible, 4: IR, 5: Microwaves, 6: Radiowaves*

A thermography instrument is a thermal pointer or a thermal scanner. The thermal pointer reads the temperature of a specific point whereas a scanner creates the thermal profile of large surface area in visual and thermal form in short interval of time [12]. The infrared system consists of an “infrared energy detector” and a “Monitor”. The scanner is an optomechanical device which converts the infrared energy received from an object surface to an electrical signal. These signals are further fed into monitor where it is processed and presented in different forms like simple digital display to indicate temperature level and a video display for thermal profile (Figure 2) [11].

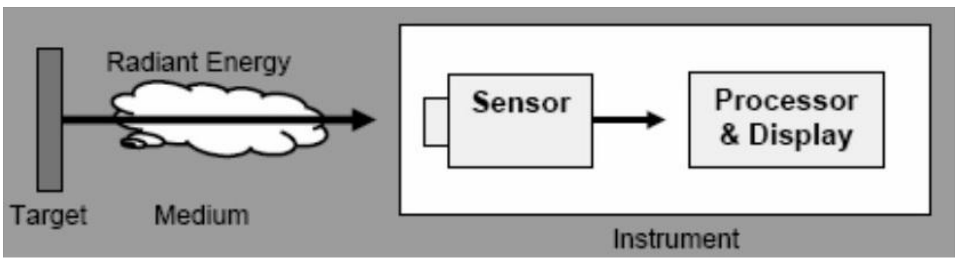

Figure 2: *A Schematic Representation Working Principle of Thermal Imaging Camera*

Thermographic scanner has facility of software backup for transfer, processing and analysis of the captured image but it cannot detect an object temperature if the medium is separated or covered by glass or polythene material etc. [11]. Therefore, application of thermographic technique to monitor the status and extent of coal mine fire plays a very vital role to diagnose and predict potentiality of this socio-technological problem.

2. Area of Interest

The most complex coal mine fire extending from surface to subsurface subsequent to opencast and deep mining of JCF has been selected for the study. The coal mining in JCF started in 1894 and the massive production of coal on regular basis lead to extension of the mining area. This extension became the reason for spontaneous heating of coal. The first coal fire was observed in 1916 [13], [14], and [15]. JCF is confined between latitudes 23°38' N and 23°52' N and longitudes 86°08' E and 86°29' E extending 38 km from East to West and 19 km from North to South with an area of 450 Sq Km [1, 13].

The total number of fires reported in all Indian coalfields was 196 including 65 fires of JCF, spreading over an area of 17.32 sq km in 1996 reduced to 8.9 sq km after controlled and combated ten fire in 2006 [16, 17]. Due to complex and critical nature of fire problem, about 37 million tons of prime coal have been lost so far and 1860 million tons of coal have blocked and become unwinnable [1, 4]. The subsurface coal fire is maintaining its status for more than five decades and still spreading and endangering hundreds of thousands of lives residing in vicinity of the fire area of JCF (Figure 3) [18].

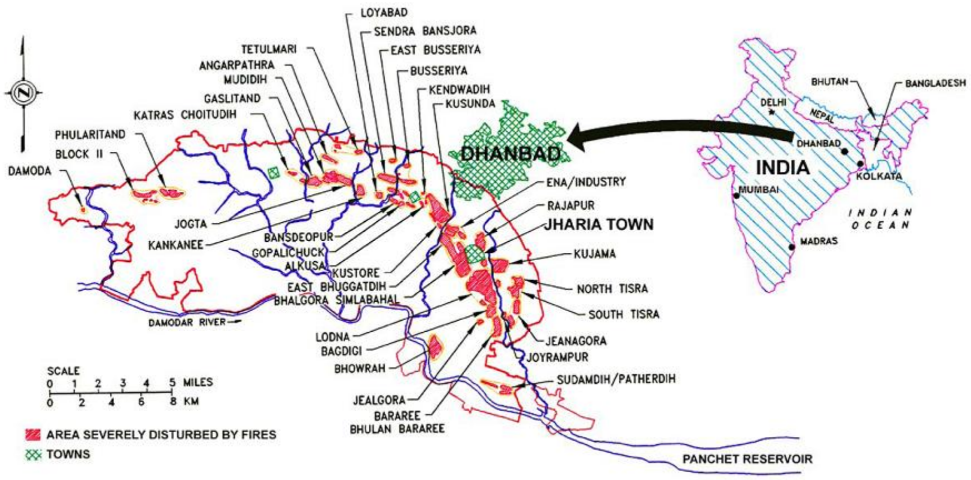

Figure 3: *Plan of the Jharia Coalfield and Principal Collieries affected by coal Mine Fires (Reproduced from Michalski, 2004)*

3. Thermographic Technique

3.1. Principle

All matters at absolute temperature (0 K) emit electromagnetic radiations continuously which are characteristic of the temperature of the body. The temperature of the earth material can be estimated on thermal radiation. Planck's black body radiation equation relates a spectral radiation and wave length with radiant temperature of an object as given in equation (1) [7].

$$T_{rad} = \frac{hc/k}{\lambda \ln\left[\frac{2hc^2\lambda^{-5}}{L_\lambda} + 1\right]} \quad (1)$$

Where, L_λ = spectral radiance (w/m^2 /sr/µm), λ = wavelength (m), T_{rad} = radiant temperature of the object (K), h = Planck's constant (6.26x10^{-34} J s), c = speed of the light (3x10^8 m/s), k = Boltzman constant (1.38x10^{-23}J/k)

The radiant temperature (T_{rad}) is defined as the equivalent temperature of the black body which would give the same amount of radiation as obtained from a real body. The radiant temperature depends on the actual surface kinetic temperature (T_{kin}) and spectral emissivity (ε_λ) of the material. Spectral emissivity (ε_λ) is the properties of material which control the radiant energy flux. Spectral emissivity (ε_λ) for black body is unity and for most natural material is less than one ranging generally between 0.70 and 0.95. When spectral emissivity of the material is known, kinetic temperature of the object may be obtained using the following mathematical equation (2).

$$T_{kin} = \frac{1}{\varepsilon_\lambda^{1/4}} T_{rad} \quad (2)$$

The radiant temperature of natural body will thus be less than that for a black body at the same temperature. In thermography technique camera receives radiation from the object itself and from the surrounding reflection via object surface (Figure 4) [11].

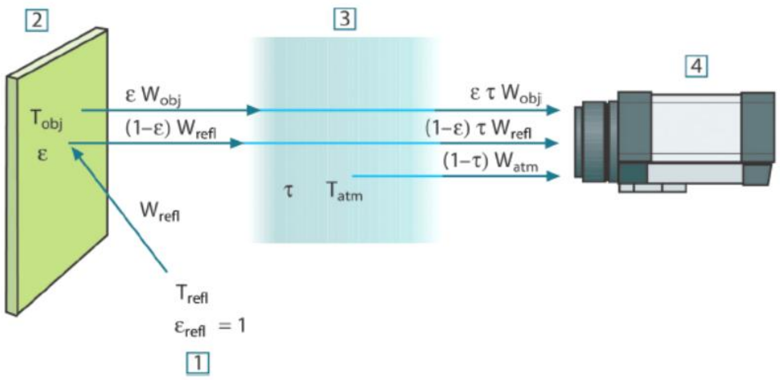

Figure 4: *A Schematic Representation of the General Thermographic Measurement Situation. 1: Surroundings, 2: Object, 3: Atmosphere, 4: Camera*

The temperature of the object depends upon the factors (i) emission from the object, (ii) reflected emission from the ambient source (iii) emission from the atmosphere. These factors are used to calculate the temperature of the object in FLIR thermal imaging camera in equation (3) [11].

$$U_{obj} = \frac{1}{(\varepsilon - \tau)} U_{tot} - \frac{(1-\varepsilon)}{\varepsilon} U_{refl} - \frac{(1-\tau)}{\varepsilon\tau} U_{atm} \quad (3)$$

Where, U_{obj} = calculated output voltage for a black body of temperature T_{obj}, U_{tot} = measured camera output for the actual case, U_{refl} = theoretical camera output voltage, U_{atm} = theoretical camera output voltage for blackbody temperature T_{atm} according to the calibration, ε = emittance, $(1-\varepsilon)$ = reflectance of the object, $(1-\tau)$ = emittance of the atmosphere.

For the measurement of thermal anomalies, some object parameters like object emissivity reflected apparent temperature, distance of the object from the camera, relative humidity and temperature of the surrounding (ambient temperature) are required to feed in the camera.

3.2. Data Acquisition and Analysis

Monitoring of coal mine fire is one of the important approaches to know the fire affected area and its extent thereof. Temperature is a direct indicator of coal fire combustion stages and can be used in mineralogical studies, ground geological surveys, as well as remote sensing detection [19]. Thermal monitoring needs temperature distribution at every point of fire affected area for the demarcation of fire zone. The key problem of monitoring is acquiring surface temperature distribution of fire affected area quickly and accurately [10]. The monitoring procedure used for thermographic technique can be divided into three stages as (i) acquiring thermal and visual images (ii) acquiring coordinates of sites using GPS, and (iii) analysis of acquired data.

Thermographic monitoring was conducted in various fire affected mines of JCF using ThemaCAM-P65 infrared thermal imaging camera having adjustable temperature measuring ranges from -20 ^{0}C to +2000 ^{0}C with sensitivity accuracy of ± 2 ^{0}C. The camera have inbuilt lens of 36mm, field of view (FOV) 24°X18° as solid angle and replaceable lenses with 18 mm wide angle lens, 19 mm micro lens and 150 mm close up lens. It includes auto calibration facility for emissivity of different materials. The camera is equipped with storing images, voice comments and text like location, spatial coordinates, surface features etc. and capable for acquiring and displaying visual as well as thermal images on 4” colour monitor with 320X240 pixels size. The acquired images and data can be transferred to computer using USB/ RS232 plug and play connection for fast download and further analysis through Reporter 8.3 Pro software [11].

There is facility of recording the fire areas by connecting DV recorder with camera or using Burst recording technique. It is useful for extensive monitoring over a large area and helpful to periodical monitoring and preparation of thermal profile of the area. All object parameters of thermal camera have been taken care to obtained high temperature precision from acquired data. Analysis of thermo-images will assess the status, extent and direction of fire propagation. The working procedures of this technique have been shown in the flow chart (Figure 5). The thermal and visual images of JCF were taken at various locations of fire affected sites along with their coordinates using GPS. The raw data of the satellite image has been processed using ERDAS 9.1 software. Selected fire locations of JCF are shown in false color composition (FCC) of satellite image (Figure 6). The calculated temperatures of Landsat ETM+ thermal band (Band-6) satellite images having spatial resolution of 60 m were compared with observed field temperature as given in Table 1.

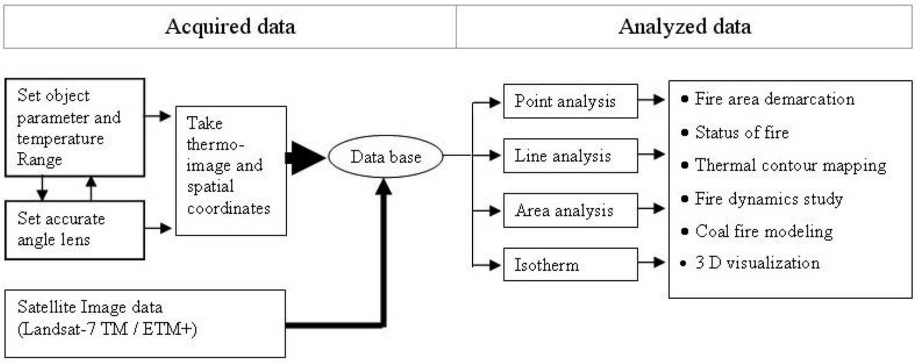

Figure 5: *Flow Chart of the Monitoring Procedure Used For Acquiring and Analysis of Thermography Technique*

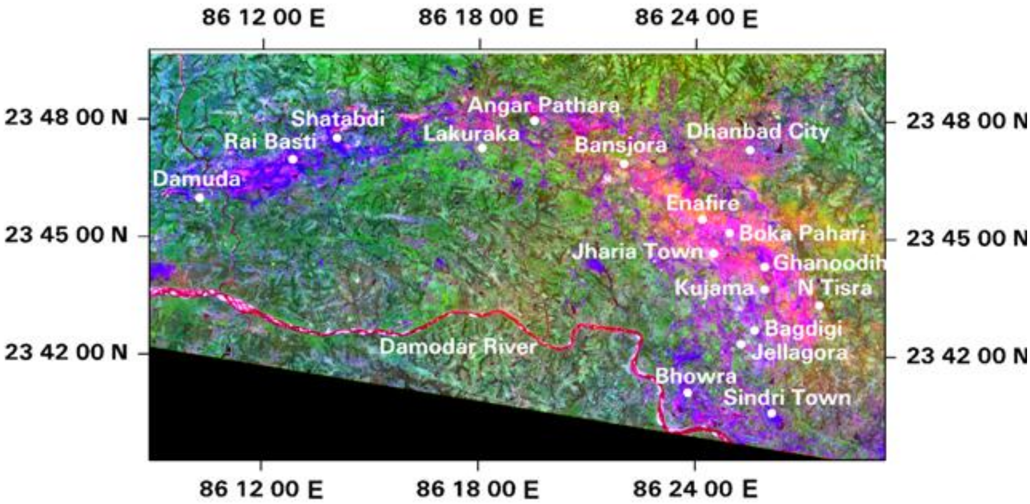

Figure 6: *The Satellite Image of Jharia Coal Field (JCF) In False Color Composition with fire location*

4. Results and Discussion

Thermal survey was carried out at different fire affected locations of JCF using Thermal imaging camera. The observed ground data were also compared with the findings of satellite data at same locations. The significant differences in both the observation were recorded. The obtained temperature of satellite data was very low in comparison to the temperatures obtained by thermal imaging camera (Table 1).

Table 1: *Ground Point Coordinates and Temperatures Taken By G.P.S and Thermal Imaging Camera with Corresponding Satellite Image Temperature of Different Fire Affected Areas of Jharia Coal Field*

Sl. No.	Name of Fire Area	Latitude ($0^0\,0^{'}\,0^{''}$ N)	Longitude ($0^0\,0^{'}\,0^{''}$ E)	Elevation (m)	Calculated Satellite Image Temp. (^{o}C)	Measured I R camera Temp. (^{o}C)
1.	Ena Fire Project	23 45 35	86 24 10	200	64.80	456
2.	Jai Rampur OCP	23 47 41	86 25 32	220	57.43	375
3.	Boka Pahari(Rajapur)	23 45 13	86 24 55	207	70.44	518
4.	Pandebera Village	23 44 09	86 25 33	167	29.22	65
5.	Ghanoodih Basti	23 44 23	86 25 54	189	46.51	255
6.	Kujama Basti	23 43 48	86 25 53	173	39.59	179
7.	Ghanoodih OCP	23 44 23	86 25 55	192	38.50	167
8.	Jairampur Road	23 43 02	86 25 20	164	38.77	170
9.	Jairampur Village	23 42 55	86 25 18	176	30.13	75
10.	Angar Pathara	23 48 02	86 19 31	195	63.43	441

11.	Tetuliya East- Katras	23 47 42	86 17 00	186	28.76	90
12.	Lodna Basti	23 47 20	86 18 04	192	38.59	168
13.	Lakuraka Basti	23 47 16	86 18 23	188	30.58	80
14.	Tetulia Village	23 47 27	86 17 35	194	30.85	83
15.	Shatabdi OCP (H.R)	23 47 36	86 14 01	209	54.33	341
16.	Shatabdi Dump Fire	23 47 33	86 14 05	209	65.62	465
17.	Shatabadi Mining Area	23 47 39	86 14 38	192	64.44	452
18.	Sendra Bansjora OCP	23 47 42	86 20 53	198	52.79	324
19.	Basjora Colliery	23 46 59	86 22 01	197	39.77	181
20.	Bagdigi OCP	23 42 45	86 45 39	160	61.79	423
21.	South Tisra OCP	23 42 09	86 26 40	197	30.13	79
22.	NorthTisra OCP	23 43 25	86 27 26	194	30.58	80
23.	Damuda B.J. Section	23 46 02	86 10 15	180	38.68	189
24.	Sijua Basti, Damuda	23 46 20	86 10 20	196	30.58	80
25.	Rai Basti	23 47 04	86 12 50	232	45.14	240

H.R.- (Haul Road), OCP- (Open cast project)

The disparity observed between temperatures obtained by remote sensing techniques is due to atmospheric effect, solar reflection and topography etc. [9] and [20]. The maximum temperatures of thermal infrared images and corresponding satellite image found near dwellings area of Boka pahari (Rajapur), Ghanoodih and Kujama 518^{0}C and 70.44^{0}C; 167.7°C and 38.59°C; and 179.3°C and 39.59 °C respectively (Figure 7). Children are enjoying the heat during winter season in the fire-affected area without knowing the intensity of fire, stability of ground and emission of obnoxious gases (SO_x, NO_x, CO) along fissures and cracks, which are dangerous for their health and safety. The maximum temperatures at old dump area and at active mining operational bench of Satabdi OCP are 465.7°C and 452.3°C respectively. The thermal and corresponding visual images of Ena fire project and Satabdi OCP showing the difficult mining operation (Figure 8)

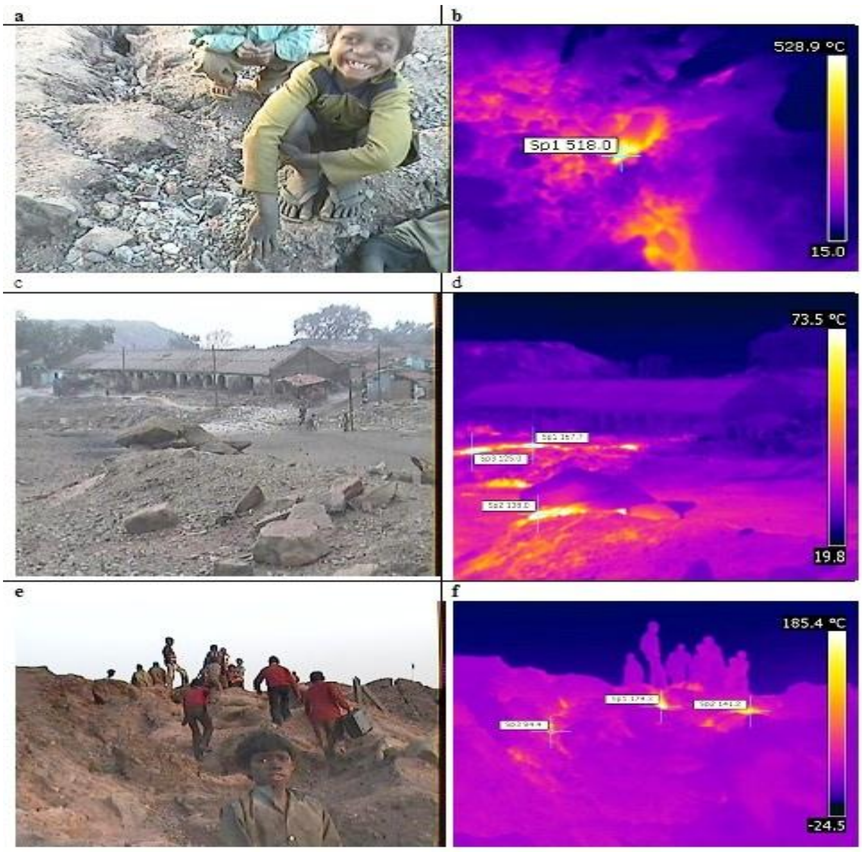

Figure 7: *Visual Image corresponding to Its respective Thermal Infrared Image Showing Maximum Temperature of (a) and (b) Boka Pahari Rajapur OCP (518°C), (c) and (d) Ghanoodih (167.7°C), (e) and (f) Kujama (179.3°C)*

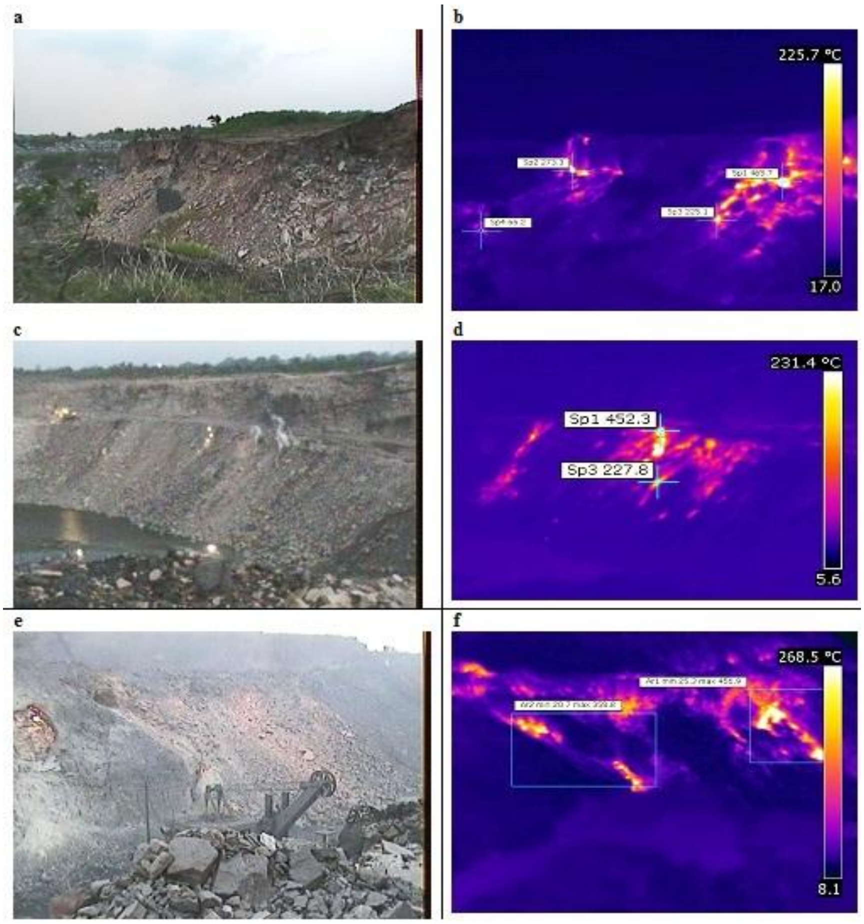

Figure 8: *Visual Image corresponding to its respective Thermal Infrared Image showing maximum temperature of (a) and (b) Satabdi OCP Old Dump Area (465.7°C), (c) and (d) Satabdi OCP Working Bench (452.3°C), (e) and (f) Ena Fire Project Working Bench (465.9°C)*

The analyses of these thermal images have been done using point, line, area, isotherms and trend analysis for interpretations of anomalies. The line analysis of thermal images help to estimate the length of fire affected zone with temperature profile along the line. Temporal monitoring along fixed line will give better result to speculate the direction and rate of fire propagation. Area analysis of a thermal image is giving thermal profile of a selected zone with respect to fire-affected area (Figure 9). Chronological trends analysis of area will be beneficial for determination of fire dynamics, where as isotherm can be used as 3-D visualization of fire area. With the help of result obtained, the status and delineation of fire area can be done more precisely.

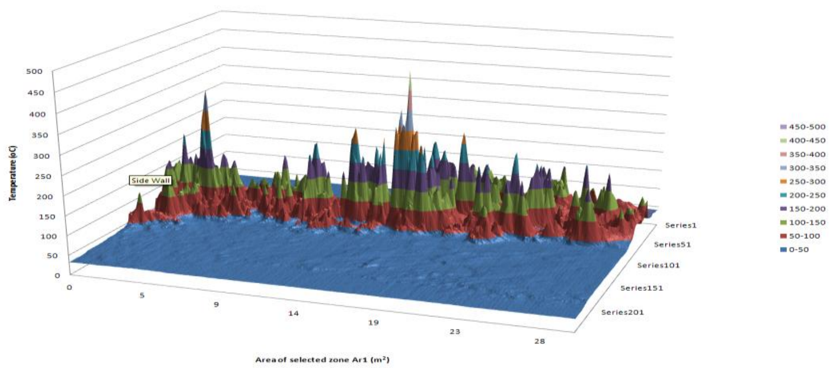

Figure 9: *Area Analysis of a Thermal Image is Giving Thermal Profile of a Selected Zone With Respect To Fire-Affected Area*

5. Conclusion

To assess coal mine fire in JCF at different fire affected area first time thermography monitoring technique was used. Ground level infrared thermographic monitoring has the advantages of being more rigorous, more flexible and less costly than other traditional technique. It will be highly effective for the assessment of coal fire in early stages by temporal monitoring of thermal anomalies. Combining thermography and topography, it is possible to work like remote sensing technique for limited surface area more precisely and effectively. In thermal remote sensing method temperature errors due to atmospheric effect, topography, slope and solar reflection were negligible in thermography. Once anomalies have been determined precisely, the database of an area can be used to determine the fire dynamics, direction and intensity of the fire as well as 3 D modeling. This paper outlined different process of thermography monitoring procedures in different field conditions. It will help to prepare control strategy in fire affected areas in due time. It can also provides an early warning and management information system for future mitigation of coal fire and useful for ground validation of spatial data acquired by the thermal remote sensing.

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