Comparative analysis of Air pollution and asthma-related visits in the Spanish cities of Santander and Zaragoza

This study compares the time patterns and levels of three urban pollutants (NO$_2$, O$_3$ and PM$_{10}$) during an eight-year period (2003-2010) in two Spanish cities (Santander and Zaragoza). Results show that particulate matter less than 10 microns in diameter is the only one of the three pollutants that breaches European standards. The study examines the behaviour of the pollutants and then, using a Poisson regression model, looks for statistically significant relations between pollution levels and asthma-related visits. Results differed according to the pollutant involved and time elapsed since inhalation: asthma-related visits in Santander varied inversely with the level of NO$_2$ and PM$_{10}$ breathed in on the same day as the asthma outbreak and positively with the level of O$_3$. In Zaragoza the relationship was the same but did not occur until one day after pollutant inhalation.


The characteristics of the atmosphere have changed down the ages, especially since the start of the Industrial Revolution in the eighteenth century. Not only has its composition patently changed but also its «quality» has declined in a process that has come to be known generically as «pollution».

Air pollution can be analysed from two main approaches; firstly the study of indoor pollution (housing, public buildings, etc.) and secondly outdoor pollution. Indoor pollution is very important and has a huge effect on public health, since over 80% of time in built-up areas is currently spent in enclosed sites. In the western world optimum environmental conditions indoors are obtained at the expense of an increase in energy consumption. This consumption peaks in summer and winter due mainly to air condition and heating. Energy costs of maintaining optimum conditions inside buildings spell high pollution for the environment and outside air; a more rational balance therefore now needs to be struck between air-conditioning demands and the ensuing environmental damage$^{(1)}$.

But it is without doubt outdoor pollution that has received most attention due to its generalised effects on nature, health and the public at large. Pollution runs parallel to economic growth; most polluting emissions come from the consumption of fossil fuels (both for generating electricity and for transport and industrial activity); the problem is aggravated by the concentration of the population in built-up areas in some parts of the world$^{(2)(3)(4)}$. The urban development trend and the growth of the urban population is a worldwide phenomenon. In most countries this is both a consequence and a stimulation of economic growth (based mainly on industrialisation); for this very reason the effects of pollution on the populations of developing countries are likely to increase in the near future.

Many studies have shown the progressive deterioration of air quality. Massie et al$^{(5)}$ showed the air pollution trend in relation to the increasing population density in cities and industrial development. Another demonstration of this worsening
trend is now observable in China. This country, due to its breakneck industrial and economic growth, has seen a huge increase in the number of people living in built-up areas and the sudden emergence of sprawling megacities since the 1990s. This has spawned a massive increase in energy consumption and emissions of airborne pollutants; the number of days with poor air quality in the main cities is soaring\(^6\). Studies have also been conducted to analyse the levels of particular pollutants; in 1984, Khalil and Rasmussen\(^7\) were already describing an increase in carbon monoxide; in a follow-up study of 1990 they confirmed that this trend could be largely put down to mankind’s activity\(^8\). Air pollution has now become one of the main environmental problems worldwide. It is present in all parts of the planet and has a serious effect on human health and natural systems as well as an economic knock-on effect.

The relation between morbidity-mortality and air quality has been the subject of many studies in recent years; figures thrown up by these studies range from 800,000 to two million early deaths due to exposure to polluted air in built-up areas and indoor pollution\(^9\); over half of these deaths occur in developing countries\(^10\).

Some studies look into the association between high levels of air pollutants and upsets to practically all bodily systems (haematological, immunological, neurological, reproductive, dermatological); particularly notable, however, are the effects on the respiratory and cardiovascular systems\(^11\),\(^12\). Furthermore, the relation between air quality and health is not limited to individuals; the problem also has social and economic consequences: increase in days off work, loss of productivity and increase in medical costs\(^13\),\(^14\).

Several studies have looked into the short-term effects of air pollution, which have revealed an increase in mortality and also in visits and hospitalisation rates due to cardiovascular and respiratory illnesses associated with high levels of pollutants. There are also some longitudinal studies showing the harmful long-term health effects on the population, caused mainly by exposure to particulate matter\(^15\).

Air pollution reduction policies are now considered to be necessary to protect and improve individual and communal health. In support of this idea, studies conducted in various parts of the planet have shown how a reduction of air pollution is directly tied in with an improvement in the population’s health\(^16\),\(^17\).

**Methodology**

**Air quality readings: culling and processing**

This study analyses the air quality of two urban-background stations: Renovales, in the centre of Zaragoza, and Tetuán, in Santander. They both have a complete series of data (>90%) and are located close to the hospitals where the illness episodes were analysed.

Three air pollutants were studied: nitrogen dioxide (NO\(_2\)), ozone (O\(_3\)) and particulate matter with a diameter of less than 10 microns (PM\(_{10}\)). The readings were furnished by the Regional Environment Ministry of Cantabria (Consejería de Medio Ambiente del Gobierno de Cantabria) and the Environment and Sustainability Agency of the City Council of Zaragoza (Agencia de Medio Ambiente y Sostenibilidad del Ayuntamiento de Zaragoza). The original data consist of hourly readings recorded from 1 January 2003 to 31 December 2010; these were validated, standardised and incorporated into a database through a series of extract transform and load (ETL) processes for subsequent display in an online analytical processing (OLAP) system in pivot table format.

OLAP representation of the data allows both calendars and time series to be drawn up.

Initially, from the hourly readings, a calculation was made of the daily mean of each pollutant; these daily means were then used for drawing up annual series (average of all data each year). Lastly, weekly calendars were drawn up.\(^18\).

**Hospital attention data: culling and processing**

The data used for analysis of respiratory-based hospitalisations was taken from visits in Hospital Universitario Marqués de Valdecilla, the most important hospital of Santander, and Hospital Universitario Miguel Servet, the most important in Zaragoza. The study includes patients who were finally registered as inpatients in one of these hospitals and those who were dealt with in not needing hospital admission.

The pathology studied is asthma, selected due to the proven relation between pollutants and asthma outbreaks shown in past studies.
Time analysis model by Poisson regression
To study the relations between pollutants and asthma an explanatory model was built up of the time trend of visits, with the aim of quantifying the effects of risk factors (exposure to airborne pollutants: NO$_2$, O$_3$ and PM$_{10}$).

The chosen model is Poisson regression (due to the data distribution), constructed for each city as follows:

$$\log E(Y) = \alpha + \gamma C + \sum_{i} \beta_i X_i$$

Where $E(Y)$ is the expected number of daily visits; $\alpha$ is the model constant; $\gamma$ is the direct or delayed effect of each pollutant; $C$ is the pollutant, and $\beta$ is the effect of each one of the covariables $X$ to be controlled.

Confounders considered were weather variables (daily averages of mean, maximum and minimum temperature, solar radiation, maximum and minimum pressure and precipitation), taken from the Spanish Meteorology Agency AEMet. An assessment was also made of possible seasonal cycles and trends, effects of respiratory infections (possible flu epidemics) and changes in the population size throughout the study years. The model also takes into account likely latency periods in the effect of confounding variables on the illnesses studied (using delays of up to three days in the explanatory variables). Furthermore, in view of the fact that control is not perfect, an autoregressive Poisson model was chosen (introducing as explanatory variables up to seven days of delay in visits) correcting the residual autocorrelation$^{(19)}$.

The base regression model was built up from covariables with a significant effect $p < 0.1$. Introduction of pollutant variables into the final model was restricted to those with an effect $p < 0.05$.

Results and Discussion
Daily variations in pollutants and levels in comparison to European standards

Nitrogen dioxide (NO$_2$)

The daily NO$_2$ trend throughout the eight years of study (2003-2010) is shown in Figure 1. Daily NO$_2$ readings clearly follow an annual cycle with winter peaks and summer troughs, chiming in with the findings of several previous studies$^{(20),(21)}$. Respiratory-based hospitalisations were analysed in two of the most important hospitals in each city: Hospital Universitario Marqués de Valdecilla in Santander (left) and Hospital Universitario Miguel Servet in Zaragoza (right). Once the final model for visits in each city had been obtained, from the Poisson regression coefficients, a calculation was then made of the relative incidence rates (RIRs), which indicate the effect on the dependent variable (asthma) of each increment in the independent variable (pollutant).

Version 21 of the SPSS statistics software was used as the statistical support for this analysis.
In general terms pollutant levels are higher in Zaragoza than in Santander, though neither city has any great industrial fabric that might account for this difference. The difference might stem from the bigger population and higher number of cars in Zaragoza. Note, however, that the NO\textsubscript{2} levels of both cities fall within European threshold limits. The highest hourly concentration clocked up in the eight years was 138 μg/m\textsuperscript{3} in the city of Santander on 21 January 2004 and 164 μg/m\textsuperscript{3} on 3 March 2004 in Zaragoza; the threshold health-protection limit is 200 μg/m\textsuperscript{3}.

The daily trend of the pollutants is not significant in Santander (Kendall’s tau 0.012, p 0.342), while in Zaragoza there is a significant downward trend (Kendall’s tau -0.204, p<0.001).

**Ozone (O\textsubscript{3})**

The study of daily O\textsubscript{3} levels during the eight-year period showed up an annual cycle, peaking in spring and summer and bottoming out in winter\textsuperscript{(22),(23)}. This cycle runs counter to the one shown by NO\textsubscript{2}, perhaps because this secondary pollutant is fuelled by interaction between sunlight and some components of the atmosphere, NO\textsubscript{2} being its main precursor.

The highest ozone levels in the period under study were recorded in Santander and the absolute minimum in Zaragoza (Figure 2). Furthermore, in the first six years Santander maximums on the coast were recorded earlier than inland in Zaragoza. The sunlight dependence for its formation and also the weather and lie of the land of each city could favour dissipation or accumulation of pollutants, thus provoking conditions conducive to the necessary chemical reactions for ozone formation or destruction at one moment or other of the year.
The daily pollutant trend is significant and positive in the two cities. In Santander Mann-Kendall’s tau correlation coefficient clocked up a value of 0.1 (p<0.001), while in Zaragoza the correlation coefficient is 0.201 (p<0.001).

Eight-hour mean ozone concentrations were calculated with the threshold limit laid down by European directives (120 μg/m³), bearing in mind that this limit should not be exceeded on more than 25 days for each calendar year averaged out over a three year period. This shows that, albeit with one-off threshold-breaking days, the standards are not breached in either of the two cities (Table 1). It is worthy of note here that Santander exceeded said threshold in the years 2005 and 2007, while Zaragoza did so between 2007 and 2010. The period in which the 120 μg/m³ is breached in Santander is April-July, most events occurring in June. In Zaragoza the threshold is breached from April to September, August being the month with the highest frequency of threshold-breaking eight-hour readings.

Table 1. Number of times a year the ozone health-protection threshold is broken

<table>
<thead>
<tr>
<th>Year</th>
<th>2003</th>
<th>2004</th>
<th>2005</th>
<th>2006</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
</tr>
</thead>
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<tr>
<td>Santander</td>
<td>0</td>
<td>0</td>
<td>14</td>
<td>5</td>
<td>9</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Zaragoza</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>7</td>
<td>4</td>
<td>14</td>
<td>7</td>
</tr>
</tbody>
</table>

Particulate matter with a diameter of less than 10 microns (PM₁₀)

The daily concentration trend of particulate matter with a diameter of less than 10 microns during the eight years under study (2003-2010) is shown in Figure 3. Unlike NO₂ and O₃, particular matter shows no clear annual behavioural cycles.
A study of the daily readings of this pollutant in the two cities shows three differentiated phases. During the first two years under study (2003-2004), the mean concentration was higher in coastal Santander (33.3 μg/m³) than in inland Zaragoza (20.9 μg/m³); in the three following years (2005-2007) Zaragoza’s PM₁₀ levels soared to a mean value of 39.2 μg/m³, while Santander’s readings fell (the mean concentration was 28.5 μg/m³); finally, in the last three years the readings in both cities tended to even out, with a sharp fall in Zaragoza (mean concentration: 29.8μg/m³) while levels held steady in Santander (mean concentration: 27.2 μg/m³).

Table 2 shows the recorded PM₁₀ readings against the European legal threshold; in general the concentration has steadily fallen during the study period, following the WHO’s health-protection indications; the number of threshold-breaking readings have also fallen in each city. During phase 1 of legislation implementation, which took in the years 2003 and 2004 of our study period, the maximum number of times the PM₁₀ threshold could not be broken per year was 35; during phase 2 (2005-2010), both the threshold and the number of times it could be broken, at only seven times a year, were stricter.

Table 2. PM₁₀ trend (daily and 24-hour means) as against the legal limit

<table>
<thead>
<tr>
<th>Standard</th>
<th>Year</th>
<th>ULegal limit</th>
<th>Santander</th>
<th>Zaragoza</th>
<th>Santander</th>
<th>Zaragoza</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase 1</td>
<td>2003</td>
<td>60</td>
<td>37</td>
<td>2</td>
<td>824</td>
<td>35</td>
</tr>
<tr>
<td></td>
<td>2004</td>
<td>55</td>
<td>29</td>
<td>1</td>
<td>701</td>
<td>30</td>
</tr>
<tr>
<td>Phase 2</td>
<td>2005</td>
<td>50</td>
<td>28</td>
<td>52</td>
<td>609</td>
<td>1110</td>
</tr>
<tr>
<td></td>
<td>2006</td>
<td>50</td>
<td>14</td>
<td>108</td>
<td>315</td>
<td>2142</td>
</tr>
<tr>
<td></td>
<td>2007</td>
<td>50</td>
<td>31</td>
<td>117</td>
<td>651</td>
<td>2648</td>
</tr>
<tr>
<td></td>
<td>2008</td>
<td>50</td>
<td>23</td>
<td>57</td>
<td>509</td>
<td>1234</td>
</tr>
<tr>
<td></td>
<td>2009</td>
<td>50</td>
<td>12</td>
<td>36</td>
<td>280</td>
<td>739</td>
</tr>
</tbody>
</table>
Table 2’s columns break down the number of times the legal threshold was exceeded: one column refers to the number of times per day (defining «day» as the mean of the 24 hours running from 8.00 hours to 7.00 hours of the following day); the other shows the number of times the rolling 24-hour mean (calculated over the whole year) was broken. The reason for including both thresholds is that Directive 1999/30/EC, which lays down the legal limits for PM$_{10}$, transposed into Spanish law as R.D.1073/2002, is ambiguous in terms of how the 24-hour means should be calculated. For our part, given the objectives of this study, we understand that the 24-hour intervals should not be governed by the civil calendar but rather by the consecutive periods in which the population continually «breathes in» the pollutant. An analysis of the findings in the table thus shows that, measured against the 24 hours running from 8.00 to 7.00, Santander breaches the European standard every year barring the last (2010) and Zaragoza meets the standard during phase 1 (2003 and 2004) and breaks it from 2005 onwards (phase 2). Taking into account all the rolling 24-hour means over the whole year, however, Santander breaches the standard during the whole period and Zaragoza in the 2005-2010 period. This second way of interpreting the legislation is stricter, so the legislation is breached more times. It should be noted here that, despite this breach, an assessment of the number of times the legal limit has been exceeded in both cities since 2007 shows a decrease, so it would seem that the emission-control measures being taken in both cities are working.

**Weekly pollutant behaviour**

Daily variations throughout the week were studied with weekly calendars. The daily pattern of NO$_2$ was a gentle rise from Monday to Thursday in both cities, peaking on the latter day and bottoming out on Saturday and Sunday. The burning of fossil fuels is estimated to account for about 50% of total NOx production so the fall in the burning of fossil fuels at weekends, as industry, farming and transport industries all reach their low point of the seven day cycle in industrialised countries, is more than likely the reason for this weekend fall in pollutant readings\(^{24,25}\).

Ozone, however, rises progressively from Monday to Sunday. This peaking of concentrations on Saturday and Sunday has come to be known as the Weekend Effect. This situation has been borne out in several countries\(^{26,27,28}\). The difference in the weekly concentration of this compound is tied in with variations in the emissions of ozone precursors (nitrogen oxides (NOx) and volatile organic compounds (VOCs); this accounts for the almost mirror-image behaviour of NO$_2$ and O$_3$ as shown in Figure 4. Given that nitrogen dioxide falls at weekends while ozone rises, the NO$_2$/NO quotient rises significantly at the weekend in comparison to the rest of the week.
The various nitrogen oxides play different roles in the tropospheric ozone cycle. Nitrogen dioxide (NO$_2$) catalyses ozone formation, whereas nitric oxide (NO) tends to destroy it. Direct oxidation of NO with O$_3$ (O$_3$ + NO → NO$_2$ + O$_2$) is the most direct nitrogen-dioxide formation route in the atmosphere and, conditions permitting (glut of NO, scarcity of organic compounds and limited actinic flow), describes the main ozone-elimination vector in the lower layers of the atmosphere. Irradiation by nitrogen dioxide, for its part, can release a highly reactive oxygen atom that then forms tropospheric ozone; all this would account for the contrary behaviours of O$_3$ and NO$_2$.

Emissions show a clear predominance of nitric oxide (NO), so ozone destruction outweighs ozone creation in built-up areas and industrial environments from Monday to Friday, the situation switching at the weekend. This process could explain the weekend effect, during which period ozone levels tend to drop in cities due largely to the fall in road traffic (lower levels of NO).

Figure 5 shows the mean weekly calendar of PM$_{10}$. To study this pollutant it was decided to separate daytime and night-time concentrations. Week-by-week daily means tend to show higher readings on weekdays than at weekends (like NO$_2$ but contrary to O$_3$). The maximum mean daytime concentration in both cities is recorded on Thursdays, while the night-time maximum comes on Thursdays in Zaragoza but on Fridays in Santander. The minimum concentration, both night-time and daytime, is recorded in both cities on Sunday. The difference between weekend concentrations and the rest of the days is much larger during the day than at night on weekdays but not at weekends. There are also glaring differences between Santander, where the daily difference with the weekend is 4.5 μg/m$^3$, and Zaragoza, where the difference is much larger, averaging out at 8.9 μg/m$^3$. 
An increase in ozone levels is associated with a higher number of asthma-related visits in both cities.

A comparison of mean weekday readings in the two cities suggests that daytime values from Monday to Friday are significantly higher (p<0.05) in Zaragoza (mean difference of 3.5 μg/m³), while at weekends there are no significant differences between the two cities. As for night-time readings there are no significant differences between the concentrations recorded in the two cities on any day of the week.

Annual pollutant variations
Table 3 summarises the annual pollutant trend throughout the whole eight-year period in the two cities studied. Red shows situations in which Kendall’s tau index indicates a growing pollutant trend for p<0.01; green shows situations in which the trend is downwards; white means the pollutant in question shows no significant annual trend.

Table 3. Annual pollutant trend (p<0.01)

<table>
<thead>
<tr>
<th></th>
<th>NO₂</th>
<th>O₃</th>
<th>PM₁₀</th>
</tr>
</thead>
<tbody>
<tr>
<td>Santander</td>
<td>+</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Zaragoza</td>
<td>-</td>
<td>+</td>
<td>+</td>
</tr>
</tbody>
</table>

Time series analysis model using Poisson linear regression

Asthma and NO₂
Table 4 shows the Poisson regression coefficient and the relative incidence rate (RIR) with a 95% Wald confidence interval. Only days showing a statistically significant (p<0.05) pollutant-pathology relation after model adjustment have been included.

Table 4. Poisson regression coefficient and RIR for NO₂

<table>
<thead>
<tr>
<th></th>
<th>NO₂</th>
<th>Poisson Regr. Coef.</th>
<th>TRI (%)</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Santander</td>
<td>On the same day</td>
<td>-4.1<em>10⁴ ± 1.6</em>10⁴</td>
<td>99.59 ± 0.16 %</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td></td>
<td>Two days earlier</td>
<td>3.35<em>10⁴ ± 1.74</em>10⁴</td>
<td>100.30 ± 0.17 %</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td></td>
<td>Poisson Regr. Coef.</td>
<td>TRI (%)</td>
<td>p</td>
<td></td>
</tr>
<tr>
<td>----------</td>
<td>---------------------</td>
<td>-----------</td>
<td>-------</td>
<td></td>
</tr>
<tr>
<td>Zaragoza</td>
<td>One day afterwards</td>
<td>-7.09<em>10^3 ± 2.36</em>10^3</td>
<td>99.29 ± 0.23 %</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td></td>
<td>Two days earlier</td>
<td>4.18<em>10^3 ± 2.52</em>10^3</td>
<td>100.42 ± 0.25 %</td>
<td>&lt;0.005</td>
</tr>
<tr>
<td></td>
<td>Three days earlier</td>
<td>5.22<em>10^3 ± 2.37</em>10^3</td>
<td>100.52 ± 0.24 %</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>

**Table 5. Poisson regression coefficient and RIR for O₃**

<table>
<thead>
<tr>
<th></th>
<th>Poisson Regr. Coef.</th>
<th>TRI (%)</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Santander</td>
<td>On the same day</td>
<td>1.24<em>10^3 ± 1.01</em>10^3</td>
<td>100.12 ± 0.10 %</td>
</tr>
<tr>
<td>Zaragoza</td>
<td>One day afterwards</td>
<td>1.37<em>10^3 ± 1.14</em>10^3</td>
<td>100.14 ± 0.11 %</td>
</tr>
</tbody>
</table>

**Table 6. Poisson regression coefficient and RIR for PM₁₀**

<table>
<thead>
<tr>
<th></th>
<th>Poisson Regr. Coef.</th>
<th>TRI (%)</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Santander</td>
<td>On the same day</td>
<td>-1.67<em>10^3 ± 1.05</em>10^3</td>
<td>99.83 ± 0.10 %</td>
</tr>
<tr>
<td>Zaragoza</td>
<td>One day afterwards</td>
<td>-1.69<em>10^3 ± 1.08</em>10^3</td>
<td>99.83 ± 0.11 %</td>
</tr>
</tbody>
</table>

Results show that a 1µg/m³ increase in NO₂ levels in the city of Santander is associated with a fall of about 0.4% in asthma-related visits on the same day and an increase of about 0.36% two days after pollutant exposure. The effects on the next day and three days later are not statistically significant (p>0.05) and are therefore excluded from the table.

In Zaragoza, on the other hand, there is no statistically significant effect on visits on the same day as the pollutant exposure but there is on the following day, when a 1µg/m³ increase in NO₂ levels is associated with a 0.7% fall in visits for asthma outbreaks. Two days after the rise in pollutant levels, for each unit of the chemical compound there was a 0.42% rise in visits; three days after the inhalation the incidence of asthmatic episodes rose by 0.52%.

In view of the physiopathological response triggered by the chemical compound, there is likely to be some delay in post-exposure effects. Castro et al found that the main pulmonary function effects of NO₂ exposure occurred two to three days afterwards(32).

Although it is true that a fall in asthma-related visits was unexpected (as occurred on the same day as the pollutant rise in Santander and the day afterwards in Zaragoza), there are a number of asthma risk factors and not all of them have been included in this study. Pride of place goes to pollen levels, which we were not able to study due to the lack of any readily available daily series for the cities analysed during the study period. Asthma triggered off by pollen hypersensitivity is very common. Pollen levels are affected by weather variables. During the pollination period (which varies from species to species) airborne pollen levels increase with a rise of temperature and fall in cold or rainy periods(33), hence following a pattern similar to ozone and contrary to nitrogen dioxide. This could bear out our results.

**Asthma and O₃**

The findings for the relation between asthma outbreaks and ozone are shown in Table 5. A 1µg/m³ increase in ozone levels is associated in Santander with a 0.12% increase in asthma-related visits on the same day and in Zaragoza with a 0.14% increase on the day following exposure. This bears out and helps to explain the negative association found when analysing NO₂.

Given that the real mean O₃ difference from one day to the next in Santander is 11 µg/m³, this would entail an increase of 1.32%.

The mean variation in ozone levels of Zaragoza, for its part, is 9µg/m³; this would entail a 1.27% increase in asthma-related A&E visits.

**Asthma and PM₁₀**

Table 6 shows that in Santander a significant association (p<0.005) between PM₁₀ levels and asthma was found only on the same day as the exposure itself and in Zaragoza on the day following inhalation.

The negative relation between PM₁₀ levels and asthma outbreaks does not tally with past studies. For the situation found in Santander, however, there is a possible explanation; Santander is a coastal city so particulate matter has a variable natural fraction stemming from sea spray(34),(35); this improves asthmatic sufferers' lung function(36). Zaragoza, on the other hand, is
An inverse relation was found between PM$_{10}$ levels and asthma outbreaks. Is it the fraction of natural origin from sea spray that is responsible for this? Is it the material of smaller size (PM2.5) that is responsible for health effects?

Nonetheless, what the latest studies show is that, although hitherto it has been the effects of PM$_{10}$ that were analysed and blamed for the respiratory symptoms, it is in fact PM2.5 that accesses the lower respiratory tracts and is deposited therein; from there its expulsion is very difficult. Particles falling within the range 2.5 μm to 10 μm, on the contrary, are deposited mainly in the tracheobronchial and nasopharyngeal region, from where they can be expulsed. Furthermore, PM2.5 is capable of inducing cytotoxic and inflammatory reactions in human epithelial lung cells. To round out the study, therefore, an attempt was made to cull data on PM$_{2.5}$ levels but these particles were not measured in the cities under study until the second half of 2009, when the control needs laid down by Directive 2008/50/EC were brought into Spanish standards. There were therefore insufficient data to go on for the period under study here.

Conclusions

Nitrogen dioxide levels recorded in the cities of Santander and Zaragoza during the period 2003-2010 remained below the legal limit; during this eight-year period they fell within the health-protection limits recommended by the World Health Organisation (WHO).

Zaragoza’s NO$_2$ levels were higher than Santander’s but the annual pollutant trend is falling in a statistically significant manner in Zaragoza.

Ozone levels did not breach European standards at any moment of the study period. Santander’s levels were higher than Zaragoza’s. The pollutant trend is upwards in a statistically significant manner in both cities.

Ozone tends to follow a weekly pattern, peaking at weekends, the exact opposite of NO$_2$.

Particulate matter with a diameter less than 10 microns exceeded legal levels in Santander throughout the whole study period; in Zaragoza it breached standards in the last six years under study. Of the two cities, Santander recorded the higher readings during 2003 and 2004, this trend reversing as from 2005. Note that the annual pollutant trend was falling in Santander and rising in Zaragoza.

The relation between asthma and air pollutants varies according to the chemical species concerned; the asthma outbreak sometimes occurs with a built-in delay after inhalation, sometimes a few days afterwards. Santander’s asthma-related A&E visits vary inversely with the level of NO$_2$ and PM$_{10}$ breathed in on the same day as the outbreak and positively with the O$_3$ level. The association in Zaragoza is the same but does not occur until one day after pollutant inhalation. Moreover, in the case of NO$_2$, there is a direct relation two days after inhalation of the compound in both cities and up to three days afterwards in Zaragoza.

REFERENCES

Génova:; 2006.


Study of geomagnetic storms and assessment of their impact on technology and infrastructure in Spain and Portugal

This article looks at geomagnetic storms and their effects on technological resources. It sets forth action guidelines that enable the most storm-vulnerable companies, institutions and public services to take emergency measures designed to avoid or reduce storm damage. The problem is studied in its broadest context: Space Weather. This helps everyone involved to build up a better understanding of the various storm-related physical phenomena and also helps to explain this threat to stakeholders and the public at large.

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Geomagnetic storms, also called “magnetic storms” are worldwide disturbances in the Earth’s magnetic field, caused by solar-wind shock wave\(^1\). Some geomagnetic storms have an intense effect on the Earth’s ionosphere, triggering off “ionospheric storms”\(^1\); these are studied particularly closely in this article due to their effect on global navigation satellite systems (GNSSs). As will soon be explained in greater detail, geomagnetic storms stem from violent energy processes occurring in the Sun, going by the generic name of “solar storms”. We are therefore dealing here with three types of storm: solar, ionospheric and geomagnetic. The three are closely bound up with each other but it is nonetheless useful to distinguish them clearly at the start.

Most geomagnetic storms are small and cause little damage. In the northern hemisphere they manifest themselves in the form of aurorae borealis, visible in high-latitude areas like Iceland, Greenland or North Norway, Sweden and Finland. In the southern hemisphere they produce a similar phenomenon called “aurora australis”. Intense storms, however, like the ones analysed in this article, are also quite frequent events, causing not only the aurorae but also great damage. The US agency NOAA (National Oceanic and Atmospheric Administration) estimates that in any 11-year solar cycle there might be four “extreme”, 100 “severe” and 200 “strong” geomagnetic storms. These figures show we are dealing with a frequent natural phenomenon.
The first notion of the importance of very intense geomagnetic storms came on 1 and 2 September 1859, when a huge solar flare produced the biggest geomagnetic storm recorded to date. This event was dubbed the « Carrington Event» in honour of the English astronomer who observed the solar flare and related it to the magnetic storm recorded on Earth\[^2\][\(^3\)]\). The storm produced aurorae that were clearly visible on the Iberian Peninsula and even at latitudes close to 20º\[^4\]. It also damaged the telegraphy systems of the time, causing many pieces of equipment to burst into flame\[^5\]. This was the first known incident of this type affecting a technological resource and the event is now seen as a wake-up call about the possible influence that a storm of this type might have on our totally technology-dependent society.

The «Quebec Blackout» of March 1989 left 5 million people without electricity for 9 hours and caused 12 million dollars’ worth of transformer damage. Some idea of the important effects of a large geomagnetic storm can be gained by considering the resources most likely to be damaged, like satellites, power grids, gas- and oil-pipelines and air- and rail-transport. The effects on satellites could unleash a chain of knock-on effects on navigation, communication and positioning systems, triggering the collapse of systems as varied as air and sea traffic, security and surveillance and banking systems. In turn, the electric fields generated by the variations in the magnetic field during a geomagnetic storm are capable of inducing electric currents in conducting systems (power cables, metal conductions and earthed conductor systems, etc.). These currents, called Geomagnetically Induced Currents (GICs), pose a great danger to underground metal pipelines like oil- or gas-lines, and also to electricity systems. Damage to high-voltage power distribution systems, especially large transformers, could trip long-lasting and wide-ranging blackouts, damaging basic services like traffic lights, transport systems, water treatment systems and critical installations like hospitals, fire stations and nuclear power plants, with the concomitant nuisance and harm for millions of people in the affected areas. Witness the famous «Quebec Blackout» of March 1989, tripped by a magnetic storm. This power-cut left 5 million people without electricity for nine hours, caused transformer damage in the United States and Canada worth 12 million dollars and knocked out some of this same type of equipment in the United Kingdom. It also seriously affected many satellites. It is calculated that about 1600 orbiting satellites were temporarily out of control\[^6\].

The likelihood of a storm like the « Carrington Event» reoccurring is currently a matter of hot debate. Riley\[^7\] has recently claimed there is a 12% chance of an event of this category occurring in the next 10 years, though many other scientists regard this probability as far-fetched. In 2013 Kataoka\[^8\] mooted a probability of 4-6%, still fairly high. Trustworthy estimates are very tricky due to the incomplete knowledge of some of the physical processes involved and absence of reliable data series to go on, but all studies do stress the reality of this natural peril.

If a Carrington-like magnetic storm should occur today, the consequences would be unimaginable, since technology dependence has soared since 1859. Estimates point to devastating cascade events in the US lasting several years and clocking up millions of dollars in losses. Odenwald and Green (2007), for example, have estimated an economic toll of 30 billion dollars due to the damage that any Carrington-like magnetic storm would do today to satellites in geostationary orbit\[^9\]. The impact could be so great that certain heavily industrialised countries like the United States and the United Kingdom have included this threat in a list of natural risks and have taken initiatives to head it off. Witness, among other examples, the recommendations published by such institutions as FEMA (Federal Emergency Management Agency) and NASA (National Aeronautics and Space Administration) in the USA and the National Risk Register (NRR) of Civil Emergencies in the United Kingdom. This concern has been tabled in international organisations like the OECD (Organisation of Economic Cooperation and Development), which published in 2011 the Geomagnetic Storms report.

**Space Weather, a new discipline**

Geomagnetic storms are a manifestation of Space Weather, a new field of study initiated back in the nineties of last century. It looks at the conditions of the Sun and solar wind, the magnetosphere, ionosphere and thermosphere, which might impact on the performance and dependability of technological systems both on the ground and in space and might even pose a threat to human health. Broadly speaking, the studies making up space weather take in three fields: the Sun and its atmosphere (as the source of the energy), interplanetary space (as the means of propagation) and the magnetosphere, ionosphere and surface of the Earth (as the effected regions). A better understanding of space weather and the design of early warning systems are crucial in the fight to mitigate risks associated with geomagnetic storms.

In Spain the social response to this problem is still very limited, although the Directorate General of Civil Protection (Dirección General de Protección Civil) organised conferences in 2011, 2012 and 2013 to explain the problem to institutions and companies most likely to be hit and affected by a strong storm. A particularly practical and timely initiative was carried out by the Regional Authority of Extremadura (Junta de Extremadura) in March 2011, when it published a Decalogue...
of Good Practices to Prevent Damage from a Severe Solar Storm (Decálogo de buenas prácticas. Tormenta Solar severa, cómo prevenir). Legislative initiatives include a Bill passed on this matter on 27 March 2012 by the Spanish lower house (Congreso de los Diputados), on a proposal made by the Socialist Group and driven by Iniciativas ciudadanas (Citizen Initiatives). In the scientific community magnetic storms are now being studied from various angles in several universities (especially Complutense de Madrid, Complutense de Alcalá de Henares and Politécnica de Cataluña) and in other organisations such as Observatorio del Ebro (Ebro Observatory), the Instituto Geográfico Nacional (National Geographical Institute) and the Instituto Nacional de Técnica Aeroespacial (National Institute of Space Technology).

**The overall context of the problem**

Contradictory as it might seem, a magnetic storm on Earth begins in the Sun. The Sun acts on the Earth through its gravitational field, electromagnetic radiation (of which visible light and heat are the most everyday examples) and the continual emission of material from its corona, making up what is known as the «solar wind». This wind is a plasma flow of protons, electrons and alpha particles. This plasma is extraordinarily thin, with a density of only 10 particles per cm$^3$ in the vicinity of the Earth. Under normal conditions this wind moves at a speed of about 400 km/s and drags along the Sun’s magnetic field with it. The characteristics of electromagnetic radiation and the solar wind vary greatly with the Sun’s activity level, which is both cyclical and sporadic in nature. Its cyclical nature is expressed in a period of about 11 years, called the solar cycle. Increasing activity is reflected by an increase in the number of sunspots and a higher number of violent outbreaks, which constitute the sporadic activity. Although unforeseeable, therefore, the sporadic behaviour also has a certain periodical character, tending to increase in number during phases when solar activity is nearing its peak.

**Violent events in the Sun reach the Earth in the form of electromagnetic radiation with an 8-minute time lag and also in the form of particles and disturbances of the interplanetary magnetic field with a time lag of several hours to a few days**

Sunspots are so called because they are visible as dark spots on the Sun’s surface, the photosphere. Their different colour from the rest of the Sun stems from their temperature, which, at about 4500 K, is lower than the c. 6000 K temperature elsewhere. The number of sunspots is measured by the «Wolf number»-, a widely used indicator to assess the Sun’s activity, with a reliable series of measurements dating right back to 1848. The magnetic field near the sunspots builds up to huge values and manifests itself violently in the form of gigantic eruptions known as solar flares. The areas with spots are therefore considered to be «active regions» of the Sun. Solar flares, together with Coronal Mass Ejection (CME), a closely related phenomenon, and coronal holes (regions with magnetic fields opening freely into the heliosphere), throw huge amounts of the corona’s mass into the interplanetary medium, modifying the speed and density of the solar wind.

Solar flares, for their part, are classified in terms of their peak X-ray flux, measured in W/m$^2$. They are thus broken down into five main classes A, B, C, M and X. Each class is further broken down into a linear scale of 1 to 9, each number being twice as powerful as the former. Classes M and X indicate phenomena that might have important effects in near-Earth space. For example, the three most important solar flares of 13 and 14 May 2013 were generated by the same active region (cluster of sunspots AR 11748) and clocked up values of X1.7, X2.8 and X3.2.

On the initiative of Wolf (1816-1893) solar activity cycles are numbered successively from 1 onwards, 1 applying to the period 1755-1766. In this article we are paying particularly close attention to cycle 23, which lasted approximately from May 1996 to December 2007, and cycle 24 in which we are still immersed today.

Violent events in the Sun reach the Earth in the form of electromagnetic radiation with an 8-minute time lag and also in the form of particles and disturbances of the interplanetary magnetic field, dragged by the solar wind, with a time lag of several hours to a few days. This means that solar events have occurred eight minutes before their observation on Earth but there is then a time lag of several hours before the disturbances generated by these solar events affect the Earth and might trigger a geomagnetic storm. There is hence a chance of predicting the appearance of a geomagnetic storm and taking preventive action against it.

Solar wind emission is constant and its interaction with the Earth’s magnetic field produces a border where the forces cancel out, called the «magnetopause», which protects a cavity known as the «magnetosphere» (fig 1). This region of space where the Earth’s magnetic field exerts its influence is, so to speak, our home in the planetary system. The magnetosphere protects us from the action of the solar wind and cosmic rays, allowing life to exist in this safeguarded region.

**Formation and measurement of geomagnetic storms**

Geomagnetic storms are triggered by an increase in the plasma density and the speed of the solar wind after a solar flare or
an earthwards-directed coronal mass ejection. These increases raise the pressure of the solar wind in the magnetopause and deform the magnetosphere\cite{11}. On the daytime side the magnetopause approaches our planet along the Sun-Earth line, moving in from 11 Earth radii to only 4-5. At the same time the region corresponding to the night-time hemisphere stretches out in a very complex manner, similar to a tube of toothpaste squeezed in the middle. This intensifies the Earth’s magnetic field and increases its bow-wave pressure against the solar wind, reaching a new equilibrium position. All these phenomena give rise to the geomagnetic storm, which affects, to a lesser or greater degree, the whole planet. Depending on the speed of the disturbed solar wind, it will occur between one and four days after the violent event on the surface of the Sun.

Figure 1. Structure of the magnetosphere in equilibrium with the solar wind\cite{8}. Under normal conditions the magnetopause lies at a distance of 11 Earth radii along the Sun-Earth line (to the left of the image) tailing off over more than 80 Earth radii in the opposite direction.

Not all coronal mass ejections produce magnetic storms on the Earth. In general, three conditions have to obtain for this to occur: (1) the solar storm has to be energetic enough, reaching either class X or high values of class M; (2) the coronal mass ejection has to be directed earthwards, meaning that the sunspot cluster or active region initiating the whole process must be on the visible side of the Sun away from its limbs; (3) the Bz component of the interplanetary magnetic field (IMF) dragged by the solar wind must be negative so that the lines of this field can join up with those of the Earth (reconnection of the IMF with the terrestrial field). It has recently been shown that IMF fluctuations, before their encounter with the magnetopause, are an important factor, little understood as yet, in whether the solar wind disturbance will trigger a geomagnetic storm.

The abovementioned conditions explain why an increase in solar activity might not necessarily be accompanied by an increase in geomagnetic storms. For example, the aforementioned solar flares of 13-14 May 2013 did not generate significant geomagnetic storms, since none of the ejections was sufficiently orientated towards the Earth.

A magnetic storm can be divided into three phases\cite{12} (fig. 2):

- **Initial Phase.** This is characterised by an increase in the density of field lines due to rising pressure of the solar wind. The pre-storm value of the horizontal component H of the Earth’s magnetic field then increases by a factor of between 30 and 50 nanoteslas (nT). This variation may last one or two hours although it does not occur in some storms.

- **Main phase.** During this phase the equatorial ring current is boosted by an injection of energised plasma. This occurs
two to ten hours after storm commencement and may last several hours. There is a characteristic sharp fall in $H$.

- **Recovery phase.** This is the stage when the magnetic field returns to normal. It might last days.

![Figure 2. Record of the geomagnetic storm of 14 November 2011 obtained from Observatorio de L’Aquila (Italy), showing the phases described in the text.](image)

Magnetic storms are measured against three geomagnetic scales; the most widely used ones are the Disturbance Storm Time (Dst) and three-hour indices. Dst is an index of magnetic activity obtained from four magnetometer stations near the equator and spread around the Earth’s perimeter. This index measures the magnetic field variation due to the equatorial ring current; it is calculated from the mean of the magnetic field’s horizontal component. The value of Dst is statistically zero on days considered to be calm by international organisations. During a magnetic storm the value falls for a few hours from zero to its minimum value and then slowly climbs back up to the initial value close to zero. Using this index, storms can be classified as shown in Table 1. Table 2 lists the geomagnetic storms that occurred in cycle 24 up to December 2013 with their corresponding Dst readings. A good idea of their size can be gained if we bear in mind that the «Carrington Event» recorded $-850 \text{nT}^{[13]}$ while the Quebec storm weighed in at $-640 \text{nT}^{[14]}$.

**Table 1. Magnetic storm classification by Dst Index**

<table>
<thead>
<tr>
<th>Category</th>
<th>Dst Value (nT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weak</td>
<td>$-30 &gt; \text{Dst} &gt; -50$</td>
</tr>
<tr>
<td>Moderate</td>
<td>$-50 &gt; \text{Dst} &gt; -100$</td>
</tr>
<tr>
<td>Intense</td>
<td>$-100 &gt; \text{Dst}$</td>
</tr>
</tbody>
</table>

**Tabla 2. Storms occurring in Cycle 24 up to December 2013**

<table>
<thead>
<tr>
<th>No.</th>
<th>Date</th>
<th>Dst</th>
<th>No.</th>
<th>Date</th>
<th>Dst</th>
<th>No.</th>
<th>Date</th>
<th>Dst</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>28/02/2008</td>
<td>-52</td>
<td>24</td>
<td>09/09</td>
<td>-69</td>
<td>47</td>
<td>18/01/2013</td>
<td>-57</td>
</tr>
<tr>
<td>2</td>
<td>09/03</td>
<td>-86</td>
<td>25</td>
<td>17/09</td>
<td>70</td>
<td>48</td>
<td>26/01</td>
<td>-53</td>
</tr>
<tr>
<td>3</td>
<td>27/03</td>
<td>-56</td>
<td>26</td>
<td>26/09</td>
<td>-101</td>
<td>49</td>
<td>01/03</td>
<td>-52</td>
</tr>
<tr>
<td>4</td>
<td>04/09</td>
<td>-51</td>
<td>27</td>
<td>25/10</td>
<td>-132</td>
<td>50</td>
<td>17/03</td>
<td>-132</td>
</tr>
<tr>
<td>5</td>
<td>11/10</td>
<td>-54</td>
<td>28</td>
<td>25/01/2012</td>
<td>-75</td>
<td>51</td>
<td>21/03</td>
<td>-64</td>
</tr>
<tr>
<td>6</td>
<td>22/07/2009</td>
<td>-79</td>
<td>29</td>
<td>15/02</td>
<td>-62</td>
<td>52</td>
<td>29/03</td>
<td>-59</td>
</tr>
<tr>
<td>7</td>
<td>15/02/2010</td>
<td>-58</td>
<td>30</td>
<td>19/02</td>
<td>-54</td>
<td>53</td>
<td>24/04</td>
<td>-52</td>
</tr>
<tr>
<td>8</td>
<td>06/04</td>
<td>-81</td>
<td>31</td>
<td>07/03</td>
<td>-78</td>
<td>54</td>
<td>01/05</td>
<td>-76</td>
</tr>
</tbody>
</table>
The three-hour indices indicate geomagnetic activity in each of the last three-hour periods, thus providing eight readings a day. The main one is the K index, introduced by Bartels in 1938, giving a quantitative assessment of a magnetic disturbance linked to the Sun’s corpuscular emission. The data series was then extended back to 1932.

K is calculated using magnetograms, daily records of the magnetic field obtained from geomagnetic observatories. From the magnetogram the H and D (declination) components are taken, cancelling out the magnetic variations due to the Sun in non-stormy conditions and the moon. The magnetogram is then divided into 8 three-hour intervals, the variation of H and D is measured and the biggest value provides the K index. The K scale varies from 0 to 9 and depends on the latitude, since the disturbance will vary in direct proportion to the nearness of the observatory to the auroral zones.

The Kp index is an indicator of planetary scope deriving from the K parameter. It is obtained as the mean value of standardised K indices in 13 observatories in the 44º-60º latitude belt in the northern or southern hemispheres. This index strikes a statistical relationship between the magnetosphere’s energy state and the five-level NOAA-rated size of the magnetic storms, represented by a G number (Table 3).

**Table 3. NOAA classification of magnetic storms in terms of the Kp index value**

<table>
<thead>
<tr>
<th>Category</th>
<th>Kp Value</th>
<th>NOAA Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extreme</td>
<td>9</td>
<td>G5</td>
</tr>
<tr>
<td>Severe</td>
<td>8</td>
<td>G4</td>
</tr>
<tr>
<td>Strong</td>
<td>7</td>
<td>G3</td>
</tr>
<tr>
<td>Moderate</td>
<td>6</td>
<td>G2</td>
</tr>
<tr>
<td>Minor</td>
<td>5</td>
<td>G1</td>
</tr>
</tbody>
</table>

Some international agencies take Kp 4 as the cut-off point for giving out warnings of a geomagnetic storm.

**Geomagnetic storm study methodology: application of this methodology to the storm of 24-25 October 2011 and its impact on the Iberian Peninsula**

With the aim of clearly presenting the various processes that trip a geomagnetic storm and its effects on the Earth in general and the Iberian Peninsula in general, a detailed monitoring is described below of the storm that broke out on 24-25
October 2011. This storm has been chosen for our example because it was intense (Dst = -132 nT), there is a lot of data to go on and it had a notable effect on the EGNOS (European Geoestationary Navigation Overlay Service), augmentation system, an essential resource for fine tuning GPS (Global Positioning Service) and Glonass (Globalnaya Navigatsionnaya Sputnikovaya Sistema) navigation systems in Europe and Africa. Some important effects of this storm on the Earth’s environment have been studied by Blanch et al[15].

The methodology studies successively the events on the Sun, the path of the solar wind to the Earth, its interaction with the Earth’s magnetic field, tripping the geomagnetic storm, the influence of this storm on the Earth’s ionosphere and the effect on EGNOS and air traffic safety.

**Start of the event on the Sun**
The whole process kicked off on 22 October 2011, with a solar eruption magnitude M1 that peaked at about 11:10 UT. This eruption produced a huge coronal mass ejection which disturbed the conditions of the solar wind. Figure 3, taken from the LASCO (Large Angle and Spectrometric Coronagraph) equipment onboard the SOHO satellite, shows the scale of the event. SOHO is located at Lagrange Point L1 where the gravitational attraction of the Sun and Earth cancel each other out; the orbits in this zone therefore have a higher gravitational stability. This zone lies 1,500,000 kilometres from the Earth.

![Diagram of CME observed by satellite SOHO](http://sohowww.nascom.nasa.gov/spaceweather/)

**Figure 3. CME observed by satellite SOHO.**

**Path of the CME towards the Earth**
Figure 4 shows the forecast pathway through space of the CME generated by the solar flare. This has been drawn up from NOAA’s WSA-Enlil cone model. In the lefthand figure the CME, marked in red, is seen to be heading clearly for Mars, represented by a red dot top right; at this point it does not seem destined to impact on Earth. The central figure shows how, six hours later, it would reach Stereo A (small red square), an observatory orbiting the Sun and observing the star from two opposite positions of the same orbit, together with its twin observatory Stereo B, both of the satellites between them therefore giving a better idea of the structure and trend of solar storms. The forecast indicates that finally (righthand figure) the CME would end up brushing the Earth (represented by a yellow circle).

Figure 4. Forecast path of the CME generated on 24 October 2011. [http://www.swpc.noaa.gov/wsa-enlil/](http://www.swpc.noaa.gov/wsa-enlil/)

During the afternoon of 24 October (18:00 UT), the ACE satellite (Advanced Composition Explorer), also orbiting the Sun at Lagrange point L1, detected an increase in solar wind speed from 350 km/s to 550 km/s, indicating the incoming impact of the CME and auguring a geomagnetic storm (Fig.5). Furthermore the magnetic field’s Bz component was facing southwards, thus satisfying one of the aforementioned necessary conditions for a geomagnetic storm being generated on Earth. The satellite was able to gauge the characteristics of the solar wind about 40 minutes before it hit the Earth. This provided a precious leeway for taking geomagnetic-storm mitigating measures.
Figure 5. Values of the magnetic field module, its components and solar wind speed, measured by satellite ACE on 24 and 25 October 2011. [http://omniweb.gsfc.nasa.gov/ow.html](http://omniweb.gsfc.nasa.gov/ow.html)

In its journey earthwards, and at only 35,800 kilometres from its surface, the disturbance hit the geostationary satellites GOES 13 (longitude 75°) and 14 (longitude 135°), which were also able to assess the solar wind. Figure 6 shows the proton and electron flux readings for 24-27 October 2011, as recorded by GOES-13. The electron flux clearly shows the change caused by the disturbance as from 18.00 hours on the 24th and lasting until 9.00 hours on the 25th. The strong compression of the Earth’s magnetic field during the impact enabled the solar wind to penetrate deep into the magnetosphere from 19:06 UT until 19:11 UT, exposing the satellites to the action of the solar wind plasma.
At 18.00 hours (Universal Time) on 24 October 2011, the ACE satellite (Advanced Composition Explorer) detected an increase in solar wind speed, auguring a geomagnetic storm that hit the Earth about 40 minutes later.

The arrival of the disturbed solar wind on the Earth generated a geomagnetic storm that was recorded in various observatories, affecting the ionosphere and throwing satellite positioning systems out of kilter. Figure 7 shows the magnetograms of 24 and 25 October obtained from the observatory of San Pablo de los Montes (Toledo). These show that the geomagnetic storm started on the afternoon of the 24th and lasted, at least, throughout the whole of the 25th. Figure 8, with the Dst index readings, shows that the initial phase of the geomagnetic storm lasted from 15 to 18.00 hours, the main phase lasted until 10.00 hours on the 25th and the recovery phase until 23.00 hours on the 29th.

Figure 6. Top down: Proton and electron fluxes measured by GOES and the Kp index on 24-27 October. On the flux panels the colours correspond to particles with different energies. For protons: red > 10 MeV; blue > 2 MeV; green > 100 MeV. For electrons: yellow > 0.8 MeV; red > 2 MeV. The units are cm^-2 s^-1 sr^-1. [http://www.swpc.noaa.gov/Data/index.html](http://www.swpc.noaa.gov/Data/index.html)

**Arrival of the solar wind on Earth. Recording of the storm on the Iberian Peninsula**

The arrival of the disturbed solar wind on the Earth generated a geomagnetic storm that was recorded in various observatories, affecting the ionosphere and throwing satellite positioning systems out of kilter. Figure 7 shows the magnetograms of 24 and 25 October obtained from the observatory of San Pablo de los Montes (Toledo). These show that the geomagnetic storm started on the afternoon of the 24th and lasted, at least, throughout the whole of the 25th. Figure 8, with the Dst index readings, shows that the initial phase of the geomagnetic storm lasted from 15 to 18.00 hours, the main phase lasted until 10.00 hours on the 25th and the recovery phase until 23.00 hours on the 29th.

Figure 7. Magnetograms corresponding to 24 and 25 October, recorded in the observatory of San Pablo de los Montes (Toledo), clearly showing the advent of the geomagnetic storm. [http://www.intermagnet.org](http://www.intermagnet.org)
Many specialist space weather stations issue a geomagnetic storm alert two days before it occurs.

Impact on the ionosphere and the Iberian Peninsula

The impact on the ionosphere (the conducting part of the atmosphere extending from 60 out to 2000 kilometres from the Earth’s surface) is crucially important for satellite communication purposes due to its strong influence on the transmission of electromagnetic waves\textsuperscript{[16]}. When the impact of the solar wind causes an appreciable variation in the ionosphere’s characteristics, then an «ionospheric storm» is said to have occurred. If this modification entails an electron-density increase (number of electrons per unit of volume) of the ionosphere, this is said to be a «positive ionospheric storm». Conversely, if the effect is a reduction in this density, it is said to be a «negative storm»\textsuperscript{[17]}. In both cases there may be significant disturbances to GNSS communication systems.

This impact has been studied in two different ways. Firstly by analysing ionograms (ionosphere readings from high frequency ionosondes) of 23, 24 and 25 October from the Observatorio del Ebro and INTEA’s Estación de Sondeos Atmosféricos (Atmospheric Sounding Station) of the Centro de Experimentación (Experimentation Centre) in El Arenosillo (Cedea) Huelva. The results (Figure 9 shows those for El Arenosillo) reveal a slight increase in the critical frequency of layer F2, foF2, and a significant increase in the height of its maximum electron concentration, hmF2. The increase of foF2 tallies with the increase in density and will show up in the electron content analysis, since the plasma frequency is proportional to the square root of the electron density. The increase in height, for its part, is a characteristic phenomenon of geomagnetic storms whenever there is a positive ionospheric storm.
Figure 9. Variation of foF2 and hmF2 obtained from ionograms recorded on 24-27 October in the atmospheric sounding station of El Arenosillo. Blue lines show mean values and red the values on the indicated days.

The second technique used for analysing the impact of the magnetic storm on the ionosphere was studying the variation in the total electron content (TEC). This parameter measures the number of electrons contained in a $1\text{m}^2$ cross-section cylinder running from the satellite to the receiver along the line of sight; its unit is called TECu and is tantamount to 1016 electrons/m$^2$. The TEC reading is obtained from the delay in the transmission of electromagnetic waves observed in GPS stations. Its variations therefore show how the ionosphere has been affected by the geomagnetic storm, i.e., they gauge the importance of the generated ionospheric storm. In our study the analysis was made by processing the RINEX files (Receiver Independent Exchange Format) obtained in the stations shown in Figure 10. For each station a calculation was made of the vertical TEC, $v\text{TEC}$, and its relative value (expressed as $v\text{TEC}_{\text{rel}}$ in this study), which is the difference of the value in each epoch divided by the monthly mean value of the days not disturbed magnetically.

The expression is:

$$v\text{TEC}_{\text{rel}}_i = \frac{v\text{TEC}_i - v\text{TEC}_i}{v\text{TEC}_i} \cdot 100$$

where subscript $i$ indicates the station under consideration.
Odenwald and Green (2007) have estimated an economic toll of 30 billion dollars due to the damage that any Carrington-like magnetic storm would do today to satellites in geostationary orbit.

Odenwald and Green (2007) have estimated an economic toll of 30 billion dollars due to the damage that any Carrington-like magnetic storm would do today to satellites in geostationary orbit.

These results were then used as the basis for analysing the ionospheric storm phases and their relation to phases of the geomagnetic storm. A positive phase of the ionospheric storm is considered to exist when the difference between vTEC and the mean value is over 10 TECus or the relative vertical TEC tops 50%. Conversely, a negative phase of the ionospheric storm is considered to exist when the difference between vTEC and the mean value is less than 10 TECUs or the relative vertical TEC is less than -50%. Figure 11 gives the results obtained from a selection of the stations distributed by latitude. The readings thus obtained clearly show that the geomagnetic storm generated an ionospheric storm over the Iberian Peninsula. There is also a positive phase of the ionospheric storm corresponding to the initial phase of the geomagnetic storm, which is appreciable only at the lowest latitudes, and another of the same sign between the...
main phase and the start of the recovery phase of the geomagnetic storm. A series of four negative phases of the ionospheric storm also shows up during the recovery phase of the geomagnetic storm. In the two positive phases the maximum variation is heavily latitude-dependent. This effect also obtains in the duration of these phases, albeit with a less significant difference. In the negative phases the latitude effect is less notable.

**Figure 11.** Difference of the TEC from the monthly mean reading for the stations BRST, CANT, ARDU, MADR, SONS, MALA, CEU1, TETN and IFR1 of Figure 17 distributed by latitude from north to south. The range of colours expresses the results in TECus.

**Geomagnetic storms and the railway**

Geomagnetic storms can also affect the railway system. The first ever mention of effects of this type came in the New York Times of 16 May 1921, when a news report linked the widespread failure of the signalling and control system of the New York Central Railroad and subsequent fire to a magnetic storm that produced visible aurorae in the region of New York\(^1\). Geomagnetic storms were later blamed too for signalling failures in Sweden on 13-14 July 1982\(^2\) and in Russia during many other magnetic storms. The explanation for these railway failures might be sudden voltage surges created by the storm-engendered geomagnetically induced currents (GICs). These voltage surges might upset the signalling system and confuse activation of free-line and occupied-line indications\(^3,4,5\).

Close attention should be paid to this problem when considering the viability of high-speed railway lines (where safety measures have to be much stricter) for high-latitude countries like north Russia, Sweden, Norway and Finland.

2. Wik, M; Pirjola, R; Lundstedt, H; Viljanen, A; Wintoft, P; Pulkkinen, A. Space weather events in July 1982 and October 2003 and the effects on geomagnetically induced currents on Swedish technical systems. Annales Geophysicae, 2009, (27) 1775-1787.
3. Eroshenko, EA; Belov, AV; Boteler, D; Gaidash, SP; Lobkov, SL; Pirjola, R; Trichtchenko, L. Effects of strong geomagnetic storms on Northern railways in Russia. Adv. Space Res., 2010, (46) 1102-1110. doi:10.1016/j.asr.2010.05.017.
To analyse in greater depth the disturbance caused on the Iberian Peninsula, a study was also made of the time trend of IPP-associated TEC readings. IPP stands for the ionospheric pierce point, i.e., the point where the satellite-receiver signal intersects with the ionosphere, which is assumed to be concentrated at a height of 350 kilometres. IPP maps are regional or global, representing the TEC readings at these points. To obtain them, a calculation is made first of the vTEC in the IPPs where the information is available. This calculation was made every minute on the days analysed for the stations of the Iberian Peninsula and with an average of five satellites for each epoch. From these readings a selection was made of those of most interest for this analysis, building up maps from them using Kriging interpolation with a 0.4° x 0.4° grid. The grid was chosen on the basis of several trials, the best results being obtained for the aforementioned distance. Figure 12 shows the maps corresponding to 11.00 hours of 24, 25 and 26 October 2011, at which time the vTEC variation reaches significant values. These maps clearly show the increase in vTEC produced in the ionospheric storm.

Figure 12. Map of vTEC readings for 24, 25 and 26 October 2011.

Effects on EGNOS services and positioning

The technological effect of greatest interest produced by this storm was the disturbance it caused to the EGNOS system, developed to improve the performance of Glonass, GPS and Galileo in Europe and Africa. The particular effect observed was a degradation of the APV-1 (Approach with Vertical Guidance) service, which ensures exact positioning with GNSS signals of 16 metres in the horizontal plane and 20 metres in the vertical plane. It includes two types of key information: HPL-VPL (Horizontal and Vertical Protection Levels) and HAL-VAL (Horizontal and Vertical Alert Limits).

Figure 13 shows the level of confidence on 23 October, with HPL and VPL falling within the alarm limits (HAL, VAL) for the satellite Egnos PRN120. A level of 99% is seen to reign almost throughout the whole of Europe and above 75% over the Iberian Peninsula. Due to the effect of the storm, this region shrank on the 24th and almost completely disappeared on the 25th (Fig. 14). On the 26th and 27th confidence levels from before the main phase of the storm were recovered, bearing out the effect of the geomagnetic storm.
Figure 13. Availability of the APV-I service with the satellite PRN120 [http://egnos-user-support.essp-sas.eu/egnos_ops/]
The objective of the developed system is not to predict the ionospheric storm but rather to announce its occurrence soon enough to ascertain the failures that might be caused in communication, navigation and positioning systems.

For this purpose the System for Rapid Information on Ionospheric Disturbances (Sistema de Información Rápida de Perturbaciones Ionosféricas) has been set up for the Iberian Peninsula and Southern Europe. This system is described below. The system is activated manually upon receiving an alert from one of the abovementioned centres. In the near future it will be tripped automatically. Once activated, the system stays in operation for 10 days to ensure the whole period of disturbances is studied. The program automatically carries out the following operations:

- Download the Rinex files and the navigation files from the 16 selected GNSS stations (Fig. 15) for the day of the possible alert and each one of the 10 previous days.
- Process the files using the abovementioned method to obtain the vTEC in each era, for each day and station.
- Calculate the mean vTEC of the 10 previous days and the vTECrel. These figures are stored in graph form for subsequent mining and review. vTECrel values are then filtered to remove wrong data that might trip the alert system erroneously. This filter consists of removing previous eras in which the vTECrel suffered brusque changes.

Design of an alert protocol

In an effort to reduce the effects of geomagnetic storms, particular attention has been paid to early detection. The approach has been two-pronged. Firstly a research line has been set up to tap into the time sequence of the phenomena leading to the geomagnetic storm; this sequence has been painstakingly described for the storm of 24-25 October 2011. This is the approach followed by specialist space weather centres, many of which issue a storm warning with one or two days’ notice. This is therefore a predictive approach of great practical interest. The second approach centres on ionospheric effects and attempts to fend off disturbance once the ionospheric storm has begun. The objective here is not to predict the ionospheric storm but rather announce its occurrence soon enough to ascertain the failures that might be caused in communication, navigation and positioning systems.
Check the vTECrel value against the threshold value (±50%); the alert message is issued if the vTECrel exceeds the threshold value in at least 50% of the stations. This message then allows users to take due preventive measures.

Figure 15. Geographical location of the stations used by the Sistema de Información Rápida de Eventos Ionosféricos.

The system is outlined in figure 16. To check out its validity, the information system has been applied to five storms that occurred in December 2006, October 2011, January 2012, April 2012 and July 2012. This crosschecking study took in 24 days around the date on which the Dst index recorded its minimum value, comparing this with the days on which an ionospheric storm alert message was issued. These tests gave a correct result in 77.18% of the days studied. Of the 29 days with an ionospheric storm, alert messages would have been issued on 23 of them; on only 21 of the 89 days without any disturbance would an unnecessary alert message have been issued. These results bear out system validity. In the near future this system will be speeded up and then made available to users on internet.
Figure 16. Outline of the Sistema de Información Rápida de Eventos Ionosféricos.
Conclusions

Geomagnetic storms are natural processes affecting the whole planet, inducing important physical phenomena like aurorae, radiation boosts, GICs and ionospheric storms. Intense geomagnetic storms might have a huge impact on many of the technological resources that now underpin our daily life. Satellites, power lines, navigation and railway systems may all be damaged by a big magnetic storm, generating huge economic losses and upsetting the workings of our society, creating a host of problems of unimaginable dimensions. There is therefore now a pressing need to pay this natural risk due attention and get across to the public at large the importance of readiness.

Notable breakthroughs in space weather, some of which have been presented in this article, enable us nowadays to give about 30-40 minutes' notice of the arrival of a solar wind disturbance on Earth, possibly sparking off a geomagnetic storm. This advanced notice gives society the chance to take measures to protect both people and material goods, providing it has been properly trained up to do so beforehand. Awareness of this threat needs to be raised by government authorities, institutions, educators and the media; this article aims to contribute to this awareness-raising effort, which now needs to be backed up by an ongoing informative effort.

REFERENCES

What sort of radiological protection and safety measures are needed in high-intensity laser facilities? This is a question that should be tabled urgently by all bodies with a remit for radiological protection and safety. This study details the necessary protocols for application of basic ionising-radiation legislation for exposed personnel of the Ultra-Short Ultra-Intense Pulsed Laser Centre (Centro de Láseres Pulsados Ultracortos Ultraintensos: CLPU), Spain’s benchmark femtosecond pulsed laser laboratory.

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Low-intensity laser has posed no great radiation protection problems in the past. As laser technology has been stepped up to higher intensities, however, its ionising-radiation generating potential has had to be taken into consideration. Whenever a high-intensity laser pulse is focused on any target (solid or gaseous), the laser’s electromagnetic field is capable of ionising the atoms of the material and producing an electron plasma. By means of target interaction, these electrons can in turn produce protons, neutrons or X/gamma rays by Bremsstrahlung (braking radiation). This ionisation-radiation problem does not arise with low-intensity laser.

Radiation emissions of this type necessarily call for the establishment of radiation protection protocols in high-intensity laser facilities.

Defining the point from which a laser system can be considered to be an ionising-radiation source is no straightforward matter. Although laser intensity is a paramount parameter, others also need to be factored into the equation, such as laser wavelength (photon energy), pulse duration and the nature of the target. Figure 1 outlines the zone of radiological risk in terms of the laser intensity (for an 800 nanometre wavelength) and the density of the target. In principle an intensity of 1016 W/cm² could generate keV electrons, so this could be taken as the cut-off point for the radiation protection risk zone.
Figure 1. Radiological risk zoning in terms of the two most important factors: laser intensity (with a wavelength of 800 Nanometres) and the density of the target being focused. It stands to reason that if the target is of very low density there will be hardly any atoms to interact with in the focal volume so no radiation is generated. The horizontal scale is in exawatts ($10^{17}$ W) per cm$^2$.

The radiological protection and safety measures to be taken in high-intensity laser facilities is an extremely important matter that needs to be addressed urgently by all bodies with a remit for radiological protection and safety, both at home (Consejo de Seguridad Nuclear: CSN) and worldwide (International Atomic Energy Agency: IAEA), International Commission on Radiological Protection (ICRP), International Commission on Radiation Units and Measurements (ICRU). This article presents the necessary protocols for application of the basic ionising-radiation legislation for exposed workers, non-exposed workers, users and the public at large, in a high-intensity laser facility. The study has focused in particular on the Ultra-Short Ultra-Intense Pulsed Laser Centre (Centro de Láseres Pulsados Ultracortos Ultraintensos: CLPU) as Spain’s benchmark lab for femtosecond pulsed laser with gigawatt, terawatt or petawatt peak power levels.

**Centro de Láseres Pulsados Ultracortos Ultraintensos (CLPU), Salamanca**

The CLPU is housed in the M5 building of the Parque Científico of the Universidad de Salamanca, in the municipal district of Villamayor (Salamanca). The consortium, formed by the Ministry of Economics and Competitiveness (Ministerio de Economía y Competitividad) - formerly the remit of the Ministry of Education and Science (Ministerio de Educación y Ciencia) - the Regional Authority of Castilla y León (Junta de Castilla y León) and the Universidad de Salamanca, is responsible for the design, construction, equipping and running of the centre. The objective of this facility is to provide an international service for the scientific and industrial community, facilitating access to state-of-the-art high-powered laser and also giving collaboration-based scientific and technical assistance.

The main line of the CLPU is a 1 PW Ti-Sapphire laser (30 joules / 30 fs, central wavelength around 800 nm) operating at a repetition rate of up to 1 Hz. This line is divided into three phases of increasing power that can be used simultaneously, scaling laser pulse use for different applications.

- **Phase 1**: 20 terawatt VEGA-1 Laser (500 mJ / 25 fs), with a pulse repetition frequency of 10 per second (10Hz).
- **Phase 2**: 200 terawatt VEGA-2 Laser (5 J / 25 fs), with a pulse repetition frequency of 10 per second (10Hz).
- **Phase 3**: 1 petawatt VEGA-3 Laser (30 J / 25 fs), with a pulse repetition frequency of 1 per second (1 Hz).

Although the CLPU’s main line is the VEGA laser, with terawatt and petawatt power peaks, the centre also runs other laser systems that are also made available to the scientific and technical community. These include a gigawatt laser with a pulse...
The output of a power plant is about one gigawatt. Though it might seem paradoxical, however, systems of this type could nowadays be considered as of only moderate intensity. Technology in this field is advancing at such a breakneck pace that laser systems of tens of gigawatts are becoming fairly commonplace. It is estimated that there are now about 20 systems falling within this operating range in Spain alone. Ionising radiation produced by systems of this type, comprising electrons and X-rays, has been studied for interaction with solid metal targets in a previous FUNDACIÓN MAPFRE project (Fonseca, 2011). Despite the low rate of radiation per laser pulse the high repetition rate of these laser systems (much higher than those of extreme power) makes them potentially quite dangerous. There are currently systems seeking to increase the repetition rate to 10 kHz or even more.

### Gigawatt laser systems

The CLPU's objective is to give an international service to the scientific and industrial community, providing access to high power lasers and scientific-technical aid. The gigawatt laser systems have a repetition frequency of 1000 per second (1 kHz). There follows a brief description of these high intensity laser systems in the context of radiation protection.

#### Gigawatt laser systems

The output of a power plant is about one gigawatt. Though it might seem paradoxical, however, systems of this type could nowadays be considered as of only moderate intensity. Technology in this field is advancing at such a breakneck pace that laser systems of tens of gigawatts are becoming fairly commonplace. It is estimated that there are now about 20 systems falling within this operating range in Spain alone. Ionising radiation produced by systems of this type, comprising electrons and X-rays, has been studied for interaction with solid metal targets in a previous FUNDACIÓN MAPFRE project (Fonseca, 2011). Despite the low rate of radiation per laser pulse the high repetition rate of these laser systems (much higher than those of extreme power) makes them potentially quite dangerous. There are currently systems seeking to increase the repetition rate to 10 kHz or even more.

#### Terawatt laser systems

Until relatively recently, terawatt peak power seemed awesome. Small wonder, since it is more or less tantamount to the electricity output of the whole of Europe. The advent of Chirped Pulse Amplification (CPA) produced a sea change. Now CPA systems have been taken up widely; they are relatively robust and are lending themselves to many applications. Obviously, a terawatt laser does not pose any huge electricity demand problem since the system is pulsed and the high power demand is very brief in time. Commercial terawatt systems (1 TW = 30 mJ/30 fs = 100 mJ /100 fs) work at pulse repetition rates of about 10 per second (10 Hz). Some systems reach 100 Hz and kHz pulsing systems are also being mooted. They are, in any case, systems with an average output of a few watts.

#### Petawatt laser systems

A petawatt is an extraordinarily high order of magnitude, currently representing the cutting edge of laser technology at world level. Although there are some 10-petawatt systems on the designing board, they are still – according to our information – far from coming on line and serving for experimental uses.

No systematic studies have yet been made of the radiological risks of these laser systems. Nonetheless, the following information can be culled from the commissioning documents of the Vulcan petawatt laser (Allot et al. 2000; J. D. & R.D. 2006): intensities of 1020W/cm² focused on a solid target generate electrons with a mean energy of 39 MeV, producing at a distance of 1 m a gamma radiation dose per pulse of 0.17 mSv/J. The expected dose in the 1021 regime would be 0.6 mSv/J; extrapolated over a year this would mean a dose of 70 Sv/year. The radiation is emitted mainly in a 40º fan. No figures are given for the neutron dose, which is likely to be high at these energy levels, with further neutrons being generated by activation processes.

#### Estimate of CLPU radiation levels

The CLPU, as a radioactive facility (RF), has set itself the objective of making all zones contiguous to the experimental...
zone free access. To fulfil this objective it has to ensure that the dose received in adjacent areas does not top 1 mSv a year. In the experiment zone two interaction chambers will be set up, housing the ionising radiation generating source, a multi-TW dedicated to laser VEGA-1 (20 TW) and VEGA-2 (200 TW) and another for VEGA-3 laser (1 PW). Figure 2 shows the scheme of the experiment zone with the interaction chambers and also the adjacent zone housing the laser compressors.

Figure 2. Scheme of the radiation zone with the interaction chambers and the layout used for FLUKA Monte Carlo simulation. The interaction chambers where laser acceleration is produced are shown in green. The interior concrete walls of the experiment zone are shown in mauve. The two access ports to the experiment zone are also shown.

There follows an account of the steps followed for estimating the radiation levels in the experiment zone housing the CLPU interaction chambers and adjacent zones. This has been drawn up in light of particular specifications for shielding the experiment zone, i.e., for the dimensions and characteristics of the materials making up this shielding. As a general rule the values producing the most conservative hypothesis have been used.

Figure 3 shows the method used in diagram form. Red indicates results obtained from this method. Some important method-application aspects will be analysed below:
Source term
A set of essential radiological-protection and -shielding variables make up the source term (type of particles generated in the facility, energy, number, angular emission distribution...). In a conventional facility these parameters are easy to determine from the device’s specified working voltage (in the case of X-ray equipment) or maximum electron energy (in the case of an accelerator). In the case of laser radiation, however, other elements need to be factored in. The radiation source is the distribution of the electrons emitted by the laser-material interaction. This distribution depends on the various types of targets, in particular their respective electron densities. In the case of solid targets the laser gives up energy by means of various indirect mechanisms, heating up the plasma, whereas in the case of gaseous targets the laser is capable of directly accelerating the generated electrons. Recorded studies (Fernández, Conejero, & Roso, 2013; Meyerhofer, Chen, Delettrez, Soom, Uchida, & Yaakobi, 1993; Gibbon, 2005; Wilks, Kruer, Tabak, & Langdon, 1992; Gordienko & Pukhov, 2005; Lu, et al, 2006) describe in detail the source terms corresponding to the different types of targets.

Monte Carlo Code: FLUKA
Working from the source term, a FLUKA Monte Carlo code simulation is then made of the transport and interaction of the source term’s particles and those it generates (Battistoni, et al, 2007; Ferrari, Sala, Fassò, & Ranft, 2005). This simulation depends on a previous description, as detailed as possible, of the facility geometry as well as the materials present therein. The simulation layout is shown in Figure 2.

Material Activation
In the presence of the laser’s intense electric field, electron movement can generate large electric fields that, depending
on the characteristics of the target, accelerate the protons and ions. Accelerated protons might produce neutrons in the elements surrounding the impact point, either through \((p,n)\) reactions or break-up reactions. In certain cases neutrons might also be produced in \((\gamma,n)\) reactions, with a typical production of \(10^4\) neutrons for each ion. Finally, \((p,n)\) reactions might spark off secondary interactions in the materials around the target or in the reaction chamber itself.

Activations of this type need to be carefully assessed, since they are the only dose-contributing activations once the laser has been switched off and may balk access to the experiment zone if they are high enough. There are various methods for reducing these knock-on activations, including the use of targets of the utmost possible purity, a painstaking selection of the detection and diagnosis material and of the materials making up the interaction chamber walls. In any case, in certain experiments, such as the generation of radioisotopes, the target is always activated and this activation has to be taken into account in terms of access to the experiment area.

**Dose rate**

The FLUKA simulation data are processed to obtain the dose rate at each point in space, including those to which personnel occupying a certain zone of the installation are exposed.

Moreover, from the material activation (also FLUKA simulated) results are analogically obtained for the dose rate produced by the activation.

On the basis of the above methodology an analysis has been made of the radiation levels of the CLPU’s ionising-radiation generating systems: multi-TW laser plasma accelerator and PW laser plasma accelerator. Figure 4 shows the distribution for VEGA-2 (200 TW laser) while Figure 5 shows the distribution for VEGA-3 (1PW laser). Dose rates are given in Sv per laser pulse. It should be borne in mind here that these figures show a cross section of the facility layout rather than a projection, therefore leaving out some parts that are involved in the simulation, as shown in Figure 2.

**Figure 4.** Estimate of the ambient dose rate of VEGA-2 (200 TW laser). Plan view of the experiment zone.
It should be emphasised here that estimates of ambient dose rates have been obtained from one laser pulse. This means that they should be multiplied by the number of pulses carried out in any period of time to record the full ambient dose rate.

CLPU has laid it down that the areas adjacent to the experiment zone should be free access. Under current law, therefore, the dose should be lower than 1 mSv a year in all these zones. On the basis of this restriction, a calculation can then be made of the number of laser pulses that would guarantee a dose rate under 1 mSv a year in these zones.

In the specific case of the CLPU facility, the study has shown that the zone imposing the most constraints on the number of pulses is the laser compressor zone (see Figure 2). The maximum readings taken in the compressor zone are summed up in Table 1, plus a simple calculation of the number of possible laser pulses. These numbers have been determined on the assumption of 35 working weeks a year and 3 working days a week. It has also been assumed that the systems will not be working simultaneously.

Table 1. Maximum dose rate readings per pulse in the compressor zone

<table>
<thead>
<tr>
<th>System @ Intensity W/cm²</th>
<th>Sv Dose rate per pulse</th>
<th>Number of pulses per dose rate =1mSv</th>
<th>Daily pulses (dose rate=1mSv) without</th>
</tr>
</thead>
<tbody>
<tr>
<td>VEGA-3@0,8E21</td>
<td>6E-11</td>
<td>16 x10⁶</td>
<td>150 x 10³</td>
</tr>
<tr>
<td>VEGA-3@1E22</td>
<td>2E-10</td>
<td>5 x10⁶</td>
<td>50 x 10³</td>
</tr>
<tr>
<td>VEGA-2@1E20</td>
<td>4E-11</td>
<td>25 x10⁶</td>
<td>240 x 10³</td>
</tr>
<tr>
<td>VEGA-2@1E21</td>
<td>6E-10</td>
<td>1,6 x10⁶</td>
<td>15 x 10³</td>
</tr>
</tbody>
</table>

These calculations are based on two different intensities in the focal point, both for VEGA-2 and for VEGA-3, which are delimited by the focal distance used for the experimental device.

Identification of the radiological risks bound up with operation of the CLPU facility

Two types of radiological risks have been identified in a high intensity laser facility like the CLPU: external irradiation and contamination.

External irradiation risk

An external irradiation risk is deemed to exist inside an experiment zone whenever laser pulses are focused on target material. When the laser is switched off there is no irradiation risk from primary radiation but there is a risk of activated
It is estimated that no CLPU worker will be exposed to an annual dose higher than 1 mSv, so checks carried out as from facility commissioning will be geared towards ensuring this.

Contamination Risk
A contamination risk exists due to the waste produced during the interaction of the laser beam with the target material. Initially this contaminateable material is confined inside the interaction chamber where the laser pulses are produced.

CLPU radiation monitoring and surveillance

Area detectors
Radiation detectors and monitors are used in conventional particle acceleration facilities (Synchrotron, LINAC, Cyclotron...) to watch over and control dose rates during facility operation. Nonetheless there are number of idiosyncrasies to be taken into account when deciding whether detectors used in conventional accelerators can also be used in high-intensity laser facilities.

The main idiosyncrasy of the radiation produced in a facility of this type is the emission timescale. Prima facie, the laser radiation emission time has to be tiny in order to achieve great power with a reasonable energy input. In practice this means that the working timescale is in the order of femtoseconds (1 fs = if carried out in a controlled manner the possible exposure of workers to zones that have remained activated is considered to be minimum or residual).

It is for this reason that no CLPU worker is considered to be exposed to an annual dose higher than 1 mSv, so all checks carried out as from facility commissioning will be geared towards ensuring this. If total dose rates (photons and neutrons) higher than 1 mSv a year are detected, measures will be taken to mitigate the cause. If this proves impossible, local shielding will be installed to guarantee compliance with the maximum public dose rate.

Initially the zones adjacent to the experiment zone (for example, the compressor zone) will be classified as monitored areas. This classification may then be changed thereafter in accordance with later radiation readings.

On users and the public
Radiological impact on users and the public at large due to the operation of laser plasma accelerators will be residual or practically nil, given that the object sought is that no CLPU worker (or any external personnel) can receive during their stay in the area a total dose higher than 1 mSv a year.

The probability of exceeding the annual dose rates given in this study is practically zero given the nature of the radiation producing that dose: if the laser plasma accelerator is switched off, direct radiation disappears and activation emissions are practically residual inside the experiment zone and nil outside it. Furthermore, if laser focussing is impeded, the generation of ionising radiation is completely impossible.

Selection and evaluation of the measures for reducing risks to acceptable levels
With the aim of controlling and reducing risks due to operation of the laser plasma accelerator, three measures will be taken to guarantee reduction of radiological risks during the starting up of the CLPU:

- Use of minimum focus intensities by means of a long focal length, stepping up the intensity thereafter in a controlled manner if all safety guarantees are met.
- Reduction of the number of laser pulses to minimum values well below the rated laser value.
- Removing all personnel from the zones adjacent to the experimental zone until such time as it has been reliably proven that no risk ensues from working in the vicinity. Should it prove to be impossible to evacuate these areas totally, presence of personnel therein will be controlled, minimising the exposure of each worker.

This modus operandi will guarantee that, from the very first day, no unnecessary and uncontrolled exposure is allowed for any CLPU worker or external workers.

Conclusions
In any radioactive facility like CLPU written protocols and procedures are primordial in the prevention of radiological risks. These procedures will be agreed between all members of the areas involved and the radiological protection service, and endorsed by the facility manager or representative. Once approved, they will be distributed amongst all involved personnel.
The CLPU is bound to draw up a Radiological Protection Handbook (Manual de Protección Radiológica: MPR) describing the necessary measures for keeping individual dose rates, the number of exposed people and the likelihood of exposure as low as possible and will then be checked regularly, not only when any change in legislation affects the activity they refer to.

The studies conducted as part of this project have set out to present the protocols (with enforcement of ruling law) for application of the basic ionising-radiation legislation for exposed workers, non-exposed workers, users, students on work practice and the public at large, in a high intensity laser facility. The study has focused in particular on the Ultra-Short Ultra-Intense Pulsed Laser Centre (Centro de Láseres Pulsados Ultracortos Ultraintensos: CLPU), identifying its radiological risks and estimating necessary shielding arrangements and detection systems for guaranteeing safety and protection from ionising radiation during centre start up and operation.

Under ruling law the CLPU is bound to apply for authorisation as an operating radioactive facility, pursuant to Royal Decree (Real Decreto) 1836/1999, subsequently modified by Real Decreto 35/2008, approving the Radioactive and Nuclear Plant Regulation (Reglamento de Instalaciones Nucleares y Radiactivas) and R.D. 2080/1999 (BOCyL 28.01.2000), devolving on the regional authority the remit for second- and third-category radioactive facilities. Moreover, application for authorisation for the operation of a first-category facility has to be submitted to the Nuclear Safety Board (Consejo de Seguridad Nuclear: CSN) as the only state body in Spain with responsibilities and powers for radiological protection and nuclear safety matters.

As a radioactive facility, the CLPU is bound to draw up a Radiological Protection Handbook (Manual de Protección Radiológica: MPR) describing the necessary measures for keeping individual dose rates, the number of exposed people and the likelihood of exposure as low as possible. The studies conducted within this project have furnished the necessary information for drawing up the CLPU’s MPR. A brief description is given below of the main means of radiological protection in the CLPU. All these will be developed further in the corresponding handbook on the basis of the study carried out:

- **Classification of personnel.** For reasons of safety, surveillance and radiological control, CLPU personnel are broken down into the following categories on the basis of their working conditions:
  - Exposed workers (categories A and B)
  - Users and members of the public.

- **Dose limits.** Three different dose limits will be applied for each type of worker dealt with by current law.

- **Classification of zones.** CLPU worksites will be classified in due accordance with the assessment of the likely annual dose rate and the probability (as well as size) of potential exposures. Initially a conservative zone classification will be made, easing up thereafter in light of reliable assessments of annual doses.

- **General rules in radiological risk zones.** Access rules will be drawn up together with associated working procedures and personal protection equipment.

- **Signage.** The various zones will be suitably indicated according to their classification and the ionising-radiation generating equipment or material.

- **Radiation control and surveillance.** This includes surveillance of the working environment, assessment of worker exposure, healthcare checks and protection rules for persons under training and students. A distinction is also made of special protection for users and members of the public.

- **Management and control of radioactive material.** The objective here is to wield proper control over radioactive material (activated material and calibration sources) to cut down risks across the board. It will be necessary to enforce safety rules from the moment of acquiring any sources or detecting any activated material.

- **Procedures for the proposal and acceptance of experiments in the facility with radiological risk.** The setting up and acceptance of any experiments implying radiological risk should follow criteria that meet all technical and scientific objectives in view while also minimising the associated dose, which must always fall within established facility limits.

- **Recording system.** Record-keeping criteria and practices will be established.

- **Radiological protection training.** A radiological protection training system will be established.

- **Optimisation criteria.** A series of criteria referring to occupational exposure and public exposure and associated dose...
restrictions will be established.

- **Quality system.** A description will be given of the quality system elements designed to strengthen the continuous improvement cycle.

- **Emergency Plan.** A description will be given of the countermeasures, responsibility, reporting and training associated with each possible emergency situation.

### Radiological-protection protocols

In light of the study carried out within this project and thanks to the interdisciplinary team set up thereunder, this article winds up with a series of radiological protection protocols in CLPU. These protocols will be agreed between all members of the areas involved and the centre’s radiological protection service, and endorsed by the facility manager or representative. Once approved, they will be distributed amongst all involved personnel and will then be periodically checked.

- Protocols for checking CLPU radiation and contamination monitors and detectors.
- Protocol for using detector-checking radioactive sources.
- Protocol for controlling the airtightness of radioactive sources.
- Protocol for classification and signage of CLPU zones.
- Protocol for classifying CLPU personnel.
- Protocol for the control of research work to be carried out in the experiment zone.
- Protocol for monitoring external radiation in the CLPU facility.
- Protocol for dosimetric control of CLPU personnel.
- Protocol for evacuating the experiment zone before starting up any ionising-radiation generating system.
- Protocol for dealing with licences and permits.
- Protocol for management of activated material in the experiment zone.
- Protocol for radiological-protection training and awareness-raising.
- Protocol for communications between the tenure holder and other involved services.
- Protocol for intervention of the radiological protection service in compulsory facility documentation.
- Protocol for dealing with any radiological accident or incident.
- Protocol for simulating emergency situations.
- Protocol for reporting accidents.
- Protocol for work carried out in controlled and monitored zones.
- Protocol for worker health monitoring.
- Protocol for improvement plans.

### REFERENCES


Fire safety in Building-Mounted photovoltaic arrays

Building-mounted photovoltaic arrays are a modern and sustainable way of producing electricity on the site where it is consumed; as such they play a vital role in the ongoing drive to achieve the target of nearly zero-energy buildings. Their increasingly widespread use has given rise to some fire incidents; these are statistically of little significance as yet but they do show that some aspects stand in need of closer study. This article, brokered by FUNDACIÓN MAPFRE’s 2012 research grant programme, sums up state-of-the-art photovoltaic-array safety for building users and firefighters. It also tries out photovoltaic arc-fault detectors and draws up a firefighting guide for buildings fitted with photovoltaic arrays.


Building-installed photovoltaic arrays are now catching on worldwide. Their future looks bright and they might soon account for over 50% of the photovoltaic market.

Photovoltaic modules can be fitted on pitched roofs, flat roofs and facades or integrated as part of the building itself (building-integrated photovoltaics: BIPV), taking over the role of structural or ornamental items such as the building envelope, roof tiling, skylights or pergolas, etc.

Upon receiving sunlight, PV modules generate a direct current that runs through connection cables inside the component cells; an inverter then converts the direct current into alternating current. This means that sizeable electric currents run through the photovoltaic building envelope itself or items attached thereto. Although the voltage falls within the range classed as low, it can still be quite appreciable.

A photovoltaic array is basically just a low-voltage electricity generating system. In theory, therefore, it should suffice to apply habitual electricity-system protection methods to ensure the safety of equipment and people. In practice, however, photovoltaic generators have some idiosyncrasies, above all the fact that the solar-power generating source cannot be switched off. This complicates application of conventional protection devices and methods, and there may even be additional risks for firefighters.

Analysis of the causes of fires in photovoltaic systems

The potential causes of fires in photovoltaic systems can best be analysed by breaking them down into two component parts: on the one hand, the photovoltaic generator (an array of multiple parallel-connected strings of series-connected
What makes these systems different from other electricity systems is the photovoltaic generator, since the risk of fires in the inverter and alternating current circuit is covered by established standards. (Figure 1)

As well as the general fire risks of any electricity system, photovoltaic generators pose the following specific fire risks:

- Hotspots in photovoltaic modules.
- Overheating or electric arcing in photovoltaic modules: interior of the photovoltaic module, PV combiner box, connectors.
- Overheating or electric arcing in «DC combiner boxes»: parallel combiner boxes, enclosures and system control boxes, etc.
- Overheating or electric arcing in the AC wiring.

To deal with these risks, due consideration has to be given to the following special characteristics of a photovoltaic generator:

- If the photovoltaic modules are exposed to sunlight it is impossible to remove voltage from the photovoltaic array.
- The short-circuit current is only slightly higher than the operating current under normal operating conditions; furthermore its value, which depends on incident irradiance, ranges from nil before sunrise to maximum values at solar midday (Calais et al. 2008).
- The voltage, which depends on variations in ambient temperature and incident irradiance, can vary by hundreds of volts from dawn to midday.
- Its output can vary from 1 kW up to several MW; the direct current can therefore range from just a few amps up to hundreds of amps.

**Electrical safety of photovoltaic systems**

Protection against surges and earth faults is a crucial fire-risk mitigation feature of any electrical system and ipso facto of any photovoltaic system.

In building-mounted photovoltaic systems, to ensure the principal of electrical bonding and thus the protection of people from indirect contact, all the metallic items of the photovoltaic system should be connected up to each other and run to
the mains earth (Figure 2).

![Figure 2. Earthing protection of a photovoltaic generator. Source: drawn up by the authors](image)

As for the earthing of a live conductor (any conductor that has a voltage under normal system operation or through which an electric current runs) of the photovoltaic generator, there are several different options: insulated, earthing the positive terminal, earthing the negative terminal and earthing of an intermediate point of the photovoltaic generator (Figure 3).

![Figure 3. Photovoltaic generator earthing options: a) insulated b) positive terminal run to earth c) negative terminal run to earth d) mid-point earthing. Source: drawn up by the authors.](image)

The most widespread earthing option in Europe is that of an insulated generator. In this case, if the inverter has a transformer, the earth-fault protection system is an insulation monitor installed in the DC combiner box or the inverter itself. In the case of the insulated photovoltaic generator and inverter without transformer, a type B differential circuit breaker is needed, connected up to the inverter output. In cases of effective earthing systems, a fuse and automatic- or differential-circuit-breaker have to be fitted in the earth of the photovoltaic generator (Sources: BENDER, Hernández et al.).
Surge protection has to be ensured by fitting protection and disconnection devices at both positive and negative terminal blocks of each string of the photovoltaic array (CTE-HE5). (Figure 4)
Electric arcing in photovoltaic generators

As previously pointed out, photovoltaic generators work with appreciable and constantly varying DC voltages and currents; they also have to withstand extreme ambient conditions and have a very long lifetime. For that reason, although the likelihood of arcing in a well-designed and -run generator made of quality material is very low, it cannot be completely ruled out.

DC arcing is more dangerous than AC arcing because there are no dips to zero as the current switches direction. Detection of arc faults in photovoltaic systems considerably cuts down the fire risk. Figure 5 shows the types of arc faults that might occur in a photovoltaic generator.

Figure 5. Types of arc fault in photovoltaic generators: S = series arc faults, P = parallel arc faults. Source: drawn up by the authors.

Series arc faults or unearthed parallel arc faults are not detected by the abovementioned protection systems generally used in photovoltaic generators. For this and other reasons the standards in some countries call for arc-fault detectors to be fitted for protection of photovoltaic generators. The USA’s National Electric Code (NEC), for example, makes it obligatory for DC series arc-fault protection equipment to be fitted in building-installed photovoltaic systems with a rated voltage equal to or above 80 VDC (NEC 2011).

When an arc fault is detected, the protection device has to be capable of disconnecting the defective circuit and all components of the system involved in the occurrence of the arc fault.

When a series or parallel arc fault occurs in a photovoltaic generator, this distorts the current and voltage signals and thereby changes the frequency characteristics of these signals. The working principle of arc-fault detectors is based on analysis of the changes produced in the frequency spectrum of the signal readings (Strobl et al. 2010, Bieniek 2011, Haeberlin 2010) (Figure 6).
Figure 6. Example of the generation of a series arc fault. Propagation of the arc-fault signal and detection by the protection device. Along its run the signal is attenuated and filtered. Source: drawn up by the authors.

Arc-fault detection devices have to work correctly without being unduly affected by attenuation and filtering of the arc-fault signal in the DC circuit or by any electrical noise that might be present in the system. Figure 7 shows the recording over time of current signals in a photovoltaic generator in absence and in presence of an arc fault. The readings have been taken by connecting an inverter or a resistive load bank as load of the DC circuit (Johnson et al. 2011).

Figure 7. Current recorded in a DC circuit with no fault and then with an arc fault for a resistive load and with an inverter. Arcing starts at second 0 and lasts for more than 0.8 seconds. Two signals have been recorded for each measurement. Source: Johnson et al. 2011.

Frequency analysis of the abovementioned signals shows up tell-tale spectrum gaps where arc faults have occurred (Strobl et al. 2010, Bieniek 2011, Haeberlin 2010).

An added difficulty in the detection of arc faults is deciding whether a series or parallel arc fault has occurred, since the arc signal is usually the same in both cases. Some authors claim that parallel arc faults can be distinguished by measuring the insulation resistance; others propose alternative methods (Strobl et al. 2010, Johnson 2012a).

Table 1 shows the types of arc fault and the required elimination or mitigation measures.

Table 1. Types of electric arc faults in a photovoltaic generator and protection measures to be taken. Source: drawn up by the authors.

<table>
<thead>
<tr>
<th>Type of arc</th>
<th>Action on the photovoltaic generator</th>
</tr>
</thead>
<tbody>
<tr>
<td>Series arc fault</td>
<td>Open the circuit</td>
</tr>
</tbody>
</table>

Type of arc Action on the photovoltaic generator

- Series arc fault
  - Open the circuit
An arc generator has been designed and built to try out the arc-fault detecting capacity of the SANTON ADU E1 arc-fault detection unit for photovoltaic installations (Figures 8 and 9).

<table>
<thead>
<tr>
<th>Type of arc</th>
<th>Action on the photovoltaic generator</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unearthed parallel arc fault</td>
<td>Short-circuit to prevent differences in electric potential</td>
</tr>
<tr>
<td>Eartheard parallel arc fault with earthed generator</td>
<td>Separate from earth</td>
</tr>
<tr>
<td>Eartheard parallel arc fault with insulated generator</td>
<td>Short-circuit to prevent differences in electric potential</td>
</tr>
</tbody>
</table>

Nowadays some commercial standalone PV arc-fault detectors are marketed but in most cases the detection function is integrated with the inverter itself.

**Arc-fault detector tests**

An arc generator has been designed and built to try out the arc-fault-detecting capacity of the SANTON ADU E1 arc-fault detection unit for photovoltaic installations (Figures 8 and 9).

Tests were conducted in the Photovoltaic Solar Energy Lab (Laboratorio de Energía Solar Fotovoltaica) of CIERMA’s Renewable Energy Department (Departamento de Energías Renovables), following in part the indications of standard UL-1699B of Underwriters Laboratories described in reference UL-1699B 2011 (Figure 10).

The tested detection unit SANTON ADU E1 is capable of detecting arc faults but not circuit interruptions. It has an acoustic arc-fault indicator and warning light and two potential-free contacts, one normally open and one normally closed. An arc fault trips a change in state of these contacts, whereupon the DC current can be disconnected (Figure 11).

The following tests were carried out:

- Series arc-fault detection test
- Detection test with signal masking
- Detection test with line impedance

The tested sample passed all the tests except detection with line impedance, which did not meet test criteria in some cases.

Figure 12 shows one of the oscillograms obtained with a wattmeter /oscilloscope to measure the series arc-fault detection time. The monitored signals were:

- Arc-fault current, in white
- Arc-fault voltage, in blue
- 12 VDC signal of the signal relay, contact normally open of the tested device, shown in red.

**Photovoltaic-roof and -module fire resistance**

There are several standards for testing the fire behaviour of photovoltaic modules (such as IS/IEC 61730-2 (2004): Photovoltaic (PV) Module Safety Qualification, Part 2: Requirements for Testing. 10.8 Fire Test). These lay down two types of fire-resistance tests: spread-of-flame test and burning-brand test. On the basis of test results, photovoltaic modules can be categorised as class A, B or C on the criteria shown in Table 2.

**Table 2. Kiln-dried Douglas fir free from knots and pitch pockets**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Class A</th>
<th>Class B</th>
<th>Class C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pitch of photovoltaic modules</td>
<td>22.6°</td>
<td>22.6°</td>
<td></td>
</tr>
</tbody>
</table>

22.6° (or per manufacturer if > 22.6°)
A photovoltaic generator is very unlikely to cause a fire, but proper precautions have to be taken in a burning building with a photovoltaic array.

### Table: Photovoltaic Module Fire-Resistance Rating

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Class A</th>
<th>Class B</th>
<th>Class C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind speeds (m/s)</td>
<td>5,3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Min. module width and length (m)</td>
<td>1 x 1,8</td>
<td>1 x 2,4</td>
<td>1 x 3,9</td>
</tr>
<tr>
<td><strong>Spread-of-flame test</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flame temperature (°C)</td>
<td>760</td>
<td>760</td>
<td>704</td>
</tr>
<tr>
<td>Test duration (minutes)</td>
<td>10</td>
<td>10</td>
<td>4</td>
</tr>
<tr>
<td><strong>Burning-brand test</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Brand type</td>
<td>Kiln-dried Douglas fir free from knots and pitch pockets</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Brand size (mm)</td>
<td>300 x 300 x 57</td>
<td>150 x 150 x 57</td>
<td>38,1 x 38,1 x 19,8</td>
</tr>
<tr>
<td>Brand size (mm)</td>
<td>1</td>
<td>2</td>
<td>20</td>
</tr>
</tbody>
</table>

Installation of photovoltaic modules might reduce a roof’s fire resistance rating if the rating of the modules themselves is lower than the roof’s. An analysis of this problem has led to the conclusion that the current fire-resistance rating of photovoltaic modules per se is not a good indication of the final rating of this same photovoltaic module and the roof as a whole.

**Photovoltaic-system requisites to ensure firefighter safety**

To ensure proper maintenance and safe extinguishment of any fire, due consideration has to be given to a series of access and spacing requirements when installing a rooftop photovoltaic system. These requisites have been laid down (OCFA 2008) with the following fundamental aims:

- Ensure access to the flat or pitched roof.
- Provide pathways to specific roof areas.
- Provide smoke ventilation areas.
- Provide a rooftop emergency exit.

In any case, with or without photovoltaic modules, roof access points must be defined as an area that does not require ladders to be placed over openings such as windows or doors; they must be sited in strong points of the building, where they do not come into contact with obstacles such as tree branches, wires or other overhead obstructions.

The main access and spacing requirements for single- and two-unit residential dwellings (Figure 13) are:

- Free space of 1 metre from the outside load-bearing wall, 1 metre from the ridge and 0.5 metres on each side of a valley or hip.
- Each roof slope containing photovoltaic modules needs two access pathways at least 1 metre wide.
Likewise, residential dwellings comprising three or more units, commercial buildings, etc, have to meet some access and spacing requirements that can be summed up as follows (OCFA 2008):

- A clear perimeter at least 1 metre wide around the edges of the roof.
- Centre line axis pathways at least 1 metre wide in both axes of the roof.
- Minimum distance of 1 metre around skylights, ventilation hatches and fire hydrants.
- Photovoltaic subarrays at most 46 metres both in length and width.

As well as the access and spacing criteria, photovoltaic systems also have to meet other conditions to guarantee firefighter safety. Although there is no consensus about some of them, a comprehensive list is given below (Meacham B. et al. 2012):

- PV systems should be labelled in a clear and systematic manner as described later
- The main shutoff valve should be easily identifiable and clearly labelled; this switch must be operable without opening doors, etc, and must be accessible from the dwelling entrance.
- All live conduits should be labelled at suitable distances.
- Any batteries should be clearly labelled.
- There must be a load disconnect switch, actionable from the dwelling entrance.
- The photovoltaic system must be fitted with an arc-fault detection device which opens the DC side in the event of arc faults
- During the permitting process when the PV system is installed, the local fire department should be given a set of the plans with disconnection points to refer to in case of emergency.

**Firefighting guide for buildings with photovoltaic arrays**

Fires in buildings with photovoltaic arrays may be sparked off by the arrays themselves or by habitual fire causes in buildings. Although a photovoltaic generator is very unlikely to cause a fire, due consideration still has to be given to additional precautions that might be necessary in a burning building with a photovoltaic array.

Safety of the firefighters and other intervening personnel depends on a proper knowledge and suitable management of these additional risks; this means proper training and instruction has to be given.

The control of building fires involving photovoltaic systems might require the fire crew to adapt some of the measures they usually apply in dealing with fires in conventional electricity or power-generating systems. If photovoltaic systems are known to be present and the associated risks are understood, the situation can then be dealt with in the most effective and
PV arc-fault detector models have not been on the market long enough yet to know how reliable they are.

About 20 building fires involving photovoltaic systems have been recorded (FPRF 2010, INES 2013); in three of these a firefighter has suffered an electric shock. There have even been cases of firefighters letting a building burn down after detecting the presence of a photovoltaic system.


The safe extinguishment of any fire in a building fitted with a photovoltaic system involves the steps and criteria described below.

**Identification of photovoltaic systems**

Firefighters should ideally have a good working knowledge of the various types of photovoltaic modules and also the various forms of building installation, inverters and connections and remaining components; this will enable them to recognise the type of photovoltaic system involved in the fire and locate the key components (Figures 14 to 22).

**Figure 14.** Examples of conventional crystalline silicon photovoltaic modules. Source: manufacturer’s website.
Figure 15. Examples of conventional wafer photovoltaic modules. Source: manufacturer’s website.

Figure 16. Examples of photovoltaic tiles. Source: manufacturer’s website.

Figure 17. Examples of photovoltaic roof-tiling over an insulation membrane.
Figure 18. Example of a photovoltaic skylight. Source: Elecnor-Atersa.

Figure 19. Examples of photovoltaic balconies. Source: manufacturer’s website.

Figure 20. Photovoltaic arrays in a shopping mall: Madrid-2 La Vaguada. Source: drawn up by the authors.
In the interests of identifying the rest of the photovoltaic-system components, and especially the cut-off switches, it is vital for them to be labelled and indicated as follows:

- The whole photovoltaic system should be marked and labelled.
- This should be both internal and external for all the items of the DC circuit: enclosures, conduits, wiring (labelled at a set distance), combiner boxes, etc, and also for the inverters and switchboards and boxes of the AC circuit.
- The marking materials used for this labelling must be reflective, weatherproof and recyclable.
- All the lettering should be in capitals and stand out clearly from the background.

There are several standards laying down the rules for photovoltaic system marking, for example UNE 20460-7-712:2006 «Electrical installations of buildings -- Part 7-712: Requirements for special installations or locations - Solar photovoltaic (PV) power supply systems». 

Identification of the risks of photovoltaic systems
The specific firefighting risks of buildings with photovoltaic systems are (UL 2011): electric shock, slips and falls, increased roof load, danger of inhaling toxic substances and battery risks.

Firefighters need to be aware that even if the switchboards and photovoltaic inverter are switched off, any cable may still be live because it is connected to the photovoltaic array. If it is cut, therefore, there might be a shortcircuit or electric arc at the cut-off point.

Establishing the size of the fire
Whenever a photovoltaic system is involved in any fire, the following safety measures should be taken:

- Always wear the self-contained breathing apparatus (SCBA) and personal protection equipment (PPE).
- Avoid wearing jewels and metal adornments.
- Use only insulated tools.

Firefighters should ascertain as quickly as possible whether or not the photovoltaic system is affected by the fire and pass up this information to higher command. Existence of the photovoltaic system does not necessarily debar the beginning of firefighting action because the system might not have any impact on the fire. In any case the firefighting strategy should be flexible due to the difficulty of “disconnecting” the photovoltaic system.

Locating and disconnecting the photovoltaic system
In buildings fitted with photovoltaic systems, control of general electricity services should also include the photovoltaic system and battery room. The crew responsible for cutting off conventional electricity supply has to locate all DC-side photovoltaic-system switches and also the inverter(s) and, if any, the power storage area on the AC side. The photovoltaic system should always be disconnected in the following sequence (FDM 2005):

- First action: open the inverter’s AC switch.
- Second action: check the inverter has stopped.
- Third action: disconnect the inverter’s DC switch or, if this does not exist, disconnect the general switch of the parallel combiner box.

It should be borne in mind here that the photovoltaic system may have a safety switch that carries out these actions. This switch, if it exists, will be labelled and located at the building entrance. In some cases these switches will open up not only the whole photovoltaic generator but also each series of modules, greatly increasing system safety (Figures 23 and 24).
Figure 23. Load disconnect switch for a string of photovoltaic modules. Source: BENDER.
Firefighters need to be aware that, even after operating all the abovementioned switches, the photovoltaic generator will still be live. In other words, throughout practically the whole of the daytime period, all wiring running from the strings of photovoltaic modules and DC combiner boxes (or the inverter if the AC switch is built into the system) will be live.

Fire extinguishing methods
When dealing with a burning building with a photovoltaic system, the decision about whether or not to use water to extinguish the fire is crucial. In principle it is not a good idea to direct jets of water directly at the flame; dry chemical/powder extinguishers should be used instead. If water is used, the following recommendations should be observed (UL 2011):

- The jet has to have a pressure of about 700 kPa.
- The jet should be angled at 30º to avoid upstream electrical current towards the operator.
- The operator has to be at a minimum distance from the flame; this distance depends on the voltage of the array or system.
- The water jets should never be launched directly at the fire.
- It should be borne in mind that wet floors, especially if puddled, increase the risk of electrical discharge.
- Weatherproof combiner boxes are not resistant to the penetration of jets from water fire-fighting lances, so they might pose an electrical risk.

Roof access (CFOSFM 2010)
A rooftop PV array may affect ladder placement and use, requiring fire crews to employ other methods to gain roof access. On buildings with a sloped roof, the PV panels will normally be found on the south-facing side. Commercial and residential structures with flat roofs may have a large portion of the roof covered by the PV array.

The building’s roof structure should be evaluated to determine the collapse potential due to the added weight placed on
the roof by the PV system. Light weight truss or wooden I-beam construction could result in a collapse if the fire has sufficiently degraded the roof’s structural components. In general, rooftop PV modules weigh up to 25 kilograms and have a surface area of up to 2 m², i.e. about 12.5 kg/m². Their structure may weigh about 30 kilograms per module; the total weight per unit area, therefore, is about 27.5 kg/m².

PV panels, mounting systems, and conduits present a trip-, slip- and fall-hazard to firefighters. This is particularly true under two circumstances:

- BIPV modules built into a sloped roof can be extremely slippery and hazardous to firefighters walking on them.
- PV arrays on commercial structures often cover large portions of the roof; there may hence be very little clear space on which to walk.

Not only are PV modules slippery when wet, they are not designed to carry weight and therefore should not be walked on by firefighters.

Because PV panels continuously produce electricity during daylight, they should not be removed from where installed unless by a qualified PV technician or electrician. Firefighters may find it necessary to contain the fire and prevent its spread until the panels can be safely removed.

Conclusions

The small number of recorded accidents shows that the likelihood of any incident with a photovoltaic system is low. This is due to the quality of the materials and equipment, the proper design of the arrays and adequate assembly and maintenance.

Nonetheless, there are some potential risks posed by photovoltaic systems, which have been addressed by differing safety criteria in each country. Some European countries insist on the quality of the array from the insulation point of view and the use of conventional electricity protection systems. Other countries, especially the US, following criteria laid down for conventional electricity systems, make it compulsory to fit arc-fault detectors.

There are as yet few arc-fault detector models for photovoltaic systems, whether as standalone devices or inverter-integrated, and they have not yet been on the market long enough to be sure about their dependability or the reliability of the tests carried out. Progress is therefore now needed along the following lines:

- Determination of the different types of electric arc-fault in DC circuits of photovoltaic systems.
- Design of arc-fault detectors that can distinguish between series arc faults and parallel arc faults.
- Fine tuning of arc detector testing to ensure smooth and proper working of those detectors that pass these tests.

There is no consensus about whether or not there should obligatorily be a photovoltaic system DC circuit interrupter accessible to firefighters or about the actions this switch should effect.

BIPV design criteria do not usually take firefighter access into account or other safety questions pertaining to emergency crews.

Proper firefighter training and instruction is vital to ensure they have a sufficient knowledge of photovoltaic systems and are able to identify them correctly. This will then be conducive to safe and efficient fire extinguishing measures.

We trust that this study will help to improve the safety of building users and firefighters who might become involved in fires in buildings with solar photovoltaic systems.

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