

HISTORICAL LOSS EXPERIENCES IN THE GLOBAL POWER INDUSTRY

AUGUST 2014



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■ INTRODUCTION

At Marsh, our claims management and power industry experience enables us to present an accurate description of the types of events that commonly lead to insurance claims. To compile this study, we used data and an analysis of global trends that many power clients will already be acquainted with.

The purpose of this document is to provide commentary on the world of power generation, the risks affecting that industry, and the importance of effective risk management in preventing or mitigating these risks.

The report is divided into two parts:

- ▶ Part one provides a brief overview of some of the key technologies being used in power generation, including details of some areas that are either emergent or in the research-and-development stage at the time of writing.
- ▶ Part two features a narrative description of some of the historical loss experiences that have affected the power generation industry in recent years.

It may be helpful to review this document along with the following recent Marsh Risk Management Research briefings on power generation:

- ▶ *The Impact of Large Losses in the Global Power Industry.*
- ▶ *Common Causes of Large Losses in the Global Power Industry.*

We trust that you will find this document both illuminating and helpful as you consider the risks your own organization faces.

PART ONE: PRINCIPLES OF GENERATING ELECTRICITY

ELECTRICITY IN OUR WORLD TODAY

The presence of electrical power in our daily lives is so pervasive that many people scarcely give it a second thought unless it poses a risk to their safety. In fact, the subject of electricity rarely comes up except to describe an area that has no power, although power disruptions in developed countries are still newsworthy events. Electricity is so readily available and easily harnessed that it is simply “there” – and we so take it for granted that when we flip a switch in our houses, we are annoyed if the light doesn’t come on.

For those companies that produce electricity, however, ensuring a regular and consistent supply to both urban and rural locations is far from being a mundane task.

Electricity is created by converting physical energy into a flow of electrons, which creates an electrical current. The original form of energy used to generate electricity is based on either the energy of motion (kinetic energy) or the energy of heat (thermal energy). Kinetic energy is derived mainly from the movement of water or the movement of air, and is converted using dams, tidal barriers, and wind turbines. On the other hand, thermal energy is derived from a variety of sources. Heat can be produced from burning coal, oil, gas, biomass, through a process of nuclear fission, or from geothermal or solar sources.

Electricity production requires a series of interlinked systems that include:

- ▶ Generation facilities (known as generation companies or “gencos”), which include plants and areas where power is generated from a source of fuel. These are typically generated below 20-kilovolt and are then stepped up to more than 100 kilovolts for transmission companies.
- ▶ Transmission companies (known as “transcos”) transmit high-voltage electricity of more than 100 kilovolts across long distances to distribution companies.
- ▶ Distribution companies (known as “discos”) step down the high-voltage power to medium and low voltages (50-kilovolt and down to 120-volt) that can be used industrially or domestically, and provide connections to homes and businesses in the area. A disco is typically the company that most businesses and consumers see as being their electricity company and to whom they pay their monthly bills.

WHERE DOES ELECTRICITY COME FROM?

Electricity is a secondary source of energy. In other words, we must use other primary sources such as gas or wind to generate it. It can be generated by harnessing various sources of primary energy, including:

- ▶ **Electrochemistry:** The transfer of chemical energy into electricity; examples include batteries, fuel cells, and other similar means of capacitance.
- ▶ **Electromagnetic induction:** The transfer of motion energy into electricity by rotating a magnet within closed loops of a conductive material.
- ▶ **Photoelectric:** The transfer of heat from solar/light energy into electricity.
- ▶ **Piezoelectric:** Generating electricity from applying mechanical stress/pressure to anisotropic molecules. Anisotropic substances are those that have physical values that differ depending on the way they are measured; an example is crystals or meat, which both cut differently across the grain than they do along it. Substances such as wood and certain ceramics are other obvious examples.

- ▶ **Nuclear:** The transfer of energy from accelerated particles, involving the conversion of nuclear potential energy into electricity via a managed process of decay.
- ▶ **Static:** Static electricity occurs when the level of charge on the surface of an object becomes imbalanced. An electrostatic discharge occurs when the electrical charge is neutralized, usually by a conductor. Lightning is a dramatic example.

On an industrial scale, the vast majority of electricity is generated using electromechanical generators, which can be driven using a variety of methods. Common methods include the use of:

- a) Kinetic energy from falling water, wind, or ocean-wave action.
- b) Thermal energy from the combustion of:
 - ▷ Fossil fuels, such as coal, natural gas, oil, and peat.
 - ▷ Biomass, such as wood and/or agricultural waste.
 - ▷ Waste streams, such as garbage and/or old tires.
 - ▷ Landfill gas.
- c) Thermal energy from geothermal heat.
- d) Thermal energy from concentrated sunlight.

NEW OR DEVELOPING IDEAS

HYDROGEN FROM ROCKS

Scientists have been developing new methods of obtaining hydrogen gas from water. Olivine, a rock mineral (known as peridot in translucent gem form), is capable of removing one hydrogen and one oxygen atom from an H₂O molecule. This reaction releases the remaining hydrogen atom, which can then be used as a source of fuel.

Interestingly, olivine has also been identified as a promising method of carbon capturing.

MICROWAVES

Researchers at Duke University's Pratt School of Engineering recently unveiled a method of generating an electric current from microwave signals. Although the concept itself is not a new one, claims by the researchers of a new method with energy conversion efficiency of 35% to 40% — not dissimilar to the conversion efficiency of modern solar cells — increases the viability of this concept.

THORIUM NUCLEAR REACTORS

With many non-nuclear countries looking to develop and harness nuclear power — one example being Bolivia, which announced an intention to build its first nuclear plant in January 2014 — thorium is an exciting proposition. As an element, thorium is more common than uranium, and is likely to produce less nuclear waste. Production costs, however, do tend to be higher.

The viability of a thorium reactor has been clear for many years from the German THTR-300 project, and the HTR-10 project in China.

One great advantage of thorium, however, is that it cannot be used to build nuclear weapons. With global concerns about the proliferation and development of nuclear power and research by countries with regimes perceived as unfriendly, thorium might provide a basis for compromise. Liquid-fluoride thorium reactors (LFTRs) also operate at atmospheric pressure, meaning that an explosion like the one at the Fukushima I Nuclear Power Plant in March 2011 would be far less likely to occur. Research into LFTRs is ongoing in several countries.

With this background in mind, a review of some of the key technologies and machinery used to facilitate the electricity generation process is in order.

WHAT EQUIPMENT IS USED TO GENERATE ELECTRICITY?

TURBINES

Turbine generators (also known as turbo-alternators) are used to generate electricity through the process of electromagnetic induction. They convert kinetic energy from water, steam, or a fuel into the circular motion of a rotating shaft inside a generator. This movement induces electricity into the generator stator. Turbines can range in size from 1 kilowatt to 1,750 megawatts, with rotational speeds varying from approximately 100 revolutions per minute (RPM) for some hydro-electric turbines to 500,000 RPM for micro turbines.

A key measurement for modern turbines, of whatever type, is mechanical efficiency – the conversion rate of the energy available in the “fuel” into electricity. The cost of fuel is a vital factor in modern power generation, driving ever-greater efficiency in the transfer of the calorific or kinetic value of fuel. As this is achieved with greater technical intricacy, new materials, increased unit sizes, and reduced margins of tolerance in materials and design clearly create more complex risks for both the insurance and power generation industries to manage.

STEAM TURBINES

A steam turbine converts the energy from pressurized steam into rotary motion. They are installed in a Rankine cycle power plant (this type of plant was responsible for approximately 90% of the world’s electrical generation in 2000). Modern steam turbines use elements of both impulse turbine and reaction turbine design, with reaction more prevalent in the low-pressure sections. An impulse turbine uses nozzles to direct jets of steam, while a reaction turbine relies on the positioning and arrangement of the blades to form nozzles, and makes use of the dynamism produced as steam accelerates through the turbine.

Water used in steam turbines can be heated by a variety of sources:

- ▶ Fossil fuels, such as coal, natural gas, and fuel oils.
- ▶ Solar heat.
- ▶ Nuclear fission.
- ▶ Biomass and waste materials.
- ▶ Geothermal heat.
- ▶ Ocean thermal energy conversion.

The steam turbine itself is used to drive an electric generator at a constant speed, and this speed determines the frequency of the electrical output of the generator. Common generators run at 3,000 RPM for 50 hertz and 3,600 RPM for 60 hertz. Four-pole generators run at half-speeds.

COMBUSTION TURBINES

A combustion turbine, sometimes called a gas turbine, is a type of internal combustion engine that operates on the Brayton cycle. It has an upstream rotating compressor that compresses air and then forces it into a combustion chamber where heat is added. The hot compressed air is then expanded through a downstream turbine. The turbine is used to drive the compressor and also an external load, such as an electrical generator or other machinery.

Hot exhaust gases vented from the turbine are used for co-generation (namely the heating of water for chemical process at a nearby plant), district heating, or combined-cycle use.

Some units are based upon machines built for the aviation industry (aero-derivative), while others are more robust, and often larger, frame machines built specifically for electrical generation. Combustion turbines have a wide range of sizes; many can burn a variety of fuels, achieve fast ramp rates, and in new power plants can be operational in anything from a matter of months to two years from the start of construction. This has made them very popular during the last few decades for generating companies, as electrical demand has increased and fuel sources have changed (moving from coal to natural gas).

COMBINED CYCLE

This is the name given to a system where hot gases from a gas turbine exhaust are used, via a heat recovery steam generator (HRSG), to generate steam to drive a steam turbine generator. This increases the efficiency of fuel use. Modern combined-cycle power plants are capable of more than 60% fuel efficiency, with technologies in development aiming for 62%-65%.

Such plants are often referred to as combined-cycle gas turbine (CCGT) plants, and use some of the steam extracted from the steam turbine for external use (industrial production or district heating). They are also referred to as co-generation plants. Often, the revenue and/or tax credits received from having a third-party “steam host” greatly improve the economic efficiency of the generating station.

WIND

Commonly known as “bulb” turbines, these single-stage turbines generate electricity from kinetic (wind) energy, driving rotor blades fixed on either a horizontal (HAWT) or vertical (VAWT) axis-wind turbine.

HAWTs can vary in size, from small models for domestic use (as low as 50 watts), to larger turbines with blade dimensions of more than 40 meters. They are attached to a tower that may be 90 meters in height, with modern variants now reaching 8 megawatts in capacity. Several companies are currently developing 10-megawatt wind turbines.

Smaller turbines can be turned to face the wind by using a wind vane, while larger turbines require a servo motor in order to be effective.

VAWTs are ideal for areas where wind direction may fluctuate, and placing the gearbox and generator closer to ground level tends to make maintenance requirements less onerous. VAWTs are smaller than the HAWT variety, with the largest vertical-axis turbine being fewer than four megawatts.

Naturally, electricity generation from wind turbines does require moving air, and is consequently subject to some geographical limitations in placement. Large-scale wind generation can sometimes prove to be unpopular with local residents, both due to the noise of revolving blades and the visual impact on the landscape.

WATER

Hydro-electric turbine blades are rotated by the physical flow of moving water. Large water turbines can now operate at a level of mechanical efficiency that exceeds 90%. Since a reliable source of water kinetic energy is required, this type of generation is highly site-specific. Installations vary from those that generate just a few kilowatts, to some of the largest power plants in the world, with individual turbines generating in excess of 500 megawatts each. Smaller turbines tend to have horizontal shafts, while larger turbines tend to be vertical. As climate change affects glacier melt and rainfall, some hydro-electric installations are in peril of losing their sources of reliable water.

Tidal/marine turbines and tidal arrays are included in this category. While not widely used at the moment, several projects with projected capacity in excess of 500 megawatts are currently under construction worldwide, with South Korea being a particular pioneer in this area. The potential scale of generation from tidal methods is demonstrated by Russia’s proposed Penzhin bay tidal project, in the Sea of Okhotsk. One design variant at this location is a facility that could generate 87,000 megawatts of power, almost four times the size of the current largest facility in the world – the 22,500-megawatt Three Gorges Dam in China.

RECIPROCATING ENGINES

The internal combustion engine, typically working in the diesel cycle, burns fuel to drive a set of pistons, which are connected to a crank. This crank then drives a generator. Similar to combustion turbines, these machines cover a wide range of sizes from 500 kilowatts to 50 megawatts, can be configured to burn a wide range of fuels, have a high ramp rate to full output, are highly responsive to changes in load demand, and can be purchased and installed within less than two years. This makes them suitable for many remote or emerging generating needs. Future subjects of research include the quantum reciprocating engine, comprising a single oscillating atom.

Mainstays of this type of engine are the nigh-on ubiquitous internal combustion engine and the steam engine. For electricity generation, diesel engines and generators are used, often either in a marine environment, or as backup to the grid system. The largest reciprocating engines in current production are for marine purposes, notably on container vessels, and are capable of producing in excess of 80 megawatts.

GENERATORS

Generators convert the rotational energy of a turbine shaft into electricity. Slip rings and brushes provide current to the rotor poles, thereby producing a magnetic field. The rotor and its magnetic field turns inside a stationary set of conductors called the stator and current, usually in three phases, and are induced into the stator conductors. In both the rotor and the stator, the conductors (windings), usually copper wire, are wound around iron cores to create unbroken magnetic fields. The rotor is supported on bearings, which must be kept lubricated due to the high speed and loads. High temperatures can be produced inside the generator, so specific cooling is required. In many units, hydrogen gas is used to provide that cooling more effectively than air. Sealing oil is also used to prevent the hydrogen from leaving the generator at the bearing areas. As will become clear later in this report, in the majority of cases where turbine generators mechanically fail, the lubricating and seal oil and hydrogen gas often contribute to resulting fires.

Electricity from generators is then transmitted along an output bus to the generator step-up transformer for conversion to a transmission voltage.

TRANSMISSION AND DISTRIBUTION (T&D) ASSETS

A key reason why electricity is so readily available and so widely used is the fact that it can be transported easily. After electricity is produced at a power station, it travels by wire to a transformer that “steps up” the voltage. The electricity then travels on a nationwide grid system on wires. When electricity flows through a conductor, there is an inherent resistance to its movement. Conductors such as copper and aluminum are used due to their low resistance. Line losses are proportional to line length (the longer the line, the more power is lost) and inversely proportional (lower) at higher voltages, so that when electricity is transmitted, it is necessary to do so at high voltages (of more than 100 kilovolts, typically). Unfortunately, high voltages are not practical for end users and so the voltage has to be stepped down to medium (less than 100 kilovolts, but typically more than 50 kilovolts) and to low voltage (less than one kilovolt) for distribution to end users such as industrial, commercial, and residential.

TRANSFORMERS

Transformers are used both to increase (step up) the voltage of electricity, enabling it to be transmitted for long distances through cables with less electrical resistance (that is, more economically), and to step down electrical voltage to enable it to be used for household and other processes.

A transformer operates using the principle of magnetic flux. In essence, an electrical current in the primary winding is transferred through the core of the transformer, and induces a current at a lower voltage into the secondary winding. During this process, the voltage of the electrical current is changed. Modern transformers are usually in excess of 98% efficient when converting voltages, with superconductive transformers being rated 99.75% or above. Transformers are vulnerable to temperature variations, however, and even minor changes in operating temperatures can potentially have a drastic impact on equipment life expectancy.

Measuring anywhere from a few kilograms to hundreds of tons, and varying substantially in terms of design, transformers are an essential part of the T&D system.

THE INTRODUCTION OF UNCERTAINTY: RENEWABLE GENERATION

When deciding on the level of generation required to ensure that the distribution network has sufficient power at the correct level of voltage, traditional thermal-energy turbines have the advantage of being highly predictable in terms of output. The only question that remains is then whether the turbine should be run, and for how long.

Hydro-turbines rely on a steady water supply and, subject to seasonal issues or incidents of drought or excessive flooding, are able to provide a constant supply of electricity. The supply of water to the turbines is something that the plant can directly influence, usually via a dam.

However, to compensate for the variable input from renewable sources — particularly wind turbines — into a commercial market where the price of power is often dictated by core elements of supply and demand, these more conventional generation methods have had to make accommodations, however. This lack of predictability has led to a decrease in demand for base-load units, and matching increase for fast-start technology that can fit around less controllable supplies. The end result is that equipment that was designed for base-load operation is now being subjected to far more frequent start-ups and cool-downs. In practice, from an engineering standpoint, one of the issues raised by this is that, instead of the creep fatigue more commonly associated with base-load running, it is logical to assume that thermo-mechanical fatigue is an increasingly frequent peril. Increasing downtime may also heighten vulnerability to stress-corrosion cracking.

The impact of this new regime, particularly on older equipment, should be a matter of great interest and concern to plant managers and those who support them. Fortunately, developments in inspection techniques, the computer modeling of stresses, new on-line monitoring methods, the sharing of industry knowledge, and improvements in managed maintenance techniques all help plant managers to prudently manage these risks when applied correctly.

MAJOR LOSS EVENTS

While it is not possible to include in this report all losses that have taken place since 1973, the list below comprises a sample of some of the most significant types of events. A note of caution: This data should not be used for statistical analysis or as guidance for future trends.

The growth of the internet has made it easier for the authors to obtain information on major electric utility losses. Media reports, blogs, and amateur videos of incidents can be accessed from anywhere in the world. Access to utility company websites with press releases, regulatory filings, and industry publications has facilitated the task. In addition, the ease of electronic communication has made it easy to reach colleagues globally.

The loss data can be broken down into four categories:

- ▶ **Grid/T&D:** Includes events that adversely affected electrical T&D systems.
- ▶ **Fossil fuel power plants:** Facilities generating power from coal, natural gas, fuel oil, biomass, and municipal solid waste fuels.
- ▶ **Nuclear power stations:** Facilities that generate power using nuclear reactors.
- ▶ **Other power industry assets:** Facilities such as hydroelectric and pumped storage, high-voltage direct current (HVDC) converter stations, photovoltaic, wind, and geothermal facilities.

I PART TWO: HISTORICAL LOSSES

GRID FAILURES/TRANSMISSION AND DISTRIBUTION (T&D) LOSSES

Despite low interest rates and the fact that venture capitalists and investors tend to seek out risks that produce guaranteed income during economically unstable periods, power generation assets have not proved to be popular investment opportunities. T&D investment, either privately or as part of government stimulus projects has, if anything, fared even worse than core-generation assets in the developed world.

Much of the lack of private investment in power generation can be attributed to uncertainty. While an increase in demand for electricity is almost inevitable – a topic addressed in previous Marsh Risk Management Research briefings on power generation – government vacillation and inconsistency in subsidies and pricing guarantees have discouraged investors.

The need to invest in both generation and T&D assets is essential. Current infrastructure across much of the developed world is, quite simply, old. Both generation and T&D assets are coping with the new challenges of

renewable generation, as well as with the variance in fuel pricing due to developments in shale gas availability and political fragility. Moreover, power-generation assets are experiencing the highest level of demand since the industry began. In fact, many of these assets, particularly T&D, have reached the 50-year mark. As a result, corrosion is increasingly common and many high-voltage and local lines were built in the 1960s, or even before. Those utility companies responsible for providing power should be lauded for their ability to do so, despite the aging infrastructure.

Unfortunately, the lack of investment in this area is resulting in higher demands being put on increasingly aging equipment and, as a result of this, blackouts – due to both lack of generating capacity and T&D bottlenecks – could potentially increase in the future.

ICE STORM

December, 20-23, 2013 - Central and Eastern Canada and Northeastern US

An ice storm, known as the “2013 North American Ice Storm,” caused freezing rain to build up on tree branches, which consequently fell off and toppled power lines. Despite accurate weather forecasts and preparations by governments and utility crews, the damage was extensive and utility workers were unable to keep up with repairs. As a result, many were without power for days and weeks before and after Christmas. In Ontario, the impact was particularly severe, with more than 130,000 power outages in mostly rural areas, and more than 300,000 customers in Toronto (Canada’s largest city) without power. Other communities in the Greater Toronto Area (GTA) were also affected, with millions of people being left without electricity for up to a week. Fortunately, the impact could have been worse, save for the fact that schools had already closed for the Christmas break and many families had left the area to vacation. Still others, who remained at home during this period, chose to take their children to work in order to access electricity, heat, and hot food from restaurants. To prevent deaths as a result of carbon monoxide poisoning from outdoor gas heaters being used indoors, the government opened numerous warming centers for the public to sleep and eat in until power was restored.

In Quebec, the storm caused 50,000 power outages, while in Nova Scotia and New Brunswick, approximately 65,000 residents lost power. In the US, there were approximately 380,000 outages in Michigan and more than 123,000 in Maine, following the worst Christmas week storm in more than 100 years.

WIND STORMS

December 4, 2013 - Europe

High winds caused a blackout for approximately 100,000 homes in Scotland and some 30,000 homes in Northern Ireland. In England, around 10,000 homes were evacuated in Norfolk and Suffolk. As a result, the Thames Barrier was closed for two days to protect London from storm surge. However, extensive flooding and property damage was reported across many locations, notably the East coast of England, as well as Hamburg, Germany – both of which recorded their largest tidal surges in 60 years. Also of note was the forced closure of the Eastern Scheldt storm surge barrier in The Netherlands.

CAUSE UNKNOWN

December 2, 2013 - Venezuela

Much of Venezuela was plunged into darkness for several hours. Government statements blamed sabotage by right-wing activists.

MECHANICAL BREAKDOWN

November 9, 2013 - Tajikistan

The failure of the T&D system surrounding the Nurek-Regar hydroelectric dam cut power for approximately 70% of the population of Tajikistan. Power was restored after a few hours.

HUMAN ERROR

May 22, 2013 - Vietnam

A truck collided with a 500-kilovolt power line, causing an outage that affected more than 20 cities and provinces in Southern Vietnam.

WINDSTORM

January 26-27, 2013 - Australia

Cyclone Oswald struck Queensland, with resulting wind damage to T&D lines that disrupted power to more than 275,000 customers. The Optus telephone network was also severely affected. In addition, power restoration efforts to areas of Brisbane were severely impacted due to extensive flooding.

WINDSTORM

October 29-30, 2012 - US

The effects of Superstorm Sandy resulted in power outages in areas within 17 states, most notably New Jersey, New York, and Pennsylvania. A reported 57,000 workers assisted in the restoration efforts. Some generators were affected by gasoline rationing, which lasted up to 15 days in some areas — most notably New York. Most homes that had been affected had power restored by Thanksgiving (the third week in November).

MECHANICAL BREAKDOWN

July 30-31, 2012 - India

This is, to date, the largest electricity blackout in history. During a period of high load, components in the system failed, resulting in subsequent trips and backup failures. This resulted in the loss of more than 30 gigawatts of capacity, resulting in the loss of power to an estimated 650 million people — some 10% of the planet's population. Crush injuries and several deaths occurred as people crowded into air-conditioned areas. Water pumps and purifiers could not be operated and transport systems failed. While service was restored within hours, a subsequent relay failure left millions of people without power again.

WINDSTORM

June 29, 2012 - US

In a weather event known as a “derecho,” a series of thunderstorms brought hurricane-strength winds across the US. Extensive damage, particularly to T&D lines, cut power to more than 8 million customers.

MECHANICAL FAILURE

January 14, 2012 - Turkey

The failure of a 340-kilovolt transformer led to voltage anomalies and a resulting blackout for more than 15 million people. Power was restored the same day. Why the transformer failed remains unknown, but damage to a transmission line from heavy snowfall has been suggested, as has a failure of a T&D line.

WINDSTORM

November 10, 2011 - Brazil

In one of the largest power failures in history, damage to T&D lines in the area of the Itaipu hydroelectric dam resulted in a blackout that affected more than 80 million people. Parts of Sao Paulo and Rio de Janeiro, as well as all of Paraguay, were without power for six hours.

WINDSTORM

August 27-28, 2011 - US

Hurricane Irene caused extensive damage to T&D lines, cutting power to more than 5 million people, including nearly 1.5 million in New Jersey alone. In addition, extensive landslides were also reported. Several power companies had pre-arranged for tree cutters and other equipment to be ready for the inevitable damage.

EXPLOSION

July 11, 2011 - Cyprus, Greece

Responsible for approximately half of the total generating capacity in Cyprus, the largest power station on the island — the Vasilikos power station — was destroyed when explosives stored at a nearby naval base self-detonated. Thirteen people were killed in what has been called the fourth largest non-nuclear artificial detonation in history. In the wake of the disaster, two government ministers resigned and demonstrations were held in the Nicosia, attended by thousands of people.

WINDSTORM

April 27, 2011 - US

A series of tornadoes destroyed in excess of 300 transmission towers, affecting more than 1 million customers.

EARTHQUAKE

February 22, 2011 - New Zealand

Measuring 6.3 on the Moment Magnitude Scale (MMS), the earthquake which struck the city of Christchurch damaged whole sections of the T&D network, cutting power to approximately 80% of the population. More than 80% of customers had power restored in fewer than five days; however, uncertainty regarding city ordinances and future building permits caused severe delays in other areas.

CYCLONE

February 3, 2011 - Australia

Cyclone Yasi, with wind speeds exceeding 180 miles per hour, caused serious wind and flood damage to numerous facilities and T&D lines. More than 150,000 customers are thought to have been affected.

HOT WEATHER/RAINFALL

September 6, 2010 - Yemen

Heavy rain and temperatures exceeding 37 °C were blamed for a blackout that left much of Yemen, including Sana'a and the port at Aden, without power for approximately 12 hours.

CAUSE UNKNOWN

September 1, 2010 - Iceland

A nationwide power outage affected more than 200,000 people, leaving many residents of Reykjavik without hot water. The three largest alumina smelting plants in Iceland lost power from the grid, and fires were subsequently reported at one plant.

MECHANICAL FAILURE

August 20, 2010 - Russia

A mechanical failure, which occurred at the Vostochnaya substation, resulted in a second failure at a different substation on the same line. Some 4.5 million people — almost the entire population of St. Petersburg — lost power during this blackout, with many also suffering from a loss of their water supply. Many stranded commuters had to walk out of the world's deepest subway system. Internet and mobile phone facilities were also reportedly affected.

ICE STORM

March 14-16, 2010 - US

In total, some 750,000 customers lost power during this storm, which affected numerous states. New Jersey was particularly badly hit, with more than 450,000 customers believed to have lost power.

MECHANICAL FAILURE

March 14, 2010 - Chile

The failure of a 500-kilovolt transformer in a substation in Southern Chile knocked out power to some 90% of the population of that country — some 15 million people. While the investigation initially centered on effects of the recent February 27 earthquake, which measured 8.8 on the MMS, the Superintendency of Electricity and Fuels (SEC) eventually concluded that the root cause was a lack of adequate communication between the various companies involved in the Chilean energy sector. A concert organized to raise money for victims of the earlier earthquake had to be cancelled due to lack of power.

WINDSTORM

November 10-11, 2009 - Brazil

A failure in the grid system surrounding the Itaipu hydroelectric dam cut the supply of some 17,000 megawatts of capacity. The cause of the failure was attributed to falling trees. Official figures indicate that nine out of 27 states were affected, in a country of nearly 200 million people. There was a complete failure of power in both Rio de Janeiro and Sao Paulo for a period of two hours. Neighboring Paraguay was also affected, but for fewer than 30 minutes.

HURRICANE

August-September, 2008 - Various Locations from the Caribbean to Canada

Hurricane Ike caused damage in locations ranging from the Caribbean to Canada. The population of the Turks and Caicos Islands suffered a total blackout, along with many residents of Louisiana in the US who were still recovering from the effects of the recent Hurricane Gustav. Several million customers were affected in Texas, with parts of Houston being off-grid for much of October. One energy company estimated that 90% of its customers had been affected.

VANDALISM

July 20, 2009 - UK

An act of arson caused a blackout for approximately 100,000 people in the London and Kent regions of the UK, and many homes were off the grid for nearly four days. Mobile generators were used in what remains, to date, the largest deployment ever undertaken in that region. The Red Cross provided assistance to the vulnerable. On the plus side, however, the Thames crossing at Dartford was made toll-free for the duration of the incident.

HUMAN ERROR

December 12, 2007 - The Netherlands

An Apache helicopter gunship was being flown at low altitude when it collided with high voltage (HV) power lines. More than 50,000 people were affected by the subsequent blackout, which cut power to the Bommelerwaard and Tielerwaard regions. Power was restored in 72 hours.

MECHANICAL FAILURE

September 26, 2007 - Brazil

A 345-kilovolt line failed due to soot that had contaminated the HV insulators causing a fault. The soot was probably from recent field burning. Power was restored to most areas after two days. Some 3 million people were affected.

MECHANICAL FAILURE

July 23, 2007 - Spain

A falling substation cable initiated a cascade failure at a minimum of six substations, cutting power to more than 350,000 people in Barcelona. At least one major hospital was forced to revert to backup generators. Full restoration efforts took three days.

HUMAN ERROR

April 26, 2007 - Columbia

A failed attempt at bus switching at a substation in Bogota cut power to more than 75% of the population of Columbia. Power was restored after five hours.

MECHANICAL FAILURE

April 19, 2007 - Costa Rica

A series of rolling blackouts throughout the early part of April, brought on by high temperatures and an alleged lack of maintenance, culminated in a transformer explosion at the Arenal substation, and a loss of more than 150 megawatts of capacity. It is estimated that some 4 million people were impacted by this event. Rolling blackouts continued to affect the area for some time afterwards.

FIRE

January 16, 2007 - Australia

At a period of exceptionally high demand due to high temperatures, bushfires in the Snowy Mountains were blamed for a shutdown of the state T&D network after the Vic-SA grid interconnection between the state and the national grid was automatically disconnected. Much of the city of Melbourne, and several other areas, suffered a blackout as a result.

The contractual pricing arrangements in the region were also badly affected, forcing some producers to pay for electricity generation for the region.

HUMAN ERROR

November 4, 2006 - Europe

The planned disconnection of a power line by a German electricity company caused a cascade failure that divided the European transmission grid into three separate parts. The distortion of supply and demand over the next two hours cut power to large parts of Western Europe, with knock-on effects on countries as far away as Morocco. The European Network of Transmission System Operators for Electricity was criticized for not giving operators sufficient real-time data that would have allowed greater control of the situation. In total, it is estimated that more than 15 million people were affected.

HUMAN ERROR

August 14, 2006 - Japan

A floating crane, between 30 meters and 35 meters in height, was being transported by barge when it struck overhead power lines. A system integration system operated successfully, but was subsequently deactivated after an increase in demand caused an imbalance between generation and load requirements. Tokyo Electric Power Company (TEPCO) representatives noted that power was restored to 1.376 million out of total of 1.391 million people who were affected in under two hours, and all power was restored in four hours and 22 minutes.

HURRICANE

October 23, 2005 - US

Hurricane Wilma, the 13th hurricane of the 2005 season, hit Puerto Rico and Florida, affecting more than 3.7 million customers. In Cuba, more than 750,000 people were evacuated from their homes. Severe damage also occurred in several regions of Mexico.

HURRICANE

September 22, 2005 - US

Following hard on the heels of Katrina, Hurricane Rita caused extensive damage to T&D lines and fuel supplies – notably gas supplies from the Gulf region. Some 2 million customers were affected in the US. Power was also turned off in Cuba on September 19, causing disruption to gas supply lines.

HURRICANE

August 31, 2005 - US

Hurricane Katrina caused extensive damage to T&D lines and fuel supplies – notably gas supplies from the Gulf of Mexico region. The resulting power outages impacted Alabama, Florida, Louisiana, Kentucky, Mississippi, and Tennessee. More than 2 million customers were affected.

MECHANICAL FAILURE

August 18, 2005 - Java and Bali

The failure of a 500-kilovolt transmission line caused a cascade failure that resulted in a blackout which, it is estimated, affected up to 100 million people, including almost all of Jakarta. Power stations at Palton, Suralaya, and Muara Karang had to be taken offline.

MECHANICAL FAILURE

May 25, 2005 - Russia

An explosion in a substation triggered a cascade failure and subsequent loss of power to much of the city of Moscow. A lack of reliable backup systems, and the notoriously complicated nature of the supply system to this region, contributed to the seriousness of this event. The stock exchange was closed for two hours, and parts of the Moscow Metro system also failed. Power was restored within two hours.

CAUSE UNKNOWN

July 12, 2004 - Greece

Officially blamed on mismanagement of the grid, the shutdown of two power plants led to a cascade failure and a subsequent blackout for much of Greece. This was particularly embarrassing, given the fact that Athens was undertaking final preparations to host the Olympic Games and concerns had already been raised about standards of preparation.

WINDSTORM

September 27-28, 2003 - Italy

Strong winds were responsible for cutting a supply line that runs from Switzerland to Italy. Four successive lines, including the France-Italy line, subsequently tripped due to high demand. This cascade failure cut power to the entire Italian mainland for three hours, forcing the early closure of the Nuit Blanche carnival being held in Rome. More than 57 million people were affected.

MECHANICAL BREAKDOWN AND HUMAN ERROR

August 14, 2003 - Canada and US

Known as the “Northeast Blackout of 2003,” this event resulted in 55 million people losing electricity throughout parts of the Northeastern US, the Midwestern US, and much of Southern Ontario in Canada. It was the second largest blackout in history at the time.

The event began on Thursday, August 14, 2003, at 4:10pm EDT (UTC-4). Power was restored in some areas by 11:00 p.m., but for other areas, up to two days later. Power supply in the affected areas was reduced for up to one week, while generating stations, especially nuclear units, worked to return to service, having been forced down by the blackout. In excess of 500 generating units at more than 250 power plants were affected — estimated at more than 75% of total capacity. The blackout contributed to at least 11 fatalities.

The blackout’s primary cause was a software bug in the alarm system at a control room of a transmission company in Ohio. A lack of tree trimming was a contributing factor, as the originating fault occurred when an overloaded transmission line touched foliage. The detailed investigation report released in February 2004 noted that the originating transmission company failed in various aspects of operating its system, which resulted in a widespread event. Weaknesses were found in the large interconnect grid, although subsequent measures were taken to address these gaps.

CAUSE UNKNOWN

July 13, 2002 - Azerbaijan

Baku, and much of Azerbaijan, lost power for reasons that were never made clear. An estimated 8 million people were affected.

MECHANICAL BREAKDOWN

May 20, 2001 - Iran

Excessively warm weather is alleged to have caused HV cables to fail, leading to extensive blackouts throughout Iran. Outages were reported in Tehran, as well as other provincial capitals, such as Shiraz, Tabriz, Kermanshah, Hamedan, Qazvin, and Isfahan. Electric buses used in cities were unable to operate and the Tehran metro system was closed for four hours. Approximately 20 people needed to be rescued from underground shafts or lifts when they became trapped. While power was restored the same day, more than 25 million people were affected.

BIRDS

May 9, 2000 - Portugal

An errant bird landing “in the wrong place at the wrong time,” resulted in much of Portugal — including Lisbon — being left without power. (Of note is that this event is not unusual. For example, the overwintering population of black storks in Northern Israel has been responsible for up to 90% of the total damage caused by birds to T&D lines in that country.)

CAUSE UNKNOWN

March 18, 2000 - New Mexico

Problems with a transmission line disrupted power to approximately 500,000 customers. Power was restored within hours.

WINDSTORMS

December 25-28, 1999 - France

Following a relatively light period of activity since 1990, 1999 was a devastating year for European storms. In addition to causing an estimated US\$6 million worth of damage over a period of two days, as well as more than 100 deaths, an estimated 3.5 million customers in France were left without power as a result of hurricane-force windstorms Lothar and Martin.

LANDSLIDE

July 29, 1999 - Taiwan

The collapse of a transmission tower, following a nearby landslide, cut power to approximately 8 million customers.

LIGHTNING

March 11, 1999 - Brazil

A lightning strike, which hit a substation in Bauru, São Paulo, tripped a number of circuits. Due to weaknesses in the power grid created by a lack of maintenance and capital investment, the electricity had nowhere to flow and, as a result, the lines and, consequently, the generators tripped. The disruption in the system created both over- and under-frequency events leading to more units tripping off-line. The resulting power outage affected more than 90 million people, and left more than 50,000 people trapped on the Rio de Janeiro metro system. Power was restored the same day. At the time of the event, this was the largest-ever blackout in the region.

ICE STORM

December 24, 1998 - US

More than 400,000 customers lost power as a result of an ice storm, and utility workers performed repair work at 12,229 locations in a restoration period that lasted throughout the Christmas week.

ICE STORM

December 22, 1998 - US

Approximately 170,000 customers lost power as a result of an ice storm. More than 3,000 utility workers were deployed to repair 1,364 downed power lines. More than 350,000 calls associated with this event were logged in five days by the public utility's call center.

MECHANICAL FAILURE

December 8, 1998 - US

Nearly 1 million customers suffered an outage when a substation, still grounded following a period of maintenance, was erroneously brought back online. Restoration efforts were completed the same day, after more than 15 substations in the area automatically shut down due to the demand that this event placed on the T&D system.

HURRICANE

September 28, 1998 - US, Dominican Republic, and Puerto Rico

Hurricane George struck various territories, with wind speeds in excess of 100 miles per hour. More than 500,000 customers in the US alone lost power. Additional damages to facilities in the Dominican Republic and Puerto Rico were recorded. The full restoration of power to all affected areas took at least one month. Due to the slow movement of the storm, more than half of the power grid in the Dominican Republic was adversely affected.

HURRICANE

August 26, 1998 - US

Hurricane Bonnie knocked out power to approximately 245,000 customers in the US. Pre-planned storm recovery strategies, and arrangements with other utility companies to provide crews to assist with restoration efforts, enabled a workforce of 3,700 to be deployed.

ICE STORM January 24, 1998 - US

Another storm, following one that had occurred on January 10 (see below), caused adversely affected ongoing repair work from the earlier event.

ICE STORM January 10, 1998 - US

This storm, which lasted for almost a week, cut power to 130,000 customers over an area of 7,000 square miles of rugged terrain. More than 375 miles of wiring needed to be replaced over a period of almost a month.

ICE STORMS January 9, 1998 - Ontario and Quebec, Canada, and Northern New York State and Central Maine, US

A massive combination of five smaller successive ice storms over a five-day period struck eastern Ontario (Ottawa); Southern Quebec (Montreal) and portions of Nova Scotia; Northern New York, and Central Maine. This caused blackouts that lasted days to weeks for millions of people. This event became known as the “North American Ice Storm of 1998,” due to its unique size.

Ice deposits on power lines, utility structures, and trees were up to 120 millimeters thick (twice the previous record set in 1961). Extensive damage was done to trees, which then impacted nearby power lines. Quebec had the highest standard in the world for ice loading of high-tension transmission lines and associated towers. Still, the ice loading exceeded that and resulted in more than 1,000 large steel towers collapsing in a dramatic chain reaction. More than 35,000 wooden distribution poles were also destroyed by the weight of the ice. In Quebec, damage was done to 600 kilometers of high-voltage transmission lines and 3,000 kilometers of medium- and low-voltage distribution lines.

The ice storm led to the largest deployment of Canadian military personnel since the Korean War (1950). Similarly, the Maine National Guard was mobilized to aid roughly 700,000 of Maine’s 1.2 million residents who were without electricity. Moreover, power crews were brought in from all over North America to assist with the restoration efforts.

Part of the Montréal region, south of Montreal, was the worst hit area and became known as the “Triangle of Darkness” (French: Triangle noir) since residents did not get power restored until February 7, 1998.

Although estimates of the storm’s economic impact vary, direct damages are estimated to be in excess of C\$1 million, with overall damage in the area of C\$6 billion. The Insurance Bureau of Canada reported 535,200 insurance claims after the storm, totaling approximately C\$790 million worth of damage to homes, cars, and other property. Canada’s economic output declined by 0.7% in January, as business fell off in many industries. The storm cost Hydro-Québec C\$725 million in 1998 and more than C\$1 million was subsequently invested in the following decade to strengthen the power grid against similar events.

ICE STORM January 1997 - US

More than 100,000 customers were affected.

ICE STORM December 30, 1996 - US

Approximately 250,000 customers were left without power. Damage was aggravated by mud slides and gusts of wind clocking in at 70 miles per hour.

ICE STORM November 1996 - US

Freezing rainfall coated T&D lines with ice in Washington State. Crews from other utility companies traveled hundreds of miles to restore service, which took nearly two weeks.

ICE STORM

October 23, 1996 - US

A total of 175,000 customers were affected by a two-day storm that dropped roughly six inches of snow. The mass of snow felled trees and power lines. More than 1,300 workers were deployed in the restoration effort.

HURRICANE

September 5, 1996 - US

Hurricane Fran left more than 1.6 million customers without power. A total of 1,500 miles of distribution lines were affected, together with more than 3,000 transformers. Repairs involved some 8,500 workers.

HURRICANE

July 12, 1996 - US

Hurricane Bertha cut power to approximately 225,000 people, although only 55,000 were without power for more than 24 hours. Final repairs took four days.

STORM

December 11-12, 1995 - US

Heavy rain and wind gusts in excess of 100 miles per hour cut power to 1.2 million customers. In total, 450 miles of transmission lines and 900 transformers had to be replaced.

HURRICANE

October 5, 1995 - US

Hurricane Opal knocked out power to more than 1.7 million customers, including 261,000 out of a total of 340,000 customers in one particular utility.

HURRICANE

August 3, 1995 - US

Hurricane Erin knocked out power to 215,000 customers. The situation was aggravated by the lack of advance warning to the affected area, due to the unpredictability of the hurricane's trajectory. In total, nine substations and 70 major distribution feeders were damaged or destroyed.

STORM

March 9, 1995 - US

Heavy rainfall over a period of almost a week resulted in 1.3 million customers suffering outages. Damage to roads, bridges, and other infrastructure caused additional difficulties in restoring service.

EARTHQUAKE

January 17, 1995 - Japan

An earthquake measuring 6.8 on the MMS was responsible for the deaths of more than 5,000 people and injuries to 26,000. In total, 48 substations were destroyed or damaged to varying degrees. More than 1 million customers were affected. Repair works were completed in one week, although extensive damage to the corporate offices of the affected utility was also reported.

STORM

January 12, 1995 - US

Heavy rainfall caused outages to more than 1.4 million customers. In total, 220 miles of wiring and 600 transformers required replacement.

SNOWSTORM

April 11, 1994 - US

More than 12 inches of snow fell within a 10-hour period, causing damage and disruption. Subsequent damage, as well as difficulties in carrying out repair work, occurred as the snow melted, causing flooding.

STORM

February 11-12, 1994 - US

Three consecutive winter storms over a 60- to 90-mile band of territory dropped nearly three feet of snow and left one foot of ice on power structures, knocking out power to almost 1 million customers. The resulting floods were so serious that helicopters and all-terrain-vehicles were required to set new poles. A total of 2,000 workers were involved in the restoration efforts and two weeks later, all but 30,000 customers were back in service.

STORM

July 28, 1993 - US

Winds in excess of 90 miles per hour disrupted power to 300,000 customers. A total of 76 miles of cable and 90 transformers were replaced, with repairs taking more than a week to conclude.

STORM

July 8, 1993 - US

Winds in excess of 100 miles per hour affected some 600 structures on two major T&D lines. Helicopters were used to avoid causing damage to crops.

SNOWSTORM

March 12-14, 1993 - US

Nearly two feet of snow caused outages for approximately 1 million customers and widespread infrastructure damage. Some 10,000 workers were mobilized to restore power, which included the replacement of some steel transmission towers that had been knocked down by the wind.

STORM

December 11, 1992 - US

Strong winds cut power to 440,000 customers. This was followed by a snowstorm and flooding, which caused additional damage. A total of 800 workers were involved in the restoration process, which took nearly two weeks.

HURRICANE

September 11, 1992 - Hawaii

Hurricane Iniki devastated Hawaii, damaging roughly 950 miles of distribution line. As a result, a military airlift of equipment and supplies was sent from the US. Some 400 workers took more than three months to completely restore service.

HURRICANE

August 26, 1992 - Various Locations

Hurricane Andrew, with wind speeds of 140 miles per hour and gusts of 160 miles per hour, cut power to more than 6.4 million customers in the US and Mexico. More than 14,000 transformers and thousands of miles of distribution cable had to be replaced. At one point, roughly half the population of Florida suffered a loss of power. Along a particular 20-mile stretch of the Gulf Coast, it was reported that almost no utility poles were left standing. Final restoration of power took nearly two months, with meter connections still ongoing six months after the event. Problems were encountered with housing and feeding the repair crews due to widespread infrastructure damage. One utility company alone fielded more than 6,000 workers.

RIOT

April 29, 1992 - US

Three days of civil disturbances left 51,000 customers without power. Due to the disturbances in the area, workers were prevented from completing repair work. Lessons learned from this event included the importance of crisis management planning and the need to communicate with customers, politicians, the media, and employees in a timely, clear, ongoing, and informative manner.

ICE STORM

October 31, 1991 - US

Approximately 80,000 customers lost power for over a week. Extensive T&D damage occurred, including the loss of 16 miles of steel transmission structures on one line.

FIRE

October 20, 1991 - US

An urban firestorm destroyed 2,800 homes and disrupted services to 8,711 electricity customers and 7,300 gas customers. As a result of the event, nearly 650 transformers were lost. A total of 1,500 workers restored service to areas capable of receiving power within five days.

HURRICANE

August 19, 1991 - US (Various Locations)

Hurricane Bob knocked out power to more than 1.1 million customers. Reinforcement work that had been done following Hurricane Gloria in 1985 proved somewhat effective in reducing damage. However, a second storm followed, which caused further repair difficulties.

STORM

July 7, 1991 - US

Tornadoes, winds in excess of 79 miles per hour, and more than 800 lightning strikes blacked out approximately 680,000 customers for up to a week. Post-loss safety measures included tree trimming, ultrasound pole testing, enhancement of power rerouting options, guarding of downed lines, and toll-free numbers for emergency calls. Total estimates for the improvements at the time were approximately US\$2 million.

ICE STORM

March 13, 1991 - US

A total of 95 transmission towers along a 25-mile corridor were destroyed, along with severe damage to a 20-mile stretch of another line. Some 44,000 hours of labor were required to restore the system. The subsequent thaw and further rainfall aggravated repair efforts, which took roughly five months to complete.

ICE STORM

March 3, 1991 - US

Widespread outages affected 206,000, out of a total of 330,000, customers of one utility company. The inability to pinpoint the exact location of the outages was a key problem in this circuit-based system, which necessitated door-to-door surveys to determine the extent of damage.

MECHANICAL BREAKDOWN/FIRE

August 13, 1990 - US

A network fault triggered an electrical failure at a distribution substation which, in turn, tripped a transformer. This resulted in an increase in load to other transformers. A subsequent fire at the substation caused a 50-block blackout, which affected the the main financial district. Commercial customers were compensated for perishable food up to US\$200, and residential customers up to US\$100.

SEVERE STORM

June 19, 1990 - US

A severe storm with winds measuring 115 miles per hour – for which there was less than one hour of warning – knocked out the power supply to 60,000 customers for nearly a week.

Tornado

June 2, 1990 - US

A tornado damaged or destroyed 100 transmission towers, resulting in up to 75,000 customers experiencing blackouts. A total of 600 workers were involved in restoration. Although a 2,850-megawatt power-generating facility remained operational, it was unable to distribute electricity, forcing the purchase of electricity from other local utilities.

EARTHQUAKE

October 17, 1989 - US

More than 1.3 million people in California lost power after the Loma Prieta earthquake, which measured 6.9 on the MMS and caused extensive damage to numerous substations. A total of 63 people lost their lives as a result of this event.

HURRICANE

September 18-22, 1989 - US (Various Locations) and Puerto Rico

Hurricane Hugo cut power to more than 1 million customers in the US and nearly all of Puerto Rico. Power generation in Puerto Rico was reduced from 2,200 megawatts to roughly 80 megawatts. More than 12,000 workers were involved in restoring power.

GEO-MAGNETIC STORM

March 13-14, 1989 - Canada

A geo-magnetic storm, blamed on solar disruption to the earth's magnetosphere, triggered the grid's protection system in Quebec, Canada. The subsequent blackout caused power supply failure to some 6 million people throughout the province. The North American utility industry took protective measures to prevent a reoccurrence, since increased geo-magnetic activity, due to the solar magnetic cycle, happens approximately every 11 years.

HURRICANE

September 27, 1985 - US

Hurricane Gloria caused blackouts for 1.25 million customers in the United States and destroyed almost the entire T&D system of the service territory. More than 85 substations and 1,400 transformers were damaged. Communication proved problematic, especially given the fact that 81% of the total customer base was affected. This storm underscored the need for full-system mapping and an effective public relations emergency response plan.

MECHANICAL FAILURE

December 27, 1983 - Sweden

A short-circuit in a transformer cut power to more than half of Sweden, affecting more than 4 million people.

EXPLOSION

January 8, 1981 - US

An explosion occurred during a work assignment in a state prison in the United States, damaging T&D lines. More than 1.5 million customers lost power.

FOSSIL FUEL GENERATING PLANTS

The majority of the world's supply of electricity comes from fossil fuel. And, despite ongoing pressure from environment groups advocating energy efficiency, demand for electricity continues to grow.

While predictions vary, the consensus is that worldwide demand for energy, including electricity, will grow rapidly in the coming decades. In its 2012 Factsheet, the International Energy Agency (IEA) predicted the following:

- ▶ Global demand for electricity will grow more than 70% to almost 32,000 Terawatt-hours (TWh) by 2035.
- ▶ The greatest demand will come overwhelmingly from non-Organisation for Economic Co-operation and Development (OECD) countries, with more than half from China and India alone.
- ▶ Despite coal maintaining its status as being the largest source of power generation globally, particularly outside the OECD, its share of the mix will be eroded from 40% to 33%.
- ▶ A total of 5,890 GW of additional capacity – more than the total installed capacity of the whole world in 2011 – will be required between 2012 and 2035. One-third of this will be to replace retiring plants, with the rest going towards meeting growing electricity demand.

The consequence of several years' worth of Canadian oil sand and US shale gas production has had a huge impact on the global markets. Turmoil in the wake of the Arab Spring has also affected supplies. To assist markets struggling to cope with environmental costs, as well as wholesale fuel prices, there is also declining political will to enforce carbon reduction at the expense of the consumer. The collapse in the price of carbon trading permits also plays a role.

Against a backdrop of new equipment developed to focus on fast demand-start capabilities and adapt to the input from renewables, the world of fossil fuel power generation faces change.

In North America, there is downward pressure on coal-fired generating stations, with many having closed due to government mandate, aging equipment, and/or increasing environmental regulations and retrofits. Consequently, this has placed downward pressure on thermal coal prices. The lost generation is being replaced with natural gas-fired combustion turbines, spurred on by the increasing availability of shale gas.

Elsewhere in the world, however, lower coal prices, a lack of inexpensive natural gas, and the shutting down of nuclear power plants due to fears arising from the Fukushima Daiichi meltdown, have resulted in the rapid construction of coal-fired power stations.

The reader will note that many of the incidents referred to below occurred as a result of severe mechanical breakdown (electrical breakdown is included in that category), often resulting in fire or explosion. The reality is that modern utility-class machines handle vast amounts of kinetic energy, and it takes careful engineering, operation, maintenance, and adherence to procedures to convert the energy into electricity. Failing to adhere to any of these measures could result in disaster.

FIRE March 29, 2013 - Ukraine

This loss involved a power plant consisting of four 300-megawatt units installed and commissioned from 1968 to 1973. At 15.14, pulverized coal leaking from the pressurized ducting system ignited from spontaneous combustion in Unit 2. The fire spread to the roof of the turbine hall, as well as through the length of the hall, causing the collapse of the roof spans, cabling, and the contents of the control rooms. Pictures and videos on the internet showed an extensive fire and resulting damage. The owner reported that there was insignificant damage to the boilers. There was one fatality and four individuals were hospitalized with burns and combustion-products poisoning.

A government-launched investigation reported on April 8 that the cause was “depressurization of pulverized-coal handling system, resulting in a leak and spontaneous combustion” and as the result of a violation of technical procedures.

Work was carried out to repair the building and the units. This resulted in reconnecting the following units to the grid: Unit 1 on October 8, 2013, and Unit 4 on November 13, 2013. At the time of this writing, the status of units 2 and 3 is unclear.

MACHINERY BREAKDOWN

April 16, 2013 - Singapore

The failure of a high-pressure turbine (HPT) blade on a 365-megawatt machine caused vibration and damage to other blades, both by rubbing and impact. The seal ring was also badly damaged, as were the burners, low-pressure turbine (LPT) blades, and parts of the casing and exhaust areas.

FIRE DAMAGE

February 14, 2013 - United Arab Emirates

During a period of maintenance at this 1,500-megawatt combined-cycle plant, a fire occurred. The cause of the fire was hot work welding on walkways, which took place in the air intake filter house.

The fire destroyed the filter house, extending the maintenance outage. Firefighting was made more difficult since no sprinkler systems were in place; the efforts focused heavily on preventing the fire from spreading to other areas.

Precautionary borescopic examination of the nearby gas turbine discovered residue from the fire and ash inside the turbine compressor and cooling air pipework. This was not unanticipated, since it was known if the air intake opening was not sealed at the time the fire occurred — a requirement during outages to ensure airflow and prevent the buildup of any harmful gases during work.

The risk that fire residue could block cooling holes, resulting in overheating if the turbine was operated, necessitated full cleaning of the affected machinery and a substantial increase in the outage period.

MACHINERY BREAKDOWN

January 17, 2013 - US

This 760-megawatt gas-fired combined cycle co-generation plant suffered damage as a result of Superstorm Sandy. At the time this loss occurred, not all of the repairs from Sandy had been completed.

At the time of the loss, the plant was isolating part of the distribution control system to enable the repair and replacement of certain components. It is suspected that an automatic transfer relay fault in the transformer control area failed to correctly isolate incoming power from two different sources. Control panel switches operated incorrectly, sending power back to the generator and the distributed control system (DCS).

This fault tripped the bus breaker, cutting power to the DCS. The plant then shut down automatically. Since the oil lubrication system controls were routed via the DCS, these systems failed to operate. The battery back-up had been damaged during the earlier Superstorm Sandy event and did not operate. As a result, the oil lubrication system did not operate correctly, and significant damage occurred to the turbine during run-down.

FLOODING

October 31, 2012 - US

Storm surge accompanying Superstorm Sandy was responsible for an initial short circuit at this facility, following backflow from a nearby substation and subsequent flooding. Restoration efforts included pressure washing to remove salt water from key components as quickly as possible.

Fast repair work was essential because of the co-generation nature of the facility, and the nearby refinery was unable to function without sufficient steam.

MACHINERY BREAKDOWN

September 17, 2012 - US

This combined-cycle plant suffered an arcing electrical fault, which occurred inside the station bus transformer breaker, and three adjacent breakers. The resulting black plant cut power to the AC motor-driven lubrication oil pumps. The emergency direct current (DC) power supply failed to operate and so the emergency DC motor-driven lubrication oil pump was not able to function. Damage subsequently occurred to the combustion turbine bearings due to lack of sufficient oil. Damage was also reported to the seals and blades.

FIRE

May 16, 2012 - UK

While operating CCTV cameras, an operative spotted a fire at this waste recycling plant. The fire is believed to have commenced in the RDF store area, and subsequently spread from the boiler house area via the conveyor system.

The return conveyor system was completely destroyed, with additional damage occurring in the RDF store and boiler house. The site was unable to run as a result.

The cause of the fire is believed to have been either ignition of materials in the hammer area, or smoldering materials delivered to the site and stored in the RDF area prior to their subsequent ignition.

MACHINERY BREAKDOWN

May 9, 2012 - Italy

This CCGT plant had a capacity of 1,000 megawatts. On the date of loss, high-exhaust temperature and vibration alarms were recorded and the machinery shut down. Borescopic inspection revealed severe damage to the power section and exhaust casing. A decision was made to open the casing.

Investigation revealed that a rotor blade in the first expander stage of the turbine had liberated. The liberated blade struck the first-stage nozzles before moving to downstream parts of the turbine, damaging all three stages and the rotor itself.

The cause was attributed to a problem where, as a result of start-up transients and vibrations, the blade-holding ring could rotate to a point where the lower end of the ring could pass below rather than above a pin. The end result would be the loosening of the blade.

The cause was agreed to by all parties, and was addressed in subsequent technical information letters (TILs).

MACHINERY BREAKDOWN

January 3, 2012 - US

Problems were first identified at this combined-cycle power plant when operators were unable to obtain the full-rated capacity of 565 megawatts. It was established that there had been a reduction in steam flow in the HP steam turbine casing.

Disassembly revealed damage to the main steam control valves, where much of the stellite valve seat material had detached and entered the turbine (domestic object damage). This caused damage to the first stage turbine blades, nozzles, diaphragms, and steam seals.

MACHINERY BREAKDOWN

November 19, 2011 - US

A 900-megawatt tandem compound steam turbine generator, located at a coal-fired generating station, suffered a catastrophic mechanical rupture with a fire following that resulted in damage to all components and almost two years of downtime.

The unit was returning from a two-month outage with an upgrade designed to increase capacity by approximately 22 megawatts.

The overhaul project included the replacement of the major components in the HP and IP turbines and upgrades to various generator components and the exciter, and the replacement of the generator step-up transformer. The unit underwent overspeed testing as part of the routine return to service testing procedures. For this test, the turbine speed is increased to more than 4,040 RPM (compared to a normal operating speed of 3,600 RPM), and the operations of the automatic steam shutoff mechanisms

are functionally tested. Operating at such high speeds imposes greater than normal stress onto the rotating elements of the turbine.

The overspeed test began on November 19, 2011. When the speed had increased to 3,960 RPM, finger-pinned blade attachments located on the next to last row (known as the L-1 row) of the low-pressure turbine ruptured. The event caused vibration that damaged many of the steam, oil, and hydrogen seals in the turbines and generator. Released oil and hydrogen caught fire and caused damage throughout the turbine area of the plant, requiring US\$7 million in clean-up costs alone. The automatic fire protection systems performed as designed and mitigated what could have been more substantial damage from the fire.

An extensive root cause investigation was performed. It found that normal operation of the LP turbine generated high-stress levels, resulting in stress corrosion cracks (SCCs) as a result of an initial design flaw at the pin holes, ledges, and at the base of the finger-pinned blade attachments which, in turn, fractured them. The fractures caused the blades to break away from their associated L-1 blade attachments, resulting in a significant imbalance and high-amplitude vibration throughout the steam turbine generator assembly. The vibration caused the fracture of the generator shaft, multiple fractures of the exciter shaft, and extensive damage to the steam turbine generator train and other plant equipment.

Extensive repair work was required to all components of the turbine generator train, including restacking the iron of the generator stator. The unit was returned to normal operations almost two years later on October 2013. This incident was described by the owner as the worst breakdown in the history of the company.

MECHANICAL BREAKDOWN

October, 17, 2011 - US

A 900-megawatt supercritical coal-fired boiler suffered a severe dry-fire incident during commissioning tests. The water walls required replacement, delaying the project by approximately 15 months, since it occurred during course of construction (COC). The insurance claim was reported in an industry publication as US\$34 million.

The overheating was caused by an inadequate water flow to the boiler. Some controls were in manual instead of automatic and this condition was not discovered until after the transition from the “day” to “afternoon” shift. By that point, the damage had been done. A contributing factor was that there were thousands of alarms coming in on distribution control system (DCS) video monitors in the control room during the commissioning, causing the level-one alarms to be lost in this cascade. This incident highlights the importance of alarm management within a modern DCS, where thousands of points of data are available for the operator.

EXPLOSION

July 11, 2011 - Cyprus

Responsible for around half of the total generating capacity in Cyprus, the largest power station on the island, the Vasilikos power station, was destroyed when explosives stored at a nearby naval base self-detonated. Thirteen people were killed in what has been described as the fourth-largest non-nuclear artificial detonation in history. This incident is also unusual in that power-generating stations are not normally damaged by external events. The station’s replacement cost was reported to be close to €1 billion, with insurance covering up to €600 million. Two government ministers resigned in the days following the explosion. Demonstrations were held in the Nicosia, which thousands of people attended.

MACHINERY BREAKDOWN May 24, 2011 – UK

It was known that the main boiler feedwater pump (MBFP) cartridge (part of the lube oil system) had worn ring seals. A seal failure occurred before a planned outage, necessitating the replacement of seals and some repair work to a thrust bearing, before the unit returned to service for a final month before the scheduled outage.

On the date of the loss, a pressure pump drive and bearing oil supply line failed, which caused damage to the rotor shaft, bearings, and impellers.

Following discussions and an investigation, which revealed a number of serious workmanship issues, repair costs were met by a contractor.

MACHINERY BREAKDOWN April 7, 2011 - United Arab Emirates

This CCGT plant had recently undergone a major outage. Following completion of the inspection, a steam turbine was returned to service and appeared to be running normally.

During the annual dependable capacity test, the steam turbine was unable to reach full load. The turbine was therefore left running at around 70% capacity.

On the date of loss, the turbine tripped. Operators observed that one of the emergency stop valves had not operated correctly. A restart, followed by shutdown, also resulted in the valve failing to close.

Upon further inspection, it was noted that the strainer had broken apart. Debris was found inside the machine and a decision was made to carry out a borescopic inspection. This revealed that the impulse chamber baffles were blocked with material. Seal strip damage and denting of the blades was also observed.

The eventual cause of the damage was ascribed to, or at least aggravated by, stellite material from the valve coating. The presence of this debris in the steam flow created abnormally high-gas flow issues and subsequent vibration. This loss served to highlight the importance of weld material dilution.

MACHINERY BREAKDOWN January 11, 2011 - US

At the time of the incident at this 1,054-megawatt gas-fired plant, the unit gas and steam turbines tripped offline, as a result of differential relay protection on the transformer. The relay trip was attributed to a failure of the transformer.

The damage to the transformer resulted in arcing and a fire that seriously damaged both the transformer and the surrounding equipment in the area.

Earlier oil tests on the transformer, which included samples taken the day before the loss, did reveal an increase in gases, which can signify a breakdown of insulation. There was general agreement that the level of such gases did not warrant removing the unit from service.

Other equipment, including the iso-phase bus, was damaged by water from fire-fighting efforts.

FLOODING August 6, 2010 - Pakistan

Water levels reached their highest point since 1929, prompting the closure of a canal that ran near the power plant in question. Following a breach in the protection dike of a nearby river, the water levels in the canal began to rise. Flood protection efforts proved unsuccessful, resulting in a serious threat of flood at this 362-megawatt plant.

Following emergency procedures, the plant was shut down.

Flood water caused serious damage to all electrical and mechanical equipment.

Transformers, pumps, electrical circuitry, paneling, insulation, compressors, switchgear, feed water pumps, and infrastructure located on the ground floor were inundated. Steam turbines and generators were not affected.

Flooding was aggravated by furnace oil and chemicals stored on site, which mingled with the flood water. All battery banks were rendered unusable. Some spare parts, held in storage, were also lost or damaged.

MACHINERY BREAKDOWN

February 10, 2010 - US

A unit was operating at approximately 150 megawatts when a lube-oil line failed, spraying oil onto the hot HP rotor casing. The oil subsequently ignited, causing the lube oil system to shut down automatically, and the rotating parts of the generator slowing to a halt with insufficient lube oil between bearings and shaft.

The loss was initially thought to be much less serious than it eventually proved to be. The HP rotor and bearings were damaged by the lack of lube oil, and while they could be repaired, the lube oil system, with related electronics and control systems, was completely destroyed. This was not unexpected. When the generator was inspected, however, it had also been run down with insufficient oil, and the rotor was deemed incapable of being repaired. A replacement rotor was therefore required.

The cause of the loss was attributed to a maintenance failure.

FIRE (INTERNAL EXPLOSION)

May 7, 2009 - UK

A CCGT station was operating at base load when a combustion flash-back occurred. The gas turbine was de-loaded to allow the emissions to be controlled and the combustion system reset. While this was being done, the operators noticed a change in rotor eccentricity, which increased until the turbine automatically shut down.

Boroscope examination revealed nothing unusual in the turbine or compressor areas. The eccentricity data indicated a possible distortion of the rotor. Necessary dismantling and inspection were carried out, which concluded that the rotor (still in the machine) showed a distortion of 0.003 inches – twice the allowable maximum allowed under OEM recommendations. Further inspection uncovered damage to part of the compressor rotor.

The failed compressor section was removed and a spare was substituted. Rebalancing was required before the rotor could be returned and installed at the site.

COLLAPSE OF RETAINING WALL

December 22, 2008 - US

A 1300-megawatt coal-fired plant suffered the collapse of a retaining wall and subsequent escape of fly ash into the surrounding area.

To control and retain fly ash and bottom ash, retention ponds were constructed in the area surrounding the plant. Ash was subsequently discharged through piping installed for that purpose. Retention lakes are divided into three layers of terracing, with ash being added at the highest elevation before becoming saturated and dropping to the bottom of the lake, then drained into a second lake, and then a third lake, prior to the water being treated and discharged.

After initial construction, the lakes were successively upgraded by adding layers of compacted clay to the retention walls – the purpose being to increase the available volume. Monitors were installed in these walls to ensure that any movement was recorded to give notice of any potential failure.

On the date of loss, the retaining wall failed and spilled ash into the nearby river system. It is estimated that some 4 million cubic meters of ash was released, causing a wave of water and ash that damaged or destroyed several residential properties and amenities in the area. More than 20 homes were evacuated in what is recorded as the largest coal-related slurry spill in the history of the US.

MACHINERY BREAKDOWN

October 21, 2008 - US

During a routine start-up procedure, a generator reached synchronization speed, but attempts to finalize the connection to the grid proved unsuccessful. Following the first attempt, the generator rotor earth fault alarm triggered. Testing revealed a ground fault, and the absence of several bolts and washers.

MACHINERY BREAKDOWN September 19, 2008 - Colombia

One of the 18-kilovolt/400-kilovolt main generating unit transformers on this site tripped while not on load. Thankfully, no personnel were nearby and no injuries caused. The repair technician who initially attended the compound discovered quantities of transformer oil on several of the walls, and also noted that the LV connection box was partially detached.

The cause of the incident was attributed to a failure of the flexible LV connection in the transformer top box.

While it was initially hoped that damage might be confined to the LV connection box alone, subsequent inspection revealed that the transformer windings were not only fouled by copper particles, but had been significantly distorted by the short circuit. Three new LV windings were required.

Repairs required a total of 212 days. The repair period was extended because the full extent of damage to the transformer took some time to establish, and there was an unwillingness to remove the transformer from the site unless there was no other alternative.

MACHINERY BREAKDOWN July 22, 2008 - UK

This coal-fired facility has a nominal output of 1,000 megawatts, generated from two steam turbo alternator sets. New rotors, of an impulse rather than the previous parsons reaction type, were fitted during 2008.

Some months after fitting, while a turbine was approaching 80% of maximum load, the abnormal expansion alarm was triggered. Two seconds later, the HP shaft position alarm also activated. Operators made the decision to manually trip the machine. The machine was dismantled in July and repairs were carried out until September.

A month later, on August 14, a similar incident took place on the other turbo alternator, although rubbing was less severe due to a less dramatic axial movement. Inspection revealed serious damage to the thrust bearing and disc.

Rubbing damage was identified on all stages of the HP turbine rotor itself. It was subsequently found that the turbine rotors had endured an axial movement of around 7 millimeters. The machine was dismantled in August and repairs were carried out until October.

The root cause of the loss was ascertained to be the failure of the thrust bearings due to an increase in thrust load level to a point that was beyond the maximum capacity of the bearing. The source of the increased thrust was identified as being the new rotors.

The return to service for the first incident was September 2008. For the second incident, it was October 2008.

MACHINERY BREAKDOWN March 18, 2008 - Italy

This gas-fired station consisting of a single-shaft set, was manufactured in 2003. On the date of the loss, technicians observed a sudden halt in the machine, which was being barred at less than 10 RPM. Several subsequent attempts to restart failed, and so the decision was made to open the gas turbine in order to identify the fault within.

The initial cause was thought to be vibration damage from a previous compressor incident, which had taken place a few months before.

MACHINERY BREAKDOWN November 16, 2007 - Italy

A gas turbine unit alarm sounded when high exhaust temperature was registered. When the turbine tripped and slowed to a halt, a high level of vibration was detected. When attempted, barring proved to be impossible to start.

Upon inspection, extensive blade damage was found to have occurred within the stator. The blades were found to have sustained several millimeters of wear and burr, as well as discoloration due to high temperatures caused by contact with the housing.

Extensive blade damage also occurred within the gas turbine itself, with all the blades described as having been reduced to a maximum of half of their original surfaces.

The cause of the loss was identified as one of the bushes, which was ripped away from the burner area and had caused impact damage to the blades. While there was no outstanding TIL, the original equipment manufacturer (OEM) had recently modified the welds used in this area to be thicker. It is postulated that the screech phenomenon, where jets produce an intense tone that can induce sonic fatigue, may also have played a part in this event.

MECHANICAL BREAKDOWN **November 6, 2007 - US**

On November 6, 2007, water tubes ruptured in boiler No. 3 at this coal-fired generating station. Three employees suffered severe burns and died shortly afterwards in hospital. The damaged boiler was shut down for nine months. The boiler, in which the failure occurred, was a 1957 water tube steam boiler, capable of producing 1,000,060 pounds of steam per hour for a turbine generating a total of 125 megawatts. The boiler was placed into service on June 8, 1958. It represented 21% of the station's typical generating output.

Three boilers located in the same generating station were shut down by the State Department of Safety on November 17, 2007, for approximately four months for inspections and repairs. In July 2008, after being off-line for nine months, boiler No. 3 returned to service. Asbestos in the boiler house, liberated by the steam explosion, complicated the investigation and repairs. No cost to repair has been reported to the author of this publication.

The tubes that ruptured were located in the dead air space – the lower vestibule area, behind where the tubes slope down to the water-filled ash hopper at the bottom of the boiler. An investigation later found that this dead air space had accumulated with ash and water (from water washing during outages) to create a corrosive environment around some tubes. Regular cyclic operation of the boiler, combined with the corrosive environment, resulted in a water-tube rupture. The rupture cut other tubes and resulted in superheated steam leaving the bottom of the boiler. The three workers who died were in the area for maintenance work.

A public report has been published by the Department of Safety that identified a lack of inspection of dead air spaces, delegation of inspections to unlicensed personnel, lack of a boiler condition assessment program, improper operating and maintenance practices, and gaps in operator actions.

MACHINERY BREAKDOWN **March 12, 2006 - UK**

This oil-fired power station consisted of three 705-megawatt turbo generator sets. On the date of loss, Unit 2 was being readied for generation and was projected to be online in the next three hours. However, a number of alarms triggered on the 400-kilovolt system during the preparatory processes, thereby tripping the boiler. After due consideration, the decision was made to continue preparations, and the unit was subsequently put online and ran at around 500 megawatts for four hours.

Further investigations into the earlier boiler trip revealed that the main generator circuit breaker for the unit had closed on two occasions, for a few fractions of a second, while the turbo-alternator was being barred. The result of such closures would be that the generator would draw power from the National Grid and would act as a motor.

Unbeknown to station operators, National Grid contractors were, at the time of the loss, engaged in work at a nearby substation. A 110-volt DC cable was being installed and, during the installation, shorted to earth. Subsequent inspection of the generator rotor revealed severe arcing damage.

This event underlines the requirement for clear communication between grid operators and plant operators.

MACHINERY BREAKDOWN November 29, 2005 - US

A rotor imbalance caused a gas turbine to trip as a result of high-turbine bearing vibration. The turbine suffered blade loss as a result.

MACHINERY BREAKDOWN October 11, 2004 - US

High vibration was detected in a unit, which subsequently tripped. Inspection revealed that damage was caused by a stationary blade in the compressor section, which had broken and moved downstream.

MACHINERY BREAKDOWN October 1, 2002 - US

An incident involving the improper sequencing of circuit breakers subsequently led to the motorization of a generator and a lubrication oil fire.

MACHINERY BREAKDOWN December 25, 1998 - Poland

Unit No. 5 at this 10-unit power station (each generating 200 megawatts) was being disconnected from the grid on December 25. Only two of three phases at a switch 20 kilometers away opened, resulting in the generator operating as a single-phase motor. The resulting imbalance of currents caused severe overheating and vibrations. Within two minutes, the turbine generator was torn apart with one shaft being hurled 250 meters outside of the turbine hall. One coupling flange flew 150 meters and hit the step-up transformer for Unit No. 2. These are solid-steel shafts that are approximately 20 centimeters to 30 centimeters in diameter, indicating the huge forces involved.

The mechanical damage resulted in the release of hydrogen and seal and lubricating oil, the latter of which ignited and caused an extensive fire. The fire did damage to the generator on Unit No. 5, and then travelled along the electrical cable tray and into the control room which was shared with Unit No. 6. There was no fire retardant sealant where the cables entered the control room, which was subsequently destroyed. Fire-fighting efforts took more than four hours.

Unit No. 5 and its foundation was a total loss. There was also damage to the roof and steel structure of the turbine hall. In addition, two new turbine rotors intended for Unit No. 3 were damaged by the fire as they had been stored, temporarily, beside Unit No. 5.

While this loss originated in Unit No. 5, it also made units 2 and 6 inoperable due to the collateral damage. Insurance industry literature reported that the machinery and fire insurance policies paid out about US\$55 million.

FIRE October 10, 1998 - UK

A fire developed in the vicinity of the 6,000-gallon lubrication oil tank. The fire spread to the turbine-generator roof, and over to the roof of the boiler house. The roofs contained bitumen-adhesive, which caused smoke to spread throughout the plant and forced an evacuation of the control room.

EXPLOSION July 28, 1998 - US

A transfer of coal caused a dust cloud to develop around the coal bunker and conveyor-tripper machine. At the same time, repeated unsuccessful attempts were made to start the coal conveyor tripper, which had recently been rewired for automatic operation. These attempts lasted for approximately 10 minutes prior to the explosion.

Investigations revealed that the control panel to the tripper was not correctly closed, which would have enabled coal dust to enter. The repeated start-up attempts likely caused a transformer to overheat and fail which, in turn, ignited the dust cloud. In addition to this initial explosion, ensuing electrical disruption at the plant also caused damage to a transformer and injured 17 workers. Repairs to the facility took six months.

MACHINERY BREAKDOWN

December 18, 1997 - UK

Days prior to this incident, maintenance work was carried out around the lubricating oil pumps of a 320-megawatt steam turbine. While this work was carried out, the AC pump was inadvertently shut down.

When the turbine was later shut down for maintenance work, the AC pump failed to operate during the slow-down period. Fortunately, the DC pump activated and the unit was run down without incident.

When the turbine was restarted after maintenance, the DC pump tripped before the rotor-driven AC pump engaged. Investigation revealed that the DC pump tripped in-line with thermal overload protection protocols. Substantial damage resulted to the high-, intermediate-, and low-pressure bearings, as well as blades and seals.

EXPLOSION

September 9, 1996 - UK

One of three 500-megawatt units suffered a last-stage blade failure, which fractured a lubricating oil pipe at the high-pressure end of the turbine. The oil ignited and fire spread to the roof, which had an external mineral felt coating. Three bays were affected, including the bus bars for the adjoining unit.

The deluge fire protection proved extremely effective at protecting the turbine, with little internal damage due to the fire being rapidly extinguished. Containment of the roof fire proved more troublesome.

Investigation revealed the blade failure was due to stress corrosion caused by improper water chemistry, citing plant design, environmental factors (the plant in question was located on a coast), and the operating mode as contributors.

The unit was returned to full service after 13 months.

EXPLOSION

September 3, 1996 - Pakistan

Extensive damage was caused to the turbine control room of the 66-megawatt Unit 2 of a 386-megawatt plant. Subsequent fire damage occurred to the remainder of the plant. No information is available as to the cause. Tragically, three workers were killed in this incident.

FIRE

June 28, 1996 - US

Hot piping ignited wooden supports that were being used for asbestos abatement in a boiler area. While the boilers were severely damaged and additional clean-up costs for the asbestos were incurred. Fortunately no injuries occurred and no asbestos entered the outside environment.

EXPLOSION

June 18, 1996 - Japan

An explosion occurred in the exhaust piping of an LNG/LPG (liquefied natural gas/liquefied petroleum gas) boiler. An investigation attributed the explosion to over-pressurization of the exhaust duct, possibly due to a system controller failure that may have arisen due to an inspection that was being carried out at the time. Unburned residual gas mixing with air during the inspection tests may also have contributed to the incident.

EXPLOSION

March 15, 1996 - US

Due to an accumulation of excess fuel, an explosion occurred during boiler start-up. The boiler, as well as the supporting structure and the building that housed it, all suffered damage. Fortunately, no injuries occurred; however, repairs took almost a year to finalize.

FIRE

April 23, 1995 - Israel

Arcing occurred in a 400-volt distribution panel at a two-unit, 140-megawatt plant. The arcing subsequently spread, leading to fire and later the explosion of a small polychlorinated biphenyl (PCB)-filled transformer. Fire subsequently spread to cabling and the control room area.

Other affected areas included the turbine and related equipment, as well as an auxiliary transformer and the control room area.

One worker died and three others were injured. PCB decontamination costs were substantial, being estimated at half the total loss. The damaged unit was out of service for approximately two years.

MECHANICAL BREAKDOWN

February 8, 1995 - US

A gas turbine generator suffered a severe mechanical breakdown and subsequent fire at a 726-megawatt gas turbine plant. The cause was related to the breaking off of a turbine blade, resulting in severe imbalance and the unit lifting off its foundation. A resulting fire caused extensive damage to the adjacent HRSG, generator, foundation, and auxiliary equipment. The sister unit was not damaged and was returned to service within two days.

The original equipment manufacturer was able to supply a replacement gas turbine from their production line and along with due diligence was able to restore the unit to full commercial operation by June 9, 1995 (after just four months), in time for the summer peak. A published report about this incident and its restoration noted repair costs of US\$43 million, which was approximately twice the replacement cost of the gas turbine.

MECHANICAL BREAKDOWN

December 3, 1993 - US

Following a seven-week maintenance outage, a 1,300-megawatt unit was brought back on-line. A low-pressure turbine blade failure caused friction on seals and a subsequent generator fire. This fire, in turn, caused a hydrogen explosion, forcing hydrogen through oil drain lines and causing yet another explosion.

Repairs took four months.

VEHICLE COLLISION

November 30, 1993 - US

An 82-ton gas turbine was struck and destroyed by a train at a rail crossing. Plant start-up was delayed by around six months, while a new turbine was obtained.

STRUCTURAL COLLAPSE

November 14, 1993 - US

After an 800-megawatt lignite-fired unit was shut down for maintenance, workers were faced with the task of cleaning the 200-meter-high chimney. While undertaking this task, the chimney collapsed without warning. One worker was killed and four were injured. Damage to the nearby machinery was extensive.

The cause of the collapse was not publicized. Repairs and restoration took 20 months to complete.

EXPLOSION

August 11, 1993 - US

A pulverized coal-fired boiler, hung from a 271-foot-high structural, was in the process of providing steam to an 842-megawatt turbine, which was under full load.

At this time, flooding in the Mississippi area contributed to coal shortages and a blending of coal from the plant's stockpiles. Concurrent issues with the ash-handling systems resulted in a substantial build-up of ash in the slope tubes. The mass of ash caused the slope tube supports to fail, subsequently affecting the water wall tubes and causing the furnace to over-pressurize. Molten ash erupted from the furnace breach and caused some minor fires. Fortunately, no one was injured.

Repairs took six months.

FIRE

August 11, 1993 - Germany

A fire occurred in one of four rubber-lined scrubber towers, causing flames 30 to 50 meters high. Rapid spread of fire severely damaged three scrubbers and caused minor damage to the fourth.

FIRE

June 9, 1993 - US

A serious coal-conveyor fire occurred, which spread rapidly. The automatic fire protection system required manual activation due to the fact that it was offline and awaiting replacement parts. While no coal was on the conveyor line at the time of the fire, heavy smoke meant workers were unable to access the manual controls. The reconstruction period and return to full operation was finalized in one month.

FIRE

March 18, 1993 - US

A serious electrical fault occurred in a 345-kilovolt main step-up transformer at this 1,200-megawatt gas and oil-fuelled plant. Oil erupted from the transformer and ignited, spreading fire to liquid propane cylinders in the nearby welding shop.

The fire spread via a 40-meter air-cooled bus-duct system to the turbine building, where hydrogen from the generator contributed to the spread of the fire. Smoke and heat damaged the roof structure, as well as equipment in the building, and trapped 12 workers in the control room. Fortunately, the fire rescue services freed the 12 workers, and no injuries were suffered to those involved.

Some two hours after the fire started, the diesel fire pump failed due to an instrument malfunction attributed to the fire.

Some 200,000 meters of cabling required replacing, along with 70 tons of structural steel. Restoration took nine months.

MACHINERY BREAKDOWN/WEATHER

December 25, 1992 - US

While the cause of this fire is unknown, it is surmised that a lubrication oil pipe serving a 14-megawatt steam turbine failed. Oil in the six-inch pipe was pressurized at 170-180 pounds per square inch (psi), and was rapidly discharged. It is suspected that a shutdown of the plant for several days due to freezing weather conditions prior to the loss may have affected the non-metallic couplings on the lubrication oil lines.

Although the plant was fitted with a partial automatic sprinkler system to protect the area in question, it did not operate due to a closed valve. Plant personnel had shut down the system because earlier heat build-up — due to non-operation of exhaust fans — had triggered at least one sprinkler head on an earlier occasion. No notification that the sprinkler system was offline was given to the fire department. The lift truck required to reach the ceiling to reactivate the sprinkler system was also out of service.

The fire was reported by a nearby pilot and a motorist. Three workers who were trapped in the second floor control room were killed. The plant was out of service for a total of 266 days.

EXPLOSION

November 23, 1992 - Africa

A supplier accidentally delivered condensate-contaminated natural gas to a generating plant. The resulting explosion shut down all six steam turbine generators for one month, cutting 50% of the normal electricity supply to a large nearby city, prompting notices of apology in the local media.

FIRE

February 26, 1992 - South America

Maintenance on a defective oil lubrication thermometer was carried out while the affiliated 125-megawatt turbine remained in operation. As a result of procedures being incorrectly followed, pressurized lubrication oil was released and ignited by an unknown source — possibly an electric light or hot panel.

Roughly 2,600 gallons of lubrication oil were consumed in a fire that spread rapidly, destroying cabling and eventually causing six bays of the turbine hall roof to collapse onto the generating equipment underneath. Seawater cooling pipes were severed, causing flooding to the lower areas of the building. One turbine generator was badly damaged; others fortunately suffered only minor damage.

The badly damaged unit was out of service for 18 months.

EXPLOSION

February 15, 1992 - Germany

The facility had recently been retrofitted to meet new environmental regulations for the control of nitrogen oxide. Gas explosions, caused by a buildup of fuel that failed to ignite due to lack of flame, damaged boiler piping and a nearby generator. The flame detection alarm failed to activate for unknown reasons. Repairs took four months.

FIRE

November 15, 1991 – US

A 250-megawatt turbine was returning to service after a two-week maintenance outage when an oil filter “O” ring failed. Roughly 500 gallons of oil erupted, which was subsequently ignited by contact with a steam line, spreading fire to cabling trays and subsequently to the control room. The fire passed through several openings that were not fitted with fire stops. Rapid smoke accumulation forced control room evacuation in less than 60 seconds. The restoration of more than 150 miles of cabling, and extensive structural work to the mezzanine flooring, along with the complete replacement of the control room, took a workforce of more than 750 workers six months to complete.

FIRE

November 5, 1991 - Pacific Rim

Both 138-megawatt steam turbines at this facility were operating near full load at a combine-cycle facility when an oil strainer on Unit 1 suffered a crack. Lubrication oil at approximately 120 PSI erupted onto a hot turbine casing and ignited. While the unit was immediately shut down, the shaft-driven lubrication oil pump continued to spray some 1,300 gallons of oil during the run-down. The subsequent fire quickly spread to the roof area.

Employee egress and firefighting efforts were hampered by heavy smoke. The ventilation system also pumped smoke into the control room area. One employee, who was unable to escape from the control room, was killed. Two other workers were injured.

STRUCTURAL COLLAPSE

July 2, 1991 – US

A 480-megawatt coal-fired plant suffered a collapse of two circulating water lines. The lines were around three meters in diameter, eight meters below the surface, and were approximately 30 years old. Buildings undermined by the collapse included a fly-ash silo, blower house, two water storage units, and one ammonia tank and duct work.

An investigation concluded that the pipes collapsed due to inadequate compaction of soil when the pipes were installed. This situation was aggravated by soil liquefaction following recent piling work.

One unit returned to service after five months, the other took six months.

FIRE

July 28, 1990 - US

An electrical fire in a 12-kilovolt switch house, thought to be caused by the failure of an auxiliary relay to open a circuit breaker, interrupted power to approximately 40,000 customers for periods varying between 90 minutes and three days.

Restoration efforts led to a second event eight days later at a nearby substation, resulting in a further 12-hour outage for 25,000 customers. In addition to equipment loss, the utility incurred substantial costs in food spoilage compensation payments.

EXPLOSION

September 26, 1989 - South America

A boiler was returning to service when a burner suffered a flame-out. Natural gas accumulated, leading to an explosion that severely damaged the boiler and related tubing.

FIRE

August 4, 1989 - Denmark

Arcing in 4-kilovolt switchgear blew out a cable penetration seal on the floor and caused cable tray fires. Five tons of PVC cable jacket were destroyed in a fire that lasted 10 hours. The manually controlled fire system could not be accessed. Hydrochloric acid damage from the smoke caused a total loss to the entire five-story control building.

FIRE

March 6, 1989 - US

A 37-year-old generating plant, which had received life extension improvements, caught fire while being brought online. The failure of an oil line caused a fire that spread to other lines. The emergency lubrication oil drainage system failed to function, and some 3,300 gallons of oil were consumed in about 45 minutes.

The equipment sustained severe heat and smoke damage; however, roof damage was averted by windows and louvers. No fixed fire suppression systems were in place, as they had not been upgraded commensurately with the plant's other systems. Total downtime for all units affected was 339 days.

FIRE

May 9, 1988 - US

Failure to follow procedures led an operator to attempt a hydrogen-seal oil filter service, while the system was pressurized at between 75 PSI and 90 PSI. As a result, oil erupted onto a hot surface and ignited. While automatic sprinklers were installed at the plant, they did not cover the affected area. The generator incurred severe damage, as did the iso-phase bus ducts and parts of the roof structure.

FIRE

February 25, 1988 - US

A pressurized lubrication oil line ruptured, and subsequent vibration caused a steam line to rupture while the unit ran down. Steam escaped from the line and ignited the oil vapor, causing a fire that damaged cables, structural steel, and concrete.

A fire protection system and a plant-based firefighting team extinguished the fire, but not until after the unit and an adjacent unit had been damaged.

STRUCTURAL COLLAPSE

November 5, 1987 - US

Six ash collection hoppers fell some 10 meters to the floor, spilling around 500 tons of fly-ash and causing some minor fires. Equipment from an adjacent unit was used by contractors who, by working 24 hours a day, restored the 1,300-megawatt unit to service in 90 days. Had this equipment not been on site, the downtime would likely have increased substantially.

FIRE

February 16, 1987 - US

A blade failure in a low-pressure turbine ruptured a lubrication oil line. Oil ignited, damaging cabling below the unit, as well as the turbine bearings, before the fire spread through unprotected wall openings to the burner management room and control room.

FIRE

January 7, 1987 - Germany

Hot sparks from welding work being done on an absorber tower caused a fire, which spread to nearby plastic materials. Heavy smoke exacerbated the difficulties faced by firefighters, and two other absorber towers were damaged by the products of combustion. Damaged steel had to be melted for recycling purposes, and extensive wash-down, sandblasting, and resealing was needed, setting the project back two years.

EXPLOSION

November 18, 1986 - US

A severe explosion split the seams on a boiler, creating a hole some three-meters-by-four-meters in size. Since the accident took place during a change of shift, no injuries occurred, and damage to other equipment was minimal. Despite this, the plant was out of service for a year.

TORNADO

July 28, 1986 - US

A tornado destroyed coal-handling equipment, a switchyard, and a turbine-generator roof. Ten company vehicles were also destroyed.

FLOOD

November 4, 1985 - US

Severe rainfall caused a nearby river to rise some four meters, damaging property, equipment, and supplies, as well as roadways, warehousing, and other structures.

MACHINERY BREAKDOWN

June 9, 1985 - US

A rupture in a 30-inch reheat pipe adjacent to the plant lunch area released steam at 600 PSI. A weld failure was identified subsequently. The unit was out of service for six months, and six people lost their lives.

NUCLEAR POWER PLANTS

Nuclear power involves the use of exothermic processes to generate heat, and then electricity.

Lauded as the only viable, long-term future of power generation by some observers, and faulted as a costly and unpredictable source of environmental catastrophe by others, nuclear power generation is a highly contentious issue, where strong opinions are not only advocated but reflect almost every possible viewpoint.

Although many people would acknowledge the benefits of nuclear power, incidents such as Three Mile Island, Chernobyl, and Fukushima have ingrained a fear of the consequences of nuclear accidents into public consciousness. The advantages of nuclear power — low carbon and smoke emissions, base-load reliability, low mass of fuel, and small waste volume — are counter-balanced by the immense costs of waste disposal, decommissioning, and the fear of a planet-changing nuclear accident.

The deep divisions and inconsistencies regarding the future of nuclear power generation, at both national and global levels, were addressed in the *Marsh Risk Management Research* report, *Common Causes of Large Losses in the Global Power Industry*.

The following are examples of some losses that have involved nuclear power plants over the last 28 years:

CAUSE UNKNOWN January 31, 2014 - UK

Non-essential staff at this facility were told not to come to the site after elevated levels of radiation were detected. The levels were described as being above what would be expected in a natural occurrence, but too low for any actions to be taken by the workforce. No interruptions to site operations were reported.

FIRE March 31, 2013 - US

A transformer explosion at a nearby switchyard resulted in a reactor shutdown at this facility. No radiation release occurred, and the reactor shutdown took place in the prescribed manner. Onsite standby diesel generators performed their intended role of supplying essential services to the reactor. Other generating stations provided power to the grid to make up for the loss of generation from the nuclear station. No injuries occurred at either the plant or the switchyard.

MACHINERY BREAKDOWN March 31, 2013 - US

An attempt to move a main turbine generator stator, weighing some 500 tons, ended in tragedy with the death of one employee and injuries to eight others. The cause of the incident was a crane, which collapsed while the stator was being moved. The falling stator damaged a water pipe, causing a consequent leak that affected other nearby equipment.

The reactor unit itself was down for a planned refueling outage at the time of the incident. A notification of an unusual event was filed, being the lowest of four possible emergency classifications permitted by the Nuclear Regulatory Commission.

The impact and damage caused by the falling stator resulted in the sister reactor, Unit No. 2, being forced off-line for more than a month.

The scheduled outage for Unit No. 1 was extended from the scheduled one month to four months. The damage to the stator was of little consequence, as it was scheduled for replacement with a new stator that was on site.

The owner reported property damage losses of in the range of US\$130 million to US\$215 million.

EARTHQUAKE/Tsunami

March 11, 2011 - Japan

The Fukushima Daiichi plant was seriously damaged by a tsunami, which struck the East coast of Japan. The plant remains closed off and an exclusion zone is in place in the surrounding area.

Failure can be ascribed to a loss of reactor coolant, which took place due to a lack of power to pumping systems when the backup generator supplies (located in the basement area) became flooded with seawater.

Three of the six units, all boiling water reactors, at this nuclear site underwent nuclear fuel meltdowns following site devastation from the massive tsunami. At the time of the incident, units 1 to 3 were on-line, while units 4, 5, and 6 were on scheduled shutdowns. As with all nuclear power sites, there are multiple back-up generators to provide power for critical control and reactor cooling systems.

The Tohoku earthquake struck off the coast of Japan, causing extensive damage to the island. The earthquake was stronger than the design rating of the nuclear power station was capable of withstanding, but initial indications noted that there was no damage to the station.

Immediately after the earthquake, the three operating reactors automatically shut down using control rods. Even in such a state, the reactor will still produce enough heat to require active circulation of cooling water to maintain safe reactor temperature. The back-up generators started in accordance to normal procedures to circulate cooling water for this purpose.

A major tsunami arrived approximately 50 minutes after the initial earthquake. The wave, at 14 meters high, overwhelmed the 10 meter-high seawall and flooded the low-lying rooms that contained the units 1 to 4 back-up generators and associated switching equipment, causing them to trip off-line or otherwise be unable to connect to the reactors. Design differences for the back-up generators for units 5 and 6 prevented similar damage. Since the grid supply to the station had been disrupted by the earthquake, the only supply to operate the essential reactor cooling water pumps was the battery supply, which

was only meant for a few hours of operation. Thus, the following day, the active cooling systems stopped, some reactor control instruments failed, and the reactors began to overheat.

Hydrogen gas developed within the reactor buildings leading to explosions in the upper secondary containment buildings 1, 3, and 4. Numerous efforts were made to provide alternative power or cooling to the reactor cores, although with limited effect, and the end result was overheating and melting of the core in reactors 1 to 3. It will take years to clean up the reactors and dismantle them.

The events at units 1, 2, and 3 have been classified as Level 5 (the most serious level) on the International Nuclear Event Scale. Events at Unit 4 were classified as Level 4. The event, as a whole, was classified as Level 7 on the scale (one of two events, the other being the Chernobyl incident referenced below), indicating a major release of radioactive material, with widespread environmental and health effects that required the implementation of planned and extended countermeasures.

MACHINERY BREAKDOWN

July 28, 2006 - UK

This station consisted of two Magnox reactors and four turbo-alternator sets. Cross-over steam pipes served to allow any of the turbo-alternators to be supplied by either reactor.

As part of the steam system, two steam pipes ran for several hundred meters from the reactor building to the turbine hall.

At the time of the loss, two turbo-alternators were being returned to service following an outage at one of the reactors. The steam pipes were being warmed in preparation for load. A loud bang was heard by control-room staff, and vibration was reported by others in the turbine hall. The output from one of the turbo-alternators fell rapidly from 200 megawatts to 0 megawatts in short order.

Inspection revealed that several pipe supports were damaged, and that 50% had failed completely. Cable ducts and cool water pipework, which provided sea water to bearing coolers, were also damaged. Deformation of the main steam pipes was also reported.

The cause of the incident related to a change in steam trap configuration that was undertaken as part of the reactor outage works. Normally, steam traps are opened in order to warm the pipe prior to admitting steam from the boilers. Only one of the three steam traps operated correctly. As a result, condensate accumulated in the steam pipe, which was pushed through the system into the steam receiver, causing some of the condensate to flash off into steam and reduce pressure. A water/steam hammer event was then responsible for the damage to the pipework and supports.

MACHINERY BREAKDOWN **January 30, 2005 - UK**

This plant had two 660-megawatt turbo-alternators. At the time of the loss, staff in the control room reported feeling significant vibration. A number of alarms also registered, and the set was manually tripped. Moments later, the chloride ingress alarm activated. The unit proceeded to run down as normal and was put on barring.

Subsequent dismantling and inspection revealed that a blade was missing. Damage to adjacent blades was reported, with tip damage to all the remaining blades. Other equipment affected included the diaphragm, diffuser, bearings, and condenser tubing. Repairs took four months.

HIGH WINDS **January 8, 2005 - UK**

Storms caused damage to more than 350 different parts of this combined heat and power plant. Many of the buildings that were most seriously affected were used for procedures involving radioactive material, potentially causing health and safety problems, and a significant increase above the normal cost of rectifying buildings after an event of this nature.

Further issues arose when necessary repairs took place, including the replacement of parts of the roof that covered exposed nuclear facilities. Some of the buildings in question were also of significant height making access problematic. At an early stage in the process, the insured expressed its intention to substantially upgrade several of the buildings at the facility, requiring the loss adjuster to address betterment issues and redesign costs as part of the indemnifiable loss calculation.

MACHINERY BREAKDOWN **March 18, 2004 - UK**

At the time of loss, the machinery at this plant consisted of a number of turbo alternator sets, each comprising a HP steam turbine and three LP steam turbines. The generator subsequently provided power to a transformer, rated at 340 megavolt amperes (MVA), at 17,500 volts, which stepped up the voltage to 145,000 volts.

Plant operators heard a loud bang, and the subsequent automatic engagement of the “main protection operated” alarm. This electrical protection consequently tripped the turbine. As a result, main control room staff made the decision to manually trip one of the reactors.

Once the inspection covers on top of the transformer had been removed, it was discovered that the top of the main section of laminations, including the transformer core, were covered by debris that included winding tape and molten copper.

While the root cause of the failure proved difficult to determine due to the level of damage, it was agreed that the most likely cause was that a turn-to-turn failure had occurred within the transformer winding, which had, in turn, been caused by an insulation failure.

MACHINERY BREAKDOWN **March 13, 1998 - Spain**

Localized burning caused a ground fault in a stator winding, with subsequent damage to the generator of a 1,066-megawatt unit. A suitable replacement was available, and the unit returned to service after a period of 86 days.

MACHINERY BREAKDOWN October 8, 1995 - Canada

A 750-megawatt CANada Deuterium Uranium (CANDU) nuclear reactor was permanently shut down due to the contamination of a steam generator. In 1986, maintenance workers inadvertently left a protective lead blanket in the steam generator of the reactor. When the mistake was discovered six years later, the blanket had melted, severely damaging the boiler. Repairs were considered too expensive, so the reactor was eventually shut down. However, it was later returned to service, along with its sister reactor, after a major refurbishment.

This massive project, the largest in Canada at the time and the most complex engineering challenge ever in Ontario, included replacing all of the steam generators, thereby eliminating the damage done by the blanket. The unit returned to service in 2012. This event highlights the importance of a robust foreign material exclusion (FME) program, especially during outages.

FIRE May 23, 1996 - US

A wooden cooling tower, which was idle at the time, was destroyed by a fire. The cause of the fire was not established.

MACHINERY BREAKDOWN December 25, 1993 - US

A 1,154-megawatt turbine, operating at 93%, was affected by an incident that increased unit vibration from 10 mils to 500 mils in 1.5 seconds. Multiple alarms were triggered, and the turbine slowed from 1,800 RPM to rest in roughly four minutes.

Vibrations in the control room were very severe and delayed operator actions.

Five last-stage blades (LSBs or L-0s) on the LP rotors broke away from the turbine, with one penetrating the turbine housing. It was later retrieved from a walkway, approximately 20 meters above the turbine. It weighed more than 20 kilograms. Five additional blades were badly damaged.

The generator seals were damaged, allowing a hydrogen leak, which ignited and caused several small fires. The fires were controlled by the plant fire brigade using portable fire extinguishers. The automatic sprinklers installed below the turbine were also credited with controlling the fires. In addition, four of the 26 roof-mounted smoke and heat vents opened automatically to release smoke and steam.

One or more of the detached blades penetrated the condenser, allowing lake water to enter the building and flood the basement area with some 17,000 gallons of lubrication and seal oil, together with 1.5 million gallons of lake water.

The severe imbalance caused damage to the complete turbine train, including the exciter, turbine rotor, and diaphragms, which subsequently required an extensive turbine overhaul and the replacement of 5,000 condenser tubes. There was little generator damage and no structural damage. The unit was restarted after one year. Fortunately, no injuries occurred to personnel on site, and there was no impact to the general public.

Identifying the cause proved problematic; however, high-cycle metal fatigue, exacerbated by excess moisture on turbine blades, may have contributed to the incident.

MACHINERY BREAKDOWN **March 31, 1993 - India**

Damage to turbine-generator seals was caused by vibration resulting from blade failure. The seals subsequently released hydrogen, which ignited and ruptured fuel and oil lines. There were no fire suppression systems or barriers on site, and cables regulating safety systems ran through the affected area, but were not separated or otherwise protected.

A pressurized heavy water reactor at the plant was operating at 190-megawatts at the time of the event. Noting that the turbine-generator had tripped, control room operators manually tripped the pressurized water reactor. Boron was added to the reactor to maintain sub-criticality.

All power, including emergency diesel generation, was lost for 17 hours adversely affecting the primary and secondary decay heat-removal systems. A fire pump was used for firefighting and emergency cooling.

Full restoration took 21 months. Fortunately, there were no injuries and no release of radioactive material occurred.

FIRE **August 24, 1992 - France**

Hydrogen leakage from a stator was subsequently ignited by an electrical fault. A secondary fire fueled by lubrication oil then occurred. Firefighting was made more difficult by controls being located in the fire area.

The generator required replacement. Service was restored after 133 days.

HURRICANE ANDREW **August 24, 1992 - US**

The eye of Hurricane Andrew — a Category 4 hurricane with winds estimated at 145 mph and gusts of 200 mph — passed over a plant with two nuclear and two oil-fired units. Despite extensive damage to the site, the nuclear units were fairly undamaged.

One nuclear unit was returned to service on October 23. The other nuclear unit, which had just begun a 53-day refueling outage, came back on-line on December 4.

MACHINERY BREAKDOWN **November 9, 1991 - US**

A routine test procedure to confirm the operational status of automatic trip devices was undertaken. During the test, a momentary oil pressure drop in the auto-stop oil system was sufficient to open the auto-stop oil interface valve. As a result, the emergency trip fluid system activated and caused the steam turbine admission valves to close, isolating steam flow to both high- and low-pressure turbines.

All load resistance had been removed from the turbine when the main generator was taken off the grid. Since both the auto-stop oil system and emergency fluid trip control valve failed to function correctly, steam was readmitted to the turbine. As a result of a combination of these circumstances, the turbine entered an over-speed condition, reaching approximately 2,900 RPM (normal speed was 1,800 RPM). Several blades then detached from the rotor, causing vibration and the subsequent rupture of generator hydrogen seals and oil lines. The oil and hydrogen then ignited.

The fire was caused by the failure of backup emergency and over-speed trip devices, due to mechanical binding of the three solenoid valves. The unit was returned to service after five months.

FIRE **October 10, 1991 - Ukraine**

Repairs to a turbine were under way when a circuit breaker closed and reconnected the generator of a 925-megawatt unit to the grid. The generator then acted as a motor. Over-current cables melted and a hydrogen-leak from the generator ignited. Fire spread to the bitumen in the roofing. A 50-by-50-meter section of the roof and four supporting columns collapsed onto the machinery underneath. The government decided not to rebuild the unit.

MACHINERY BREAKDOWN

March 18, 1991 - US

An auxiliary boiler was supplying heat and hot water to the plant during a scheduled maintenance outage period. During this time, radioactive material from a liquid waste evaporator entered the boiler via a steam coil. Low-level radioactive material was subsequently released by excess steam via a boiler vent.

The material was deposited on the grounds and buildings of the site. Due to rainfall, some 10,000 gallons of contaminated water were routed to a nearby lake by the storm drainage system. Contamination levels at the vent averaged 10 millirems — comparable to a normal chest x-ray.

A full radiological assessment concluded that no release reached the atmosphere or general area. A temporary replacement boiler was used until a permanent new boiler could be installed. Decontamination efforts of pipework and buildings were extensive.

MACHINERY BREAKDOWN

February 6, 1991 - Japan

A steam generator was operating at 500 megawatts when a tube ruptured and allowed radioactive primary coolant to flow into the secondary system. Attempts to manually trip the reactor were superseded by an automatic trip. The emergency cooling system activated and worked as intended. While the incident occurred, however, a main steam isolation valve needed to be manually closed by an operator after automatic closing methods failed to function. Two pressure relief valves also failed to open. Steam relief valves in the B-steam generator were used to cool the primary system.

Cause was attributed to tube fatigue resulting from the improper installation of anti-vibration bars when the steam generator was assembled some 20 years before. The plant was shut down for three and a half years.

FIRE

October 19, 1989 - Spain

A lubrication oil line ruptured as a result of turbine vibration. A lack of bearing oil led, in turn, to a hydrogen explosion and oil fire. Emergency cooling and heat exchange systems were put out of action; however, no release of radioactive material occurred. Water also flooded the reactor and turbine buildings when a condenser seal was ruined by the fire.

The International Nuclear Event Scale (since 1990, known as the International Nuclear and Radiological Event Scale [INES]) registered this incident as Level 3, due to the safety of the reactor area having been threatened. The 17-year-old plant was removed from commercial operation.

MACHINERY BREAKDOWN

May, 1989 - US

Metal flakes, left behind from works done to the thermal shield wall two years previously, caused damage to fuel rods and assemblies. This damage put the plant out of service for a year.

MACHINERY BREAKDOWN

March 17, 1989 - US

Fracturing of reactor vessel thermal shields occurred which, having been deemed unnecessary, were removed and sent to a suitable waste disposal plant. Contamination and precautions for work in a radioactive area significantly complicated this undertaking.

FIRE

May 10, 1986 - US

A fire, believed to be electrical, destroyed an idle cooling tower. No sprinkler systems were fitted.

CHERNOBYL April 26, 1986 - Ukraine

This is generally believed to be the worst nuclear power plant incident ever to have occurred, and one of only two incidents (the other being the Fukushima Daiichi loss referenced previously) to have been classified as a Level 7 on the International Nuclear and Radiological Event Scale.

A test procedure was being undertaken at the plant to test the theoretical possibility that rotational energy from the steam turbine could be harnessed to power cooling pumps for the roughly 60-second period following a SCRAM (emergency reactor shutdown) event that would be required to start back-up generators.

The full details of the loss are known only from evidence-based supposition and mathematical theory. It is known that a power surge occurred, most likely due to the initial insertion of graphite rod tips that caused a jump in power levels. The criticality event — an uncontrolled nuclear reaction — caused a massive and rapid increase in steam pressure within the coolant pipes. A steam explosion subsequently occurred. At that point, the fuel cladding failed and fuel was released into the coolant.

The nominal output of Reactor 4 was 3,200 megawatts. The last recorded reading on the control panel was 33,000 megawatts. For comparison, the average reading for consumption on the UK National Grid varies between 25 megawatts and 40,000 megawatts. The temperature of the melting reactor fuel increased to levels in excess of 2,000 °C.

The resulting steam explosion launched the approximately 2,000-ton steel plate, which acted as the clasp for the reactor assembly, through the roof of the building. In addition, a sizeable percentage of the reactor core material was released into the surrounding environment. The official death toll at the plant of 31 people has been the subject of prolonged debate. The World Health Organization estimated that additional deaths from cancer stand at around 4,000 people. The cities of Chernobyl and Pripyat, with their combined populations of more than 60,000 people, were permanently evacuated, and an exclusion zone of nearly 20 miles was enforced around the plant.

The steam explosion exposed graphite inside the reactor, which subsequently ignited. The resulting fire spread radioactive contamination over much of Europe and the (former) Soviet Union. Radiation levels in the Reactor 4 building were measured at some 20,000 roentgens per hour — more than 40 times what would normally be considered a lethal dose for a human.

The total number of evacuees from contaminated areas over the next decade is estimated in excess of 300,000. Mutations of both animals and plant-life were widely reported.

A 20,000-ton steel case called the New Safe Confinement (designed as a permanent containment structure for the whole plant) is under construction. Following numerous delays and setbacks, it is now scheduled for completion in 2015.

MACHINERY BREAKDOWN November 21, 1985 - US

A reserve auxiliary transformer tripped, cutting power to one feed water pump and two condensate pumps. A transient electrical fault in the condensate system ruptured the flash evaporator shell. A water hammer — a surge that occurs when moving fluid is suddenly forced to change its direction of flow — occurred in the main feed water line to the steam generator, causing damage to piping and valves.

MACHINERY BREAKDOWN July 7, 1985 - Taiwan

Torsional vibration in a turbine resulted in eight blades in the low-pressure turbine being liberated. The resultant vibration in the unit caused the generator seal oil lines to fail and the oil to catch fire. A manual carbon dioxide fire suppression system was activated but did not operate, and there were no fire suppression systems beneath the operating floor area.

The resulting fire took over two hours to extinguish and required that the 900-megawatt turbine generator be replaced, which took more than 14 months.

MACHINERY BREAKDOWN

March 25, 1983 - US

During an outage period, it was found that damage had occurred to a thermal shield wall within a reactor vessel. The core barrel was also damaged after loose positioning pins caused cracks.

The cause of the loss was high-cycle and loss-stress fatigue cracking. The plant was out of service for 450 days.

LOSSES IN OTHER TYPES OF FACILITIES

HYDROELECTRIC-GENERATING FACILITIES

EXPLOSION

August 26, 2013 - US

This 325-kilovolt, three-phase step-up transformer was five years old at the time of the loss, and was one of four transformers on site. At the time of loss, the transformer suffered an internal fault and resulting explosion while it was in the process of being synchronized with the grid.

At the time of explosion, the transformer was operating at an estimated 50 megawatts. Two days prior to the incident, both the Bucholz Relay and the Kelman Transfix UNITS had registered concerns with the dissolved gas analysis test results. Oil samples provided to third-party testers confirmed the presence of gases indicative of an internal fault.

The transformer suffered damage to the windings and significant casing deformation.

FLOODING

June 14-17, 2013 - India

Flash-flooding caused serious equipment damage at several facilities in India.

MACHINERY BREAKDOWN

October 14, 2012 - Australia

This station had two hydroelectric units, each consisting of a 30-megawatt, turbine-driven generator. On the date of loss, one transformer had recently been tested and reserviced before being reconnected to the 132-kilovolt local grid. Despite being connected to the grid, however, the transformer was not under load.

The control center registered a number of alarms, and a technician who subsequently visited the site noticed dark smoke above the transformer area.

Firefighting efforts were limited to water from hydrants only, to comply with environmental restrictions. No injuries or river contamination were reported.

Investigation revealed serious electrical damage to earth windings across a range of high-voltage circuitry. The most likely cause was identified as a short circuit in a cable-connection box, with the resulting increase in internal pressure causing a release of oil and damage to ceramic bushings. The oil within ignited due to arcing, with the subsequent fire destroying the transformer and surrounding plant.

STRUCTURAL FAILURE

August 7, 2010 - Panama

Some 19 months of repairs were required after damage was discovered inside sections of the headrace tunnel at this facility, following incongruities discovered in both water pressure and megawatt output.

Initial dewatering of the tunnel revealed large quantities of debris had fallen from various areas. Repair works were slowed by the necessity of safeguarding workers by reinforcing the tunnel structure in five-meter intervals while clearing progressed.

MACHINERY BREAKDOWN

August 17, 2009 - Russia

A total of 75 people were killed and an entire 6,400-megawatt facility was rendered inoperable following a catastrophic event. The cause of the event has been the subject of much speculation and many public statements, but can be summarized as a catalogue of serious management failures. The official report blamed a parts failure caused by fatigue, resulting from excessive turbine vibration.

Numerous safety failures and breaches were noted by the subsequent investigation. An estimated 30 tons of transformer oil was released into the water system. Repair workers, working 24 hours a day, took more than two years to complete the restoration. The director of the plant was replaced after the event.

The initial event tore the entire turbine generator set from its foundation. Water then poured into the turbine hall, trapping workers in their offices, pushing transformers off their foundations, and causing various levels of damage to the remaining nine units in the turbine hall. A large portion of the turbine hall roof and walls also collapsed.

FLOODING

June 21, 2007 - US

This 15-megawatt hydroelectric generating facility used two penstocks to deliver water to two turbines. Following the loss event, which involved a penstock failure, extensive damage occurred to both controls and electrical equipment, requiring the generators to be rewound. Two nearby substations also suffered damage, including the loss of two transformers. Buildings, notably roofing areas, required repair and storage rooms were flooded. Repairs took approximately 15 months to complete.

STRUCTURAL DAMAGE

December 14, 2005 - US

The wall of the upper reservoir of this pumped-storage structure failed catastrophically, releasing an estimated 1.25 million gallons of water into the adjacent parkland and local river system.

The cause was ascribed to inaccurate data readings, which meant that the upper reservoir continued to have water pumped to it even though it was full. The lack of any overflow spillway was also held to have contributed to the collapse.

Full restoration of the structure and water-storage systems required five years of work. Miraculously, no one was killed in this event.

STRUCTURAL

December 12, 2000 - Switzerland

A penstock rupture, between five and ten meters in length, left this facility unable to function for nearly a decade, while redesign and repair works took place. The water, which escaped from the penstock, caused three deaths, as well as extensive damage to local facilities and orchards.

The cause of loss is thought to have been related to a low level of strength in the surrounding rock, combined with a flow rate that may have been in excess of the rated design.

FIRE

March 21, 1997 - Portugal

An unattended hydroelectric station suffered a fire in a control cabinet. An alarm was triggered and an employee was sent to investigate. The employee attempted to extinguish the fire with hand-held equipment, but did not succeed.

Having failed to extinguish the fire, the employee contacted the local volunteer fire brigade. By this time the fire had progressed to plant cabling. The fire brigade made several attempts to enter the plant, but were unable to do so. The fire took more than seven hours to eventually extinguish.

Cabling, monitoring equipment, and the control room were damaged. PVC insulation on the plant cabling was blamed for the spread of the fire. Corrosive soot and smoke required extensive cleaning and decontamination.

One generating group returned to service in nine months. The other two groups took one year to return to service.

HYDROELECTRIC GENERATING FACILITY AND SURROUNDING GAS AND ELECTRICITY UTILITY SYSTEM

FLOODING

December 22, 1996 - US

Two weeks of winter snow accumulation in the mountains was followed by a period of warm temperatures and rainfall. Soil saturation and run-off combined to create a landslide, which inundated a hydroelectric generating station to a level of two meters above the operation deck. Return to service required more than two years of work.

More than 120,000 customers were left without power, and approximately 900 employees were engaged in the repair efforts. Blocked roads required helicopters to be used to spot damage. In several areas, workers had to physically hike and carry tools, and replace wires and poles by hand to effect repairs.

FIRE

February 8, 1996 - Switzerland

A malfunctioning overload switch caused a fire, which spread to all four units of this facility. All capacity was closed down, affecting electricity supply to a major city.

TRANSMISSION STATIONS

MACHINERY BREAKDOWN

Converter Station - March 20, 2012 - US

One of seven identical transformers, manufactured 36 years previously, suffered severe damage as the result of an internal explosion. The transformers stepped up voltage from a nearby hydroelectric plant from 115 and 230 kilovolts to 735 kilovolts for transmission. The transformer was located at a substation — no other nearby equipment was affected and no damage was sustained by the grid.

The subsequent cause of loss investigation revealed that an internal part of the transformer concerned had degraded over time, eventually failing and causing internal arcing. The transformer grounded itself, resulting in internal damage and damage to the external casing. Approximately 1,000 gallons of oil was successfully contained by the concrete structure in which the transformers were housed. The remaining oil was later removed by a tanker vehicle.

EARTHQUAKE

Natural Gas T&D System - January 17, 1995 - Japan

An earthquake measuring 6.8 on the MMS killed more than 5,000 people and injured more than 26,000. Approximately 70,000 structures were destroyed.

Underground gas lines were severely damaged and, as a result, gas supplies were suspended to 387,000 customers. The total number of customers affected over the next 10 days rose to 857,000, with more than 3,750 miles of medium-pressure pipeline out of service. Many of these customers were affected by deliberate service interruptions that proved necessary to carry out repair works.

Thousands of distribution lines — those between the main transmission lines and individual customers — required repair or replacement. Fortunately, the high-pressure trunk lines themselves were largely undamaged.

A recurring point of damage was at the “screw and thread” pipe joints on steel pipes.

Medium-pressure system repairs were completed in three weeks, although distribution network repairs took longer due to access difficulties and damage to the structures being supplied.

EARTHQUAKE

Converter Station - January 17, 1994 - US

The Northridge earthquake, which measured 6.7 on the MMS, damaged a +/-500-kilovolt facility. Much of the damage occurred to switchyard-based equipment, namely porcelain insulators, shunt capacitor assemblies, and smoothing reactors. Hundreds of gallons of insulating oil escaped from a transformer, and mercury arc valves were also damaged.

Little damage was sustained by either the building itself or the equipment inside it.

Undamaged equipment was back in service in one month. Final repairs to mercury arc valves required a year, with 50% capacity back in service within six months.

FIRE

Converter Station - October 30, 1993 - US

An 846-mile transmission line was used to send DC to this facility, which converted it to alternating current for local consumption. The facility was unoccupied when the fire broke out.

No fire detection or suppression systems were installed. The first indication of a problem was an alarm at a nearby converter station, followed by a technician, who had been sent to investigate, discovering smoke coming from the solid-state thyristor hall. A subsequent emergency shutdown required some 90 minutes to de-energize the equipment, during which firefighting was restricted to the exterior of the station.

In addition, the thyristor valves fell to the ground during the fire and were destroyed.

EXPLOSION

Natural Gas Underground Storage/Gathering Facility - October 1, 1993 - US

The failure of a clamping mechanism on the quick opening door of a 2,000 PSI, high-pressure separation vessel caused natural gas to escape with such thrust that the vessel was torn from its saddle, subsequently striking and damaging adjacent equipment and breaking gas piping.

Escaping natural gas under static pressure ignited and caused fire damage to process equipment.

FLOOD

Hydroelectric Generating Facility - March 10, 1992 - Canada

A 472-megawatt facility flooded when the Unit 1 head cover burst from the stay ring and struck the generator bottom bracket. All four units – the lower galleries, machine shop, compressor room, and oil room – were flooded despite operators immediately tripping all head gates.

Although all of the water was pumped out by the next day, extensive damage occurred to the turbine head cover, servo motor, turbine shaft, oil lines, turbine guide bearing, wicket gates, and thrust bearings. The generator windings sustained serious damage.

The cause was attributed to fatigue cracking, which may have been contributed to by vibration. Two units returned to service within five months. Unit 1 did not return to service for 26 months.

FIRE

Converter Station - June 14, 1990 - India

The manufacturer of four thyristor valves was carrying out start-up testing at this +/- 500-kilovolt, 1,500-megawatt bi-pole HVDC station. An explosion occurred in the valve hall, which blew out a heavy steel door. Less than three minutes later, the valve hall and adjacent control room were filled with smoke.

The most probable cause was a loose electrical connection on the distribution capacitors that arced and ignited combustible components.

The fire burned for several hours; however, fears of electrical contact meant that firefighters who attended the scene were not allowed to tackle the fire.

Extensive damage to components occurred, with the valve in question being deemed a total loss. Cleaning and restoration of the facility took 18 months.

MECHANICAL DAMAGE

Hydroelectric Generating Facility - May 2, 1990 - Australia

This unattended hydroelectric facility housed a single 180-megawatt unit, commissioned in 1981. Two hoist-house structural support scissor beams became dislodged from their supports and fell into the gate shaft. The cause was attributed to long-term vibration that caused welds to crack, thereby allowing the beams to separate and move.

It is believed that one beam separated from the other and fell at a point past the main inlet water valve into the spiral casing. The beam was then drawn into the turbine runner. The closing of the guide vanes markedly increased water pressure, until the reinforcing bars failed and the turbine generator moved off of its foundation and into the turbine hall causing flooding.

The turbine, generator, spiral casing, guide vanes, governor, and control system all sustained serious damage. The plant took three years to be returned to service.

FIRE

Solar Plant - January 10, 1990 - US

A major fire occurred at a gas-fired auxiliary heat transfer unit. A total of 18,000 gallons of heat transfer fluid fueled the fire before the supply valves could be turned off. Army ordinance engineers used two shaped explosive charges to contain and extinguish the fire; however, the resulting shock wave damaged several of the parabolic mirror glass solar collectors.

The plant was out of service for six months.

EARTHQUAKE

Gas Plant - October 17, 1989 - US

An earthquake, measuring 7.1 on the MMS, caused damage to substations, plants, and pipework. One power plant also tripped as a result of the event. Some 1.4 million customers lost power and 150,000 had their gas supplies cut off.

Thirteen miles of gas pipeline were replaced with more flexible plastic piping.

FIRE

Converter Station - May 29, 1989 - Brazil

A +/- 600-kilovolt, double-bipole HVDC converter station suffered a cooling water line failure. A subsequent electrical arc resulted in a thyristor valve flashover. The ensuing fire then destroyed the valve.

MECHANICAL FAILURE -

Pumped Storage Plant - September, 1982 - US

A 1,200-megawatt pumped storage plant suffered a rupture in part of its extensive network of tunnels. The tunnels had been filled with water some 48 hours before. A concrete footing failure was blamed for the rupture, which resulted in more than 900 million gallons of water being released in a period of 60 minutes before contractors could close the slide gates.

FIRE

Hydroelectric Generating Station - July 20, 1981 - US

At the time, this was the largest hydroelectric plant fire on record. An electrical fault in oil-filled cables caused the fire, which was made more serious by tunnel entry issues, lack of adequate water supply, and delays in fire detection.

A 700-megawatt unit was out of service for roughly one year. Two other 600-megawatt units were also affected, but returned to service more quickly.

I CONCLUSION

The recurrent themes in many of these loss summaries should serve to help risk managers increase their awareness of the potential exposures that exist in the power generation industry, so that they can take measures to prevent similar losses from occurring at their facilities.

■ ABOUT THIS REPORT

Marsh's Power and Utilities Practice is dedicated to providing industry consultation and risk management services for gas, water, electric, and nuclear utilities, and the independent power industry. We specialize in identifying events, issues, trends, and regulations that impact the global management of utility risk, and the ability of the organization to compete profitably. Our global team of specialists prides itself on understanding the unique risk management needs associated with the electricity, coal, gas, nuclear, water, and green energy industries. Our knowledge, expertise, and strong insurance market relationships are reflected by the fact that we offer risk transfer solutions, risk analysis (benchmarking), and claims consultancy to more than 200 power and utilities clients around the world, including vertically integrated, nationalized, regulated, de-regulated, and independent power producers. In addition, the power and utilities team are familiar with issues that impact the provision of insurance including new technology, regulatory constraints, and environmental and economic considerations. We utilize this knowledge in the design and placement of insurance programmes.

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