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# Oakland Bulk & Oversized Terminal v. City of Oakland

# Fire and Explosion Safety at the Proposed OBOT Facility

## EXPERT REPORT

**by**

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## 1.0 INTRODUCTION

### 1.1 Scope of work

I was retained by Burke, Williams and Sorensen LLP on behalf of the City of Oakland, California to provide my opinion regarding the fire and explosion safety of transporting, storing and handling of coal and pet/coke at the Oakland Bulk and Oversized Terminal (OBOT) facility. More specifically, I was provided with the materials identified in Section 5, and asked to prepare an expert report that comments and opines on the following issues:

- Spontaneous heating and spontaneous combustion of coal and pet/coke
- The effect of coal characteristics and ambient conditions on the propensity for coal to spontaneously combust
- Coal storage implications on the propensity for coal to spontaneously combust
- If the spontaneous ignition of coal occurs what kind of fire could result
- What are the potential emissions from a coal fire
- What are the potential safety issues of the proposed OBOT facility
- Have the safety issues addressed properly by OBOT

This report states my opinions and basis for the opinions regarding the above subjects. Specifically: the fire and explosion risk during the transport, storage and handling of coal; the management of the fire and explosion risk at the OBOT facility; the consideration of health and safety consequences of a coal fire at OBOT.

The opinions reached are based on work that has been published in peer reviewed technical journals and on my research and teaching in the combustion and fire fields. Further analysis may be conducted if deemed necessary to complement this report.

### 1.2 Statement of Qualifications

My credentials are outlined in the attached CV. Particularly relevant in support of my knowledge on self-heating and spontaneous ignition and combustion are my co-authorship of the book *"Fundamental of Combustion Processes"* published by Springer; my chapter in the book "*Combustion Fundamentals of Fire"* on the Solid Phase Ignition and Flame Spread; my co-authorship of the chapter in the book *"Microgravity Combustion"* on the Mechanisms of Flame Spread and Smolder Wave Propagation; my keynote lecture "On Fire Ignition" published in the Proceedings of the 10th Symposium of the International Association of Fire Safety Science; my plenary lecture on the "Spot Ignition of Wildfires by Embers and Sparks" at the 14th Symposium of the International Association of Fire Safety Science; as well as my multiple publications on ignition, smoldering, transition from smolder to flaming and fire spread; my teaching and research of Combustion Processes at the University of California Berkeley; and my professional consulting activities in fire ignition and development.

My work involves applying fire dynamics and combustion principles to analyze various aspects of fire and combustion processes, ranging from laboratory-scale solid fuel combustion to wildland fire dynamics. I have conducted research in and published on several aspects of combustion and fire, including ignition, smolder, flame spread, flammability, pyrolysis, and fire growth. I have more than 35 years of experience applying fire dynamics analysis in support of scientific research, and forensic fire reconstruction. My research work on fire has been funded by NIST, NASA and NSF.

A list of my publications during the last 10 years is included in section

## 2. BACKGROUND

The construction and operation of a coal, and pet-coke, shiploader at the Oakland Bulk and Oversized Terminal (OBOT) has been proposed to the City of Oakland. The facility would be located at the Gateway Development Area in the location of the former Oakland Army Base adjacent to the Bay Bridge entrance in northwest Oakland. The facility would be used to transfer coal, coke, among other commodities, brought to OBOT in train cars to ships for the transport of the commodity overseas. The transfer would be made by means of a conveyor system. It is proposed that around 5,000.000 tons of coal, pet-coke would be transferred per year. There is concern among the City of Oakland regarding the public health and safety risk that the facility would cause to the communities and transportation corridor adjacent to the OBOT. The concerns are related to the environmental pollution and the fire and explosion safety, of transporting, storing and handling of coal and pet/coke so close to a densely populated community.

This report addresses the issues related to the coal, and pet-coke, fire and explosion safety at the proposed OBOT facility. Pet-coke has similar fire and explosion characteristics as coal and for clarity of presentation it is implicitly included in this report whenever coal is referenced. The reason for the concern is the well- known risk of fires and explosions in the coal transportation and storage industry. A primary reason for the risk is that coal is an energetic fuel (hydrocarbon) with the propensity to spontaneously combust and explode. Although there are ways to reduce the risk of these events, coal related accidents can occur for several reasons that are difficult to prevent, such as mechanical failures and human error.

## 3. OPINION AND BASIS FOR THE OPINION

### Opinion 1: The transportation, storage and handling of coal and pet/coke has an inherent fire and explosion risk that make them hazardous

The risk of coal fires, explosions, and pollution from coal-handling processes in the transportation and storage industry is widely recognized and has been a source of economic loss, and a health and environmental danger for many years. The insurance industry has been attempting to reduce the occurrence of large industrial losses caused by the spontaneous combustion of coal for years (Fitzpatrick 1912). Despite all the efforts dedicated to preventing accidents in the sector, coal fires and coal-dust explosions continue to be a constant threat. According to data provided by The National Institute for Occupational Safety and Health (NIOSH), in the coal industry sector, about 264 fatalities were registered in the US between 2006 and 2015 (McAteer et al. 2006; Fletcher et al. 2006; Page et al. 2010). Although many of the incidents occurred in coal mines, there were also incidents in the transportation and utilization of coal.

A primary reason for the risk of fire from coal is that they are energetic fuels (hydrocarbon) with the propensity for self-heating and spontaneous combustion (Appendix 1). Also, coal handling generates coal dust that has the propensity to ignite and explode in the same fashion that a gaseous fuel has. Although there are ways to reduce the risk of these events, coal related accidents can occur for several reasons among which human error and mechanical failures represent a high percentage, and can occur at any time in the life cycle of the commodity (Chen et al. 2012). The transportation and storage of large volumes of coal inevitably expose coal to air and thus creates favorable conditions for self-ignition or spontaneous combustion of the coal. The frequent accidents of coal fires in the mining sites, storage facilities, and transport like train and ship have been reported worldwide (Smith & Lazzara 1987; Smith et al. 1991; Stracher & Taylor 2004; Song & Kuenzer 2014; Anne M Carpenter et al. 2003)

Large coal fires have also occurred in shiploaders (Appendix 2). Fire accidents that are particularly relevant to the OBOT facility are the shiploader coal fires that occurred at the Los Angeles Export Terminal (LAXT) in September 2000 and then again in February 2001 (Fig. 1). In these fires coal and coke being moved from a stockpile to a ship ignited in the conveyor of a coal loader. It appears that both fires could have had their origins in failed bearings from one of the conveyor return idlers (Carnahan et al. 2007), although it could also have resulted from spontaneously ignited hot spots in the coal collected on the loader or transported from storage piles.

**Opinion 2: The risk of a coal fire or an explosion during the planned operation of the OBOT facility is under-estimated**

This opinion is based primarily on statements made by CCIG/OBOT/TLS response to City of Oakland of 9/28/15 questions, the HDR Report, the Jensen Hughes Technical Memorandum included in the HDR report, and technical literature on the fire risk of coal. Specifically to the question #16 , what is the public safety/combustion risk of coal? it is stated

> ...... "the fire and explosion risk associated with the transport, containment
> of the coal does not pose a public safety risk". …..

Based on this premise the issue of public safety at OBOT is primarily addressed from the point of view of emissions from coal handling, with fire and explosion addressed in very general terms.

Analyzing further the Jensen Hughes Technical Memorandum (JHTM) - Potential Bulk Transfer of Coal at the Proposed Oakland Bulk and Oversized Terminal Project -of September 15, 2015, authored by Peter L. Senez of Jensen Hughes the following critique can be made.

In the Introduction (second paragraph) it states

> “Coal is a chemically stable material that has typical risks associated with the handling of bulk commodities such as sugar, grain, wood chips, sulphur or other materials”.

Quoting the US Bureau of Mines Bulletin 680 (USBMB)"Investigation of Fire & Explosion Accidents in the Chemical, Mining & Fuel Related Industries - A Manual" authored by J. Kutcha. In page 51 under the section of Properties of Agricultural, Carbonaceous, Chemical and Plastic Dusts, it is stated

> “Coal, which is a carbonaceous material, is given special emphasis because of the high fire or explosion risk in the coal mining industry and because of the great usefulness of the many mine safety data that has been generated”

Also quoting the Lloyd’s Register – “Carrying solid bulk cargoes safely. Guidance for crews on the International Maritime Solid Bulk Cargoes Code” it states.

> “Coal (bituminous and anthracite) is a natural, solid, combustible material consisting of amorphous carbon and hydrocarbons. It is best known as a Group B cargo due to its flammable and self-heating properties, but it can also be classed as Group A because it can liquefy if predominantly fine…... In these cases, it is classed as both Group A and B……Coal may create flammable atmospheres, heat spontaneously, deplete oxygen concentration and corrode metal structures. Some types of coal can produce carbon monoxide or methane”

Furthermore, the JHTM statement ignores the energetic characteristics of coal and its propensity for self-heating and spontaneous combustion. Coal is a hydrocarbon fuel that, unlike sugar or grain, is used in the electrical power generation industry because of its elevated heating value (heat of combustion) and its reactivity. For example, coal and pet-coke have approximately twice the heating value of sugar, grain, wood, and consequently are more hazardous because the heating value determines the rate of heat released by a fire. The reactivity (reaction rate) of coal and pet-coke is also much larger than the other materials at a given temperature.

In the Coal and Coal Dust Properties section of JHTM it states

> “The coal that potentially would be transported to the facility would primarily be Utah bituminous coal, which is considered a high rank coal and is less likely to pose a hazard than lower ranking coal”

Also, in the letter from TLS to The Honorable Mayor Libby Schaaf of July 15, 2015 it is stated

> “..the coal TLS is considering would emanate principally from Utah with smaller amounts from neighboring Western Bituminous states and would

> be "Compliance Coal". …………Because of the unusually high heat value and low sulfur content of this Western Bituminous coal, it is among the cleanest burning coals in the world."

Quoting the USMB in page 57, it is stated

> "The tendency of coals to self-heat may be roughly predicted by their CO-$O_2$ index……most reactive coals have an index close to 200 and less reactive coals less than 100". Table 35 shows a bituminous coal from Utah (Sunnyside #1) with a CO-$O_2$ index of 178, which is close to the most reactive coals. Furthermore, in Figure 73 shows that high ranking bituminous coal have a higher potential for a gaseous explosion than a lower rank coal".

Furthermore, Powder River Basin (PRB) coal is notorious for the spontaneous heating hazards it presents due to the high moisture and oxygen content in the coal. This type of coal is predominantly found in Montana, Wyoming, Utah, Colorado, New Mexico, Washington, and Alaska (Anon n.d.).

JHTM also states:

> "Under atmospheric conditions coal dust is stable, and it requires a combination of numerous factors occurring at the same time (e.g., moisture content, temperature, humidity, dust particle size, dust concentration and an ignition source) to be considered dangerous".

Here again JHTM under-estimates the risk of potential coal dust explosions. In transfer, coal dust can easily be lofted into the air by small air currents and form a dust cloud that could have the potential to ignite and explode. The primary requirements for the ignition of a coal dust cloud is that the dust-air mixture is flammable, i.e. a concentration above the lower explosion limit, and that there is an ignition source (spark). Quoting the USMB in page 52, under section of flammability limits in air it is stated

> "It is evident from tables 31 and 27 that all industrial dusts are capable of forming flammable dust-air mixtures……..the lower explosion limit for high volatile bituminous coal dusts are 0.04 to 0.06 g/L (0.06 $oz/ft^3$) in air by the above spark ignition method……The lower limits of carbonaceous dust-air mixtures decrease greatly with increased volatility of the dust or increased methane content of the atmosphere …..minimum spark ignition energies of many agricultural, carbonaceous, chemical and plastic dusts (minus 74 -m) are about 100 mJ or less".

These are very low coal dust concentrations, and reaching them would be facilitated by the planned covering of the OBOT installation (train cars, silos and conveyors). The spark ignition energies could be easily produce by friction sparks or even static electricity.

Furthermore, the covering would also exacerbate the potential ignition of mixtures of dust coal and methane, or hydrogen, off-gassed from the coal (Appendix 1).

In the JHTM it is also stated regarding the potential spontaneous ignition of coal

> “Many materials are recognized for this potential including hay, canola meal, wood chips, all of which are prone to spontaneously ignite when stored for extended periods. Extended storage is not anticipated at OBOT given that it is primarily a transfer terminal. Further, it is anticipated that only higher ranked coal (which is less likely to spontaneously combust) would be received and temporarily stored at OBOT”.

Time is not the major parameter determining the potential for a material to spontaneously ignite. Spontaneous ignition is primarily a function of pile size and material/ambient temperature (Appendix 1). Other parameters such as porosity, moisture, wind etc. also play a role although less predominant. Time is a factor in the sense that if the coal is undergoing self-heating the process accelerates with time as the coal temperature and consequently its reaction rate increase. Therefore, the time required for spontaneous ignition to occur depends on the pile size, ambient temperature, material characteristics etc. Stating that extended storage is not anticipated at OBOT, is irrelevant unless the coal storage and transfer characteristics are specified. There will always be delays due to multiple factors, such as breaking of mechanical components, weather, maintenance, strikes, ship delays etc. Furthermore as stated above quoting USBM high ranking bituminous coal have a higher potential for a gaseous explosion than a lower ranking coal.

In the response of CCIG/OBOT/TLS to City of Oakland questions 10/6/15 Does the transport, containment present the potential for catastrophic explosion or fire danger? it is stated

> “During transport of coal via train, fire risk will be negligible due to the nature and type of coal being shipped (low potential for spontaneous combustion), the short duration of transport (limited to a few days of travel), the proper conditioning of the coal at the mine (pre-transport controls), and the cooling effects of air on the cars and the surface of the coal. Using enclosed cars will further reduce potential exposure of the coal to rain and other atmospheric moisture,

There is a misconception in this statement. Using enclosed train cars will reduce the heat loss from the coal to the outside air on top of the car, thus favoring self-heating. Furthermore, enclosing the cars will increase the concentration of coal dust and off-gassed methane and hydrogen in the space between the coal and the cover, thus enhancing the flammability of the dust-air mixture and making it more explosive (Appendix 1). This together with the fact that higher ranking coal has a higher potential for a gaseous explosion makes enclosing the train cars more hazardous from the point of view of a fire and explosion.

Another indication that the risk of a coal fire or an explosion during the planned operation of the OBOT facility is not addressed properly are the statement in the CCIG/OBOT/TLS to City of Oakland quoting the JHTM

> “Handling of coal at OBOT does not present a disproportionate hazard compared to other commodities, all of which have a strong safety track record and infrequent event occurrence”

This statement contradicts warnings of potential hazards, and description of fire and explosion risks associated with coal cargos of the International Maritime Solid Bulk Cargoes (IMSBC) Code. Regarding the hazards of coal, the IMSBC states,

> “Coal may create flammable atmospheres, may heat spontaneously, may deplete the oxygen concentration, may corrode metal structures. Can liquefy if predominantly fine 75% less than 5 mm coal”.

The IMSBC also specifies in more detail that

> “Coals may emit methane, a flammable gas. A methane/air mixture containing between 5% and 16% methane constitutes an explosive atmosphere which can be ignited by sparks or naked flame, e.g., electrical or frictional sparks, a match or lighted cigarette. Methane is lighter than air and may, therefore, accumulate in the upper region of the cargo space or other enclosed spaces. ……Coals may be subject to oxidation, leading to depletion of oxygen and an increase in carbon dioxide or carbon monoxide concentrations in the cargo space. Carbon monoxide is an odourless gas, slightly lighter than air, and has flammable limits in air of 12% to 75% by volume. It is toxic by inhalation with an affinity for blood hemoglobin over 200 times that of oxygen. ……Some coals may heat spontaneously and the spontaneous heating may lead to spontaneous combustion in the cargo space …..Some coals may be liable to react with water and produce acids which may cause corrosion. Flammable and toxic gases, including hydrogen, may be produced. Hydrogen is an odourless gas, much lighter than air, and has flammable limits in air of 4% to 75% by volume”

These are significant hazards fire protection engineering, and clearly contradict the CCIG/OBOT/TLS statement that handling of coal at OBOT does not present a disproportionate hazard compared to other commodities.

Also in the response of CCIG/OBOT/TLS to City of Oakland question 10/6/15, it is stated

> “The fire and life safety risks associated with the movement of coal and other bulk materials is readily addressed using good, standard fire protection engineering practices…….the JHTM recommends specific facility design and procedural measures that would effectively mitigate the risk of fire and explosion at OBOT”

This statement refers to the section 3.0 Facility Design of the JHTM. The section only contains generic a description of the features that “will need to be taken into consideration in the design of the OBOT facility”. Based on the risks identified in Appendix 1 related to transport, handling and storage of coal, and the fact that there are still accidental fires and explosions in these processes particularly in ship coal loaders (Appendix 2) even after all of the knowledge of coal dangers and efforts to mitigate against such dangers, the features indicated in the JHTM are inadequate. Human error and mechanical breakdown are common failure mechanisms. Human perfection and perfect mechanical maintenance and efficiency are unlikely over continuous years of operation involving 5000 tons of annual throughput and associated wear and tear.

**Opinion 3. The health and safety consequences of a coal fire or an explosion during the planned operation of the OBOT facility have not been properly considered**

There are environmentally catastrophic effects from coal fires, including the emission of noxious gases and particulate matter into the atmosphere and condensation products responsible for stream, ocean and soil pollution (Szabo 1978; Jangam et al. 2011). Coal fires have killed people, forced entire communities to abandon their homes and businesses, destroyed floral and faunal habitats, and are responsible for perilous land subsidence (Stracher & Taylor 2004).

Burning coal can release a number of potentially hazardous materials. Some of these are the byproducts of the combustion process such as carbon monoxide, soot, mineral particulates, and polycyclic aromatic hydrocarbons (PAHs) (Reisen et al. 2017). Others are due to naturally occurring contaminants in the coal, such as Mercury and Sulfur. Uncontrolled coal fires can exhibit both smoldering and flaming combustion. Smoldering by nature is an incomplete combustion process and releases a large amoun of uncombusted hydrocarbons like methane ($CH_4$), ethylene ($C_2H_4$), and toxic PAHs compared to gas phase combustion, although at a smaller rate than in a flaming fire.

Neither the HDR report or CCIG/OBOT/TLS replies to City of Oakland have addressed properly this issue, as reflected by the statement that

> “Based on the above, the fire and explosion risk associated with the transport, containment of the coal does not pose a public safety risk”

This is in part the result of the assumption that a fire or explosion will not occur at the OBOT facility or that if it occurs it will be quickly put out. As it is shown in Appendix 3, the rates of chemical released in a coal fire, although they are dependent on the size of the fire, are significant. The data can be used together with FDS computer models to predict the impact on the health and safety of the community around OBOT (Dr. H. A. Grey report). The report shows that a medium size accidental fire at the OBOT facility has the potential to create very high PM2.5's concentration levels at many nearby locations.

## 4. MATERIAL CONSIDERED

I was provided with and have considered the following documents:

2014 07 17 Bowie Presentation to UPRR Circulated to CCIG - OB057454_imag...
2015-07-15 Ltr from J Bridges TLS to Mayor re Bulk Terminal
2015-09-14 - Flexco Submission to City re Coal Handling Conveyor Transfer...
2015-10-06 CCIG OBOT TLS Response to City Questions - CTRL0000000851-000..
2015 10 06 Cardno Peer Review Report - Preliminary Engineering - OBOT - ...
June2015TLS OperatingPlanFramework(OB082060-83)
2016 06 23 Agenda Report re Options to Address Coat and Coke Issues
2016-05-02 - May 2, 2016 letter from Stice Block (OBOT)
2017-05 The Local Air Pollution Costs of Coal Storage - NBER
EarthJustice Letter of Opposition
ESA Report Chapter 2 - Project Description and Operation
ESA Report Chapter 6 - Safety Effects
HDR Engineering Report for CCIG - Sept 2015
OAK.Drawings.054829
OAK0548.commodities2
OAK054936-1
oak054816
oak054817
OAK054820.Loader
OAK054821 Agreement
OAK054822.drawings
OAK054825materialsdata
OAK054827
oak055098
Ordinance no. 13385 CMS banning storage and handling of coal (2016)

I have also reviewed and considered the following documents:
Literature cited in the reference section
Miscellaneous documents contained in my file not explicitly listed above.

## 5. PREVIOUS TESTIMONY SUMMARY, last four years

| **Court** | **Case** | **Law Firm** | **Deposition/ Trial** |
|---|---|---|---|
| Superior Court of California, County of Plumas | California Department of Forestry and Fire Protection vs. Eunice Howell et al. | William R. Warne<br>Downey Brand<br>621 Capitol Mall<br>Sacramento, CA 95814 | Deposition 2013 |
| Superior Court of California, County of Santa Barbara | California Department of Forestry and Fire Protection vs. Dana Neil Larsen et al. | Gregory P. Waters<br>Engstrom, Lipscomb & lack<br>10100 Santa Monica Blvd<br>Los Angeles, CA 90067 | Deposition 2013 |
| State of Michigan. Judicial Circuit Court for the County of Emmet | Allstate Property & Casual Insurance Co v. Mechanical Contracting Services et al. | Philip T. Carroll<br>Cozen O'Connor<br>333 West Wacker Dr.<br>Chicago, Il 60606 | Deposition 2013 |
| Superior Court of California, County of Loa Angeles | Sayre Fire Litigation v. Southern California Edison | Joseph A. Lack<br>Engstrom, Lipscomb & lack<br>10100 Santa Monica Blvd<br>Los Angeles, CA 90067 | Deposition 2014 |
| United States District Court for the Central District of California | Star Envirotech, Inc. vs Redline detection, et al. | Mathew A. Newboles<br>Stetina Brunda Garred & Brucker<br>75 Enterprise, Suite 250<br>Aliso Viejo, CA 92656 | Deposition 2015 |
| Superior Court of California, County of San Diego | Gregory Saska et al v. Omni Hotels Management Corp. et al. | Anthony Livingston<br>Butler Weihmuller Katz Craig<br>400 N Ashley Dr. Suite 2300<br>Tampa, FL 33602 | Deposition 2016 |
| Superior Court of California, County of San Diego | CAL FIRE v. Paradise Associates, Inc., et. Al | D. Rockey Goodell III<br>Manning & Kass<br>550 West C St. , Suite 1900<br>San Diego, CA 92101 | Deposition and Trial 2016 |
| Superior Court of the State of Arizona, County of Maricopa | Nationwide Mutual Ins. and AMCO Ins.as subrogees of Farnsworth Wholesale vs. Town of Gilbet et al. | Kenneth W. Maxwell,<br>Bauman Loewe Witt & Maxwell, PLLC<br>8765 E. Bell Road, Suite 210<br>Scottsdale, AZ 85260 | Deposition 2017 |

## 6. PUBLICATIONS -last ten years

Co-author of the book *Fundamentals of Combustion Processes*, Springer Publishing. Over 200 peer reviewed publications in technical journals in the fields of combustion, fire, and heat transfer. Four book chapters. Over 250 other publications.

### I. PEER REVIEWED PUBLICATIONS

### A. Archival Journals (numbering starts in 1976)

74. G. Rein, A. Bar-Ilan, A.C. Fernandez-Pello, and N. Alvares, "A Comparison of Three Fire Models in the Simulation of Accidental Fires" *Journal of Fire Protection Engineering*, 16 (3), 183-209, (8/2007).

75. A. Fuentes, G. Legros, S. Rouvreau, P. Joulain, J.-P. Vantelon, J.L. Torero, and A.C. Fernandez-Pello, "Sooting Behavior Dynamics of a Non-Buoyant Laminar Diffusion Flame" *Combustion Science and Technology*, 179 (1-2), 3-19, (1/2007).

76. S.B. Sprague, S.-W. Park, D.C. Walther, A.P. Pisano, and A.C. Fernandez-Pello, "Development and Characterization of Small-Scale Rotary Engines" *International Journal of Alternate Propulsion, Innovative Combustion Technologies*, **1**, Issue 2/3, 275-293, (2/2007).

77. M.A. Mikofski, T.C. Williams, C.R. Shaddix, A.C. Fernandez-Pello, and L.G. Blevins, "Structure of Laminar Sooting Inverse Diffusion Flames" *Combustion and Flame*, 419, 463-478, (6/2007).

78. N. Sardoy, J-L. Consalvi, B. Poterie, J-C Loraud, and A.C. Fernandez-Pello "Modeling Transport and Combustion of Firebrands from Burning Trees" *Combustion and Flame*, V. 150, 151-169, (2007)

79. O. Putzeys, A.C. Fernandez-Pello, G. Rein and D. Urban "The Piloted Transition to Flaming in Smoldering of Fire Retarded and Non-Retarded Polyurethane Foam" *Fire and Materials Journal*, **32**, 8, 485-499, (2008)

80. N. Sardoy, J-L. Consalvi, J-L Kais, B. Poterie, and A.C. Fernandez-Pello "Numerical Study of Ground-level Distribution of Firebrands Generated by Line Fires" *Combustion and Flame*, **154**, 478-488 (2008)

81. F. Nmira, J-L. Consalvi, A. Kaiss, B. Porterie and A.C. Fernandez-Pello "A Numerical Study of Water Mist Mitigation of Tunnel Fires" *Fire Safety Journal*, 44, 198-211, 2009

82. C. Lautenberger and C. Fernandez-Pello "Spotting Ignition of Fuel Beds by Firebrands" *Computational Methods and Experimental Measurements XIV*, C.A Brebia and G.M. Carlomagno Editors, WIT Press, 603-612, 2009

83. C. Lautenberger and C. Fernandez-Pello “Generalized Pyrolysis Model for Combustible Solids” *Fire Safety Journal*, 44: 819-839 (2009)

84. C. Lautenberger and A. C. Fernandez-Pello “A model for the Oxidative Pyrolysis of Wood” C*ombustion and Flame,* 156: 1503-1513 (2009)

85. K. Chetehouna, T. Barboni, I. Zarguili, E. Leoni, A. Simeoni and A.C. Fernandez-Pello “Investigation on the Emission of Volatile Organic Compounds from Heated Vegetation and their Potential to Cause an Eruptive Forest Fire” *Combustion Science and Technology* , Vol 181, Issue 10, 1273-1288 (2009)

86. S. McAllister, C. Fernandez-Pello, G. Ruff and D. Urban “Effect of Pressure and Oxygen Concentration on Piloted Ignition Delay of Combustible Solids” *Combustion and Flame,*157, 1753–1759, (2010)

87. R. Hadden, S. Scott, C. Lautenberger and C. Fernandez-Pello “Ignition of Combustible Fuel Beds by Hot Particles: An Experimental and Theoretical Study” *Fire Technology,* V47, 341, (2011)

88. S. Fereres, C. Lautenberger, C. Fernandez-Pello, D. Urban and G. Ruff “Mass Loss Rate at Ignition in Reduced Pressure Environments” *Combustion and Flame,* 158, 1301-1306, (2011)

89. N. Alvares and A.C. Fernandez-Pello “A Methodology to Determine Pre-crash Fuel Quantity from Post-crash Fire Thermal Damage to an Aircraft Structure” *Journal of Fire Protection Engineering,* 21 (3), 223-236 (2011)

90. A. B. Dodd, C. Lautenberger, C. Fernandez-Pello “Computational Modeling of Smolder Combustion and Spontaneous Transition to Flaming *Combustion and Flame,* V. 159, 1,448-461 (2012)

91. S. Fereres, C. Lautenberger, C. Fernandez-Pello, D. Urban and G. Ruff “Understanding Pressure effects on Piloted Ignition Through Numerical Modeling ” *Combustion and Flame,* V.159, 12, 3544-3553 (2012)

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92. A. Osorio, A.C. Fernandez-Pello, D. Urban, and G. Ruff “Limiting Conditions for Flame Spread in Fire Resistant Fabrics” *Proceedings of the Combustion Institute,* **34**, 2691-2697 (2012)

93. S. Manzello, T. Yamada, A. Jeffers, Y. Ohmiya, K. Himoto and A. C. Fernandez-Pello “Summary of Workshop for Fire Structure Interaction and Urban and Wildland-Urban Interface (WUI) Fires-Operation Tomodachi-Fire Research” *Fire Safety Journal,* V 59, 122-131 (2013)

94. K. Chetehouna, L. Courty, J.P. Garo, D.X. Viegas and C. Fernandez-Pello "Flammability Limits of VOCs Emitted by Fire Heated Vegetation (Rosmarinus officianalis L.) and its Potential Link with Accelerating Forest Fires in Canyons: a Froude-Scaling Approach" *Journal of Fire Science,* V.32:316-327 (2013)

95. L. Courty, K. Chetehouna, L. Lemee, C. Fernandez-Pello and J.P. Garo, "Biogenic Volatile Organic Compounds (BVOCs) Emissions at High Temperatures of Common Plants from Mediterranean Regions Affected by Forest Fires," *Journal of Fire Science,* V.32:459-479 (2014)

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## 7. COMPENSATION

The compensation for my work on this matter is at a rate of $350 per hour. My opinions are not contingent upon my compensation.

# 8. APPENDICES

## APPENDIX 1: Self-heating, spontaneous combustion and explosion of coal

### A.1.1 Self-heating and spontaneous ignition

Self-heating, or spontaneous heating, refers to the spontaneous phenomenon where a combustible material's temperature increases spontaneously under certain ambient conditions. The U.S. Department of Energy defines spontaneous heating as "*Spontaneous heating is the slow oxidation of an element or compound which causes the bulk temperature of the element or compound to rise without the addition of an external heat source. Spontaneous heating may be the result of direct oxidation of hydrocarbons (for example, oils, coal, and solvents)*" (Yoder 1994). Within the compound, some chemical and physical processes, including oxidation of the material, and heat transfer to the surroundings can rise its temperature. This spontaneous temperature rise may eventually lead to the ignition of the combustible, to its combustion (fire) or an explosion (Carras & Young 1994; P. C. Bowes 1984).

Certain materials, particularly porous materials, are known for their self-heating propensity. This has long been recognized in rural areas, particularly as it affects stacks of hay or seeds (Quintiere 2006). Similarly, coal is a porous material and have relatively low thermal conductivity (i.e., a good heat insulator), consequently they are susceptible to self-heat. The self-heating of coal in a stockpile is well recognized and explained in combustion textbooks (Bowes 1984, Babrauskas 2003).

Once the combustible material is self-heated above the environmental temperature, the heating rate increases because oxidative reactions increase with temperature. For example, as the coal temperature increases, oxidative reaction rates also increase, approximately doubling with every 20 °F increase in temperature (Vance et al. 1996). However, the cooling rate to the environment also increases as the material temperature increases. Depending on the fuel properties, geometry, size, and various environmental factors, the material pile reaches either a semi thermal balance or a further increase in its temperature (Fig. A1.1). In the former case, the material remains at an elevated temperature but stationary. In the latter case, this phenomenon can lead to a positive feedback mechanism where a material's temperature increases at an accelerating rate. It is this positive feedback loop that causes in some cases, self or spontaneous ignition. Such self-heat process leading to self-ignition may last for weeks before a clear fire could be detected (Anne M Carpenter et al. 2003). Once ignited, the coal may burn in the form of smoldering (glowing) as in Fig. A1.2 (left), or flaming (fire) as in Fig.A1.2 (right).

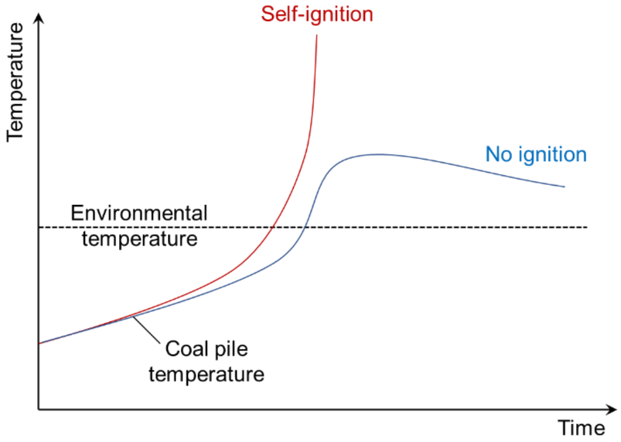

**Figure A1.1.** Diagram of the self-heat process and self-ignition phenomena.

**Figure A1.2.** Glowing combustion in coal stockpile (left). Flaming combustion of coal in a cargo ship (right)

In general, the self-ignition risk of a porous combustible material with self-heating propensity will increase significantly as the size of the stockpile and the environmental temperature increase, because of the reduction in the cooling from the material in the stockpile to the surrounding air. The reason for this is that oxidative heat generation is proportional to the volume of the stockpile, while heat losses (by conduction, convection, and radiation) are proportional to the exposed surface area. Since the ratio of heat generation to heat losses is the controlling factor for self-heating, the stockpile volume to surface ratio is also a controlling factor in the propensity to self-heat. With everything else held constant, a higher volume to surface ratio corresponds to a higher propensity for self-heating. The volume/surface ratio changes with the stockpile geometry, which is the higher for a pile, and is progressively lower for a thin and long layers of fuel (Babrauskas 2003).

Other environmental factors, like solar irradiation and wind, can increase the self-heating risk of a material by reducing the environmental cooling and increasing the oxygen supply. Even the humid wind and periodic rain could promote the ignition of a pile of a material with self-heating propensity. The condensation of water on the material from the humid air releases a significant amount of heat, which raises the temperature of the material and induces spontaneous ignition. This has been observed in coal mine sites where intensive self-ignition with a clear smoke plume has been observed right after a light rain.

### A1.2 Coal self-heating causing self-ignition and fire

Coal is a naturally occurring substance that forms over millennia. It is thought that several hundred million years ago, vegetative matter began to accumulate in swampy areas thereby forming thick layers of peat. As environmental or geological conditions changed, this peat eventually became buried by (usually sedimentary) rocks. The resultant increase in pressure and temperature subsequently converted this peat to coal over millions of years. Coal has a high carbon percentage, but commonly contains other compounds such as sulfur, iron, and trace minerals in varying degrees.

Coal is a material that is known to self-heat to ignition under certain circumstances. In general, the self-ignition risk of coal is strongly dependent on the size of coal stockpile and ambient temperature, because they affect both the rate of heating of the coal in a pile. Specifically, the heat generation is proportional to the volume of the coal pile while the amount of cooling is proportional to the exposed surface area. Thus, the propensity to self-heat is proportional to the volume/surface ratio. Anecdotal experience has provided guidance on the size limit of coal stockpiles to prevent spontaneous ignition. The 2013 *Coal-Fired Power Generation Handbook* (Speight 2013) states "*If practical, the coal should be stored in several small stockpiles instead of one large stockpile to prevent heat buildup and allow more facile inspection of the coal. Coal piles should not be stacked higher than 12 feet and should not contain more than 1,500 tons in a single pile, and no point in the interior of the stockpile should be more than 10 feet from an air-cooled surface*." However, because coal is a porous material, depending on its structure (pulverized, lump, etc.) it can have a large surface area in contact with the ambient oxygen in the air, which is one of the key facts to support self-heating. Thus, the porosity and particle size of the coal also come into play in determining the propensity of coal to self-heating, which increases as the coal is more porous and as the particles are smaller. However, their quantitative effect varies from coal to coal and case to case. Other environmental factors, like the solar irradiation and wind, can increase the self-ignition risk of coal by reducing the environmental cooling and increasing the oxygen supply. Even humid wind and periodic rain could promote the self-ignition of a coal pile. In addition to the heat released by water condensation, another possible reason for the potential effect of rain in promoting the ignition of the coal is that the rain droplets remove the surface coal layer, allowing the air to reach the hot coal inside (Bhagat 1980).

The probability of self-ignition increases as the coal ranking decreases. Lower rank coals, like sub-bituminous coals, mostly found in the western states of the US, have a high volatile matter content, compared to other coals. These coals are also very fragile, resulting in faster degradation and particle size reduction during the handling process which can lead to spontaneous combustion and methane off-gassing. Sub-bituminous coal from the West of the US contain about 35 – 45% carbon and have a heating value between 8,300 to 11,500 Btu per pound. Powder River Basin (PRB) coal is notorious for the spontaneous heating hazards it presents due to the high moisture and oxygen content in the coal. This type of coal is predominantly found in Montana, Wyoming, Utah, Colorado, New Mexico, Washington, and Alaska, accounting for about 37% of the coal reserves in the United States (Fig. A1.3) (Anon n.d.).

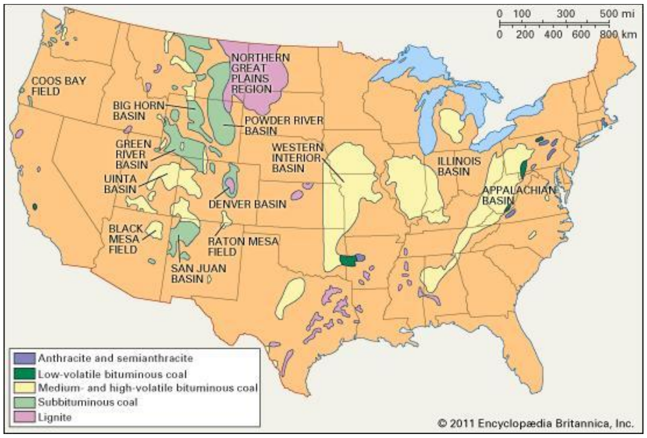

**Figure A1.3.** Coal-bearing areas of the conterminous United States. (Encyclopedia Britannica, Inc)

### A.1.3 Coal dust cloud explosions

Coal dust clouds form when small particles of coal are lofted into the air by small air currents because of the particles small size. Even though the coal particles in the dust cloud are solid, their small size causes them to behave in many ways like a gas regarding combustion. Dust clouds, like gaseous fuel air mixtures (e.g., propane and air) need enough fuel for the reaction to sustain itself. A common metric for this in gaseous fuel air mixtures such as propane is the Lean Flammability Limit (LFL), which is the minimum concentration of fuel in air for ignition to occur. In the case of dust clouds, the LFL is often reported as the minimum density of fuel dust in the air, or Minimum Explosive Concentration (MEC). According to the ignition handbook (Babrauskas 2003), for coal, the MEC is about 100g/m$^3$ (Babrauskas 2003). The MEC can vary between different types of coal (e.g., bituminous, sub-bituminous, and lignite) and the specifics of the coal sample tested such the size of the dust particles, their specific chemical components, and other parameters. For example, bituminous coal (high volatility) with median particle size of 4 microns has a Minimum Explosive Concentration (MEC) of 60 g/m$^3$ (Kodur V. K. R. 2002), which is typical of the more reactive bituminous coals. Enclosing the coal dust also contributes to the potential of an explosion since it is easier for the dust cloud to reach the LFL. It is for this reason that coal silos are vented to dilute the coal dust clod and prevent it from reaching the LFL.

While it is possible for combustible mixtures not to have enough fuel to ignite, it is also possible for them to not have enough oxygen to ignite a sustained reaction. For dust explosions, this is often reported as the Limiting Oxygen Concentration (LOC). The LOC for bituminous coal has been reported between 11% and 16% (Babrauskas 2003). This can occur if the dust is in a confined space and volatile matter (e.g., flammable vapors such as methane, or hydrogen) is released by the coal dust. The oxygen level can also be decreased if the coal begins to oxidize with the air, which will consume the oxygenand produce carbon monoxide which is also flammable.

If the dust cloud has the required MEC and LOC, then all that is needed to start an explosion is an ignition source. The Ignition Handbook (Babrauskas 2003) lists some common ignition sources:

1. *Open Flames (welding torches, burning dust pile/layer*
2. *Hot Surfaces (overheated devices, hot bearings)*
3. *Hot Particles (pieces of burning debris/embers, welding spatter, etc.)*
4. *Frictional, grinding or impact sparks (rubbing machinery, power tools, or metal on metal impacts)*
5. *Electric Sparks (short circuiting devices)*

While there are specifics for each of the listed ignition sources, standard metrics for analyzing the ignition characteristics of dust clouds are typically a Minimum Ignition Energy (MIE) and minimum hot surface temperature. Reported minimum ignition energies for bituminous coal are roughly of the order of 200 mJ. This is a very small energy and consequently many types of small sparks have the potential to ignite a coal dust cloud, including static electricity. The MIE decreases with increasing auto-ignition temperature of the dust cloud (Babrauskas 2003). Another possibility is that if the dust cloud and air are at a high enough temperature the cloud can spontaneously-ignite. Reported spontaneous ignition temperatures for coal dust are 590C (1100F) for bituminous coal (Babrauskas 2003).

## APPENDIX 2: Potential for Accidental Coal Fires

### A2.1 Accidental fires in coal storage

Fire accident have been quite common in coal storage since the industrial revolution. Coal fires in stockpiles pose significant safety, environmental and economic problems. In addition to the economic loss of coal fires, the heat-affected coal adjacent to the fire may become partially or totally unsuitable for its intended use.

Coal silos present a particular problem in relation to self-heating (Nalbandian 2010), because they can provide ideal conditions for accelerated self-heating, due to the large size of the stockpiles and potential availability of air within the coal. Coal stored in silos continually oxidizes and generates heat (Systems 2000) before it is fed into a coal mill or loaded in a conveyor for transportation. In the event of an unscheduled shut-down, coal trapped in the silo may oxidize enough to eventually start to burn. The length of the time that it takes to heat the coal to the burning point is a function of the reactivity of the coal. Some Western US coals will reach this point in just a few days. In addition, fires are more frequent if the silos are not cleaned periodically and/or proper filling procedures are not followed.

An example of the risk associated with the storage of coal is what happened on September 2011 in South Dakota, where a coal storage silo ended up with an explosion that cost the lives of two fire fighters that were attempting to extinguish the fire. Some of the factors that contributed to the ignition of the fire are specific characteristics to the design of the structure added to the unique explosive characteristics of coal (The National Institute for Occupational Safety and Health 2012). Another example is the June 1991 fire in the J.P. Pulliam Station in Wisconsin, where an undetected fire in a coal bunker at a coal-fired plant, believed to have started by spontaneous combustion, gave rise to a minor explosion, which ignited coal dust that resulted in a massive explosion. The estimated cost of this explosion exceeded US$ 4 million (Nelson & Chen 2007).

## A2.2 Accidental fires in coal transport

Coal fires can also occur during transport in ship and train, so caution is required in selecting transport method and path (Anne M Carpenter et al. 2003). The reasons for the potential of fires during coal transportation are similar than those for its storage, i.e size of train car or ship’s bulk cargo compartments, ambient temperature, availability of oxygen to reach the coal, etc. It is suggested that the maximum mean ambient temperature that a container in a shipping hold will be exposed to for a reasonable amount of time during transport is 100 ºF (38 ºC) (Nelson & Chen 2007), although this temperature may change somewhat depending on the type of coal, size of the cargo compartment, humidity, etc.

Shipboard fires due to spontaneous heating and combustion have been reported when coals from the USA were exported to the Far East (Smith & Lazzara 1987). Recently, a ship containing about 75000 tons of coal from Kalimantan in Indonesia was forced to return to port after the coal caught on fire after three days of voyage (Rahmatullah 2017). Also a ship containing 54,000 tons of coal was forced to set anchor inside the San Pedro Bay, Long Beach, CA breakwater for several weeks waiting for a solution to the problem that its coal cargo was too hot (132 degrees) to continue the trip (LA Times article 1987). The Coast Guard determined that the overheating was due to the humid conditions that the coal was loaded in the Mississippi Delta. The moisture in the coal prevented the release of heat that normally occurs through the evaporation of water in coal. To prevent incidents of this type, the International Maritime Organization (IMO) requires all coal carriers to provide suitable equipment for the early detection of cargo heating. However, Minton Treharne & Davies Group concluded that it may not be possible to always follow these procedures (Anon 2008).

In addition to the danger of spontaneous combustion due to self-heating, a hazard in the transport of bituminous coal is the slow release of methane and of molecular hydrogen. When gaseous bituminous coal is stored in a confined environment, methane accumulations can become a latent explosion hazard (Speight 2013; Lascola et al. 1981). Over the course of transport methane concentrations in the dead space above the coal can reach levels close to the lower explosion limit for methane in air. Over more than a century ago, explosions were a common danger on board of ships carrying coal. Because of this, during 1875 the English parliament appointed a Royal Commission to investigate the spontaneous combustion of coal and gas explosions in ships (Rowan 1982). As a result of their investigations, the Royal Commission noticed that the explosions were related to the amount of gas liberated and the volume of air that it was mixed with. Indicating that surface ventilation, when efficiently applied, could provide a key factor in the prevention of explosions. The risk of a methane explosion in coal cargo ships is also addressed in the recommended precautions prior to loading and during voyage by the CJA Marine Services (CJA Marine Services n.d.). These loading precautions are consistent with those specified in the IMSBC Code referred to below.

Methane exists in the pores or cells of the coal; therefore, the higher risk of explosion will usually be encountered when the surface of the material is fractured and the gas can be released. In the case of cargo ships, explosions have usually taken place in the holds of ships during the loading operations or after some severe motions of the ship (Rowan 1982). Similar case was also encountered near the feeders when coal is unloaded from silos or during stockpile operations (Stahl & Dalzell 1965). Explosions have also been recorded to happen inside of silos during the charging/discharging process (Eckhoff 2003). In 1982, a coal silo exploded in Elkford, Canada, after a methane alarm went off indicating that gas concentrations where higher than 2% by volume (Eckhoff 2003).

Current federal regulations in the US require that the methane content in the air of any structure or enclosure be less than 1.0% vol. (Regulations n.d.), which is lower than the lean flammability limit of methane (5.0% vol.), and this is usually achieved by various means of ventilation. In general terms, the gassier the coal is, the more gas is going to be produced and the higher the risk of explosion. However, they have noticed that mines producing coal with higher gasification rates found it necessary to use open-top silo or additional fan systems to improve ventilation.

Also, over the course of transport hydrogen concentrations in the dead space above the coal can reach levels close to the lower explosion limit for hydrogen in air (Nelson & Chen 2007; Nalbandian 2010). Recent self-ignition tests on six Scottish coals (Nelson & Chen 2007) shows that their self-ignition temperature is lower than the maximum ambient temperature that a container will be exposed to during shipping (100 ºF).

The above issues regarding the hazards of coal cargoes and storage are confirmed by statements in the International Maritime Solid Bulk Cargoes (IMSBC) Code and other insurance companies information like Lloyd’s and Gard. The IMSBC states that “coals may emit methane, a flammable gas. A methane/air mixture containing between 5% and 16% methane constitutes an explosive atmosphere which can be ignited by sparks or naked flame, e.g., electrical or frictional sparks, a match or lighted cigarette. Methane is lighter than air and may, therefore, accumulate in the upper region of the cargo space or other enclosed spaces. ……Coals may be subject to oxidation, leading to depletion of oxygen and an increase in carbon dioxide or carbon monoxide concentrations in the cargo space. Carbon monoxide is an odourless gas, slightly lighter than air, and has flammable limits in air of 12% to 75% by volume. It is toxic by inhalation with an affinity for blood hemoglobin over 200 times that of oxygen. ……Some coals may heat spontaneously and the spontaneous heating may lead to spontaneous combustion in the cargo space. Flammable and toxic gases, including carbon monoxide, may be produced. …..Some coals may be liable to react with water and produce acids which may cause corrosion. Flammable and toxic gases, including hydrogen, may be produced. Hydrogen is an odourless gas, much lighter than air, and has flammable limits in air of 4% to 75% by volume"

### A2.3 Accidental fires in coal moving - Conveyor Belts

Besides the coal in storage, another common place where fires are developed is at the conveyor belts used to move coal from the stockpiles to the transporting train car or ship. Coal on the conveyor belt may heat up to the point of ignition because of the frictional overheating in the belt (Litton et al. 1991; Teacoach et al. 2010). According to the Mine Safety and Health Administration (MSHA) between 2000 and 2009, twenty-five fires in underground coal mines were caused by friction of conveyor belts against pulleys, drives, rollers, idlers, and bearings. Conveyers systems have also started fires in coal fired powerplants. An example is a fire occurred in 2007 in a powerplant when a hot roller on a coal conveyor ignited western coal. Embers from the fire are believed to have helped the fire to spread fast (NFPA 850 2015). In New South Wales firefighters had to put out a fire after an overheating caused by friction in a machine after the conveyor belt snapped (News n.d.). About 10 fire trucks were required to put out the fire and extreme care was taken due to the risk of a dust explosion. Similar situation was experienced in Lamberts Point Coal Terminal in Norfolk, Virginia were an overheated bearing ignited a fire on a couple of rollers on the coal conveyors and rendering the loader useless (Brown n.d.).

Coal fire accident that are particularly relevant to the OBOT facility are the conveyor coal fires that occurred at the Los Angeles Export Terminal (LAXT) in September 2000 and then again in February 2001. In these fires coal and pet-coal being moved from a stockpile to a ship ignited in the conveyor of a coal loader (Fig. A2.1). Investigations of the fires revealed that both had their origins in failed bearings from one of the conveyor return idlers that reached temperatures over 1100°F, igniting coal and coke particles that had accumulated near the bearing (Carnahan et al. 2007), although it could also have resulted from spontaneously ignited hot spots in the coal collected on the loader, or transported from storage piles. After the coal was ignited, the fire extended to the flammable conveyor belt, which eventually snapped and spread the fire even more, causing extensive damage.

**Figure A2.1:** Fires in the ship loader at the LAXT in September 2000 (left) and February 2001 (right) (Carnahan et al. 2007).

Other examples are the large blaze that covered a shiploader at the Hunsterston coal port in North Ayrshire in 2015 (BBC 2015), Figure A2.2. The damaged loader was being used to supply coal to feeder ships to be transferred to coal-fired power stations in Northern Ireland. In New South Wales firefighters had to put out a fire after an overheating caused by friction in a machine after the conveyor belt snapped (News n.d.). About 10 fire trucks were required to put out the fire and extreme care was taken due to the risk of a dust explosion. Similar situation was experienced in Lamberts Point Coal Terminal in Norfolk, Virginia were an overheated bearing ignited a fire on a couple of rollers on the coal conveyors and rendering the loader useless (Brown n.d.).

**Figure A2.2**: Fire at the Hunterston coal port.

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## APPENDIX 3. Environmental Effects of Coal Fires

### A3.1 Background

There are environmentally catastrophic effects from coal fires, including the emission of noxious gases and particulate matter into the atmosphere and condensation products responsible for stream, ocean and soil pollution (Szabo 1978; Jangam et al. 2011). Coal fires have killed people, forced entire communities to abandon their homes and businesses, destroyed floral and faunal habitats, and are responsible for perilous land subsidence (Stracher & Taylor 2004).

Burning coal can release a number of potentially hazardous materials. Some of these are the byproducts of the combustion process such as carbon monoxide, soot, mineral particulates, and polycyclic aromatic hydrocarbons (PAHs) (Reisen et al. 2017). Others are due to naturally occurring contaminants in the coal, such as Mercury, Sulfur and Vanadium. When considering the emissions of an accidental coal fires, comparison should be drawn to accidental fires and less sophisticated burning methods. Uncontrolled coal fires can exhibit both smoldering and flaming combustion. Smoldering combustion by nature is an incomplete combustion process and releases a large amoun of uncombusted hydrocarbons like methane ($CH_4$), ethylene ($C_2H_4$), and toxic PAHs compared to gas flaming combustion, although at a smaller rate than in a flaming fire.

There are many long-lasting, underground coal fires burning around the world (Kuenzer & Stracher 2012). Their persistence and potential harm to residents nearby resulted in some studies to evaluate their emissions. Hower et al. (2013) sampled emissions from the Truman Shepherd coal fire over an eight-month period. They reported the rate of release carbon dioxide ($CO_2$), carbon monoxide (CO), methane($CH_4$), hydrogen sulfide($H_2S$), and mercury (Hg). Fabiansak *et al.* (2013) investigated emissions from the self-heating of coal waste dumps in the Silesian Coal Basins of Poland. In addition to $CO_2$, CO, CH4, $H_2S$, and Hg, they measured hydrogen chloride (CHl), ammonia ($NH_3$), carbon disulfide ($CS_2$), chloromethane ($CH_3Cl$), and a wide range of hydrocarbons, including many PAHs (Fabiańska et al. 2013). Silva et al. (2011) characterized nanomaterials and ultrafine particles released by the Ruth Mullins Coal Fire in eastern Kentucky. They found a variety of plain, metal-bearing, and halogenated carbon nanoparticles as well as Aluminum-Silicon spheres and particles containing chromium and lead.

Residential coal burning, particularly in fire pits or fire places, is largely like the burning of piles of coal. Watson et al. (2001) examined the release of particles smaller than 2.5µm ($PM_{2.5}$) from many sources, including residential coal combustion in stoves and fireplaces. Specifically, they measured a range of elemental contaminants, as well as $SO_4^-$, $NO_3^-$, and $NH_4^+$, in the primary carbon particles. Chen et al. (n.d) measured the emissions from coal burning residential stove with both raw coal and manufactured briquettes. In their characterization of the PAHs released, and the particle size distribution they found that raw coal emitted larger quantities of PAHs.

## A3.2 Rate of emission of hazardous chemicals from a coal fire

For a given coal fire it is possible to calculate the rate at which a hazardous chemical is emitted during the fire by relating measurements reported in the scientific literature to a rational analysis of likely accidental fire scenarios. For this, it necessary to express the release of the potentially hazardous material relative to an amount of coal burnt. Then for a given rate of coal mass burnt, the rate of hazardous material emitted can be determined

Quantifying the rate of emission of hazardous chemicals from the fire source is important to evaluate the transport of these chemicals to adjacent communities, and the resulting influence on the local environment and the health of the communities. There are diverse ways that data is reported in the scientific literature regarding the emission of pollutants from a coal fire. Some give the yield, $Y_X$ , of the chemical component, which is the ratio of the rate of mass of the component emitted to the rate of coal consumed. Others give the mass release rates of different components and their ratio. Here we use the former approach to calculate the rate of emission of different hazardous chemical as a function of the rate of carbon consumed in a fire.

Using the yields of different chemicals for different fires reported in the literature and summarized in Table 2, and estimating the burning rate of coal in a pile, the rate of emission of a chemical component can be calculated as

$$\dot{m}_X = Y_X \dot{m}_{coal} \qquad \text{[g/s]}$$

alternatively, expressed as the flux (mass loss per unit area) as

$$\dot{m}''_X = Y_X \dot{m}''_{coal} \qquad \text{[g/m}^2\text{-s]}$$

Where $Y_X$ is the yield of the chemical component, $\dot{m}$ is the mass rate and the subscript "X" represents a particular chemical.

An example of calculating the rate of emission of a component using this approach is as follows. Carbon monoxide is a major component in the products of coal smoldering. For example, Wu et al. (2017) recently reported that after the self-ignition of coal and during its smoldering combustion, about 40 vol.% of total carbon (C) in a bituminous coal can be released in the form of CO for a coal that has 67.5% carbon mass fraction. In the same work Wu et al. 2017 provide information about the mass rate of carbon monoxide, $\dot{m}_{CO}$, emitted in a laboratory fire and the mass rate of coal burnt in the same fire, $\dot{m}_{coal}$,. Then the yield, or emission factor (lb/lb), of CO per unit mass of coal burnt can be expressed as

$$Y_{CO} = \frac{\dot{m}_{CO}}{\dot{m}_{coal}} = \frac{\dot{m}_C}{\dot{m}_{coal}} \frac{\dot{m}_{CO}}{\dot{m}_C} = 2.33 \frac{\dot{m}_C}{\dot{m}_{coal}} \frac{\dot{V}_{CO}}{\dot{V}_C}$$

Based on this information, it can be estimated that

$$Y_{CO}(\text{smoldering}) = 2.33 \frac{\dot{m}_C}{\dot{m}_{coal}} \frac{\dot{V}_{CO}}{\dot{V}_C} = 2.33 \times 0.675 \times 0.4 = 0.63$$

For a flaming of coal fire, Tian et al. (2018) measured the CO yield in a coal stove as

$$Y_{CO}(\text{flaming}) = 0.1$$

It is seen that the yield for a smolder fire is six times larger than that for a flaming fire, although the rate of burning of a smolder fire is much smaller than for a flaming fire.

Other chemicals emitted during a coal fire include different hydrocarbons ($C_mH_n$) like $CH_4$, $C_2H_4$, PAH, and other chemicals such as $NO_x$, $H_2S$, and PM (Nelson & Chen 2007; Wu & Wu 2011). Also as an example, for methane ($CH_4$) it has been observed that in a small coal fire about 4 vol.% of total carbon is converted to $CH_4$ (Wu et al. 2017). Then, the yield of $CH_4$ per unit mass of coal burnt [lb/lb] is calculated as

$$Y_{CH_4} = \frac{\dot{m}_{CH_4}}{\dot{m}_{coal}} = 1.33\frac{\dot{m}_C}{\dot{m}_{coal}}\frac{\dot{V}_{CH_4}}{\dot{V}_C} = 1.33 \times 0.675 \times 0.04 = 0.036$$

Table A3.1 summarizes the yield, or emission factor, [lb/lb] the calculations of the yields of several chemical products in different fires as reported in the literature. Notice that the release of some of these flammable gases also increases the risk of a gas explosion. The maximum yield is selected because is the most dangerous case. Also, except for CO, it was measured for large fires.

**Table A3.1. Yields or emission factors [lb/lb] of several chemicals in different coal fires.**

| $Y_x$ [kg/kg coal] | $CO_2$ | CO | $CH_4$ | $C_mH_n$ | PAH | PM | $SO_2$, $H_2S$ | $NO_x$ | Hg | Source |
|---|---|---|---|---|---|---|---|---|---|---|
| **Coal fire field** | 190% | 13% | 17% | 19% | 0.1% | - | - | - | 0.01% | (Hower et al. 2013) |
| | 246% | 11% | 18% | - | - | - | - | - | - | (Ide & Orr 2011) |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | - | 10% | - | - | - | 0.05% | 0.14% | 0.003% | - | (Liu et al. 1997) |
| | - | - | 0.5% | - | - | - | 1.26% | - | - | (Fabiańska et al. 2013) |
| **Small coal fire** | 227% | 7% | - | 3.7% | - | 1.12% | - | 0.26% | - | (Tian et al. 2008) |
| | 175% | 9% | - | 1.6% | - | 0.29% | - | 0.11% | - | (Tian et al. 2008) |
| | 150% | 63% | 3.6% | - | - | - | - | - | - | (Wu et al. 2017) |
| | | | | | 0.21% | 1.2% | | | | (Oros & Simoneit 2000; Bond et al. 2002) |
| **Maximum** | 246% | 63% | 18% | 19% | 0.21% | 1.2% | 1.26% | 0.26% | 0.01% | |

### A3.3. Estimation of potential sizes of coal fires

The size of a fire is often quantified by the heat release rate (HRR). This value depends on whether the coal fire is smolder or flaming. For a given coal fire heat release rate  the rate of emission of a chemical X can be estimated as

$$\dot{m}_X = \frac{HRR}{\Delta H_C} Y_X$$

where $\Delta H_C$ is the heat of combustion of the coal. For a sub-bituminous coal, the heat of combustion is around 20 MJ/kg (Anon n.d.).

Using as a base fire the burning of a pile of coal with the minimum size prescribed by the rule of thumb for self-ignition stated above, i.e., a 12’ (height) by 10’ (radius) cylindrical stockpile of coal, the HRR for this minimum size fire can  be calculated as follows

$$m(\text{coal pile}) = \rho V = 800 \frac{kg}{\text{m}^3} \times \frac{\pi}{4} (20 \times 0.3)^2 (12 \times 0.3) \approx 90{,}000\ \text{kg}$$

Where the density of the coal has been taken as $\rho = 800 \frac{kg}{\mathrm{m}^3}$ (Anon n.d.).

Considering that it could take about 2 days to burn all the coal, its burning rate would be

$$\dot{m}(\mathrm{coal}) = \frac{m}{\Delta t} = \frac{90{,}000\ \mathrm{kg}}{2 \times 24\ \mathrm{h}} \approx 1880\ \frac{\mathrm{kg}}{\mathrm{h}} \approx 0.5\ \frac{\mathrm{kg}}{\mathrm{s}}$$

And the corresponding heat release rate is

$$HRR(\mathrm{stockpile}) = \dot{m}\Delta H_C = 0.5 \frac{\mathrm{kg}}{\mathrm{s}} \times 20 \frac{\mathrm{MJ}}{\mathrm{kg}} \approx 10\ \mathrm{MW}$$

which will be considered here as a small-size coal fire.

Another possible fire is that of the coal contained in a train boxcar. For a 86' standard boxcar of coal, about 87’ (length) × 9’ (width) × 13’(height), that only has the top surface exposed to air, and assuming that the fire occurs only on the surface, if the coal burning is the similar as the stockpile, the burning flux is

$$\dot{m}'' = \frac{\dot{m}}{A} = \frac{0.5\ \mathrm{kg/s}}{\frac{\pi}{4}(20 \times 0.3)^2\ \mathrm{m}^2} = 0.018\ \frac{\mathrm{kg}}{\mathrm{m}^2{\cdot}\mathrm{s}}$$

The coal fire will have a heat release rate

$$HRR(\mathrm{boxcar}) = (\dot{m}''A)\Delta H_C = \left(0.018\ \frac{\mathrm{kg}}{\mathrm{m}^2{\cdot}\mathrm{s}} \times 2 \times 87 \times 9 \times 0.3^2\ \mathrm{m}^2\right) \times 20 \frac{\mathrm{MJ}}{\mathrm{kg}} \approx 25\ \mathrm{MW}$$

which can be considered as a medium-size coal fire.

Another fire possibility is in a cargo ship. For a 3,000-t general cargo ship of 90 m (length) and 15 m (beam), and assuming that 10% of the top surface area is burning, the coal fire will have a heat release rate of

$$HRR(\mathrm{cargo\ ship}) = (\dot{m}''A)\Delta H_C = \left(0.018\ \frac{\mathrm{kg}}{\mathrm{m}^2{\cdot}\mathrm{s}} \times 10\% \times 90 \times 15\ \mathrm{m}^2\right) \times 20 \frac{\mathrm{MJ}}{\mathrm{kg}} \approx 50\ \mathrm{MW}$$

which is considered as a large-size coal fire.

### A3.4 Rate of emission of chemicals from a coal fire

With the estimated size of the coal fire, HRR, and with the yield data $Y_X$ of Table 2, the rate of emission of a chemical X for different fire sizes is calculated as

$$\dot{m}_X = \frac{HRR}{\Delta H_C} Y_X$$

where $\Delta H_C$ is the heat of combustion of the coal. For a sub-bituminous coal, the resulting emission rates of the chemicals in Table 2 are presented in Table 3.

**TableA3.2. Rate of emission of chemicals for different fire sizes.**

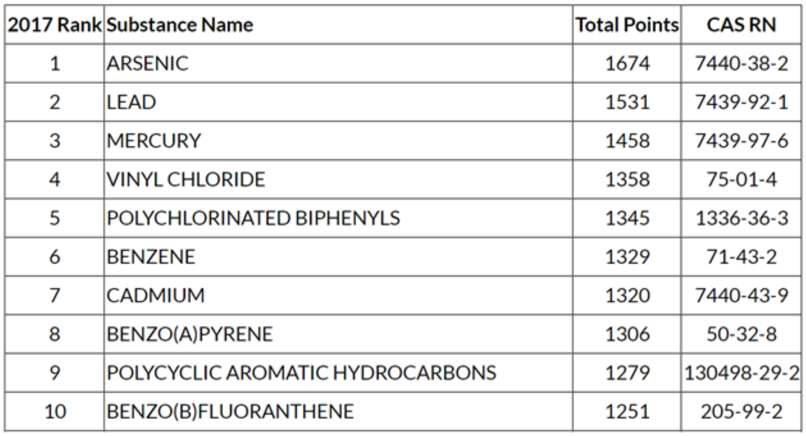
| | **$CO_2$** | **CO** | **$CH_4$** | **$C_mH_n$** | **PAH** | **PM** | **$SO_2$, $H_2S$** | **$NO_x$** | **Hg** | **Unit** |
|---|---|---|---|---|---|---|---|---|---|---|
| **Small (10 MW)** | 1,230 | 315 | 90 | 95 | 1.1 | 6.0 | 6.3 | 1.3 | 0.05 | **[g/s]** |
| **Medium (25 MW)** | 3,075 | 788 | 225 | 238 | 2.6 | 15.0 | 15.8 | 3.3 | 0.13 | **[g/s]** |
| **Large (50 MW)** | 6,150 | 1,575 | 450 | 475 | 5.3 | 30.0 | 31.5 | 6.5 | 0.25 | **[g/s]** |

These rates can be used together with wind pattern models, and toxicity data to estimate the potential health effect of the coal fires in the community downwind from the fire

### A3.5. Emission of other hazardous chemicals from a coal fire

In addition to the chemicals described above, there are some highly toxic elements that may be released in a coal fire, including mercury (Hg), arsenic (As), selenium (Se), lead (Pb), polycyclic aromatic hydrocarbons (PAHs) and fluorine (F). Some of these components, although they may be emitted in small quantities, are in the top list of hazardous substances shown in Table A3.3 (Fu et al. 2011)), and they can be released from the coal fire through flying ashes (Liang et al. 2014).

**Table 3.** The CERCLA priority list of hazardous substances.



| 2017 Rank | Substance Name | Total Points | CAS RN |
|---|---|---|---|
| 1 | ARSENIC | 1674 | 7440-38-2 |
| 2 | LEAD | 1531 | 7439-92-1 |
| 3 | MERCURY | 1458 | 7439-97-6 |
| 4 | VINYL CHLORIDE | 1358 | 75-01-4 |
| 5 | POLYCHLORINATED BIPHENYLS | 1345 | 1336-36-3 |
| 6 | BENZENE | 1329 | 71-43-2 |
| 7 | CADMIUM | 1320 | 7440-43-9 |
| 8 | BENZO(A)PYRENE | 1306 | 50-32-8 |
| 9 | POLYCYCLIC AROMATIC HYDROCARBONS | 1279 | 130498-29-2 |
| 10 | BENZO(B)FLUORANTHENE | 1251 | 205-99-2 |

Furthermore, the fire ashes can travel dozens of miles away to contaminate both the atmosphere and the water of local communities. It has been measured that in the soil near coal fire areas, Hg and As concentrations were 129 and 7.5 times higher than those in normal soil (Liang et al. 2014). The total gaseous Hg concentrations in the smoke emitted from a coal fire can be 500 times higher than the normal air near a fire zone. The Hg concentrations can still be 30 times that of normal air (Fu et al. 2011). Some coals also have trace amounts of radioactive material such as uranium and thorium that can be released during combustion and can be transported as ash (Mcbride et al. 1978; Tadmor 1986).

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**Education**

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Dr. Eng – Aeronautical Engineering, Polytechnic University of Madrid, Spain, 1972
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**Overview**

Dr. Carlos Fernandez-Pello is an internationally-recognized mechanical/aeronautical engineer specializing in thermo-fluids with emphasis on fire physics, fluid mechanics, heat transfer, and thermodynamics. His primary areas of specialty include: ignition and fire spread in solid and liquid fuels; self-heating and spontaneous ignition of combustible materials; smoldering; wildland fire spotting ignition by metal fragments and embers and subsequent fire propagation; metal particle and embers trajectories in high winds. In addition to teaching, he has conducted research in the above areas funded by NASA, DOD, DOE, NIST, NSF and several industries. He has also consulted for research organizations, government agencies and industrial companies in a variety of subjects ranging from LNG spills to aircraft fire safety. Dr. Fernandez-Pello is currently a Professor of Mechanical Engineering at the University of California at Berkeley where he has been a faculty member since 1980.

A significant component of his consulting activities for the last 30 years has included forensic work on mechanical and aeronautical engineering. This work includes cause, origin and development of thermo-mechanical failures, and fires and explosions, with emphasis on the analysis, testing and modeling of the incident. His litigation activities have involved many areas such as ignition of different fuels; fire spread; liquid pool fire burning; self heating and spontaneous combustion; smoldering and flaming; thermal failure of metal structures; pressure failure of containers and pipelines; explosive boiling; embers and hot particle trajectories in high winds; spot ignition of wildland fires by metal particles and embers; aircraft and vehicle fires; pyrotechnic explosions; residential, warehouse and industrial fires and explosions; television and laptop fires; smoke detector failure; fire reconstruction and modeling; and several other areas. He has testified as an expert witness in State and Federal courts.

**Work History**

2008 – present**Reax Engineering**, *Partner*

2010 – present **University of California, Berkeley** Dept. of Mechanical Engineering, *Almy C. Maynard and Agnes Offield Maynard Endowed Chair of Mechanical Engineering*

1986 – 2010 **University of California, Berkeley** Dept. of Mechanical Engineering, *Professor*

2003 – 2013 **University of California, Berkeley** Graduate Division, *Associate Dean*

1982 – 1986 **University of California, Berkeley** Dept. of Mechanical Engineering, *Associate Professor*

1980 – 1982 **University of California, Berkeley** Dept. of Mechanical Engineering, *Assistant Professor*

1980 – present **Freelance technical consultant for liability-related litigation and industry**

1980 – 1980 **Northwestern University** Dept. of Mechanical Engineering, *Associate Professor*

1977 – 1980 **Princeton University** Dept. of Mechanical and Aerospace Engineering, *Research Staff Member*

1975 – 1976 **Harvard University** Division of Engineering and Applied Physics, *Post-doctoral research fellow*

### Expert Witness and Engineering Practice

Between 1980 and 2011, Dr. Fernandez-Pello has served as a consultant to law firms, industry and government organizations for work related to thermo-mechanical failures, combustion, fire, and explosions.

***Representative litigation/expert witness clients include:***

- **Beardsley, Jensen & Von Wald** (Rapid City, SD) – Wildland fire involving power lines (deposition)
- **Begs & Lane** (Pensacola, FL) – Fire and crash of a general aviation aircraft
- **Bishop, Barry, Howe, Haney & Ryder** (San Francisco, CA) – Explosion of liquid fuel (depo & testimony)
- **Berger Kahn,** (Irvine CA) Wildland fire spot ignition by metal particles
- **Burke & Bauermeister** (Anchorage, AK) – Structure fire involving large television (deposition)
- **Cozen & O’Connor** (Atlanta, GA) – Fire in a enamel drying industrial facility (deposition)
- **Cozen & O’Connor** (Philadelphia, PA) – Fire in an industrial oven facility (deposition)
- **Cozen & O’Connor** (Philadelphia, PA) – Industrial fire involving naphthalene (deposition)
- **Cozen & O’Connor** (Philadelphia, PA) – Electrical heater fire in warehouse (deposition & testimony)
- **Cozen & O’Connor** (Chicago, Ill) – Ignition of cellulose insulation in an attic(deposition)
- **Dale Sprik & Associates** (Grand Rapids, MI) – Residential fire originating in a kitchen (deposition)

- **Ernest M. Thayer** (Oakland, CA) – Automobile/structure fire (deposition & testimony)
- **Fetterly & Gordon** (Minneapolis, MN) – Rack storage fire in a paper recycling warehouse (deposition)
- **Fetterly & Gordon** (Minneapolis, MN) – Smoke detector product liability in structure fire (deposition)
- **Fowler et al.** (Miami, FL) – Crash and subsequent fire of a general aviation airplane (deposition)
- **Gordon & Rees** (San Francisco, CA) – Electrical transformer fire
- **Griffin & Laser** (Houston, TX) – Ignition of spilled solvent by water heater pilot
- **Haight Brown & Bonesteel** (Santa Ana, CA) – Residential fire involving ignition of a solvent (deposition)
- **Hallmark et al.** (Portland, OR) – General aviation airplane crash and fire
- **HellerEhrman** (San Francisco, CA) – Modeling of wildland fire involving power lines
- **Herrick, Hart, Duchemin, Spaeth, Sullivan & Schumacher** (Eau Claire, WI) – Tanker fire (deposition)
- **Hillsinger & Costenco** (San Diego, CA) – General aviation airplane fire (deposition)
- **Kirtland & Packard** (Los Angeles, CA) – Smolder initiated structure fire (deposition)
- **Knox et al.** (Oakland, CA) – Smolder initiated fire in a commercial building (deposition & testimony)
- **LA DWP** (Los Angeles, CA) – Office building fire involving transformer (deposition & testimony)
- **Laser, Proctor & Cole** (Houston, TX) – Oil well gas ignition and explosion (deposition)
- **Mackenroth, Ryan, Jacobson, Fong** (Sacramento, CA) – Fire in general aviation aircraft
- **Maloney & Smith** (Dallas, TX) – General aviation aircraft fire (deposition)
- **Martin** (Reno, NV) – Propane gas explosion and smolder initiated fire (deposition)
- **Martin, Ryan, & Andrada** (Oakland, CA) – Propane container explosion
- **Morgenstein & Jubelirer** (San Francisco, CA) – Residential fire involving a laptop
- **Morgenstein & Jubelirer** (San Francisco, CA) – Structure fire involving electrical heater (deposition)
- **Morris, Haynes & Hornsby** (Birmingham, AL) – Residential fire involving a gas heater (deposition)
- **Murchison & Cumming** (Los Angeles, CA) – Spontaneous ignition in coal loader (deposition & testimony)
- **Murchison & Cumming** (Los Angeles, CA) – Wildland fire involving power lines (deposition & testimony)
- **O'Melveny & Myers** (Los Angeles, CA) – Gasoline pipeline failure and fire
- **O'Melveny & Myers** (Los Angeles, CA) – Spontaneous ignition of chemical product
- **Paine, Hamblen, Coffin, Brooke & Miller** (Spokane, WA) – Wildland fire
- **Pretzel & Stouffer** (Chicago, IL) – Fuel tanker truck fire (deposition)
- **Pretzel & Stouffer** (Chicago, IL) – Rack storage fire in a cold storage facility

- **San Diego Gas & Electric** (San Diego, CA) – Wildland fire (deposition & testimony)
- **Schwartz & Cera** (San Francisco, CA) – Hydrogen explosion in gas mixing and storage facility (deposition)
- **Shield & Smith** (Los Angeles, CA) – General aviation airplane fire
- **St. Clair, McFertridge, & Griffin** (San Francisco, CA) – Pier fire (deposition)
- **Subrogors Committee** (Las Vegas, NV) – Explosion in a rocket propellant plant
- **Youngerman & McNutt** (Los Angeles, CA) – pyrotechnic explosion (deposition & testimony)

***Consulting for other institutions:***

- **National Institute of Standards and Technology, NIST** (Gaithersburg, MD)
- **National Aeronautics and Space Administration, NASA** (Cleveland, OH)
- **National Research Council, NRC** (Washington, DC)
- **Lawrence Livermore National Laboratories, LLNL** (Livermore, CA)
- **Sandia National Laboratories** (Albuquerque, NM)
- **Bechtel Corporation** (San Francisco, CA)
- **Failure Analysis/Exponent** (Menlo Park, CA)
- **Exxon** (Florham Park, NJ)
- **Fire Science Applications** (San Carlos, CA)
- **IHI** (Tokyo, Japan)
- **SENER** (Madrid, Spain)

## Research (representative)

*Ignition of Natural Fuel Beds by Embers and Heated/Burning Metal Particles (NSF)*

- The objective of this work is to develop quantitative predictive capabilities for determining whether or not an ember or hot/burning particle will ignite a fuel bed based on particle properties, fuel bed characteristics, and ambient conditions.
- Experiments and numerical modeling are conducted investigate the ignition of vegetation fuel beds by woody embers, hot molten and burning metal particles.

*Tackling CFD Modeling of Flame Spread on Practical Solid Combustibles (NSF)*

- Project involves the development of a generalized pyrolysis model that can simulate the pyrolysis and burning of real-world materials encountered in fires
- The computer model is coupled to an existing CFD code and used to calculate flame spread on real-world solid combustibles over a range of length scales.

*Smoldering Combustion and its Transition to Flaming in Spacecraft (NASA Space Flight Program)*

- Research concerns smoldering and the transition to flaming of foams, composite, and cellulosic materials
- Experimental studies performed at normal gravity and in reduced gravity in the Space Shuttle

*Test Method for Materials Flammability in Spacecraft (NASA Space Flight Program)*

- Work leading to the development of a new test method for the fire properties of materials used in aircraft and spacecraft
- The test is based on the piloted ignition (hot spot or spark) of materials exposed to external heating

*Ignition, Flame Spread and Extinction in Solid and Liquid Fuels (NIST/NSF)*

- Research on the initiation and spread of flames over solid and liquid fuels
- Includes studies of fuel ignition, the subsequent spread of flames and steady burning, and flame extinction

*Transport and Combustion of Embers and Metal Particles in Wild-land Fires (Various)*

- Objective is to model the trajectory of embers and burning metal particles generated in wildland fires to predict fire spotting
- Results of the project could help predict wildland fire development to help fire fighters to direct fire efforts in wild-land fires
- Results could also protect the life of firefighters that are often caught in the middle of two propagating fires due to fire spotting by flying embers

*Liquid Fuel Spray Ignition (ARO/TACOM)*

- Studies of the mechanisms of ignition and burning of liquid fuel droplets and sprays under supercritical conditions for diesel engines applications.

*Liquid Fuel Pool Fires and Boilover Burning of Fuels Spilled on Water (Various)*

- Collaboration with ENSMA, Poitiers, France to study the boilover burning of heavy hydrocarbon fuels (diesel oil, heating oil, etc.) spilled on water

## PhD Dissertation and MS Thesis Advising

- Chaired 30 PhD dissertations and 72 MS Theses in UC Berkeley Department of Mechanical Engineering

## Publications (selected)

Co-author of the book *Fundamentals of Combustion Processes*, Springer Publishing. Over 200 peer reviewed publications in technical journals in the fields of combustion, fire, and heat transfer. Four book chapters. Over 250 other publications. Selected publications:

1. Fernandez-Pello, A.C. “The Challenge of Fire Prediction,” *Combustion Science and Technology*, Special Silver Anniversary Issue, The Next 25 Years **98**: 281-290 (1994).
2. Garo, J.P., Vantelon, J.P., & Fernandez-Pello, A.C. “Boilover Burning of Oil Spilled on Water,” *Proceedings of the Combustion Institute* **25**: 1481-1487 (1994).
3. Cordova, J., August, M., & Fernandez-Pello, A.C., “Auto-ignition of a Flat Solid Fuel in a High Temperature, Oxidizing, Boundary Layer Flow,” *Combustion Science and Technology* **113-114**: 573-595 (1996).
4. Tse S.D. & Fernandez-Pello, A.C. “On the Flight Paths of Metal Particles and Embers Generated by Power Lines in High Winds and Their Potential To Initiate Wildland Fires,” *Fire Safety Journal* **30**: 333-356 (1998).

5. Anthenien, R.A., Walther, D.C., & Fernandez-Pello, A.C. “Smolder Ignition of Polyurethane Foam: Effect of Oxygen Concentration,” *Fire Safety Journal* **34**: 343-359 (2000).
6. Alvares, N. & Fernandez-Pello, A.C. “Fire Initiation and Spread in Overloaded Communication System Cable Trays,” *Experimental Thermal and Fluid Science* **21**: 51-57 (2000).
7. Stevanovic, A., Mehta, S., Zhou, Y.Y., Walther, D., & Fernandez-Pello, A.C., “Effect of Fiberglass Concentration on the Piloted Ignition Delay of Polypropylene Fiberglass Composites,” *Combustion Science and Technology* **174**: 169-185 (2002).
8. Alvares, N. & Fernandez-Pello, A.C. “A Methodology to determine Pre-crash Fuel quantity from Post-crash Fire Thermal Damage to Aircraft Structure” *Fire and Explosion Hazards: Proceedings of the 4th International Seminar* (2004).
9. Fernandez-Pello, A.C, Rein, G., Bar-Ilan, A., and Alvares, N. “Estimating the Performance of Enclosure Fire Models by Correlating Forensic Evidence of Accidental Fires” *Interflam 2004* (2004).
10. Anthenien, R., Tse, S. & Fernandez-Pello, A.C. “On the Trajectories of Embers Initially Elevated or Lofted by Ground Fire Plumes in High Winds,” *Fire Safety Journal* **41**: 349-363 (2006).
11. Rein, G., Bar-Ilan, A., Fernandez-Pello, A.C. & Alvares, N., “A Comparison of Three Fire Models in the Simulation of Accidental Fires,” *Journal of Fire Protection Engineering* **16**: 183-209 (2006).
12. Lautenberger, C., Torero, J.L., & Fernandez-Pello, A.C, “Understanding Material Flammability,” Chapter 1 in *Flammability Testing of Materials in Building, Construction, Transport and Mining Sectors*, V. Apte, Editor, Woodhead Publishing, pp. 1-21 (2006).
13. Sardoy, J., Consalvi, J., Porterie, B., Loraud, J., & Fernandez-Pello, A.C., “Modeling Transport and Combustion of Firebrands from Burning Trees,” *Combustion and Flame* **150**: 151-169 (2007).
14. Lautenberger C. and Fernandez-Pello, C. “A Model for the Oxidative Pyrolysis of Wood,” *Combustion and Flame* **156**: 1503-1513 (2009).
15. Chetehouna, K., Barboni, T., Zarguili, I., Leoni, E., Simeoni A., & Fernandez-Pello, A.C., “Investigation on the Emission of Volatile Organic Compounds from Heated Vegetation and their Potential to Cause an Eruptive Forest Fire,” *Combustion Science and Technology* **181**: 1273-1288 (2009).
16. Nmira, F., Consalvi, J-L., Kaiss, A., Porterie, B., & Fernandez-Pello, A.C., “A Numerical Study of Water Mist Mitigation of Tunnel Fires,” *Fire Safety Journal* **44**: 198-211 (2009).
17. McAllister, S., Fernandez-Pello, C., Ruff, G., & Urban D., “Effect of Pressure and Oxygen Concentration on Piloted Ignition Delay of Combustible Solids,” *Combustion and Flame* **157**: 1753–1759 (2010).
18. Hadden, R., Scott, S., Lautenberger, C. & Fernandez-Pello, C., “Ignition of Combustible Fuel Beds by Hot Particles: An Experimental and Theoretical Study,” *Fire Technology* **47**: 341 (2011).
19. Fernandez-Pello, A.C., “On Fire Ignition,” plenary paper at the *10th International Symposium on Fire Safety Science*, University of Maryland (2011).
20. A. B. Dodd, C. Lautenberger, C. Fernandez-Pello “Computational Modeling of Smolder Combustion and Spontaneous Transition to Flaming *Combustion and Flame,* V. 159, 1,448-461 (2012)
21. C. Zak, E. Tjahjono, D. Rich, C. Fernandez-Pello “Ignition of Powdered Fuels by Hot Particles: An Experimental Study” Forest Fires 2012, New Forest, UK, May 22-24 (2012)
22. A. Osorio, A.C. Fernandez-Pello, D. Urban, and G. Ruff “Limiting Conditions for Flame Spread in Fire Resistant Fabrics” *Proceedings of the Combustion Institute,* **34**, 2691-2697 (2012)

23. S. Manzello, T. Yamada, A. Jeffers, Y. Ohmiya, K. Himoto and A. C. Fernandez-Pello "Summary of Workshop for Fire Structure Interaction and Urban and Wildland-Urban Interface (WUI) Fires-Operation Tomodachi-Fire Research" *Fire Safety Journal*, V 59, 122-131 (2013)
24. C.D. Zak, J. L. Urban and C. Fernandez-Pello "Ignition Behavior of Hot Spheres Landing in Combustible Fuel Beds" *Combustion Science and Technology*, V.10-11:1618-1631 (2014)
25. C. Fernandez-Pello, C. Lautenberger, D. Rich, C.Zak, J. Urban, R. Hadden, S. Scott, and S. Fereres "Spot Fire Ignition of Natural Fuel Beds by Hot Metal Particles, Embers and Sparks" *Combustion Science and Technology*, 187:1-2, 269-295 (2014)
26. J.L. Urban, C.D. Zak, and C. Fernandez-Pello "Cellulose Spot Fire Ignition by Hot Metal Particles´" *Proceedings of the Combustion Institute*, DOI:10.1016/j.proci.05.081 (2014)
27. O. Fujita. K. Mitzutani, A. Osorio and C. Fernandez-Pello "Microgravity Flammability Limits of ETFE Insulated Electrical Wires Exposed to External Radiation" *Proceedings of the Combustion Institute*, DOI: 10.1016/j.proci.09.003 (2014)
28. J. L. Urban, C.D. Zak, and C. Fernandez-Pello "Spot Fire Ignition of Natural Fuels by Hot Aluminum Particles" 14th International Conference of Fire and Materials, San Francisco, CA 2-4 February 2015
29. J. L. Urban, C.D. Zak, and C. Fernandez-Pello "The Effect of Fuel Bed Composition on the Spot Fire Ignition of Natural Fuels by Hot Aluminum Particles" AOFST10, Tsukuba, Japan, October 2015.
30. M. Thomsen, X. Huang, D. Murphy, C. Fernandez-Pello, D. Urban and G. Ruff "Flammability Limits of Fire Resistant Fabric" 8th International Seminar on Fire and Explosion Hazards, Hefei, China, April 25-28, (2016)
31. K. Miyamoto, X. Huang, N. Hashimoto, O. Fujita, and C Fernandez-Pello, "Limiting Oxygen Concentration of Polyethylene Insulated Wires under Varying External Radiation" *Fire Safety Journal*. V.86, 32–40, (2016)
32. J.L. Urban, C.D. Zak, J. Song and C. Fernandez-Pello" Smolder Spot Ignition of Natural Fuels by a Hot Metal Particle" *Proceedings of the Combustion Institute*, V. 36, 3211-3218, (2016)
33. L. Hu, K. Yoshioka, Y. Lu, Y. Zhang, C. Fernandez-Pello, S. H. Chung and O. Fujita. "Limiting Oxygen Concentration (LOC) for Extinction of Upward Spreading Flames over Inclined Electrical Wires with Opposed-flow under Normal- and Microgravity" *Proceedings of the Combustion Institute*, V. 36, 3046-3053, (2016)
34. Y. Kobayashi, X. Huang, S. Nakaya, M. Tsue, C. Fernandez-Pello "Flame Spread over Horizontal and Vertical Wires: the Role of Dripping and Core, Fire Safety Journal, 9, p. 112-122. (2017)
35. M. Thomsen, D. C. Murphy, C. Fernandez-Pello, D. L. Urban and G.A. Ruff " Flame Spread Limits (LOC) of Fire Resistant Fabrics" Fire Safety Journal, 91.p. 259-265, (2017)
36. C. Fernandez-Pello "Wildland Fire Spot Ignition by Sparks and Firebrands" Fire Safety Journal, 91, p. 2-110 (2017). Int. Ass. of Fire Safety Science Howard Emmons Plenary Lecture.

## Honors, Scholarships, and Fellowships

- H. Emmons Award of the International Association of Fire Safety Science
- Member of The Royal Academy of Engineering of Spain
- Distinguished Alumnus Award University of California San Diego
- ASME Fellow
- Pi Tau Sigma Award for Excellence in Teaching

- Fellowships from Fullbright Foundation, Juan March Foundation, the Japan Society for the Promotion of Science and MITI, Japan, the French and Italian CNR

## Editorial Advisory Board

- *Combustion Science and Technology* (1992-present), Combustion Institute (2014-present), *Journal of Combustion* (2010-2012 )*Progress in Energy and Combustion Science* (1995-2006), *Combustion and Flame* (1994-2001),