An Experimental Investigation of Ignition Propensity of Hot Work Processes in the Nuclear Industry

by

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I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Abstract

The National Fire Code of Canada (NFCC) is one model code which regulates hot work in Canada. The code specifies that hot work processes need only create heat to be considered hot work processes, and requires that precautions taken adhere to those in Canadian Standards Association (CSA) W117.2, which is intended for welding, cutting and allied processes. CSA W117.2 requires a 15 m spherical radius of separation in which combustibles are ideally relocated or, at minimum, be protected with fire blankets. Openings, cracks and other locations in which sparks or hot particles must also be protected within this distance. Additionally CSA W117.2 requires a fire watch during, and one hour following the completion of the work. The NFCC stipulates more stringent requirements on the fire watch than CSA W117.2, requiring a check back 4 hours after the work. The code in its current form requires the same precautions be taken when using a soldering iron or epoxy resin as when using an oxyacetylene torch to flame cut steel. The lack of hazard characterization of hot work processes, and the umbrella prescription of required fire safety precautions can result in insufficient measures to prevent fires in some scenarios, and inordinate precautionary measures in others. While not applicable law in all jurisdictions, the NFCC is relied on in various Canadian industries for regulative purposes. Nuclear power generation in Canada is one such industry facing onerous fire protection costs resulting from following these precautions for the smallest of jobs requiring heat producing tools. The literature review highlights the dearth of scientific knowledge regarding the propensity of hot work as an ignition source and how this shortcoming manifests itself in issues across the various standards governing hot work practices.

The objective of this research is to assess fire hazards resulting from various processes considered hot work under the National Fire Code of Canada (NFCC). Due to the breadth of processes covered by the NFCC, a spectrum of hot work activities was investigated from processes as innocuous as the application of heated adhesive, to well known sources of ignition such as a variety of welding processes, oxyacetylene cutting and plasma cutting. To streamline the hazard assessment, processes were categorised into three groups based upon expected hazards such that testing could focus on the most prominent ignition danger presented by each. The groups were those processes exhibiting hot surface ignition hazards, processes with hot surface ignition hazards in addition to limited potential to generate hot particles, and those processes in which the generation of significant quantities of spark and hot particles is guaranteed.

For the first two process categories, experimentation focused on determining a critical process temperature with which to rank processes and also compare with ignition temperatures of combustibles commonly involved in hot work fires. The critical process temperature was determined as the highest measured temperature of the workpiece or tool during the chosen process and was typically measured with the use of thermocouples and infrared thermography. Characterization of any hot particles in the second category was performed using infrared thermography, and in some cases, thermal paper.

Literature sources indicated that sparks and hot particles are the largest factor in hot work fires, so specialised methodology was developed for the third category of processes to characterise the distribution of many thousands of hot work particles generated during welding, thermal cutting and other hot particle producing work. The distributions collected were used to determine the area enveloped by the ignition hazard of hot particles as well as areas encompassing the highest threat to combustibles in relative terms.

Several of the processes as studied were found not to exhibit any measurable form of ignition hazard, including forms of manual sanding and filing and rotary filing of steel. Heated adhesive, cutting steel with a reciprocating saw and drilling of steel were shown to exhibit moderate degrees of hazard with temperature rise of 195°C or less, suggesting potential hazard to a limited group of combustibles. Welding and cutting processes were shown to have a relative ignition potential across a wide area. Typical welding procedures produced hot particles which travelled a maximum of approximately 3 - 4 m while thermal cutting processes ejected sparks, slag and hot particles up to 9.8 m from the work.

Incorporated properly into updated standards and codes, the results and findings of this research could drastically improve the Canadian model codes regarding the regulation of hot work by decreasing cost and difficulty for Canadian Industry without increasing the risk of loss.

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E_{TC}	Measurement error imparted by thermocouple
E_{DAQ}	Measurement error imparted by Data Acquisition System
E_{Total}	Combined measurement error
D_{MAX}	Maximum distance traveled by a particle
$\overline{D}$	Average distance of population of particles
$A_{D_{MAX}}$	Area of the mark left by the D_{MAX} particle
A_{TOTAL}	Total area of population of particles
R_{SAT}	Maximum radius where thermal sheet mark area exceeded 10% of total

List of Acronyms

ANSI	American National Standards Institute
ASTM	American Society for Testing and Materials
AWG	American Wire Gauge
AWS	American Welding Society
CANDU	Canadian Deuterium-Uranium
COG	CANDU Owners Group
CSA	Canadian Standards Association
CWA	Canadian Welding Association
DAQ	Data Acquisition System
DGUV	Deutsche Geszliche Unfallversicherung - German Social Insurance Authority
DPI	Dots Per Inch
FM	Factory Mutual
FOV	Field of View
GMAW	Gas Metal Arc Welding
GTAW	Gas Tungsten Arc Welding
IR	Infrared
JWES	Japanese Welding Engineering Society
NFCC	National Fire Code of Canada
NFPA	National Fire Protection Association
NIOSH	National Institute for Occupational Safety & Health
OECD	Organisation for Economic Co-operation and Development
OSHA	Occupation Safety & Health Administration
PAI	Permit Authorizing Individual
PPE	Personal Protective Equipment
SMAW	Shielded Metal Arc Welding
SRS	Savannah River Site

Chapter 1

Introduction

Hot work is a fundamental and necessary activity commonly undertaken in Canadian industry. There exist only very limited 'cold work' alternatives to processes such as welding, thermal cutting and machining, resulting in the omnipresence of hot work processes, and their coinciding fire potential in construction, manufacturing and maintenance tasks.

One method used to mitigate the dangerous fire potential of hot work is through the used of codes and legislation. Although not adopted as law in all jurisdictions, Division B, Section 5.2 of the National Fire Code of Canada (NFCC), defines hot work and required fire prevention precautions. Under the code, hot work is defined as any process involving the use of open flames, the production of heat or sparks and is specifically inclusive of cutting, welding, soldering, brazing, grinding, adhesive bonding, thermal spraying and thawing of pipes. The NFCC further stipulates that, in terms of fire precaution measures, all hot work shall conform to CSA-W117, the Canadian Standards Association's standard for Safety in Welding, Cutting and Allied Processes. In addition to the measures stated in CSA-W117, the code requires the posting of a fire watch for the duration of the hot work plus sixty minutes, and a mandatory final inspection four hours after completion of the work. Full fire precaution requirements are presented in 2 with a comparison of standards across industry sectors and geographical locations.

Annex A of CSA-W117 provides a master chart explicitly defining welding and allied processes covered under the standard, and is used as the minimum safety standard for hot work across Canadian industry. Indeed, a willing reliance on this standard, its American counterpart AWS Z49, or the more general and international NFPA 51B, is seen in manufacturing, mining, ship building, chemical processing and the petroleum industry. This reliance is more ingrained in firmly regulated industries such as nuclear power generation, where use of CSA W117 as a recommended minimum standard is replaced with a requirement to follow the NFCC to the letter in specific standards such as N293.

With mandated use of CSA W117, a literal interpretation of the code is required and therefore, in the nuclear industry, the same levels of precaution are required for all hot work processes regardless of the severity of hazard involved. Common sense might dictate that this could lead to situations whereupon unrealistic fire precautions and fire watch criteria are specified, significantly increasing the cost and difficulty of controlling fire hazards of hot work.

The objective of this research is to assess the fire hazards associated with a wide range of hot work processes identified as important to the nuclear industry. Table 1.1, developed with Nuclear power industry counsel from Canadian CANDU operators, is a list of processes defined as hot work under current legislation. In generating the process list, an emphasis was placed on portable activities which frequently must be performed outside of protected work shop environments, and therefore readily implementable engineering controls to manage fire hazards, such as welding enclosures, are not present.

Table 1.1: List of Assessed Processes

Welding	SMAW GMAW GTAW
Thermal Cutting	Plasma Air Carbon Arc Gouging Oxyacetylene
Mechanical & Abrasive Cutting	Drilling Reciprocating Saw Cut Off Saw Sanding Filing Grinding
Other	Heat Gun Iron Soldering Torch Soldering Heated Adhesive

Hazards due to hot work can be characterised and classified by investigating several parameters, including process heat input, maximum temperatures of the workpiece and tool and, as experience has shown, the propensity of a process to generate and propel sparks and molten material great distances. The importance and range of values characteristic of each of these parameters need to be explored and documented across hot work processes to determine the potential fire danger each process might pose. This undertaking comprises two main components; firstly, a review of literature providing sufficient context within which to approach the problem of assessing fire hazards associated with hot work. Secondly, and depending on the results from the literature, experiments will be designed and performed to further characterize those processes for which the fire hazard parameters are not fully defined and understood. In setting context to the present research, statistics of hot work accidents are first examined in an attempt to understand which processes are problematic, and so confirm or edit the list in Table 1.1 as appropriate. The history, basis and development of standards of hot work protection are then reviewed, to understand the requirements of each standard and how the legislature has evolved over time. Finally, an overview of scientific research on the topic of fire potential of hot work is presented, highlighting those processes for which fire hazards have been studied, as well methods used and key results found.

Following this, practical testing of hot work processes will be undertaken, as determined pertinent in Chapter 2, in order to better define the fire hazard parameters associated with those processes and assess the potential for those parameters to ignite a fire.

Chapter 2

Literature Review

The literature review is focused on three primary areas; statistical sources providing insight into which of the hot work processes listed in Table 1.1 have historically been the most problematic in terms of fire hazard; the state and development of hot work legislation and standards across industry sectors and countries; and finally, studies of hot work as an ignition source. As the prevailing model code in Canada, this literature review relies on the NFCC definition of hot work processes, even if the source itself does not describe the activity as such. The NFCC definition of hot work is any process involving the use of open flames, the production of heat or sparks and is specifically inclusive of cutting, welding, soldering, brazing, grinding, adhesive bonding, thermal spraying and thawing of pipes.

2.1 Statistical Sources

Statistical records of hot work fire events are useful for compiling probability data, and if detailed enough, can provide a general measure of the potential consequences of certain events. The NFPA Torch Report [1,2] provides data concerning fires which resulted from hot work performed using welding, cutting, brazing and/or soldering in operations involving the presence of a combustible gas. Through its focus, the report flags torch involving processes as more problematic than other forms of hot work in the event that a combustible gas is present. The data presented includes statistics on fires by structure type, alarm time, total loss, cited cause and ignited combustible. Data from the 2006 and 2009 reports clearly show that working too close to combustibles is the cause of at least 70% of fires resulting from hot work processes using both cutting torches and welding processes [1, 2]. Torch fires inclusive of welding, accounted for 2.4% of non-residential structure fires, showing such fires cause disproportionately large monetary and human losses, at 3.5% and 5.4% respectively. For FM Global insured facilities, outside contractors were found to account for 66.5% of all hot work losses from 1999 to 2004, indicating that there is a substantially higher fire risk when hot work activities are not performed by company employees.

A detailed report on the root cause of fires during welding and oxyacetylene cutting in U.S. coal mines was published by NIOSH in 2006 [3]. Thanks to the robust systematic approach used by the Mine Safety and Health Administration to investigate, report and catalogue details of mining accidents in the U.S., the report revisited all accidents involving unplanned ignitions or explosions as a result of hot work since 1995, whether they involved injuries or not. In addition to merely recording the instances of a fire, sufficient detail in the accident reports allows for analysis of such factors as the fuel ignited, the ignition source, number and type of injuries due both to fire as well as improper use of Personal Protective Equipment (PPE) or tools, and finally, perhaps most importantly, a recording of the root cause of the accident. 31 fires were caused by oxyacetylene cutting and 15 were caused from some form of arc welding [3], with ignition of methane bleeders being by far the most common fuel ignited. The report concluded that the most common root cause of fires and other accidents was a failure to properly prepare the area being worked in for hot work; including checks for methane or other combustibles, erecting spark barriers and having fire fighting equipment and personnel on hand. The next most pertinent root cause of fires involved inadequate post work fire checks, while the root cause of injuries was lack of appropriate of PPE and failure to inspect and ensure equipment was in working order.

Statistics of fire incidents within the nuclear industry, specifically those caused by hot work operations, are considerably more difficult to obtain, though two sources found and evaluated; the Organisation for Economic Co-operation and Development (OECD) Fire Event Database [4], and a separate, smaller database of fire incidents at the Savannah River Site (SRS) incorporating details of fires in SRS facilities between 1975 and 1995 shut down events are not included. Comprising 158 events including hot work, electrical, and other accidental fires, the SRS fire event database was made available as an appendix to a 1995 report by the Westinghouse Savannah River Company [5]. The database includes the date, facility and location of the fire, the combustible, ignition source and method of extinguishment if known. Of the 158 SRS fire events, eight events were classified as severe, rather than controlled events, meaning fire extinguishment required emergency response crews and specialised fire fighting tactics. Two of the severe events were explicitly caused by welding. In all, 34 events were caused by hot work as defined by the NFCC; these 34 events deliberately exclude many welding equipment malfunction events such as shorted cables and overheating welding leads. Hot work fire events are shown by process frequency in Table 2.1 while the ignition pathways and combustibles involved in the hot work fires are arranged by frequency in Tables 2.2 and 2.3 respectively.

Table 2.1: Hot Work Fires by Process Frequency: SRS 1975 - 1995

Process	**Frequency**	**% of Hot Work Events**	**% of All Events**
Welding	15	44%	9%
Oxyacetylene Cutting	6	18%	4%
Portable Heater	3	9%	2%
Grinding	3	9%	2%
Pipe Soldering	2	6%	1%
Cut-off saw	2	6%	1%
Arc Gouging	1	3%	1%
Epoxy	1	3%	1%
Heat Gun	1	3%	1%
Total	**34**		**22%**

Table 2.1 shows that hot work comprised 22% of all fire events at the SRS over a 20 year period, with welding accounting for nearly half of all hot work fire events, and 9% of all fire events. In addition to this, thermal and abrasive cutting processes as seen in Table 1.1 account for another 12 hot work incidents in Tables 2.1. The correlation between Table 2.1 and the in Table 1.1, prospective list of processes to test, supports that a study of those processes will be relevant. Unlike the mining study discussed above, detailed analysis of the root causes and consequences of these events are absent, and similarly no indication is provided on the relative frequency with which the processes are undertaken. This means that welding could account for a very large proportion of the events because it is a particularly hazardous process, it is poorly controlled, or it is simply performed far more frequently than other heat producing processes. Nonetheless, due to the number of fires and potential impact on a nuclear plant, all processes should be considered in a detailed study of ignition propensity of hot work.

Table 2.2 indicates that the fires from hot work processes discussed above were primarily a result of sparks or hot particle ejection and hot surface ignition. The table shows that sparks and hot particle ejection from welding, thermal and abrasive cutting account for 27, or nearly 80%, of all ignitions. This again provides strong support for the prospective list of test processes in Table 1.1 as the majority of them are well known to exhibit this potential. Hot surfaces, open flames and heat produced by chemical reaction, however, equally have been linked to fires in these power plants so must also be investigated as viable potential sources of ignition affiliated with hot work processes.

Table 2.2: Ignition Pathways: SRS 1975 - 1995

Ignition Pathway	**Frequency**
Sparks or Hot Particle Ejection	27
Hot Surface	5
Open Flame	1
Chemical	1
Total	**34**

Table 2.3 provides insight into which combustible materials are the most frequently involved in hot work related fires, suggesting that they may be most frequently overlooked by an operator assessing the potential for fire in their working space. Plastics, grease or oil, insulation and clothing represent over 50% of the fuels ignited, although as can be seen from Table 2.3 many other fuels also have the potential to ignite as a result of hot work.

Of the 34 hot work fires, three were smoldering fires, while the remainder were fought at ignition. The three smoldering events were initiated in a variety of ways; the first involved coveralls covered in epoxy adhesive discarded in a garbage can; the second involved sparks from a grinding activity landing on a duct and causing a layer of dust to begin to smolder; and the third involved a pipe soldering job which led to a fire involving a cardboard waste box and the wheel of an acetylene cutting rig, though the precise source of ignition was not mentioned. The statistics in Tables 2.1, 2.2 and 2.3 demonstrate that the any hot work process as defined in the NFCC can cause an unintentional fire under the required set of circumstances, and in so doing support the selections of prospective processes to test made in Table 1.1.

The OECD hot work fire incident database includes 49 hot work incidents between 1987 and 2005. This database spans incidents across many different countries and therefore provides information on hot work fires that have occurred despite different specifications of procedure, precaution and legislation [4]. The OECD report format is structured, but it is evident that many of the reports are incomplete and missing details of importance such as the type of hot work being performed, the combustible involved, whether a fire watch was present, or if hot work procedures were followed. The reports are also sometimes incongru-

Table 2.3: Ignition Frequency by Combustible in Hot Work Fires: SRS 1975 - 1995

Combustible	**Frequency**
Plastics	5
Grease, Oil	5
Insulation, Cork, Foam or Fibre	4
Clothing	4
Equipment	2
Gasket	2
Paint	2
Trash, Cardboard	2
Unspecified Class A Material	2
Dust	1
Rags and Cleaning Equipment	1
Dry Grass	1
Gasoline	1
Wood	1
Alcohol	1
Total	**34**

ent on the root cause, for example labeling the root cause as procedural when the report states that procedures were ignored, suggesting the cause was human error. To the extent possible, summaries of the processes causing the hot work, and root cause were compiled by the author from the OECD database and are summarized in Tables 2.4 through 2.7.

Table 2.4: Hot Work Fires by Process Frequency: OECD Fire Events Database

Process	**Frequency**
Welding	14
Generic Hot work	13
Thermal Cutting	8
Grinding	7
Cut Off Saw or Wheel	6
Drilling	1
Total	**49**

Table 2.4 shows the frequency of hot work fires according to process. The hot work processes identified in this table are again well aligned with the prospective test processes in 1.1. As was seen in the SRS report [5], welding is the single largest contributor to hot

work fires. The next largest category is generic processes which unfortunately were not well specified in the reports and therefore could not be categorized appropriately. Similarly, the third largest group falls under thermal cutting as the incident reports provided only sufficient to identify them as such. Abrasive cutting processes including grinding, cut-off saws and wheels and drilling together account for a significant proportion of hot work incidents, in combination these lead to approximately the same number of incidents as does welding.

Table 2.5: Ignition Frequency by Combustible in Hot Work Fires: OECD Fire Event Database

Combustible	**Frequency**
Plastics	10
Insulation, Cork, Foam or Fibre	8
Equipment	9
Solvent/Oil Soaked Fabric	5
Paper, Wood	2
Trash, Cardboard	4
Gaseous	3
Clothing	2
Fabric	2
Gasket	2
Unspecified Class A Material	2
Total	**49**

Table 2.5 confirms that plastics and insulation present a large hazard of fire in environments in which hot work is being performed. It can also be seen that grease, oil and solvents present an equivalent hazard or higher, particularly when absorbed into cleaning rags which can act as a wick for the fuel [6].

Table 2.6: Ignition Pathways: OECD Fire Event Database

Ignition Path	**Frequency**
Sparks or Hot Particle Ejection	35
Unspecified	11
Open Flame	3
Total	**49**

Table 2.6 shows that sparks and hot particle ejections account for a large proportion of the fires listed in the OECD database, 71% of those specified in fact. This value is comparable to

the 81% corresponding figure at the SRS site. Again this indicates that investigation into the number and distribution of sparks from these processes is likely to yield the most significant benefit in terms of mitigating fire hazard potential from hot work processes. Generating an understanding of the distribution of hot particles across a variety of hot work processes is one means to achieve this goal.

Table 2.7: Root Cause of Hot Work Fires by Frequency: OECD Fire Event Database

Root Cause	**Frequency**
Human	36
Human & Procedure	9
Procedure	4
Total	**49**

As can be seen in Table 2.7, several of the reports listed multiple root causes as prerequisites for the fires, which is an issue that may arise from different approaches to root cause analysis in different countries and organizations within the OECD. Procedural errors indicate scenarios where the operator followed specified precautions for performing hot work, but an incident still occurred. Reports of this nature typically state corrective actions were implemented as a result. Unfortunately, investigating the procedures required in each country at the time of each incident is not feasible, but the metric does indicate that procedural problems are occasionally realised and rectified as a result of accidents. Human error, specifically, not following accepted procedures, was a dominant root cause of the events studied. Serving as a dominant root cause in this database, human error is clearly an important aspect of hot work fires, and is also not well understood. Therefore, hot work experimentation in this study will attempt to address this lack of understanding.

Statistical review has indicated that the majority of processes in Table 1.1 present a credible ignition hazard to a wide variety of combustible materials common in industrial settings. Despite the lack of clarification within some of the groups, it is clear from the analysis of the SRS and OECD databases that the processes identified with counsel from industry stakeholders as listed in 1.1 cover those which have been involved in recent hot work fires. Therefore, there is excellent precedence in literature to use this list of prospective processes, and variations thereof as a basis for the investigations in this research. Moreover, many of the processes in Table 1.1 are known to generate hot particles during operation, and statistical sources have clearly indicated that it is these processes producing the hazard which is hardest to control.

2.2 Standards & Legislation

Understanding the past and current state of hot work legislation both globally and across industries provides vital perspective and understanding on how hot work standards have developed and may continue to develop in Canada and abroad. Across the standards and legislation reviewed, those applicable to hot work in the Canadian nuclear industry appear to be some of the most stringent in terms of encompassing a wide variety of processes and requiring significant precautions.

A licensure requirement of nuclear power plant operators in Canada is to meet the minimum fire protection requirements for CANDU Nuclear Power Plants pursuant to Canadian Standards Association (CSA) standard N-293 [7]. Other industries and individuals are governed only by their respective provincial fire codes. For the purposes of controlling hot work, CSA N-293 requires licensees to follow precautions outlined in the National Fire Code of Canada. The National Fire Code of Canada (NFCC), however, does not directly provide a complete set of precautions on controlling hot work; rather, the code provides a definition of 'hot work' and refers to CSA W117 for fire prevention related precautions which include specification of separation distances and fire watch provisions, with the NFCC being the minimum standard in the light of any difference [8].

It is the definition of hot work in the NFCC which drives the need for the present research. The NFCC defines hot work as processes involving open flames, or producing heat or sparks, including and not being limited to cutting, welding, soldering, brazing, grinding, adhesive bonding, thermal spraying and thawing pipes [9]. The specification by the NFCC that any process producing heat is a hot work process is in stark contrast to other general hot work standards, including the National Fire Protection Association (NFPA) 51B which defines hot work clearly as related to only those processes involving open flame or arc as well as those capable of initiating fires or explosions [10]. While the wording 'capability to initiate fires' at first sounds as vague as the NFCC definition of a heat producing process, upon further inspection it is not. Though the terminology remains open-ended, functionally, the wording in NFPA 51B coincides with the objective of the document; to prevent hot work fires. Meanwhile, there are many heat producing processes which are widely disregarded as fire hazards under normal circumstances, such as the respiration of human beings, and therefore the wording in the NFCC betrays the purpose of the legislation as it cannot feasibly be complied with in a literal sense. The NFCC definition is also in contrast to welding standards such as American Welding Society (AWS) Z49 [11], Australian Standard AS 1674 [12] and CSA W117, all of which concern an identical body of clearly defined list of cutting, welding and allied processes. The list can be found in Annex A of CSA W117 [8].

In addition to differing in the definition of hot work, the NFCC continues to diverge from other standards and legislation. This is particularly true in the specification of required separation distance between a given hot work process and adjacent combustibles, as well as in defining the requirements for a fire watch. The separation distance is defined as the minimum distance allowed between a given hot work and combustible if the hot work process cannot be moved to a safe location, as is often the case, particularly in the nuclear industry. A safe location could be considered a work shop, or work space where no combustible materials are present and the work can be fully contained. Inside of the radial separation distance, combustibles and openings must be shielded by noncombustible protection, most often fire blankets, curtains or refractory plates typically approved by a standard such as American National Standards Institute - Factory Mutual (ANSI-FM) 4950 [13]. As discussed in the next section, this requirement carries significant cost and safety implications. The fire watch requirement encompasses having one or more individuals present during the hot work and ready to take relevant actions in case of a fire or potential fire. These might include raising a fire alarm, alerting the worker and/or attempting to extinguish the fire. Depending on the specific legislation, the responsibilities of the fire watch may extend until well after the work as is the case with the NFCC requiring a 60 minute fire watch after the work is complete as well as a 4 hour check-back. Further fire watch issues are discussed in Section 2.2.2.

2.2.1 Separation

All current Canadian hot work standards and legislation require a 15 m radial distance separation in situations where hot work cannot be moved to a safe area free of combustibles. This distance is the same as specified in AS 1674. Initial versions of CSA W117 required only 11 m (35 ft) separation, but this value was increased to 15 m (50 ft) prior to 1987 when it was determined by the CSA W117 committee that an 11 m separation was insufficient due to the substantial portion of fire cases involving welding and cutting.

American equivalent legislation, Occupation Safety & Health Administration (OSHA) 1910.252 pertain to cutting, welding and brazing, and standards NFPA 51B, AWS Z49 feature a smaller separation, or the so-called '35 foot rule'. The more general American standard on hot work, NFPA 51B incorporated the '35 foot rule' in the first edition in 1962. Although only adopted in the 1967 edition of AWS Z49, the earliest allusion to the '35 foot rule' is found in the 1930 information circular *Portable Cutting and Welding Equipments* authored by the Associated Factory Mutual Fire Insurance Companies, more recently known as FM Global. The document states that cutting and welding work which is transportable should be carried out in safe, sprinklered locations, and failing that, combustible materials should be removed from a zone up to thirty or forty feet away from the work [14]. The 1937 edition of the Oxwelder's handbook corroborates this, stating that combustible material should be moved a reasonable distance away "say, thirty to forty feet" from the hot work [15]. Personal communication with August F. Manz [16] the chair of the AWS Z49 technical committee suggests that the rule originated through experience rather than being based on scientific grounds and that it has since stood the test of time.

Early studies and reviews of hot work and associated accidents, as will be seen in the next section, seem to corroborate that the '35 foot rule' was adopted primarily by experience and anecdotal accounts. The most recent, 2012, edition of AWS Z49 notes that specific processes, namely air carbon arc gouging and plasma cutting are liable to send sparks further than 35 feet and notifies that in Canada the recommended distance is 50 feet. In a similar fashion, NFPA 51B authorizes the Permit Authorizing Individual (PAI) to increase the separation envelope radius in circumstances where the scope of work, such as the elevation or the tools used, warrant. New to the 2014 edition of NFPA 51B is an authorization for the PAI to reduce the size of the separation envelope if hot work being conducted is known to be incapable of generating slag, sparks, spatter or similar mobile sources of ignition. Nonetheless, there is little scientific data to which the PAI can turn in order to support a decision to vary the safe separation zone in a given situation. As such, more work is needed to define and justify the appropriate distances for the wide range of processes defined as hot work under current regulation.

Deutsche Geszliche Unfallversicherung (DGUV) oversees a mandatory statutory accident insurance system within Germany and publishes requirements governing a wide variety of industrial practices, with DGUV-R 500 chapter 2.26 governing cutting, welding, and other hot work practices [17]. In contrast to the already discussed, more rigid approaches to prescribing precautions, this legislation lists differing requirements of separation depending on the process in question and also features tailored envelope prescriptions for areas both above and below the work as displayed in Table 2.8. Whereas the North American standards discussed prescribe a radial (spherical) distance, the German requirements allow for lower precautionary requirements above the work - from 2 m for a processes like flame soldering to 4 m for welding and cutting processes. Below the work, the separation zone is the same as at grade, but may be expanded by the PAI if considered necessary.

The impact of allowing a smaller envelope in the upward direction is illustrated in Figure

Table 2.8: Separation Envelope Required by DGUV R-500

Process	Separation Envelope		
	Horizontal Direction	Above Work	Below Work
Flame Soldering	2 m	2 m	10 m
Manual Arc & Gas Welding	7.5 m	4 m	20 m
Thermal Cutting	10 m	4 m	20 m

2.1 for a work height of 3 m; a section of the required envelope of separation for DGUV R-500 is compared to that prescribed in the NFCC, and the standard envelope for NFPA 51B. The lateral protection zone for DGUV R-500 and NFPA 51B are similar, while CSA W117 is substantially larger. Upon looking at the envelope in the vertical direction, though, it can be seen that the NFPA and CSA standards require protection substantially further above the workpiece than the DGUV standard. While there are scenarios where protecting combustibles above the work area is both a prudent and necessary precaution, there are also economic, ergonomic, health and safety issues associated with suspending fire blankets on overhead exposures, particularly when the nature of the work being performed is understood and known not to expel hot particles far enough into the air to post an overhead hazard.

In Japan, fire prevention ordinances are legislated at the local government level, and overall are enforceable under the Fire Defense Law. Ordinances may change from area to area and may provide guidelines or reference outside standards such as the one published by the Japan Welding Engineering Society (JWES). JWES 9009 section 5 pertains to fire precautions for cutting and welding and recommends creating a separation between the hot work and combustibles, but does not identify a suitable distance [18]. The Kyoto City fire ordinance contains some specific guidelines as to suitable distances for cutting and welding derived from actual hot work studies; these are discussed in section 2.3.

2.2.2 Fire Watch

The earliest instance of a requirement for a fire watch was also found in the 1930 information circular published by the Associated Factory Mutual Fire Insurance Companies, stating that men should be stationed with a fire hose and chemical extinguishers when work cannot be carried out in safe places, and to "keep a man at the scene of the work to make sure sparks have not started smoldering fires" [14].

A fire watch or watchers are personnel put in place with the intent to watch the operator performing hot work and mitigate the risk of fire. Typically this responsibility extends well

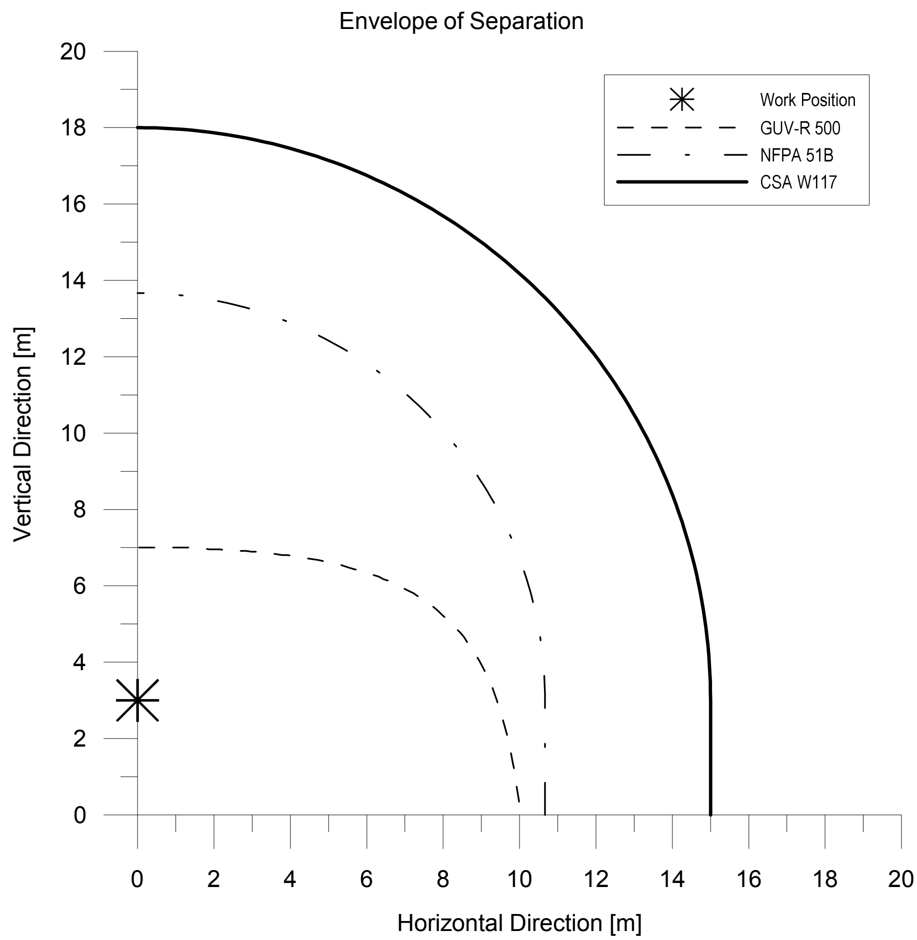


Figure 2.1: Comparison of the envelope of separation required by different hot work standards

after the work is complete. Numerous hot work incidents have demonstrated that for many varieties of hot work, the operator cannot simultaneously perform their tasks while ensuring the hot work does not cause ignition of a combustible, or initiate smoldering within debris or small spaces where there is combustible material present. During the procedure, the fire watch is intended to observe the work going on, note where any potential ignition sources are traveling, and if problems arise stop the work. JWES 9009 section 5 [18] and the Kyoto City fire [19] ordinance similarly require fire watches, but do not recommend a specific duration, stating only that the work site is to be thoroughly checked after the hot work process is complete. The consensus of standards is that the fire watch should be equipped to raise emergency alarms and begin appropriate fire fighting procedures should an incident occur. Most standards also specify how long after the work a fire watch must stay at the site as well as the requirements for rechecking the site at regular intervals of time. While consensus exists between standards on the role of the fire watch, differences arise over what circumstances create the need for a fire watch and what duration of fire watch is appropriate. These range from not having a fire watch at all unless required by the PAI, to a conditional requirement if special exposures (combustibles or openings) are nearby. It is the NFCC which mandates the 60 minute fire watch as well as the 4 hour check back, regardless of the actual hazard involved in the process and the environment in which it is performed.

2.2.3 Summary of General Standards

Universally the standards note that combustibles should not be permitted within each respective separation envelope and that combustibles should preferably be moved, but if impractical, that they must be protected.

Table 2.9 shows the fire precautions of concern to this work in the various general hot work standards studied. The table shows how the conditions necessitating a fire watch, the duration of the fire watch and the time when a final inspection is required change for the various standards and pieces of legislation investigated [8–12, 17, 20]. It can be seen that despite covering largely the same processes, excepting the NFCC, there is consensus on only the general purpose of separation and fire watch, and not on specific size of the separation or the duration the fire watch.

Fires can readily translate into events which compromise reactor control, the catastrophic outcome of which is grimly illustrated by the ongoing Fukushima Daiichi crisis [21]. The lack of congruence between general hot work standards points to a lack of understanding regarding the fire hazards of hot work, and again leaves the PAI and regulators with little place to turn when expected to make decisions about the implicated risk of hot work in Canadian nuclear power plants. By investigating hot work standards in other industries facing catastrophic loss scenarios as a result of fires, a more scientific basis for precautionary choices may be evident.

2.2.4 Regulations and Standards in Other Industries

The American Petroleum Institute has published a standard entitled API RP 2009 Safe Welding, Cutting and Hot Work Practices in the Petroleum and Petrochemical Industries [22]. The standard includes any process which produces enough heat or energy to ignite flammable vapours, gases or dust and refers to NFPA 51B for recommendations on the allowed minimum proximity of combustibles, as well as for required fire watch procedures.

Table 2.9: Comparison of Prominent Standards; Scope & Fire Watch Requirements

Standard	Included Processes	Separation Requirement [m]	Fire Watch Condition	Post Work Duration [min]	Final Inspection
CSA W117	Welding & allied processes as listed directly in Annex A of standard	15	Combustibles or openings inside or near extent of separation	60	At work completion or determined by PAI
NFCC	Any spark or heat producing process	15	Mandatory	60	At work completion and after 4 hours
OSHA 1910.252	Welding, cutting & brazing	10.7	Combustibles or openings inside or near extent of separation	30	Not Required
AWS Z49	Welding & allied processes as listed directly in Annex D of standard	10.7	Combustibles or openings inside or near extent of separation	30	Not Required
NFPA 51B	Welding & allied processes, heat treating, grinding, thawing, powder-driven fasteners, hot riveting, other processes producing or using a spark, flame or heat	10.7	If required by PAI	Set by PAI	End of Watch
AS 1674	Welding & allied processes; grinding, thermal or oxygen cutting or heating, and other related heat-producing or spark-producing operations	15	If required by PAI	Set by PAI	Mandatory
DGUV R500	Welding, cutting & related processes	Variable	If required by PAI	Set by PAI	Mandatory

Unfortunately no reference to scientific studies, data or research is present.

Petrochemical companies are faced both with catastrophic losses should a hot work incident take place, and the ever-present hazard of combustible gases; so measures taken to manage hot work are second only to the nuclear industry, particularly for refineries. Fire watches are mandatory in all of the standards studied here with other relevant details such as processes covered and other requirements summarized in Table 2.10. In the Table, Marathon Oil Corporation SAF-044 [23] and British Petroleum SAF-009 [24] are examples of standards which are more stringent in terms of separation at 15 m, than the local 11.7 m regulations would require [24] in the United States. Despite very slight disparities between the included processes, there is coherence regarding the required measures of precaution against fire. For further context, GM-11-036-06 is the company safety standard concerning hot work precautions for CSBP, an Australian firm producing chemical fertilizers and operating a number of chemical processing plants with similar combustible gas hazards as typical in oil refineries [25]. While not more stringent than local Australian standards as seen in 2.9, the CSBP standard is equivalent to the BP and Marathon standards.

In addition to providing a standard for performing hot work, the British Petroleum refinery standard introduces a second tier of controlled activities it refers to as Hot Work Spark Potential activities [24]. According to the BP Oil standard, the term hot work spark potential activities refers to any task, tools or activities capable of producing a spark with examples including motor driven equipment, buffing, needle gunning and use of cell phones, cameras and computers. These processes are controlled in specific areas of the facility despite their low probability of sparking due to the potential for explosive atmospheres to exist in petrochemical refineries. Therefore, they are assigned a lower level of precaution and smaller safety zone that covers only the immediate area in which the device is operated. This is an important example of how different levels of precaution can be tailored to address areas at higher or lower fire risk; provided the nature of the induced hazard is understood well enough, it is immaterial whether the risk is primarily a function of impact or likelihood.

In addition to the basic specifications in Table 2.10, it is typical in hot work procedures in the chemical processing industries to further alter hot work procedures and required precautions according to a hazard classification of the area in which the work is being performed. In the British Petroleum standard, both Hot Work and Hot Work Spark Potential processes are exempt from SAF-044 permitting and precaution requirements when performed in specifically listed areas. Such work is only required to conform to the level of local legislation. Classifications of this kind are a result of Probabilistic Safety Assessments (PSA), which screen out areas representing inconsequential contributions to risk. This can either be on a basis of impact, e.g. a fire in a specific area would be inconsequential, or on the basis of probability, e.g. conservative estimates of damage frequency are below a certain threshold. In the case of the chemical industries, the regulator has seen it fit to allow organizations to enact exemptions on the basis of a PSA. The CNSC requires operators to perform routine PSAs [7], and best practices recommended by the International Atomic Energy Agency to streamline the PSA warrant enacting a screening system to exclude compartments comprising an "inconsequential contribution" to risk [26]. Despite this, operators are not permitted to lower hot work precautions in these excluded compartments to a level below the NFCC, nor can they exempt specific low hazard areas from permitting requirements.

Table 2.10: Select Hot Work Standards in Chemical Refineries

Standard	Included Processes	Separation Requirement [m]	Post Work Duration [min]	Final Inspection
Marathon Oil-SAF-009	Welding, cutting, brazing, hot tapping, or creates a spark, flame or hot surface (>260°C)	15	30	Not Required
British Petroleum-SAF-044	Welding, cutting, open flames, or creates uncontrolled ignition sources	15	30	Not Required
CSBP GM-11-036-06	Processes generating sufficient heat intensity to ignite flammable gases, liquids or dusts	15	30	Not Required

Regulated hot work controls for mines in Nova Scotia are an example of variations in precautions specified to control hazards in different industrial settings. These precautions revolve around the type of mine and whether the work is being carried out above or below ground. N.S. Reg. 115/2011, mandated in Nova Scotia, defines hot work as work producing arcs, sparks or heat and specifically includes welding, cutting and soldering; tabulated in Table 2.11 are the mandated safety precautions. Presumably the potential for hot sparks to fall down a mine shaft, remain hot due to continued oxidation and a combustible is the reason for increasing separation at the surface, but no such scientific reasoning is provided.

Judging from the sources explored across countries and industrial sectors, there is little consensus on an appropriate level of fire precaution for hot work, or even on the definition

Table 2.11: Nova Scotia Mining Regulation 115

Location & Mine Type	Separation	Post Work Duration	Final Inspection
Below Ground Non-Coal	10 m	No requirement	2 hours
Below Ground Coal	20 m	24 hour continuous	No requirement
Above Ground	25 m to opening of mine	No requirement	No requirement

of what hot work actually is. As is the case with many standards, changes are reactionary in nature, but there exists a tendency for motivation and reasoning behind changes to get left by the wayside over the decades as these items are not publicly available. It is clear through examination of the hot work procedures specified across different industries and in different geographical areas that there are many and varied interpretations of the hazards associated with hot work processes, as well as the appropriate levels of precaution that should be applied with respect to mitigation of potential risks due to even a particular hot work process in various settings. Differences in hot work precautions and included processes across industry are expected, as different industries face different exposures and potential losses. In the nuclear industry it is an unfortunate reality, given the stakes, that little scientific data is available to guide the deliberation of standards. This is due to a dearth of scientific information on distances and energy involved in the possible ignition sources arising due to hot work. The information that is available in the literature is discussed in the next section.

2.3 Hot Work Studies

While the origin of the '35 foot rule' is not definitively known, Chapter 10 of the NFPA Introduction to Employee Fire & Life Safety [27] attributes the earliest printed documentation to a 1948 article illustrating sparks flying and bouncing as far as 34 feet away from an unspecified hot work process. A 1938 article entitled *Preventing Welding Fires* in the periodical Safety Engineering is a precursor to the study and discusses many of the then current hot work fire prevention strategies such as boxing in hot work with sheet metal guards, using catch pans to prevent slag from breaking apart and spreading as it hits the floor, posting a fire watch and protecting or moving combustibles within 30 to 40 feet, especially when using cutting processes [28]. An earlier reference was found to the study mentioned in the NFPA Introduction to Employee Fire & Life Safety [27]. In October 1942, an article detailing a study in which sparks from acetylene cutting were found to travel up to 34 feet was published in *Oxy-Acetylene Tips*, a trade publication by Linde Air Products [29]. The study varied oxygen pressure while cutting 25.4 mm (1 in) thick steel plate from a height of 2.1 m (7 ft) from the floor. Sparks were allowed to fall onto newspaper below and the distance travelled was determined by scorch marks left on the paper by the sparks [29]. At the recommended pressure of 36 psi, sparks were noted to fly a maximum of approximately 3.3 m (11 ft) and roll to a maximum of 5 m (16.5 ft). At 70 psi, sparks were observed to fly approximately 4.3 m (14 ft) and roll up to 8 m (26 ft). Finally, at 100 psi, sparks flew 4.9 m (16 ft), rolling to a maximum of 10.3 m (34 ft). After extensive searching, it is believed that this rudimentary study is the source of the '35 foot rule'. The report on the study is accompanied by a diagram which illustrates the result and has been found in many publications since, including Okegawa's 1966 hot work study [30], detailed later, and the current Kyoto City fire protection ordinance [19]. A series of *Safety Engineering* articles featuring the original *Oxy-Acetylene Tips* article followed its original publication [29] and referenced Linde Air Products studies in 1945 and 1946 demonstrating its relevance to different fields of manufacturing [31], including the automotive industry in 1946 [32] and the ship building industry [33].

In 1948 an information circular was published by the United States Department of the Interior on the topic of mine fires caused by cutting and welding activities [34]. The paper covers several incidents which are of interest because, as in the nuclear industry, work in mines must frequently be done in situ where the challenge of protecting combustibles is significant. The information circular contains details of two fires started in mine shafts due to cutting work that was being completed on the surface, 12 m from the opening [34]. Some very important details are highlighted by the cases, particularly the lack of recognition that is generally given to the possibility for heated particles to fall great distances before cooling sufficiently to mitigate their potential to cause ignition. In one instance cutting particles formed at the top of a mine shaft ignited combustible material 61 m (200 ft) below the work; in another, a welding fire was caused by sparks falling a shorter distance [34]. Conventional wisdom might dictate that the farther sparks have to fall, the greater the opportunity for them to cool. Research into the physical processes underlying the behaviour of incandescent sparks explains why this notion is not only incorrect, but dangerous. In the case of slag from a steel workpiece, iron atoms within the steel shavings can undergo exothermic oxidation upon reaching sufficiently high temperatures, causing the particle temperature to continue to increase [35]. In a situation where a heated particle is supplied continuously with additional oxygen, as is the case when a hot particle falls through the air, the particle temperature can rise significantly above its initial point [36]. As a result, the information circular concluded with a set of guidelines for hot work in mining situations where the work cannot be performed in safe locations. The list includes moving or protecting combustibles to a safe distance, using fire watches for all cutting and welding, wetting the area before and after hot work, and frequently checking the work area for hot spots or fires for a minimum duration of eight hours after the hot work has been completed.

In the time since the aforementioned studies, little in the area of hot work research has been published from North American sources outside of the field of mining. One exception to this is the *Ignition Handbook* which contains a section dealing specifically with welding spatter as an ignition source [37]. The section outlines a number of Japanese studies on the matter, beginning with a 1966 study by Okegawa et al. [30] noting that hot work fires and other accidents are commonplace, yet documentation and understanding of the causes is limited. Indeed, the study actually references the previous American study which is believed to be the origin of the '35 foot rule' [29]. The group conducted welding, acetylene cutting and arc gouging at different elevations and orientations in an attempt to identify and examine differences in the spread of spatter from the different processes. The process heights tested were 8.25 m, 12.25 m and 20 m above the floor; the group concluded that spatter from arc gouging behaved similarly to arc welding and oxyacetylene cutting, but that heated particles from arc gouging flew slightly further than those from the other two processes. For arc gouging, particles generated at the 8.25 and 12 m heights were found to travel a maximum of the same distance laterally, 8.25 and 12 m away from the operation respectively, including the extra distance traveled after each particle first impacted the ground. At the 20 m height particles were found to travel less distance; approximately 16 m laterally in total and further, at the 20 m height, it was found that the orientation of the work had no impact on the distance of particle spread. Other conclusions of note were that the particle distance was found to be largely unaffected by wind speed, and that particle spread was found to increase for both cutting and gouging thicker material [30]. Okegawa et al. continued their study by demonstrating that a variety of flammable gas mixtures were ignited readily by the cutting and welding spatter generated in their test processes [30]. While this study indicates some characteristic travel distances, spatter from only two varieties of hot work are measured, with more modern processes like GMAW, GTAW and plasma cutting notably missing. Moreover, no indication is provided of the quantity of particles that fall at any given distance.

Tanaka performed ignition tests using spatter from arc welding and oxyacetylene cutting of steel in his 1977 study [38]. He showed flame cutting would produce a great deal more spatter particles than arc welding, but that the overall size distribution of the particles was similar. He used calorimetry to measure the temperature of spatter particles generated by arc welding and oxyacetylene cutting, and found that they did not follow a simple model of convective cooling and in fact, remained at a constant temperature of 2,100°C over a distance of 5 m. Welding particles were found to cool rapidly over the first meter from a peak of 3,500 °C to around 2,500°C, at which point the temperature change slowed abruptly, falling to only around 2,350°C at 6 m [38]. While a cooling effect was observed for welding particles, the cooling was far less drastic than simple models of convective cooling might indicate, suggesting that exothermic oxidation of the particles may cause them to remain at high temperatures as they fall. To complement the hot particle generation studies, Tanaka also performed an ignition study using heated steel balls of different diameters to ignite saw dust. For dry saw dust, he found an ignition threshold temperature of 550°C [38]. These studies indicate the ignition potential of spatter from hot work in terms of high temperature, and how the temperature stays high after a considerable distance. Unfortunately, results are only inclusive of two of the types of hot work found in Table 1.1 and do not indicate a distance over which particles may be expected to travel if the work is performed at a given height.

In 1982 Hagiwara et al. [39] showed that there is a significant increase in the amount of welding spatter generated when performing shielded metal arc welding (SMAW) on steel specimens at higher than normal currents, but that the overall size distribution of spatter particles remained the same independent of the welding amperage employed. Weld processes that used deeper penetrating rods were also found to produce substantially more spatter than those using regular filler rods. In general, 90% of the spatter particles were found to be below 1 mm in diameter, with roughly 60% found to be 0.149 mm or less in all cases. In all cases, it was demonstrated that hot particles generated during welding activities could readily ignite a wide range of liquid fuels including acetone, benzene and light oil as well as solid fuels such as urethane foam and cotton [39]. This study verifies the potential danger of welding spatter, and characterises typical size ranges for the spatter and slag particles but does not indicate how far they might travel and over what distance the spatter remains a credible ignition threat. Other processes of interest as identified in Table 1.1 were not studied.

Kinoshita et al. used a thermographic camera during welding of steel in their 1989 study into how spatter cools as it falls away from the work piece [40]. With the camera, they measured the temperature of particles at a range of distances below the welding work. Although the frame rate of the camera did not permit the size of the particles to be determined accurately, peak temperatures of 1,850 °C were observed very close to the work piece, with temperatures of 1,592°C at distance 1 m below and 1,572°C at the lowest location of 2.8 m below the work. These results again suggest that the particles cool more slowly than a simplified model of convective cooling would suggest, lending further support to the possibility of exothermic heating of particles which are generated during welding of steel specimens. A limitation in this study is that only SMAW process particles were studied. The discrepancy in temperatures observed between this study and the last could arise due to a number of factors including the use of different welding parameters, procedures and materials as well as differences in the measurement techniques employed (thermographic vs. calorimetry) [40].

Hagimoto et al. [6] performed shielded metal arc welding on steel specimens and measured the size and scattering distance of particles produced when using 2.6 mm and 4.0 mm diameter welding electrodes with the welding current held the same for each electrode type. It was found that approximately 90% of all particles had diameters of 0.074 mm or less for both cases. Particles generated during welding with both electrodes scattered very similarly across the concrete floor, with 80% of particles landing within a 0.5 m radius of the work, and approximately 15% between 0.5 m and 1.0 m and 5% extending beyond 1.0 m. The hypothesis was that the 4.0 mm diameter electrode would supply more power to the weld pool and thus generate more hot particles, but the result suggests that particles breaking and scattering against the concrete floor had a larger effect on overall particle distribution during welding than does the size of welding electrode used [6]. In additional studies, shielded metal arc welding was performed 3.5 m above several types of combustible material [6]. It was found that large particles, with diameters ranging from 0.9 mm to 3.0 mm, caused ignition of combustibles in the tests and that many solid fuels would combust immediately when hit by a particle, while others would smolder first, and that some liquid fuels required the wicking action of a cloth to combust. The results shown in Table 2.12 illustrate the capability of spatter produced by the SMAW process to ignite common work site materials such as wood shavings, foam and solvent soaked cloth.

German studies of hot work were published in the 1980s in the publication *Schweien und Schneiden*, a welding publication organized by the German Welding Society. In 1982, Schönherr performed a study of fire risks during torch cutting and manual arc welding. The study endeavored to measure the distance through which particles could be thrown once detached from a work piece during each process. The distinction was made between droplets, molten drops of material falling off the work piece, and spatter, sparks and slag which are propelled from the work piece and oxidize in the air, elevating their temperature as they travel. The distances traveled by droplets and sparks were measured by means of

Table 2.12: Ignition Study Performed by Hagimoto et al., Combustibles ignited from height of 3.5 m [6]

Combustible Material	**Time to Ignition**	**Particle Diameter [mm]**
Urethane Foam	Immediately	0.9
Styrene Foam	3- 4 seconds	1.3
Cotton Wool	Immediately	0.9
Acrylic Wool	Immediately	1.1
Cotton Cloth	5 - 6 seconds	3.1
Wood Shavings	4 -5 seconds	1.9
Saw Dust	Smoldering after 4 -5 seconds	1.5
News Paper	4 -5 seconds	2.5
Corrugated Paper	7 - 8 seconds	2.5
Etyhl Alcohol	Immediately	1.1
Gasoline	Immediately	1.4
Kerosene	No Ignition	1.5
Kerosene with Cloth	Immediately	1.3
Light Oil	No Ignition	2.0
Light Oil with Cloth	Immediately	1.9

examining the burn holes made in tissue paper laid across the floor around the work area, as well as by long exposure photographic techniques. Droplets for cutting were formed in two ways. The first emulated a hot work process being done poorly; a large area of pipe was overheated before it was cut such that larger than realistic droplets were formed during the cutting process.

In the other study, nominal sized droplets were formed by melting large diameter wire to emulate droplets formed during proper execution of the cutting process. In these tests, the trajectories of particles generated at different work piece heights and for different landing conditions, soft and hard floor impingement, were investigated. A strong correlation was found between the distance traveled by the droplets and their initial size. Droplets coming from the wire traveled a maximum of 6.7 m with additional statistical analysis suggesting that a particle would not be expected to travel more than 7.7 m under these nominal conditions. For larger droplets formed from the pipe, which would only be expected in the case of extremely poor workmanship, the largest distance traveled was 9.8 m. Maximum distances were seen for tests with hard floor impingement, suggesting again that the breaking of particles upon hitting the floor has a large impact on the final distance traveled by the hot particles. For all droplet tests, only 10 to 30 droplets were observed per run, so the study population is limited, but the results show a loose correlation between the height which a droplet falls and the distance traveled; on average, particles which fell further also traveled longer distances along the floor, consistent with the Japanese results discussed above [6].

Schönherr [41] also investigated particle generation during upset conditions for oxyacetylene cutting. For this, a pool of molten metal was created in the centre of a steel work piece and then the tip of the torch was dipped into the pool to deliberately cause a back fire and shower of hot particles. Upon performing this process 25 times, only six spots were found to have landed as far as 3.5 m and 4.0 m from the work site, and none of those particles had sufficient heat to burn through the tissue paper.

Finally, Schönherr studied particle generation during shielded metal arc welding of 6 mm plate. The process was carried out twice, with two different welders performing the operation. Across both jobs, no particles traveled over 4 m, and only six passed the 3 m mark. The study also notes that differences between the two tests indicate that both the number of particles and the distance traveled by them depend strongly on the way in which the welder works [41].

Schönherr's testing was inclusive of many factors of interest to this research, but the manual nature of the methodology allowed the researchers to concern themselves only with the maximum distances traveled by a few particles, and for this reason the study popilation is limited. Comprehensive information revealing the distribution of the welding spatter is not available. Schönherr's work also did nothing to establish whether the traveling spatter remained a potential ignition hazard or not.

Hölemann et al. [42] developed an optical measuring system with which to measure the temperature, speed and size of particles of slag generated during oxyacetylene cutting. The study endeavored to use the apparatus to determine a relative ignition potential for different positions and cutting configurations. 10 and 20 mm thick plates of steel were cut in the horizontal plane with the apparatus set at 0.6, 1.0, 2.0, 3.0 and 4.0 m from the bottom edge of the plate. From literature values, temperatures of 1,600 to 1,650 °C were expected within the kerf and the temperatures of 1650 °C and 1790 °C measured at the 0.6 m location for the 20 and 10 mm plates respectively seem to corroborate this. It is further suggested that the difference in hot particle temperatures observed during cutting of the two plates is a result of more complete oxidation of the particles during cutting of the 10 mm plate; the smaller particles from the 10 mm plate have a much larger ratio of surface area to volume and therefore may oxidize faster than those generated during cutting of the 20 mm plate. The effects of particle oxidation are illustrated again in this work; while particles generated by cutting the 10 mm plate have cooled significantly (average temperature of 1560 °C) by 4 m from the work piece, particles generated from cutting the 20 mm plate are on average hotter at the 4.0 m distance than at the 3.0 m distance (1680 °C and 1650 °C respectively). In addition to the temperature measurements, the ignition potential of the particles was determined using a micro calorimeter to determine the specific heat of the particles which combined with temperature data allowed an estimation of the energy content of expelled particles. Results yielded values substantially larger than found using previous energy balance approaches [37], but no further investigation in causes for these discrepancies is provided [42].

More recent hot work studies were performed in the United States for the mining industry, where cutting and welding represent the cause of 14% and 16% of all fires in coal and metal mines respectively [43]. A series of studies by the National Institute for Occupational Safety & Health (NIOSH), focussed on using infrared (IR) thermography to measure the temperature of large particles of metal generated during oxyacetylene cutting, and to be used to assist with the fire watch after the hot work is complete [43]. It was shown that pieces of metal cut with an oxyacetylene torch were sufficiently hot to ignite several coal dust samples as well as to ignite methane-air mixtures. It was also demonstrated that hot spots that were generated in float coal dust by hot oxyacetylene cutting slag could be readily detected with commercially available IR cameras, even when invisible to the naked eye. The coal dust hot spots were also verified as a smoldering fire hazard as they could be reignited when sufficient ventilation was provided [44]. This result confirms yet again that oxyacetylene cutting creates a large fire hazard and, in addition, suggests the value in the use of IR thermography in measuring the workpiece temperature.

Omar et. al [45] used infrared thermography as a means to investigate welding related industrial fires. The study showed that observing and measuring temperatures of hot pieces of slag from welding is difficult but possible. By using two infrared cameras operating in spectrally distinct regions, they could employ the "gray-body" assumption to estimate temperatures and thus eliminate the need to estimate a value for the rapidly changing emissivity of the particles in order to determine accurate temperatures. Particle temperatures during GMAW of steel plates were measured close to the welding exhaust duct and found to be on average 410°C, close to the melting temperature of the zinc coated filler metal. This seemed to confirm the hypothesis that welding spatter tends to be comprised of the filler metal rather than the base metal used in the process. This result demonstrates the difficulty in using IR thermography when attempting to measure the temperature of small, quick moving slag particles which change temperature rapidly.

2.3.1 Mechanical Sparks

In addition to hot particles and slag produced during welding and cutting operations, hot work processes can also present a fire hazard as a result of sparks generated due to mechanical friction between the tool and the work piece. In this respect, it has long been recognized that the work piece material is critical in terms of the propensity for the creation of sparks from this class of hot work processes. In fact, spark testing was very popular, starting in the 1920's, as a method by which experienced operators could quickly and easily identify ferrous metal samples, as is well documented in trade guides such as Linde Air Products Oxwelders Handbook [15] and the Oxy-acetylene Welding Manual [46].

It has also been known for some time that sparks produced by a process are often at higher temperatures than those characteristic of the process through which they were created because of exothermic oxidation reactions occurring in the small particles making up the sparks [34,35]. This is consistent with more recent results which determined that in order for a metal to spark, the material must have low enough specific heat to reach high temperatures when subject to friction, it must be supplied with sufficient energy to heat to those high temperatures, and it must be able to oxidize readily [47]. As such, softer metals typically deform too much to promote the formation of sparks [47].

Behrend et al. [36] conducted one of the most comprehensive studies to date of sparks generated during the grinding process. They identified that sparks occur if particles are at a high enough temperature to glow or burn when they separate from the main work piece. The study investigated steel grinding dust and found two categories of particle shape: irregularly shaped particles which remained the same shape as they separated from the work piece, and spherical particles which have been formed by surface tension of molten metal. Consistent with theories of exothermic oxidation of particles generated during welding and cutting, grinding dust generated in nitrogen comprised only the the former shape, as exothermic oxidation did not occur so particle temperatures did not exceed the melting temperatures of the metals involved. Further, the temperature and size of the separated particles were found to be strongly correlated, with several elements contributing to the increase of both [36]. When one of the surfaces is not plastically deformable and remains rough, as in the use of an angle grinder, the temperature of the wearing element will increase and result in an increase in the size of separated particles. If the grinding wheel is a poor conductor of heat, the energy of the process will be dissipated into the worked material and result in elevated size and temperature of ejected particles.

General observations made included [36]:

- Flight distance of particles increases with increasing size
- Among identical sizes, flight distance increases with grinding speed
- Spherical particles fly further than chip-shaped particles
- Increasing grinding speed tends to decrease particle size
- Over longer flight distances, particles have more time to reach the highest possible temperature

Much less studied is the generation of sparks from other processes, such as friction between the blade of a typical reciprocating saw and the work piece. With a standard stroke of 1.125” and 2,400 strokes per minute, typical for a budget reciprocating saw, the blade operates at an average velocity well above the 1 m/s relative velocity thought to cause sparking when unloaded [36]. Resistance during a cut generally lowers the blade speed such that sparks from a saw are expected to be much less common than from other cutting processes. Nonetheless, fire fighters have reported sparks from the use of reciprocating saws during extrication procedures, especially when cutting through hard reinforcing materials [48] so a viable fire hazard is documented and must be considered here.

Use of cold cut off saws and low speed reciprocating saws is, and should be, recognized as a viable alternative to hot work. Such saws use flood coolant systems and are intended to cut at low relative velocities such that sparks and heat buildup are avoided, and thus these processes present a low fire hazard and are not considered here.

2.4 Summary & Objectives

The sources and research discussed above place into context what specific processes are included under the definition of hot work in different countries and industries, as well as how the issue of managing the ostensible hazards arising from hot work processes is approached. Many forms of hot work have been observed to cause fires in a variety of scenarios. Sparks and ejection of hot particles, most frequently originating from welding but equally being the cause of fires due to other hot work processes, have been shown in two data sets to represent the most frequent ignition pathways in hot work fires. This suggests that the list of processes in Table 1.1 is a suitable starting point for studying the fire potential of hot work processes. Existing literature has shown that technique and workmanship can take precedence over process and material in defining the magnitude of risk involved in hot work activities. Literature has further highlighted the methodologies and techniques which have been used to approach the problem of assessing fire hazard due to hot work in the past. Perhaps the most thoroughly studied metric of fire potential due to hot work has been measuring hot particle temperature of processes through pyrometry and calorimetry studies. Pyrometry has been used further to demonstrate the tendency of oxidizing particles to heat up as they travel, and so causes worrisome implications about the remote ignition hazards associated with particles produced during hot work. By means of ignition testing, several of the studies confirmed the capability for hot particles to ignite solid and liquid fuels in close proximity to the hot work operation, but none examined this ability at a distance. Use of charring tissue paper has been used with some success to determine the distances particles can travel, but only the maximum distance traveled by a few particles was generally reported. The cumbersome nature of manually examining burn marks from particles, assuming a mark is left, coupled with measuring and recording each mark has limited the amount of useful data gathered from these studies. Overall, it is concluded that new methodologies could be used to better understand the distribution and distances traveled by hot particles from the wide range of processes of interest in this research.

The literature shows some research has been conducted into defining appropriate separation envelopes for processes such as shielded metal arc welding and oxyacetylene cutting, though the most recent work remains decades old. It is not clear that any of the results and findings of previous research have permeated their way directly into standards and regulations. No ostensible coincidence with scientific findings could be identified in legislature or standards outside of the Kyoto City fire ordinance corroboration between the 1942 Linde Air Products Study [29], and Hagimoto's 1966 study [30]. It is evident however, that the creation of a body of scientific results could serve to enrich and support engineering solutions to reduce the risk of fire inherent in performing hot work in industry. By characterization of the potential fire hazard exhibited by various hot work processes, assessing the magnitude and potential of that hazard becomes less difficult. It is in pursuit of this objective that the remainder of this thesis will focus. Explicitly stated, the objectives are:

- To develop experimental methods to systematically collect data relevant to assessing fire hazards of hot work
- Use the scientific data base collected to develop appropriate fire hazard parameters
- Use identified fire hazard parameters to assess the potential for ignition of a fire (ignition propensity) for the studied hot work processes

Chapter 3

Ignition Propensity Testing

3.1 Approach

To streamline assessment of the ignition potential of processes listed in Table 1.1, potential hazards arising from each process were identified and subsequent classification of the process was performed on that basis. Table 3.1 shows the fundamental differences in the nature of the hazards arising from the various hot work processes, necessitating that different strategies be applied in measuring and assessing the hazard posed by each.

It can be seen from Table 3.1 that four main categories of hazard were identified across the processes of interest here. These include hazards due to open flames, high temperature arcs, hot particles and hot surfaces. It should further be noted that the hot surface category considers the temperature of both the work piece and the tool, during and after use, as potential sources of ignition. The more hazards exhibited by a process, the larger the number of metrics upon which the cumulative hazard must be assessed. For processes exhibiting only local process heat and heated surfaces, measurement of localised temperatures is sufficient to determine a level of fire risk. For processes with the potential to expel hot particles over distances of 10 m or more, tests had to take into account far more factors. Therefore, processes were classified into three main groups. The first were those processes that presented only hot surface ignition hazards, including processes such as iron soldering and use of a heat gun. While the second group is similar, again concerning processes in which hot surface ignition is the primary hazard, the processes in the second group also exhibit the potential to generate hot particles or sparks, and therefore include processes such as brazing, drilling and sanding. The third and final group comprises processes which are well known to generate large numbers of sparks and hot particles, and so includes processes such as welding, thermal

Table 3.1: Hazards Exhibited by Hot Work Processes

	Nominal Hazards As Performed By Experienced Operator			
Joining Processes	**Open Flame**	**High Temperature Arc**	**Hot Particles**	**Hot Surface**
Gas Metal Arc Welding		**X**	**X**	**X**
Gas Tungsten Arc Welding		**X**		**X**
Shielded Metal Arc Welding		**X**	**X**	**X**
Brazing	**X**			**X**
Torch Soldering	**X**			**X**
Iron Soldering				**X**
Gas Welding	**X**		**X**	**X**
Thermal Cutting Processes				
Oxy-Acetylene Cutting	**X**		**X**	**X**
Air Carbon Arc Gouging		**X**	**X**	**X**
Plasma Cutting		**X**	**X**	**X**
Abrasive Cutting Processes				
Grinding			**X**	**X**
Cut Off Wheel			**X**	**X**
Cut Off Saw			**X**	**X**
Sanding				**X**
Drilling			**X**	**X**
Filing				**X**
Other				
Heat Gun				**X**
Thermal Adhesive				**X**

cutting and the use of abrasive cut off wheels.

It is generally understood that processes using an open flame or high temperature arc pose a fire hazard if there are combustibles in the area. As a result, no experiments were undertaken to characterise these active ignition sources. Less intuitive sources of ignition relate to the temperatures of hot surfaces and/or the possibility of ejection of hot particles, the distances over which these particles might travel and therefore their propensity to ignite remote combustibles. Therefore, experiments were designed and instrumentation chosen by which to characterise the temperatures of hot surfaces and to determine the distribution of hot particles generated by the various hot work processes. Since the distribution of hot particles depends not only on the specific hot work process being performed, but also on specific parameters such as the work piece material, dimensions, orientation and operator skill, a cross section of specific processes was chosen in order to limit the number of test cases required.

Based on the hazard categorization and subsequent process grouping, the hazard parameters required to characterise each process become more clear. For hot surface ignition hazards, the determination of a critical surface temperature, either of the workpiece or the tool, can effectively characterise the fire hazard associated with the process. This temperature can then be used in comparison to ignition or degradation temperatures of typical combustible materials to determine the level of hazard present. Similarly, for the hybrid group, the largest hazard is anticipated to be the hot surface, so the concept of a critical process temperature can also be applied here, combined with the use of infrared footage to characterise the temperature and distribution of any particles leaving the work. For processes which produce sparks and hot particles, the selection of characteristic hazard parameters is far less straightforward as significant quantities of data must be generated to determine hot particle distributions, including size, spatial distribution, quantity of particles, and distance of travel. As such, further analysis was required to determine the most pertinent hazard parameter from these data sets.

For all processes, attempts were made in the experimental design to emulate the process as it might be performed on site at a CANDU facility. To address issues associated with human error and workmanship, attempts were also made to generate a realistic nominal process profile as a reference condition and, where possible, to then shift key hot work process parameters to represent worst-case scenarios which might better represent a task being performed in adverse conditions, in an accident situation, or in a situation where less qualified personnel were performing the hot work.

With the goals of experimental design understood for each of the process groupings, the specific methods and instrumentation used in the various experiments are discussed in more detail in the next several sections.

3.2 Measurement Techniques for Hot Surface Temperature

Thermocouples and infrared thermography were used to measure temperature rise and determine critical process temperatures during those hot work processes deemed via the categorizations listed in Table 3.1 to present hot surface hazards. A FLIR S60 (spectral range 7.5 - 13 μm) thermographic camera was used to record temperatures of the work piece and the tool where possible. Alongside basic measurements of temperature, the camera provides the value of temperature for a specific spot (pixel) or region (rectangular group of pixels) and allows variation of emissivity for each region of temperature as well. K-type thermocouples were used to measure bulk work piece temperatures and thereby assist in setting the values of emissivity needed to quantify temperatures determined using the thermographic camera. To further assist with determination of the surface emissivity, tape of known emissivity and low thermal inertia was applied to the work piece surface and used as a reference material in many scenarios. In situations where thermocouples could not be used, measurements were taken exclusively using the infrared camera and a deliberately low estimated value of emissivity was used to provide a factor of safety in the reported values of measured surface temperature.

3.2.1 Uncertainty Analysis

The K-type thermocouples utilised in this portion of the research are subject to measurement error comprising the greater of ±2.2°C or ±0.75% of the measured temperature. The data acquisition system (DAQ) used for thermocouple measurements, the Omega HH85 may impart a total error of 0.1% of the reading, plus 1°C. Table 3.2 illustrates E_{Total}, the total error for this system of measurement. As is typical, the thermocouple error is larger than the error of the measurement system. The magnitude of total error in this application is small in comparison with ignition temperature ranges to which critical process temperatures will be compared. Therefore, for the purposes of identifying a critical process temperature hazard parameter for each process, measurement error with the thermocouple system is of little concern.

Error in temperatures measured using infrared thermography is considerably more dependent on the measurement scenario. The FLIR S60 offers two useful calibration ranges: 0 - 500 °C and 300 - 2500 °C. Within these ranges manufacturer specifications indicate that the camera can be expected to deliver accurate temperatures within the larger of ±2°C or ±2%; outside of these ranges the camera warns of potentially inaccurate measurements prior to saturation of the signal and thus loss of temperature data. The accuracy of the measured temperature depends critically on several factors; the distance from the measured surface to the FLIR S60, the ambient temperature, the temperature of the surface being measured, and most importantly, the assumed emissivity of the surface being measured. In situations with high measured surface temperatures relative to ambient, typical for processes tested in this research, the influence of distance and ambient interference are significantly diminished, resulting in lower measurement uncertainty, than would be the case for measurement of lower temperatures.

Therefore, choice of emissivity and calibration are the largest expected sources of error in the thermographic measurements taken here. For determination of emissivity, manufacturer tables were consulted, and techniques such as use of diffuse black tape and thermocouple temperature matching were also employed. Errors in temperature data obtained using thermographic imaging is expected to be lower than 10%, which is not expected to adversely affect results for purposes of identifying a critical process temperature as a hazard parameter.

Table 3.2: K-Type Thermocouple Measurement Error

Measured Temperature [°C]	$\mathbf{E_{TC}}$ [±°C]	$\mathbf{E_{DAQ}}$ [±°C]	$\mathbf{E_{Total}}$ [±°C]
25	2.2	1.025	3.225
50	2.2	1.05	3.25
100	2.2	1.1	3.3
200	2.2	1.2	3.4
400	3	1.4	4.4

3.3 Techniques for Measurement of Hot Particle Distribution

Design of an experiment to measure the distribution of, and ignition potential posed by, hot particles generated by a hot work process presents unique experimental challenges. Safety of the proposed tests is a large concern, as is the suitability of the test space, since the processes under test can themselves lead to serious fires. A large space was necessary, with minimal air currents, well controlled humidity and temperature and sufficient clearance so as not to constrain the distances travelled by the particles during the various hot work processes under study. With these considerations in mind, tests were performed using the state of the art commercial welding and cutting machinery at the Canadian Welding Association's Advanced Welding Technology Centre. The test area there had an unobstructed clearance 12 m long by 4.5 m wide and 4 m height. The Canadian Welding Association provided Brian Chmay[1] as a consultant for the test design and as operator for all of the welds and cuts required in this set of tests.

As each hot work process was performed, a combination of methods was used to characterise the spread and quantity of hot particles from the process and relate those to the potential fire risk presented by the particles. Given the number of processes to be tested, the chosen method had to be fast and repeatable. After consideration of the use of infrared thermography, thermochromic paint, long-wavelength video, long exposure photographic methods, and ignition testing as possible characterization techniques, it was decided to use a combination of conventional video photography, IR thermography and thermal paper to characterise the numbers and distributions of particles from each process, whilst also recording other details of the experiment.

3.3.1 Use of Thermal Paper for Measurement

Similar to the tissue paper used in studies reported in the literature [41], thermal paper serves as a good tool via which to locate and also record the landing positions of heated particles. Rolls of high sensitivity fax paper with a transition temperature of 70°C were laid on the floor in the area below the operator and main work-piece, as well as along various planes extending away from the centre of the process. The paper was found to readily show the landing positions of the particles, with the size of a mark made by each individual particles

[1] B. Chmay is a welder with 30 years of experience and a member of the CSA W117 committee

corresponding to a combination of the following lumped parameters:

- Particle Size; larger particles leave larger marks
- Particle Temperature; hotter particles radiate sufficient heat to cause the paper temperature to increase above the transition temperature at distances further from the particle, leaving larger marks
- Particle speed; slower moving particles have more time to transfer energy into the paper causing larger marks

It can be noted then, that all measures which increase mark size, similarly indicate a larger ignition potential for the originating particle as the criteria suggest either larger amounts of energy contained within or radiated by the particle as well as slower speeds providing for longer contact times for heat transfer and ignition.

Figure 3.1 shows a mark left on the thermal paper at a distance of approximately 7.6 m from the work piece. The mark was made by the particle in the upper right of the image, produced during angle grinding of mild steel. The diameter of the spherical particle was approximately 1.8 mm.

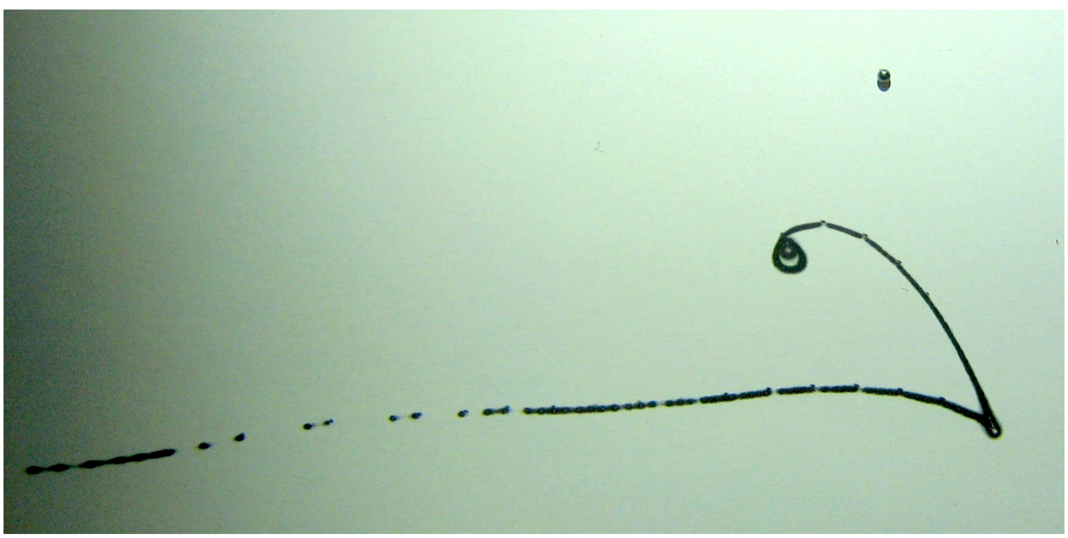


Figure 3.1: Mark left on thermal paper by 1.8 mm mild steel grinding particle

It can be seen that the mark left by the particle on the thermal paper is a good deal larger than the size of the particle itself, due to heat radiated by the metal onto the paper, as well as the manner in which the particle travels along the page after its initial impact. In Figure 3.1 there are a number of discreet markings left behind by the singular particle. The opposite case is also possible of course. The markings of several particles may agglomerate into one large mark. This is typically observed close to the workpiece during processes which generate significant numbers of hot particles. The impact of this issue on the results will be discussed in the next section, as will the remedies developed to alleviate the effects.

Experimental Approach & Analysis

Figure 3.2 demonstrates a plan view of the layout of the thermal fax paper, as well as the coordinate system that will be used throughout discussion in this paper. The same layout was used for all processes except the cut-off saw. Because most of the hot work processes under study were known to eject sparks and hot particles in a biased direction, the origin of the measurement domain was positioned at the centre of the work-piece and the paper was positioned to capitalize on the maximum dimension of the room. The remainder of the layout was chosen as a compromise between maximising the collection of useful data and the available floor space, while minimizing time taken for pre-test setup and post-test analysis of results.

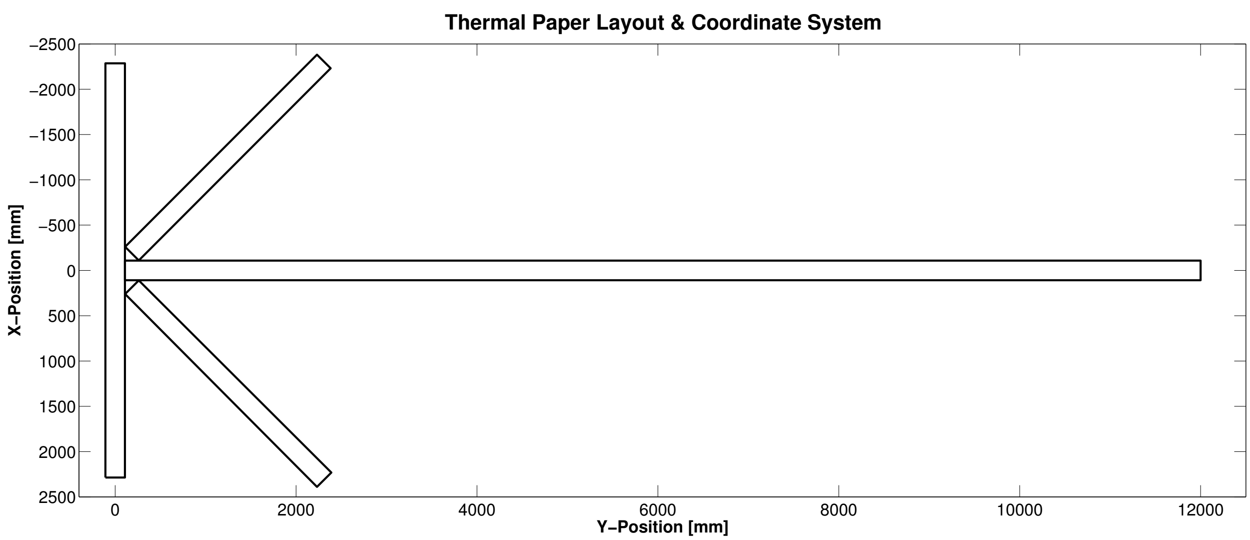


Figure 3.2: Plan view of paper layout

After each test, the particle marks on the thermal paper were digitised to a gray scale bitmap format by systematically scanning each length of paper at 300 DPI, affording resolution of any particle mark longer than 85 μm, sufficient to resolve the majority of particle marks left for the processes studied. Segmentation of each image was performed using image analysis algorithms written in MATLAB, with thresholds set for each image individually based on Otsu's method [49]. In this way, recognition of the marks was optimised while noise introduced by the scanning process was minimised. MATLAB algorithms were utilised further to generate a list of landing coordinates for each particle based on the sequential sheet number and also to perform an area calculation for each mark on each length of paper. Finally, the total percentage of paper covered by marks in each image was calculated and recorded for each sheet. The measurements provided information regarding the distribution of heated particles, the overall envelope within which most hot particles and sparks fell and a relative measure of the potential for ignition from each process in terms of the total area of paper marked through the course of a process. The latter parameter is considered an integrated measure of the relative energy imparted to the floor area from heated particles and sparks ejected during execution of each hot work process.

The image analysis routines developed in this work are not capable of discerning between a mark made by a single particle, and a mark made by an agglomeration of several particles. Therefore, for those processes where thousands of particles impact the thermal paper in a relatively small area, it is difficult to discern the number and sizes of single particles which fell; instead the area marked by the particles is smeared and is interpreted by the measurement algorithms as indicating the presence of less, larger marks. The effect on the present results is that in those areas with the highest potential for fire hazard, it sometimes appears that fewer, but larger, particles are being produced by a process, even though this is not the case.

To determine situations where such overlapped marks might skew results, a mark saturation threshold of 10% was adopted; when 10% or more of the area of a thermal paper sheet was marked, the sheet was considered saturated. Since this often occurs adjacent to the work piece, determination of the radius within which the saturation level is more than 10% was used to determine a minimum 'saturation radius' for a given process. The larger the saturation radius, the higher the potential hazard due to ignition of combustibles in the immediate vicinity of the hot work process. Inside of this radius, the quantity of marks and individual particle metrics such as size and position are not accurate, but determination of the total area marked on a sheet still remains valid indicator of potential fire hazard.

Uncertainty Analysis

Aside from errors introduced from overlapping marks, the largest expected source of error with this technique is a result of the reliance on manual cutting techniques to prepare the sheets for scanning. The measurement process used here renders these errors additive such that if a mistake is made cutting a sheet, e.g. a non-square cut is made introducing 1 mm high triangle of empty space into the bitmap, this erroneous distance is manifested twice in each ensuing sheet, one for each side of the erroneous cut. Although cutting of the lengths of paper was done with proper equipment and the utmost care, an average of 1 mm per cut could be expected. With an approximate length of 300 mm per sheet and 10.6 m for the total length, the maximum number of usable sheets is approximately 35, in which case the maximum error is about 68 mm or 0.6% of the 10.6 m range of measurement, which is a readily acceptable figure of accuracy given the goals of this research.

3.3.2 Conventional Video

A wide angle video camera is used to record a lateral view of all processes at 1080p resolution and 60 frames per second. The camera is positioned to capture a view of the process spanning from the work piece to 4.5 m along the main direction of particle travel. Figure 3.3 shows the camera field of view. A circular grid, superimposed on the image and in plane with the floor, serves as a rough distance reference with which hot particles can be located.

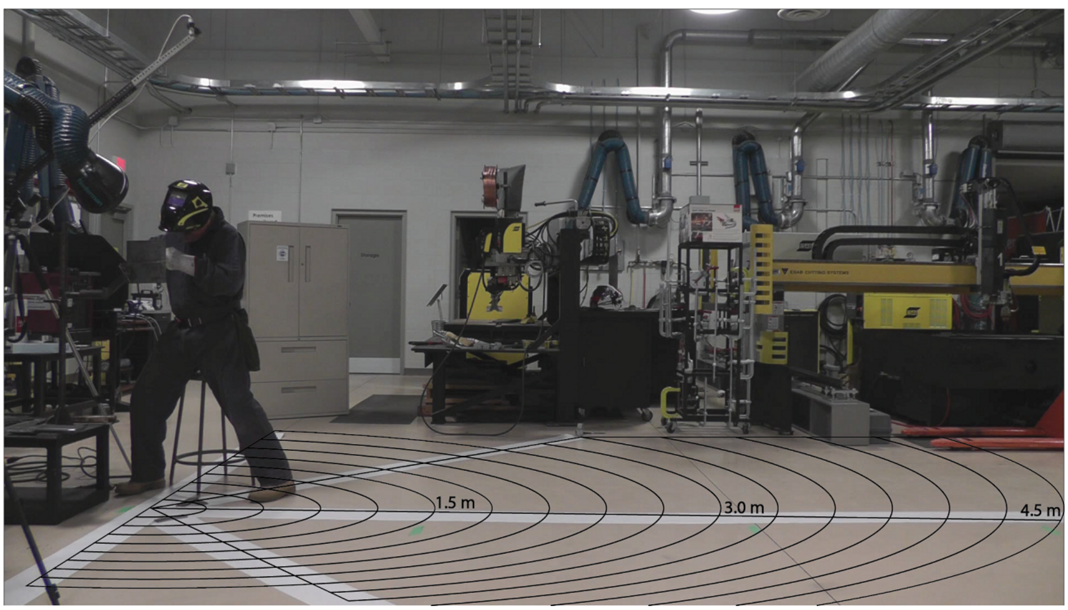


Figure 3.3: Demonstration of Lateral Camera FOV

The video is separated into constituent frames which are then compiled into a singular image through a process known as 'stacking'. This is an image addition process where a resultant image is formed by retaining the lightest pixel from each constituent image. Subtracting an initial dark frame from the resultant image serves to remove background illumination caused by welding arcs and bright sources of light. The resulting composite image detail where incandescent sparks, with temperatures greater than 500°C, travel after leaving the work piece during the hot work process. This methodology was found most suitable for recording single welding or cutting passes, rather than entire procedures which create too many sparks and saturate the entire image, or require too much movement on part of the operator, causing unwanted blurring. As well as providing excellent visualization of particle travel during each process, these results are used to confirm that the traces on the thermal paper have captured distributions representative of the process, including distances travelled by the farthest travelling sparks. Limitations of this methodology are that particles with temperatures below 500 C are not tracked, particle temperatures cannot be measured and particles cannot be precisely located unless they are on the ground. Therefore, the image stacking technique is utilised primarily to make qualitative observations about behaviour of particles and understand the effectiveness of the thermal paper measuring process in capturing sufficient numbers of particles.

3.4 Equipment

Characterization of the large number of hot work processes which present fire hazards due to elevated work piece and tool temperatures necessitated the use of a large array of equipment to perform representative hot work operations. Equipment used to conduct each process and a description of the expected hazards are provided in each section below. A full list of equipment, manufacturers and models used in this research is available in Appendix A.

3.5 Test Methods for Hot Surface Processes

Experiments detailed in this next section aim to assess the fire hazard associated with processes exhibiting hot surface ignition hazards. To accomplish this, the experiments aim at determining a critical process temperature, whether of the tool or the workpiece, which can be compared with threshold temperatures of common combustibles.

3.5.1 Heat Gun

Hazards involved with operation of a heat gun arise due to elevated surface temperatures, particularly that of the gun nozzle, as well as those of any surfaces toward which the gun is aimed. Exact temperatures will vary with the size of heat gun, the heat setting used, and the proximity of the gun to the affected surfaces, but even with relatively small heat guns, the temperatures of the tool and surface can easily reach hazardous values from the perspective of ignition of common combustible materials. Statistical sources indicate one hot work accident where wood being dried by a heat gun became charred and caught fire [5]. This suggests the heat flux emitted from the nozzle of a typical heat gun poses a considerable threat in terms of ignition of paper, wood, and other combustibles such as the insulation on wiring.

A Wagner HT1000 1200W heat gun was chosen to exemplify a heat gun used in the nuclear industry. The gun features two temperature settings which alter the speed of the blower and therefore the outlet temperature of the heated air. According to the product literature, the 'high' setting features an outlet temperature of air heated to 540°C, while the 'low' temperature outlets at 400 °C. Due to these high temperatures, the temperatures of the air issuing from the gun, as well as the surface temperature of the gun nozzle itself, were evaluated for both 'high' and 'low' heat gun settings to determine its characteristics of the heat gun as a potential source of ignition. In ambient temperatures of 25°C, the heat gun was powered on and allowed to run for 60 seconds. A K-type thermocouple was inserted into the nozzle at the centreline, and slowly drawn out of the barrel of the heat gun while the value of the maximum temperature and corresponding distance from the nozzle was recorded. The temperature was then verified by means of measuring the temperature of the inside surface of the barrel with the infrared camera. An emissivity of 0.65 was chosen for the stainless steel surface of the barrel.

Following this initial characterization, the application of heat-shrink tubing and stripping paint were chosen as processes which typified the use of a heat gun in the nuclear industry. The experimental approach to determine critical process temperatures for each are detailed below.

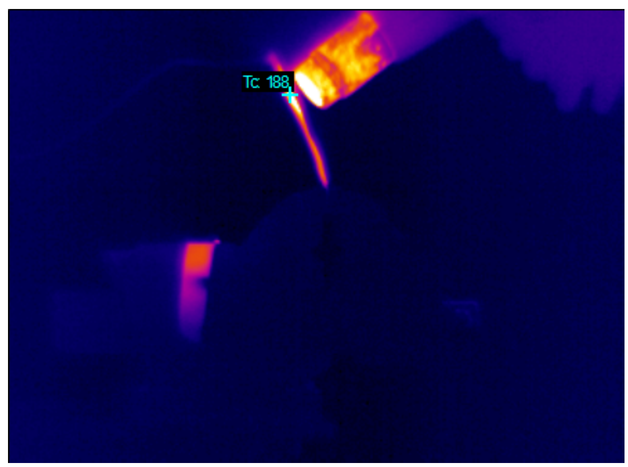
Application of Heat-Shrink Tubing

Heat shrink tubing is typically applied after making electrical repair. The heat shrink insulates the joined wires and protects them from abrasion. Heat shrink tubing is best, and most safely applied, using a heat gun, but in reality any source of heat can be used, including a soldering iron or open flame such as a lighter. Independent of the source of heat, care must be taken to avoid overheating and igniting the heat shrink tubing during application.

To determine the temperatures involved in the process of applying heat shrink, two 18

AWG wires as well as a K-type thermocouple were sheathed into a bundle using 6 mm heat shrink as shown in Figure 3.4a. In the figure, the experimental setup can be seen with the ends of the wires and the thermocouple inserted into the length of heat shrink. The sheathing of the thermocouple was removed allowing the exposed leads to be bundled with the 18 AWG wires, the bead sat approximately midway through the 50 mm length of heat shrink. The gun was operated for approximately 60 seconds to reach steady state on the 400setting, and then the barrel of the heat gun was held approximately 5 - 10 cm away from the surface of the bundle and slowly moved to direct the hot air stream across the length of the heat shrink in order ensure even application. The DAQ was configured to record the highest temperature during the process, while the infrared camera was used to measure transient surface temperature on the outside of the bundle corresponding to the position of the thermocouple bead. The IR camera was used in the 0 - 500 °C calibration range with a spot emissivity of 0.95; a typical experimental view from the IR camera is shown in Figure 3.4b.

(a) Heat shrink bundle

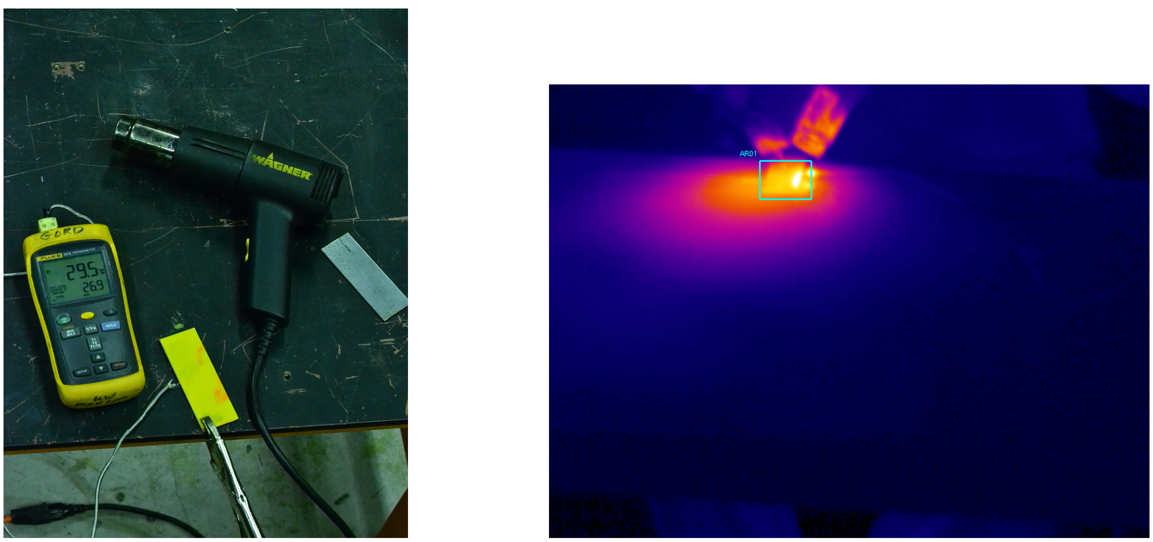


(b) IR camera view of the heat shrink process

Figure 3.4: Heat Shrink Experiment Setup

Thermal Paint Stripping

A 3 mm thick steel plate measuring 50 mm by 100 mm was painted with yellow anti-rust paint and allowed to dry. The painted plate was affixed flat against a steel work table, with a K-type thermocouple positioned centrally in between the sample and the table as shown in Figure 3.5a. The heat gun was given approximately one minute to reach steady state on the 400°C setting. Once at steady state, the heated air st was directed at the plate from a distance of approximately 50 mm and slowly moved across the face of the plate until the paint began to bubble, at which point a paint scraper was used to remove the heated paint. The data logger and infrared camera recorded temperature data throughout the heating process. The DAQ was configured to record the maximum temperature of the thermocouple on the underside of the steel plate during the operation. Figure 3.5b shows an image recorded by the infrared camera immediately prior to scraping. The infrared camera was used to measure transient surface temperature of the painted sample with a rectangular area as shown in the Figure with an assumed value of emissivity of 0.88. The figure shows that the infrared camera has an excellent vantage from which to see the work table, and any paint scrapings which may separate from the work.



(a) Painted sample clamped to work table (b) IR camera view of paint stripping process

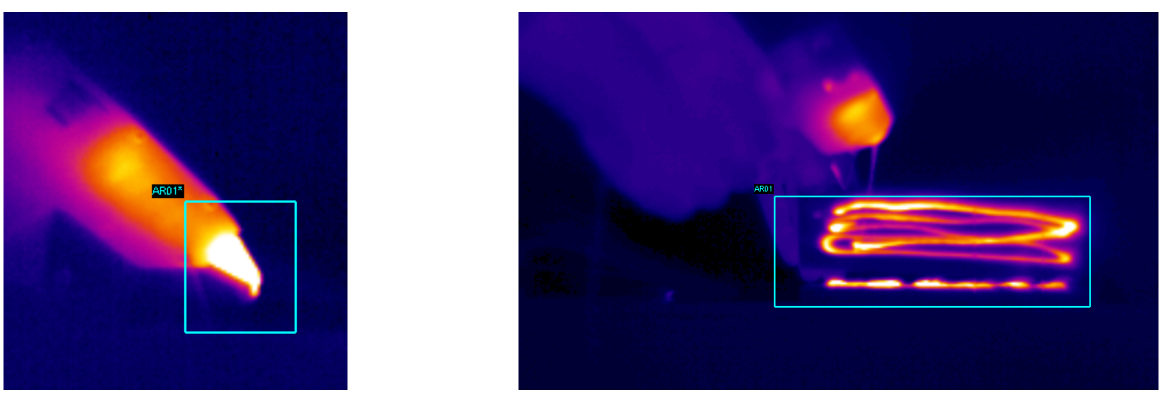
Figure 3.5: Paint Stripping Experimental Setup

3.5.2 Heated Adhesive

Heated adhesive guns have not been linked to fires in the statistical literature reviewed [4,5]. However, stakeholder members in the nuclear industry attested to the frequency of their use and, given the high temperatures associated with heated adhesive tools, characterisation of this hazard was considered a necessity.

A Steinel GF 3002 was chosen to exemplify a heated adhesive gun that may be used in the nuclear industry. The gun does not feature any temperature settings, and the manufacturer specifies an operating temperature of 205°C. When plugged in, the tool was found to require approximately 60 seconds to reach an operational state. Prior to performing any practical tests with the adhesive gun, the temperature of the tool was characterised at steady state with thermocouples and infrared thermography. Temperatures of the exterior surfaces of the gun were measured with the infrared camera using temperature analysis of the tip area as shown in Figure 3.6a and a value of emissivity of 0.90. A K-type thermocouple was inserted into the nozzle of the gun to obtain the temperature of the glue.

Potential hazards associated with the use of heated adhesive were investigated by using the adhesive to adhere two rectangular pieces of soft wood to one another. The wood measured 50 mm wide by 100 mm long, and was 10 mm thick. After applying glue to each wooden surface, the pieces were pressed together. The IR camera was positioned to obtain an area temperature analysis as shown in Figure 3.6b. Images indicated the temperature of the glue as a function of time as well as temperatures in the space between the wooden surfaces once pressed together. An emissivity of 0.88 was assumed for the value of glue.



(a) IR camera adhesive gun characterisation (b) IR camera view of adhesion process

Figure 3.6: Adhesive gun experimental configuration

3.5.3 Iron Soldering

The heated tip of a soldering iron or gun in operation presents a potential hot surface ignition hazard. Typically, the tools used for soldering of electronic components do not have sufficient thermal inertia to remain hot for substantial lengths of time after the process is complete. In these types of operations, then, the only other anticipated hazard is from solder that is melted from the wire during soldering and drops onto an adjacent surface in an area that contains combustible material. No explicit examples of hot work accidents caused by hot solder, or soldering irons, were found in the statistical sources reviewed in the course of this work [4, 5].

In this study, a 230 W Mastercraft soldering gun was used to solder the ends of two 18 AWG wires together using 60/40 tin/lead solder of 1/16" diameter. The thermal imaging camera was used to measure the maximum tip temperature which could be expected during prolonged use by tracking temperatures at the joint during soldering of the wires. For this an area measurement spot with emissivity of 0.80 was located at the location of the solder joint. Attempts to include a K-type thermocouple in the joint to obtain an independent measure of temperature were not successful as the solder would not properly wet the thermocouple resulting in improper joints; instead, the maximum temperature immediately after soldering was measured by pressing the thermocouple bead into the soldered joint.

Further, to differentiate the hazard represented by a properly executed soldering process from that of one characterised by molten, dripping solder, the temperature of one characterised by molten beads of solder were measured as they fell from the work area and struck the floor from a height of 1 m. The heated soldering iron was clamped in a position with the tip hanging over the edge of the workbench, approximately 1 m above the floor. Solder placed on the tip of the hot soldering iron, was allowed to bead, and then fall to the floor. An area analysis spot on the IR camera images, with emissivity of 0.80, was used to record the temperature of the solder beads upon impact with the ground.

3.5.4 Torch Soldering

Soldering with a torch was not explicitly linked to fires in the statistical sources studied in Chapter 2, but the use of torches and open flame ignition pathways were seen to happen frequently [4, 5]. Aside from the apparent open flame hazard related to the torch, potential hazards due to torch soldering operations include those due to hot surfaces; heated workpiece surfaces as well as the potential for molten solder to form and drip from the work area.

Torch soldering is frequently used in plumbing applications where lead free solder is typically required and larger joints are made, both necessitating larger heat input than the iron soldering discussed in the previous section.

For this experiment, torch soldering was employed to join 3/8" copper tube to a copper elbow fitting using lead free plumbing solder. The IR camera was configured with a view of the soldered joint as well as any molten material falling from the work area during soldering. Temperature measurement was by means of an area analysis on the soldered joint using an emissivity of 0.60. A thermocouple placed in through the top of the copper tube was used with the DAQ set to record the maximum internal surface temperature of the pipe. The joint was then made using a propane torch; the elbow was supplied with sufficient heat to melt the solder.

Beading and dripping of the solder was not specifically investigated since the maximum temperatures reached by beads of solder are determined by the melting temperature, size and composition of the specific solder used. In previous literature, the size of drops from molten wire was found to approach a maximum based on the wire diameter, though melting temperature was not examined [41]. Use of a higher melting temperature solder, such as lead-silver solder, would result in higher temperatures in the solder beads; potential hazards can then be characterised by examination of the range of melting temperatures characteristic of the solders in use for particular applications.

3.6 Test Methods for Hot Surface, Potential Hot Particle Generating Processes

As with processes in the previous category, hot surfaces have been identified as the most pertinent ignition hazard with the processes in this next section, so experiments again aim at determining a critical temperature that characterised the hot work process. The processes in the coming section differ from those above because they also exhibit the potential to propel hot material away from the work, so efforts have been made to use IR thermography and, where necessary, thermal paper, to characterise this additional hazard.

3.6.1 Brazing

While brazing has not been explicitly linked to fires in the statistical sources studied, open flames and oxyacetylene torches have been seen to cause accidental ignitions frequently, solidifying this process as a credible ignition hazard [4, 5]. Hot surface and open flame ignition hazards encountered during brazing operations are similar to those for torch soldering, though brazing is typically performed at much higher temperatures, necessitating use of an oxyacetylene flame and non-ferrous filler metal. With properly cleaned surfaces, well adjusted flame and appropriate technique, as well as the non-ferrous filler metal, brazing is not expected to produce sparks or heated particles that leave the work piece, though projectiles of heated bronze may be ejected from the work area if the braze weld pool is overheated, or if the torch head is placed inside the molten weld pool. Out of concerns for safety, neither of these upset cases were deliberately enacted.

To characterise hazards associated with brazing, 3/8" mild steel pipes were brazed together lengthwise using an oxyacetylene torch with flux coated 3/32" rods. Figure 3.7 shows the infrared camera was set to view the process over the operators shoulder such that both the work and the area below the work could be observed. A temperature measurement region was placed over the brazing area and set to record the maximum temperatures observed during the process, using an emissivity of 0.92. The 0 - 500°C scale on the camera was used in order to capture any hot particles or slag separating from the work piece, since these particles were expected to cool quickly to temperatures below 300°C and therefore would not be observed using the 300 - 2000°C calibration. By using the lower temperature range, hot slag particles can be tracked, but maximum brazing temperatures could not be discerned as they were well in excess of 500°C, so the signal is saturated.

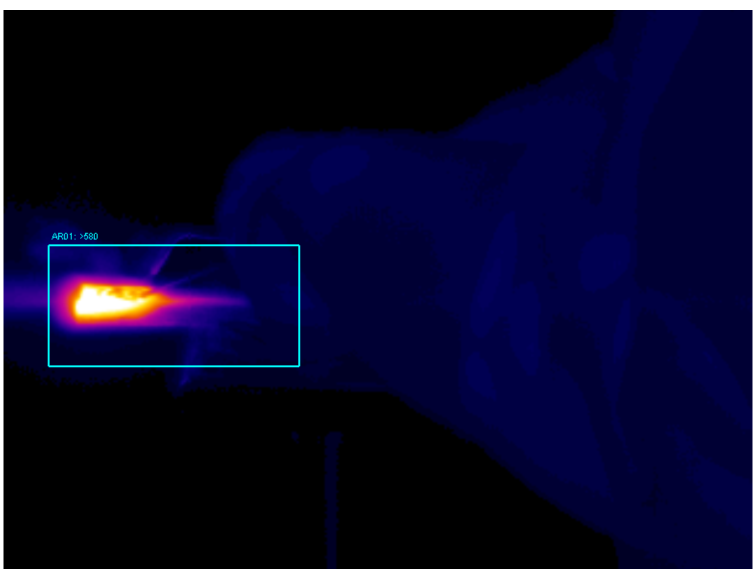


Figure 3.7: IR camera vantage for brazing

3.6.2 Filing

In filing processes, a hard abrasive tool is used to remove material from the work piece. Friction between the file and work piece can result in elevated surface temperatures leading to a potential ignition hazard. Further, the intent of filing is removal of material, so particles generated during the process could also pose a potential hazard, although they have been shown in previous studies to be of insufficient size and temperature to cause ignition [37]. This is further supported by the review of statistical sources which did not report any cases of filing activities leading to hot work accidents [4, 5].

Both manual filing and the use of a carbide rotary file were investigated to determine critical process temperatures and if any discernible remote ignition hazard could be identified for either method. Vigorous manual filing of wood, concrete or steel samples was performed in front of the infrared camera with significant pressure on the work piece to achieve the highest temperature rise possible. Temperatures were measured using IR thermography in an analysis area comprising the filed edge of material with emissivity values of 0.75, 0.85 and 0.95 used for steel, concrete and wood respectively.

The rotary file was used in conjunction with a DW505 hammer drill to file ASTM A516 Gr. 70 steel. The infrared camera, with an emissivity of 0.75 was used to record temperatures as a function of time in an area comprising the filed edge of the workpiece. Figure 3.8 shows the positioning of a K-type thermocouple affixed to the surface of the workpiece at a distance of 5 mm from the filed surface, which was also used to record temperature as a function of time throughout the process. Finally, a piece of thermal paper was laid 50 mm below the work area to determine if any particles landing on the work table had temperatures above 70°C.

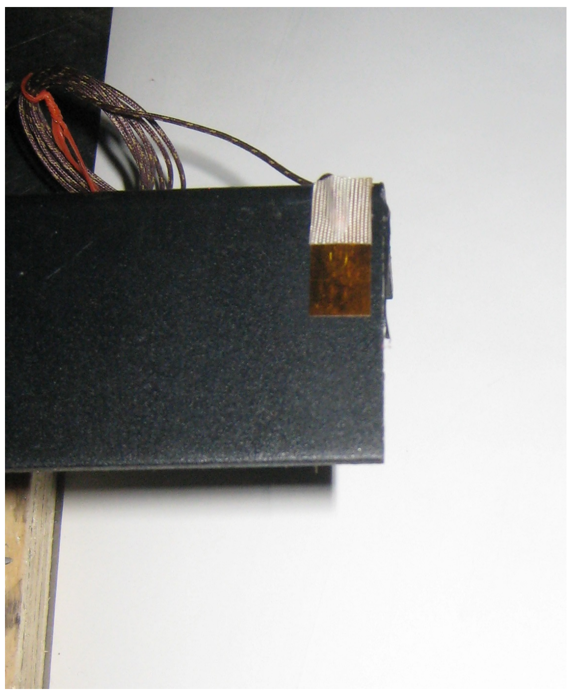


Figure 3.8: Rotary file thermocouple setup

3.6.3 Manual Sanding

Manual sanding is a hot surface process that is similar to filing where the intent is to remove material from the work piece in order smooth the surface of the piece by abrasion. Due to the similarity of the processes, the nature of the particles separated from the work piece in sanding may also be very similar to those seen in filing operations. No fires have been directly linked to manual, or even powered sanding [4, 5], but the process is well understood to cause an increase in surface temperature of the work piece and the sanding medium which have not previously been characterised.

80 grit sandpaper was affixed to the surface of a work table, and concrete, steel or wood samples were rubbed vigorously on the sandpaper, exerting pressure to obtain the highest temperature possible. The temperature rise on the sandpaper was measured in a region with a corresponding emissivity of 0.75, 0.85 and 0.95 for steel, concrete and wood respectively. The infrared camera was positioned to view the work as well as see any hot particles leaving the work area.

Power sanding obviously exhibits much greater potential to cause elevated temperatures and sparking, but, after discussion with the nuclear industry representatives, was not investigated due to time constraints.

3.6.4 Reciprocating Saw

Saws have been listed as ignition sources in the literature studied, though the statistical sources do not specify the type of saw involved in each instance [4, 5]. Reciprocating saws have been chosen for testing because of their flexibility and ensuing frequency of use in the nuclear industry. Anecdotal reports from emergency services have noted high temperatures and occasional sparking with the use of reciprocating saws in extrication practices [48], so the study of their potential fire hazard was deemed to be of value in this research.

The DeWalt DW304PK reciprocating saw was chosen as a representative example of reciprocating saws used in the nuclear industry. With a medium bi-metallic metal cutting blade, the saw was used to cut 10 mm rebar. The model of saw utilised offers only trigger control of the speed, such that precision control was impossible, therefore the saw was operated at maximum capacity while cutting the rebar. This was approximately 2,800 strokes per minute with a stroke length of 1-1/8". At such a relative cutting velocity, sparking can be expected in steel [36].

A regional temperature analysis of the infrared camera images was conducted to determine the time dependent temperatures of the workpiece and the blade during the process. An emissivity of 0.88 was utilised for the analysis. Figure 3.9 shows the vantage of the IR camera and positioning of the analysis area in the image. Due to the imprecise positioning of the tool with respect to the workpiece, thermocouples were not used for temperature measurements of this process.

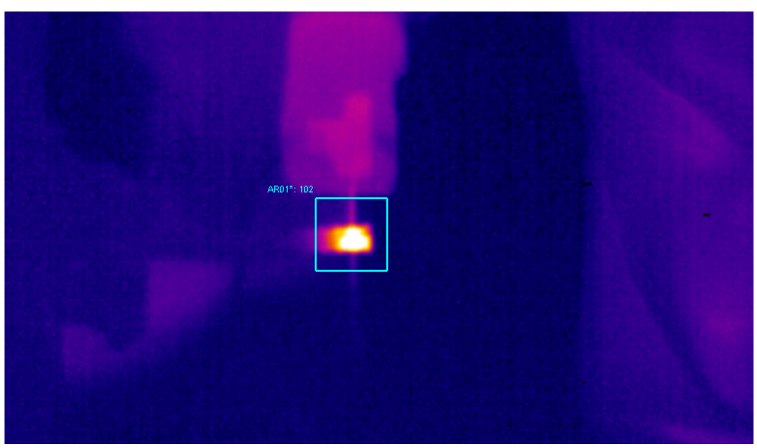


Figure 3.9: IR Camera Vantage for Reciprocating Saw

3.6.5 Drilling

Ignition hazards associated with drilling include hot surface hazards and under specific conditions, generation of heated particles. During typical drilling into common metallic materials, the relative velocity of the cutting edge and the workpiece are far below the 1 m/s threshold required to impart sufficient energy to separate fine metal particles from the work piece and to seed exothermic oxidation reactions that would cause those particles to become incandescent. Review of literature has identified one hot work accident attributed to drilling [4].

Potential hazards encountered with drilling into plywood, steel, aluminium and laminate phenolic were investigated. A DeWalt DW505 Hammer Drill was used with hammer mode switched off to horizontally drill 3/8" holes into vertically mounted samples as shown in Figure 3.10. The horizontal drill orientation was chosen to promote hot particle separation from the workpiece and enable the characterization of hot particle temperatures as they fell approximately 50 mm to thermal paper laid out on the work table. The 3/8" hole size was chosen to represent the largest diameter an operator is likely to drill with a hand held drill in steel, particularly without a pilot hole. Materials tested included 25 mm thick plywood, 10 mm thick A516 Gr. 70 Steel and 6061 Aluminium and 25 mm thick laminate phenolic. Infrared temperature analyses were assigned different emissivities for each material as described in Table 3.3. Across each test run, the hole was drilled in a corner of the sample material, 10 mm from each edge using a new DeWalt tungsten carbide drill bit. New drill bits were used for each test to control variability introduced by drill wear.

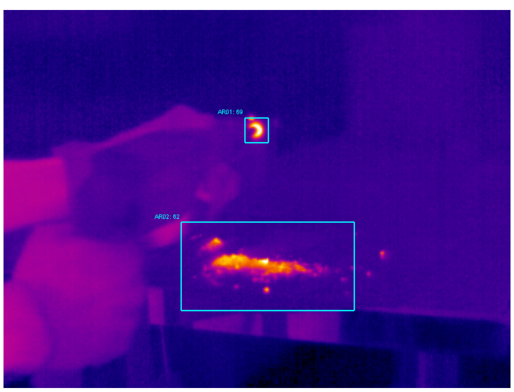
Figure 3.10: General Drilling Setup

Figure 3.11a shows the region used in the IR camera temperature analyses for measurement of typical temperatures of the drilling process as well as the landing area of the hot particles. In all tests except for plywood, a K-type thermocouple was affixed to the edge of the workpiece 10 mm from the centre of the drilled hole, as shown in Figure 3.11b. The thermal paper on the work bench is again expected to register any particles which have temperatures exceeding 70°C.

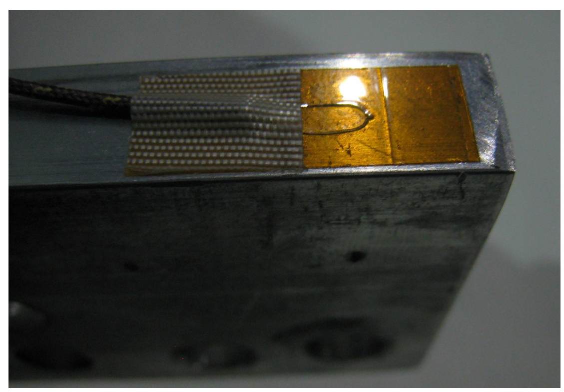
Table 3.3: Material Emissivity Selection for Drilling Tests

Material	**Emissivity**
Plywood	0.94
6061 Aluminium	0.45
A516 Gr. 70 Steel	0.85
Laminate Phenolic	0.90

Difficulties and high temperatures associated with drilling into steel indicated a necessity for further testing; for this, two approaches were taken. In the first, intended to be the 'nominal' approach, a large amount of axial pressure was placed on the drill and a low drill bit speed was used. In the second, emulating a worst case situation with more friction and heat generation, the highest possible bit speed and a lighter axial force was applied.



(a) IR camera vantage for drilling experiment



(b) K-Type thermocouple placement for drilling tests

Figure 3.11: Drilling Test Configuration

3.7 Test Methods for Hot Particle Generating Processes

The final category of hot work processes, the hot particle generating processes as identified in Table 3.1, are discussed in this section. Processes here include welding as well as thermal and abrasive cutting, and generally involve high temperature arcs and open flames so are well understood to be credible ignition sources. Instead of determination of critical temperatures for the processes, then, the assessment focuses on the use of the thermal paper for characterising the hot particles generated by each process. In considering the processes, it is well known that the work piece orientation and material composition will have a large impact on the results; thus, even within the nuclear context, there are far too many possible process combinations to test for even a single hot work operation. It is therefore necessary to carefully choose test configurations that represent key facets of each process whilst still allowing comparison across processes. Both nominal and wort-case test scenarios are described in subsequent sections and the experimental methods used to investigate each hot work process are outlined.

Within the industry, each process may be performed on a wide variety of materials and the material used will affect hot particle generation and distribution. For the experiments here, a single material, ASTM A516 Grade 70 steel, was selected as the primary test material due to its availability and extensive use in boiler and pressure vessel applications in the nuclear industry. To ensure consistency amongst the work pieces used, sheets of A516 steel were machined into coupons measuring 10 mm by 100 mm by 200 mm with a beveled edge forming a 75°inclusive angle. The thickness of the material was selected such that multiple passes of each process were required. For some processes, other materials and coupon thicknesses were also tested. All test processes and, where appropriate, special cases are detailed in the sections below.

3.7.1 Welding

The welding processes chosen for testing include GMAW, GTAW and SMAW. GTAW welds were performed using a Miller Dynasty 350, GMAW welds were performed using a Lincoln Powerwave 300, and SMAW welds were performed using a Miller Pipeworx 400. In all cases, horizontal groove welds in the 2G position (illustrated in Figure 3.12) were used to join 10 mm thick ASTM A516 Grade 70 steel plates. Use of a single material promotes consistency of results and is not expected to affect the results for welding processes where sparks and spatter are typically generated by filler material which, in the nuclear industry, is a controlled engineering selection and is limited to specific choices within weld specifications. Throughout all tests, the height of the weld groove was set to a distance of 1.2 m above the floor. The groove was aligned parallel with the floor or the y-direction as seen in Figure 3.2, and aligned with the main lay of thermal paper on the floor. The welded side of the plate faces the negative x-direction of the coordinate system shown in Figure 3.2.

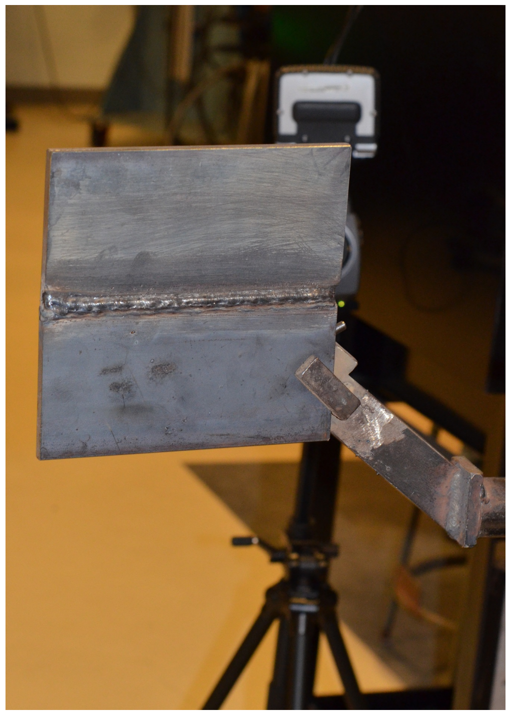


Figure 3.12: Horizontal Groove Weld, 2G Position

For each welding process, experimental weld procedures were developed from nuclear industry weld process specifications. Each joining operation including root, fill and cap passes in addition to interpass cleaning was performed as a single test run on the same set of paper. Together, these provide an aggregate characterization of the hot particle distributions that would occur for a typical welding job while also decreasing the number of test runs and data processing required to study a wide range of welding processes. Further, the welding procedures in these experiments emulate the welding tasks required of nuclear welders to obtain certification and so represent genuine welding procedures as used in the nuclear industry. The drawback to the approach, however, is that the aggregate results of the testing make it difficult to attribute heated particle generation to each specific aspect of the whole welding hot work process.

A total of six aggregate welding tests were performed, each with a number of parameters altered to investigate nominal versus worst case hot work operations. Table 3.4 summarises the six welding tests with a case identifier and brief process description to clarify the distinction between test cases elaborated on in the following paragraphs. Full specifications for the welding test procedures used are provided in Appendix B.

Table 3.4: Test Cases for Welding

Process	**Case**	**Description**
GTAW\SMAW	Nominal 1	2.4 mm E4918, Cleaning with manual brush
GTAW\SMAW	Nominal 2	2.4 mm E4918, Cleaning with 4" grinder wire brush
SMAW	Worst 1	3.2 mm E6011, Cleaning with 4" grinder
SMAW	Worst 2	4.0 mm E6011, Cleaning with 9" grinder
GMAW	Nominal	Cleaning with manual brush, 85% Argon, 15% CO_2
GMAW	Worst	Cleaning with 4" grinder, 100% CO_2

Due to the characteristically low metal deposition rate for GTAW, this procedure is typically not used exclusively for a welding task. Rather, root passes are typically made with GTAW to take advantage of its limited spark and slag production such that the inside of the welded joint will be clean and free of inclusions. A faster, more suitable process is then performed to finish the joint. As such, the first two tests combine a GTAW root pass and nominal SMAW procedure but differ in the method used to clean between passes. For the nominal SMAW tests, low hydrogen E4918 electrodes were chosen due to their characteristically low spatter formation. Cleaning between passes is performed using a manual brush in the first instance and a 4" wire brush powered by a grinder in the second.

For the two worst-case SMAW tests, the GTAW root welding procedure was not used with the intent to investigate the unimpeded travel of spatter and hot particles from welding in a non-optimal configuration. The worst case SMAW welds utilised deeper penetrating E6011 electrodes at the suggestion found in literature that such rods tend to cause more spatter [6, 37]. Furthermore, to generate a worst case, larger diameter rods were used with higher welding amperage, conditions which are again expected to generate significantly more spatter from the process than would occur with optimum process settings. Finally, more aggressive methods of cleaning were also used in the worst case SMAW tests, notably 4" and 9" grinding wheels.

In testing the GMAW process, all welds were made using 0.9 mm ER49S-6 filler material and a constant wire feed. Nominal welds used an 85% CO_2 15% Ar shielding gas mixture, and interpass cleaning was done using a manual wire brush. For the worst case test, the shielding gas was changed to pure CO_2 to promote spatter generation and interpass cleaning was done using a 4" grinding wheel.

Gas welding is typically used in the nuclear industry for training purposes only; as such and due to time constraints, it was not included here.

3.7.2 Thermal Cutting

Hot particle generation and distribution is investigated in the following sections for plasma cutting, air carbon arc gouging and cutting with an oxyacetylene torch. In total 13 thermal cutting tests were performed comprising one oxyacetylene test, four air carbon arc gouging tests and eight plasma cutting tests.

For consistency across processes, each cut was 200 mm in length, with the plane of cutting positioned at a height of 1.2 m above the floor and the principal direction of cutting aligned with the y-direction in Figure 3.2. Cuts were performed with the plate held vertically (perpendicular to the floor), and the cut made parallel to the floor (horizontally across the plate). This orientation was chosen to direct any slag removed from the kerf onto the thermal paper, while maximizing the available space as shown in Figure 3.2. Select air carbon arc gouges were performed with the plate held horizontally and the cut made longitudinally such that hot particles were driven downwards toward the floor.

3.7.3 Plasma Cutting

Eight tests were performed to investigate hot particle generation and distributions from nominal and worst case plasma cutting operations using four combinations of material and coupon thickness. Plasma cutting is a versatile process, so different materials were used to investigate the wide array of metals that might be cut using a plasma cutting torch. Table 3.5 below summarizes the type and thickness of the materials cut for each case. All cuts are performed using a Hypertherm Powermax 85 cutting apparatus, with amperage set to 85 A and 90 psi air pressure and an appropriate cutting speed determined by the operator for each case. Increasing the air pressure was not feasible, and is not expected to affect the characteristics of slag and spatter propulsion[2]. Instead, the worst case configurations were

[2]Operator Brian Chmay indicated that the plasma expansion of the gas in the torch head is by far the largest contributor to the cutting pressure, and so, beyond providing the torch with sufficient pressure to cut, additional propulsive force is not provided by increasing pressure to the unit. The unit in fact, accepts a maximum of 100 psi air pressure, and product literature warns that increasing pressure excessively will

performed by cutting through the material at a 45°upward angle, with the intent that the kerf would direct slag up into the air, causing it to travel farther than for the nominal cases.

Table 3.5: Plasma Cutting Test Cases

Worst & Nominal Case	Material
1	10 mm A516 Gr 70
2	13 mm A516 Gr 70
3	13 mm 6061 Aluminium
4	6 mm 304L Stainless

3.7.4 Air Carbon Arc Gouging

Four carbon arc gouging tests were conducted using different plate materials, thicknesses, orientations and cutting amperages to determine hot particle generation and distribution from the gouging process. The set of test cases run is summarised in Table 3.6. The table shows that the air carbon arc process was used for vertical cuts and horizontal gouges of the material. Each test run was performed with a Lincoln Powerwave 300, using copper clad 5 mm electrodes and 90 psi air pressure.

For vertical cuts, the plate was mounted vertically as for the plasma cutting tests and the cut was performed such that the slag travelled in the positive y direction. For horizontal gouges, the plate was held horizontally and the cut made longitudinally driving hot particles downwards toward the floor, as if removing a weld via carbon arc gouging. Two passes were taken such that approximately 50% of the material was cut through as shown in Figure 3.13.

Table 3.6: Air Carbon Arc Gouging Test Cases

Test Case	Material	Orientation	Amperage [A]
Nominal 1	10 mm A516 Gr. 70	Vertical Cut	200
Worst 1	10 mm A516 Gr. 70	Vertical Cut	295
Worst 2	10 mm A516 Gr. 70	Horizontal Gouge	295
Worst 3	25 mm Carbon Steel	Horizontal Gouge	295

extinguish the arc.

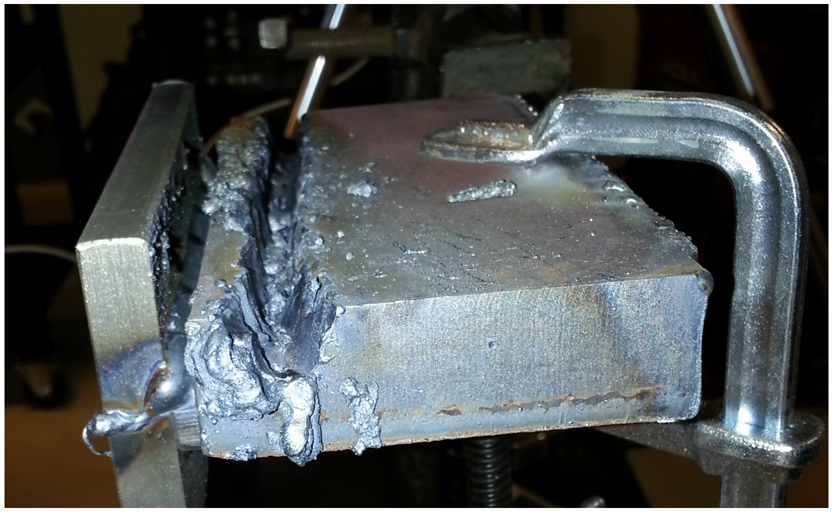


Figure 3.13: 25 mm Plate Following Horizontal Gouge

3.7.5 Oxyacetylene Cutting

To examine hot particle generation and distribution during oxyacetylene cutting operations, the same test conditions were employed as for the plasma cutting tests, with the plate mounted perpendicular to the floor, and oriented such that slag travelled from the kerf in the positive y-direction in Figure 3.2. A 1.6 mm gas cutting nozzle was used to perform a 200 mm long cut into 10 mm thick plate of ASTM A516 Gr. 70 steel. Operating at approximately 30 psi oxygen and 5 psi acetylene, the torch was used to preheat the steel along the length of the cut until that steel reached an oxidizable temperature, then the oxygen lever was pressed to oxidize, melt and propel the steel from the kerf. Due to time constraints, only a single test of oxyacetylene cutting was performed.

3.7.6 Cut-Off Saw

To study the distribution of hot particles generated by the use of a cut off saw, a 14" Dewalt D28715 Cut-Off saw was used in multiple configurations to cut through 50 mm lengths of 10 mm thick A516 Gr. 70 steel coupons. The saw was attached to a work table which was approximately 1.1 m high. In each test, the coupon was cut twice with the process oriented such that the majority of hot particles landed on a strip of thermal paper aligned with the y-axis of the coordinate system shown in Figure 3.2. The diagonal and "x-direction" lays of thermal paper were not used for the cut off wheel tests. Nominal and worst case situations were obtained by altering the position of the spark shield attached to the saw as shown in

Figures 3.14 (a) through (c). In Figure 3.14a, the guard was positioned as intended by the manufacturer to capture sparks leaving the cutting surface, and direct them onto the floor. As configured in Figure 3.14b, the guard was positioned such that the majority of the hot particles travelled over the guard, causing it to be bypassed almost entirely by any sparks. In Figure 3.14c, the guard was removed entirely.

(a) Guard in Position (b) Guard Out of Position (c) Guard Removed

Figure 3.14: Cut-Off Saw Guard Configurations

3.7.7 Cut-Off Wheel

Hot particle distributions generated through use of a cut-off wheel were examined using a 4.5" Dewalt D8402 angle grinder with a metal cut off wheel. The wheel was used to make several deep cuts in a 5 mm thick A516 Gr. 70 steel coupon over the course of roughly 30 seconds. The operation was oriented such that the direction of spin in the cutting wheel would propel heated particles out over a lay of thermal paper in the positive y-direction as in Figure 3.2. The steel was mounted about 1.2 m from the ground.

Chapter 4

Results

Detailed in this chapter, using the methodology and instrumentation outlined in Chapter 3, are the results and findings for tests conducted on processes identified in Table 1.1. The results are presented and summarised in the same process groups as seen previously in Chapter 3; hot surface processes, potential hot particle hot surface processes and finally, hot particle processes.

4.1 Hot Surface Processes

A critical process temperature was determined for each hot work process in this group. It can then be used to assess fire hazard by comparison with ignition or degradation temperatures of typical combustible materials. Where multiple runs of a single experiment have been performed, the highest temperature is presented below, with temperature data from the other additional runs available in Appendix C.

4.1.1 Heat Gun

The temperatures observed in the Wagner HT1000 heat gun were characterised for the low and high settings using both the infrared camera and K-type thermocouples. Results are shown in Table 4.1 with comparison to the manufacturers specification. It can be seen, for both cases, that the infrared camera measured barrel temperatures equal to those specified by the manufacturer, while the highest thermocouple measurements were slightly lower. Overall the agreement between readings is sufficient for determination of a critical process temperature for the use of the heat gun alone.

Even on the lowest setting, the 400 °C temperature of the air emitted from the nozzle of this heat gun poses a credible ignition threat to the combustibles prevalent in previous hot work accidents (Tables 2.3 and 2.5), especially if the hot air impinges on the combustible for a sustained period at short range. ASTM D1929 is a test which measures piloted and unpiloted ignition temperature of plastics by a hot air furnace [50]. When comparing the measured heat gun temperatures to ASTM D1929 unpiloted ignition results [51], it can be seen that the heat gun could potentially ignite hazard to wood 260-416 °C, cotton 254 °C, polyethylene (PE) 349 °C, polyvinylchloride (PVC) 454 °C, acrylonitrile-butadiene-styrene (ABS) 466 °C and polystyrene 488-496 °C.

Table 4.1: Wagner HT1000 Temperature Characterization

Measurement [°C]	**High Setting**	**Low Setting**
Thermocouple at Centreline, 5 mm from nozzle	530	387
IR Camera	540	400
Manufacturer Specification	540	400

4.1.2 Heat Gun: Application of Heat-Shrink Tubing

Two test runs were performed using the heat gun above to apply heat shrink tubing to a bundle of wires as shown in 3.4a. Figure 4.1 shows the measured values of temperature rise above ambient for the run in which the highest temperatures were measured. In Figure 4.1, the maximum temperature measured by the thermocouple in the bundle is plotted with the time varying temperature of the outside surface of the heat shrink tubing as measured by the IR camera. The maximum temperature rise measured by both the thermocouple and infrared camera was 146°C; the agreement in values indicates that the choice of a relatively high emissivity of 0.95 was suitable. Measured values of temperature were well below those observed during characterization of the heat gun, indicating that the critical process temperature for use of a heat gun, even for application of heat shrink tubing, should be that of the heat gun itself, 400°C.

Using the threshold of 400°C measured for the low setting of the heat gun, the temperature is sufficient to cause pyrolysis of nylon heat shrink, 310-380°C [52]. On the high setting, temperatures are well into the auto ignition range of nylon, 424-532°C [52]. While the heat-shrink itself is not readily flammable, it is evident that operators must apply heat shrink with great care so as not to overheat the workpiece, because ignition of heat-shrink is un-

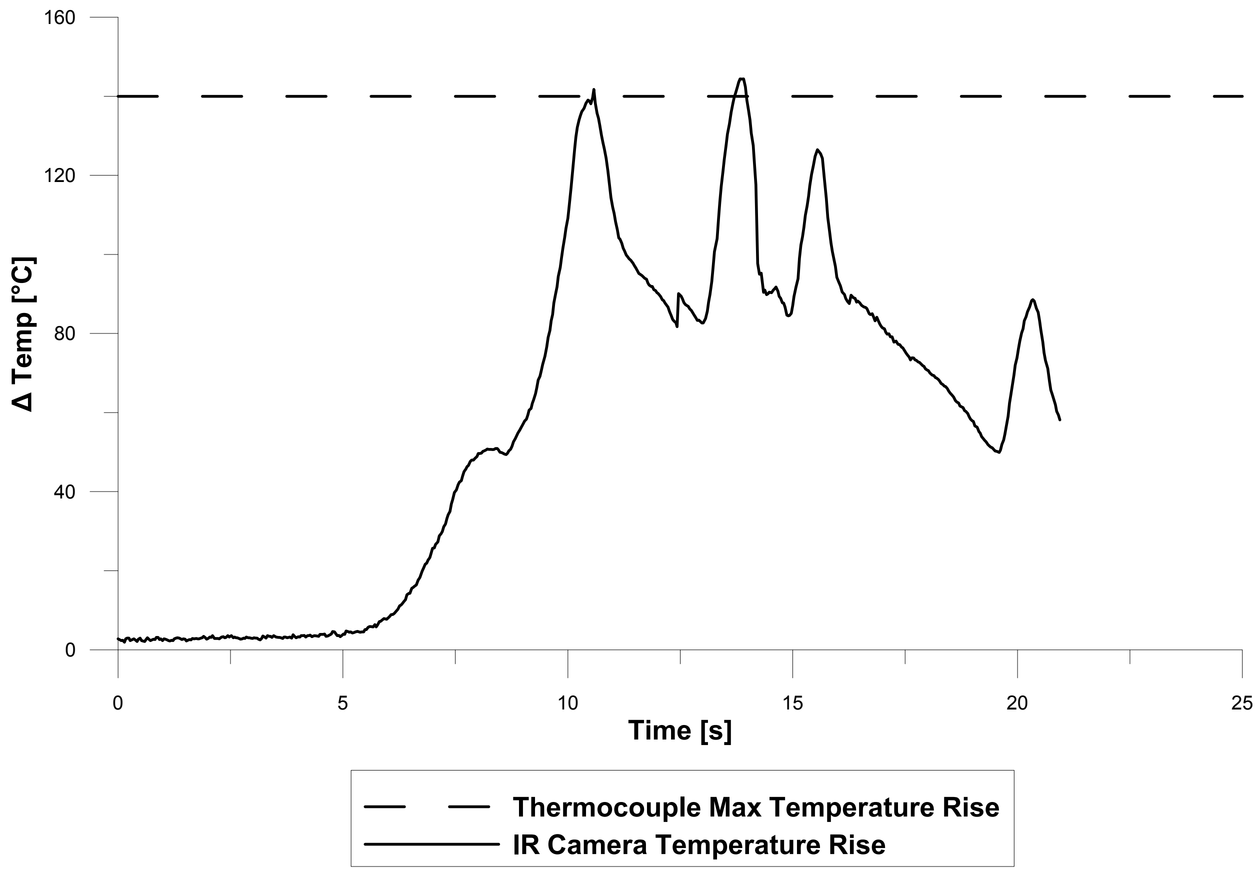


Figure 4.1: Heat-Shrink Application; Temperature rise as measured by the IR camera in comparison with the maximum temperature rise measured by a thermocouple

doubtedly possible. Similarly, any flammable and combustible materials should be removed from the immediate area during heat shrink application processes in order to minimize the possibility of ignition and fire.

4.1.3 Heat Gun: Thermal Paint Stripping

Two test runs of paint stripping with the Wagner HT1000 heat gun were performed. Measured values of temperature rise above ambient as measured by the IR camera are plotted against time in Figure 4.2, with the maximum temperature measured by the thermocouple also plotted for comparison. The highest temperature measured by the thermocouple, located centrally underneath the workpiece, was 138°C while the maximum temperature measured on the surface of the painted sample during the process was slightly lower at 136°C. Since the thermocouple is under the workpiece, it might be expected that it would register a lower temperature than the IR camera, suggesting that the chosen value of emissivity of 0.88 was too high. This also demonstrates the difficulty in estimating accurate values for the changing emissivity of the workpiece surface as the paint is removed. Overall, however, the discrepancy is small and the maximum surface temperature rise of the sample during the process is again low in comparison to the temperatures measured during the characterization tests for the heat gun so critical temperatures of 400°C and 540°C are appropriate for the low and high heat gun settings respectively.

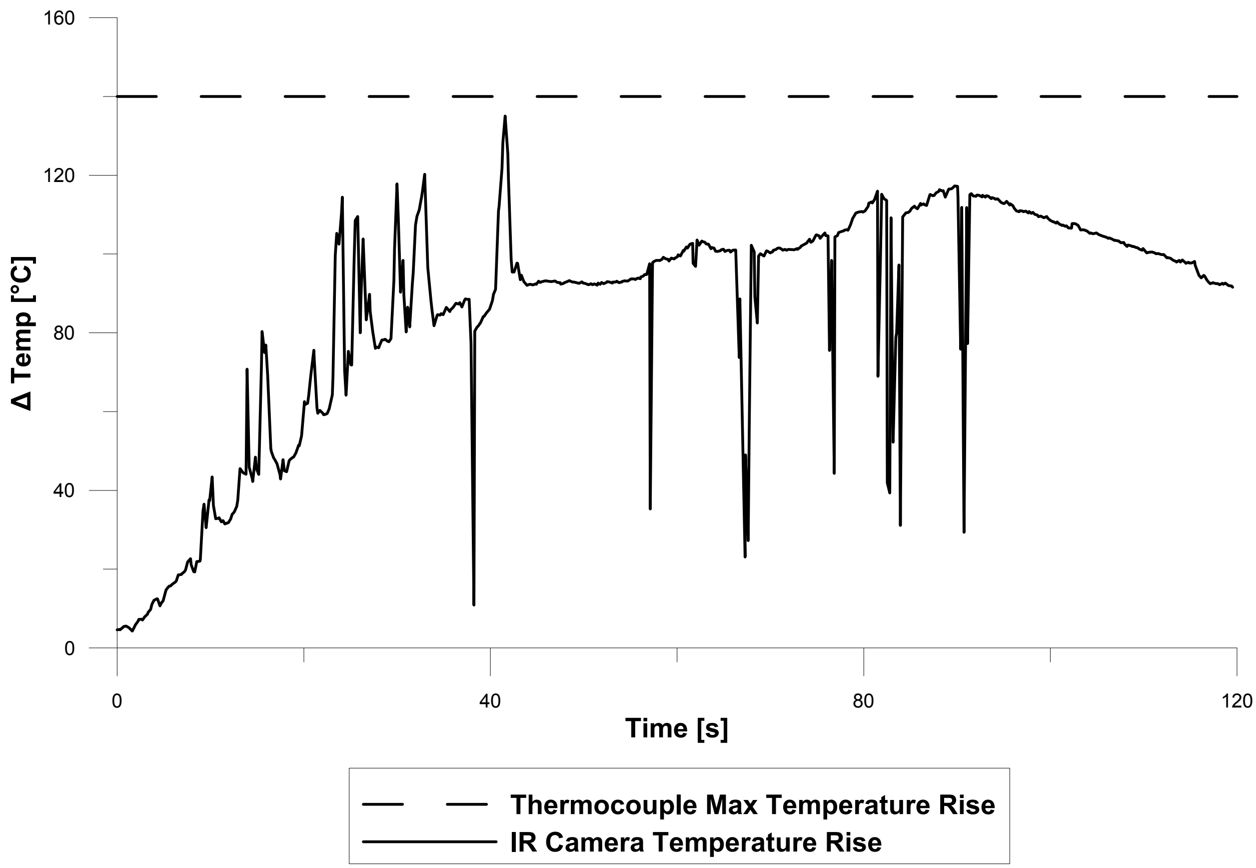


Figure 4.2: Paint Stripping; Temperature rise on the face of the painted sample as measured by the IR camera with comparison to maximum thermocouple temperature underneath the sample

It was hypothesised that the heated paint being stripped from the work piece surface may comprise a remote ignition hazard once separated from the work piece as it could retain heat and be propelled away by the blower in the heat gun. In practice, this was not observed but instead, as shown in the IR image of Figure 4.3, the hot paint removed during the process adheres firmly to the scraping tool and so remains in the immediate area in which the work is being conducted. The paint used in this test softens and becomes quite viscous, requiring the use of a rag to remove the paint from the scraping tool; however this behaviour was not confirmed for other varieties of paint, and as such operators should be cognizant that some paints may separate from the work piece and land some distance away. For the present paint stripping operation, Figure 4.3 confirms that the region of high temperature on the work table is limited to a few widths of the 50 mm steel sample, and certainly extends no further than an arm's length from the operator so that the sphere of ignition potential is limited to the immediate area in which the work is being performed.

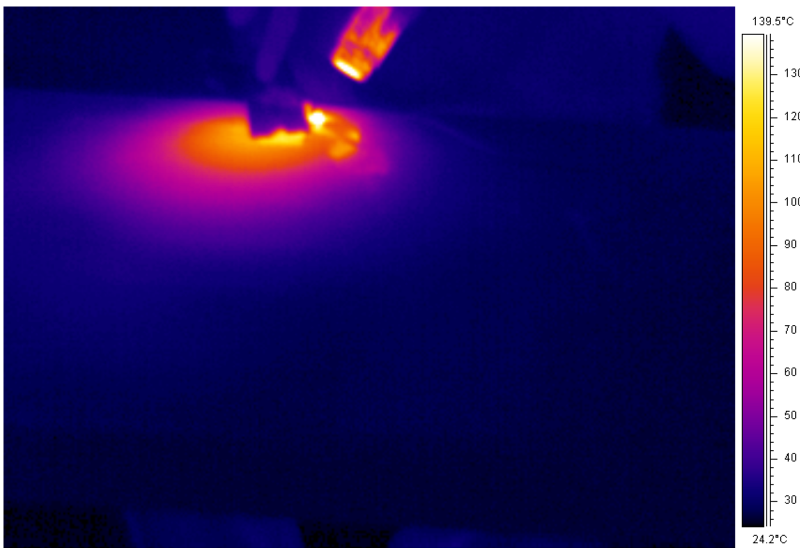


Figure 4.3: Paint Stripping IR Camera Vantage

In summary, the greatest hazard associated with the hot work processes that involve use of a heat gun arises from the temperatures seen on the inside of the gun barrel, the exterior of the gun nozzle, and in the hot air issuing from the nozzle. Characterisation of the tool confirmed that temperatures in the present heat gun can reach values as high as 540°C, the temperature specified by the manufacturer. Other, significantly more powerful models of heat gun are available on the market and would be expected to reach even higher operating temperatures. Although the ignition hazard is local, within an arms length of the operator, it should be noted that the heat gun is not a conspicuous ignition source and an operator may inadvertently aim the gun at combustible material without recognizing the potential ignition hazard. Further, the high temperatures and thermal inertia of the heat gun barrel cause it to cool relatively slowly in comparison to workpieces on which heat guns are commonly used. Even after the heat gun is turned off, if it is put down or dropped in the vicinity of flammable or combustible material while it is still hot, it could readily cause ignition after the work process is complete. As a result, this tool must be properly handled during and after use or it will pose a potential fire hazard. Thus when using a heat gun for any process, the work area in reach of the operator must be cleared of combustibles. The operator should be mindful of the presence and direction of heat emitted, and the heat gun should be cooled for several minutes prior to storage.

4.1.4 Heated Adhesive Gun

Prior to practical testing, the heated adhesive gun was characterised via temperature measurements using both the infrared camera and a thermocouple. Infrared images showed a maximum temperature on the outside of the nozzle of 140°C. Thermocouple readings from inside the nozzle showed glue temperatures of 185°C, higher than the outer nozzle temperatures but slightly lower than the manufacturer specified operating temperature of 205°C.

Figure 4.4 shows temperature rise on the glued surfaces of the wood, measured with the infrared camera and plotted as a function of time after the glue gun is up to temperature[1]. From the Figure, it can be seen that maximum temperatures observed during hot gluing are similar to those measured during the heat shrink process, namely 155°C above ambient, so that the critical process temperature for the use of the heated adhesive is again the temperature of the glue or approximately 185°C.

The infrared footage showed no mechanism by which hot glue can leave the work, other than dripping from the nozzle in areas not intended by the operator. Since the heat is contained within the tool and glued surfaces the sphere of influence of hot gluing is limited to the immediate area of the work. Therefore, the most severe hazard associated with this process is the chance that the heating element of the glue gun may come into contact with a flammable material during or after use. Since operating temperatures of the tool are lower than autoignition temperatures of items listed in Tables 2.3 and 2.5 it is difficult to determine whether this process will lead to ignition; however, many items such as wood and paper will readily pyrolyse at the temperatures measured for the hot glue process, and so this process may lead to ignition with sustained contact [53]. Oil soaked insulation, kerosene, gasoline, diesel and light fuel oil may also ignite at the temperatures measured for this process [53].

[1]Temperatures derived from the infrared images begin after the glue gun is at temperature. The warm up period could not be recorded due to data limitations on camera

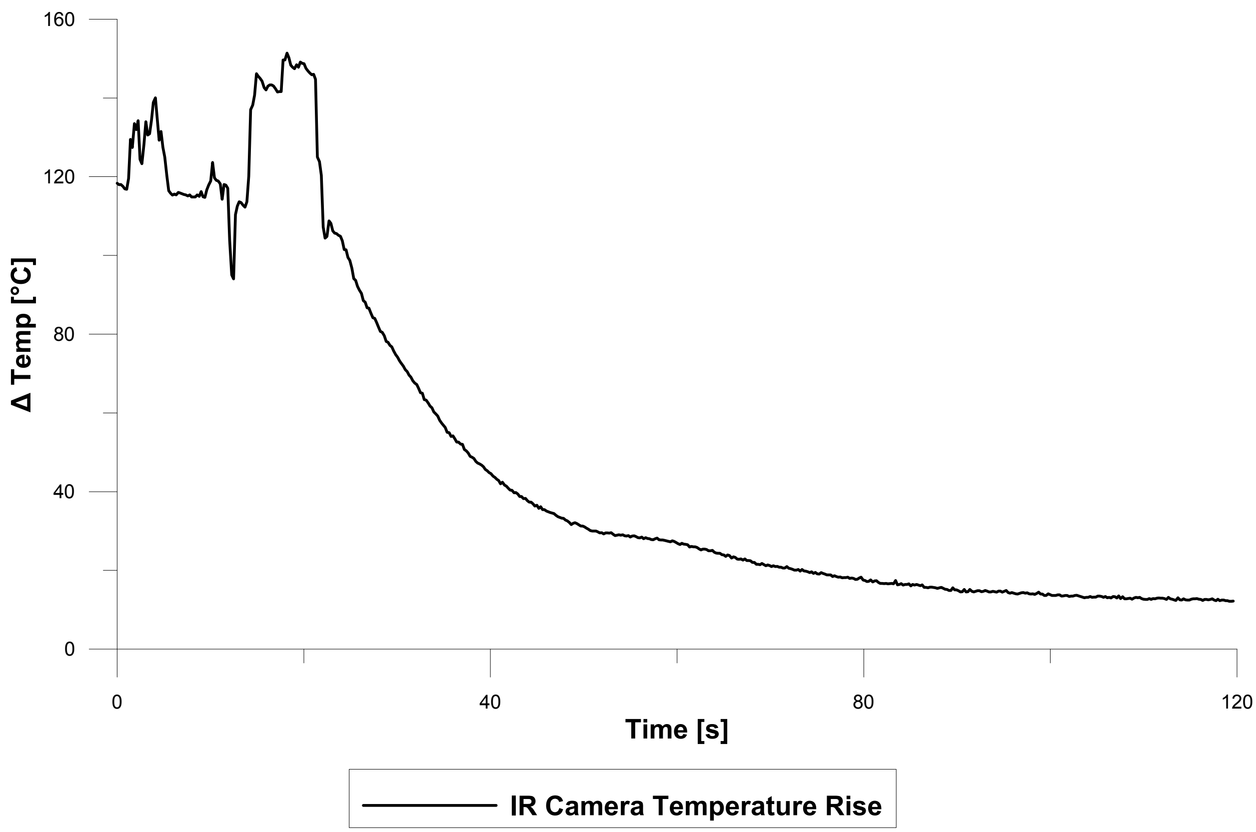


Figure 4.4: Heated Adhesive; Temperature rise as measured by the IR camera

With the exception of oil soaked insulation, though, these materials are not commonly found on nuclear sites.

4.1.5 Iron Soldering

The temperature of the solder iron was measured using the IR camera in order to characterize the ignition potential of the iron itself. Using an emissivity of 0.8, estimated via thermocouple measurements, the temperature determined from the IR thermographs was 530°C which is in good comparison with the specified operating temperature for the iron - 540°C. At this operating temperature, direct contact by the tool presents aa ignition hazard to nearly all combustibles in Tables 2.3 and 2.5, and thus the use of a soldering iron warrants great care on the part of the operator.

Figure 4.5 shows the temperature rise of the soldered joint with respect to time as measured by the IR camera during the soldering operation. Also shown is the maximum temperature rise recorded by a thermocouple placed in contact with the joint promptly after the soldering operation. Figure 4.5 shows a peak temperature rise of 350°C, with the peak thermocouple temperature reaching 305°C. Poor contact between the solder bead and thermocouple, as well as delay in placing the thermocouple at the joint after finishing the solder operation, explain the difference in thermocouple and IR camera temperatures. The soldered joint therefore reaches substantially lower temperatures than the tool since good soldering technique involves the gradual, intermittent addition of heat to the solder and base material near the joint, such that the temperature of the joint reaches only the reflow temperature of the solder, allowing the solder to wet and bond the wires without the solder overheating, melting and dripping from the work.

The high temperatures of the soldering iron and the soldered workpiece present a considerable fire hazard; however, due to the low thermal inertia of the solder and materials being joined, the workpiece cools very quickly. Cooling clearly will take varying lengths of time for each tool and wire-solder combination; however, for the joint tested here, measured workpiece temperatures rapidly drop to 50°C and then decrease more gradually back to ambient temperature. The soldering iron itself, however, cools much more gradually, and this it will remain a potential ignition threat for a longer period of time. For this latter reason, as well as the significantly higher temperatures seen for the soldering iron tip, the critical process temperature for iron soldering is the tool temperature of 530°C.

Under normal conditions, drops of molten solder should not fall from the work piece during iron soldering; however, with the molten solder forming part of the process it was deemed important to assess any ignition hazard from this potential situation as well. The special tests described in Section 3.5.3 have been performed to assess this hazard. Figure 4.6 shows a plot of the temperature rise on the floor as a series of small drops, followed by three large drops of solder, fall from the soldering iron. Although the internal temperatures of the drops are thought to be notably higher than their cooler exteriors, after falling 1 m, measured temperatures of residue from the drops are below 30°C above ambient. After impacting the ground, the solder beads break apart and the resulting metal spatter cools very quickly, presenting a minimal hazard in terms of ignition for this type of solder. It must be noted again, however, that other compositions and sizes of solder may vary drastically in their characteristic temperatures and rates of cooling.

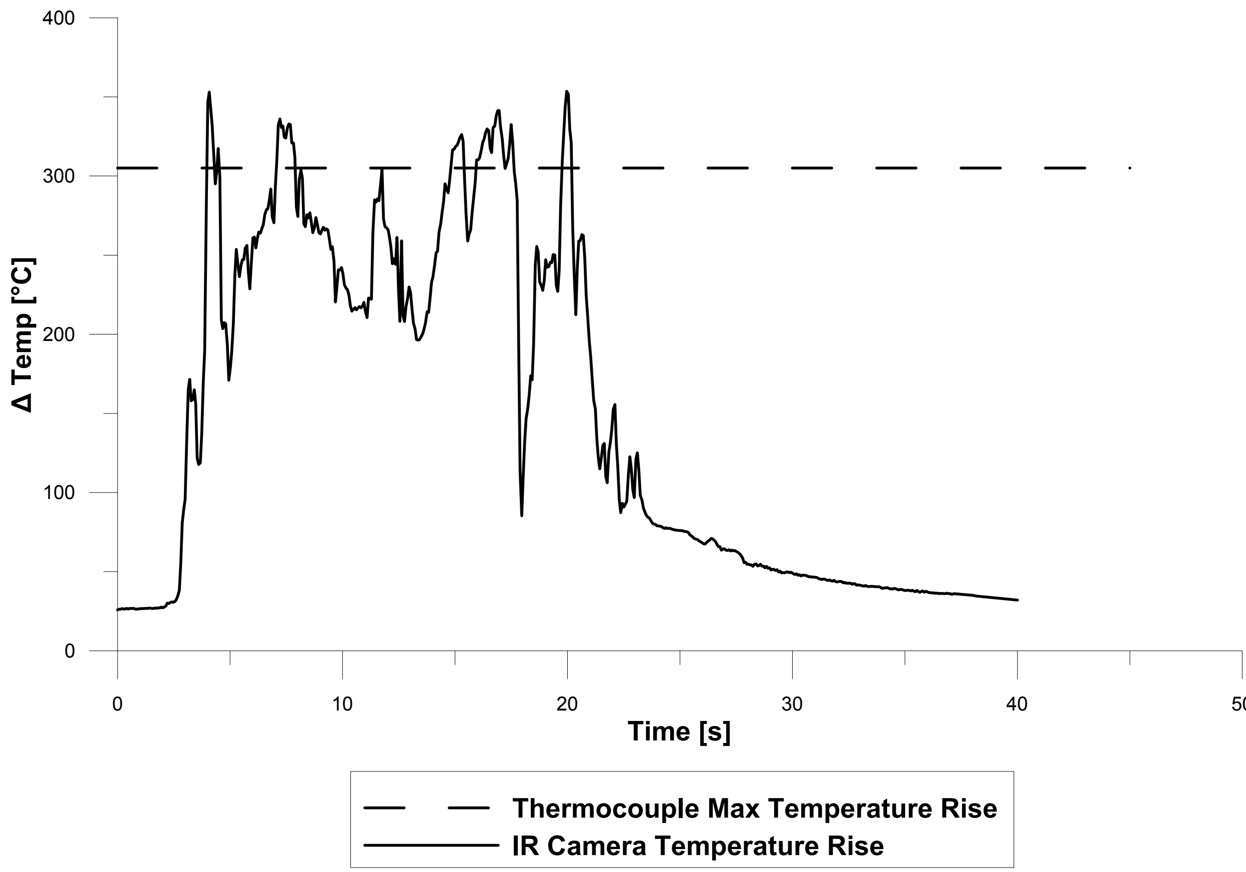


Figure 4.5: Iron Soldering; Temperature rise as measured by the IR camera in comparison with the maximum temperature rise measured by a thermocouple

Based on the above results, the ignition hazard due to iron soldering processes can be considered slightly higher than those for the heat gun and heated adhesive processes because the soldering iron itself is characterised by higher temperatures which presents a hazard to a wider variety of combustibles. Similar to the aforementioned hot work processes, though, these high temperature hazards will remain localised within the immediate area of the process, and though the potential exists for solder to fall from the work, the overall ignition potential from molten solder is, under normal operations, considered very low.

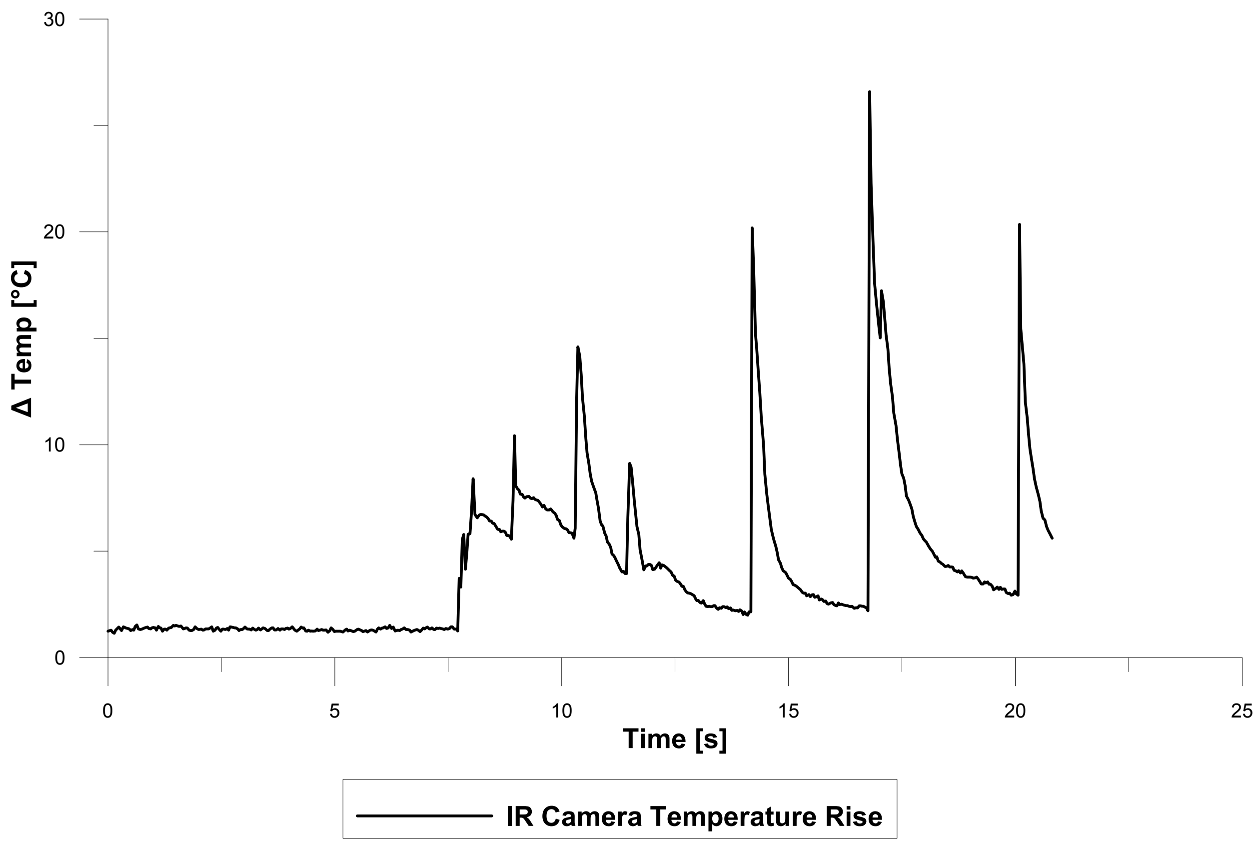


Figure 4.6: Falling Solder; Temperature rise at the floor measured by the IR Camera

4.1.6 Torch Soldering

Filler metals for torch soldering melt in the temperature range of 170°C to 450°C [54]. Because flame temperatures this low are not sustainable, these temperatures are obtained by using the cooler extremities of a much hotter flame to do the soldering. The actual torch flame temperatures are in the vicinity of 1000°C.

Figures 4.7 shows the time varying temperatures recorded on the outside of the elbow by the infrared camera, and by a thermocouple placed inside the elbow during normal torch soldering operations. The peak temperature rise above ambient measured by the infrared camera during a representative run was 265°C. The peak temperature rise measured by the thermocouple was significantly lower at 150°C because the thermocouple was placed on the interior surface of the work piece and so was not directly impacted by the hot torch flames.

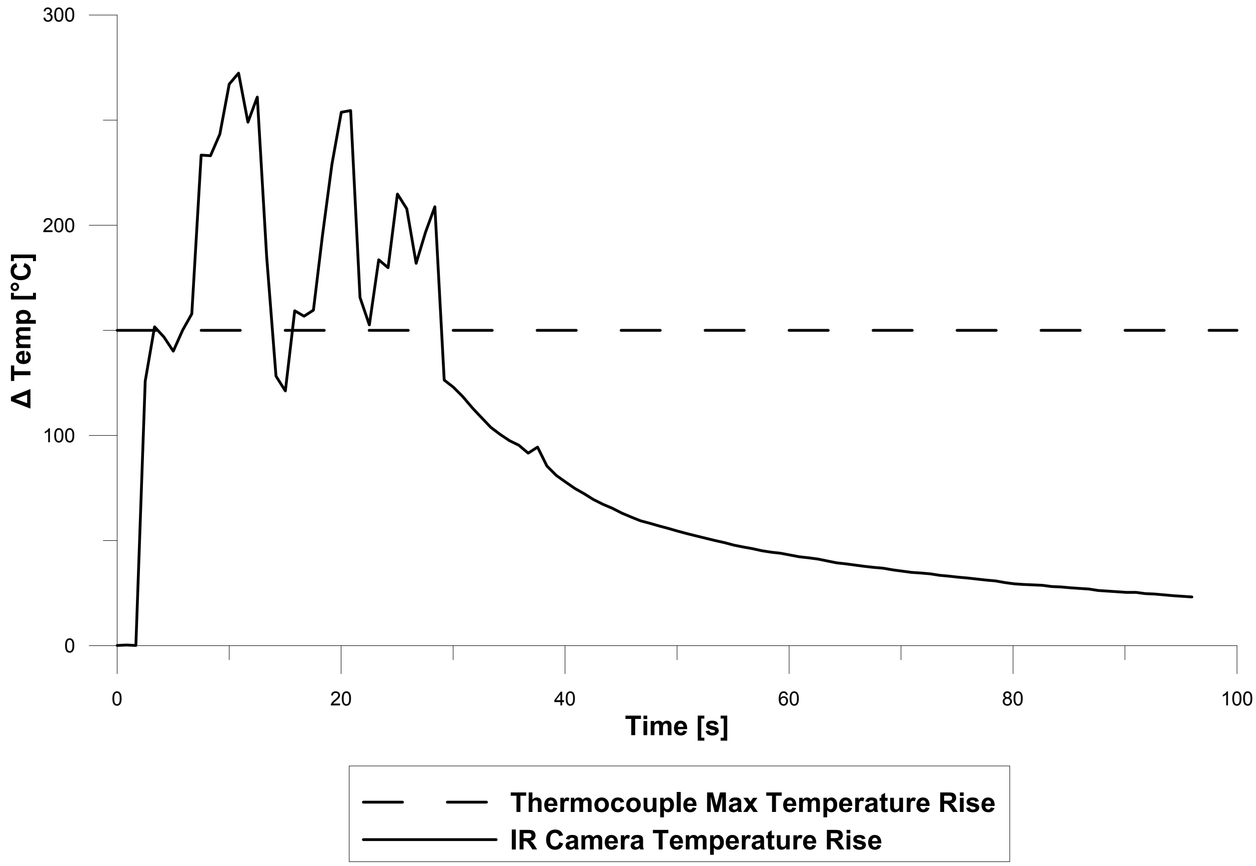


Figure 4.7: Torch Soldering; Temperature rise as measured with the infrared camera in comparison to maximum value of temperature rise measured by thermocouple inside of the fitting

Due to the difference in size and material, and thus thermal inertia of the workpiece, a markedly slower cooling rate is seen in torch soldering of a copper tube versus iron soldering of wires. In the torch soldering operation, therefore, the time taken for the temperature of the work piece to fall to less than 50°C above ambient is approximately 30 seconds after removal of the torch flame.

Temperatures of the workpiece measured here for torch soldering operations are similar to those measured during the iron soldering process, albeit with more variance in the results because torch soldering is a more demanding skill. As with the soldering iron, the potential for solder to fall away from the work should be considered by the operator. However this potential should be mitigated with a knowledgeable operator applying the method correctly. Thus the torch soldering process may also be considered to pose a minimal hazard based on the potential for expulsion of material from the workpiece. The torch and iron soldering processes differ, however, due to the inclusion of the much hotter "tool", the torch flame, used in torch soldering. Therefore, the critical process temperature for the torch soldering hot work operation is 1,000 °C, significantly higher than that for iron soldering, or any of the other processes investigated so far. Temperatures of this magnitude present a credible ignition hazard to all combustibles commonly involved in hot work fires on nuclear sites as seen in Tables 2.3 and 2.5. The high temperature, piloted ignition source present during torch soldering comprises the most severe hazard of the processes studied so far.

4.1.7 Summary

Table 4.2 summarizes results for the suite of hot surface hot work processes tested in this work. Measured workpiece and tool temperatures are listed as are the critical process temperatures determined for each. Processes are listed in order of decreasing fire hazard, as reflected by the critical process temperature which is deemed the most appropriate hazard parameter for all these situations. In all the processes, the tool temperature is the hottest and most credible ignition source.

Though tool temperatures have been adopted in this analysis as the most pertinent fire hazard parameter, workpiece temperatures have also been measured and taken into account. This is because higher tool temperatures may not always translate into higher work piece temperatures so both should be considered in a full assessment of potential fire hazards from any hot work operation.

Table 4.2: Test Result Summary for Hot Surface Processes

Process	**Tool Temperature [°C]**	**Measured Workpiece Temperature [°C]**	**Critical Process Temperature**
Torch Soldering	1000	265	Tool
Heat Gun: Thermal Paint Stripping	540	138	Tool
Iron Soldering	530	350	Tool
Heat Gun: Heat Shrink Tubing	400	146	Tool
Heated Adhesive	185	155	Tool

4.2 Hot Surface, Particle Potential Processes Testing

Processes in this section are considered hot surface ignition hazards, but have the potential to propel hot particles from the work under certain conditions. Tests were conducted to determine critical process temperatures, as well as to capture the extent to which particles are propelled from the work and assess this additional ignition hazard.

4.2.1 Brazing

Ideal temperatures for brazing range from 450 to 815°C [54], depending specifically on the metals being joined and more importantly, on the filler metal used. The high temperatures required for brazing necessitate the use of the oxyacetylene flame, typically run at flame temperatures of 2,400 to 2,800°C [55].

Figure 4.8 shows temperature rise of the workpiece as a function of time during the brazing process, as measured using the infrared camera. Due to the choice of measurement range, the signal from the infrared camera measurement is saturated at maximum temperatures of 580°C. This range was determined as a trade-off between capturing the highest temperature of the work piece and tracking any hot particles that were ejected from the work during the brazing process. Actual process temperatures were much higher than this measured value, as evident by the cooling curve shown. The high thermal inertia of the workpiece can still be seen, however, and results in a cooling time of nearly four minutes from the 580°C level to where data collection ceased at approximately 150°C.

While the choice of calibration range precluded accurate measurement of highest values of work piece temperature during brazing, any hot particles leaving the work could have been readily observed from the footage. Out of concerns for safety, deliberate scenarios certain to cause spatter during the brazing operations, such as overheating of the molten weld pool or dipping the torch tip in the molten weld pool were not tested and consequently, no hot particles were produced during the brazing tests. Spatter from brazing would consist of molten filler metal, and is therefore considered a credible remote ignition hazard.

The temperature of the oxyacetylene flame as configured for this brazing experiment was approximately 2,700°C. This temperature is far higher than the temperatures reached by the workpiece while brazing, and therefore the torch temperature should be considered the critical process temperature. Furthermore, this critical process temperature definitely constitutes a credible hazard to all materials commonly implicated in hot work fires on nuclear sites as seen in Tables 2.3 and 2.5.

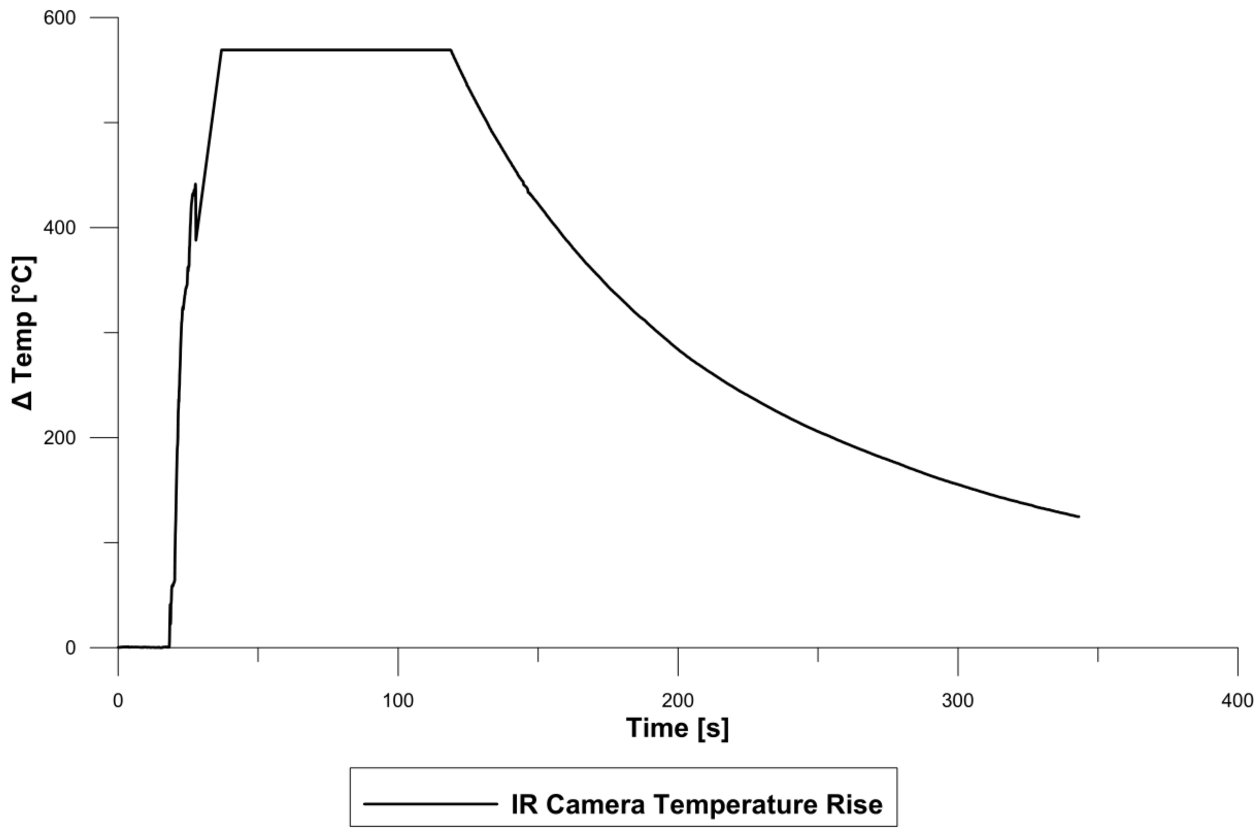


Figure 4.8: Brazing; Temperature rise of the brazed workpiece as measured by the infrared camera

4.2.2 Filing

Figures 4.9 through 4.11 show the temperature rise at the contact site measured with the infrared camera when manually filing concrete, wood and steel. Figure 4.9 shows that the temperature rise during filing of concrete peaked at approximately 55°C while a similar peak value, 52°C, was found during filing of wood, shown in figure 4.10. For filing of steel, a maximum temperature rise of a mere 15°C was observed due to the high thermal conductivity of the work piece and consequent high heat transfer away from the site of the filing contact location.

The results shown in Figures 4.9 through 4.10 suggest that a critical process temperature of 55°C is appropriate for manual filing processes. This temperature is not sufficient to cause concern that the hot work piece could ignite any of the common combustibles involved in hot work fires on nuclear sites as listed in Tables 2.3 and 2.5. In all test cases, the infrared footage showed that any particles separated from the work remained in the vicinity of the

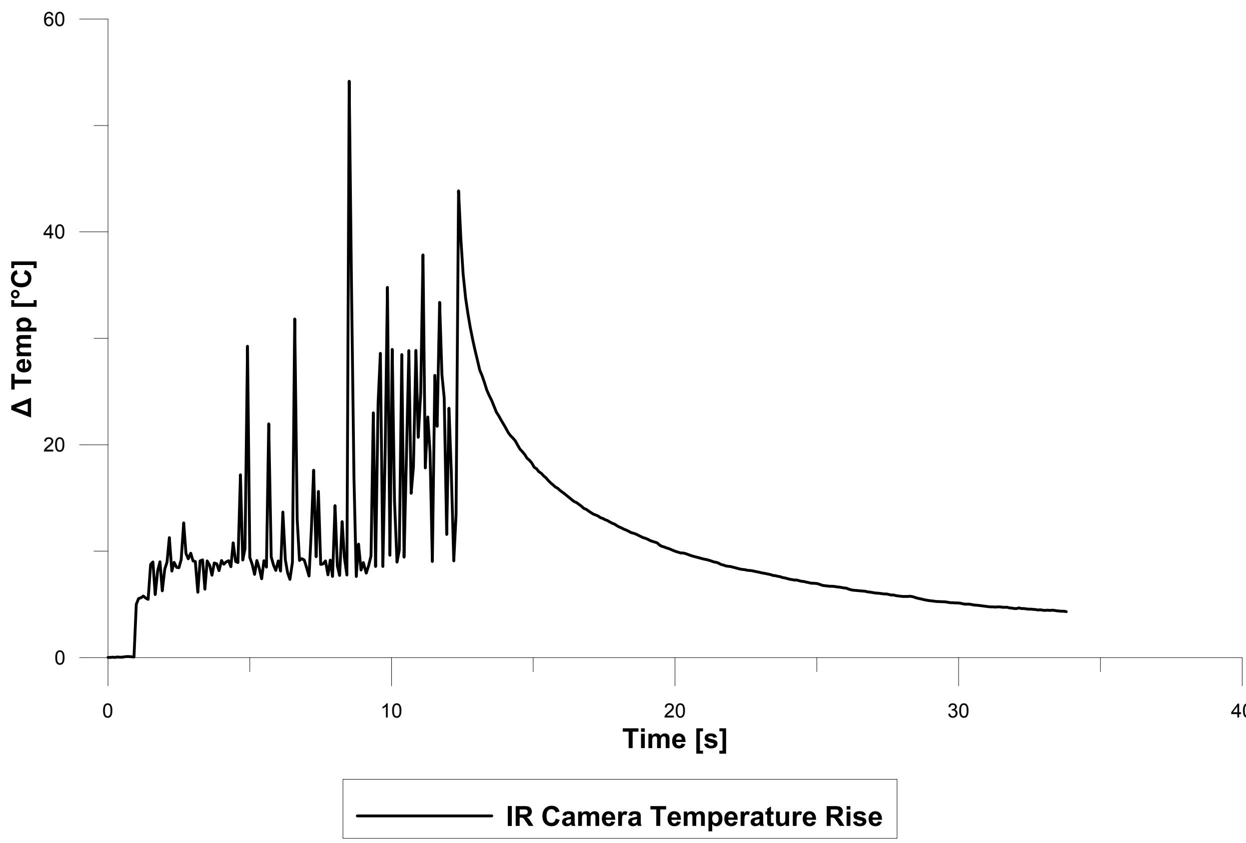


Figure 4.9: Manual Concrete Filing; Temperature rise of the filing site as measured by the infrared camera

workpiece, so the process is not considered to pose remote ignition hazards to materials outside of the immediate area either.

Figure 4.12 shows temperature readings measured as a function of time on a steel workpiece being filed using a rotary file. Plotted temperatures were measured using the infrared camera, as well as a K-type thermocouple positioned on the surface of the piece 5 mm from the filed edge. measured with the k-type thermocouple. As can be seen from the Figure, rotary filing of the steel specimens did not lead to a large temperature rise in either the work piece or the tool. A maximum increase in temperature of only 10°C above ambient was registered by the infrared camera, while an even lower temperature increase, 5°C, was measured by the thermocouple.

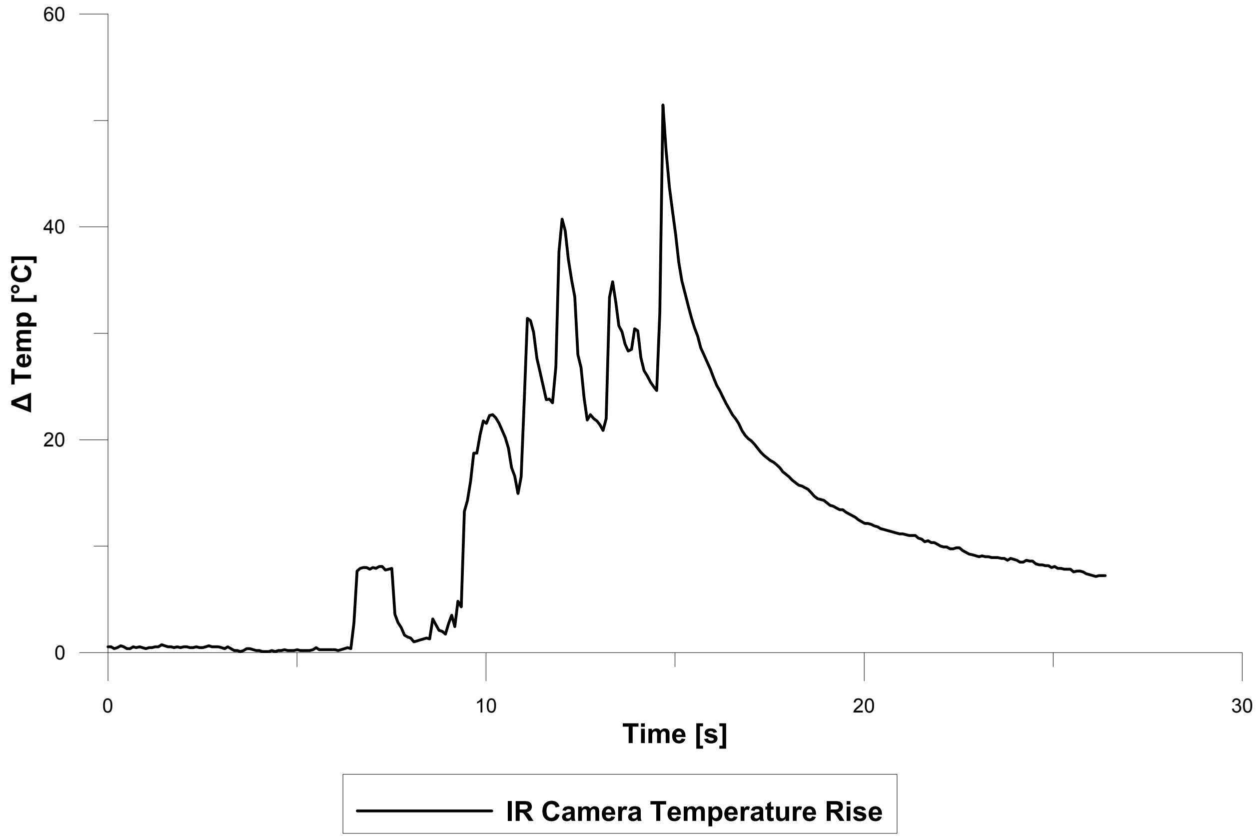


Figure 4.10: Manual Wood Filing; Temperature rise of the filing site as measured by the infrared camera

While small metallic particles were left behind on the thermal paper after completion of the filing process, none of them was sufficiently hot to mark the thermal paper. As such, the critical process temperature for rotary filling has been determined to be 10°C, and there is no evidence of a propensity for this hot work process to pose a remote ignition hazard.

The use of a faster spinning, and larger diameter tool, such as a dremel, is well known to cause spark production when cutting ferrous and other oxidizable metals. On this basis, any filing operation that produces sparks should be considered to be as hazardous as a grinder operated cut off wheel, covered in a later section.

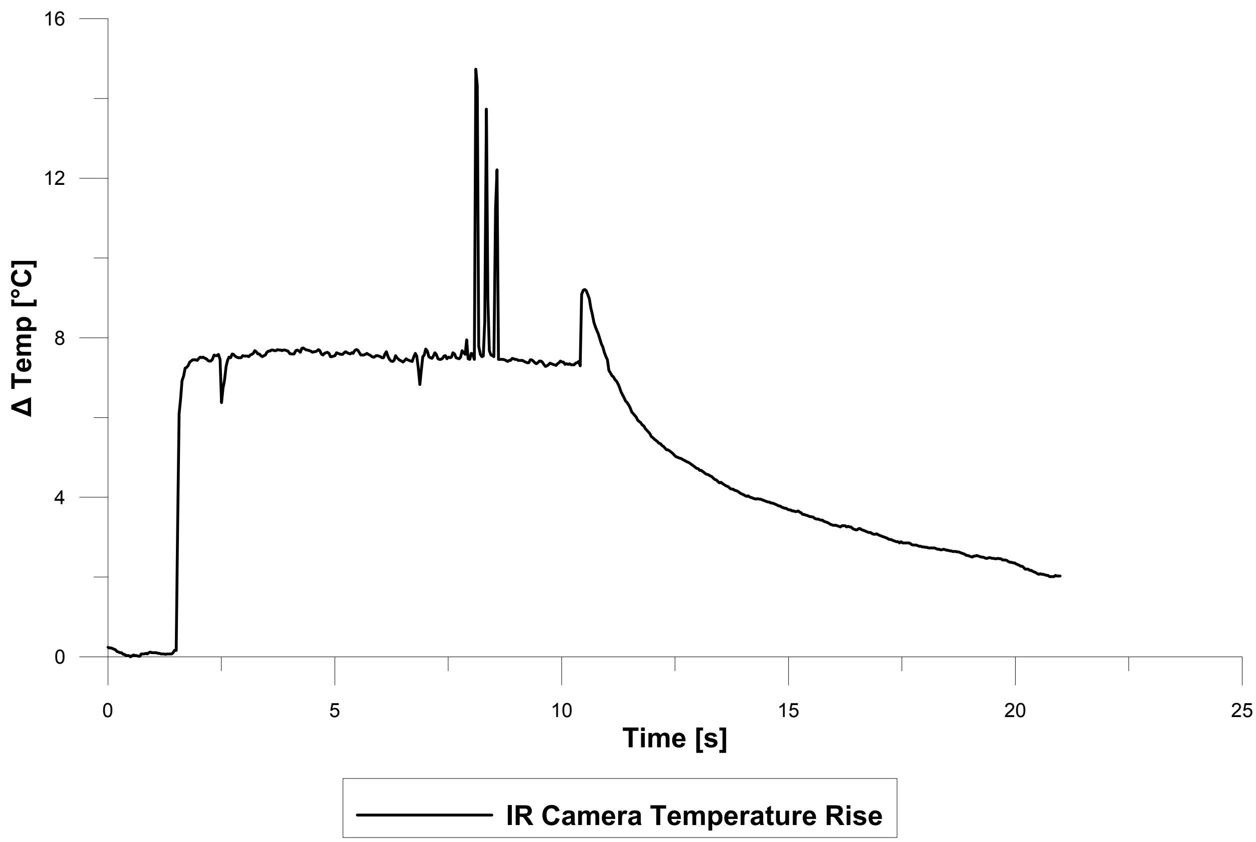


Figure 4.11: Manual Steel Filing; Temperature rise of the filing site as measured by the infrared camera

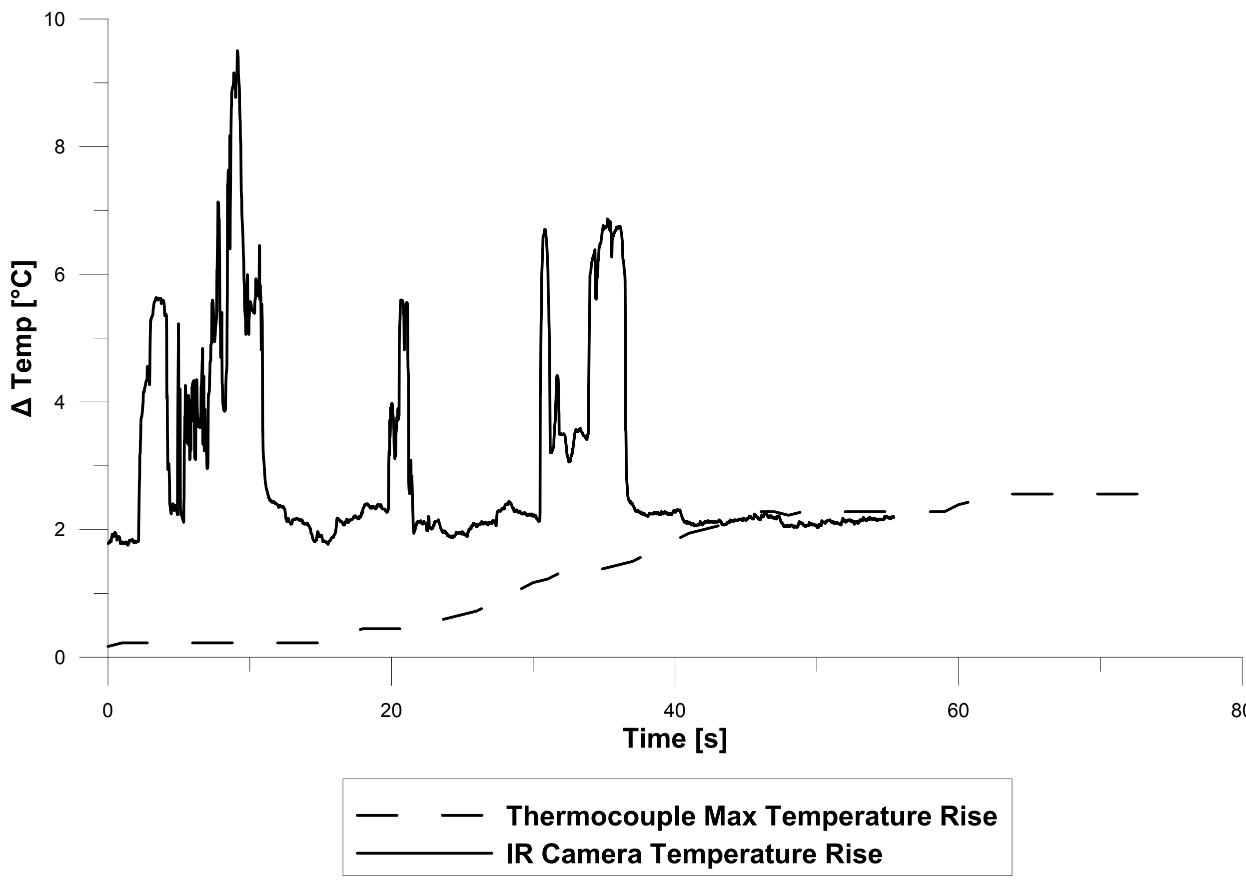


Figure 4.12: Rotary Filing; IR Camera Temperature Rise

4.2.3 Manual Sanding

Temperature rise versus time plots measured during sanding of wood, steel and concrete are overlaid in Figure 4.13. The temperature rise measured using the IR camera aimed at the portion of sand paper used for the sanding operation is shown, and is lowest for steel at 15°C, followed by concrete at 18°C and finally, highest for wood at 35 °C. This is consistent with the filing results in that the peak temperature reached is related to the thermal conductivity of the workpiece material. The lower the thermal conductivity, the higher the temperature reached. The peak sanding temperature rise for wood is the highest and is therefore taken as the most appropriate critical process temperature for this operation.

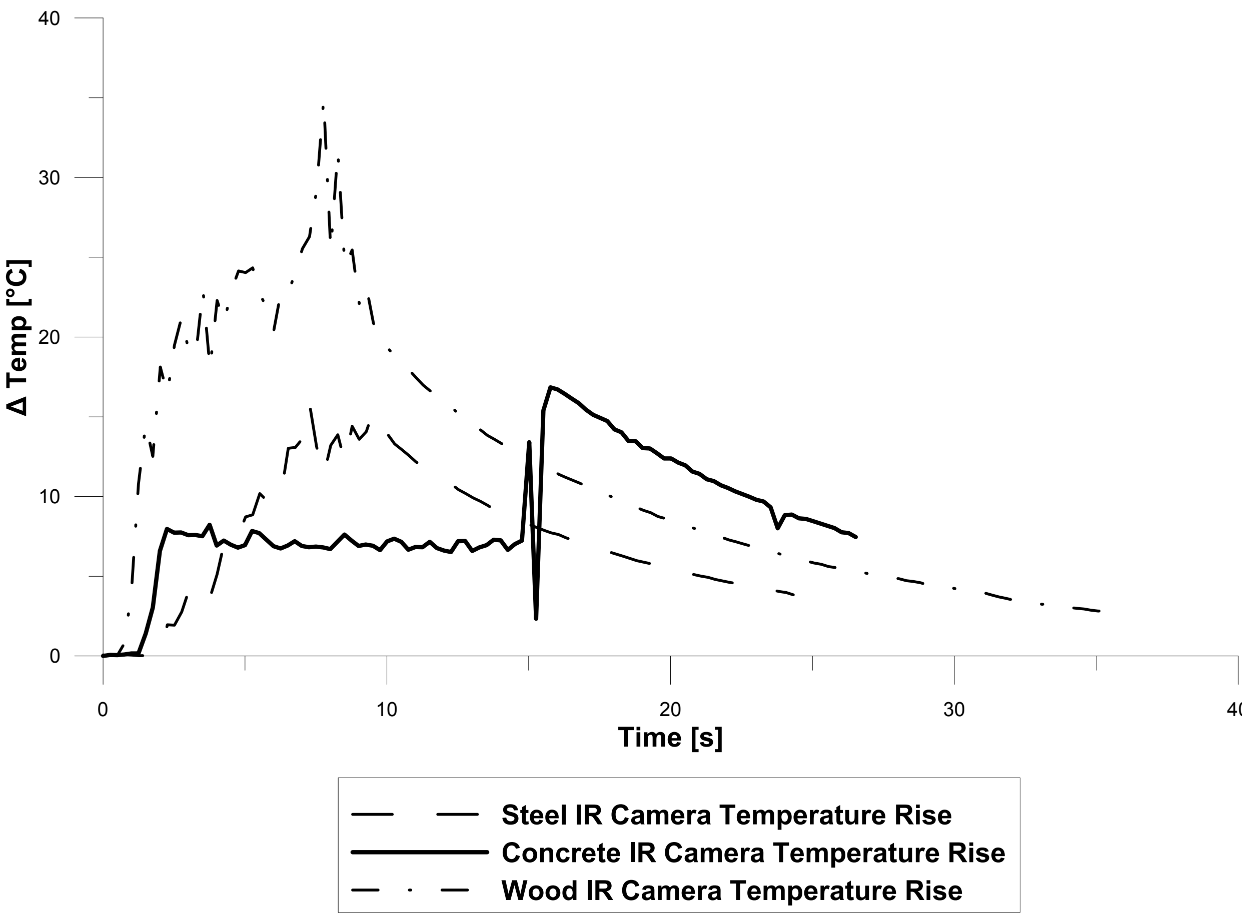


Figure 4.13: Sanding; IR Camera Temperature Rise

There was no evidence observed during these experiments that would suggest manual that sanding presents a remote ignition hazard. In the infrared camera footage, any material removed from the work piece contains limited energy and does not appear to leave the vicinity of the sand paper so this hot work operation remains very localised.

Large power sanding tools can also potentially produce sparks when used on ferrous and other oxidizing materials. Whilst not studied explicitly in this work, on this basis, power sanding tools are considered as hazardous as grinding in terms of fire hazard. Further information regarding the fire hazards of grinding are covered in Section 4.3.

4.2.4 Reciprocating Saw

Figure 4.14 shows the measured temperature rise of the work piece-blade interface during a rebar cutting operation. Results from an additional experimental run can be found in Appendix D. Peak temperatures measured 134°C above ambient, so this value has been selected as the critical process temperature.

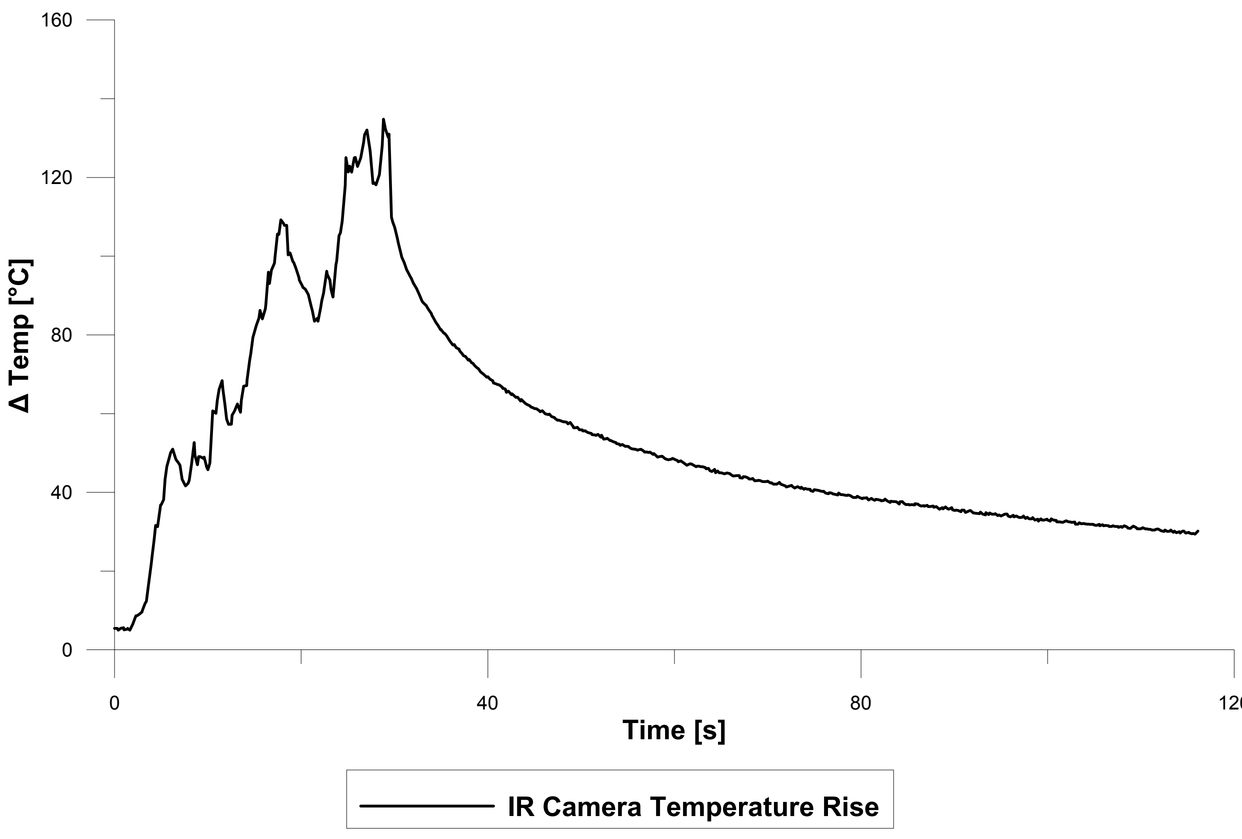


Figure 4.14: Reciprocating Saw Cutting 10 mm Rebar; Temperature rise as measured by the infrared camera

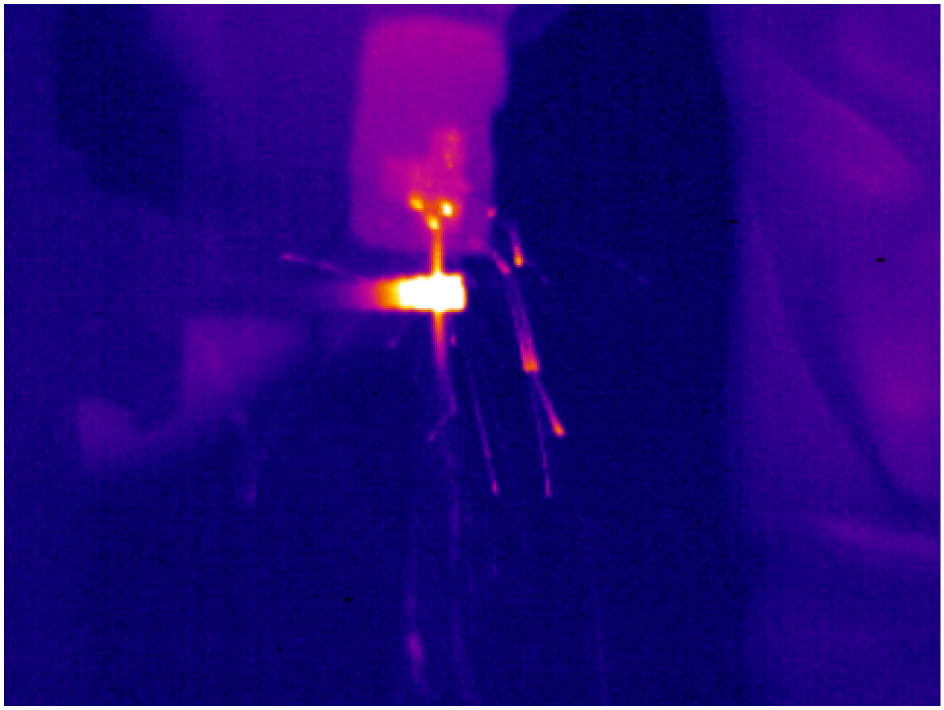


Figure 4.15: IR Footage showing hot particles leaving the rebar prior to separation during the cut

The piece removed from the bulk material in this test was approximately 30 mm long, and of size which may separate and roll away from the work area in an unpredictable fashion. The temperature of the separated piece was measured to 130°C which is high enough, within a small allowance, to pyrolyse wood or paper, and may readily ignite clothes or rags soaked in solvents.

Neither spark, nor incandescing particles, during either test, so the temperature of any particles leaving the workpiece was below approximately 480°C [56]. Figure 4.15 is a still image from the infrared footage showing hot particles leaving the kerf immediately prior to completion of the cut. The temperatures of the hot particles leaving the workpiece reached a maximum value of only 55°C as measured with the infrared footage, suggesting that the particles form and then cool too quickly for the system to measure their highest temperatures. Furthermore, the particles that are generated fall to the ground rapidly and in a direction perpendicular to the ground; since they do not travel laterally, they should not normally travel outside of a 1 m radius of the work piece during sawing.

4.2.5 Drilling

Drilling tests were performed by drilling 3/8" holes into four materials comprising 6061 Aluminium, plywood, A516 Gr. 70 steel and a laminate phenolic material. Metallic samples were 10 mm thick while the non-metallic samples were 25 mm thick. In each case, the temperature rise at the drilling site was measured with the infrared camera and, with the exception of the plywood case, a thermocouple was positioned close to the drill site to measure the workpiece temperature rise. The distribution of hot particles falling from the work area during drilling was characterised with thermal paper positioned 50 mm below the work following the procedure outlined in Section 3.6.5.

Temperatures measured during the drilling tests are summarised in Table 4.3, including peak temperature rise of the drill site measured by the infrared camera and workpiece temperature rise measured by the K-type thermocouple. Comments outlining the key results of the analysis of marks on the thermal paper are in the final column of the Table. More detailed traces of temperature rise versus time as measured by the IR camera and thermocouples during drilling into the different materials are in Figures D.2 through D.6.

Table 4.3: Drilling Results

Material	Case	IR Rise [°C]	Thermocouple Rise [°C]	Marks on Paper
Plywood	-	27	-\-	None
6061 Aluminium	-	24	20	None
Laminate Phenolic	-	78	17	None
A516 Gr. 70 Steel	1	172	56	10 marks
A516 Gr. 70 Steel	2	195	77	Hundreds

As summarised in the third column of Table 4.3, the temperatures of the drill sites, as measured by the IR camera remain below 30°C during drilling of plywood and 6061 Aluminum. During drilling into aluminum, a modest temperature rise of 20°C was also registered on the thermocouple. No marks were left behind on the thermal paper while drilling into either wood or aluminum. Drill site temperatures observed during drilling into laminate phenolic were higher, peaking at 78°C, while the workpiece temperature measured by the thermocouple was again low, at only 17°C. In comparison to aluminum, both the higher drilling temperature and the lower work piece temperature for the laminate phenolic are a function of the low thermal conductivity of the material. Despite the higher drill site temperature, the removed phenolic material was still not sufficiently hot enough to mark the thermal paper located 50 mm below the hot work operation.

By far the highest temperature measurements were found during drilling of steel. In case one, where an optimal drilling technique was used, peak drill site temperatures of 172°C were observed with workpiece temperatures reaching 56°C. Extracted material was sufficiently hot to leave a few marks on the thermal paper. In case two, where suboptimal drilling techniques were employed, peak drill site temperatures reached 195°C, with workpiece temperatures of 77°C measured by thermocouple. The material removed from the work piece during this test was sufficiently hot to leave hundreds of marks on the thermal paper below, indicating a potential remote ignition hazard for the most vulnerable materials, such as solvents and spirits wicked by rags. No marks on the thermal paper were seen outside of a 20 cm lateral radius from the drilling operation, suggesting any particles that fell onto the paper outside that range had cooled to below 70°C.

The peak temperature of 195°C measured during drilling into steel samples has been selected as the critical process temperature for drilling since it is the maximum observed temperature during these experiments. This temperature presents a pyrolysis hazard to many of the materials seen in Tables 2.3 and 2.5, such as wood and paper. Similarly, soaked into fabric or cloth, solvents and spirits are likely to ignite if exposed to such temperatures.

4.2.6 Summary

The processes tested in this section exhibit ignition hazards primarily comprising hot surfaces, but they also have the potential to expel hot material. Where possible, tests performed here attempted to characterize each process both through determination in the form of a representative critical process temperature for the hot surface hazards associated with that process, but also through more qualitative observation, with the infrared camera and thermal paper, of whether hot particles were formed and if so how far they travelled from the work area during the operation under study. The critical process temperature data are summarised in Table 4.4 alongside commentary summarizing observations about hot particle formation and travel. The processes are listed in the Table in order of decreasing ignition hazard potential. For processes with multiple configurations, the highest measured temperature has been selected as the critical process temperature. With the exception of brazing, this is determined from the peak temperature rise of the work as measured by the infrared camera. For brazing, the workpiece temperatures, though in excess of 580°C, are far below the temperature of the oxyacetylene flame, at approximately 2,800°C; the oxyacetylene flame temperature is therefore the critical process temperature selected for brazing.

Workpiece temperatures measured for processes in this section are generally lower than

Table 4.4: Test Result Summary for Hot Surface Processes

Process	**Critical Process Temperature [°C]**	**Observation of Hot Particles**
Brazing	2,800	Hot particles were not observed[1]
Drilling Steel, poor technique	195	Separated metal retains enough heat to mark thermal paper inside of a 20 cm radius
Reciprocating Saw	133	Hot particles are of limited temperature, and are not observed traveling laterally
Manual Filing, Concrete	55	Particulates confined to file and work table
Manual Sanding, Wood	35	Particulates confined to sandpaper
Rotary filing, Steel	10	Particulates insufficiently hot to mark thermal paper, not seen to travel laterally

[1] For safety reasons, techniques to create spatter were not deliberately enacted and could not be tested.

those in the previous section. This is because the processes discussed in the previous section used heat to accomplish the useful portion of the work, whereas heat is an unwanted byproduct of processes in this section (with the exception of brazing). Of the processes studied here, brazing, sawing and drilling are the only ones presenting credible hot surface ignition hazards to materials in Tables 2.3 and 2.5. The same three are the only processes presenting realistic remote ignition hazards, though in the case of sawing and drilling this has been demonstrated to be a possibility only over a small region very near where the operation is being performed. Regrettably, a safe way of performing upset cases while brazing was not conceived during the course of this work; nonetheless, it is likely that the pressurised brazing torch could propel molten material over a significant distance during upset conditions, in similar fashion to the processes in the next section.

4.3 Hot Particle Generating Processes

Hot particle generating hot work processes investigated in this research involve high temperature arcs and pressurised gases for welding and cutting as well as high speed abrasive wheels; nearly all are expected to drive high temperature particulate from the work area at considerable speed and over considerable distances. To address the challenge of characterizing the hazard imposed by these processes, the novel methodology described in Section 3.3 that uses thermal paper to track characteristics of the particulate distribution was applied in combination with analysis of side views of the processes taken using a digital video camera. For each process that was tested, image processing algorithms were applied to generate a list of landing coordinates and calculated area for each mark (particle) that landed on each length of paper. Since the number of recorded marks was vast, ranging from approximately 10,000 for plasma cutting of aluminum pieces to 1.2 million in the worst case GMAW welds, integrated metrics that describe the nature of the particle deposition and distribution were derived for each test. These include: the maximum measured distance traveled by any particle for each process, $\mathrm{D_{MAX}}$ [m], the average distance travelled by particles from a process, $\overline{D}$ [m], the size of the mark at maximum distance, $\mathrm{A_{D_{MAX}}}$ [$\mathrm{mm^2}$], the total area of paper covered by hot particle marks, $\mathrm{A_{TOTAL}}$ [$\mathrm{m^2}$], and the radius within which the paper is saturated with marks (more than 10% of the area of the paper is covered making it difficult to discern the characteristics of individual marks in the distribution), $\mathrm{R_{SAT}}$ [m]. These parameters relate to the overall extent of travel of hot particles and sparks ejected from each hot work process, as well as to the relative energy imparted to the floor area by those particles and sparks which, in turn, may be interpreted to deduce a value for the ignition intensity which is the critical hazard parameter used to differentiate the processes tested. The data measured for each process is outlined and discussed in the next few sections, followed by further comparison and discussion of ignition intensity, and its implication in hazard differentiation, across hot work processes that usually generate significant quantities of hot particles.

4.3.1 Gas Tungsten Arc Welding & Shielded Metal Arc Welding

As indicated in the experimental program described in Chapter 3, a total of four configurations of GTAW and SMAW process welding tests were performed. Tests involved welding two 10 mm thick ASTM A516 Gr. 70 plates in the 2G position along a length of 200 mm. Initially, industry welding process specifications were going to be used, specifically those that required the use of a GTAW root pass followed by SMAW paths as necessary to complete the weld. The need for multiple investigations into hot particle generation from the GTAW process were quickly ruled out due to the low volume of hot particles produced in comparison to SMAW or GMAW welding procedures. Table 4.5 shows the average shielded metal arc welding process parameters used for each test including the electrode used, those welding amperage and the welding speed that the process parameters afforded during the filler passes. The Table shows that the worst case configurations involved use of lower welding current and yielded lower welding speeds. During root passes, the difference was even more pronounced, where welding speeds of only 43 mm/min and 152 mm/min were attainable in Worst Case 1 and Worst Case 2 respectively. For further information on the welding procedure specifications, refer to Appendix A.

Table 4.5: SMAW Average Process Parameters

Case	**Electrode**	**Amperage [A]**	**Welding Speed [mm/min]**
Nominal 1	3 mm E4918	120	240
Nominal 2	3 mm E4918	120	250
Worst 1	3 mm E6011	82	180
Worst 2	4 mm E6011	95	180

Figures 4.16, 4.17 and 4.18 contain composite plots of video images recorded during nominal GTAW and nominal and worst case SMAW processes. The figures illustrate, during one welding pass, the volume of hot particles that were produced during the procedure as well as the trajectories they took as they left the local area in which the process was being

performed. Comparison of these images shows that few hot particles were generated during the GTAW root pass (Figure 4.16), while considerably more particles were produced for nominal and worse case SMAW operations (Figures 4.17 and 4.18, respectively). Specific to GTAW processes, Figure 4.16 shows that only a few incandescent particles fall from the weld during the GTAW root pass. The particles cease to glow before hitting the floor indicating that their temperatures are below about 480°C. Consistent with this, visual inspection of the hot particle marks collected on the thermal paper after each GTAW pass indicated that very few particle marks, approximately five to ten, accumulated on the paper for each GTAW pass. Accordingly, GTAW joining processes, though, are not considered to present a credible remote ignition or smoldering hazard; given the high temperature arc involved in the process, though, coupled to the possibility of some particles falling in a localised area around the work piece, the area and environment surrounding a GTAW hot work operation should be free of combustibles and a fire watch should be considered, since the operator cannot weld and look out for fires simultaneously. For GTAW welding jobs which also require SMAW or other welding techniques as filler processes, a greater separation is required as many thousands of particles were found to travel several meters in both cases of SMAW shown in the figures and discussed below.

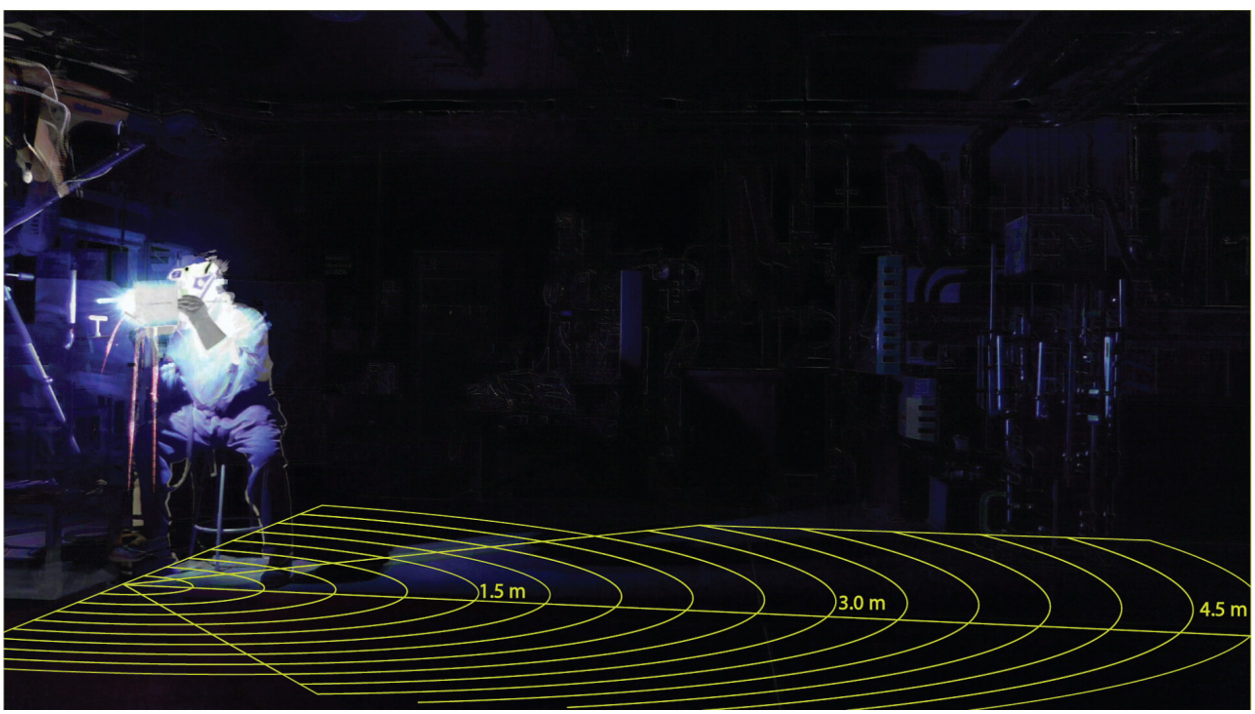


Figure 4.16: GTAW Root Pass; Nominal 1

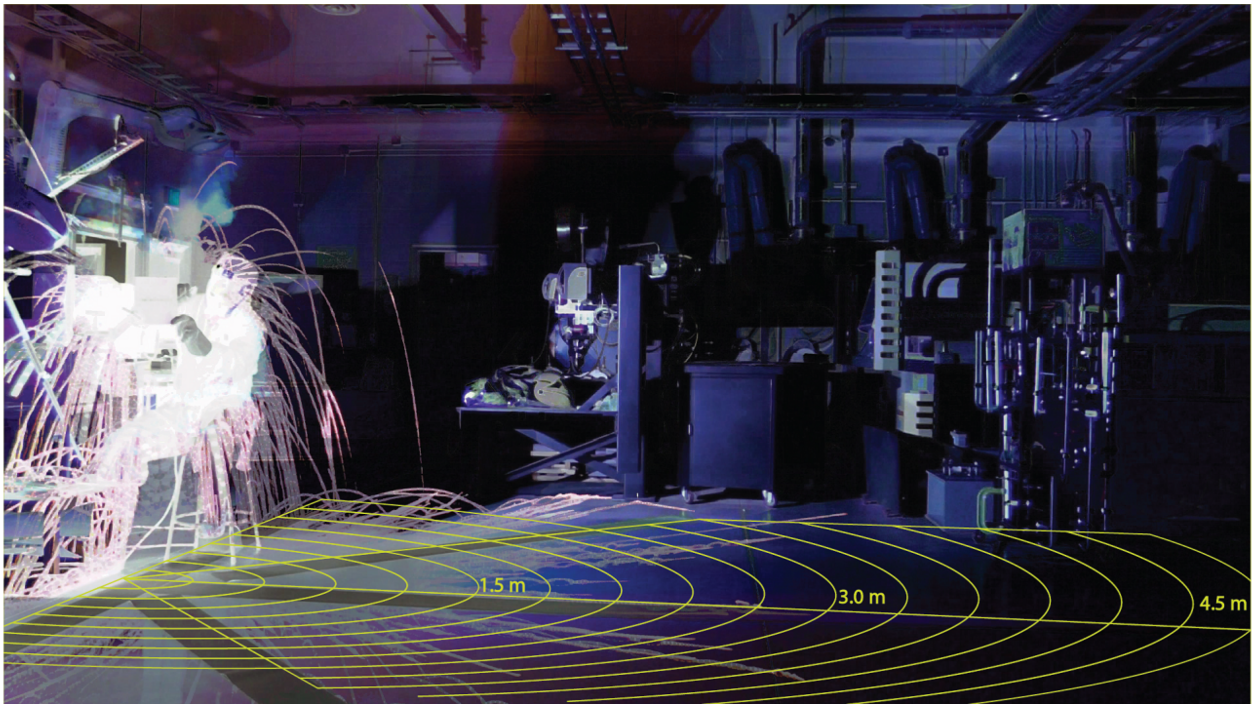


Figure 4.17: SMAW Fill Pass; Nominal 1

Figure 4.17 shows that there are many more particles produced during a nominal pass of the SMAW process than in the previous GTAW pass. These particles are propelled into the air, and follow parabolic trajectories from where they are generated until they hit the ground. Examination of the detailed video images, indicates that the particles break up as they hit the floor and, in some cases, the remaining particle pieces roll past the extents of the runs of thermal paper (i.e. along the diagonal and into the depth of the image). This inevitably introduces some error into the measured hot particle distribution, and is an unavoidable constraint of the experimental method when performed in areas with limited available space.

In contrast to Figures 4.17 and 4.17, Figure 4.18 shows the combined trajectories of particles produced during a welding pass made using the worst case configuration of the SMAW process. For this configuration, the chosen electrode size could not deliver sufficient penetration to complete the weld unless the welding amperage was set sufficiently high that the electrode would eventually overheat. According to experiment welding operator Brian Chmay, this suboptimal configuration resulted in the production of more hot particles than the optimum process settings, but also longer weld times. This adversely affected the additive methodology used to compile the composite images, as interference from the arc is

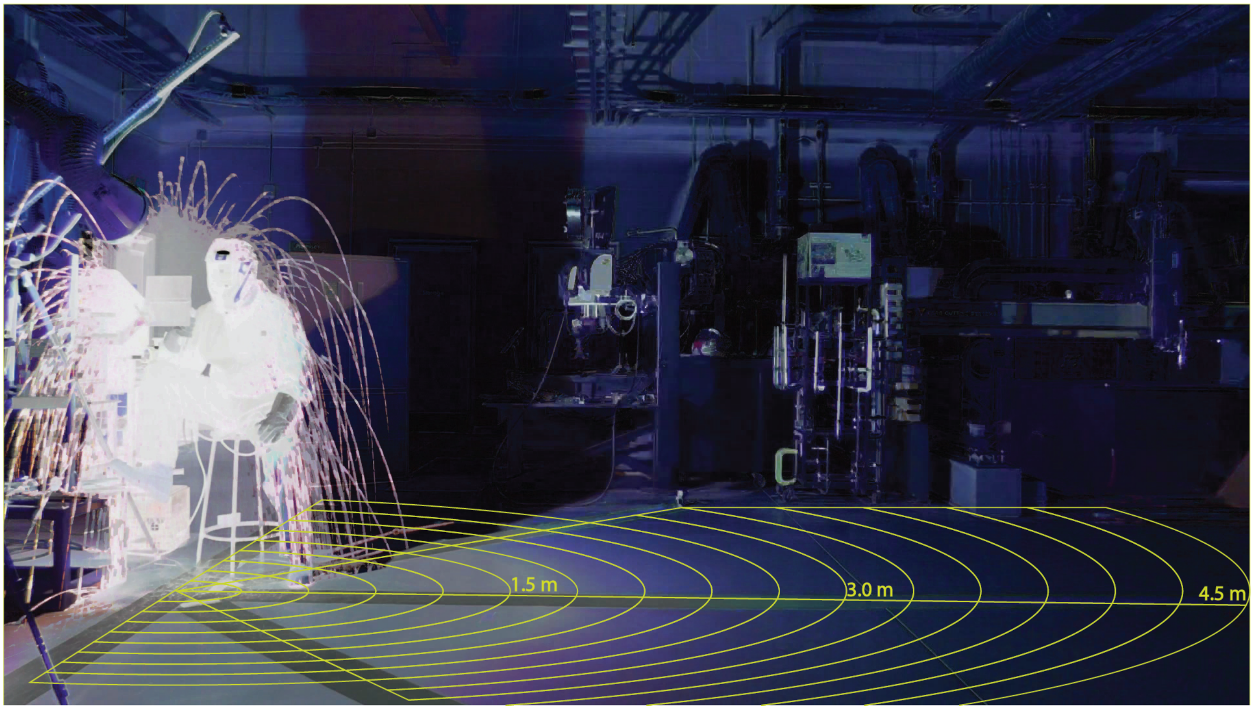


Figure 4.18: SMAW Fill Pass; Worst 1

superimposed over a longer duration resulting in overexposure of the composite image. This outcome is particularly apparent on the floor in the image. As a result, while more particles and their trajectories are visible in the air in comparison to the nominal case (Figure 4.17), fewer are resolved on the floor because image contrast has been lost. It was also necessary to manually remove frames that contained images of severe arc flash from the composite image, carrying the unfortunate side effect of reducing the distinction between the nominal and worst cases. For this reason, composite images such as those shown here should only be relied upon to provide qualitative checks of particle distribution during hot work (or other similar) operations.

Plots illustrating hot particle distributions that landed on the thermal paper on the floor surrounding combined welding and interpass cleaning operations, including nominal GTAW-SMAW and worst case SMAW processes are in Figures 4.19 and 4.20. In contrast to the Figures above which included just the welding operation, these show the particle distributions digitised for several welding passes with interpass cleaning done using various techniques. Larger versions of the particle distribution plots for all four test runs listed in Table 3.4 are available in Appendix E. The figures illustrate the vast difference in particle distribution between the process configurations.

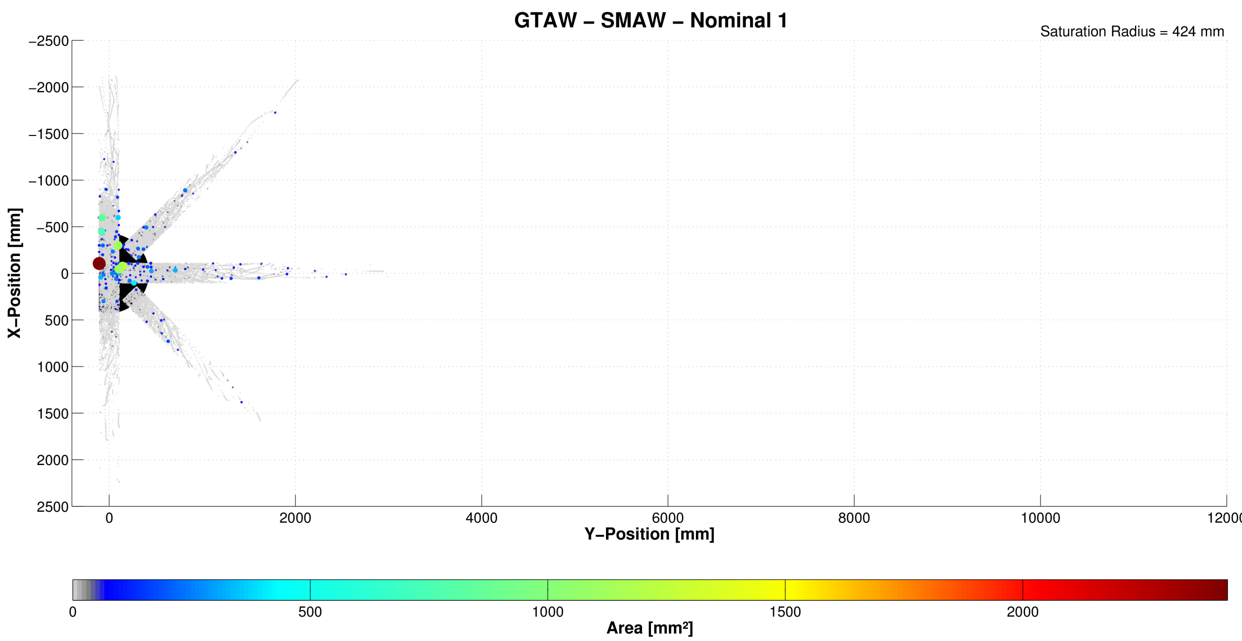


Figure 4.19: Gas Tungsten Arc Welding - Shielded Metal Arc Welding: Nominal 1

The particle distribution measured for the nominal GTAW-SMAW process in Figure 4.19 is characterised by a small saturation radius of approximately 0.4 m (as shown by the solid black hemisphere in the Figure) compared to the 1.0 m saturation radius seen in the particle distribution measured for the worst case welding configuration and shown in Figure 4.20. The larger saturation radius indicates that the footprint of the area that contains the most intense ignition hazard is larger for the worst case welding procedure than for the nominal case. In addition, not very many hot particles fell at radii beyond 2 m from the work area for the welding test conducted with nominal process settings whereas many marks were observed well beyond that radius in the particle distribution that was measured for the worst case welding configuration. While the total area covered relates most closely to details of the

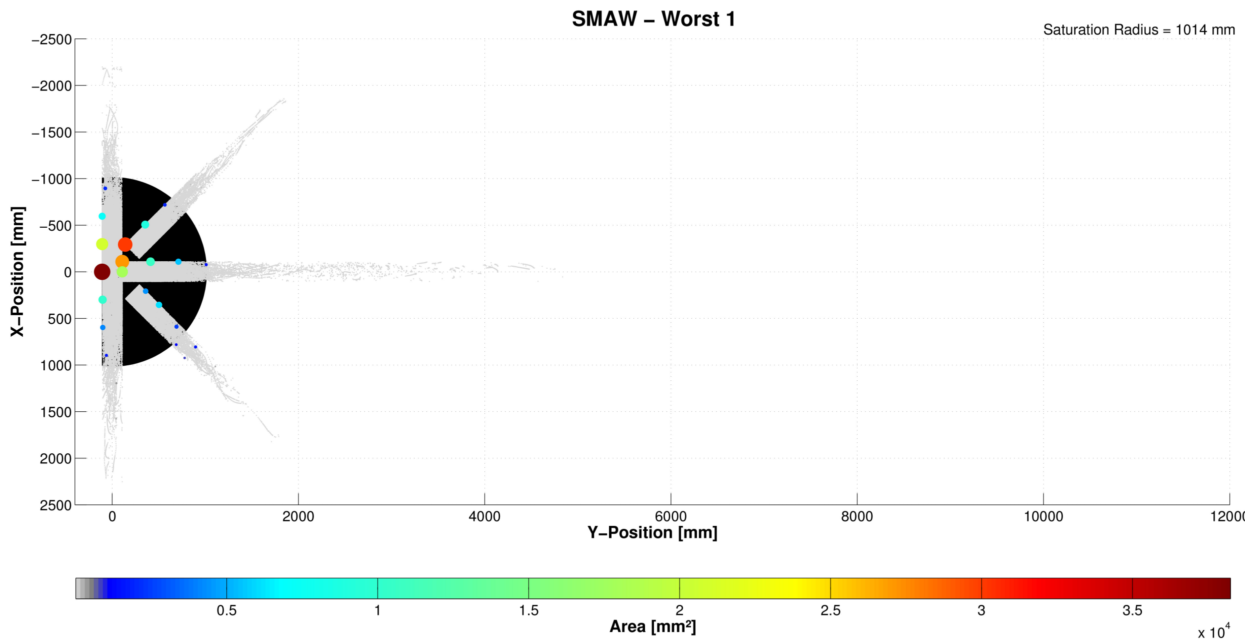


Figure 4.20: Gas Tungsten Arc Welding - Shielded Metal Arc Welding: Worst 1

welding procedure used, the difference in the extent of the envelope of the marks is primarily a function of interpass cleaning, which will be addressed later.

Table 4.6 summarises the key statistics determined from the distribution of hot particle marks on the thermal paper for the GTAW - SMAW results. Substantial differences can be seen between tests for each of the metrics in the table. D_{MAX} indicates the distance covered by the farthest travelling particle for the population, while $\overline{D}$ is the mean distance traveled by all particles in the distribution. R_{SAT} describes the radius from the centre of the work piece within which the potential for hot particle ignition is most intense, while A_{TOTAL} is a measure of the total area impacted by hot particles; a larger value corresponds to a larger potential impact of the hot particles and therefore a higher level of ignition potential. The results measured for each of the processes above are discussed in turn below.

Table 4.6: GTAW - SMAW Results

Case	D_{MAX} [m]	$\overline{D}$ [m]	A_{TOTAL} [m^2]	$A_{D_{MAX}}$ [mm^2]	R_{SAT} [m]
Nominal 1	3.0	0.5	0.051	11.4	0.4
Nominal 2	6.5	0.5	0.048	1.0	0.4
Worst 1	4.8	0.6	0.259	4.9	1.0
Worst 2	7.5	0.6	0.117	5.7	0.6

The Nominal 1 and Nominal 2 GTAW - SMAW tests differed only in the method used for interpass cleaning of the welds, yet a profound difference is seen in D_{MAX}. The weld area was cleaned using manual wire brushing in the Nominal 1 test, while a 4", grinder operated, wire brush was used for interpass cleaning in Nominal 2. The maximum distance travelled by hot particles more than doubled from $D_{MAX} = 3$ m to $D_{MAX} = 6.5$ m when a grinder operated wire brush was used to clean the Nominal welds between passes rather than a manual wire brush. While the 4" wire brush did not itself produce incandescent particles, the welding slag being removed during the interpass wire brushing process was hot enough to leave marks on the thermal paper at distances of more than 6.5 m away from the welded joint. No substantial difference in $\overline{D}$ is seen between Nominal Case 1 and Nominal Case 2 because the overall quantity of particles produced by the interpass cleaning operation was small in comparison to that of welding.

Comparison of D_{MAX} values obtained for the GTAW - SMAW Nominal Case 2 and SMAW Worst Case 1, further indicates that the 4" grinding wheel used for cleaning in the Worst Case 1 operation did not send material as far as when the weld was cleaned with the wire brush. D_{MAX} was only 4.9 m in Worst Case 1 versus 6.5 m in Nominal Case 2, though in the case of interpass grinding (Worst Case 1), the particles created by the grinding process were incandescent and therefore much hotter than those seen during any of the wire brushing operations. Similarly, when the 9" grinder was used for interpass cleaning in SMAW worst case 2, D_{MAX} increased to 7.6 m, the furthest extent of all tests in this section.

The trajectories of particles that were generated during the Worst Case 2 operation can be seen in the side view composite image in Figure 4.21. Significant numbers of particles can be seen traveling larger distances than for any of the other welding examples, with many still traveling off the frame in the Figure (i.e. 4.5 m from the work piece location).

The value of $A_{D_{MAX}}$ is substantially larger for Nominal Case 1 than for any of the processes tested. Since only manual cleaning was used in this test, the substantially larger mark was a result of a hot particle or group of hot particles from the welding rather than from the interpass cleaning operations. Comparison of the values of $A_{D_{MAX}}$ for the other tests summarised in Table 4.6 suggests that marks created with the 4" and 9" grinders, from Worst Case 1 and 2, are larger than those generated by the grinder operated wire brush used for interpass cleaning in Nominal Case 2.

Other differences amongst the distributions of hot particles produced from different welding processes are reflected in measured values of the total marked area determined from the thermal paper sheets. The total marked areas, A_{TOTAL}, measured for GTAW - SMAW Nom-

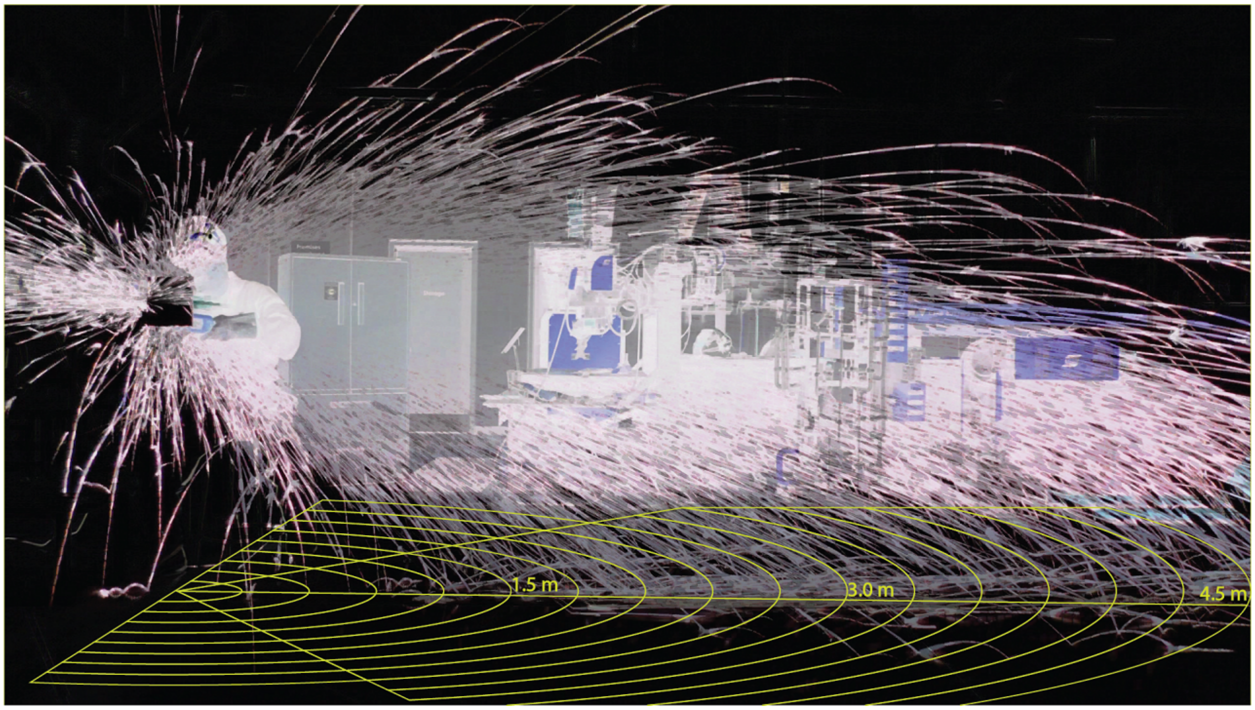


Figure 4.21: Interpass Cleaning with 9" Grinder

inal Case 1 and Nominal Case 2 do not vary appreciably, which is to be expected since the same low-hydrogen E4918 electrodes and welding amperage are used for both. Deeper penetrating E6011 electrodes of the same 3 mm diameter as those in the nominal cases were used in the SMAW Worst Case 1 process, resulting in a marked increase in production of spatter, because of overheating of the deep penetrating electrode despite substantial decreases in welding amperage (to 85A from 120A compared to the E4918 welds). The increased spatter, lack of a GTAW root pass and difficulty in using E6011 welding electrodes resulted in an increase in total marked area by approximately a factor of 5. For SMAW Worst Case 2, a larger 4 mm E6011 electrode is employed, allowing for use of larger welding currents (approx. 95 A) and fewer passes to fill the weld, thus resulting in less spatter and a slightly lower value of marked area than seen for SMAW Worst Case 1.

The results above indicate that during GTAW - SMAW combined welding and interpass cleaning operations, welding spatter alone is likely to travel a lateral distance of 3 to 4 meters, while different methods of interpass cleaning can substantially increase this value. Overall, it is concluded that choice of interpass cleaning method greatly influences the maximum distance travelled by any hot particles generated during welding operations, though the overall intensity of the hazard from hot particles generated during cleaning may be smaller than that of those generated during welding. Differences in A_{TOTAL} suggest that the hazard from welding can be drastically reduced by ensuring welding electrodes and related weld process parameters are properly selected and the work is carefully done. Changing other weld parameters such as workpiece material, dimensions and orientation will also play a large role in determining the integrated energy available in hot particles and spatter and thus the propensity of each process to cause remote ignition.

4.3.2 Gas Metal Arc Welding

Two GMAW process configurations were tested by performing the same welding task as used for the combined GTAW - SMAW process tests discussed above, so the results could be compared directly. For both nominal and worst cases of the GMAW process, a 0.8 mm ER49S-6 GMAW filler wire was used for root, filler and cap passes. To obtain worst case conditions, the 85% Argon, 15% CO_2 gas mix was exchanged for 100% CO_2, and interpass cleaning was performed with a 4" grinder.

Side view composite images of the Nominal GMAW and Worst Case GMAW operations are illustrated in Figures 4.22 and 4.23 respectively. For the worst case, in Figure 4.23, particles traveled slightly further to a distance closer to 4 m, particularly in the image foreground. A greater volume and variance in trajectory of projectile sparks can also be observed to travel above the operator and the work. In the Nominal figure, particles are seen to travel to an approximate maximum of 3 m. It appears there are more particles produced in both GMAW welding cases than for GTAW-SMAW processes.

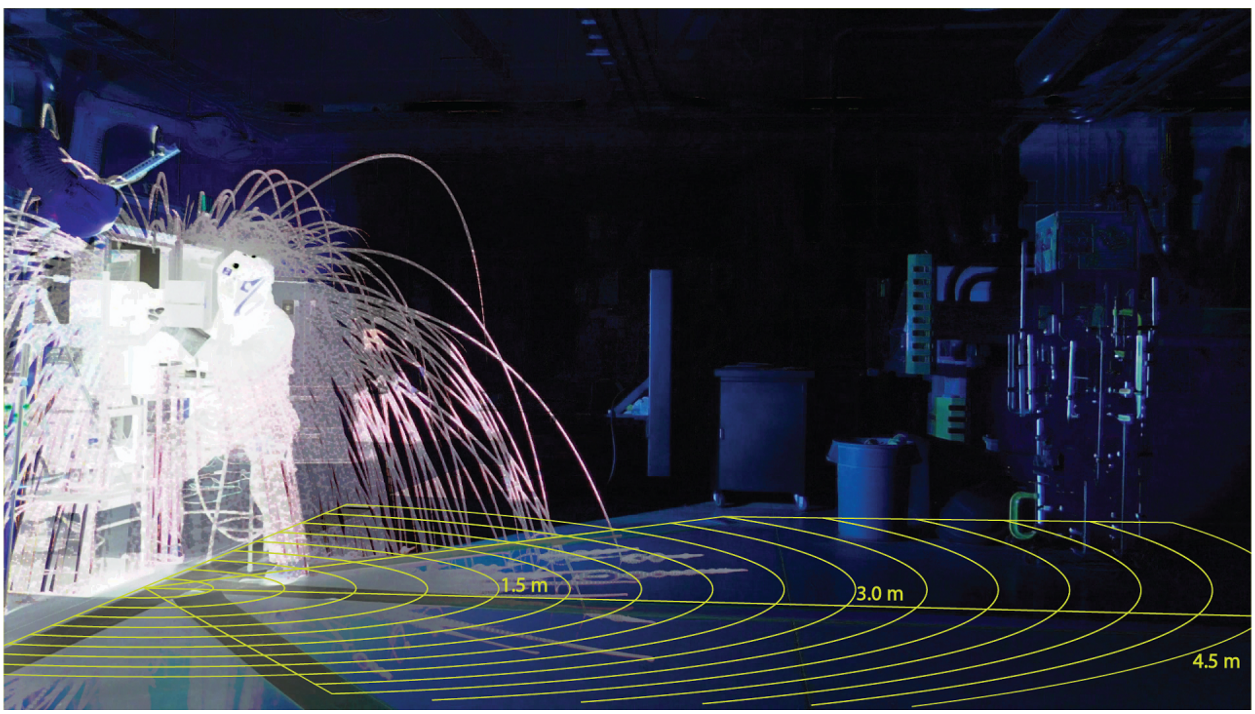


Figure 4.22: Gas Metal Arc Welding: Nominal

Figures 4.24 and 4.25 show the particle distribution created during Nominal and Worst Case GMAW process. Similar saturation radii of approximately 1 m can be seen in both Figures, indicating that the region of highest propensity for ignition was roughly equal in

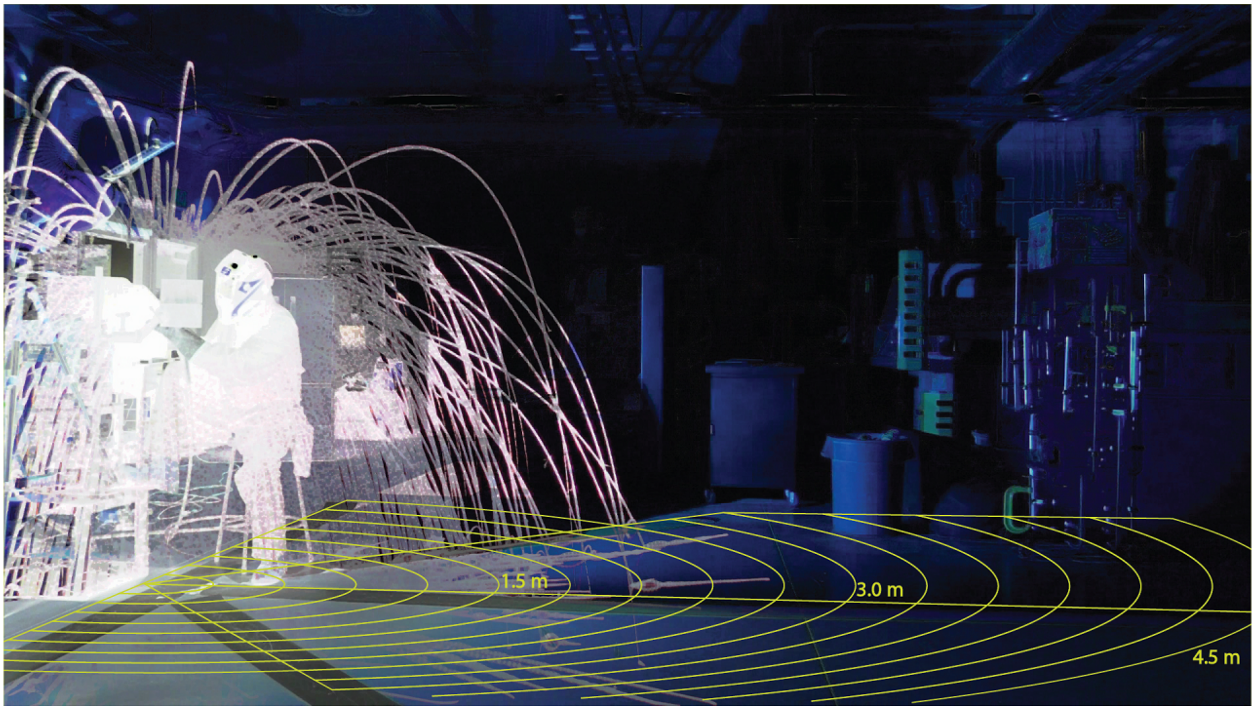


Figure 4.23: Gas Metal Arc Welding: Worst

size between the two cases. The Nominal case shows that most particles traveled about 3 m from the work piece just as is shown in the side view composite, Figure 4.22. Particles in the Worst Case plot distribution extended 4 m away from the work piece because the 4" grinder was used for interpass cleaning. Figure 4.26 is a composite picture which illustrates interpass cleaning with the 4" grinding wheel. The Figure shows many particles traveling to 4 m and beyond, highlighting the possibility of ignition at some distance from the work area as well as the possibility that some far-travelling particles could have missed the thermal paper. Since grinding was only performed to facilitate sufficient interpass cleaning, the process was not performed for a significant quantity of time. Therefore, the sample size of the hot particle distributions created with the grinder may be insufficient to characterize the maximum distance expected, particularly with the limited area of thermal paper in the region which many particles are seen to have fallen in Figure 4.26. Accordingly, the combined results suggest there is benefit in studying the grinding process in more detail.

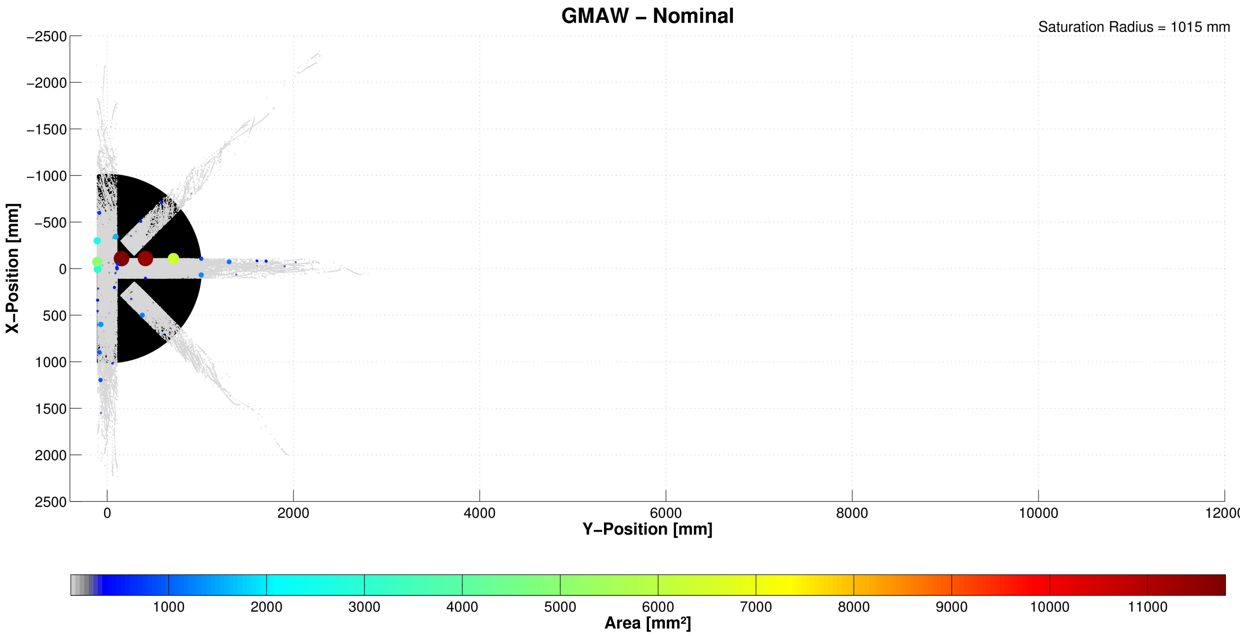


Figure 4.24: Particle Distribution, GMAW Nominal

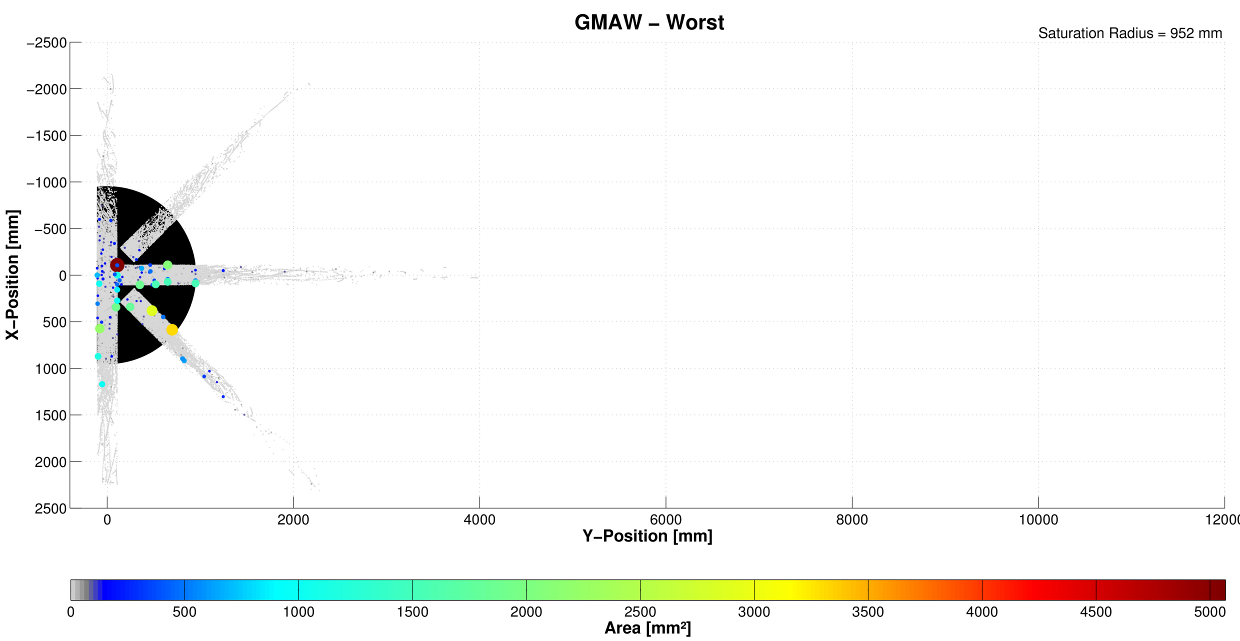


Figure 4.25: Particle Distribution, GMAW Worst

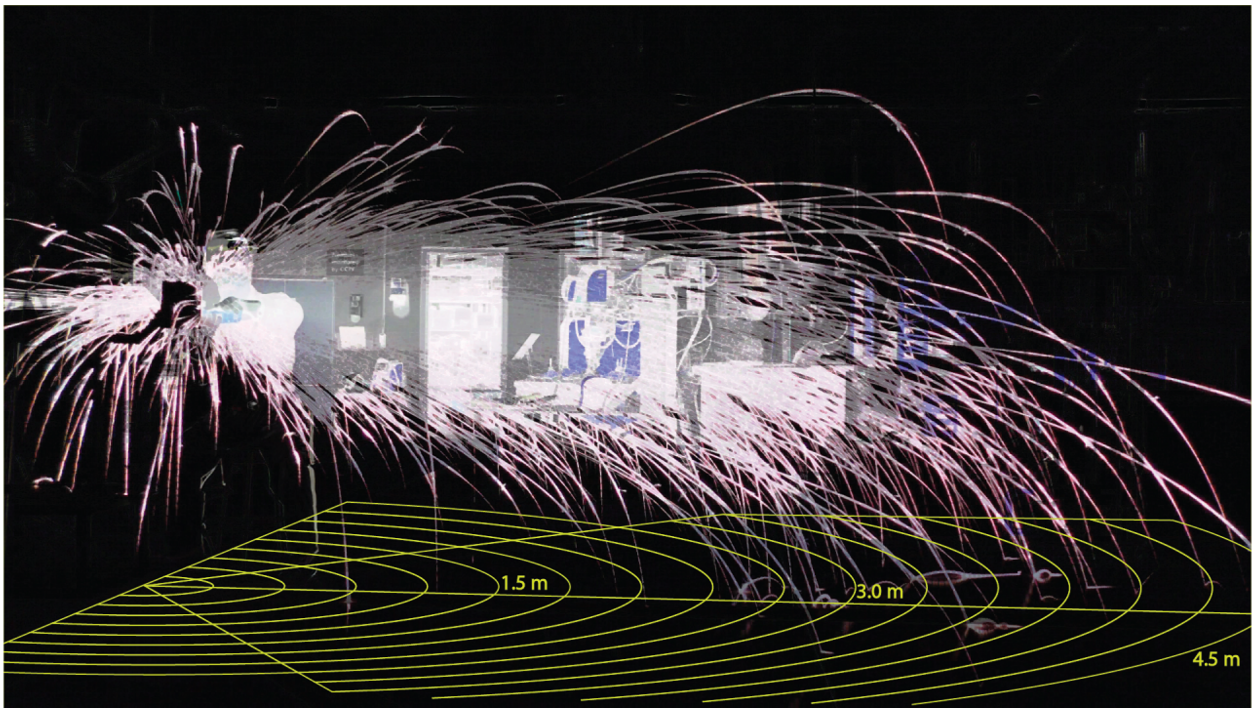


Figure 4.26: Interpass Grinding; Gas Metal Arc Welding

Important statistics describing the hot particles recorded during the GMAW process tests are summarised in Table 4.7. These metrics again highlight important similarities and differences between the test cases.

Table 4.7: GMAW Results

Case	$\mathbf{D_{MAX}}$ [m]	$\overline{D}$ [m]	$\mathbf{A_{TOTAL}}$ [$\mathbf{m^2}$]	$\mathbf{A_{D_{MAX}}}$ [$\mathbf{mm^2}$]	$\mathbf{R_{SAT}}$ [m]
Nominal	3.3	0.6	0.108	18.0	1.02
Worst	4.0	0.6	0.100	2.8	0.95

From Table 4.7, it can be seen that the maximum distance travelled by hot particles during the Nominal GMAW welding process was 3.3 m, a value similar to that measured for the Nominal GTAW-SMAW case with manual interpass cleaning. In contrast, hot particles traveled a maximum distance of 4.0 m in the worst case GMAW process, which was less than, but comparable to, the distance that particles traveled in SMAW Worst Case 1 which was also cleaned using a 4" grinding wheel. This is explained by the fact that the GMAW process was performed using more suitable welding parameters than the SMAW Worst Case 1 and required less stopping and starting. Therefore, more interpass grinding was necessary for the SMAW Worst Case 1 than the GMAW Worst Case.

As was the case with the GTAW - SMAW processes, the size of the mark at the longest distance was much larger for the manually cleaned case than for the case in which the grinder was used for interpass cleaning of the weld. The marks left by hot particles generated during welding versus those generated during grinding were larger by a factor of six, highlighting again that the welding spatter did not travel as far as grinding particulate, but welding particles were larger and hotter, and therefore present a more credible ignition hazard.

The total marked areas for the GMAW Nominal and GMAW Worst cases were very similar, with little observable difference evident due to replacement of the shielding gas with of 100% CO_2 in the Worst Case experiment. Both values fell between those measured for the nominal and worst case GTAW-SMAW processes suggesting that a range of values are required to define the integrated indices of hot particle generation amongst the various welding processes.

Figure 4.26 substantiates the observation made in Section 4.3.1 that particles traveled substantially further when interpass cleaning was performed using a 4" grinder than when manual interpass cleaning was employed for GMAW processes. Commensurate with results previously presented for the GTAW - SMAW process, and based on the measured areas of the marks left by the farthest traveling particles in nominal versus worst case GMAW, the farthest travelling particles produced during GMAW welding, $A_{D_{MAX}}$, again mark substantially larger areas, and therefore potentially present a larger, but more localised, ignition or smoldering hazard than particles generated during interpass grinding operations.

Based on the results, the interpass cleaning method was the dominating factor in the determination the maximum distance over which hot particles generated during a welding process will travel. In contrast, total areas marked by the farthest travelling particles are not significantly different between these cases. As such, the results substantiate that the hazard of ignition further from the work piece was lessened when manual cleaning of the weld was performed.

4.3.3 Plasma Cutting

Plasma cutting does not rely on oxidation of the workpiece material to obtain high enough temperatures in order to perform the cut. Instead, the heat is generated by the formation of a high temperature arc, so any electrically conductive material can be plasma cut. To study hot particle and slag formation during plasma cutting operations, four material combinations were tested in nominal and worst case configurations. The tested materials were 13 mm thick 6061 Aluminium, 6 mm thick 304L stainless steel and A516 Gr. 70 carbon steel in two thicknesses, 10 mm and 13 mm; for each, a 200 mm length was cut. Cuts were performed with the plates at the same height, but perpendicular to the welding tests, such that hot particles leaving the kerf would travel out over the thermal paper on the floor. Nominal cutting cases were performed by cutting directly through the plate, while worst case cuts involved cutting the plate at a 45°upward angle, with the aim to propel hot particles farther.

Table 4.8 shows key statistics regarding the hot particle populations recorded during plasma cutting experiments. Large variance in the value of D_{MAX} was observed between the two cutting cases as well as amongst the different materials being cut. It can be seen that plasma cutting of stainless steel in the nominal case propelled particles up to 8.4 m away. Stainless steel does not oxidize as readily as carbon steel and has a much lower thermal inertia, so since the torch must melt the material to make the cut, these differences in properties lead to relatively larger particles which hold their heat as they travel longer distances from the work piece. In contrast, plasma cutting aluminium propelled particles to a maximum distance of only 5.7 m. Nonetheless, even in the best case studied here, plasma cutting propelled particles much farther than either SMAW or GMAW joining processes. A comparison of the D_{MAX} results suggests that the attempts to cut at an upward angle were ineffective in increasing the distance traveled by hot particles. Indeed, in all but one material the value of D_{MAX} in the nominal case is larger than for the intended Worst Case situation of cutting at a 45°upward angle. The exact reason for this is not understood, but is likely a result of inherent variability in the plasma cutting process across the various materials.

During plasma cutting, a considerable number of variables, including material type and thickness, as well as cutting and shielding gases to name a few, combine to affect the temperature, viscosity and surface temperature of molten metal produced by the arc. With oxygen present, as is the case when using air or oxygen as the plasma gas, oxidizing materials such as carbon steel will increase the cutting temperature, and thus decrease the viscosity of the molten metal in the kerf [57]. These are all factors which are typically well understood in terms of their affect on cut quality and post cut weldability, but are not understood in terms of their effect on the relative sizes and distribution of hot particles leaving the kerf. Further complicating the issue is that hot particles have varying aerodynamic properties depending on the manner in which they were formed, thus also altering the distributions and particle distances traveled.

Table 4.8: Plasma Cutting Results

Case	**Material**	$\mathbf{D_{MAX}}$ [m]	$\overline{D}$ [m]	$\mathbf{A_{TOTAL}}$ [$\mathbf{m^2}$]	$\mathbf{A_{D_{MAX}}}$ [$\mathbf{mm^2}$]	$\mathbf{R_{SAT}}$ [m]
Nominal 1	10 mm A516 Carbon Steel	6.78	1.39	0.132	99	0.92
Worst 1		7.3	1.4	0.109	27	0.91
Nominal 2	13 mm A516 Carbon Steel	7.93	1.93	0.206	38	4.00
Worst 2		6.4	1.9	0.189	52	2.80
Nominal 3	13 mm 6061 Aluminium	5.74	1.58	0.018	3	0.00
Worst 3		4.6	1.1	0.010	33	0.00
Nominal 4	6 mm 304L Stainless Steel	8.40	1.12	0.055	14	1.02
Worst 4		5.8	0.9	0.161	68	1.31

Examining side view composite images for the plasma cutting operations reveals the large differences in aerodynamic behaviour between particles formed when cutting aluminium and those formed when cutting carbon steel. Side view composite images of plasma cutting of aluminum and steel are depicted in Figures 4.27 and 4.28 respectively. In Figure 4.27, particles separating from the aluminium work piece are fewer in number, larger, and do not travel as far as the more numerous but finer particulates separating from the carbon steel workpiece in Figure 4.28. The aluminium particles appear to curve sharply downward suggesting that they may be different sizes or take on non-aerodynamic shapes relative to the carbon steel. Figure 4.29 is a composite image of particles traveling from the much thinner piece of stainless steel. These have a similar appearance to those of the carbon steel in Figure 4.28. Many likely possibilities can explain differences in maximum distance traveled by particles produced in each of the cases. Chemical interactions between the base material and the cutting media are likely to affect particle size and travel and the plate thickness may also play a role. These apparent variations warrant further testing of different thicknesses and variations of material, and in particular the use of different cutting media such as oxygen, which is ideal as cutting gas for carbon steel, or nitrogen which is ideal for aluminium and stainless steel.

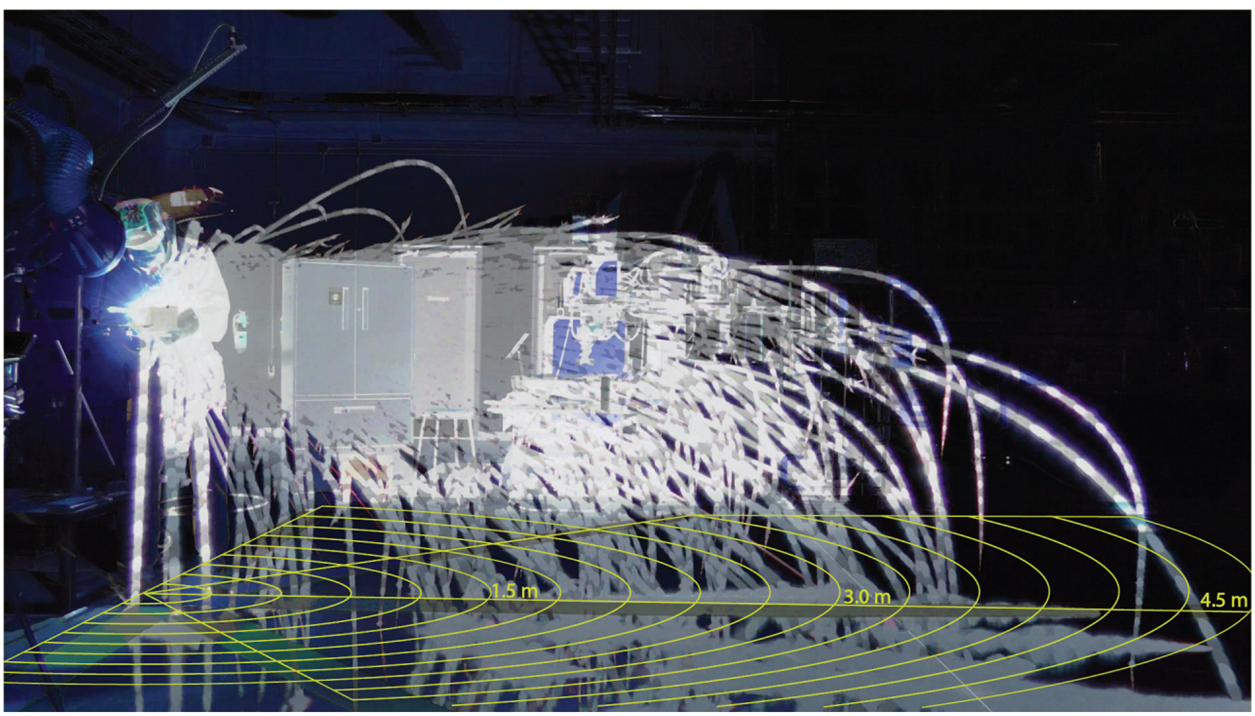


Figure 4.27: 13 mm 6061 Aluminium Plasma Cutting; Nominal Case

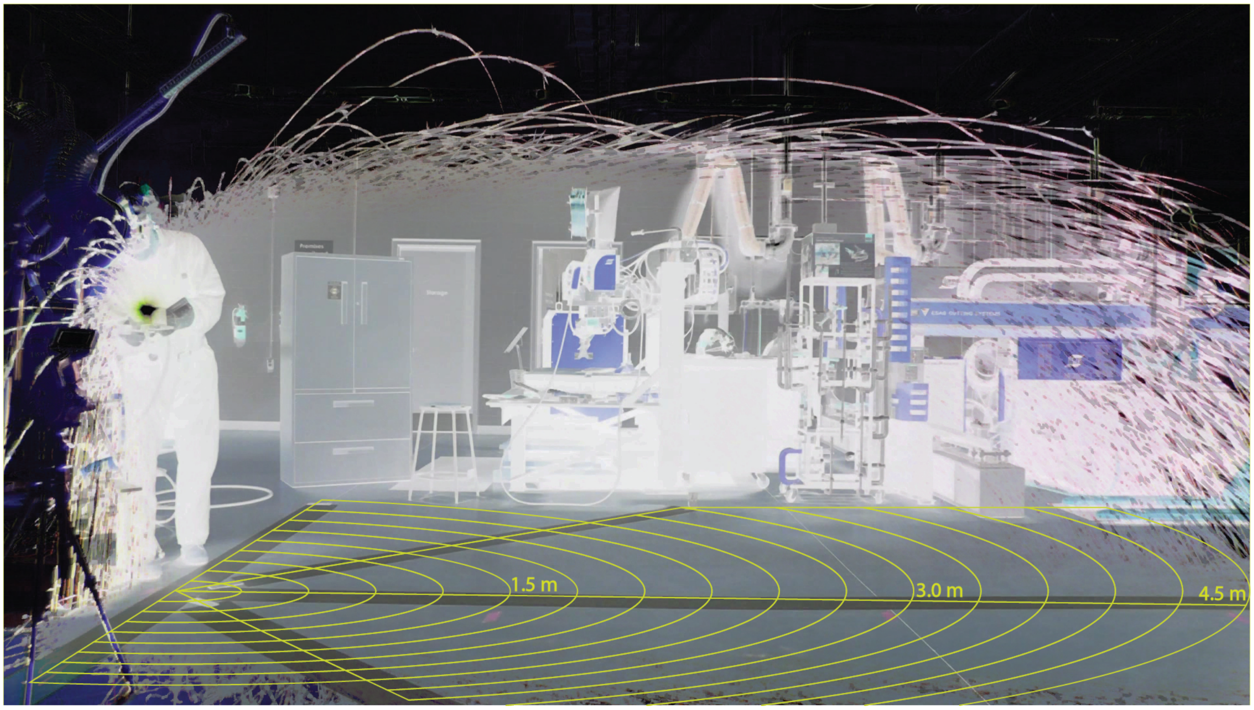


Figure 4.28: 13 mm A516 Plasma Cutting; Nominal

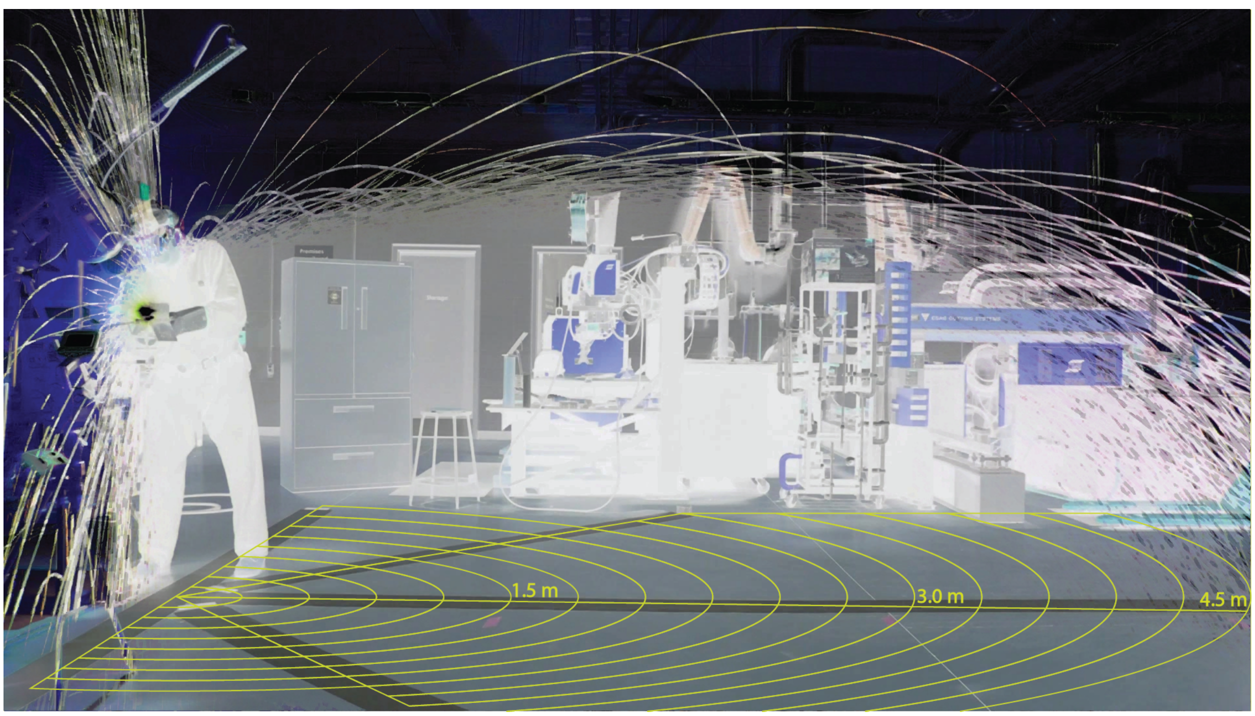
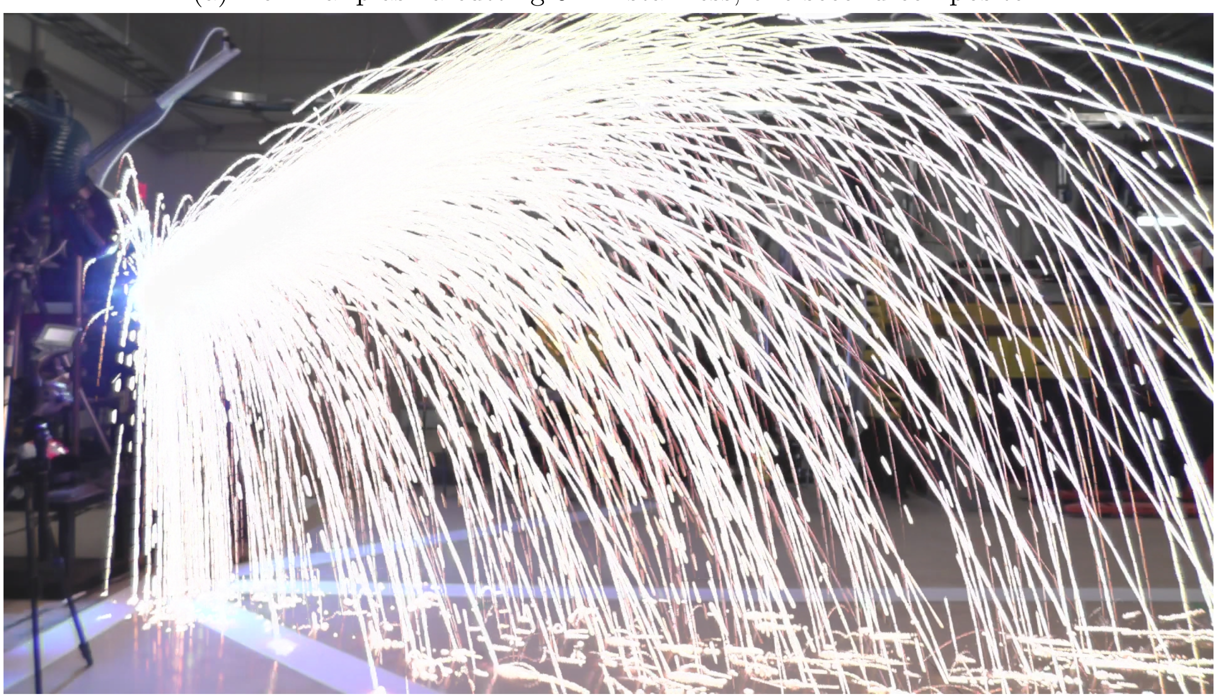


Figure 4.29: 6 mm 304L Stainless Steel Plasma Cutting; Nominal

For cutting processes, it is intuitive that the value of total marked area is related to the thickness of the material that is being cut, because the particulates formed are from the volume of material removed during cutting, and in thicker sections of material, more material was removed in a cut. Upon examining A_{TOTAL} across each of the material types, this is the case for the most part, with a few exceptions as discussed here. Cutting of the 13 mm thick carbon steel specimen produced the highest value of marked area, followed by the 10 mm thick carbon steel specimen and then the 6 mm thick stainless steel specimen. The saturation radii follow similar trends, with the 13 mm carbon steel cutting operation saturating the paper 4.0 m from the workpiece. Decreasing values of saturation radii observed with thinner workpieces indicate that the thinner workpieces present a lower hazard for the same distance from the work piece. This rule is not totally general however, as both the aluminium and stainless steel materials both present caveats to this observation. Firstly the aluminium, despite being 13 mm thick, left a total marked area an order of magnitude below that of the 13 mm carbon steel. Plasma cutting of aluminium produced a substantially lower total marked area, and did not lead to a measurable a saturation radius because none of the thermal paper located beneath the work piece was sufficiently marked to reach the threshold 10%. As figure 4.27 shows, there are simply far fewer particles produced when plasma cutting aluminium in comparison to steel. Secondly, the marked area for the worst case of 304L stainless steel is large, both in comparison to the nominal case, as well as to the marked areas seen for the substantially thicker 10 mm carbon steel specimens. In a similar fashion, the saturation radius for 304L stainless sample is the only one for which the worst case is the larger of the two. Figure 4.30 a) and b) show a single second composite from midway through the nominal and worst case 304L stainless steel cuts, respectively. Examination of the figures reveals some enlightening details. Firstly, in each case a significant portion of the particles produced are falling in the foreground of the image. The operator rotated the torch backward for this cut in a manner which was not done to the same extent with previous cuts, and in so doing a significant amount of the hot particles were not registered by the thermal paper. Further confirmation of this can be seen in overhead plots of hot particle populations Appendix E. The plots show that the stainless steel plasma cutting tests are heavily weighted towards the front of the image, or the positive 'X' direction as compared to the experiments conducted with the other materials. This unfortunate occurrence suggests that plasma cutting of stainless steel has not been characterised as effectively as the other cases. Secondly, Figure 4.30b shows that the upward angle of the torch, in addition to the angling of the torch backward, is causing a significant number of the hot particles to travel directly downward to the thermal paper at the operators feet. This shower of sparks falling directly at the operators feet suggests why the worst case stainless steel cut has a more severe marked area in comparison to the nominal case when intuition might suggest they should be similar values.

Despite the differences observed in cutting of different materials, in general the long distances travelled, the large areas marked by the particles and the large saturation radii seen in the present results indicate that the plasma cutting process can pose a significant local and remote ignition hazard.

(a) Nominal plasma cutting 6mm stainless, one second composite



(b) Worst case plasma cutting 6mm stainless, one second composite

Figure 4.30: Comparison of Plasma Cutting 304L Stainless, one second composite

4.3.4 Air Carbon Arc Gouging

Four experiments to characterise the hot particle generation and distribution from air carbon arc gouging processes were performed on A516 carbon steel, comprising two cuts with the plate in the vertical plane, and two gouges with the plate in the horizontal plane. All tests were performed using 5 mm copper clad electrodes with the nominal case performed at a current of 200 Amps, while the worst cases were performed at a current of 295 amps.

Table 4.9 contains the key statistics of the hot particle distributions gathered during air carbon arc gouging using the nominal and several worst case process procedures. The table shows that particles traveled the farthest in the cutting operations. In fact, in Worst Case 1, particles traveled 9.9 m, which is the farthest that hot particles travelled in any process studied in this work. The high velocity compressed air involved in the cutting process had the effect of propelling material extreme distances.

Table 4.9: Air Carbon Arc Gouging Results

Case	**Type**	$\mathbf{D_{MAX}}$ [m]	$\overline{D}$ [m]	$\mathbf{A_{TOTAL}}$ [$\mathbf{m^2}$]	$\mathbf{A_{D_{MAX}}}$ [$\mathbf{mm^2}$]	$\mathbf{R_{SAT}}$ [m]
Nominal 1	Cut	9.4	1.1	0.086	40	0.72
Worst 1	Cut	9.90	1.1	0.077	95	0.32
Worst 2[1]	Gouge	8.3	1.8	-/-	46	0.61
Worst 3	Gouge	8.0	1.4	0.171	38	1.92

[1] Note that Arc Gouging worst case 2 was performed with only the main length of thermal paper laid out, so the total area comparison is not applicable, but the measurement is still valid for maximum distance

Figure 4.31 is a side view composite image of the Worst Case 2 air arc gouging process and indicates the trajectories of the many particles ejected from the work piece during this hot work operation. The paths of the particles which traveled well past 4.5 m from the operation can clearly be seen.

For purposes of visual comparison with previously discussed results, the distribution of hot particles produced with the air carbon arc gouging process is shown in Figure 4.32, an overhead plot of Worst Case 1. Larger size overhead plots for all air carbon arc gouging experiments can be found in Appendix E. Because less of the paper is saturated in comparison with the welding tests, the mark index at the bottom shows a much smaller magnitude at the upper end of the mark size. The path taken by the very far reaching hot particles can also be seen on the plot. The air carbon arc gouging process clearly produces particles which

Figure 4.31: 10 mm Air Carbon Arc Gouge Cut; Worst Case 2

are prone to travel along the ground upon impact, as the farthest reaching one rolled at least 4.5 m from its initial impact. As can be seen from Table 4.9, this particular particle was also the largest of all of the particles that travelled the greatest distances in the air carbon arc gouging data set.

While using the tool to horizontally gouge the plate, as in Worst Case 2 and 3, the shape of the kerf inhibited the length of the travel distance of the heated particles in comparison to the cutting orientation in Nominal and Worst Case 1. Accordingly, the maximum distance traveled by the hot particles in the Worst Case 2 and 3 gouging tests was lower, 8.3 and 8.0 m respectively. There was a marked increase in the average distance traveled by the particles for Worst Case 2 and 3 in comparison to the cutting operations, because the plate inhibited particles from landing directly at the feet of the operator until the end of each pass. Figure 4.33 illustrates this issue clearly. Figure 4.33a shows how the horizontal plate in front of the torch deflects hot material up and out over the thermal paper, impeding it from falling at the operators feet. This occurs for as long as there is sufficient space on the horizontal section to deflect the hot particles, until the situation in Figure 4.33b occurs, where the horizontal portion of the plate no longer interferes with the slag coming from the torch, at which point the slag can travel more directly to the floor.

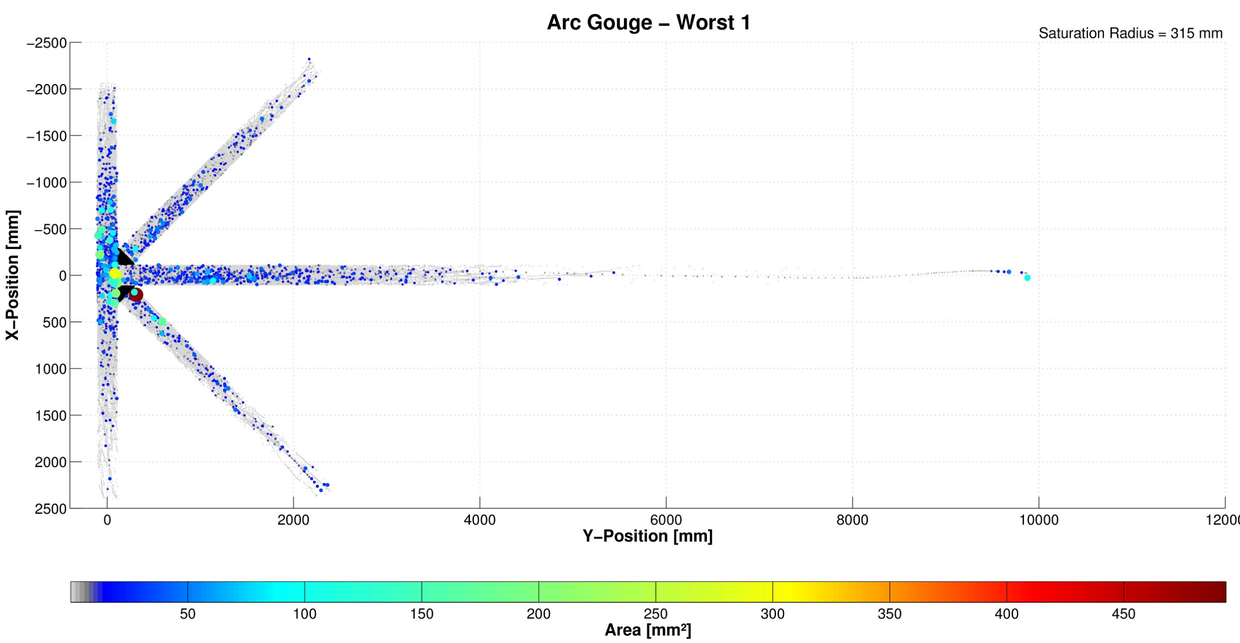
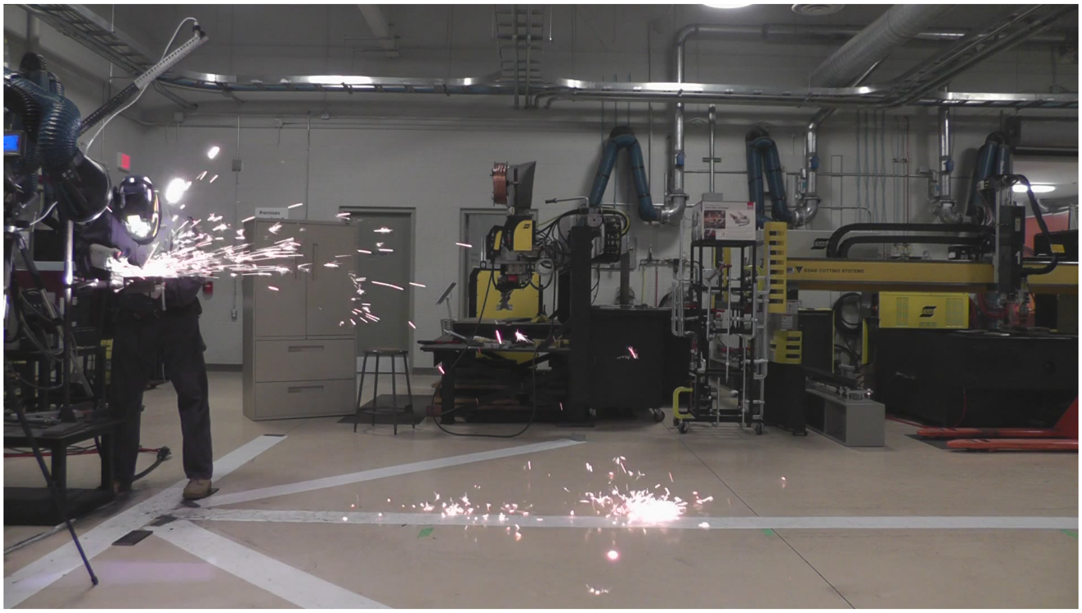


Figure 4.32: Air Carbon Arc Gouging Cut Hot Particle Distribution, Worst Case 1



(a) Worst Case Air Carbon Arc Gouging, 25 mm carbon steel, single frame at beginning of run

(b) Worst Case Air Carbon Arc Gouging, 25 mm carbon steel, single frame at end of run

Figure 4.33: Comparison of Beginning and End for Air Carbon Arc Gouging Worst Case 3, Run 2

Finally, the overall increase in hot particles and material ejected during carbon arc gouging the 25 mm plate in Worst Case 3 is reflected by significant increases in the value of total measured area, and also the magnitude of the saturation radius. Both the saturation radius and total marked area are double those of the next closest case. This demonstrates the drastic effect that increasing the cross section of the material has on the severity of hazard in the area surrounding a gouging operation. Independent of the differences between the cases studied here, it is clear that in general the carbon arc gouging process poses a significant remote ignition hazard regardless of orientation due to the sizes, temperatures and distances covered by the hot particles produced.

4.3.5 Oxyacetylene Cutting

A single experimental test of oxyacetylene cutting was performed; a single 200 mm long cut was made in 10 mm thick A516 carbon steel.

A composite side view image of the oxyacetylene cutting process is displayed in Figure 4.34 and the overall distribution statistics are shown in Table 4.10. From the Figure, it can be seen that a large number of heated particles fell to the floor directly below the process, while the Table shows that the maximum recorded distance travelled by any of the hot particles generated by the process was 4.7 m. While the bulk of the particles were expected to travel in the cutting direction, Figure 4.34 indicates that particles traveled to the operator's left, or into the depth of the image. This is because the torch was being angled to maintain preheat in the metal in front of the cut. Closer examination of Figure 4.34, then, suggests that in this case, hot particles may have traveled farther than is actually indicated by the marks on the thermal paper. The requirement to preheat the metal in front of the oxyacetylene torch when cutting should be remembered and accounted for when studying the process in future work.

Table 4.10: Oxyacetylene Cutting Results

$\mathbf{D_{MAX}}$ [m]	$\overline{D}$ [m]	$\mathbf{A_{TOTAL}}$ [m²]	$\mathbf{A_{D_{MAX}}}$ [mm²]	$\mathbf{R_{SAT}}$ [m]
4.7	1.1	0.168	6.7	0.98

Oxyacetylene cutting is the only process in this study during which large portions of the thermal paper ignited. In fact, figure 4.35 shows the paper within the immediate area of the cutting operation was consumed, inhibiting discernment of the number of particles, and to a lesser extent, the total marked area in that region. It is clear, then, that the particles generated during oxyacetylene cutting have been heated sufficiently to undergo exothermic oxidation and attain high temperatures. Due to their size and temperature, the hot particles removed from the kerf in the oxyacetylene cutting process have a high propensity to ignite any materials in the immediate vicinity of, and large area surrounding, the operation.

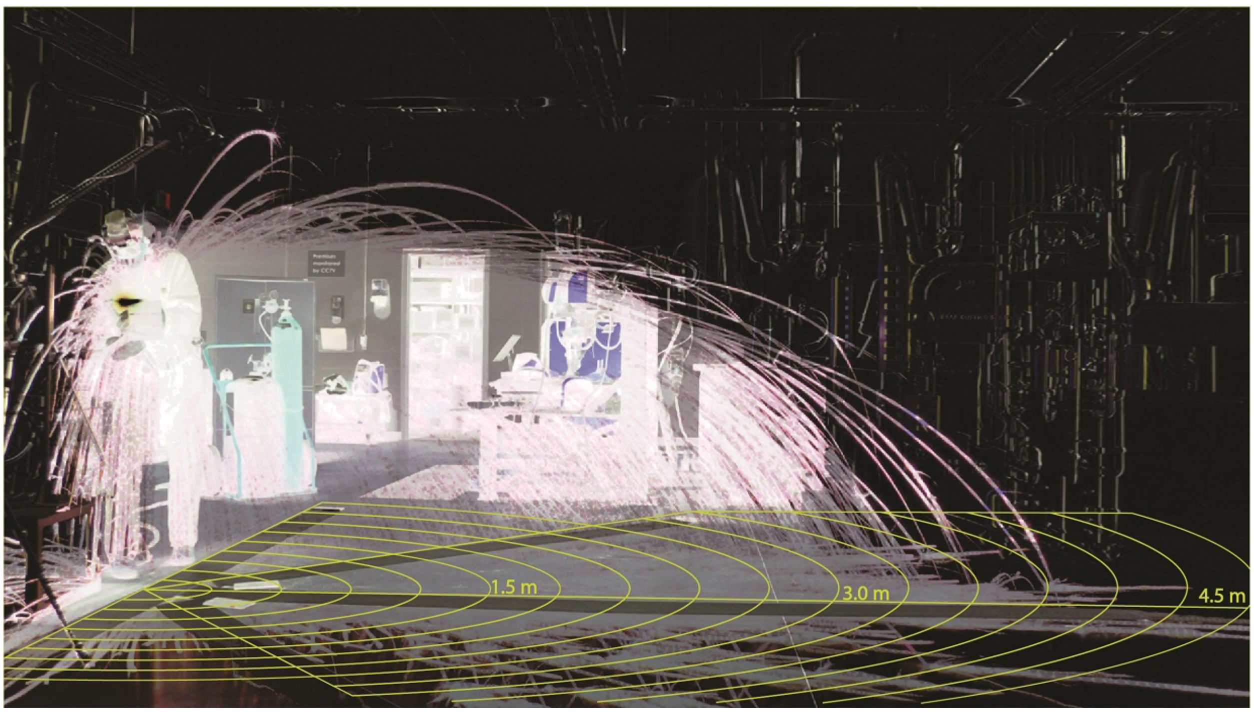


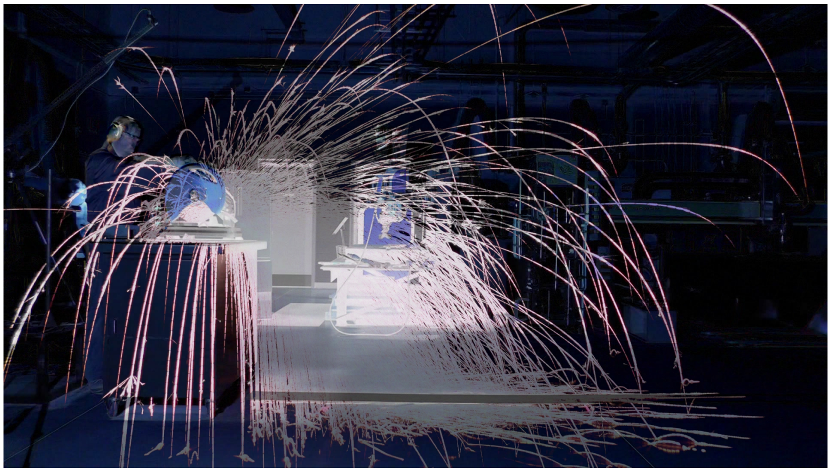
Figure 4.34: Composite of Heated Particles Ejected During Oxyacetylene Cutting

Figure 4.35: Thermal Paper Set Alight by Oxyacetylene Slag

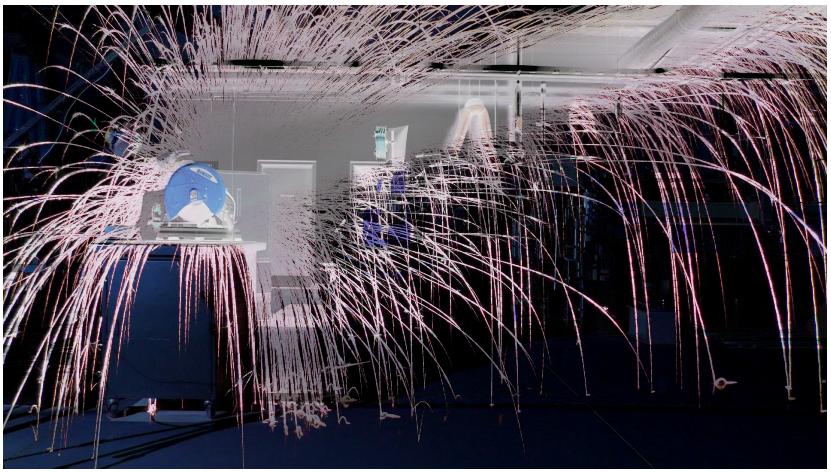
4.3.6 Cut-Off Saw

The hot particle distribution generated during use of the cut-off saw was tested for three different configurations of the spark guard on the saw. The spark guard was manipulated to achieve nominal, intermediate and worst case results while performing a 50 mm long cut of 10 mm thick A516 carbon steel. Due to the directional nature of the sparks produced by this process, only the main length of thermal paper, the 'Y' direction in Figure 3.2, was used.

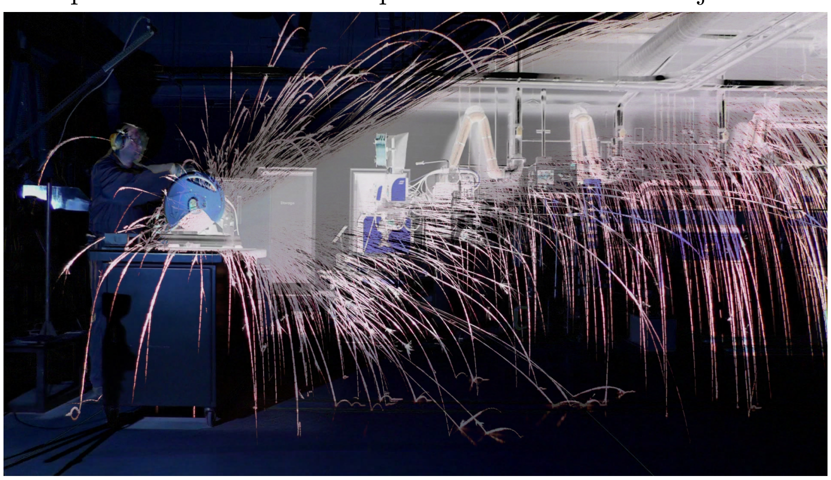
Figure 4.36a) through c) are composite images of the cuts performed using the saw in each of the three scenarios. Comparing and contrasting the different cases shown in the images provides useful context for understanding the statistical results. Figure 4.36a shows the operation with the guard in the proper position to catch sparks produced during the cutting operation; it can be seen that a large number of sparks were routed directly to the floor a short distance in front of the table. With the guard positioned properly, some hot particles did travel out of frame, but the number was small in comparison with the particle distribution shown in Figure 4.36b, where the guard was poorly adjusted. In Figure 4.36b, sparks traveled out of frame, upward and even back behind the operator. Finally, Figure 4.36c shows the operation as performed with the guard removed. While particles traveled in a less erratic manner in comparison to the case with the guard poorly positioned, it can be seen that a larger number of particles traveled up and out of frame than for either of the other two cases.



(a) Composite of Cut-Off Saw Operation With Guard Adjusted Properly



(b) Composite of Cut-Off Saw Operation With Guard Adjusted Poorly



(c) Composite of Cut-Off Saw Operation Without Guard

Figure 4.36: Composite Images, Cut-Off Saw Guard Configurations

Table 4.11 shows key statistics of the hot particle distributions produced while using the cut-off saw in the three scenarios. The results in the Table support the observations made above. A properly positioned guard served to catch hot particles generated from the work, such that they traveled shorter distances, on average only 1.1 m, and are directed downward onto the paper at the base of the table as shown in Figure 4.37. This did not happen for the other two cases in which the particles were observed to travel larger average distances of 2.6 m with the guard positioned poorly and 4.1 m with the guard removed. Similarly, the total marked area[2] determined with the guard in position was substantially higher than for either of the other two cases because the guard focused hot particles onto a specific spot on the thermal paper.

With the guard removed, particles were unimpeded and traveled the farthest. The average distance traveled in this configuration was 4.1 m while the value of D_{MAX} was 8.8 m. With the guard poorly positioned, the majority of sparks travel over the guard resulting in a wide variation in the direction of particle travel as seen in Figure 4.36b. This resulted in a maximum travel distance of 7.1 m and average measured travel distance of 2.5 m. Interestingly, with the guard properly adjusted, hot particles traveled farther than when it was poorly adjusted. Though the guard is seen to be highly effective, it is not perfect. As Figure 4.38 shows with the guard properly adjusted, there are sparks which traveled over the guard as well as others which ricochet off the table and off frame, thus travelling greater overall distances from the work piece.

Table 4.11: Cut-Off Saw Results

Case	$\mathbf{D_{MAX}}$ [m]	$\overline{D}$ [m]	$\mathbf{A_{TOTAL}}$ [m²]	$\mathbf{A_{D_{MAX}}}$ [mm²]	$\mathbf{R_{SAT}}$ [m]
Guard In Position	7.9	1.1	0.017	7	0.00
Guard Out of Position	7.1	2.6	0.002	12	0.00
Guard Removed	8.8	4.1	0.004	38	0.00

While the guard does not stop all of the particles, it is clear that this feature significantly reduces the remote ignition hazard during metal sawing operations, as sparks are less likely to travel away from the work and strike combustibles or become lodged in cracks. The thermal paper was not saturated for any of the cut-off saw experiments because a relatively small volume of material is removed when performing a cut with a cut-off saw, particularly

[2]The marked area for this process is based on a considerably different cut, including the orientation and cross section. The overall volume of removed material was lower, so this result is not directly comparable to other cutting processes.

in comparison to plasma or oxyacetylene cutting operations. Despite this, the experiment shows that the cut-off saw can propel hot material significant distances and is a credible local and remote ignition hazard.

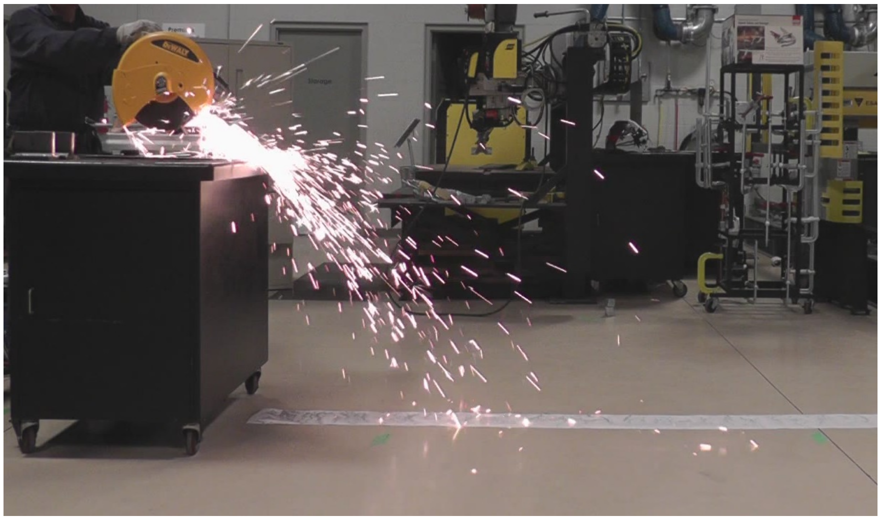


Figure 4.37: Well Adjusted Cut-Off Saw Guard, Directing hot particles onto floor

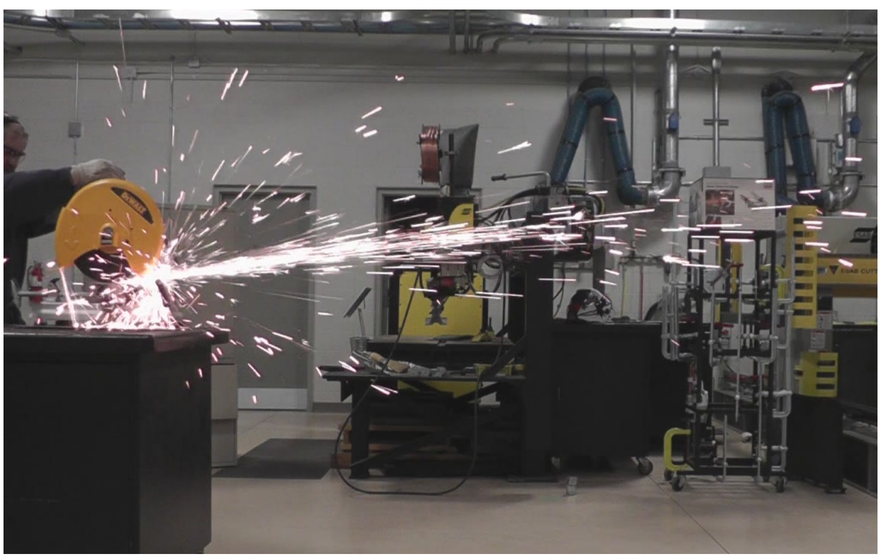


Figure 4.38: Well Adjusted Cut-Off Saw Guard, Bypassed by hot particles

4.3.7 Cut-Off Wheel

Use of a 4" cut off wheel was tested by using a new wheel to make gouging cuts into a 5 mm thick piece of ASTM A516 carbon steel. Figure 4.39 shows an overhead plot of the particle distribution left on the thermal paper during the cuts. The figure shows the distribution of particles is heaviest around the 2 m mark and that insufficient area on the thermal paper was marked during the cuts to saturate the paper.

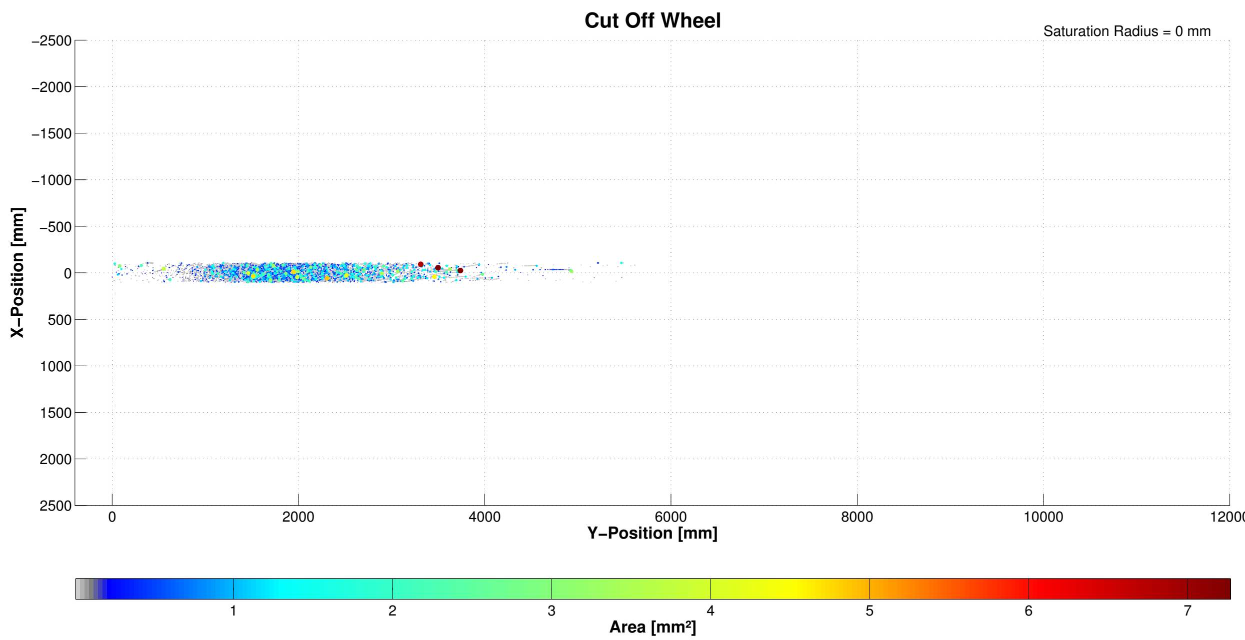


Figure 4.39: Particle Distribution, Cut-Off Wheel

Key statistics of the hot particle population generated whilst cutting with the cutting wheel are shown in Table 4.12. The maximum distance traveled by any hot particles in these tests was 5.7 m, with an average travel distance of 2.1 m. The value of marked area is based upon a different volume of removed material for this test than others, and so the figure should not be compared directly to the thermal cutting processes.

Table 4.12: Cut-Off Wheel Results

$\mathbf{D_{MAX}}$ [m]	$\overline{D}$ [m]	$\mathbf{A_{TOTAL}}$ [m^2]	$\mathbf{A_{D_{MAX}}}$ [mm^2]	$\mathbf{R_{SAT}}$ [m]
5.61	2.09	0.002	2	0.00

4.3.8 Summary & Analysis of Ignition Potential

Table 4.13 summarizes key statistics of the particle distribution for each of the processes in this section.

Table 4.13: Summary Statistics of Spark Producing Processes

Process	**Case**	$\mathbf{D_{MAX}}$ **[m]**	$\overline{D}$ **[m]**
GTAW - SMAW	Nominal 1	3.0	0.5
GTAW - SMAW	Nominal 2	6.5	0.5
SMAW	Worst 1	4.8	0.6
SMAW	Worst 2	7.5	0.6
GMAW	Nominal	3.3	0.6
GMAW	Worst	4.0	0.6
Arc Gouging	Nominal 1	9.4	1.1
Arc Gouging	Worst 1	9.9	1.1
Arc Gouging	Worst 2	8.3	1.8
Arc Gouging	Worst 3	8.0	1.4
Plasma Cutting	Nominal 1	6.8	1.4
Plasma Cutting	Worst 1	7.3	1.4
Plasma Cutting	Nominal 2	7.9	1.9
Plasma Cutting	Worst 2	6.4	1.9
Plasma Cutting	Nominal 3	5.7	1.6
Plasma Cutting	Worst 3	4.6	1.1
Plasma Cutting	Nominal 4	8.4	1.3
Plasma Cutting	Worst 4	5.8	1.1
Oxyacetylene Cutting	Nominal	4.7	1.1
Chop Saw Guard In	Nominal	7.9	1.1
Chop Saw Guard Out	Worst 1	7.1	2.6
Chop Saw No Guard	Worst 2	8.8	4.1
Cut Off Wheel	Nominal	5.6	2.1

Comparing D_{MAX} and $\overline{D}$ can provide a good basis upon which to compare the overall size of the envelope of influence of each of the processes in this section, and it is clear that characteristic distances exist through which hot particles travel from a given group of hot work processes. However, it is also clear from comparing measured values of A_{TOTAL} that stark differences exist between the relative intensity of the ignition hazard inside of the envelope area affected by a process. Since the mark area correlates positively with ignition propensity, and is less susceptible to interference of overlapping marks, it was chosen as the most appropriate parameter with which to develop a process hazard parameter for comparison of hot particle producing processes. Therefore, to establish a measure of the ignition potential, the cumulative area of thermal paper marked by all particles within discrete radial bands away from the work piece was determined for each process studied. To ease the comparison, corresponding marked areas from the plasma Nominal Case 1 were selected as a suitable value with which to normalize the values of ignition intensity, because the nominal plasma case had a relatively large marked area in each of the three intervals. The result is a unitless index for the potential ignition hazard from each process at discrete intervals of distance from the work piece.

Figure 4.40 shows ignition hazards as calculated relative to the data for the plasma Nominal Case 1, using intervals from 0 to 1 m (first interval), 1 to 5 m (second interval) and greater than 5 m (third interval). Within a distance interval, a process value below one indicates a lower threat to combustibles than the nominal case of plasma cutting, while a value greater than one indicates a larger threat. A score of zero or approaching zero indicates that the process had zero or minimal influence at the distance interval in question, as observed using the methodology and data collected here.

From studying the results for welding in Figure 4.40 it can be seen that the majority of the relative ignition intensity due to the processes is inside of the first two intervals, hot particles clearly do not have a tendency to travel as far as the cutting processes. Results show that poorly configured SMAW welding, Worst Case number 1, ensued in the highest measured relative ignition intensity in the first interval, over 2.5 times larger than for plasma cutting. The poor choice of electrode resulted in overheating and many starts and stops leading to significantly larger marked area in the first interval, and the largest of any welding process within the second interval. SMAW Worst Case 2 registered much lower because the larger electrodes used resulted in faster welding travel and less overall welding time than the SMAW Worst Case 1. Additionally, SMAW Worst Case 2 is the only welding process to register in the third interval because interpass cleaning was performed using the 9” grinding wheel, producing larger volumes of far travelling hot particles than other cleaning methods.

The GTAW-SMAW results represent the nominal counterpart to the SMAW welds. The combined effects on the relative ignition intensity of the GTAW root pass and the use of appropriately sized, low hydrogen electrodes are drastic across the first two intervals. Both GTAW-SMAW cases are near identical in Figure 4.40, again demonstrating that powered interpass cleaning methods increase the envelope traveled by hot particles, but do not significantly impact the relative ignition intensity.

GMAW welding produced an ignition intensity in the first interval which was equivalent to plasma cutting, and also demonstrates the significant drop in relative ignition intensity between the first and second intervals characteristic of welding. Little to no difference in ignition intensity is seen between the Nominal and Worst case GMAW results despite the difference in shielding gas and manual versus grinding interpass cleaning.

When examining welding results, it is ultimately clear that the largest relative ignition intensity is inside the first interval, at less than 1 m. However, there is a distinguishable effect inside of the 5 m interval as well. The only registration in the third interval for welding was SMAW Worst Case 2, and coincides with the use of a 9" grinder for interpass cleaning. Outside of the specific welding process used, the most significant factor affecting the relative ignition intensity is the electrode selection and sizing, as electrode types only changed between the cases involving the SMAW process, and are the only test cases between which the relative ignition intensity alters significantly. The reason for this is that the electrode selection governs a plethora of welding parameter selections such as appropriate selections for welding voltage, current and travel speed, all of which affect the amount of hot particles, slag and sparks produced during the process.

The thermal cutting processes have a markedly increased influence in the second and third intervals in comparison to the welding operations. While the plasma cutting processes show wide variation depending on the material being cut, all configurations in ferrous materials on the Figure register in the third interval. With 10 mm material as the benchmark, cutting 13 mm carbon steel results in over 3 times the relative hazard in the second interval and just under 1.5 times the hazard at distances over 5 m. In stark contrast, cutting 13 mm 6061 Aluminum produced the lowest hazard in the 0 to 1 m interval, and second lowest in the 1 to 5 m interval, while not registering as an issue beyond 5 m. In addition to differences between workpiece materials, the wide variation between the nominal and worst case configurations for each, reflecting the variability in the process, is again apparent. This is most notable in the relative ignition intensity in the second interval, where the ignition intensity was over 1.5 times larger than the worst case.

Although arc gouging is the process with the farthest travelling hot particles, the relative ignition intensity for the process appears less severe than for plasma cutting. When removing significantly more material than the plasma cutting, as in Arc Gouging Worst Case 3, the relative ignition intensity approaches that of the Worst Case 2 of plasma cutting.

Oxyacetylene cutting represents the third highest relative ignition intensity measure in the first interval, but drops to half of the value of normative process in the second interval and does not register on the plot beyond 5 m. As stated previously, large amounts of molten slag fell directly on the paper, and oxyacetylene cutting is the only process to have ignited the thermal paper.

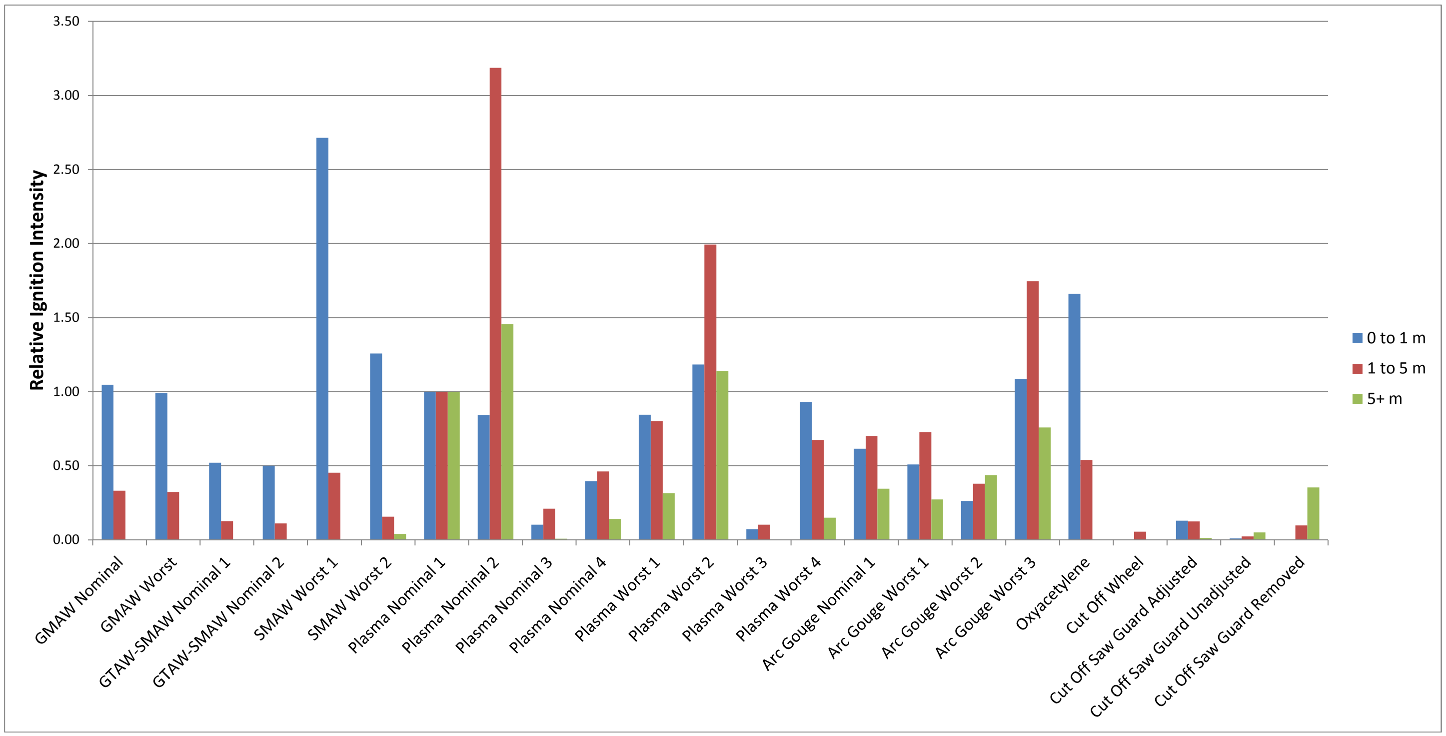


Figure 4.40: Process Ignition Intensity

Chapter 5

Closure

5.1 Conclusions

In light of the objective of this work, to asses the fire hazards associated with performing various forms of hot work relevant to the nuclear industry, the following conclusions have been made.

1. Hot work is a necessity, not only in the nuclear, but across all industries. With proper understanding of the hazards involved, controls can be employed to mitigate the inevitable risk resulting from hot work operations.

The necessity for understanding and being able to assess the potential fire hazards associated with hot work processes is deep-seated. Hot work is an inevitable part of the operations in Canadian industry, but even the most carefully performed hot work processes open organizations up to the risk of loss, and in the nuclear industry, the magnitude of such events can be catastrophic. As is true with any risk, steps to mitigate the possibility of loss are most effective if the nature of the hazards is understood; developing a better understanding of the fire hazards involved in various forms of hot work is essential to reducing the risk inherent to hot work processes in future.

2. A dearth of scientific understanding of the ignition hazards of hot work permeates into standards, resulting in weaker legislation and less effective hot work programs.

Review of literature showed a dearth of scientific understanding of the ignition hazards of hot work. Hot work standards diverge on specification of crucial fire prevention measures such as separation and the need to post a fire watch. Other standards, such as the NFCC, diverge yet further on matters as fundamental as the definition of hot work itself. The lack of consensus from authoritative bodies points strongly to a lack of understanding of the issues and proves frustrating and costly for operators and organizations alike, since controlled processes require ticketing systems, and adherence under current regulation requires excessive precaution for many forms of hot work.

Scientific studies into hot work processes typically focused only on potential hazards associated with a single process and included only shielded metal arc welding, oxyacetylene cutting and arc gouging. The scope of the available research was so narrow that identifying consistent hazard parameters across studies was impossible. The development of understanding of ignition hazards associated with hot work therefore presents many opportunities to increase safety while removing frivolous requirements from legislation.

3. Significant differences in ignition propensity of hot work processes can be measured.

Ignition tests, burn marking of tissue paper, and optical methods were used in previous studies to assess sparks and hot particles from welding or cutting processes and to assess their potential to ignite fires. In this work, an experimental protocol was developed in order to create a scientific database of temperatures and hot particle distributions associated with those hot work processes of interest to the Canadian nuclear industry. Combinations of thermocouple temperature measurements and infrared thermography, supplemented with data from a new experimental method by which to study particle distributions arising from a given process, proved successful for identification of potential hazards associated with each of the relevant hot work processes.

4. A new method was developed and successfully applied to categorize the ignition propensity of hot work processes.

Experimental data were used to classify each of the candidate hot work processes into one of three categories: processes presenting hot surface hazards, those presenting hot surface hazards with potential to generate hot particles and finally those which are expected to generate hot particles all of the time.

The first category of processes, presenting only hot surface hazards, included iron and torch soldering, use of a heat gun for paint stripping, application of heat-shrink, and application of heated adhesives. These were found to best be characterized by a critical process temperature, defined as the highest measured temperature of either the workpiece or the tool that was measured during the process. This temperature is useful for indexing across processes and comparing to ignition and pyrolysis temperatures of common combustibles.

The second category of processes involved those with hot surfaces and the potential to generate hot particles. These included manual sanding and filing, brazing, sawing and drilling. For these, critical process temperature was one parameter of interest, but did not fully describe the hazards associated with these operations. Therefore, both the volume and distribution of hot particles produced by each process were determined using infrared and visual photographic methods. It was found that manual sanding and filing, while considered hot work under the NFCC, generate temperatures less than 50°C over ambient and therefore pose little fire hazard. Particles from the other three processes pose a significant ignition hazard and, in the past, sawing and drilling have been implicated in fires on nuclear sites.

The final category of processes involved high localised process temperatures and, for the most part, are known to generate significant numbers of hot particles. These included welding, thermal and high speed abrasive cutting and arc gouging processes. For this category, it was necessary to develop a new test methodology to determine the overall distributions of hot particles generated by each process. Based on the data, analysis methods were also developed to evaluate the relative ignition hazards across processes. Welding processes do not pose a significant relative ignition hazard beyond 5 m from the operation; however, the impact of welding process and electrode selection on the level of hazard is large. Powered methods of interpass cleaning have a large effect on the maximum distance travelled by hot particles in welding. Cutting processes propel particles significantly further than welding processes and pose a higher ignition hazard than welding at distances between 1 and 5 m and over 5 m from the operation. Plasma cutting of similar sections of carbon steel led to higher relative ignition hazard than was seen for arc gouging.

The three category system developed in this research allowed identification of key ignition hazard parameters with which to assess and compare hot work processes, providing a new, tailored approach to analysis of ignition propensity from hot work operations.

5. A new experimental method was developed to characterize those hot work processes which generate hot particles.

Characterization of hot work processes which generated hot particles proved challenging and few consistent methods were described in previous studies. Therefore, a new thermal paper methodology was developed to facilitate tracking of hot particles produced by Category 3 processes. Thermal paper was laid on the floor in a strategic pattern, while various forms of hot work were carried out at a consistent distance above the floor. Image analysis was performed on digitized sections of the paper to define the landing coordinates and size of each mark left by the thousands of particles generated by each process. While the maximum distance that particles travelled was certainly of interest, it was found that this value had to be combined with a measure of the total marked area on the thermal paper to determine the overall ignition propensity of a process. The integrated area of marks in the discrete spatial intervals of 0 to 1 m, 1 to 5 m and greater than 5 m was calculated and normalised by the total marked area measured in that interval for the nominal plasma cut into 10 mm thick carbon steel. This allowed determination of the relative ignition intensity both between processes and at different distance intervals from each hot work operation.

6. Results of this study can be generally applied to hot work processes in any industry.

Although the processes studied here are tailored specifically to the nuclear industry, the methods, hazard parameters and findings are relevant to hot work operations that can be found in many other facets of industry. Once understanding in this area improves, information regarding the critical temperatures, hot particle distributions, and the extent of the envelope of influence of each process will become even more valuable in the assessment and mitigation of fire hazards resulting from hot work.

5.2 Recommendations

This work is by no means exhaustive. Despite attempts to emulate switching between nominal and worst case parameters for many of the processes, more work is required. Due to the complexity and number of tests that are required to characterize even one hot work process across various key parameters, welding and cutting processes were limited to a singular orientation and work piece shape, with a limited selection of metals. 3G and 4G welds as well as fillet welds in various workpiece dimensions may generate drastically different hot particle distributions. Pipe welds are some of the most common, and challenging welds to perform, and are almost always required to be performed in situ and should be tested so that a comparison between other welding formats and orientations and the work done here may be drawn. Welding processes that involved workpieces of dissimilar metals, or any material other than carbon steel could not be investigated and judging from results of other processes for which different metals were studied alongside carbon steel, the hot particle distribution can be completely different for the same process conducted using different base metals. Tests to ascertain the characteristic difference of welding other materials, and certainly dissimilar metals, would be of value.

For cutting processes, both thermal and mechanical, it is well understood that oxidation is the largest factor in determining the severity of the hot particle distribution, and metals such as titanium are known to oxidize much more readily during cutting processes. This is a factor which should be investigated to gain better understanding of ignition potential from those processes as well.

All cutting and welding tests were performed on the ground at a comfortable level for the operator. Understanding the role that elevation plays in terms of increasing the expected spread of hot particles is critical as the elevated hot work scenario frequently is encountered in industry. Results such as these could be made even more applicable if elevation was also taken into account.

Finally, it is recommended that the data and conclusions of this work be taken into account by safety authorities and regulatory bodies[1] in the improvement and further development of future standards promoting the safety of hot work practices. The implementation and reference of technical data in the safety standards is expected to promote discussion and awareness that is sure to fortify both the effectiveness as well as recognition of the necessity of such standards in Canadian industry.

[1] At the time of writing, this work has been presented to both the Canadian Nuclear Safety Commission and the Canadian Standards Association W117 Committee. Additionally, the Ontario Fire Marshal has expressed interest in utilising the data to improve existing clauses in the National Fire Code of Canada.

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APPENDICES

Appendix A

Project Equipment Listing

Table A.1: Project Equipment List

Tool	Manufacturer	Model Number
Hammer Drill	DeWalt	DW505
Heat Gun	Wagner	HT1000
Hot Melt Adhesive Gun	Steinel	GF 3002
Reciprocating Saw	DeWalt	DW304PK
4.5” Angle Grinder	DeWalt	D8402
7” Angle Grinder	DeWalt	DW840
14” Cut-Off Saw	DeWalt	D28715
Soldering Gun	Mastercraft	58-6361-8
GTAW Machine	Miller	Dynasty 350
GMAW Machine	Lincoln	Powerwave 300
SMAW Machine	Miller	Pipeworx 400
Arc Gouging Machine	Lincoln	Powerwave 300
Plasma Cutter	Hypertherm	Powermax 85

Appendix B

Welding Process Specifications

B.1 Gas Tungsten Arc Welding (GTAW) & Shielded Metal Arc Welding (SMAW)

CWB Form 160E/99-1

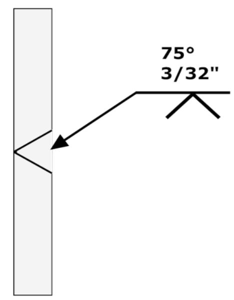
CANADIAN WELDING BUREAU	**WELDING PROCEDURE DATA SHEET**	WPDS NO.:	
		DATE: 3/19/2013	Rev.:

GTAW-SMAW Nominal 1

Welding Processes:	1	GTAW Pulsed: ☐ Yes ☐ No	2	SMAW Pulsed: ☐ Yes ☐ No
Shielding Gas Type:		100% Argon		

Positions:	2G (Horizontal)
Process Mode:	☑ Manual ☐ Semi-Auto ☐ Machine ☐ Auto
Joint Type:	☑ Butt ☐ Tee ☐ Corner ☐ Lap ☐ Edge
Penetration:	☑ Complete ☐ Partial ETT= ☐ Fillet
Backing:	Material: Thickness:
Backgouging:	☐ Yes Method:
	☑ No Depth:
Electrode Extension:	5/16" GTAW
Nozzle Diameter(s):	
Flux Classification:	N/A
Tungsten Electrode:	Type: 2% Thoriated Dia.: 3/32"
Cleaning Procedures	Manual Wire Brushing
CSA W186 Rebar Splice Type:	☐ Direct Splice ☐ Indirect Splice ☐ Lap Splice ☐ Rebar to Structural Member Only

Joint Configuration & Pass/Layer Sequence



Identification of Base Material (for CSA W186 indicate carbon equivalent, max. phosphorus & sulphur content)

Part	Specification & Grade	Thickness or Dia.	Special Requirements
I	ASTM A516 Grade 70	3/8"	
II	ASTM A516 Grade 70	3/8"	

Identification of Filler Material

Process	Trade Name	Classification	Group	Filler Treatment
GTAW		ER49S-2		
SMAW		E4918-1	4	

Welding Parameters

Thick-ness ( )	Weld Size/ ETT	Layer	Pass Number	Welding Process	Dia. (in.)	Wire Feed Speed	Current A	Volt V	Current Polarity	Welding Speed (in/min)	Burn-Off Rate ( )	Gas Flow Rate (CFH)	Heat Input ( )
		1	1	GTAW	3/32		140		DCEN	2		20	
		2	2-3	SMAW	1/8		120	22-24	DCEP	8			
		3	4-5	SMAW	1/8		120	22-24	DCEP	9.6			
		CAP	6-7	SMAW	1/8		120	22-24	DCEP	9.6			

Heat treatment :

Preheat min:	24^0C	Interpasstemp.max.:	250°C
		Interpasstemp.min.:	175°C

Remarks:

Figure B.1: Weld Process Specification for GTAW-SMAW Nominal 1

CWB Form 160E/99-1

CANADIAN WELDING BUREAU

WELDING PROCEDURE DATA SHEET

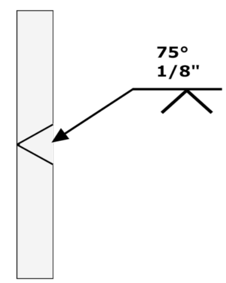
WPDS NO.:
DATE: 3/19/2013 Rev.:

GTAW-SMAW Nominal 2

Welding Processes:	1	GTAW Pulsed: ☐ Yes ☐ No	2	SMAW Pulsed: ☐ Yes ☐ No
Shielding Gas Type:		100% Argon		

Positions:	2G (Horizontal)
Process Mode:	☑ Manual ☐ Semi-Auto ☐ Machine ☐ Auto
Joint Type:	☑ Butt ☐ Tee ☐ Corner ☐ Lap ☐ Edge
Penetration:	☑ Complete ☐ Partial ETT= ☐ Fillet
Backing:	Material: Thickness:
Backgouging:	☐ Yes Method: ☑ No Depth:
Electrode Extension:	5/16" GTAW
Nozzle Diameter(s):	
Flux Classification:	N/A
Tungsten Electrode:	Type: 2% Thoriated Dia.: 3/32"
Cleaning Procedures	4" Grinder Operatred Wire Brush
CSA W186 Rebar Splice Type:	☐ Direct Splice ☐ Indirect Splice ☐ Lap Splice ☐ Rebar to Structural Member Only

Joint Configuration & Pass/Layer Sequence



Identification of Base Material (for CSA W186 indicate carbon equivalent, max. phosphorus & sulphur content)

Part	Specification & Grade	Thickness or Dia.	Special Requirements
I	ASTM A516 Grade 70	3/8"	
II	ASTM A516 Grade 70	3/8"	

Identification of Filler Material

Process	Trade Name	Classification	Group	Filler Treatment
GTAW		ER49S-2		
SMAW		E4918-1	4	

Welding Parameters

Thick-ness ( )	Weld Size/ ETT	Layer	Pass Number	Welding Process	Dia. (in.)	Wire Feed Speed	Current A	Volt V	Current Polarity	Welding Speed (in/min)	Burn-Off Rate ( )	Gas Flow Rate (CFH)	Heat Input ( )
		1	1	GTAW	3/32		140		DCEN	2		20	
		2	2-3	SMAW	1/8		120	22-24	DCEP	7			
		3	4-5	SMAW	1/8		120	22-24	DCEP	10			
		CAP	6-7	SMAW	1/8		120	22-24	DCEP	10			

Heat treatment :

Preheat min:	24℃	Interpasstemp.max.:	225℃
		Interpasstemp.min.:	250℃

Remarks:

Figure B.2: Weld Process Specification for GTAW-SMAW Nominal 2

CWF Form 160E/99-1

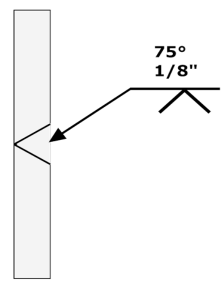
CANADIAN WELDING BUREAU	**WELDING PROCEDURE DATA SHEET**	WPDS NO.:
		DATE: 3/21/2013 Rev.:

SMAW Worst 1

Welding Processes:	1	SMAW Pulsed: ☐ Yes ☐ No	2 Pulsed: ☐ Yes ☐ No
Shielding Gas Type:			

Positions:	2G (Horizontal)
Process Mode:	☑ Manual ☐ Semi-Auto ☐ Machine ☐ Auto
Joint Type:	☑ Butt ☐ Tee ☐ Corner ☐ Lap ☐ Edge
Penetration:	☑ Complete ☐ Partial ETT= ☐ Fillet
Backing:	Material: Thickness:
Backgouging:	☐ Yes Method:
	☑ No Depth:
Electrode Extension:	3/16"
Nozzle Diameter(s):	
Flux Classification:	N/A
Tungsten Electrode:	Type: Dia.:
Cleaning Procedures	DeWalt 4" Grinder
CSA W186 Rebar Splice Type:	☐ Direct Splice ☐ Indirect Splice ☐ Lap Splice ☐ Rebar to Structural Member Only

Joint Configuration & Pass/Layer Sequence



Identification of Base Material (for CSA W186 indicate carbon equivalent, max. phosphorus & sulphur content)

Part	Specification & Grade	Thickness or Dia.	Special Requirements
I	ASTM A516 Grade 70	3/8"	
II	ASTM A516 Grade 70	3/8"	

Identification of Filler Material

Process	Trade Name	Classification	Group	Filler Treatment
SMAW		E6011	4	

Welding Parameters

Thick-ness ( )	Weld Size/ ETT	Layer	Pass Number	Welding Process	Dia. (in.)	Wire Feed Speed	Current A	Volt V	Current Polarity	Welding Speed (in/min)	Burn-Off Rate ( )	Gas Flow Rate (CFH)	Heat Input ( )
		1	1	SMAW	1/8		74	24	DCEP	1.7			
		2	2-5	SMAW	1/8		82	27	DCEP	7.5			
		3	5-9	SMAW	1/8		82	24-27	DCEP	9			

Heat treatment :			
Preheat min:	24^0C	Interpasstemp.max.:	250℃
		Interpasstemp.min.:	175℃
Remarks:			

Figure B.3: Weld Process Specification for SMAW Worst 1

CWB Form 160E/99-1

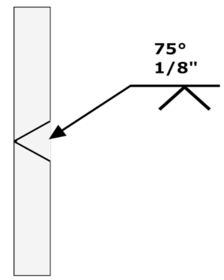
CANADIAN WELDING BUREAU	WELDING PROCEDURE DATA SHEET	WPDS NO.:			
		DATE:	4/8/2013	Rev.:	

SMAW Worst 2

Welding Processes:	1	SMAW	Pulsed: ☐ Yes ☐ No	2	Pulsed: ☐ Yes ☐ No
Shielding Gas Type:					

Positions:	2G (Horizontal)
Process Mode:	☑ Manual ☐ Semi-Auto ☐ Machine ☐ Auto
Joint Type:	☑ Butt ☐ Tee ☐ Corner ☐ Lap ☐ Edge
Penetration:	☑ Complete ☐ Partial ETT= ☐ Fillet
Backing:	Material: Thickness:
Backgouging:	☐ Yes Method:
	☑ No Depth:
Electrode Extension:	3/16"
Nozzle Diameter(s):	
Flux Classification:	N/A
Tungsten Electrode:	Type: Dia.:
Cleaning Procedures	DeWalt 9" Grinder
CSA W186 Rebar Splice Type:	☐ Direct Splice ☐ Indirect Splice ☐ Lap Splice ☐ Rebar to Structural Member Only

Joint Configuration & Pass/Layer Sequence



Identification of Base Material (for CSA W186 indicate carbon equivalent, max. phosphorus & sulphur content)

Part	Specification & Grade	Thickness or Dia.	Special Requirements
I	ASTM A516 Grade 70	3/8"	
II	ASTM A516 Grade 70	3/8"	

Identification of Filler Material

Process	Trade Name	Classification	Group	Filler Treatment
SMAW		E6011		

Welding Parameters

Thick-ness ( )	Weld Size/ ETT	Layer	Pass Number	Welding Process	Dia. (in.)	Wire Feed Speed	Current A	Volt V	Current Polarity	Welding Speed (in/min)	Burn-Off Rate ( )	Gas Flow Rate (CFH)	Heat Input ( )
		1	1	SMAW	5/32		90	23-28	DCEP	6			
		2	2-3	SMAW	5/32		95	24-25	DCEP	7.0			
		3	4-7	SMAW	5/32		95	24-26	DCEP	7.5			

Heat treatment :			
Preheat min:	24^0C	Interpasstemp.max.:	450℃
		Interpasstemp.min.:	185℃
Remarks:			

Figure B.4: Weld Process Specification for SMAW Worst 2

B.2 Gas Metal Arc Welding (GMAW)

CWB Form 160E/99-1

CANADIAN WELDING BUREAU

WELDING PROCEDURE DATA SHEET

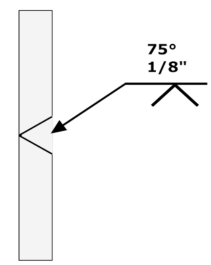
WPDS NO.:
DATE: 3/21/2013 Rev.:

GMAW Nominal

Welding Processes:	1	MIG Pulsed: ☐ Yes ☐ No	2	Pulsed: ☐ Yes ☐ No
Shielding Gas Type:		85 Argon 15 CO2		

Positions:	2G Horizontal
Process Mode:	☑ Manual ☐ Semi-Auto ☐ Machine ☐ Auto
Joint Type:	☑ Butt ☐ Tee ☐ Corner ☐ Lap ☐ Edge
Penetration:	☑ Complete ☐ Partial ETT= ☐ Fillet
Backing:	Material: Thickness:
Backgouging:	☐ Yes Method:
	☑ No Depth:
Electrode Extension:	5/16"
Nozzle Diameter(s):	
Flux Classification:	
Tungsten Electrode:	Type: Dia.:
Cleaning Procedures	Manual Wire Brush
CSA W186 Rebar Splice Type:	☐ Direct Splice ☐ Indirect Splice ☐ Lap Splice ☐ Rebar to Structural Member Only

Joint Configuration & Pass/Layer Sequence



Identification of Base Material (for CSA W186 indicate carbon equivalent, max. phosphorus & sulphur content)

Part	Specification & Grade	Thickness or Dia.	Special Requirements
I	A516 Grade 70	3/8"	
II	A516 Grade 70	3/8"	

Identification of Filler Material

Process	Trade Name	Classification	Group	Filler Treatment
		ER49S-6		

Welding Parameters

Thick-ness ( )	Weld Size/ ETT	Layer	Pass Number	Welding Process	Dia. (mm)	Wire Feed Speed ( )	Current A	Volt V	Current Polarity	Welding Speed ( )	Burn-Off Rate ( )	Gas Flow Rate ( )	Heat Input ( )
		1	1	1	1.2	241	130	17.9	DCEP	17			
		2	2-3	1	1.2	360	128	21	DCEP	20			
		3	4-6	1	1.2	360	128	21	DCEP	12			

Heat treatment :

Preheat min:	24°C	Interpasstemp.max.:	330^0C
		Interpasstemp.min.:	300^0C

Remarks:
Testing Initialised 10.21 AM

CWB Acceptance

Company Authorization

Date:

Figure B.5: Weld Process Specification for GMAW Nominal

CWB Form 160E/99-1

CANADIAN WELDING BUREAU

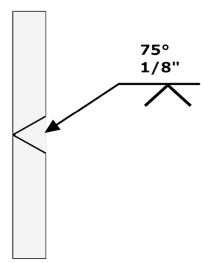
WELDING PROCEDURE DATA SHEET

WPDS NO.:
DATE: 3/21/2013 Rev.:

GMAW Worst

Welding Processes:	1	MIG	Pulsed: ☐ Yes ☐ No	2	Pulsed: ☐ Yes ☐ No
Shielding Gas Type:		CO2 100%			

Positions:		Joint Configuration & Pass/Layer Sequence
Process Mode:	☑ Manual ☐ Semi-Auto ☐ Machine ☐ Auto	
Joint Type:	☑ Butt ☐ Tee ☐ Corner ☐ Lap ☐ Edge	
Penetration:	☑ Complete ☐ Partial ETT= ☐ Fillet	
Backing:	Material: Thickness:	
Backgouging:	☐ Yes Method:	
	☑ No Depth:	
Electrode Extension:	5/16"	
Nozzle Diameter(s):		
Flux Classification:		
Tungsten Electrode:	Type: Dia.:	
Cleaning Procedures	4" Grinding Wheel	
CSA W186 Rebar Splice Type:	☐ Direct Splice ☐ Indirect Splice ☐ Lap Splice ☐ Rebar to Structural Member Only	



Identification of Base Material (for CSA W186 indicate carbon equivalent, max. phosphorus & sulphur content)

Part	Specification & Grade	Thickness or Dia.	Special Requirements
I	A516		
II	A516		

Identification of Filler Material

Process	Trade Name	Classification	Group	Filler Treatment
		ER49S-6		

Welding Parameters

Thick-ness ( )	Weld Size/ ETT	Layer	Pass Number	Welding Process	Dia. ( )	Wire Feed Speed ( )	Current A	Volt V	Current Polarity	Welding Speed ( )	Burn-Off Rate ( )	Gas Flow Rate ( )	Heat Input ( )
		1	1			241		21.3	DCEP				
		2	2-3			360	176-180	20.9	DCEP				
		3	4-6			360	176-180	20.9	DCEP				

Heat treatment :			**CWB Acceptance**	**Company Authorization**
Preheat min:		Interpasstemp.max.:		
		Interpasstemp.min.:		
Remarks:				
# 5 MIG Worst Case 11.30 AM				Date:

Figure B.6: Weld Process Specification for GMAW Worst

Appendix C

Hot Surface Process Results

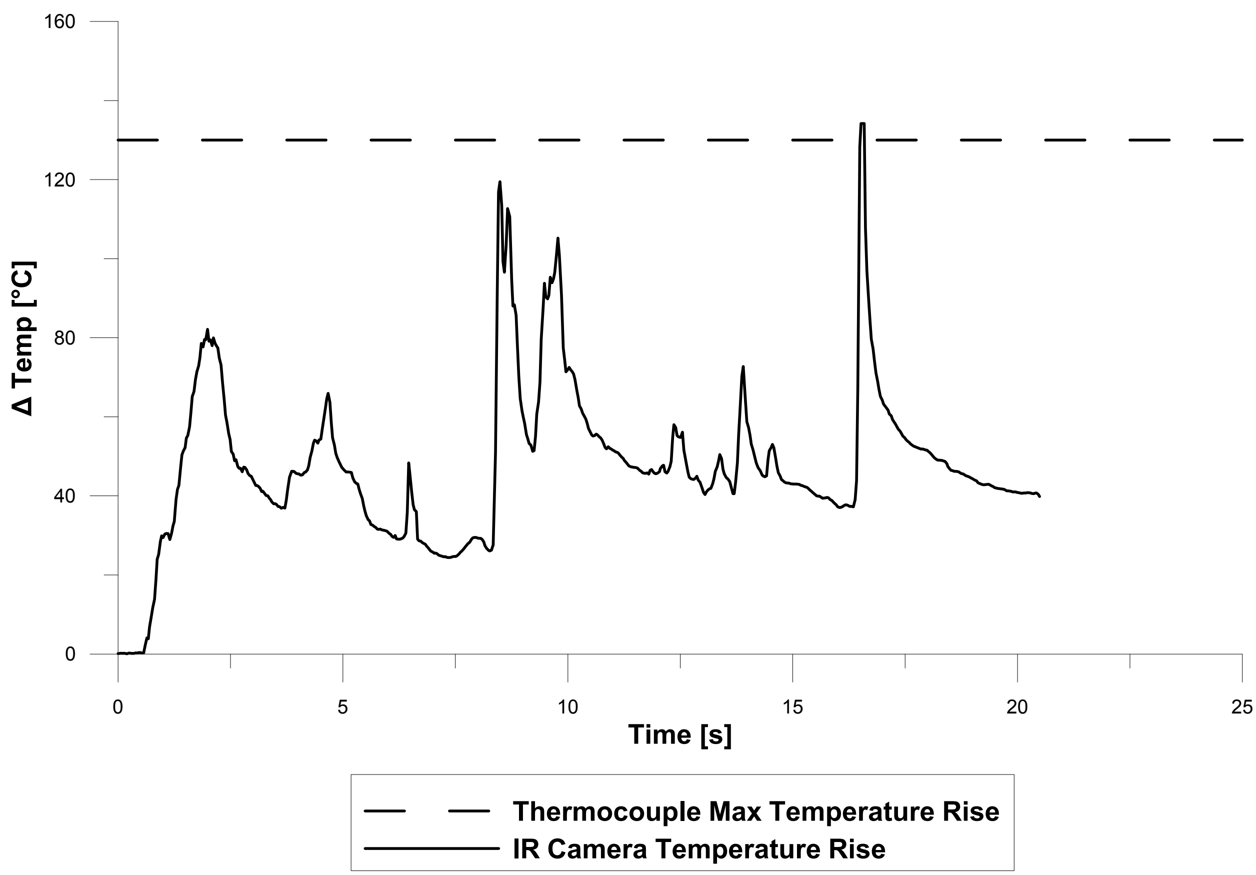


Figure C.1: Heat-Shrink Run Two; IR Camera Temperature Rise at Point of Thermocouple

Figure C.1 shows the maximum temperature rise recorded with both methods are in good agreement, about 140°C in case of run one and 134 °C for run two. The profile of each temperature curve is different because of slight variation in the motion of the heat gun over the surface of the heat shrink bundle, but overall peak temperatures are very similar and the results are congruous.

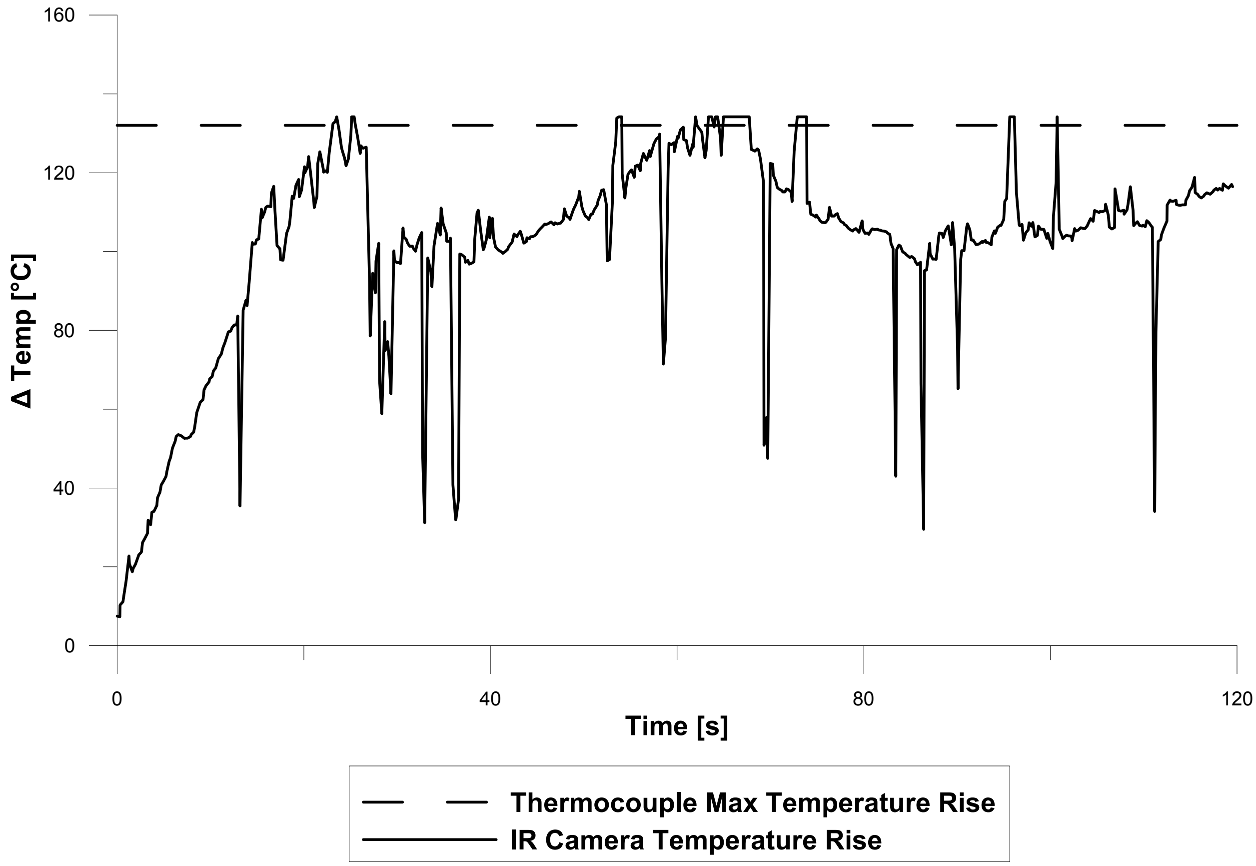


Figure C.2: Paint Stripping Run One; IR Camera Temperature Rise at Point of Thermocouple

In Figure C.2, a steeper heating curve than for run one is seen, most likely the nozzle of the heat gun was held closer to the painted surface at the start of this test, but overall peak temperatures are slightly lower, with the peak barely breaching 130°C.

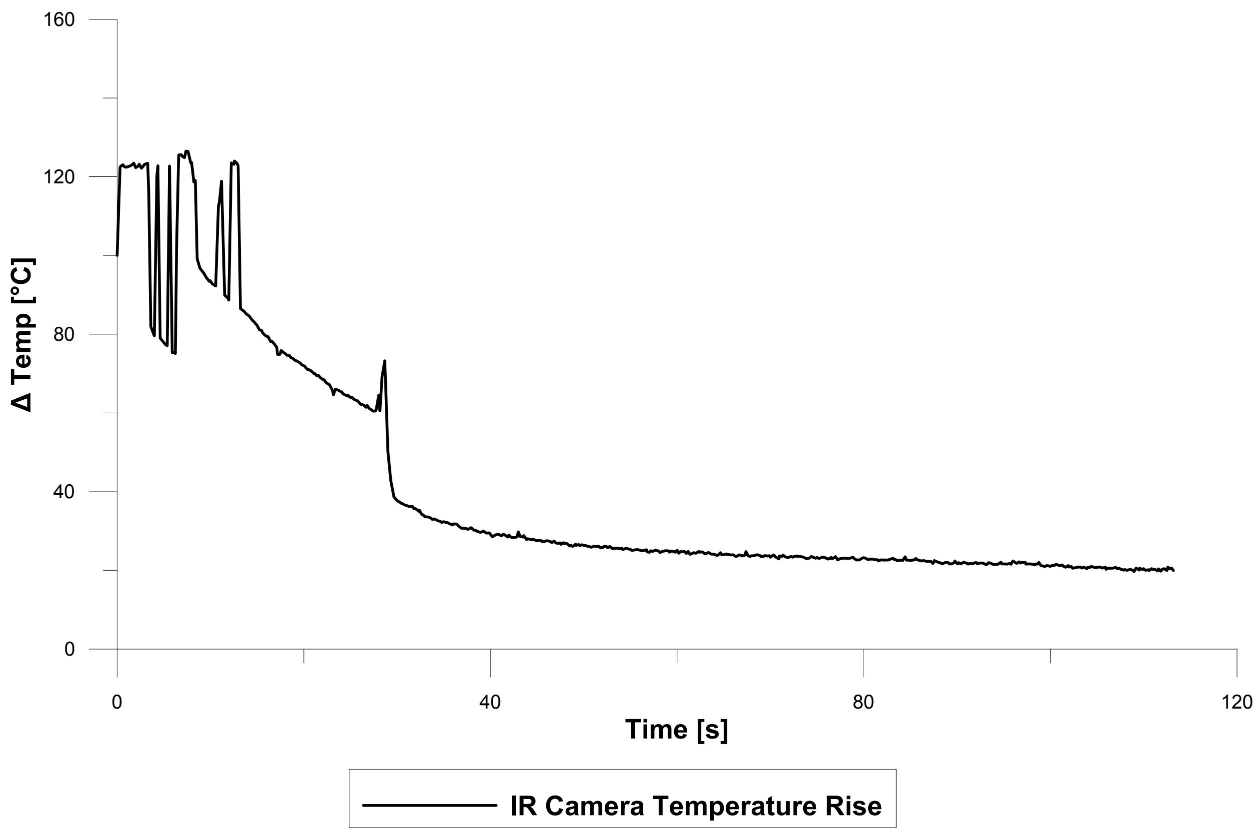


Figure C.3: Heated Adhesive Run Two; IR Camera Temperature Rise

Figure C.3 shows the temperature rise as measured by the IR camera. It is hypothesised that the slightly lower temperature is a result of the cycling of the heating element within the tool; for run one the heating element was either on or had recently turned off, while for run two it has been off for some time.

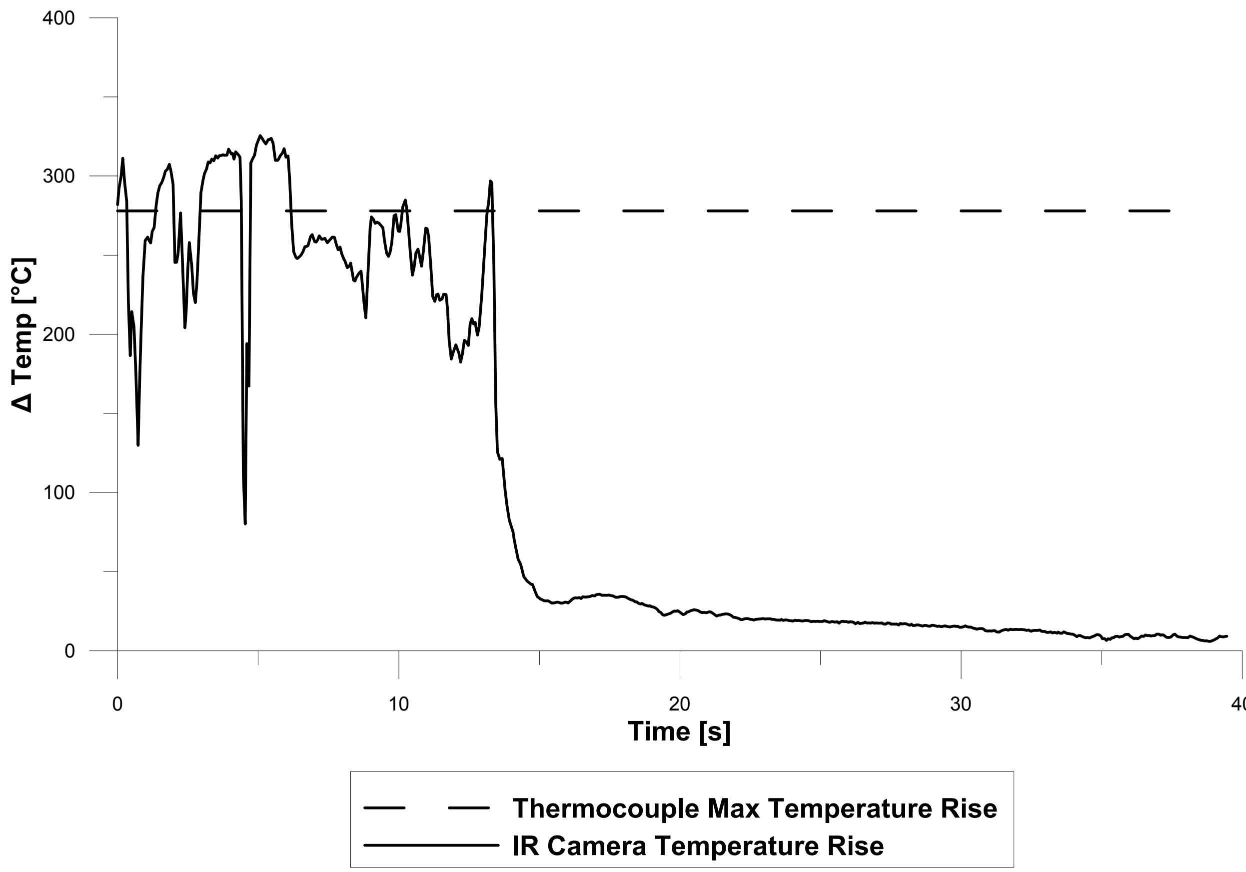


Figure C.4: Iron Soldering Run One; IR Camera Temperature Rise at Point of Thermocouple

It can be seen from Figure C.4 that the peak temperature rise of the process is typified by about is 325°C above ambient. In contrast, the maximum measured thermocouple temperature is lower at 280°C. Both values are lower than run two. Temperatures are expected to fluctuate during and between runs because soldering involves the intermittent application and removal of the tip of the soldering tool such that the work approaches the reflow temperature of the solder and wets the wires without exceeding the reflow temperature so excessively that it solidifies before it can drip off the wires. For this reason, soldering temperatures are drastically lower than the actual maximum operating temperature of the tool.

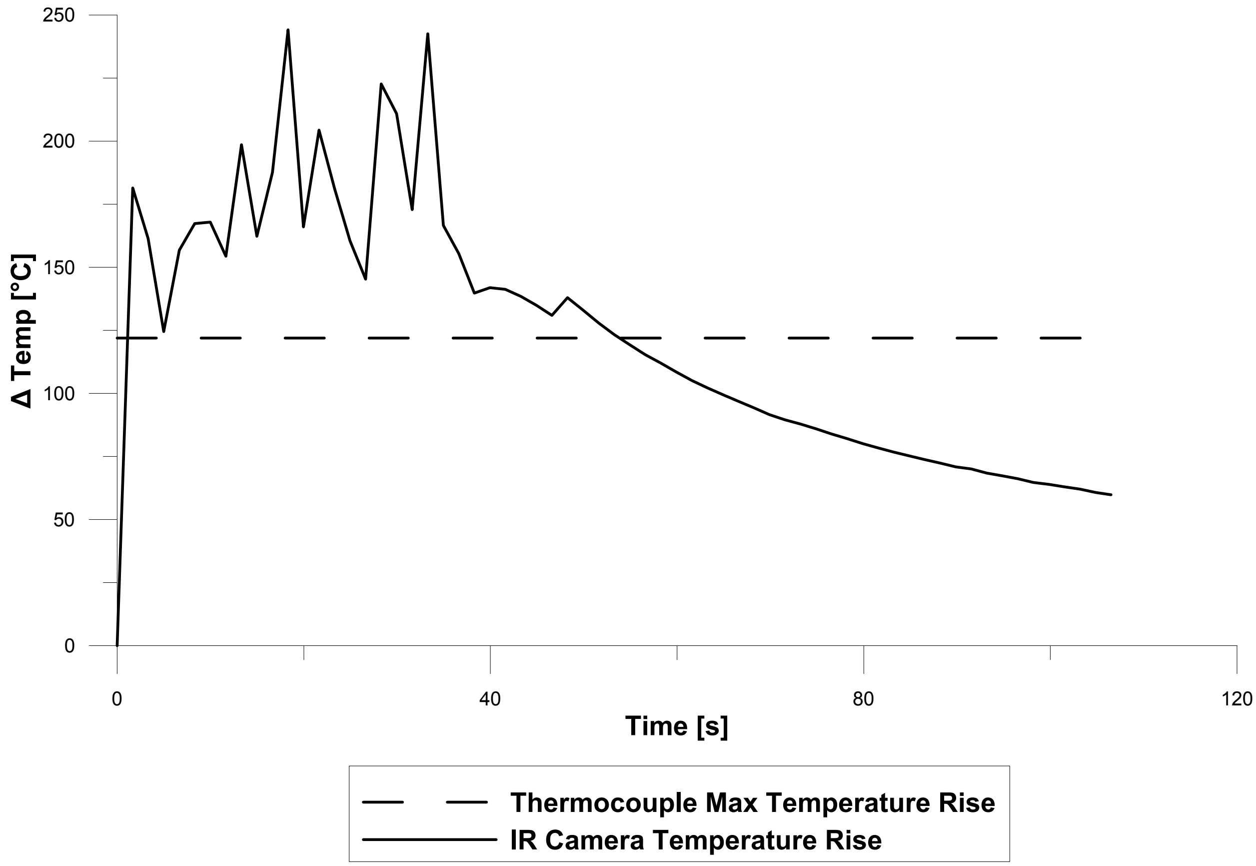


Figure C.5: Torch Soldering Run Two; IR Camera Temperature Rise

Figure C.5 shows only a slightly lower temperature for the infrared camera and thermocouple measurements for run two in comparison to run one.

Appendix D

Hot Surface, Particle Potential Process Results

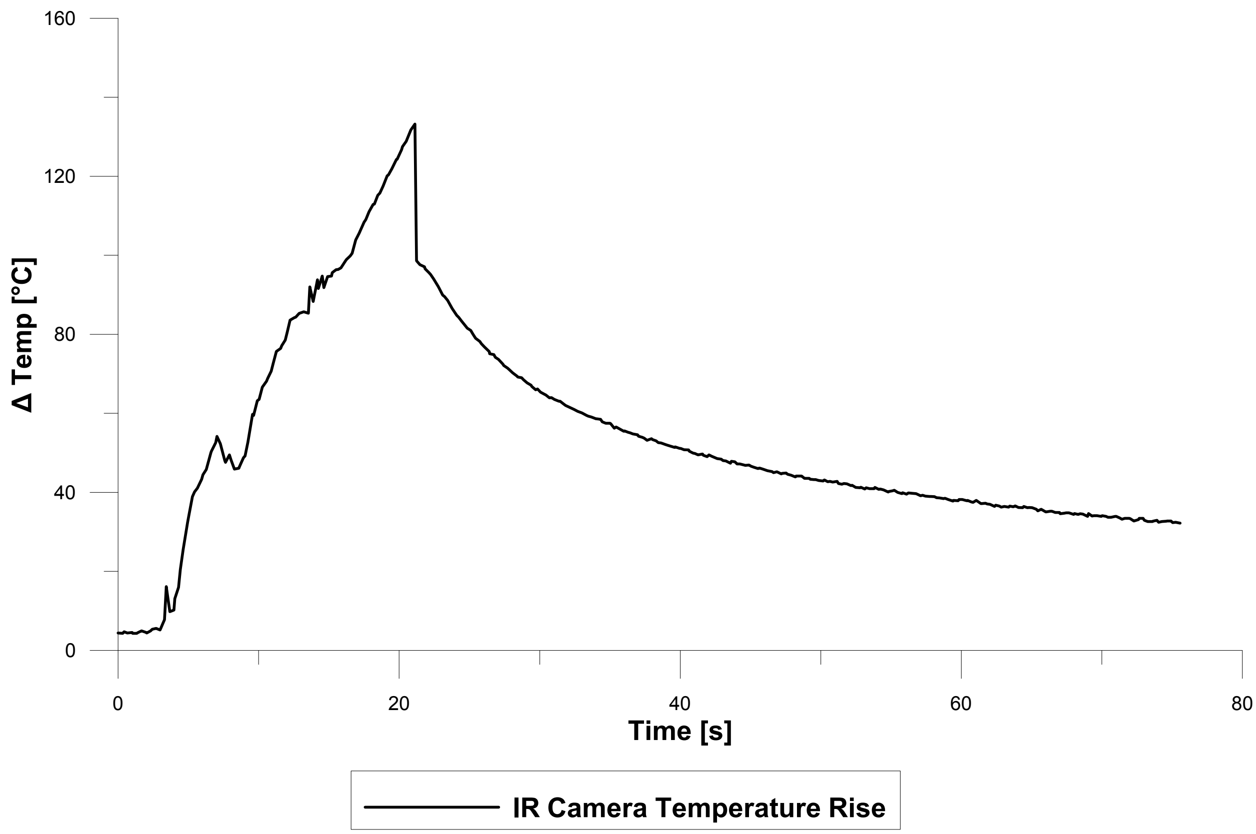


Figure D.1: Reciprocating Saw Cutting 10 mm Rebar Run One; IR Camera Temperature Rise

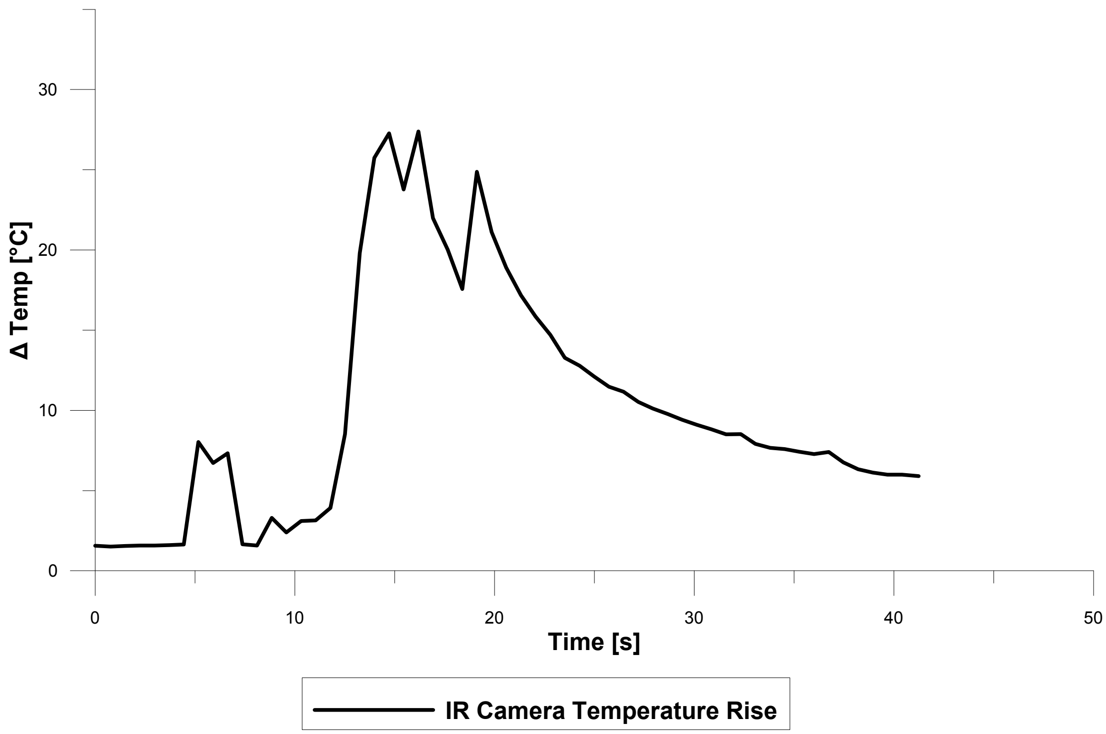


Figure D.2: Wood Drilling; IR Camera Temperature Rise

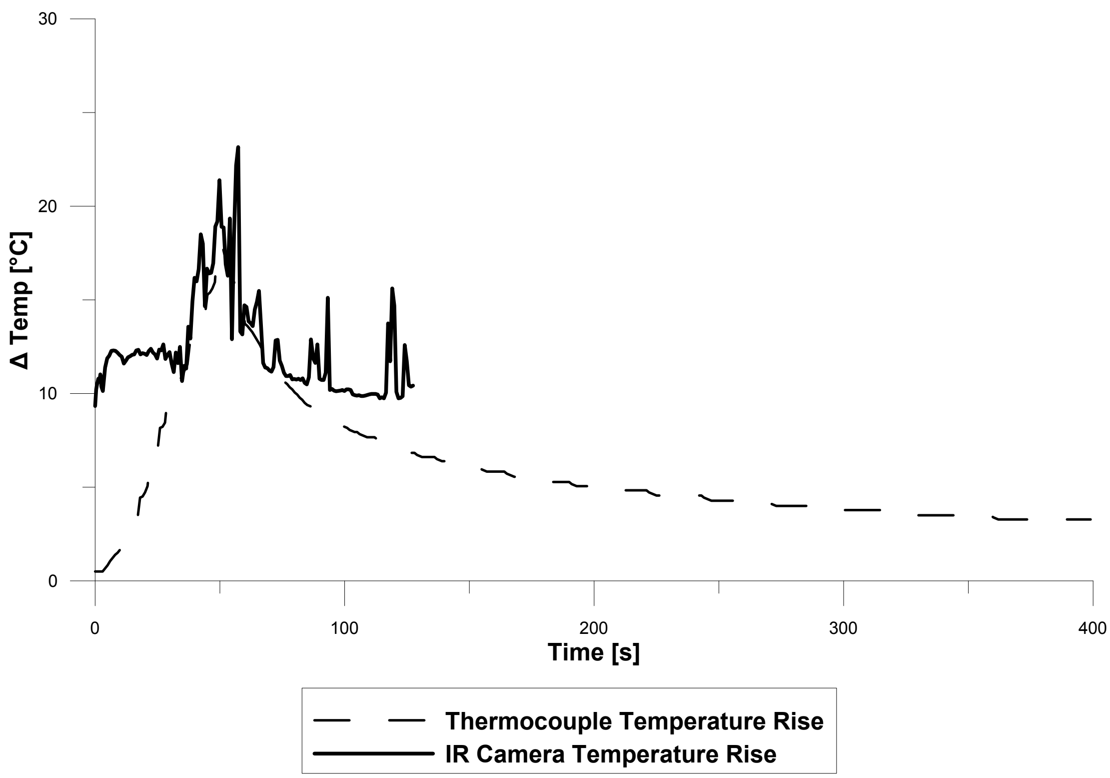


Figure D.3: Aluminum Drilling; IR Camera Temperature Rise

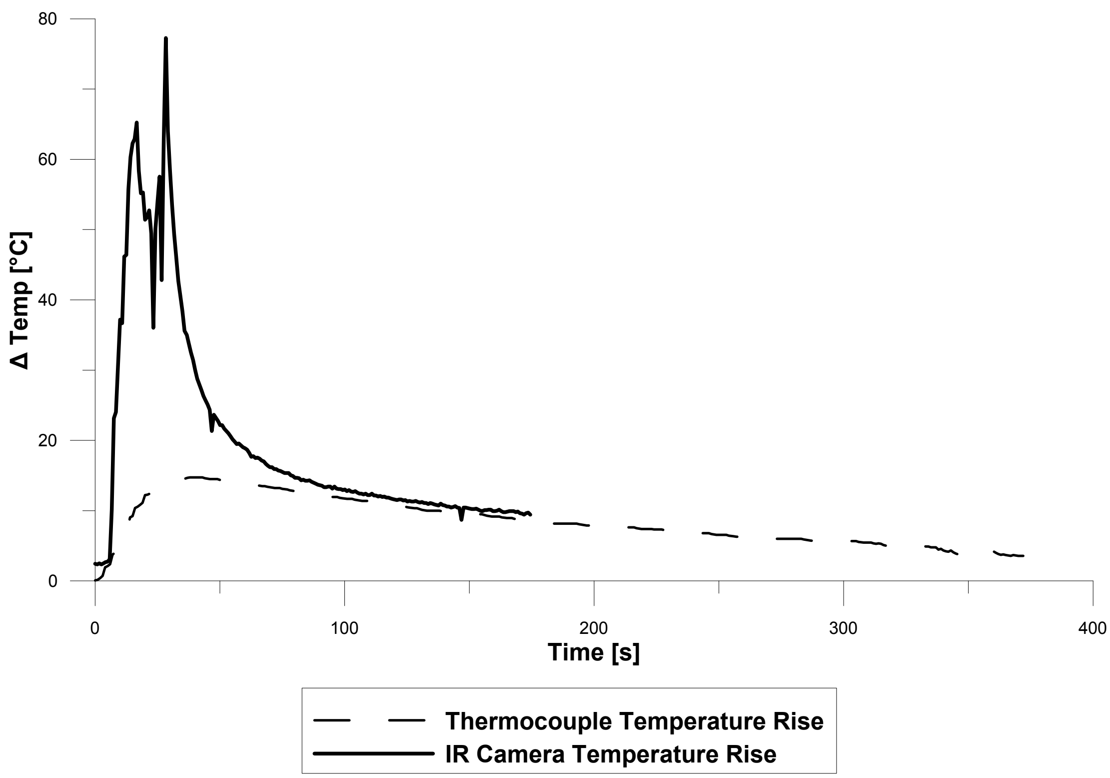


Figure D.4: Phenolic; IR Camera Temperature Rise

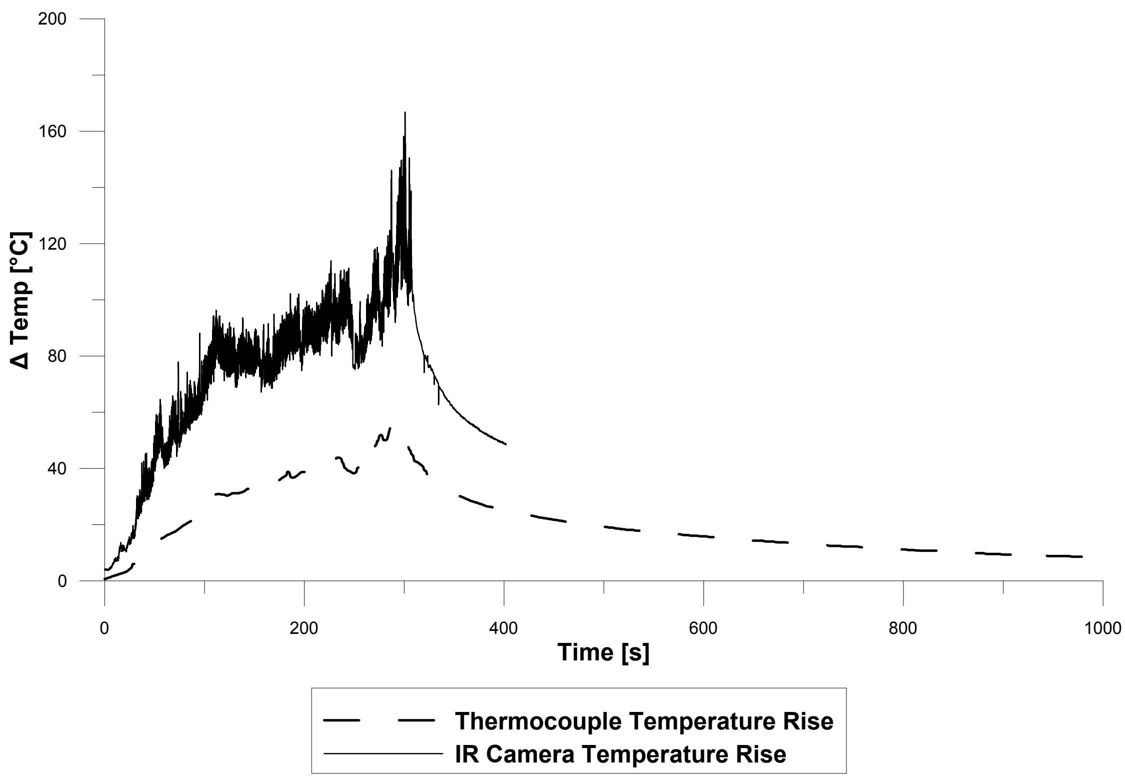


Figure D.5: Nominal Steel Drilling; IR Camera Temperature Rise

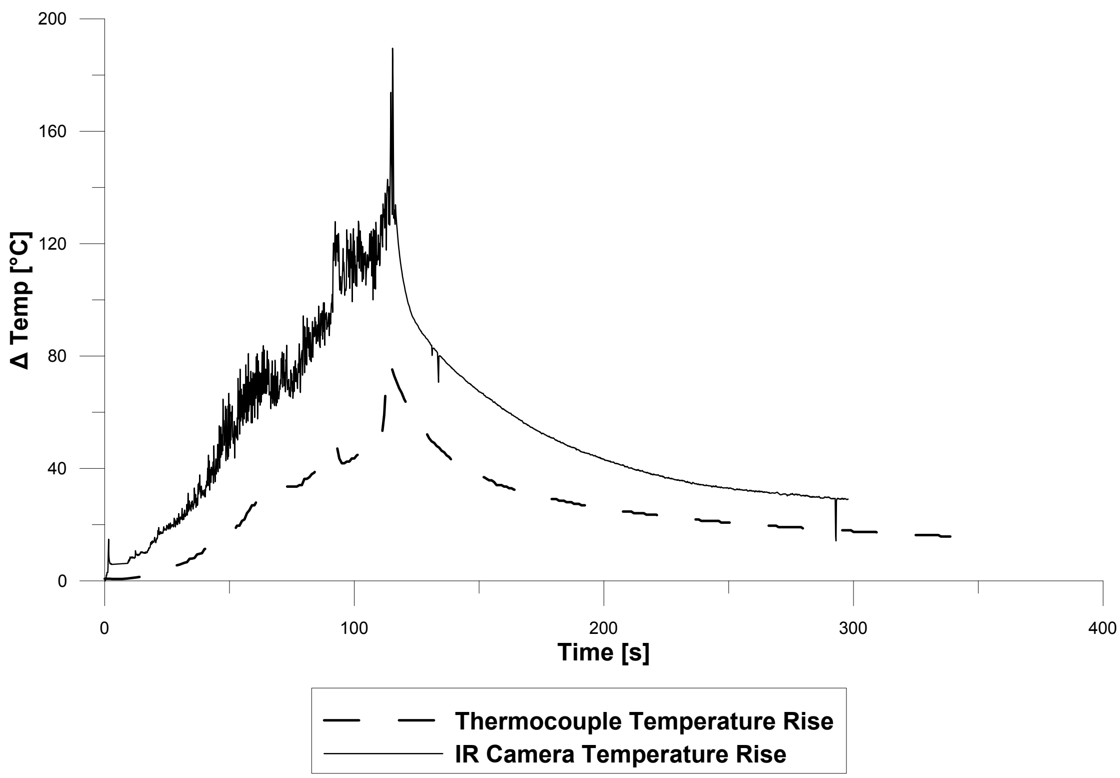


Figure D.6: Worst Case Steel Drilling; IR Camera Temperature Rise

Appendix E

Hot Particle Generating Processes

E.1 Gas Tungsten Arc Welding (GTAW) & Shielded Metal Arc Welding (SMAW)

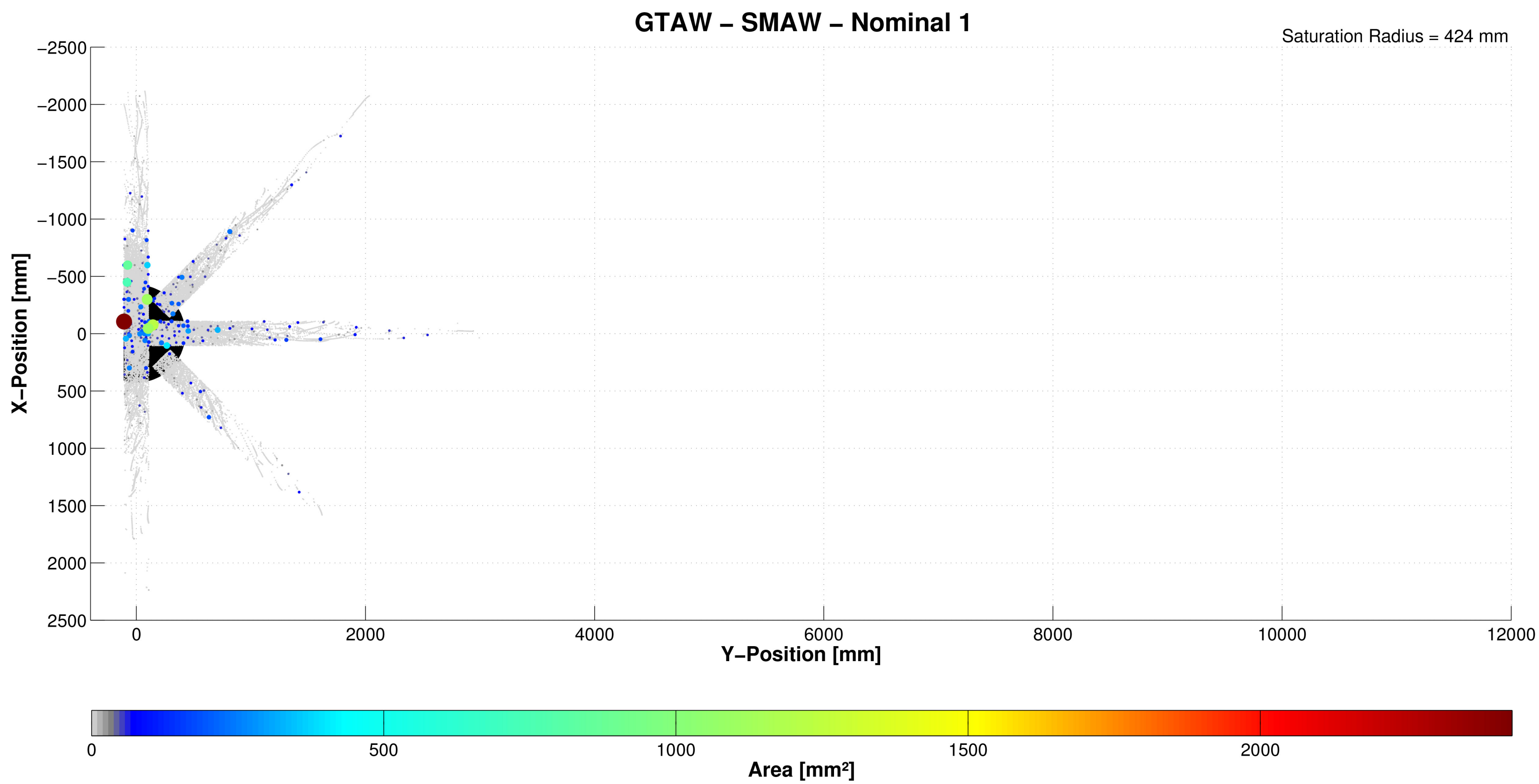


Figure E.1: Particle Distribution, GTAW-SMAW Nominal 1

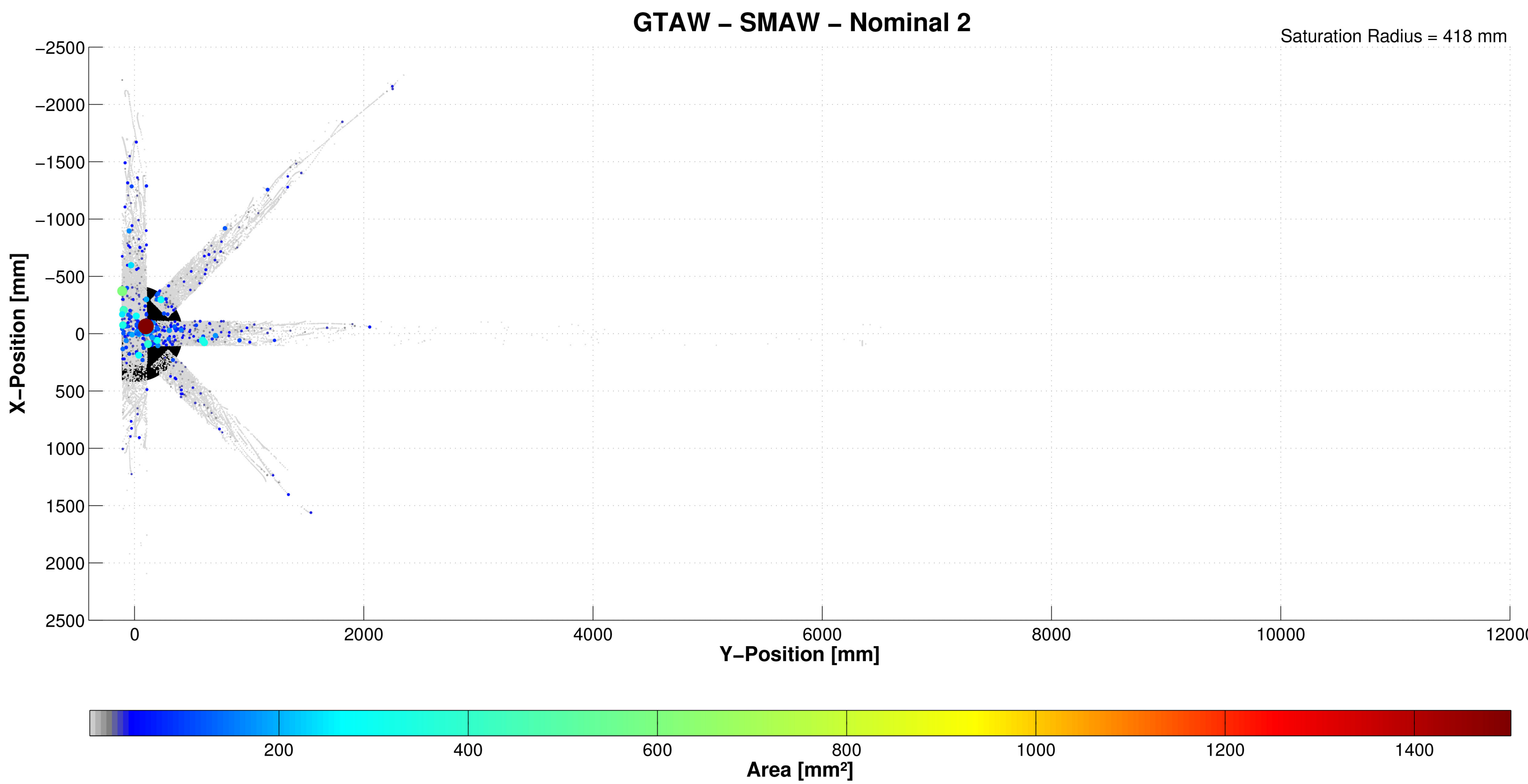


Figure E.2: Particle Distribution, GTAW-SMAW Nominal 2

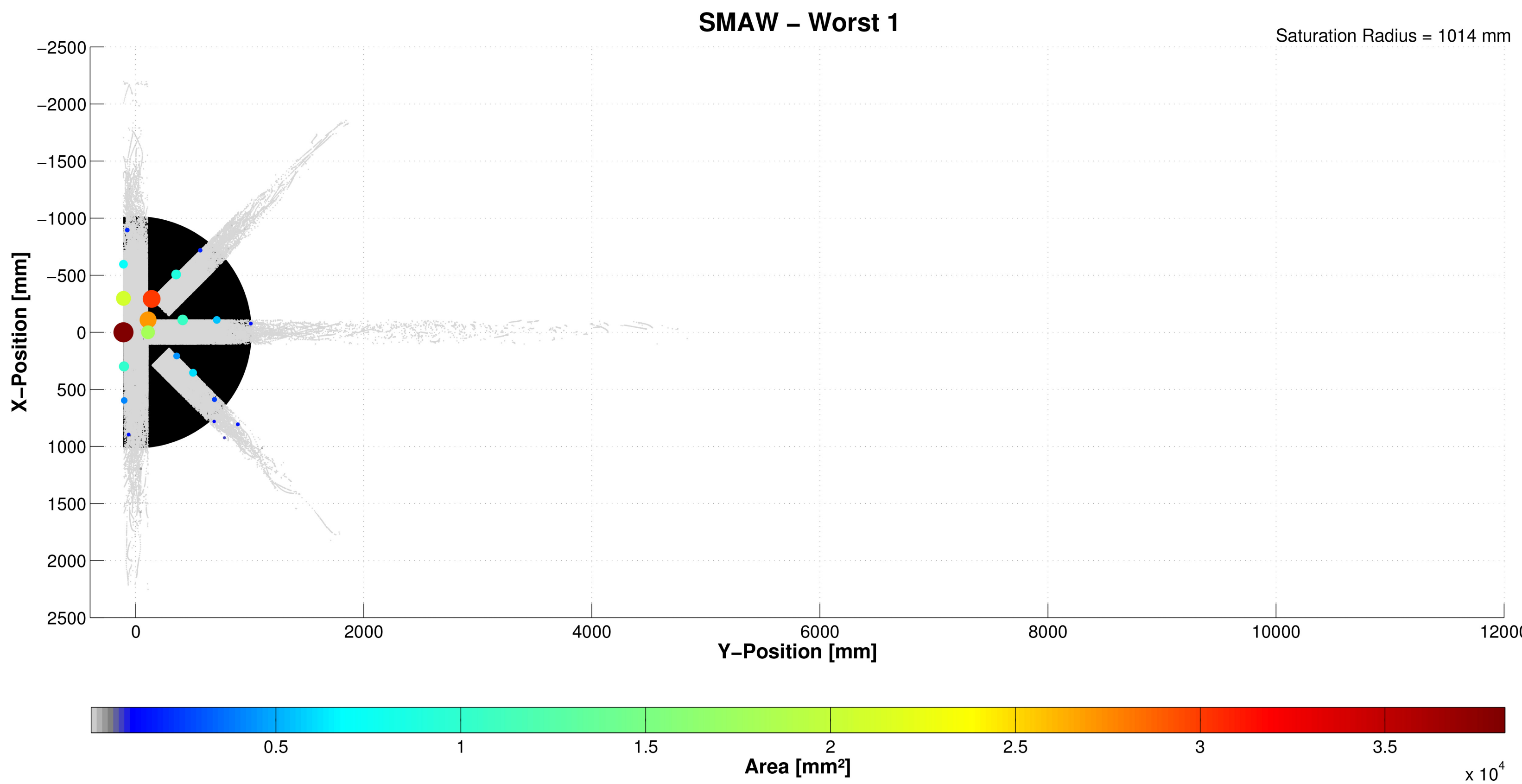


Figure E.3: Particle Distribution, SMAW Worst 1

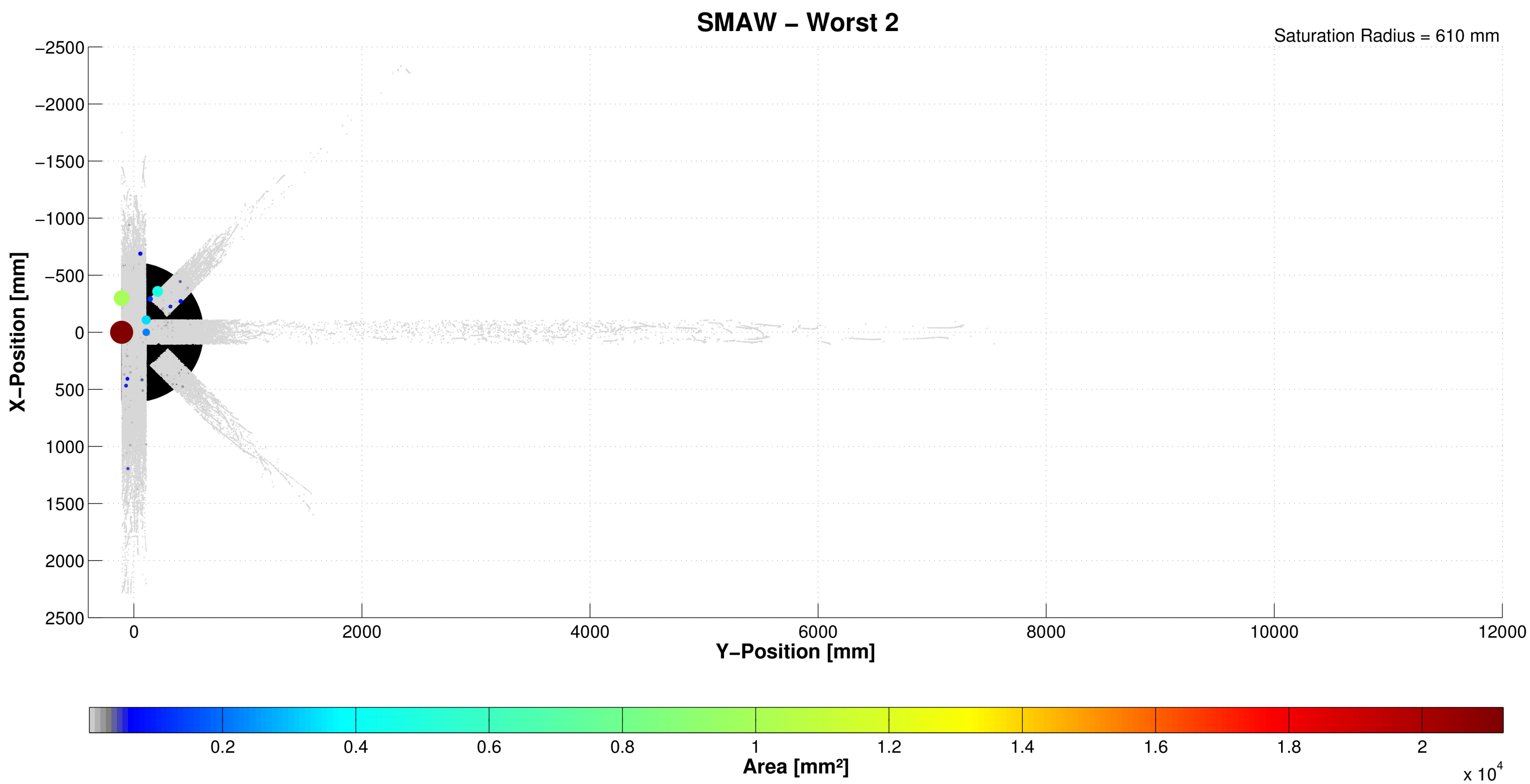


Figure E.4: Particle Distribution, SMAW Worst 2

E.2 Gas Metal Arc Welding (GMAW)

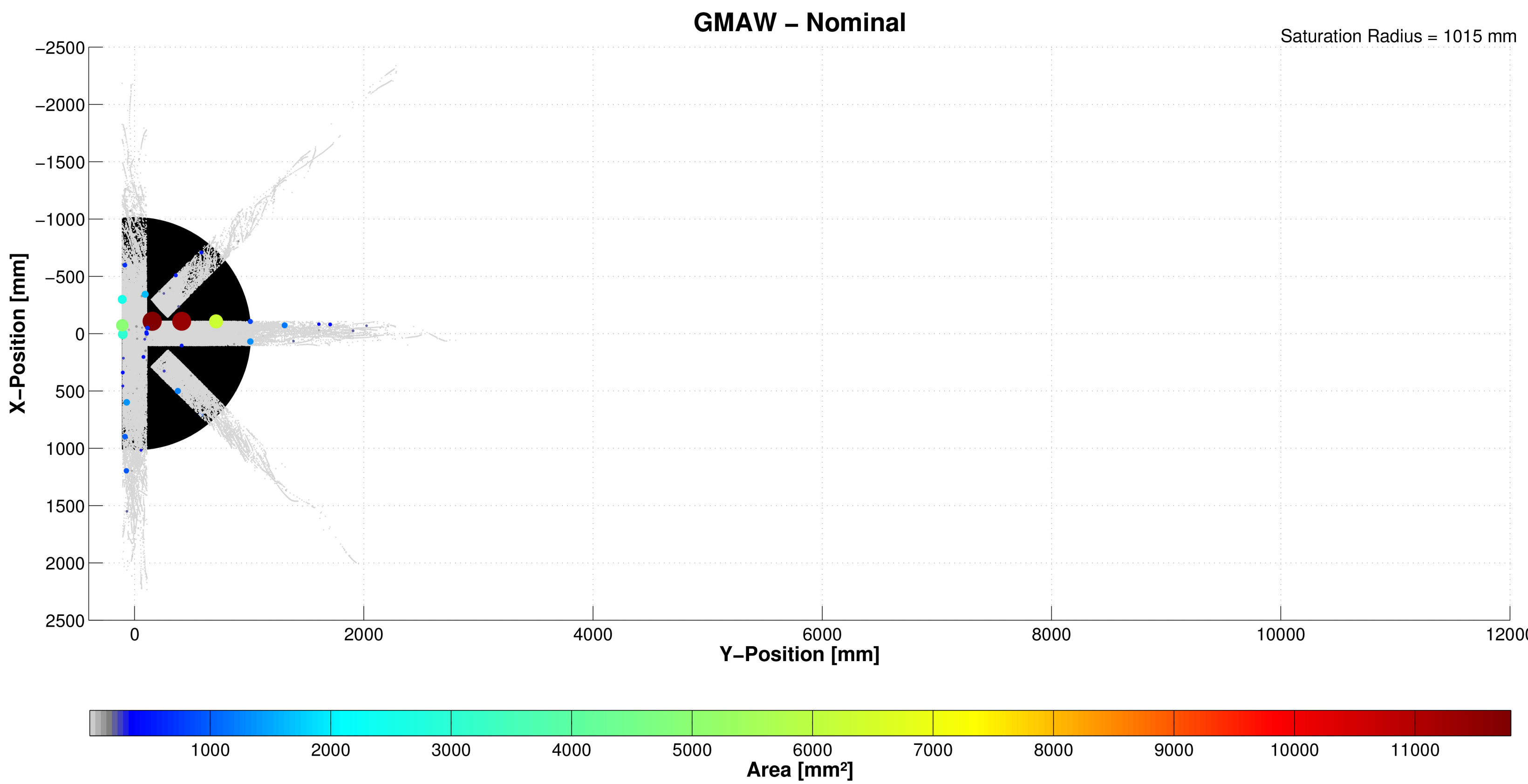


Figure E.5: Particle Distribution, GMAW Nominal

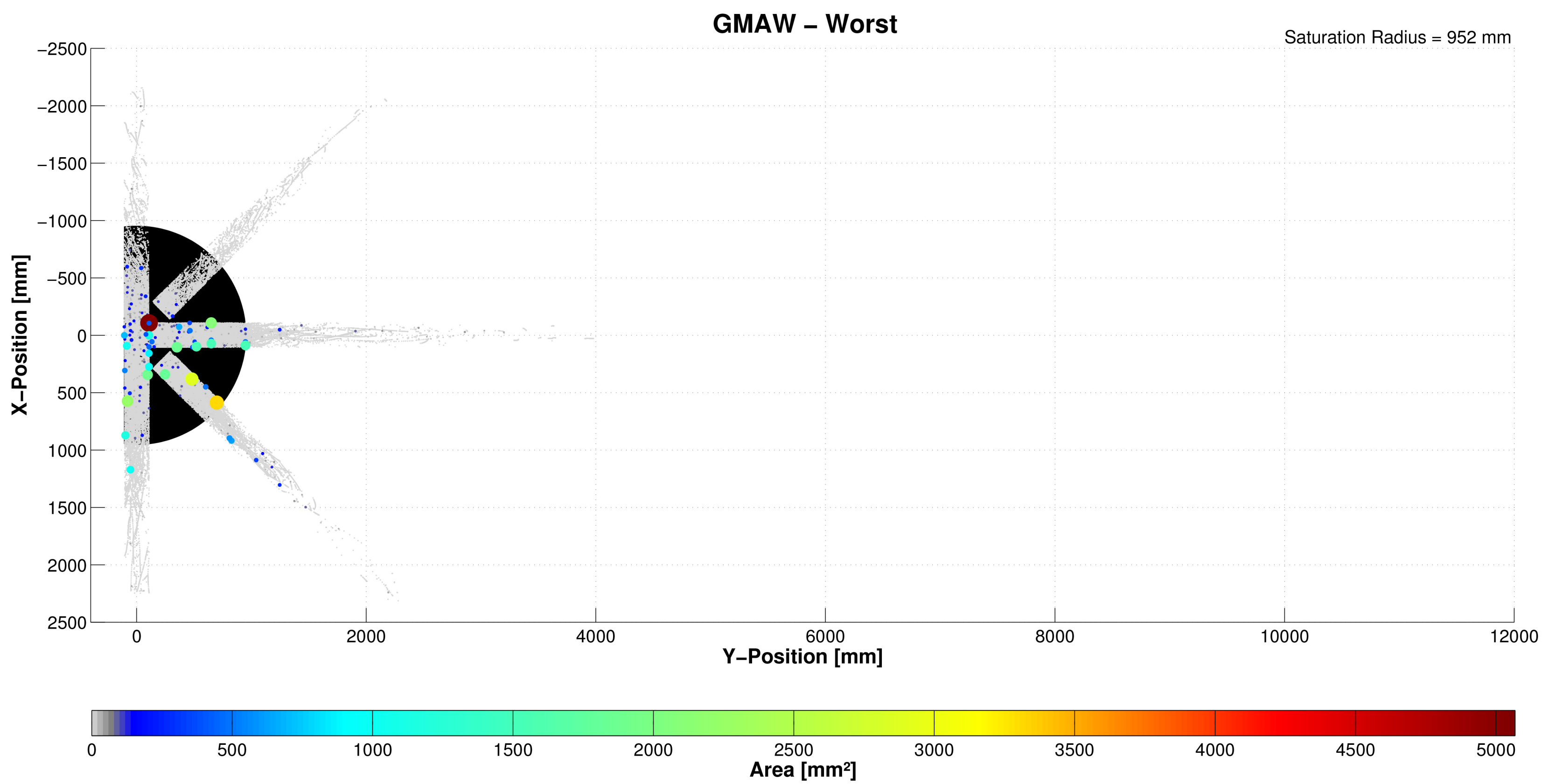


Figure E.6: Particle Distribution, GMAW Worst

E.3 Plasma Cutting

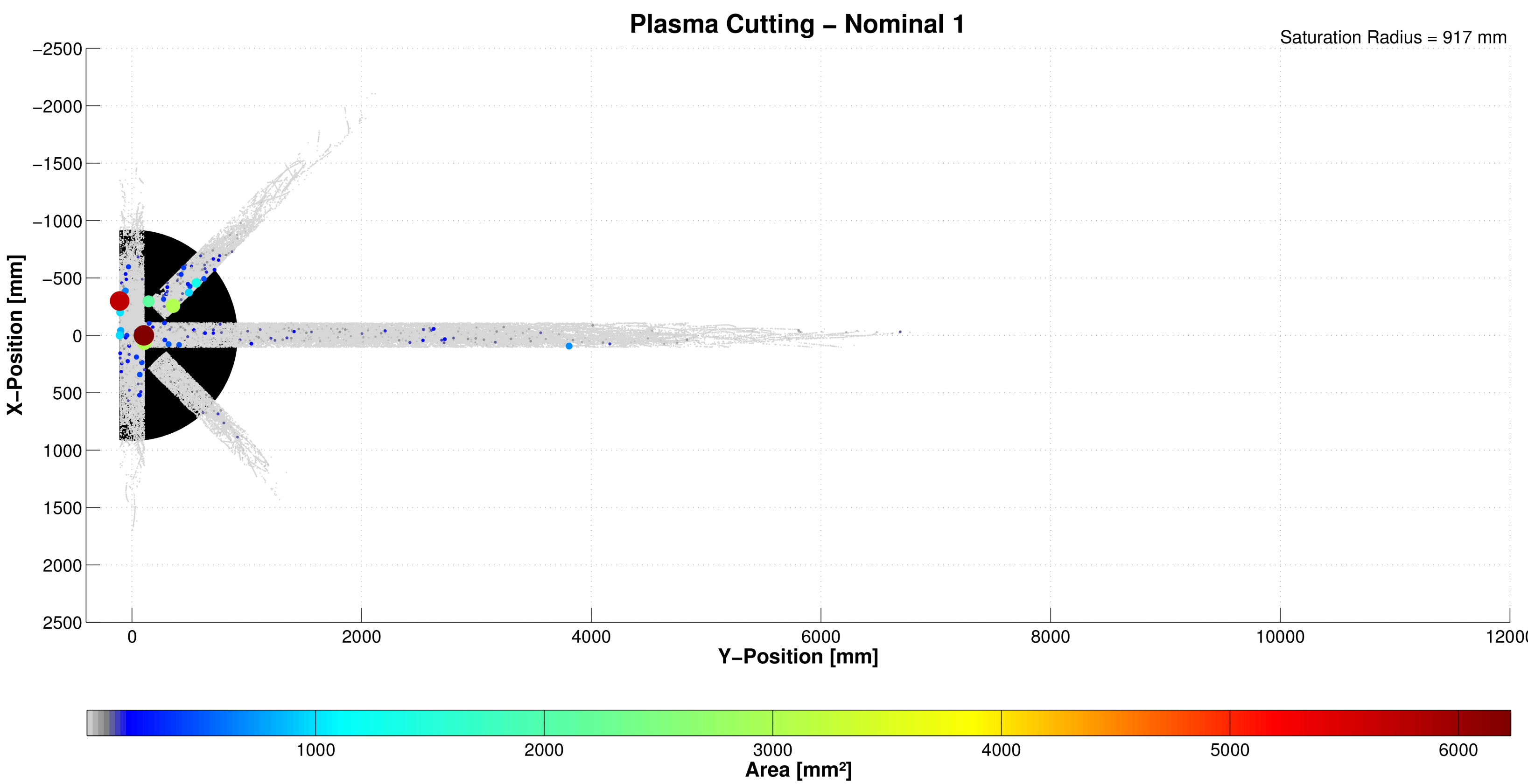


Figure E.7: Particle Distribution, Plasma Cutting Nominal 1

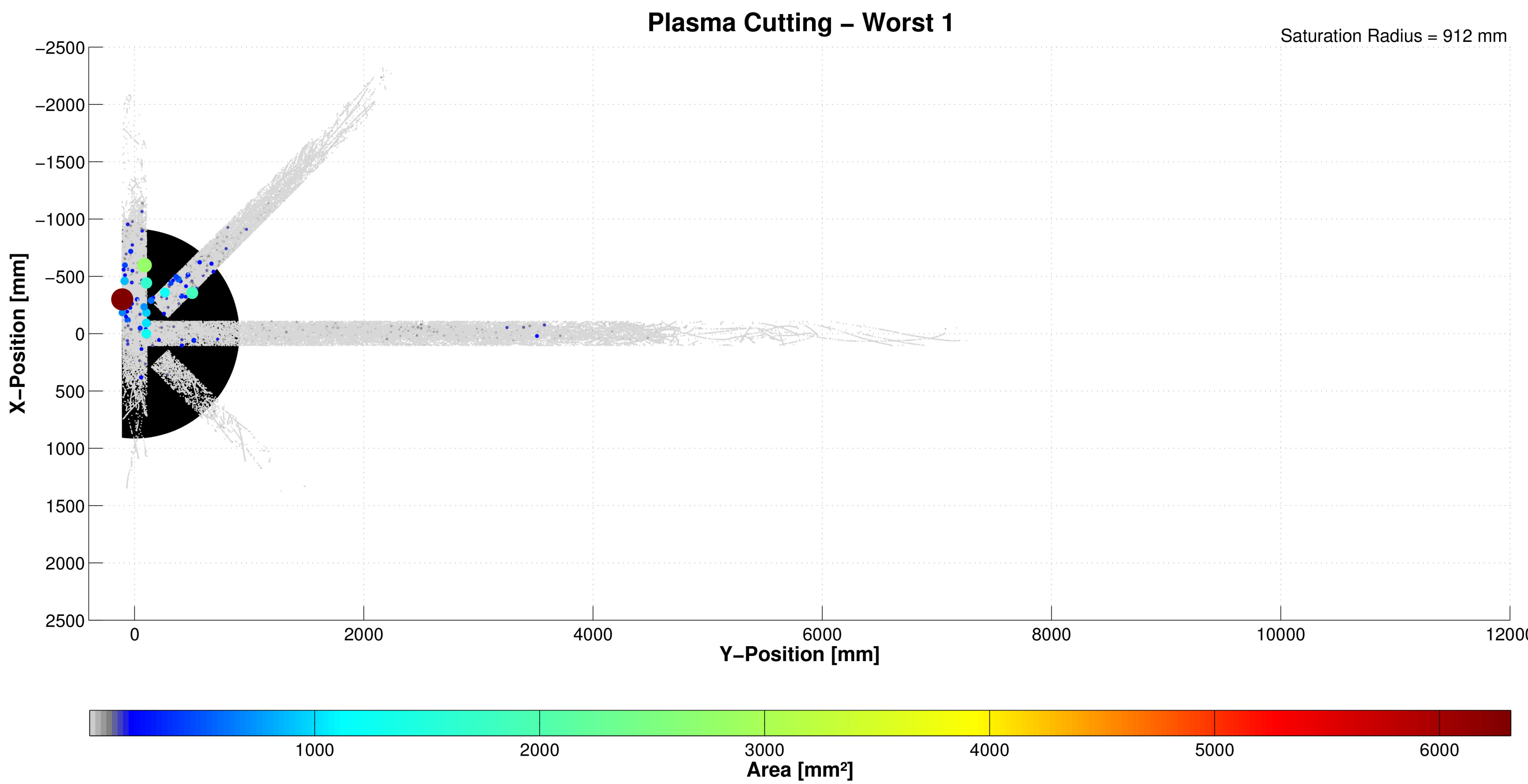


Figure E.8: Particle Distribution, Plasma Cutting Worst 1

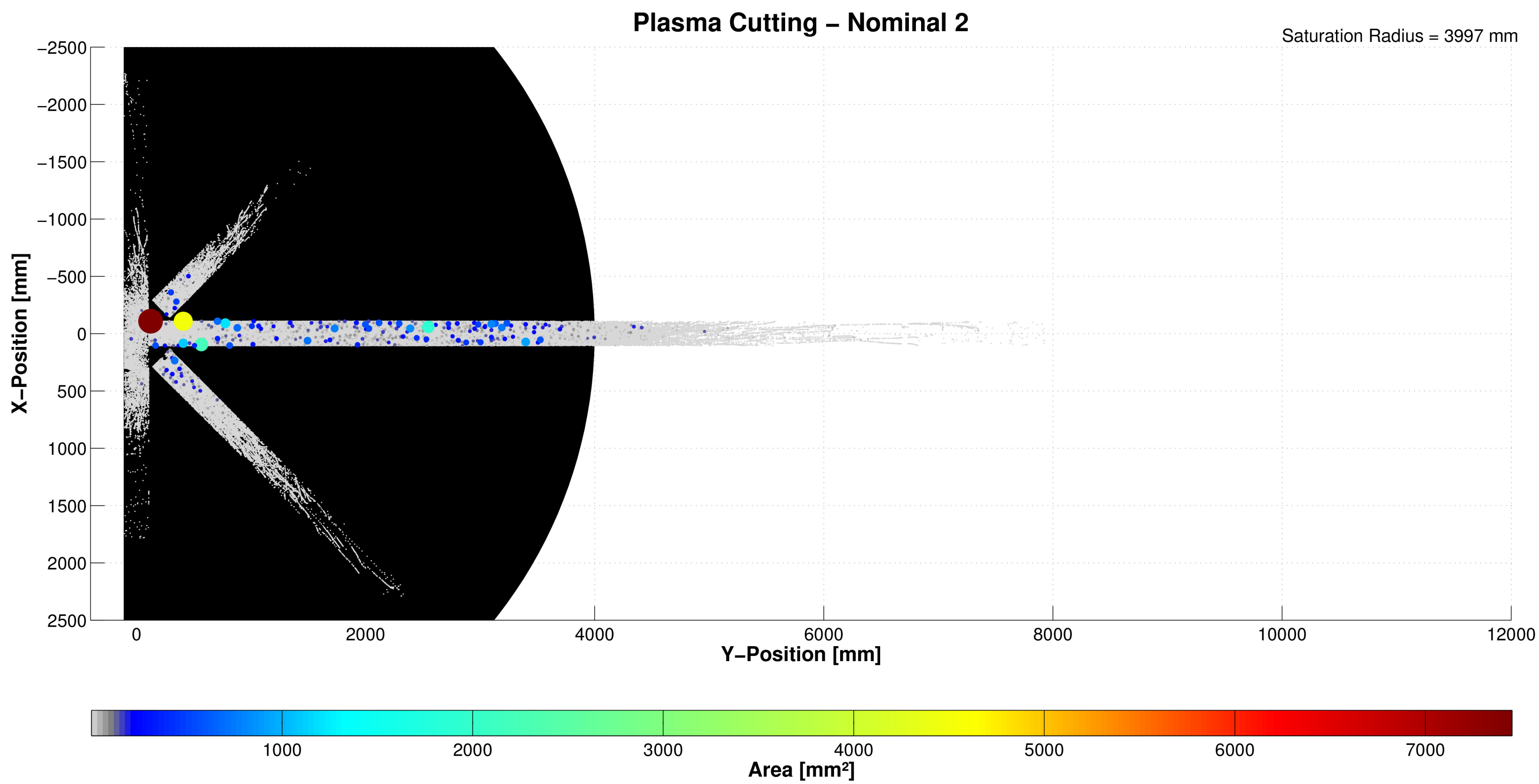


Figure E.9: Particle Distribution, Plasma Cutting Nominal 2

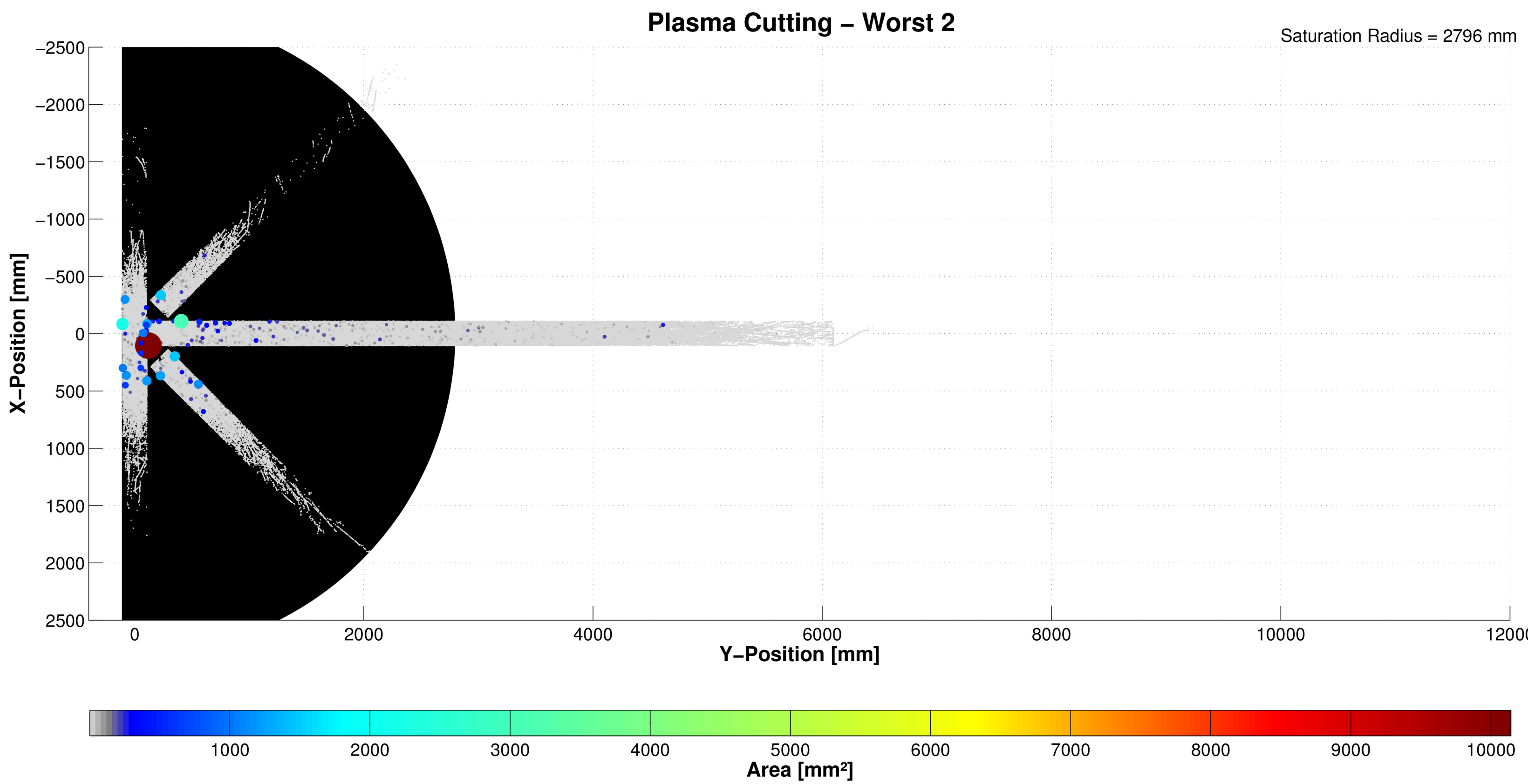


Figure E.10: Particle Distribution, Plasma Cutting Worst 2

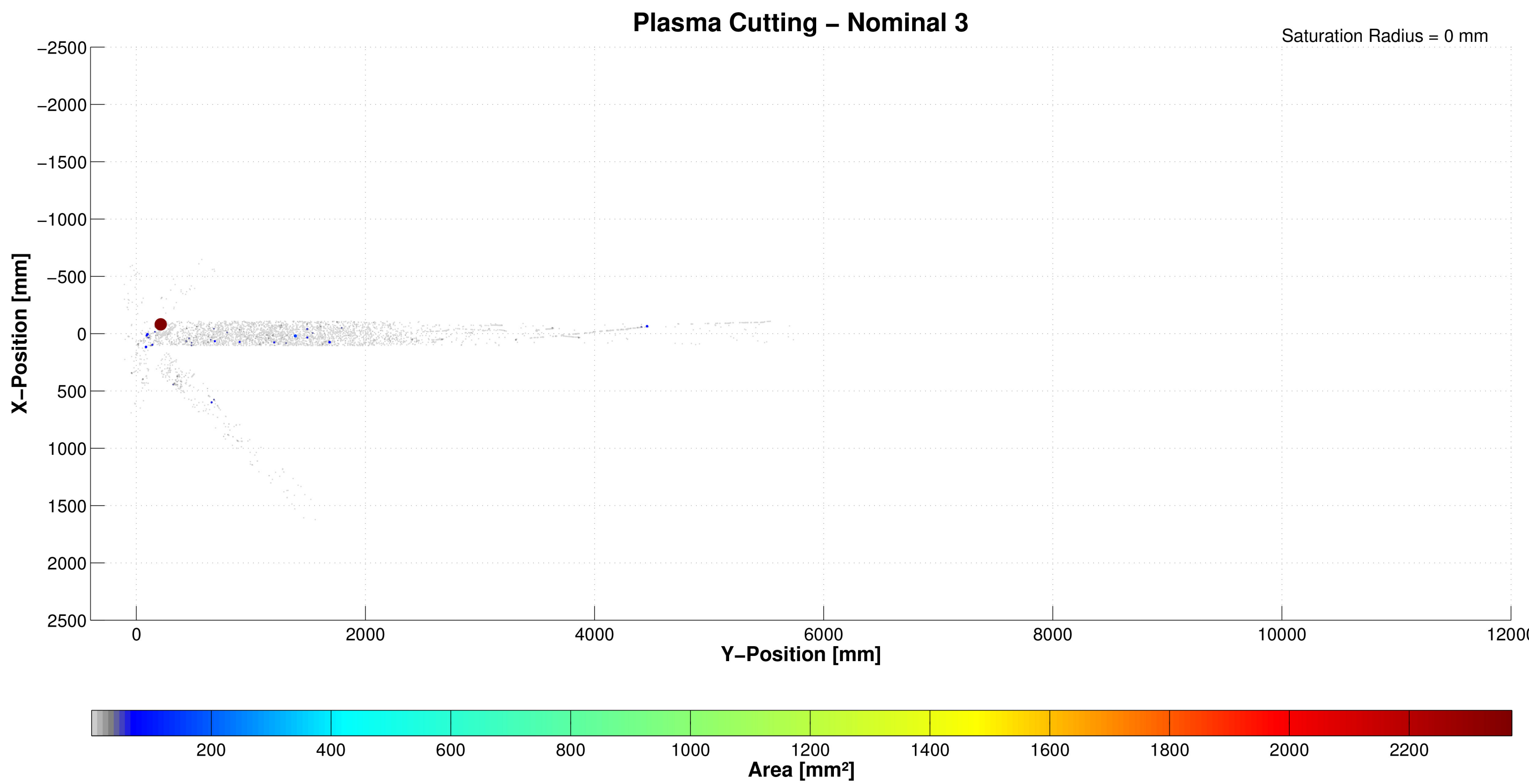


Figure E.11: Particle Distribution, Plasma Cutting Nominal 3

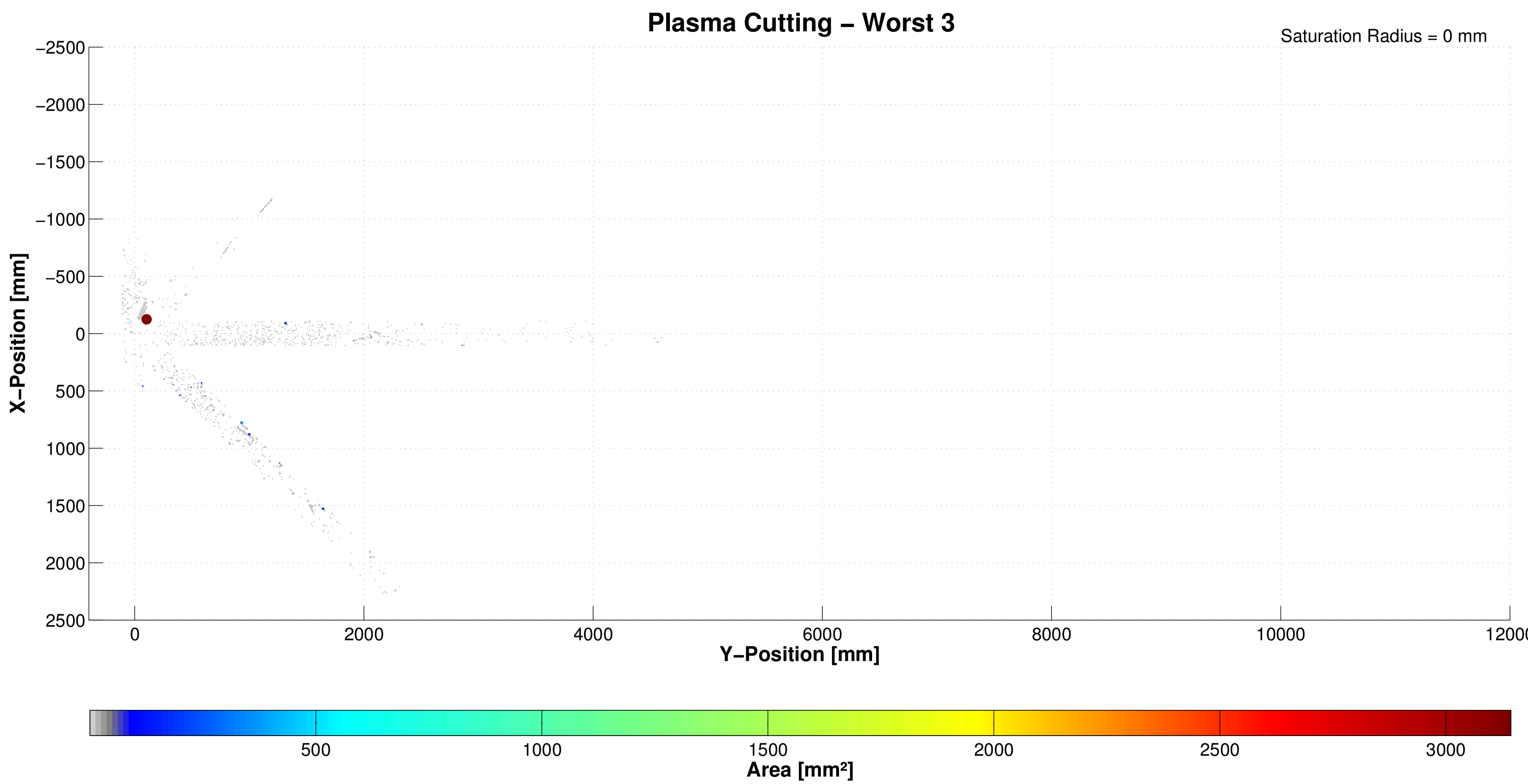


Figure E.12: Particle Distribution, Plasma Cutting Worst 3

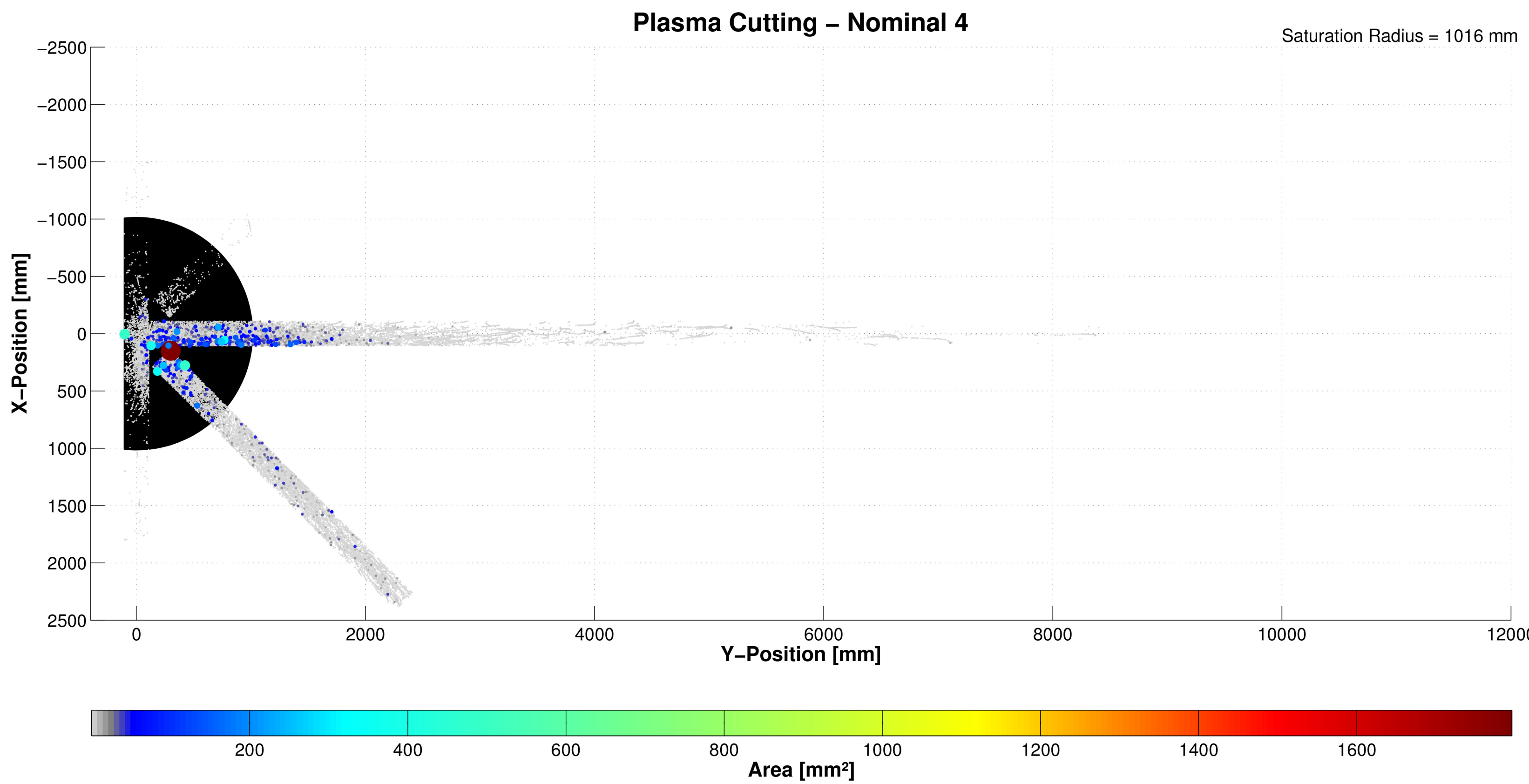


Figure E.13: Particle Distribution, Plasma Cutting Nominal 4

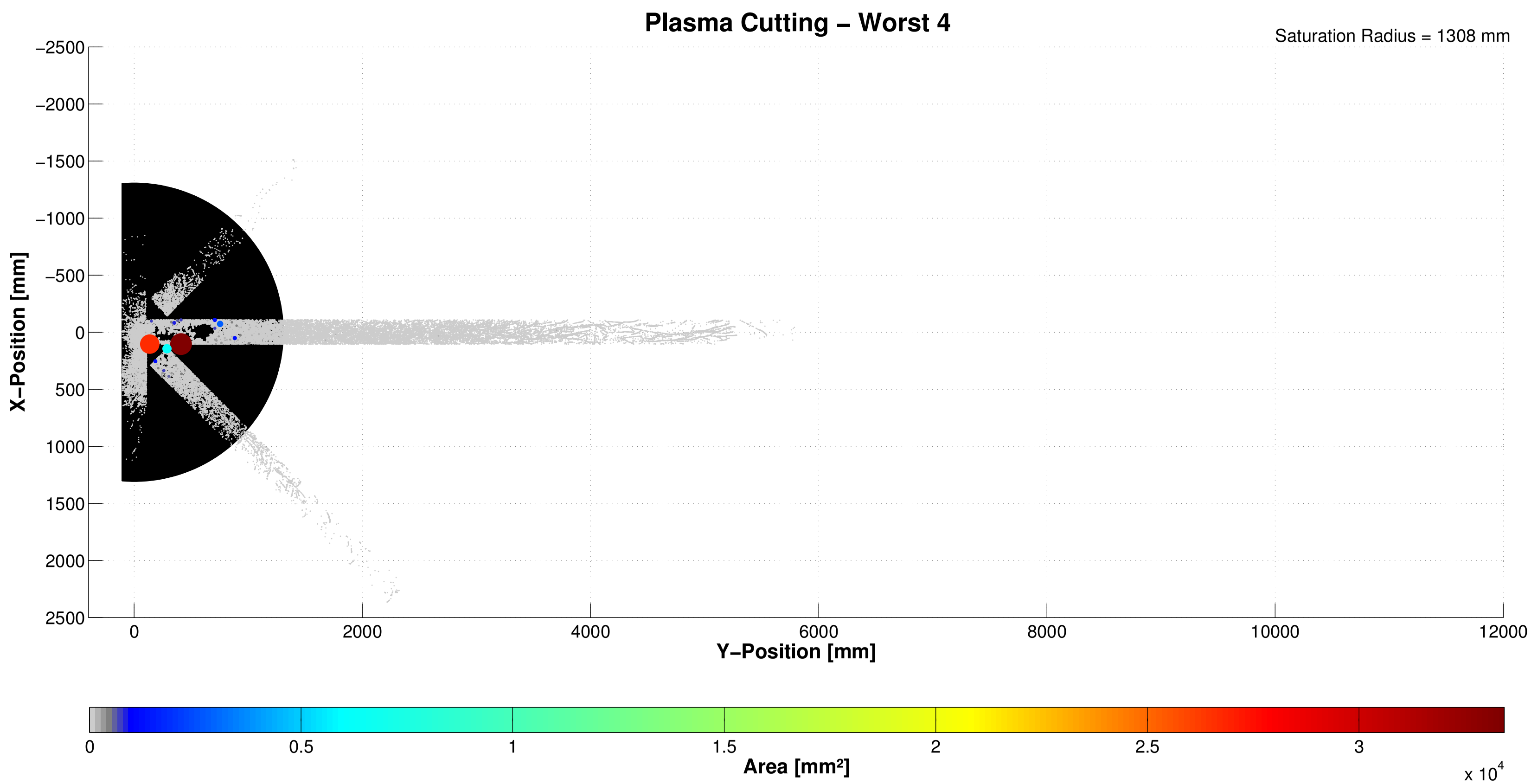


Figure E.14: Particle Distribution, Plasma Cutting Worst 4

E.4 Air Carbon Arc Gouging

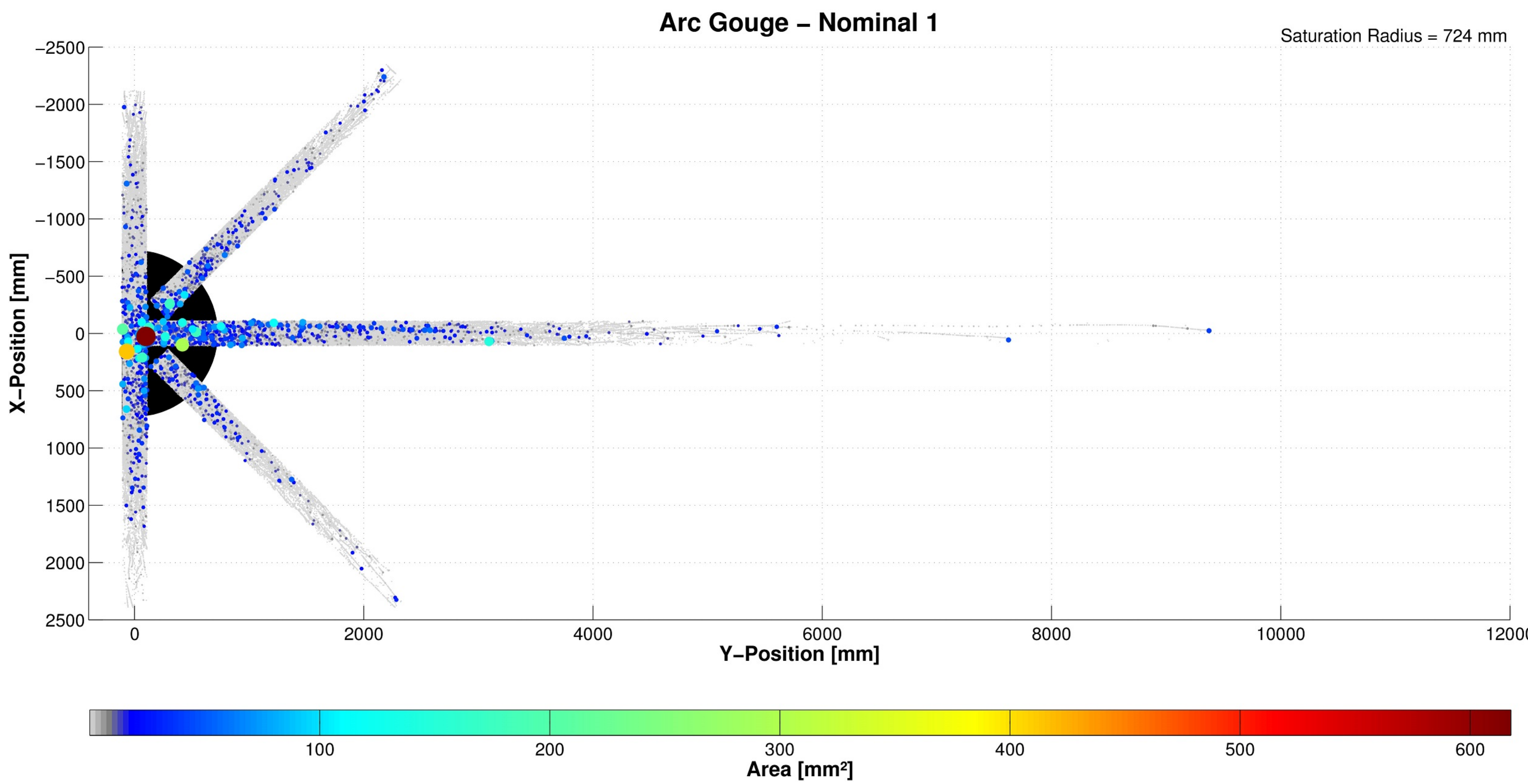


Figure E.15: Particle Distribution, Air Carbon Arc Gouging Nominal 1

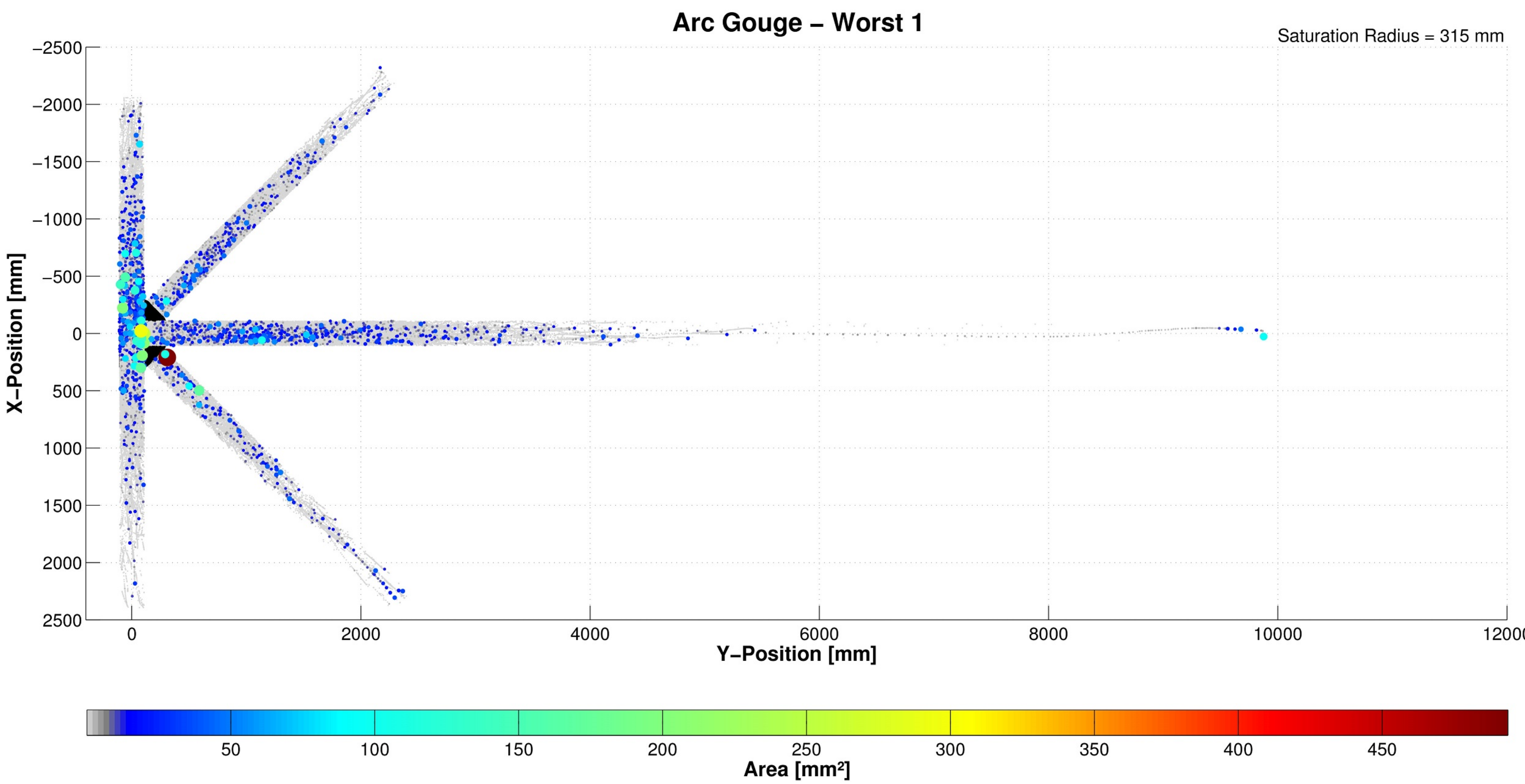


Figure E.16: Particle Distribution, Air Carbon Arc Gouging Worst 1

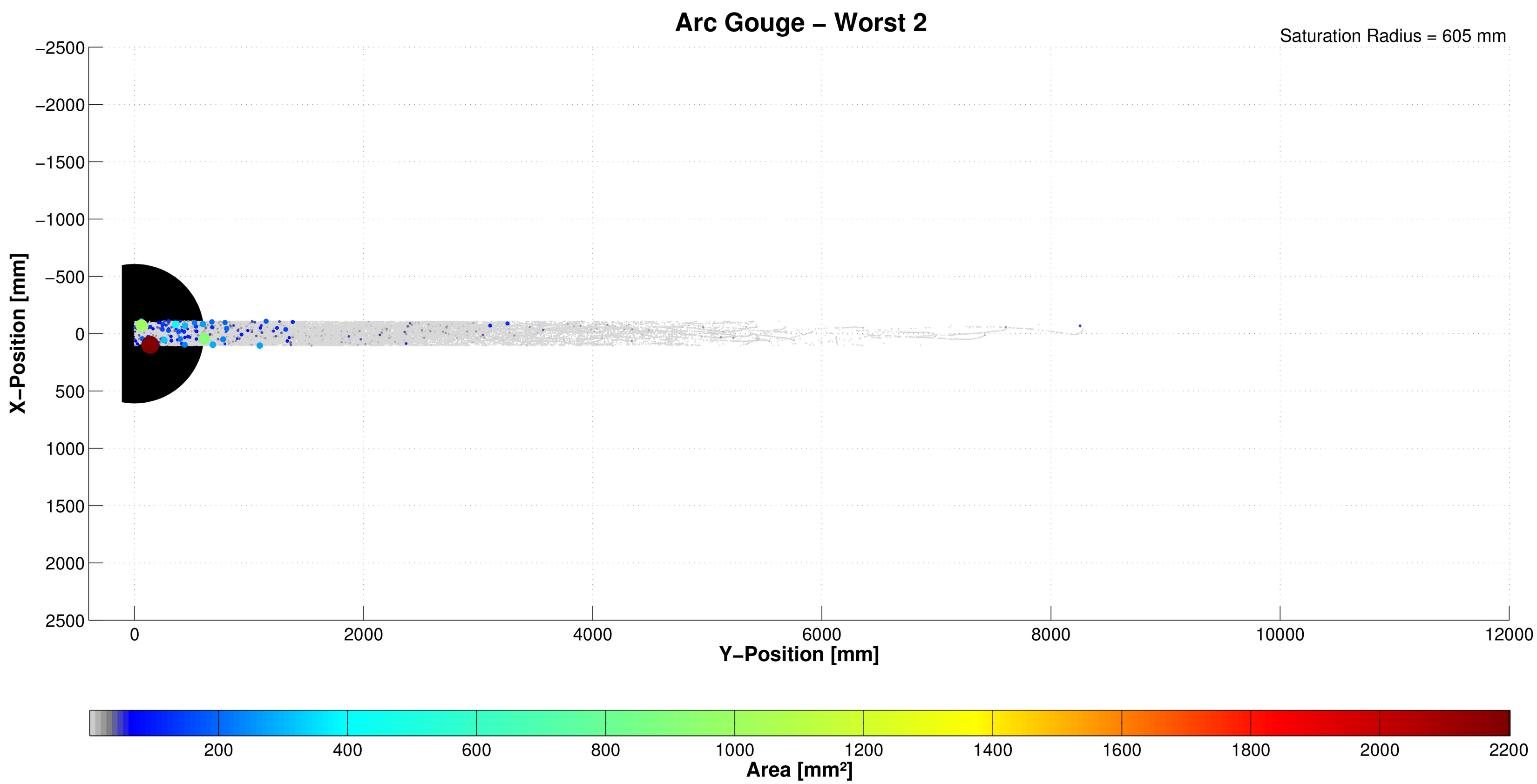


Figure E.17: Particle Distribution, Air Carbon Arc Gouging Worst 2

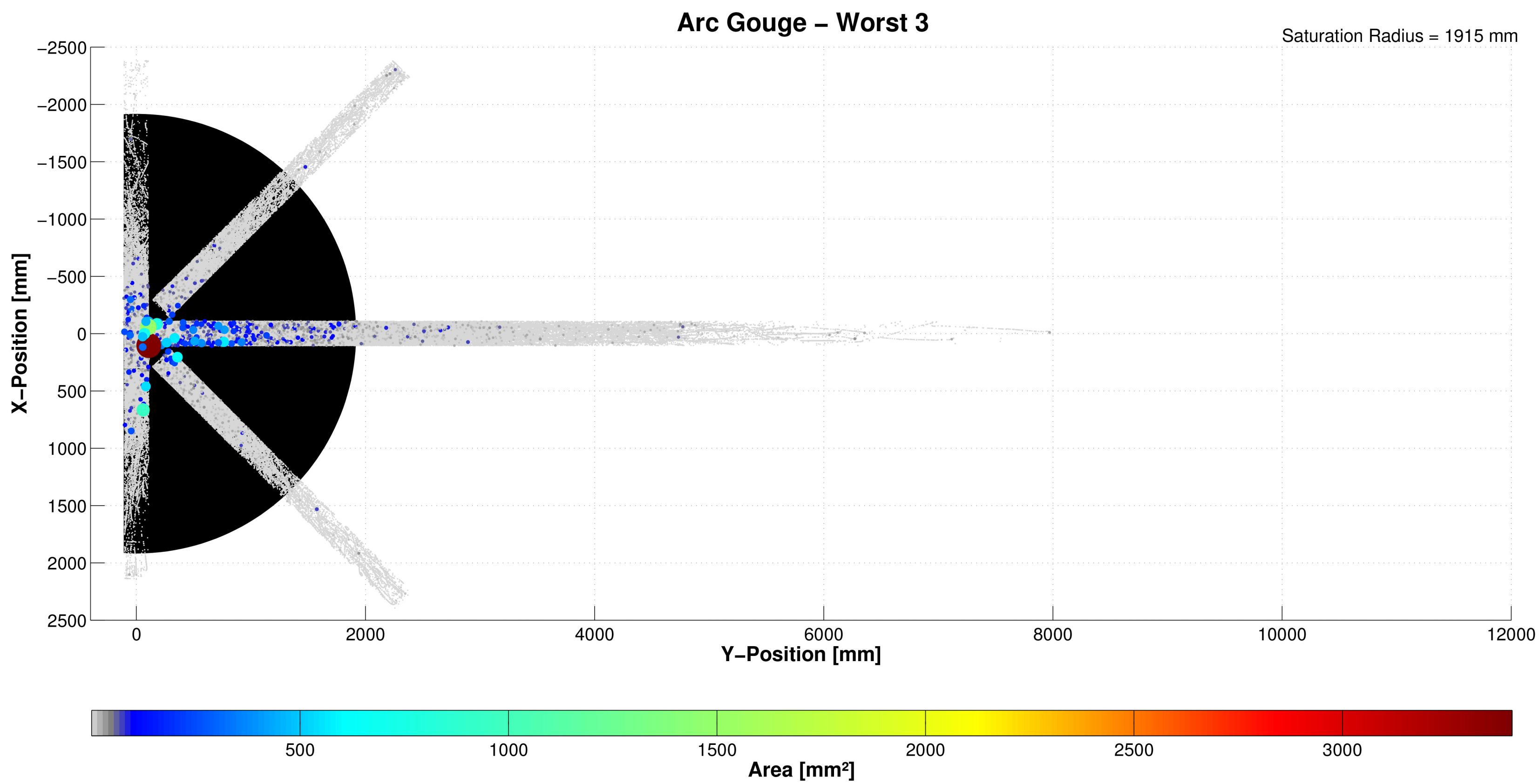


Figure E.18: Particle Distribution, Air Carbon Arc Gouging Worst 3

E.5 Oxyacetylene Cutting

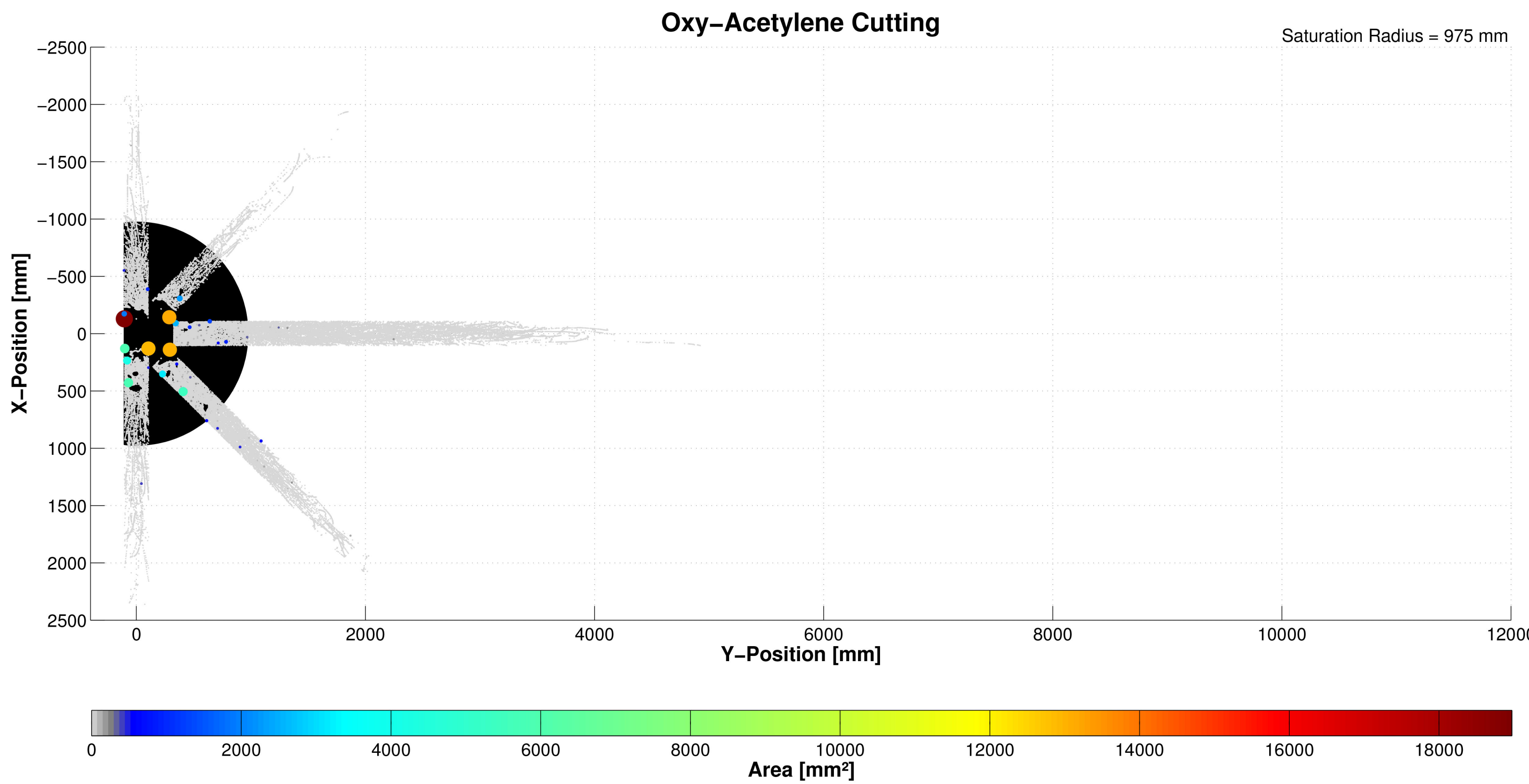


Figure E.19: Particle Distribution, Oxyacetylene Cutting

E.6 Cut-Off Saw

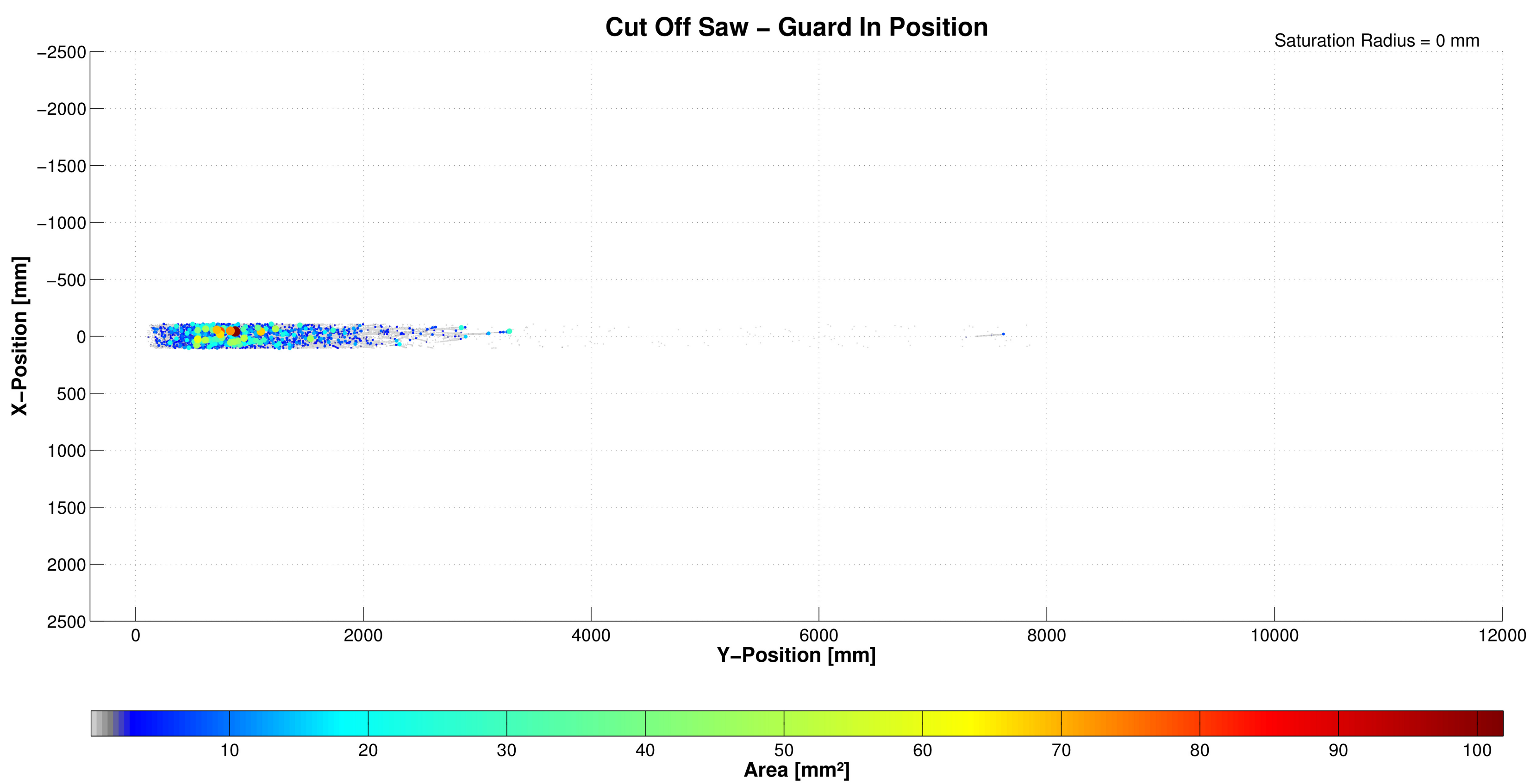


Figure E.20: Particle Distribution, Cut-Off Saw Guard In Place

Figure E.21: Particle Distribution, Cut-Off Saw Guard Out of Place

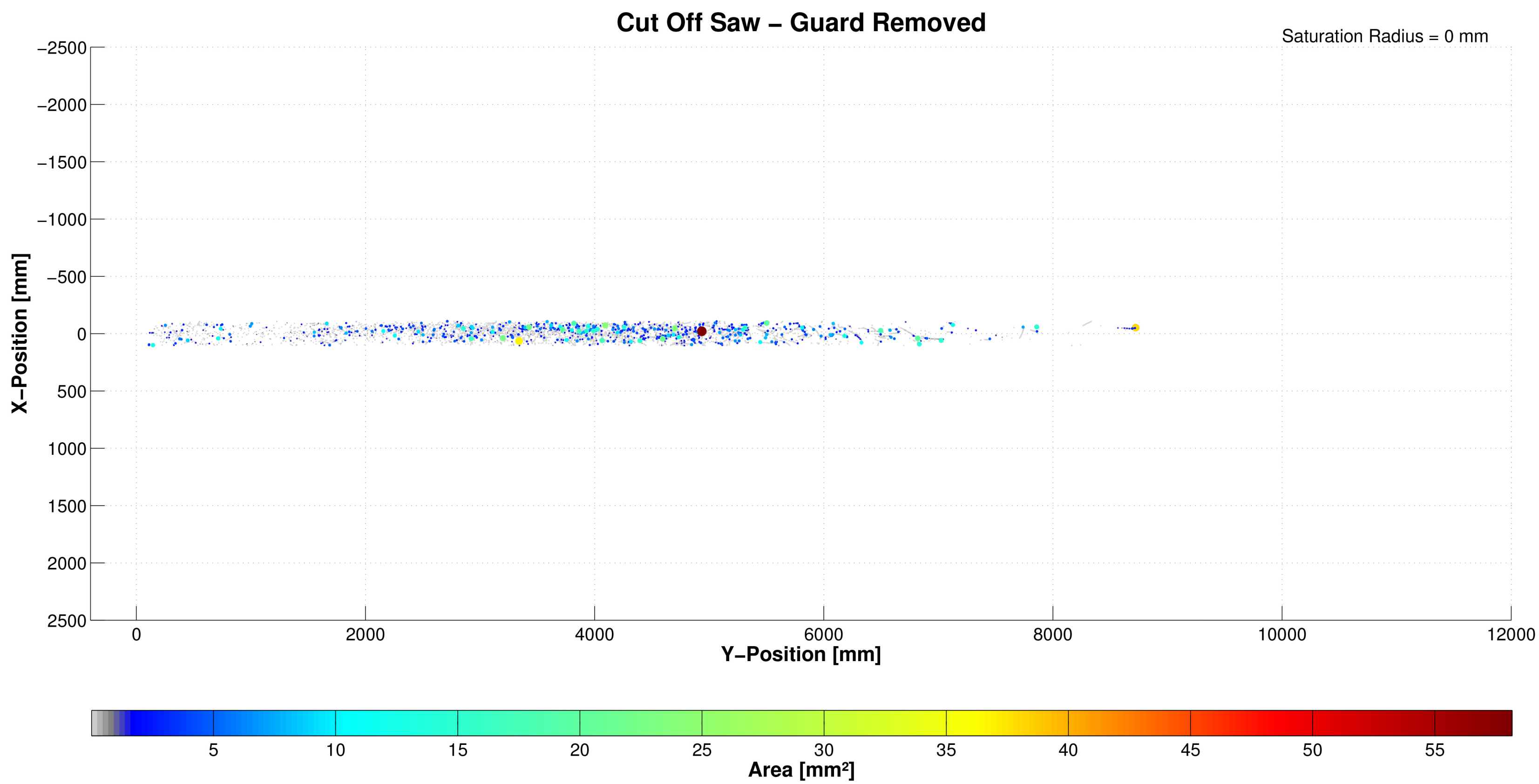


Figure E.22: Particle Distribution, Cut-Off Saw Guard Removed

E.7 Cut-Off Wheel

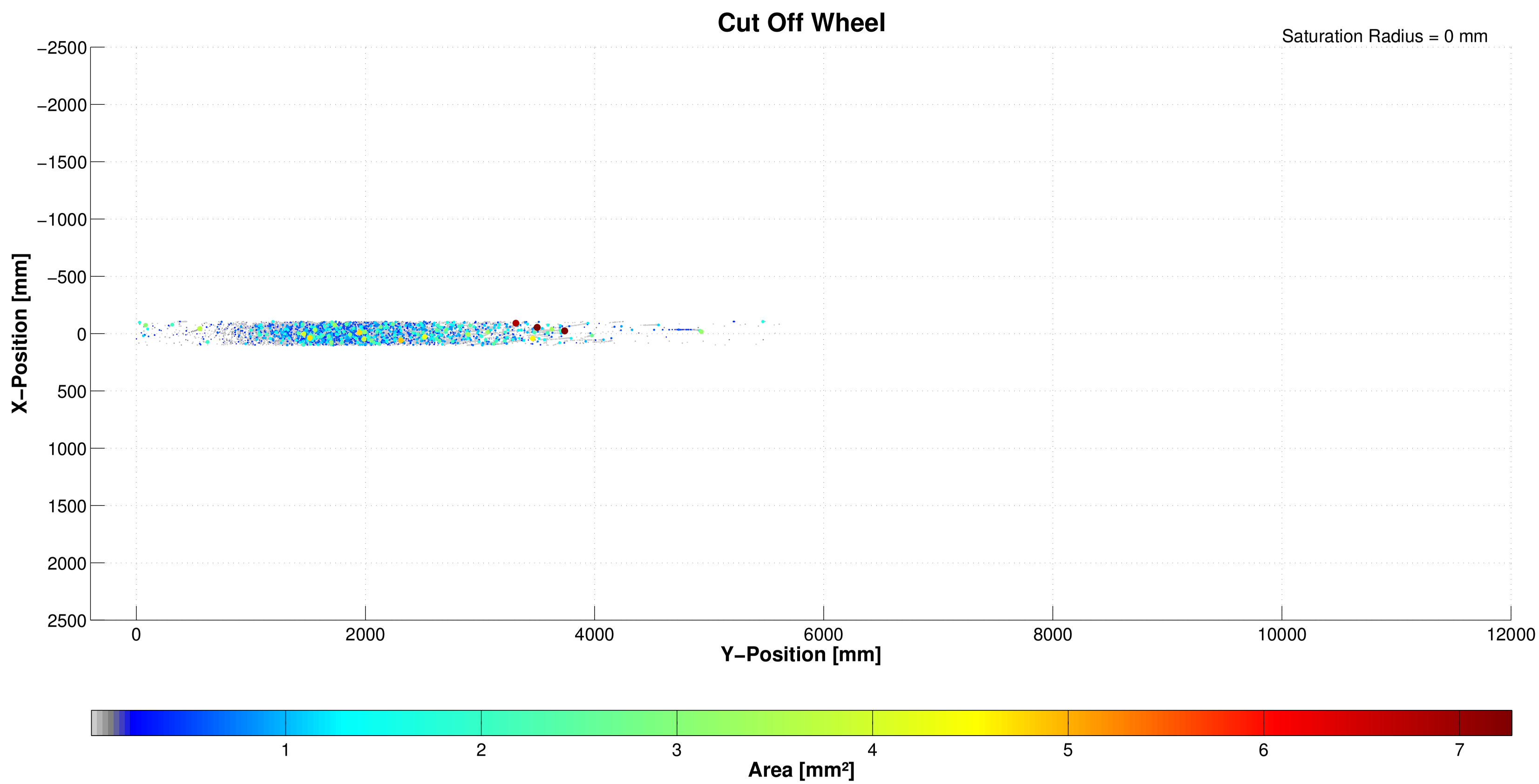


Figure E.23: Particle Distribution, Cut-Off Wheel