Appendix A

Description of the Plants

A.1 Introduction

In this Appendix, real processes used as case studies in the various book chapters are described in some detail. Nevertheless, the tags of the variables involved in the following descriptions will be omitted for reasons of confidentiality. Care has been taken to keep to descriptions that will be as useful as possible for the reader to follow.

One set of processes described concerns a large refinery where soft sensors were required to monitor and control routine production. The final two case studies refer to two experimental nuclear fusion plants, where model-based sensor validation strategies were required to assess the quality of experimental observations made during research experiments.

A.2 Chimneys of a Refinery

The atmosphere contains a number of nitrogen oxides. Among these, nitric oxide (NO) and nitrogen dioxide (NO₂) are collectively given the name NOₓ. The level of nitrogen oxides in general, and of NOₓ in particular, in the atmosphere has been increasing in the last century, mainly due to human activities. Unfortunately, nitrogen oxides have a number of negative effects on air quality: they contribute to photochemical smog, cause reduction of visibility and acid rain and, last but not least important, they have a negative impact on human health.

The main source of NOₓ is fossil fuel combustion, caused by human activities both in urban and industrial areas. However, it has a short lifetime in the atmosphere so that its effect tends to be regional, with greater concentrations in urban and industrial areas than in rural ones.

In past decades, a number of industrialized nations enforced more and more restrictive limits on NOₓ emissions and, as a consequence, sophisticated
monitoring strategies for NO\textsubscript{x} emissions are now a matter of interest. It is also worth noting that they are included in the Kyoto treaty.

Stationary sources, such as power plants and refineries, significantly contribute to the emission of nitrogen oxides by means of chimney fumes produced by the combustion of residuals deriving from a number of processes. Hence, industries are deeply interested in the development of measurement and/or estimation strategies for these pollutants.

In particular, Italian laws establish a limit on the monthly average NO\textsubscript{x} emission level, computed on the base of hourly recorded data. Moreover, the average value is considered valid if the minimum percentage of acquired hourly data is 80\% or greater. In the event that such a percentage is not reached, e.g. due to failure of on-line analyzers used for NO\textsubscript{x} measurements, Italian laws require the use of mathematical models that estimate their level on the basis of chimney inputs.

Liquid (called fuel oil, FO) and gaseous residuals (called fuel gas, FG), produced by a large number of processes, are burnt in a number of reactors and the resulting fumes are conveyed to the refinery chimneys, as schematically reported in Figure A.1, in order to minimize NO\textsubscript{x} emission. In fact, it is generally accepted that conveying a large number of process residuals into big chimneys has a positive effect on the total amount of emitted NO\textsubscript{x}.

NO\textsubscript{x} emissions are measured using an on line analyzer, located as reported in Figure A.1, where it is indicated with an arrow. The measuring instrument is a gas chromatograph that measures the NO\textsubscript{x} level with a sampling time $T_s = 1$ min.

To have comprehensive information about emitted pollutants, other chemicals are also monitored. In particular, measuring instrumentation is also used by the refinery to acquire data on:

- hash;
- sulfur oxides (SO\textsubscript{2});
- carbon oxide (CO).

Data produced by the analyzer are collected in a refinery database, marked with a corresponding validity flag, and subsequently used to compute the monthly average value. Due to the harsh environment, the analyzer is frequently off-line for scheduled maintenance and during these periods mathematical models need to be used to estimate the NO\textsubscript{x} level.

Eighteen fuel gas and fuel oil flows considered in the models described in this book represent the inputs to the reactors.
Figure A.1. A schematic view of chimneys used in the refinery to reduce the total amount of NO\textsubscript{x} emission in the atmosphere. FG and FO from a number of refinery plants are burnt in reactors and the fumes obtained are conveyed to the chimneys. The arrow indicates the location of the on-line gas chromatograph used to acquire data on NO\textsubscript{x} concentration.

Data considered in the design of soft sensors described here were obtained using records produced by the gas chromatograph during a period lasting about six months; they were collected in the plant database and used by plant operators for the estimation of mean monthly average emission values.

A.3 Debutanizer Column

The debutanizer column is part of a desulfuring and naphtha splitter plant, shown in Figure A.2, where two gray circles, A1 and A2, can be recognized. They represent the location of two gas chromatographs whose data were used to design soft sensors, while the two white circles, N1 and N2; indicate the points where soft sensors were required.

In particular, data acquired by the device A2, \textit{i.e.}, the C4 (butane) content in the bottom flow to stock have been used in Chapter 6 as a study case for the design of the Soft Sensor named N2.
In the debutanizer column C3 (propane) and C4 (butane) are removed as overheads from the naphtha stream.

The debutanizer column is required to:

- ensure sufficient fractionation in the debutanizer;
- maximize the C5 (stabilized gasoline) content in the debutanizer overheads (LP gas splitter feed), while respecting the limit enforced by law;
- minimize the C4 (butane) content in the debutanizer bottoms (Naphtha splitter feed).

A detailed scheme of the debutanizer column is shown in Figure A.3.

A number of sensors, indicated with circles in Figure A.3, are installed on the plant to monitor product quality. The subset of sensors relevant to the application described, indicated with gray circles in Figure A.3, is listed in Table A.1, together with the corresponding description.
Figure A.3. Block scheme of the debutanizer column. Variables, as used in the case study described in Chapter 6, are indicated, along with the corresponding names, with gray circles. Open circles indicate variables, measured by instrumentation used by the refinery, but not used in the applications described.

Table A.1. List of variables used in the design of soft sensors for the debutanizer column described in Chapter 6. Instrumentation location is reported in Figure A.3

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$u_1$</td>
<td>Top temperature</td>
</tr>
<tr>
<td>$u_2$</td>
<td>Top pressure</td>
</tr>
<tr>
<td>$u_3$</td>
<td>Reflux flow</td>
</tr>
<tr>
<td>$u_4$</td>
<td>Flow to next process</td>
</tr>
<tr>
<td>$u_5$</td>
<td>6th tray temperature</td>
</tr>
<tr>
<td>$u_6$</td>
<td>Bottom temperature</td>
</tr>
<tr>
<td>$u_7$</td>
<td>Bottom temperature</td>
</tr>
</tbody>
</table>

The C4 content in the debutanizer bottoms, \textit{i.e.}, the Soft Sensor output, is measured on the overheads of the deisopentanizer column, as can be observed in Figure A.2, where the location of the measuring device is indicated by the gray circle named A2. It measures the C4 content in the flow to stock that can all assumed to be coming out of the debutanizer bottoms.
A.4 Powerformer Unit

The powerformer unit used as a case study in Chapters 5 and 7 is shown schematically in Figure A.4.

The powerformer unit is designed to produce reformed gasoline with specified RON values. The RON value of the reformed gasoline, used to monitor the product quality and to control the powerforming process, is measured using a NIR analyzer. It receives as input the heavy virgin naphtha (HVN) flow from the Naphtha Splitter bottom that, combined with H₂, feeds the first of four cascaded reactors; furnaces between them are used to obtain the designed temperature profile during the catalytic process.

The output flow is a liquid high in octane number (RON) and rich in aromatic composites. Hydrogen, oil gas, and liquefied petroleum gas (LPG) are also obtained. The output flow feeds the de-ethanizer and debutanizer distillation columns.

Depending on the input flow, two different RON target values are defined. Also, the catalytic reactors need to be periodically regenerated and this phase is monitored on the basis of the four reactor temperature profiles. During the regeneration phases, the RON value drops below the desired level and flow is conveyed to an off-spec tank.

The process variables used in soft sensor design described in Chapters 5 and 7 are reported in Table A.2.

Table A.2. List of variables used in the design of soft sensors for the powerfomer unit described in Chapters 5 and 7

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>u₁</td>
<td>RX1 Temperature</td>
</tr>
<tr>
<td>u₂</td>
<td>RX2 Temperature</td>
</tr>
<tr>
<td>u₃</td>
<td>RX3 Temperature</td>
</tr>
<tr>
<td>u₄</td>
<td>RX4 Temperature</td>
</tr>
<tr>
<td>u₅</td>
<td>Input flow</td>
</tr>
<tr>
<td>u₆</td>
<td>Top debutanizer pressure</td>
</tr>
</tbody>
</table>
A.5 Sulfur Recovery Unit

The sulfur recovery unit (SRU) removes environmental pollutants from acid gas streams before they are released into the atmosphere. Furthermore, elemental sulfur is recovered as a valuable by-product.

Acid gases are among the most dangerous air pollution factors and are one of the main causes of acid rain. Hydrogen sulfide is particularly dangerous because it prevents the cells of the human body from breathing.

The SRU takes in two kinds of acid gases as input. The first, rich in H₂S, called MEA gas, comes from the gas washing plants; the second, called SWS gas, rich in H₂S and NH₃ (ammonia), comes from the sour water stripping (SWS) plant. Acid gases are burnt in reactors, where H₂S is transformed into pure sulfur via a partial oxidation reaction with air. Gaseous combustion products from furnaces are cooled, causing the generation of liquid sulfur, which is collected in catch basins, and then passed through high temperature converters, where a further reaction leads to the formation of water vapor and sulfur. The remaining, non converted gas (less than 5%), is fed to the Maxisulfur plant for a final conversion phase. The final gas stream (tail gas) from the SRU contains residual H₂S and SO₂.
A simplified scheme for the SRU whose data have been used in the book is illustrated in Figure A.5. It is made up of a reaction furnace, which is divided into two separate combustion chambers.

The main chamber is fed with MEA gas, and combustion is regulated, in air deficiency, by supplying an adequate air flow (AIR_MEA). The secondary combustion chamber is mainly fed with SWS gas and a suitable air flow is provided (AIR_SWS).

The combustion of SWS gas occurs in a separate chamber with excess air, in order to prevent the formation of ammonium salts in the equipment, thereby giving rise to the generation of nitrogen and nitrogen oxides. The gas input flow in the secondary chamber is kept constant by adding some MEA gas (MEA_SPILLING) when the SWS gas flow is too low. Thus, an adequate air flow is added (MEA_SPILLING_AIR). Air flows are controlled by plant operators to guarantee a correct stoichiometric ratio in the tail gas. Control is improved by a closed-loop algorithm which regulates a further air flow (AIR_MEA_2) on the basis of analysis of the tail gas composition.

Air, which supplies oxygen for the reaction, is an important parameter in the conversion of H$_2$S, being responsible for the tail gas composition. In particular, an excessive air flow tends to increase the concentration of SO$_2$ with respect to H$_2$S, whereas a low air flow leads to the opposite situation.

On-line analyzers are used to measure the concentration of both hydrogen sulfide and sulfur dioxide in the tail gas of each sulfur line. The analyzers adopted are able to measure the quantity $[\text{H}_2\text{S}]-2[\text{SO}_2]$ (where the brackets indicate concentration), in order to monitor the performance of the conversion process and control the air-to-feed ratio in the SRU with the aim of improving the sulfur extraction process.

Hydrogen sulfide and sulfur dioxide frequently cause damage to sensors, which often have to be removed for maintenance. The design of soft sensors able to predict H$_2$S and SO$_2$ concentrations is therefore required, as in the case study reported in Chapter 5.

![Figure A.5. Block scheme of the SRU](image)

Figure A.5. Block scheme of the SRU

In order to predict the concentration of H$_2$S and SO$_2$ in the tail gas using soft sensors, the variables listed in Table A.3 were used.
Table A.3. List of variables used in the design of soft sensors for the SRU described in Chapter 5

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$u_1$</td>
<td>gas flow MEA_GAS</td>
</tr>
<tr>
<td>$u_2$</td>
<td>air flow AIR_MEA</td>
</tr>
<tr>
<td>$u_3$</td>
<td>secondary air flow AIR_MEA_2</td>
</tr>
<tr>
<td>$u_4$</td>
<td>gas flow in SWS zone (SWS_GAS_TOT=SWS_GAS+MEA_SPILLING)</td>
</tr>
<tr>
<td>$u_5$</td>
<td>air flow in SWS zone (AIR_SWS_TOT=AIR_SWS+MEA_SPILLING_AIR)</td>
</tr>
</tbody>
</table>


In a nuclear fusion reaction, the nuclei of light elements (such as hydrogen) fuse together to form heavier ones, producing energy as a by-product. Nuclear fusion can be considered, in some sense, as the opposite of nuclear fission, a well-established technology in which energy is released by splitting heavy nuclei, such as uranium, in controlled chain reactions. The drawbacks of nuclear fission are related to the risk of nuclear meltdown with a large, uncontrolled release of energy, followed by heavy nuclear contamination. Moreover, fission reagents and by-products are highly radioactive and must be stored, handled, and disposed of with special care; in addition, they need to be kept under control for thousands of years. Unlike the case of fission, the loss of control in a fusion process naturally leads to the end of the reaction, without causing any disastrous nuclear meltdown; reagents and by-products can be safely stored and disposed of within a few decades. Fusion appears to offer many advantages over any other form of power production. Nevertheless, to control fusion for effective power production is an extremely challenging activity, involving scientists and engineers from all over the world. At present, only reactor prototypes exist, which are not designed to produce energy, but only have the aim of investigating various aspects of fusion technology.

Below, the basic principles underlying nuclear fusion are described, and the working principles of one of the most promising reactor prototypes, the tokamak, are given (Wesson, 1987). Finally, the measurement systems which are the subject of the sensor validation strategies presented in this book are described.

A.6.1 Nuclear Fusion

A typical fusion reaction can occur between two heavy isotopes of hydrogen, deuterium and tritium:

$$D + T \rightarrow ^4\text{He} + n + \text{Energy} \quad (A.1)$$
Most of the energy released in this reaction is possessed by the high speed neutron, indicated in (A.1) with $n$. The remaining energy is carried by the helium nucleus $^4\text{He}$, also called alpha-particle. In a fusion reactor, a lithium jacket or blanket around the reactor region would slow down the neutrons, converting their energy into heat. This heat could be extracted to raise steam for conventional electricity generation.

As deuterium is a common and readily separable component of water, there is a virtually inexhaustible supply in the oceans of the world. In contrast, tritium does not exist naturally in significant quantities, and must be manufactured. This can be done by exploiting chemical reactions between the neutrons formed during the fusion reactions and the lithium present in the blanket. As a consequence, although the fusion reaction occurs between deuterium and tritium, the consumables will be deuterium and lithium, as described by the following reactions, where $^6\text{Li}$ and $^7\text{Li}$ indicate heavier lithium isotopes:

\[
^6\text{Li} + n \rightarrow T + ^4\text{He} \\
^7\text{Li} + n \rightarrow T + ^4\text{He} + n
\] (A.2)

Experts agree that the reserves of lithium available are sufficient to enable world electricity generation using fusion reactors, to be maintained at present levels for several hundreds of years.

Under a fusion reaction, hydrogen isotopes change their state, becoming a gaseous mixture of ionized particles, which is called plasma. An important property of plasma, which makes it very different from a gas, is that it can be shaped and moved by magnetic fields. Plasma is often referred to as the fourth state of matter.

Fusion reactions can only take place if the nuclei are brought close to one another. However, this requirement is opposed by the fact that all nuclei carry a positive electric charge and therefore repel each other. By heating the gaseous fuels to very high temperatures, sufficient energy can be provided to the atoms to overcome the repulsive force and make them fuse together. In the deuterium–tritium reaction, temperatures in excess of $10^8 \, \text{K}$ are required, several times hotter than the center of the sun. Below $10^8 \, \text{K}$, the D–T reaction rate falls off very rapidly: to one-tenth at $0.5 \times 10^8 \, \text{K}$, and 20 000 times lower at $10^7 \, \text{K}$. Concurrently, the plasma must be kept under very high pressure, in order to keep the particles very close to each other and increase the frequency at which they collide and consequently fuse.

In an effective reactor, the fusion reaction must obviously be self-sustained, i.e. more energy must be produced than that consumed to initiate and maintain the reaction.

A straightforward performance parameter for a reactor is $Q$, which is the ratio between output and consumed power. In a reactor for power production, the condition $Q >> 1$ should obviously be achieved. $Q = 1$ has already been achieved in experimental plants. In the so-called burning plasma, the high-temperature alpha-particles produced by the fusion reaction carry more energy than that supplied by external heating. This condition corresponds roughly to $Q > 5$. When the alpha-particles can provide sufficient heat to self-sustain the reaction without
external sources of heating, the ignition condition is achieved, which corresponds to \( Q=\infty \).

Reactor power output depends on the square of the density of nuclei \( n_i \), and on the volume of the gas. Power losses must also be kept to a minimum acceptable level by holding the hot gases in thermal isolation from their surroundings. The effectiveness of this isolation can be measured by the energy confinement time \( \tau_E \), which is the time taken for the system to cool down once all external forms of heating are switched off. Energy confinement time typically takes into account the capability of a reactor to achieve a steady-state operational condition.

In a fusion reactor, the values of density, energy confinement time, and temperature must be such that their product \( n_i \cdot \tau_E \cdot T_i \) exceeds \( 5 \times 10^{21} \text{ m}^{-3} \text{ s} \text{ keV} \). Typical values for the parameters that must be attained simultaneously for a reactor are:

- Central ion temperature \( T_i = 10–20 \text{ keV} \);
- Central ion density \( n_i = 2.5 \times 10^{20} \text{ m}^{-3} \);
- Energy confinement time \( \tau_E = 1–2 \text{ s} \).

Extremely high temperature and density are mandatory elements to obtain a self-sustained plasma. At the same time, they are the main causes of instability: the more temperature and density increase, the more unstable is the plasma. Consequently, the fundamental challenge in fusion technology is to discover adequate methods for confining and heating the plasma, without undergoing destructive instabilities.

Under the name of plasma confinement we refer to all the techniques able to maintain a plasma within a prescribed volume. Because of its nature, plasma cannot be contained in a volume in the usual sense, that is to say, plasma cannot physically touch the walls of the volume in which it is created. The interaction with the walls, in fact, leads to plasma destruction and, consequently, to an abrupt ending of the reaction.

A plasma can be confined through three different physical principles:

- **Gravitational confinement.** This is the way the sun confines plasma around itself. Plasma is confined because of extremely high gravitational forces.
- **Inertial confinement.** With this technique, hydrogen gases are compressed through a controlled implosion. The consequent inertia is able to keep particles close enough to make the reaction occur.
- **Magnetic confinement.** As the plasma is a mixture of charged (ionised) particles, magnetic fields can be exploited to maintain, shape, and control plasma.

Magnetic confinement is one of the most promising confinement techniques. A very effective structure in which plasma can be magnetically confined is the tokamak. The next section deals with the basic working principles of tokamaks.
A.6.2 Tokamak Working Principles

A.6.2.1 Main Phases of a Fusion Reaction in Tokamaks

Tokamak is originally a Russian acronym for toroidal chamber and magnetic coil. As the name implies, in a tokamak plasma is confined within a toroidal structure, by means of suitable magnetic fields generated by electric currents flowing in coils. There are usually several coils placed around the plasma, with the purpose of generating, shaping, heating plasma, and driving current in the plasma column.

Several tokamaks have been installed all over the world, each of them with its peculiar characteristics. Nevertheless, all of them share the same working principles, which are described below.

All tokamaks are pulsed devices, in which plasma is created and maintained for a period of time ranging from a few seconds to a few minutes. However, it has not been envisioned yet whether a power reactor will be working in a real steady-state or in a pulsed fashion with very long pulses.

Each experiment on a tokamak, called pulse, or shot, or discharge, consists mainly of the same sequence of events. To illustrate the working principles of a tokamak pulse, we refer to the JET machine, the largest fusion facility in the world, managed by EFDA, located in Culham, Oxfordshire, UK.

Plasma is confined in a toroidal chamber, the vacuum vessel. The JET vacuum vessel is made up of eight identical sectors or octants. Each octant is composed of thick rigid box sections and bellows. Into the vacuum vessel, a vacuum condition of $10^{-9}$ mbar has been achieved through strict manufacturing and cleanliness procedures. The vessel is bakable up to 500°C under vacuum, to remove gas and impurities adsorbed on the inner wall surface.

In a tokamak, two main magnetic fields must be distinguished: the toroidal field is a magnetic field, acting along the toroidal axis of the vacuum vessel. All the magnetic fields acting on a plane which is orthogonal to the toroidal axis of the vessel are referred to as poloidal fields.

The toroidal field is generated by a set of 32 identical, D-shaped, conventional copper wound, water-cooled coils. The toroidal coils are wound around the minor circumference of the torus and equally spaced around the machine. At the beginning of the experiment, prior to plasma formation, the toroidal field is brought to a constant value, in order to confine the plasma when it is initially created. After the toroidal field has reached a steady value, either hydrogen or deuterium is puffed into the vacuum vessel.

Simultaneously with the gas puffing, the current in the inner poloidal coil located at the center of the torus is brought up to its maximum value in preparation for pulse initiation. Subsequently, its current is driven down very quickly to produce a large electric field able to provide the energy needed for plasma creation. As plasma is made up by charged particles free to move, it is actually a conductor. Therefore, a transformer effect is established, in which the inner poloidal coil is the primary one and the plasma column is the secondary. At JET, this effect is enhanced by a transformer iron circuit, made up of eight limbed transformer cores surrounding the vessel. The transformer effect causes an electric current to flow into the plasma along the toroidal axis (called plasma current, $I_p$), by means of the...
Appendix A

opposing flows of oppositely charged particles. The combination of toroidal and poloidal fields on the one hand, with the plasma current on the other, produces a helical magnetic field which, in principle, is able to keep the plasma away from the vessel walls and confined in a toroidal shape.

The initial plasma heating is produced by the plasma current, as the collisions of the plasma electrons and ions make the plasma resistive. Therefore, this form of plasma heating is called ohmic heating. The current in the inner poloidal coil is now regulated in order to maintain the plasma current at a target flat-top value. Unfortunately, the ohmic heating effect is reduced as the electrical resistance of the plasma decreases with increasing temperature. Therefore, the plasma must be supplied with additional heating by several means. Two common ways of achieving this are the injection of neutral particles beams, commonly referred to as neutral beam heating or the emission of high-power radiofrequency waves.

The three phases, during which the plasma current $I_p$ increases, is kept constant, and decreases, are often referred to, respectively, as ramp-up, flat-top, and ramp-down phases of the plasma.

In addition to the inner poloidal coil, outer poloidal field coils are installed. Their task is to control the shape and position of the plasma. The inner poloidal coil is actually divided into two sections. The outer sides of the coil are used exclusively for driving current into the plasma and for ohmic heating, whereas the central portion of the coil works together with the outer coils in shaping and controlling the position of the plasma column. Plasma position and shape are, in fact, unstable and the helical field arising as a combination of the toroidal field, the main poloidal field and the plasma current is not sufficient to reach a stable condition. The greatest instability of the plasma is along the vertical direction, and control of the vertical position of the plasma is a challenging task.

A.6.2.2 Plasma–Surface Interactions: Limiter and Divertor Configuration

A fusion reaction must occur in an environment free from impurities of any kind. Since the very first experimental studies on tokamaks, it has been found that a vessel in strict vacuum condition is not sufficient to guarantee pure plasma. Impurities can arise from the interaction of plasma with components located at the interior of the vessel, and they can also be released within the reaction. In particular, the helium by-product of the fusion reaction (also called helium ash) can interfere with subsequent fusion reactions. All impurities tend to remain in the plasma for a finite time before leaking out. When impurities leave the plasma, they are still charged and tend to follow magnetic field lines.

A first strategy for coping with impurities is to limit the plasma confinement region by inserting a material structure, called a limiter, into the vacuum vessel. The limiter intercepts a fraction of the magnetic lines and creates a separation between the plasma and the interior plasma-facing wall of the vessel (also called the first wall). As a consequence, the last closed flux surface which confines the plasma is kept separated from the first wall. Therefore, the limiter acts by protecting the chamber wall from plasma bombardment and helps in defining the edge of the plasma. The high energy impurity particles which leave the plasma collide with the limiter and can dislodge atomic impurities (i.e. the process of sputtering). Particular care must therefore be adopted in the choice of limiter
material, and pumping devices (such as cryocondensation pumps) must be installed to remove the impurities created by the sputtering process.

Alternatively, it is possible to exploit the fact that impurities are electrically charged and tend to follow a magnetic field line. Consequently, they can be removed by designing adequate divertor regions, in which nonhydrogen particles can be diverted away from the plasma and subsequently cooled down and pumped out from the vacuum vessel. A tokamak endowed with divertors has additional coils (i.e. divertor coils), able to create a drop-shaped plasma, in such a way that the external magnetic lines are guided away from the main plasma and collide with a collector plate. With this magnetic configuration, impurities leave the plasma and subsequently strike against the first wall at fixed locations called strike points.

A.6.2.3 Plasma Disruptions
Fusion experiments performed in tokamaks are intrinsically unstable. Large-scale plasma instabilities, which in most cases are the main causes of an abrupt end of the pulse in a tokamak are called plasma disruptions. These are fast events in which most of the plasma thermal energy is rapidly lost. Most disruptions, called major disruptions, lead to almost instantaneous termination of the plasma current, whereas, more rarely, minor disruptions can occur, in which the energy loss is less important and the experiment can be recovered.

Plasma disruptions can be preceded by a loss of vertical stability. This is the most frequent case in tokamaks producing vertically elongated (D-shaped) plasmas, which are intrinsically unstable along the vertical direction, like that produced in the JET apparatus. In this case, the event which triggers the disruption is called a vertical displacement event (VDE), and occurs when vertical position control is lost. Then, the position instability tends to grow, the plasma strikes the internal surface of the vessel, eventually producing a large-scale instability which causes the loss of all plasma thermal energy. Consequently, the plasma becomes too cold and resistive, the transformer effect induced by the main poloidal field is no longer able to sustain the plasma current, and the plasma current is suddenly terminated. Disruptions always cause important thermal and mechanical stress on the tokamak structure, which must be carefully monitored. In view of this, the JET machine has been endowed with a measurement system, called the machine diagnostic system (MDS). A subset of MDS sensors, in particular a set of 32 strain gauges located at the vertical restraints of the vessel, is the subject of the first sensor validation strategy presented earlier in this book. The measurement systems and the background needed to develop the related sensor validation strategy is introduced in the next section.
A.7 Machine Diagnostic System at JET and the Monitoring of Mechanical Stresses Under Plasma Disruptions

A.7.1 The MDS Measurement System

The MDS is a measurement system developed at JET by the Magnet and Power Supply Division (Marchese et al., 1997). It was installed during the 1995/96 JET shutdown and is devoted to performing a large set of mechanical measurements, such as forces, displacements, accelerations, and pressures, along the mechanical structure of the JET machine. At present, it consists of 512 measurement channels. All the installed probes are passive, due to the high neutron fluxes expected during operation under active conditions, and the noise induced by the high magnetic fields is reduced by means of a carrier at 5 kHz, followed by demodulation and filtering.

The top and bottom main vertical port (MVP) restraints (lockable brakes), equipped with 64 strain gauges, support most of the vertical force acting on the vacuum vessel during plasma disruptions caused by VDEs. The axial movement of the brakes is measured with 32 linear variable resistors (LVRs). Up to 62 LVRs are used to monitor a wide set of radial, vertical and tangential movements of vertical ports, horizontal ports, and inner walls.

The lateral restraints of the main horizontal ports (MHPs), recently introduced to reduce the vessel’s sideways displacements, are monitored by 16 pressure gauges, together with four triaxial accelerometers, with a measurement range of 0 to 50 g (g=9.81 m/s²), installed at the MHPs of octants, 2, 4, 6, and 8.

The measured data are sent to a host computer via a dedicated network. Measurements are performed at a sampling rate of 2.5 kHz, and are stored, after smoothing and filtering, at different rates, according to the different operational status of the machine. Three sample ratings are used:

- **Fast** (2.5 kHz). This rate is used when either a disruption or a major plasma instability or misbehavior occurs. Related data are stored in a database called Jet Pulse File (JPF) for about 800 ms.
- **Slow** (25 Hz). This rate is used during the active phase of the pulse (from ramp-up to ramp-down), lasting about one minute.
- **Continuous** (0.25 Hz). This rate is used to evaluate statical properties of the experiment. Related data are continuously stored.

The MDS data, flowing through a VME bus, are accessible in real time via a PC equipped with a double Pentium 300 MHz board, a VME-PCI adapter, and the LabView™ software package. Both thresholding and the algorithm based on physical redundancy described in Section 9.9.2 are continuously run on this PC and duty officers are warned via e-mail of the occurrence of detected sensor faults.

On the occurrence of a disruption, the validation algorithms described previously do not allow one to validate the vertical stress measurements, performed at fast rate by the set of 32 strain gauges installed on the bottom supports of the
vacuum vessel. In view of this, the validation system described in Section 9.9.3 was developed.

A.7.2 Disruptions and Mechanical Stresses

With a disruption caused by a VDE, high mechanical and thermal stresses are produced on the machine structure (Buzio et al., 1996). Disruption-induced loads are characterized by radial and vertical components of several millions of newtons, with typical time scales ranging from 20 to 50 ms. Since the installation of additional restraining rings (1989), the vessel has become more rigid with respect to radial axisymmetric forces and the most important mechanical loads are now due essentially to vertical forces. Because of the particular configuration of the supports, vertical forces exert a torque around a rotation centre, generating a vessel axisymmetric oscillating motion around a centre, called rocking motion, with a frequency of 14 Hz. Experts summarize the force history into the following phases (Buzio et al., 1996):

1. initial steady state phase, during pulse flat-top, due to the interaction between plasma and the divertor coils;
2. upward force, due to eddy and halo currents induced by the plasma vertical instability;
3. large downward swing, due to the plasma current quench and to the currents induced in the divertor coils;
4. rocking motion at 14 Hz, caused by the fact that the vertical forces exert a torque around a rotation centre located near the root of the main vertical ports of the vessel, in the inner side.

The downwards swing occurring in phase 3 is the most important, with regard to the fatigue life of the vessel, considering that the machine is now operating above its original design goals. This swing is estimated by computing the so called F-number. This is a simple nonlinear function of seven typical currents, that are part of the settings of the experiments. They are:

1. The plasma current $I_p$
2. The current in the inner poloidal coil, that provides the energy to create the plasma by a transformer effect in which the inner poloidal coil is the primary and the plasma is the secondary, $I_{pfs}$
3. The current in the plasma shaping circuit (shaping current), multiplied by the effective number of turns in the shaping circuit, $N_{sh} I_{sh}$
4. The four divertor coil currents, $I_{D1}$, $I_{D2}$, $I_{D3}$ and $I_{D4}$.

A good estimate of the downward swing is obtained by evaluating the F-number formula at a time known as $STIME$, 200 ms before the detected disruption time. This choice is adopted in order to avoid considering corrective actions, which are performed on the relevant currents by the plasma position control circuit in an attempt to recover from the disruption, that actually modifies the natural trend of the experiment. Consequently, the currents measured at $STIME$ reflect the effective...
current values at the disruption more than the current values taken at the actual disruption time. For this reason, the input of the neural network described in Section 9.9.3 consists of the currents evaluated at \( STIME \).

### A.8 Interferometry-based Measurement System for Plasma Density at FTU

The measurement system described above is useful to investigate the mechanical stresses of the vessel. This issue is extremely helpful for engineers, who are concerned with keeping the plant in good and safe working condition.

Physicists, instead, are interested in the study of many aspects of the reactions. Many other measurement systems must therefore be developed in order to investigate all the physical phenomena involved in the reaction. These kinds of measurement systems are called diagnostics (Hutchinson, 1990) in the fusion community. However, we prefer not to use this term in this book, as when we refer to diagnosis it has a more extensive meaning (see Chapter 9). Diagnostics can be used in nuclear fusion for studying problems in five main areas:

1. Methods of setting up stable plasmas.
2. Determination of important plasma parameters such as energy, density, temperature, and particle confinement time.
3. Study of additional heating techniques.
4. Study and control of plasma impurities.
5. Control of plasma shape and position.

Plasma density measurement is of fundamental importance. To measure this quantity, one of the most widely used techniques is based on laser interferometry. Lasers are exploited as good diagnostic tools in plasma studies, as they are sufficiently bright and monochromatic to compete with the self-emission of the plasma in a narrow band; their use does not require electrodes, probes, or other protuberances inside the vessel, and they offer good spatial and temporal resolution, due to their natural collimated beams and the short duration of their pulses. A laser beam can interact with a plasma producing different modes of interactions: scattering, absorption, reflection, refraction and transmission. Many measurement systems can be designed and implemented by exploiting each of the basic interaction modes.

In a laser interferometer, the plasma electron density is measured by exploiting the change in the refractive index of the laser caused by the presence of the electron gas (\textit{i.e.} the plasma). In a high temperature plasma, the refractive index is dominated by the electron contribution, as the ion to electron mass ratio is very large. In a plasma without external magnetic field, or collisions, the solution of the wave equation gives the following dispersion relation for the wave number \( k \)

\[
k^2 = \frac{\omega_p^2}{c^2} - \frac{\omega_{ce}^2}{c^2}
\]  
(A.3)
where $c$ is the light speed, $\omega_0$ is the laser frequency, and $\omega_{pe}$ is the plasma frequency, which can be expressed as

$$\omega_{pe} = \left( \frac{n_e e^2}{\varepsilon_0 m_e} \right)^{1/2}$$  \hspace{1cm} (A.4)

where $e$ is the electron charge, $m_e$ is the electron mass, $n_e$ the plasma electron density and $\varepsilon_0$ is the vacuum permittivity. Generally $\omega_0 \gg \omega_{pe}$. The refractive index, $\mu$, can be derived from equation (A.3) as

$$\mu - 1 = -\frac{e^2}{2\varepsilon_0 m_e} \frac{n_e}{\omega_0^2} = \left( \frac{e^2}{8\pi^2 \varepsilon_0 c^2 m_e} \right) n_e \lambda_0^2$$  \hspace{1cm} (A.5)

where $\lambda_0$ is the laser wavelength. As can clearly be seen from Equation A.5, the refractive index of a laser interacting with a plasma is a function of the plasma electron density. Because of the change in the reflective index, when a laser beam is transmitted through a plasma along a line $l$, it undergoes a phase shift $\Delta \phi$ which is function of the refractive index and, consequently, of the plasma electron density, as

$$\Delta \phi = \frac{2\pi}{\lambda_0} \int [1 - \mu(z)]dz = r_e \lambda_0 \int n_e(z)dz$$  \hspace{1cm} (A.6)

where $r_e$ is the classical electron radius and $z$ the line coordinate.

The interferometer installed at FTU is based on the Mach-Zehnder type (Wesson, 1987). The laser adopted is based on a deuterium–carbonium–nitrogen (DCN) gas. In the interferometer, a probing beam is transmitted through the plasma, and the phase change is revealed by comparison with an outside reference beam. The measurement of the phase shift determines the integrated density along the chord through which the laser interacted with the plasma. The phase difference is counted by a high-frequency electronic clock, called fringe counter, and when the value $2\pi$, i.e. one fringe, is reached the counter reverts to zero. A typical fault generated in an interferometer is fringe skip, which consists of missing whole fringes in the fringe counts. This leads to measurements affected by step-like discontinuities. After counting, fringes are converted into absolute line densities. In order to obtain the radial distribution of the plasma density, several measuring channels are used at varying distance from the plasma centre. A mathematical inversion procedure (Abel inversion) can then be used to find the density as a function of plasma radius. At FTU, a five-channel interferometer has been installed to measure plasma electron density. It performs the plasma line density measurement along five parallel lines.
Appendix B

Structured References

B.1 Theoretical Contributions

B.1.1 Books

B.1.2 Data Collection and Filtering, Effect of Missing Data

Lopes VV, Menezes JC, (2005) Inferential sensor design in the presence of missing data: a case study. Chemometrics and Intelligent Laboratory System 78:1–10
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Spinelli W, Piroddi L, Lovera M, (2005) On the role of pre-filtering in nonlinear system identification. 16th IFAC World Congress, Prague


B.1.3 Variables and Model Structure Selection


Flynn D, Ritchie J, Cregan M, (2005) Data mining techniques applied to power plant performance monitoring. 16th IFAC World Congress, Prague


Lang ZQ, Futterer M, Billings SA, (2005) The identification of a class of nonlinear systems using a correlation analysis approach. 16th IFAC World Congress, Prague


Lind I, (2005) Nonlinear structure identification with linear least squares and ANOVA. 16th IFAC World Congress, Prague
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Liu J, (2005) On line soft sensor for polyethylene process with multiple production grades. 16th IFAC World Congress, Prague
Nagai EY, Arruda LVR, (2005) Soft sensor based on fuzzy model identification. 16th IFAC World Congress, Prague

B.1.4 Model Identification

Feng S, Chen J, Tu XY, (2005) Nonlinear system identification with shortage of input–output data. 16th IFAC World Congress, Prague
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Nagai EY, Arruda LVR, (2005) Soft sensor based on fuzzy model identification. 16th IFAC World Congress, Prague


B.1.5 Model Validation


B.1.6 Fault Detection and Diagnosis, Sensor Validation

B.1.6.1 Survey works

B.1.6.2 Fault Detection

B.1.6.3 Fault Diagnosis
Struss P, Malik A, Sachenbacher M, (1996) Qualitative modeling is the key to automated diagnosis. Proc. of 13th IFAC World Congress, San Francisco, CA, USA

B.1.6.4 Dedicated Conferences

B.2 Applicative Contributions
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Shi Z, Cuimei B, Bin L, Yonghua W, (2005) The advanced process control system for an industrial distillation column. 16th IFAC World Congress, Prague
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