Co-Variances Between the Unavailability of Electricity from Several Differing Sources in the UK:

Use of the Concepts of

BUSINESS INTERRUPTION
&
REALISTIC DISASTER SCENARIOS,

-borrowed from the World of Insurance

Prepared By

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Thursday, August 12, 2004

PROFESSOR JOHN H GITTUS.

John Gittus was elected Regents' Professor at the University of California in Los Angeles in 1990. He is Visiting Professor of Nuclear Engineering at the University of Plymouth, England. He was a Director of the United Kingdom Atomic Energy Authority (later AEA Technology) and is now a Consultant to Governments and private industry on nuclear matters world-wide. His recent clients include BNFL Plc, The UK Government's Department of Trade and Industry, Serco Plc, The Sumitomo Corporation, the French nuclear company COGEMA, Amersham Plc the radio pharmaceutical company, Cox Insurance Plc, the world's largest commercial insurer of nuclear risks, Chaucer Insurance Holdings and ESKOM, the South African utility.

Professor Gittus is a Fellow of the Royal Academy of Engineering (Britain's top 1,000 engineers) and has Doctor of Science degrees from the Universities of London and Stockholm. He has held over 30 patents and published over 100 papers in learned Journals describing his personal research. He invented Nimonic 115, the strongest of the early creep-resistant alloys used for the hottest turbine blades in jet engines and went on to develop a theory of creep that forms the basis of many of his papers to the Royal Society and the Philosophical Magazine. He used this theory to develop one of the world's first computer models of nuclear fuel elements, with which he forecast that some of the fuel element designs then extant would fail as their lives were extended in a quest for cheaper power. He was able to model the failure processes and deduced remedies that have been applied throughout the world. Fuel element failures are now rare, due in part to this early work.

He held a series of senior posts in the UKAEA, where he headed the late Lord Marshall's Task Force at Harwell and produced the UK's first nuclear-reactor Probabilistic Risk Assessment, for Sizewell B. He became Director of the R&D programme that underpinned the design details of Sizewell B, then Director of Safety and Director of Communications. He left the UKAEA to become the first Director General of the British Nuclear Industry Forum, where he helped with the restructuring of the UK nuclear industry, a process that is still going on. When his term of office there was complete he became a consultant, first to his successor and then, quickly, to other nuclear companies at home and overseas. On the death of Lord Marshall of Goring, Professor Gittus was appointed to succeed him at Cox Insurance Holdings Plc, advising on the insurance of the world's nuclear power stations and other nuclear installations. Since January 2003 Professor Gittus and Mr Michael Dawson have led Syndicate 1176, the biggest commercial nuclear insurer in the world and Lloyds of London's most profitable syndicate.

Amongst his published papers are two communicated to the Royal Society by P.A.M. Dirac and describing Professor Gittus's solution of a problem with the structure of matter which Dirac said he himself had been unable to solve.

Entry From Who's Who

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Uranium, 1962; Creep, Viscoelasticity and Creep-fracture in Solids, 1979; Irradiation Effects in Crystalline Solids, 1979; (with W. Crosbie) Medical Response to Effects of Ionizing Radiation, 1989; numerous articles in learned jls.

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Summary

In this Report I compute covariances for the various sources of electricity.

I have divided the analysis of the non-availability of electric power into two areas, one of which I have already dealt with and the other of which I deal with in the present Report.

The area with which I have already dealt is that of Large Interruptions of ***individual*** sources, such as wind power, gas-fired power stations or nuclear power stations. These I have dealt with in separate reports, one on each of the various sources of electricity, such as gas and nuclear energy.

However, there ***are*** cases in which two or more different sources of electric power can be interrupted s***imultaneously***. These I deal with in the present Report.

For example a severe storm might simultaneously

- damage a wind-farm,
- disconnect customers from the national grid and
- initiate a nuclear accident (by Loss of Offsite Power or flooding, for example).

A second example is ***political***: later this century, Iran and Russia might collude to interrupt the supplies of gas that both countries, by then, will probably be providing to the UK. Their objective would be to hike the price: Russia has stopped its supplies of gas to Latvia since January 2003 because of a dispute over price. Russia and Iran have entered into trade-agreements in the energy sector.

The Insurance and Finance Sectors routinely compute the effects of such ***co-variations*** of factors. In the Insurance sector they are termed "***Realistic Disaster Scenarios***" and that is what I shall term them here.

Of course the ***normal variability*** in the generating capacity of our power stations, or in the availability of electricity to meet the demands of consumers, is itself dictated by the simultaneous variations in many factors. This "background variation" is determined by random fluctuations in the performance of individual power stations. For example, a single generator may be shutdown to repair a turbine or replace a transformer. Simultaneously, another station may be down for annual maintenance. These are the kind of interruptions that lead to the "Normal Distribution" of probabilities for the generating capacity of the system of power stations. In the first section of this Report I deal with these small-scale co-variations in factors that interrupt the supply of electricity. I show that these generally lead to interruptions that can be assimilated by the economy without major financial losses. In part this is because such interruptions are insured.

We are passing through a ***trough*** in the availability of electric power at the moment: the Market Regulator has set such a low price for electricity that power stations are being priced out of service whilst some stations are proving unreliable because they are near the End of Life. Their replacements employ a new technology (CCGT) that is still suffering teething troubles. A current global political imperative, “the environment”, necessitates improvements to our power stations and has resulted in the temporary closure of substantial capacity in Canada and Japan, adding to the financial woes of our biggest generator, BE.

The biggest single Business Interruption that we have suffered in the present “trough” of the cycle was the closure of a reactor at Heysham for a year. However that loss was largely recompensed by the Insurance Market and this is the characteristic of these “normal fluctuations” in the availability of electric power: either by the substitution of other generators (probably uneconomic under normal market conditions) or by Insurance payments, the effects of such fluctuations are absorbed without major financial loss to the economy as a whole.

The larger losses with which these studies are concerned are too big to be compensated by the insurance market. Then the ***Realistic Disaster Scenarios*** which I calculate in the balance of this Report are ***extreme*** points on the probability density distribution.

In this Summary, there follow all of the Tables arising out of this work.

The first of these Tables shows the covariances.

Then come the Tables showing the frequencies with which I calculate there will be separate interruptions of each source of electricity. These have appeared previously in my separate Reports on each source of electricity, but now I have subtracted from each the frequency with which this, and another source (s) are simultaneously interrupted by a common cause, such as a storm or earthquake or political activity. That is to say, the Covariances are now subtracted from these, the “single effects” Tables to avoid double-counting.

Figure 1: Covariances.

Combined Effects upon LNG and Gas Supplies of Simultaneous Political Action in Qatar and Russia or Iran. Return Period 263 years.

POLITICAL	Source of Electricity	Interrupted for, days.	Loss.	
RETURN PERIOD, YEAR	LNG from Qatar	90	2.41641	billion cu m.
263	Gas from Russia and Iran.	180	36.00	% of Year's Contracts.

Combined Effects upon Gas Supplies and Grid Connections of the Earthquake with Return Period of 5,000 years.

SEISMIC	Source of Electricity	Interrupted for, days.	Loss.
RETURN PERIOD, YEARS	Gas	10	0.00274% of Year's Contract lost
5000	Grid	70	70 million connection-days

Combined Effects upon Wind, Nuclear, LNG and Grid of a Severe Storm with a Return Frequency of 3580 years.

STORM.	Source of Electricity	Interrupted for, days.	Loss.
RETURN PERIOD, YEARS	Wind	180	315 Gwe.d
3580	Nuclear	180	180 Gwe.d
	LNG	5	0.13 bcm.
	Grid	20	100 million connection.days.

Figure 2: Separate Forecasts for Interruptions to LNG: Covariances Subtracted.

LNG.

Source of Interruption.	Days: Duration	Per Year: Likelihood	$ Maximum Insurable Amount	Loss, bcm/day
Political Risk in France and Algeria	90	0.02	100,000,000	0.026849
Political Risk in Algeria	180	0.002	100,000,000	0.026849
Political Risk in UK: Algeria supplies.	90	0.0008	100,000,000	0.026849
Algeria Tanker Strike Action	10	0.002	100,000,000	0.026849
Algeria Tanker Accident	5	0.049	100,000,000	0.026849
Algeria Port Accident	10	0.0065	200,000,000	0.026849
French Port Accident	10	0.0065	200,000,000	0.026849
Algeria Port Terrorist Attack.	180	0.0059	10,000,000	0.026849
Political Risk in Qatar	90	0.0682	100,000,000	0.026849
Political Risk in UK: Qatar supplies.	90	0.0008	100,000,000	0.026849
Qatar Tanker Strike Action	20	0.0032	100,000,000	0.026849
Qatar Tanker Accident	10	0.097	100000000	0.026849
Qatar Port Accident	10	0.0130	200,000,000	0.026849
UK Port Accident	10	0.0130	200,000,000	0.026849
UK Port Terrorist Attack.	180	0.0117	10,000,000	0.026849
Qatar Port Terrorist Attack.	180	0.0117	10,000,000	0.026849

Figure 3 Separate Forecasts for Interruptions to Windpower: Covariances Subtracted

WIND POWER

Source of Interruption.	**Days: Duration of Consequent Interruption**	**Per Year: Likelihood**	**GBP Maximum Insurable Amount**	**Loss, Gwe.d**	**Loss, GWe**	**% of wind power lost**	**MGBP Cost of lost power**	**Cost of generating Loss MGBP/y**	**MGBP Cost of replacement**	**MGBP Cost of capital loss per year**
Storm	180	0.000221	200,000,000	315	1.75	25	151	0.033	1750	0.3861
Surge on west coast	130	0.0004	200,000,000	241	1.86	26.54	116	0.046	1858	0.7431
Surge on east coast	130	0.0004	200,000,000	158	1.22	17.42	76	0.030	1219	0.4876
Tornado	60	0.003	100,000,000	29	0.49	7	14	0.042	490	1.4700
Seismic	70	0.00002	100,000,000	10	0.14	2	5	0.000	140	0.0028
Hail	30	1E-07	100,000,000	0.3	0.01	0.14	0	0.000	10	0.000001
High Sea	40	0.001	100,000,000	3	0.07	1	1	0.001	70	0.0700
Ship runs into windfarm	180	0.003	100,000,000	25	0.14	2	12	0.036	140	0.4200
Plane runs into windfarm	120	0.0003	100,000,000	17	0.14	2	8	0.002	140	0.0420
Cable is cut	50	0.0003	20,000,000	7	0.14	2	3	0.001	140	0.0420
								0.194		3.6637

Figure 4 Separate Forecasts for Interruptions to Nuclear Power: Covariances Subtracted

	Source of Interruption.	Days: Duration of Consequent Interruption	Per Year: Likelihood	MGBP Maximum Insurable Amount.	Loss, Gwe.d	Loss, GWe	% of nuclear power lost
	licensing event	*180*	*8.33E-05*	*0*	*315*	*1.75*	*25*
internal event	*cold zone*	*123*	*6.02E-03*	*200*	*123*	*1*	*14.29*
	design basis	*180*	*5.59E-04*	*1,000*	*180*	*1*	*14.29*
	core damage	*360*	*5.59E-05*	*1,000*	*360*	*1*	*14.29*
	core damage and containment leakage.	*720*	*5.59E-06*	*1,000*	*720*	*1*	*14.29*
	core damage and containment failure.	*1,800*	*5.59E-07*	*1,000*	*1,800*	*1*	*14.29*
external and shutdown events	*cold zone*	*123*	*6.02E-03*	*200*	*123*	*1*	*14.29*
	design basis	*180*	*2.79E-04*	*1000*	*180*	*1*	*14.29*
	core damage	*360*	*5.59E-05*	*1000*	*360*	*1*	*14.29*
	core damage and containment leakage.	*720*	*5.59E-06*	*1000*	*720*	*1*	*14.29*
	core damage and containment failure.	*1800*	*5.59E-07*	*1000*	*1,800*	*1*	*14.29*
terrorist event	*design basis, internally initiated*	*180*	*7.11E-04*	*3*	*180*	*1*	*14.29*
	core damage, internally initiated	*360*	*7.11E-05*	*3*	*360*	*1*	*14.29*

	core damage and containment leakage, internally initiated.	*720*	*7.11E-06*	*3*	*720*	*1*	*14.29*
	core damage and containment failure, externally initiated. Political decision to defuel half our reactors	*1800*	*7.11E-07*	*3*	*6,300*	*3.5*	*50.00*
Uranium Imports Cease		*180*	*1.00E-06*	*0*	*360*	*2*	*28.57*

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Figure 5: Separate Forecasts for Interruptions to Grid: Covariances Subtracted.

GRID

Source of Interruption.	Days: Duration of Consequent Interruption	Per Year: Likelihood	$ Maximum Insurable Amount	mean % of power lost	Million Disconnection.days
Storm	20	0.000721	2E+08	25	100
Storm	5	0.01	2E+08	10	10
Storm	3	0.05	2E+08	8	4.8
Surge on west coast	10	0.001	2E+08	5	10
	5	0.01	2E+08	1	1
Surge on east coast	10	0.001	2E+08	5	10
	5	0.01	2E+08	1	1
Tornado	10	0.001	1E+08	5	10
Seismic	70	0	1E+08	5	70
Hail	5	0.0003	1E+08	2	2
Terrorist Action	10	0.03	0	1	2
Control software or hardware failure	3	0.03	2E+08	10	6
Plane crash	5	0.001	2E+08	2	2
BLEVE	10	0.001	2E+08	2	4

Figure 6: Separate Forecasts for Interruptions to Gas: Covariances Subtracted

GAS FINAL ESTIMATES						
GAS	Frequency/year	% Flow	Duration of Interruption, days	fraction of year during which flow is reduced	% of Year's flow lost	% of year's contract uk receives
Political Risk in Russia, Ukraine, Belarus and Iran	0.001	0	10	0.03	2.74%	97.26%
Political Risk in Russia, Ukraine, Belarus and Iran	0.0065	37%	30	0.08	5.21%	94.79%
Political Risk in Russia, Ukraine, Belarus and Iran	0.0152	27%	180	0.49	36.09%	63.91%
Political Risk in Russia, Ukraine, Belarus and Iran	0.0425	73%	180	0.49	13.22%	86.78%
Political Risk in Russia, Ukraine, Belarus and Iran	0.1235	63%	180	0.49	18.05%	81.95%
Minor Terrorist Risk	0.009	90.00%	30	0.08	0.82%	99.18%
Major Terrorist Risk	0.00009	50.00%	180	0.49	24.66%	75.34%
Minor Equipment Failure.	0.0098	90.00%	10	0.03	0.27%	99.73%
Major Equipment Failure.	0.0001	50.00%	60	0.16	8.22%	91.78%
Diversion of gas by Ukraine and Belarus.	0.1	98.00%	10	0.03	0.05%	99.95%

Figure 7: Separate Forecasts for Interruptions to Oil: Covariances Subtracted. [1]

OIL

	Frequency/year	% Flow	Duration of Interruption, days
Political Risk in Middle East	0.125	0	120

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[1] There were no Covariances to subtract in the case of oil and so this table is unchanged.

Figure 8: Separate Forecasts for Interruptions to Hydro: Covariances Subtracted.[2]

HYDRO

Source of Interruption.	**Days: Duration of Consequent Interruption**	**Per Year: Likelihood**	**MGBP Maximum Insurable Amount**	**% of Hydro lost**
Seismically induced Dam Failure	permanent	0.000005	200,000,000	20
Dam failure due to aircraft crash	720	0.000005	200,000,000	20
terrorist action.	720	0.001	0	20
Drought.	30	0.03	10,000,000	50
Accident, Machinery Breakdown.	60	0.0005	50,000,000	10

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[2] There were no Covariances in the case of Hydro, so this Table remains unchanged.

Figure 9: UK coal imports will be interrupted for a period of 6 months with a frequency of *0.00018/year*[3]**.**

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[3] This figure remains unchanged since we have not identified an important covariance for coal.

Introduction.

In this Report I deal with cases in which several factors combine to interrupt the availability of electric power. In the next section, I place these in context:

Variations and Covariations in the Non-Availability of Electric Power.

I have divided the analysis of the non-availability of electric power into two areas, one of which I have already dealt with and the other of which I deal with in the present Report.

The area with which I have already dealt is that of Large Interruptions of ***individual*** sources, such as wind power, gas-fired power stations or nuclear power stations. These I have dealt with in separate reports, one on each of the various sources of electricity, such as gas and nuclear energy. In these Reports I have dealt with separate interruptions of each source: a nuclear accident, politically-inspired stoppages of Russian gas, an accident to an LNG tanker are examples. In these Reports I have not considered cases in which, for example, a nuclear accident was accompanied by a shipping strike that stopped LNG deliveries for months. The reason is obvious: the events that I considered were un-correlated and so the chance of two occurring simultaneously was remote.

However, there ***are*** cases in which two or more different sources of electric power can be interrupted s***imultaneously***. These I deal with in the present Report.

For example a severe storm might simultaneously

- damage a wind-farm,
- disconnect customers from the national grid and
- initiate a nuclear accident (by Loss of Offsite Power or flooding, for example).

A second example is ***political***: later this century, Iran and Russia might collude to interrupt the supplies of gas that both countries, by then, will probably be providing to the UK. Their objective would be to hike the price: Russia has stopped its supplies of gas to Latvia since January 2003 because of a dispute over price. Russia and Iran have entered into trade-agreements in the energy sector.

The Insurance and Finance Sectors routinely compute the effects of such ***co-variations*** of factors. In the Insurance sector they are termed "***Realistic Disaster Scenarios***" and that is what I shall term them here.

Of course the ***normal variability*** in the generating capacity of our power stations, or in the availability of electricity to meet the demands of consumers, is itself dictated by the simultaneous variations in many factors. This "background variation" is determined by random fluctuations in the performance of individual power stations. For example, a single generator may be shutdown to repair a turbine or replace a transformer. Simultaneously, another station may be down for annual maintenance. These are the kind of interruptions that lead to the "Normal Distribution" of probabilities for the generating capacity of the system of power stations. Then the ***Realistic Disaster Scenarios*** are ***extreme*** points on the probability density distribution.

The Background Variability in the Availability of Electric Power.

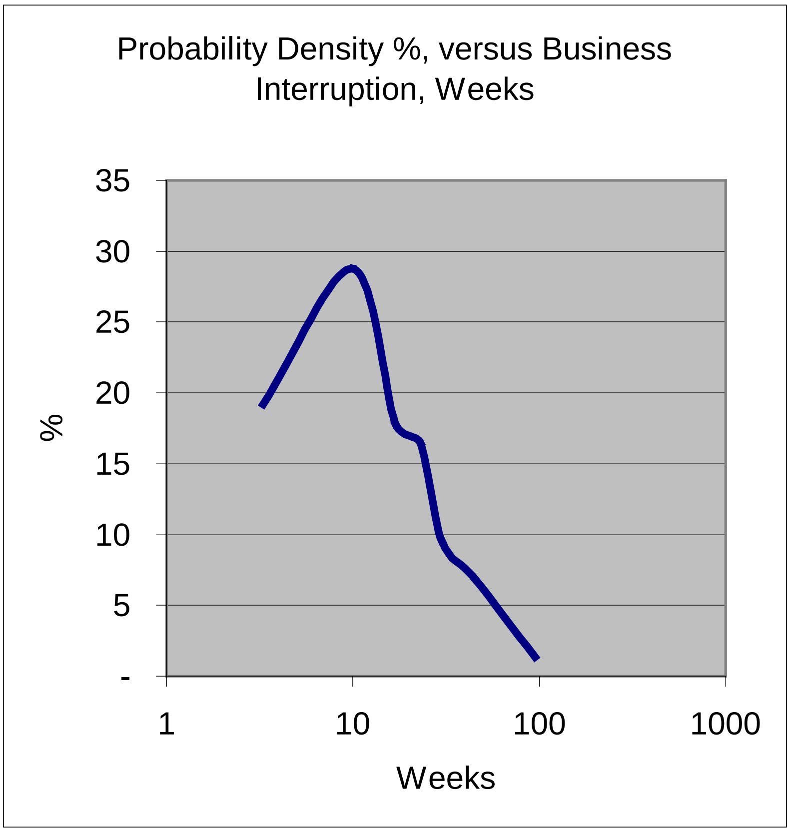
In this section I deal with small-scale co-variations in factors that interrupt the supply of electricity. I show that these generally lead to interruptions that can be assimilated by the economy without major financial losses. In part this is because such interruptions are insured. The larger losses with which these studies are concerned are two big to be compensated by the insurance market.

Power Stations of all types buy insurance against ***Business Interruption***; that is to say if a power station has an accident as a result of which it ceases to generate electricity for a substantial period, then the insurer will recompense the owner for the an agreed part of the income that he has lost. Typically, for a large generator, this will amount to half a million pounds for each insured day.

Insurers therefore have very detailed records of the frequency and duration of this so-called Business Interruption for Power Stations. Of course it is with Business Interruption, for electricity generation, that this whole study is concerned with and so these records are valuable.

The power of the databases that have been amassed is illustrated in Figure 10, where the probability density of Business Interruptions is plotted for all of the World's power stations for a 44-year period. Note that some of these interruptions lasted for well in excess of one year. Insurance, where available, would typically cover a period in the decade from 10 weeks to 100 weeks.

Figure 10: Probability Density versus Business Interruption for the World's Power Stations for 44 year period.[4]



Analysis of the Insurance market reveals that several cyclic processes are at work and the actual observed behaviour of the market is the sum of these. Amongst the factors that may be observed in the UK electricity generation market are the following:

- *The hand of the Market-Regulator in the Market for Electricity*: here the low price-target set by the Market-Regulator has compelled the owners of power stations to cut back on maintenance. Consequently stations are tending to be shut down for repair. Some have been taken out of service because they are no longer viable in this highly competitive market.
- *The end-of-life of power stations that were built during the aftermath of world-war two*. They are being replaced currently. Insurance companies in the UK and overseas (a similar pattern exists in many countries) have been badly "burned" by BI claims from these old stations.
- *The start-of-life of the new power stations now being built to replace the post-war batch*. Many of these are, and will be, CCGT. The gas turbines of a

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[4] From Insurance Industry records. The integral frequency of BI is omitted for commercial reasons.

number of these have proved unreliable, since they are designed to run under extreme conditions of temperature and stress so as to maximize thermodynamic efficiency and reduce the cost of electricity. The same insurers who had to pay BI claims on the old stations have had to pay BI claims on the new. The implication in the present context is that two troughs, in the availability of electricity from power stations, have virtually coincided. The old stations have become unreliable and the new ones have teething troubles: the classic “bathtub distribution”.

- *A Sharper Focus on Safety and Environmental Issues*. The recent activities of the Nuclear Regulators in Canada, Japan and to a lesser extent in the UK typify this factor. In all cases there are both political and technical elements at work. In Canada and Japan several nuclear reactors were shut down by the Nuclear Regulator and are restarting following improvements. Japan has made substantial increases in its imports of oil to tide over the shortfall in nuclear generating capacity. These interventions by the Canadian and Japanese Nuclear Regulators have had repercussions in the UK, since BNFL supplies nuclear fuel services to Japan and BE rents the Canadian Nuclear Power Stations that were forced to stop generating electricity. The viability of BE, the UK’s largest generator of electricity was already threatened by its inability to make a profit at the prices set by the UK Market Regulator. The closure of its Canadian stations added to the likelihood that our largest Utility would fail. BE, like BNFL, was itself under pressure from the UK HSE to make costly changes to safety provisions. A global focus on safety and environmental issues threatened to cause failure of BE, which generates a quarter of the UK’s electricity, and would still threaten, had HMG not supported BE in the financial markets. These targets, set by the political/environmental sector, are recursive, since standards never fall, but simply ratchet ever upwards as environmental concerns are driven in large measure by political imperatives.

We are passing through a ***trough*** in the availability of electric power at the moment: the Market Regulator has set such a low price for electricity that power stations are being priced out of service whilst some stations are proving unreliable because they are near the End of Life. Their replacements employ a new technology (CCGT) that is still suffering teething troubles. A current global political imperative, “the environment”, necessitates improvements to our power stations and has resulted in the temporary closure of substantial capacity in Canada and Japan, adding to the financial woes of our biggest generator, BE.

The biggest single Business Interruption that we have suffered in the present “trough” of the cycle was the closure of a reactor at Heysham for a year. However that loss was largely recompensed by the Insurance Market and this is the characteristic of these “normal fluctuations” in the availability of electric power: either by the substitution of other generators (probably uneconomic under normal market conditions) or by Insurance payments, the effects of such fluctuations are absorbed without major financial loss to the economy as a whole.

Realistic Disaster Scenarios.

In this section of the Report I calculate ***Realistic Disaster Scenarios***. These are adventitious coincidences of failure in more than one source of electricity. In this sense they resemble the random fluctuation in the background generating capacity. However they are much larger interruptions in electric power than those that characterize the background fluctuations and are therefore “disastrous”: hence the phrase Realistic Disaster Scenario.

Realistic Disaster Scenarios are calculated by Insurers to determine the maximum losses that they could face, should, for example, a hurricane simultaneously cause damage to shipping, houses and vehicles, all of which the insurer has insured.

In this Report I postulate Realistic Disaster Scenarios, RDS’s, for UK Electricity Supplies. I calculate the frequency of each RDS, the period for which electricity supplies will be interrupted and the percentage of electric power that will be lost.

These losses of electric power supplement the losses that I have calculated in other Reports where I dealt with individual sources of electricity, such as nuclear or wind power, separately. In this Report I cover cases in which two or more sources are interrupted simultaneously.

An example is provided by the Storm that simultaneously flooded Blayais nuclear power station (in France) and disconnected several other French power stations from the French National Grid. Similarly a storm could cause an interruption in Wind Power, accompanied by a large-scale failure in the national grid: in that case a high wind would be the " common cause".

Again, an earthquake may damage a hydro plant and a gas fired plant, interrupting supplies from both. These " external events" are the main source of coincidental failures and are very unlikely to shut down the nuclear power stations because these latter are designed to resist external events that have return periods in the range 10,000 to 100,000 years.

It is with such events that this Report is concerned.

Storm.

In this, the first RDS, which is suggested by one of the RDS's that the Lloyds of London Insurance Market requires its Members to investigate, we look at the simultaneous effects of a storm on several sources of UK electricity.

We begin with a nuclear accident. It might be thought that a nuclear accident cannot be initiated by a storm. We shall therefore begin by describing two accidents to foreign nuclear power stations that have been so initiated.

Nuclear.

The basis of the hypothetical storm-induced accident that we are going to postulate, to a coastal UK nuclear power station, is either an accident that occurred in Taiwan or one that occurred in France. Both could have led to core-damage had they not been successfully terminated by safety equipment and safety measures. Here we calculate the frequency with which such an accident could lead to a core-damage accident in the UK.

Loss of Offsite Power: Accident at Maanshan, Taiwan.

During a storm, sea spray caused a salt deposit which caused the malfunction of all four 345 KV power transmission lines in southern Taiwan, resulting in an loss of offsite power event at the Maanshan nuclear power plant (NPP). As both the safety-related A/C power systems of unit 1 went out of service and both the emergency diesel generators (EDG) failed to operate, the consequence was a complete loss of power of the two 4.16 KV essential buses at the unit. The reactor automatically shut down. The diesel generators that should start-up failed to do so at first, but before any damage was done a supplementary diesel was started.

Had this sequence of events not been safely terminated, the cooling pumps could have failed to operate to remove decay heat from the reactor-core. There would then have been first a release of the "gap inventory" of fission products from some fuel elements into the reactor pressure vessel. If the accident was not terminated by safety equipment at that stage, then the core would have begun to melt and large quantities of fission products would have been released into the pressure vessel. Much of this material could then enter the containment. The containment seals itself automatically; the containment sprays and coolers operate. No radioactivity is released to the environment.

Should the accident have proceeded to these more extreme stages, the reactor would have been inoperable for a substantial period whilst it was cleaned-up and repaired.

Loss of RHR Systems: Accident at Blayais, France.

In December 1999, France was struck by four severe storms. The waters of the Gironde were pushed by the winds over the protective dike around Blayais, which houses four nuclear power reactors. Units 2 and 4 were stopped in the evening of December 27, unit 1 around 12.00 on December 28; unit 3 was already shut for maintenance. Invading the site through underground service tunnels, the waters flooded the pumps of unit's 1 Essential Service Water System (ESWS). This disabled the residual heat removal system, which is necessary to cool the reactors. Shortly afterwards the flood waters reached the spent fuel buildings for units 1 and 2, knocking out their safety inspection system and containment spray system too. After the internal emergency was declared, firefighters from nearby town Blaye assisted Blayais' own flood-fighting team. On December 30, the ESWS resumed operation and Blayais-4 was restarted. Electricité de France (EDF) needed its power badly to power the southern grid, which was no longer connected to the north because of the storm damage to the transmission system.

EDF said that the level of the Gironde river during the storm had been higher than the millennial level against which the dike around Blayais was designed. The French national safety agency DSIN allowed EDF to repair provisionally the pumps, motors and valves of the safety inspection system and the containment spray system of units 1 and 2. Since the incident, the two reactors had been cooled through their steam generators. After the provisional repair, EDF brought units 1 & 2 to cold shutdown, to allow installation and qualification of the new equipment and the repair of the safety systems. EDF first planned to restart units 1 & 2 by early January. But plant management later declared that other piping and concrete structures were being checked.

According to Quintin of the regional inspectorate and Goelnner, assistant director of DSIN, the dike was inadequate, the service tunnels were not protected against flooding.

This accident was safely terminated by safety equipment. If the safety provisions had failed then there could have been an accident that rendered the reactor inoperable for a substantial period whilst it was cleaned-up and repaired.

Hypothetical UK Nuclear Accident.

We hypothesize that a storm, like the ones that hit France in 1999 but more severe, strikes the UK and causes an accident at one of the coastal nuclear power stations. Whether the accident is due to Loss of Offsite Power (which was caused by a storm in Taiwan, as explained above) or to flooding and consequent Loss of Residual Heat Removal Systems (which was caused by a storm in France, as explained above) is irrelevant. These are examples of what has happened. Theoretically there are other types of nuclear accident that have not happened, which could be initiated by storms. The important facts, in the present context, are that storms can theoretically initiate nuclear accidents: the nuclear power stations are designed against this threat and nevertheless storms have initiated nuclear accidents; in the two cases exemplified here the safety equipment prevented serious damage to the reactor.

We postulate that in our hypothetical UK nuclear accident the safety equipment prevents severe core damage. However there is some loss of cooling and as a result some fuel elements fail, releasing the “gap inventory” of fission products.

We estimate that this accident will cause a loss of power for 180 days from a nuclear power station of 1 Gwe capacity.

We calculated, in the Report on nuclear power, that the total frequency of such accidents is 0.00056/year in the UK, as the following excerpt from the Table in the Report on Nuclear Power reveals:

Figure 11: Design Basis Nuclear Accidents due to External and Shutdown Events.

.	Days: Duration of Consequent Interruption	Per Year: Likelihood	MGBP Maximum Insurable Amount.	Loss, Gwe.d	Loss, GWe	% of nuclear power lost
design basis	180	0.00056	1000	180	1	14.28

As we shall see, below, we are only concerned with the subset of such accidents that occur simultaneously with

- a “Loss of grid”,
- failure of some wind generators and
- a delay to a LNG tanker.

Loss of Grid.

We are going to consider the Realistic Disaster Scenario in which the storm that causes an accident to a UK coastal nuclear power station also causes wholesale disconnections from the national grid. Indeed it was disconnection from the Grid that initiated the nuclear accident at Maanshan, Taiwan, which we have used in developing the model for the nuclear accident above.

Additionally, when the nuclear accident at Blayais, which we have also pressed into use in developing our model for a storm-induced nuclear accident, was accompanied by massive damage to the French grid. We are invoking precisely the same coincidence of grid failure and a nuclear accident for the UK as happened in France. Only the severity and frequency are different.

Loss of Grid in France, when the Blayais Nuclear Accident Occurred..

The passage of storms Lothar and Martin across France in December 1999 caused the greatest devastation to an electricity supply network ever seen in a developed country. EDF did not restore power to all homes before the new year.

Following Lothar, more than 120 high-voltage transmission pylons were toppled, 36 high-tension transmission lines were lost (a quarter of the total lines in France), and all electricity links with Germany were severed. Two million homes and businesses were left without power, and up to 1.6 million domestic customers had no water due to the lack of pumping capacity. After Martin, all the main electricity connections between northern and southern France had been severed, the number of toppled high-voltage pylons had risen to 280, and the total number of homes and businesses without power had risen to 3.5 million, affecting 10 million people. Worst affected was Charente-Maritime, where 30 high-tension transmission pylons were down, along with 1,000 middle-voltage distribution towers. In La Rochelle, two hundred 20,000-volt pylons and thirty 100,000 to 200,000-volt pylons were blown down or damaged by falling trees. A day after the storm, 90% of people in the departments of Correze and Dordogne and 80% of people in Cantal were without power. The lack of electricity deprived 360,000 telephone subscribers of phone service as of December 27th. By December 28th the number was one million-many batteries that France Telecom was using for backup had reached the end of their useful lives.

The state-owned Electricité de France (EDF) recovery effort was military in scale, expanding day by day until it involved up to 50,000 EDF employees, with 45,000 subcontractors and 6,000 soldiers.A total of 400 helicopters were in operation, and having exhausted all supplies in France, 650 km (400 mi) of spare cable had to be air-lifted on 14 transport planes from Italy. After a week, the number without power had fallen to 500,000 and power was completely restored within 20 days. On December 30, EDF offered any domestic customers who were not reconnected by the evening of the 31st free electricity for the year 2000. Compensation for power cuts to farmers was negotiated region by region, based on a 1987 national agreement. In February of 2000, EDF estimated its losses from the storms at € 1.5 billion ($1.5 billion). By December, the company estimated that future investments to upgrade their network could be as high as € 7.6 billion ($7.7 billion).

The Passage of the Storms into France.

The windfields from the two storms covered more than half of France and extended into Switzerland and Germany. Between them, these windstorms produced over € 14.2 billion ($14.4 billion) in economic damage, approximately € 7.7 billion ($7.8 billion) of which was insured. This ranks as the third largest insurance loss ever, after Hurricane Andrew in 1992 and the 1994 Northridge Earthquake. Windstorm Lothar alone represents the largest monetary insurance loss in European history. The storms caught Europe by surprise. Meteorological forecasts failed to predict

Lothar's dramatic inland intensification. Modern infrastructure such as electrical distribution systems, transportation, and communication lines were hit particularly hard, leading to several very large insured and uninsured losses throughout the industrial and public sectors. Observed damage to residential structures was in line with previous experience, however the total damage from Lothar and Martin covered an exceptionally large area leading to higher overall losses. The French insurance industry also was not prepared for losses of this magnitude. Common risk transfer practice in France was for insurers to buy cover based on the level of losses in the 1990 storms Daria and Herta. These covers proved inadequate, because windspeeds in the 1990 storms were almost 20% lower than those experienced in Lothar and Martin. In addition, the occurrence of two storms within the typical 72-hour interval for reinsured events tested reinsurance contract definitions and previous assumptions.

Windstorm Lothar first developed east of Newfoundland early on December 25.The storm was swept along by an exceptional jet stream early in the morning of the 26th, at forward speeds of up to 130 km/h (80 mph). As Lothar reached the coast of northern France, the speed of the storm slowed to 97 km/h (60 mph) and the system began a rapid phase of intensification --the pressure falling an almost unprecedented 32 millibars (mb) in 8 hours, reaching 960 mb as the storm hit Paris. Although Windstorm Lothar was only 300 km (190 mi) in diameter, far smaller than most extra-tropical cyclones, the dramatic intensification resulted in internal pressure gradients comparable to those found in a strong Category 2 hurricane. Unlike a hurricane, however, the system did not weaken after landfall, but continued to intensify as it travelled inland. High winds were located in a 150-km (90-mi) wide band immediately to the south of the track. The winds on the ground reached more than 180 km/h (112 mph) on the coast, and inland up to 172 km/h (107 mph) at Orly Airport to the south of Paris, where the storm was at its most intense. Even before Lothar had dissipated, a new westerly moving disturbance was developing close to where Lothar was born. Tracking 200 km (125 mi) south of the first storm,Windstorm Martin reached its lowest recorded pressure (964 mb) and highest windspeeds as it crossed the French coast on the evening of December 27.Windspeeds were comparable to those of Lothar --up to 190 km/h (119 mph) at the coast and 158 km/h (98 mph) inland.

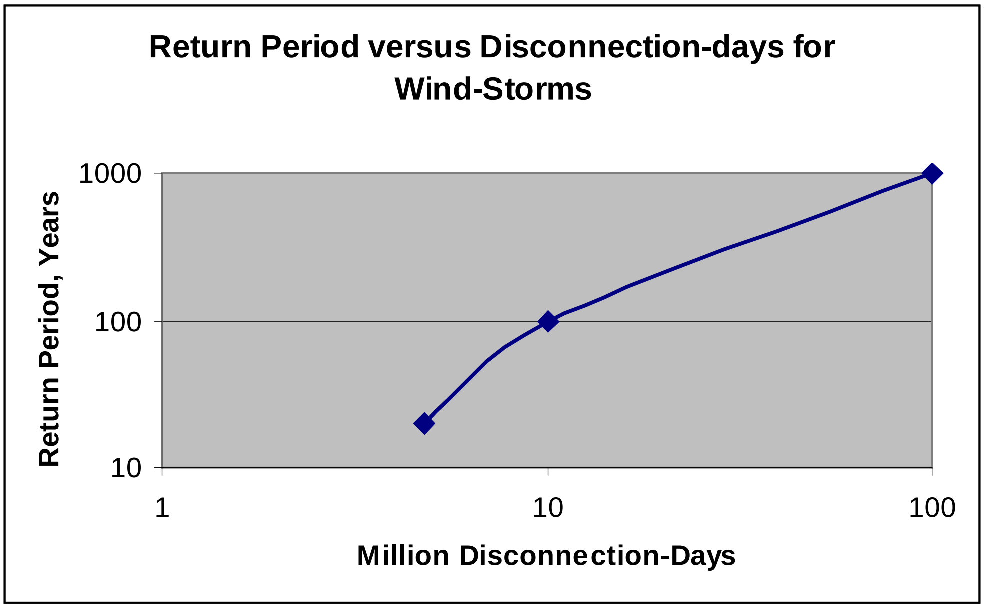
On the night of December 24-25, 1999, a vast counter clockwise circulation associated with a depression over England brought Arctic air from north-eastern Greenland down to interact with tropical air circulating around the Bermuda High. Lothar developed along the cold front where these air masses met. The location and strength of the jet stream that ran above this front turned a small vortex disturbance into the most intense cyclonic depression to make landfall in Western Europe in a decade. There was a marked boundary to the south, with warm moist air raised into the upper atmosphere by the intense convective activity over the Caribbean during December. At 9-km (6-mi) elevation on Christmas Day, the jet stream reached 400 km/h (250 mph), evidenced by Christmas Day flights from New York to London that arrived 90 minutes ***early***.

Hypothetical UK Loss of Grid due to Storm.

From the data on Lothar, Martin and 1987J summarized in the earlier part of this Report, I have deduced that storms having a return period of 100years will cause a loss of an average of 10% of electric-power to UK consumers for a period of 5 days, leading to 10 million disconnection-days.

Similar considerations lead to the forecasts for more frequent and less frequent windstorms. The following Figure shows the relationship between Return Period and Disconnection days for Windstorms:

Figure 12: Forecast Return Period versus Disconnection-Days in the UK: Wind Storms.



The following is an excerpt from the Table contained in the Report on the National Grid. It deals with the more severe of the storms that I have forecast for the UK. It is based on the data on Lothar, Martin and 1987J.

Figure 13: Loss of Grid Due to Severe Storm.

Source of Interruption.	Days: Duration of Consequent Interruption	Per Year: Likelihood	$ Maximum Insurable Amount	mean % of power lost	Million Disconnection.days	
Storm	20	0.001	2E+08	25	100	

We are going to examine the case in which such a storm is accompanied by a nuclear accident, failure of some wind generators and a delay to a LNG tanker bound for the UK. Therefore the likelihood of “our” RDS storm will be lower than 0.001: the RDS storm is part of a subset.

Wind Power.

In this section we are going to examine the impact of our RDS storm on Wind Generation in the UK.

Using a deterministic approach to estimating potential catastrophe losses, one might ask, for example: what would losses be today from a repeat of Daria, the winter storm that caused significant losses in the United Kingdom and continental Europe in 1990? It is interesting to speculate on these questions and catastrophe models are, in fact, well equipped to provide reliable loss estimates in response. As intriguing as such questions are, however, we also know that an exact repeat of these or other historical events has near zero probability of occurrence.

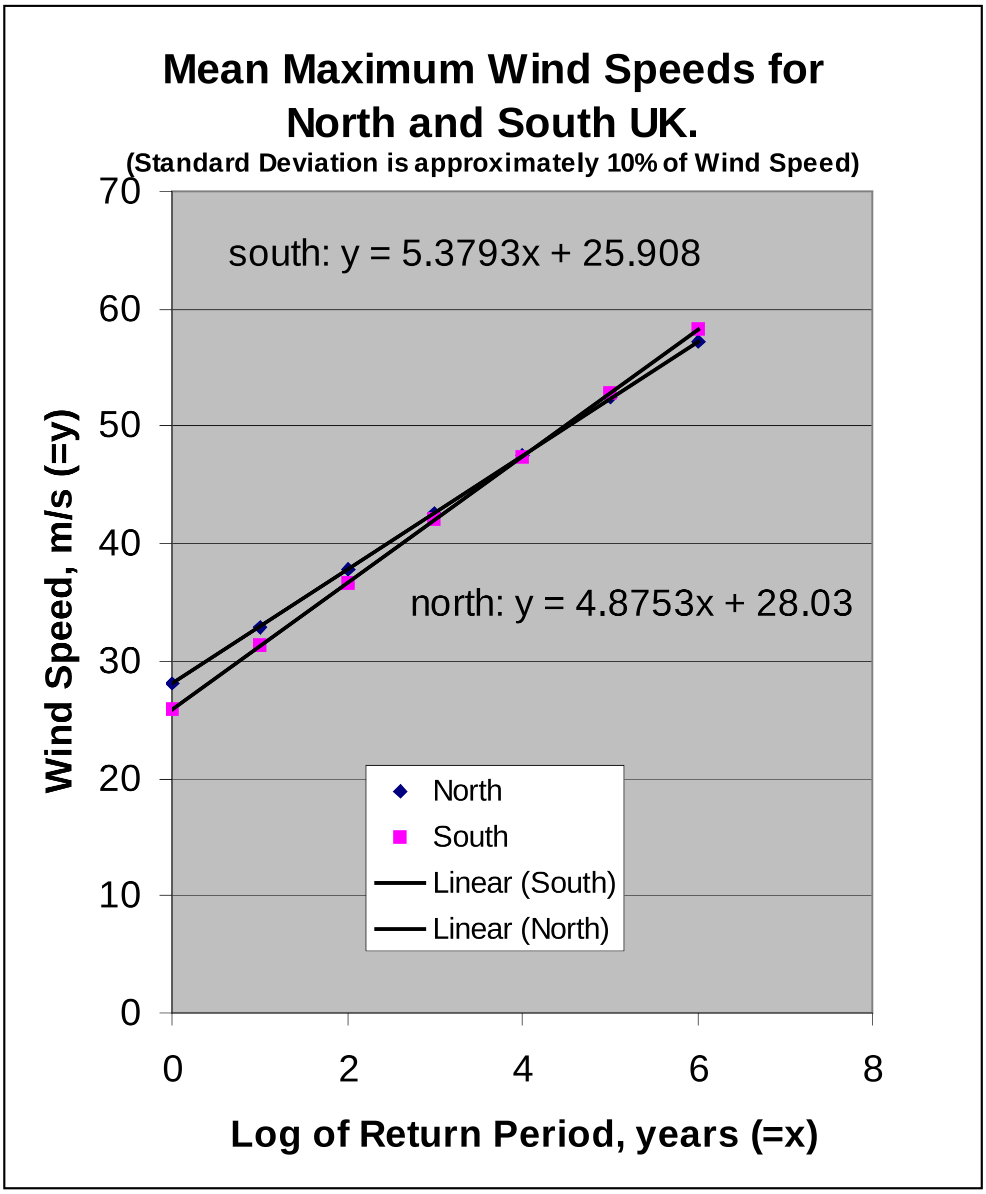
A more interesting question, then, is: what would losses there have been had Daria taken only a slightly more northerly course than it did and swept directly across London, much as winter storm Lothar roared through Paris in late 1999? What about a ``Super Daria" that is more intense and larger than the real Daria? There are many more scenarios that one might imagine. This is exactly what the event generation component of catastrophe models is designed to do: generate all types of possible, yet realistic, scenarios. Furthermore, because these events are being generated using high-speed computers, many thousands of potential events can be simulated in accordance with their relative probability of occurrence. Detailed scientific analyses are performed on the historical and geophysical data to develop the probability estimates. Through this large sample, or catalog, of simulated events, the event generation component determines the frequency, magnitude, and other primary characteristics of potential catastrophe events by geographical location.

The wind speed is always fluctuating, and thus the energy content of the wind is always changing. Exactly how large the variation is depends both on the weather and on local surface conditions and obstacles. Energy output from a wind turbine will vary as the wind varies, although the most rapid variations will to some extent be compensated for by the inertia of the wind turbine rotor.

In storms there is the possibility that wind turbines will be damaged. They are provided with over-speed protection and are designed to resist storm- force winds, but these provisions will fail with a calculable probability.

I have calculated the return periods of the mean maximum wind speed for the north and south of Great Britain. The results are given in Figure 14

Figure 14: Mean Maximum Wind speeds for North and South UK.



Wind generators are normally designed to resist the wind that has a return period of 50 years. We see that this has a velocity of just over 30 m/s, whereas at longer return periods much greater velocities are forecast: about 50 m/s with a return period of 10,000 years and, allowing for the 10% standard deviation of these predictions, around 60 m/s with a return period of 1,000,000 years. These are the mean maximum wind speeds and gusts of substantially higher velocities are to be expected (Figure 15).

Figure 15: The Highest Wind speeds Recorded in the UK.

Low-level site:	123 knots	Fraserburgh, Aberdeenshire, 13 February 1989
High-level site:	150 knots	Cairngorm (1,245 m AMSL), 20 March 1986

In the UK, the storms that generate these wind speeds cover areas equal to or greater than that of the whole country. They last on average for an entire day.

My forecasts have been made using the techniques developed at Riso Laboratory in the EU Joule programme, [5] for the frequency with which storms will interrupt the UK's wind generation, for the case where the UK has 7 Gwe of installed wind generation capacity.

The verification of the structural integrity of a wind turbine structure involves analyses of fatigue loading as well as extreme loading arising from the environmental wind climate. With the trend of persistently growing turbines, the extreme loading seems to become relatively more important. The extreme loading to be assessed in an ultimate limit state analyses may result from a number of extreme load events including transient operation (start/stop sequences), faults, and extreme wind events. Examples of extreme wind events are extreme mean wind speeds with a recurrence period of 50 years, extreme wind shear, extreme wind speed gusts and extreme wind direction gusts. The present analysis addresses extreme wind turbine loading arising only from (a particular class of) extreme wind events included in the IEC-standard (IEC 61400-1, 1998) as extreme load conditions that must be considered as ultimate load cases when designing a wind turbine.

Within the framework of the IEC-standard, these load situations are defined in terms of two independent site variables - a reference mean wind speed and a characteristic turbulence intensity. The available experimental data material relates to the mean wind speed regime between 5m/s and 25m/s, and the present analysis is consequently limited to extreme wind conditions occurring during normal operation of the wind turbine. In the code these are described exclusively in terms of the turbulence intensity. In addition to the code, which is somewhat empirically based, theoretical models, based on probabilistic analysis of multi-variate random processes, exist that predict probability density functions of gust events. Also these models rely heavily on

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[5] Riso Report R 1111 EN. Gunner Chr. Larsen, Knut Ronold, Hans E. Jørgensen, Kimon Argyriadis and Jaap de Boer, 2002.

the site turbulence intensity. Thus the turbulence intensity - defined as the standard deviation of the wind speed divided by the mean wind speed - is the crucial parameter concerning modelling of this class of extreme wind conditions.

The standard deviation of the horizontal turbulence component plays a prominent role in the IEC 61400-1 formulation of the fatigue and extreme loading of wind turbines. The values for the class B turbulence intensities in the code claim to represent an 80% quantile level for a data material including measured turbulence characteristics covering “all wind turbine relevant (on-shore) sites”. The turbulence intensity specification in the code is thus intended to represent the turbulence characteristics of many different sites rather than to give precise information of one particular site.

IEC 61400-1 does not provide any specific information on turbulence intensities suitable for offshore sites. Although differences in wind climates for off-shore sites definitely exist, these differences seem smaller than the mutual differences between wind climates related to on-shore sites in general, where large variations in terrain forms inevitably are represented. It is consequently expected that data from relative few offshore sites can provide sufficient information to give a general idea of the off-shore wind climate. The extreme loading relates to atmospheric turbulence described in terms of a statistically stationary process.

Without the cutout speed included in the reliability analysis, the variability in the mean wind speed would have become a much more important uncertainty source with a design point value in the range 35-40 m/sec, which is unrealistic for operation of the wind turbine. This would have led to a significantly higher failure probability in ultimate loading than the one reported here.

The results of these calculations are shown in Figure 16, which shows that the return period of wind speeds that will cause 50% of the wind turbines to fail is 2000 years. Storms that produce this wind velocity typically cover an area similar to that of the UK and it is assessed that half the wind turbines would be subjected to these wind speeds.

Figure 16: Design Wind Speed and Return Speed for Wind Turbine Failure.

Design Life, years	Design Speed, m/s	25% Above Design Speed.	Return period of 25% over design velocity, y
50	35	44	2000

Figure 17 shows my forecast for the interruption of wind-generation in the UK. I assume that there is 7 Gwe of wind generators. The data are taken from the summary table in my Report on Wind Power.

Figure 17: Interruption of Wind-Generation in the UK by Severe Storms.

Source of Interruption.	Days: Duration of Consequent Interruption	Per Year: Likelihood	GBP Maximum Insurable Amount	Loss, Gwe.d	Loss, GWe	% of wind power lost
Storm	180	0.0005	2E+08	315	1.75	25

Liquid Natural Gas.

We consider the scenario in which the UK receives LNG from France and France receives it by Tanker from Algeria. Details are given in my Report on LNG.

The most likely effects of storms on LNG are delays to shipping. Annex 1 shows details of the 30 shipping accidents that have occurred during the period since 1964 during which LNG has been moved around the world in Tankers. Of these accidents, many were attributable to bad weather and caused a delay to the delivery of LNG from a single Tanker.

These accidents resulted in the interruption of a trip and we shall assume that this interruption was the equivalent to the cancellation of that trip. As each trip is part of a contract, save for those undertaken for the spot market, supplies will have been made up by additional trips and on-land storage will have usually served to even out the amounts of regasified LNG pumped into the customer-country's gas pipelines. However, this effect of storage is a separate issue, to be included separately as a distinct factor in the estimation of the UK's future of electricity supplies.

The overall safety record compiled by LNG ships during the thirty-nine year period 1964 - 2002 has been remarkably good. During this period, the LNG tank ship fleet has delivered more than 30,000 shiploads of LNG, and traveled more than 100 million kilometers while loaded (and a similar distance on ballast voyages).

There are approximately 200 LNG tankers today and each could make the round trip from Algeria to France at least 20 times per year, making a total of 4,000 such trips per year. Of course they are engaged on other trips, for the most part, but those trips are equivalent to 4,000 round trips between Algeria and France. Fifty years ago the number of such equivalent round trips was virtually zero and so, on the assumption that the number of equivalent round trips per year has risen monotonically between 0 and 4000 in 50 years, the total number of round trips is of order 100,000. The same result is obtained when it is considered that the LNG tank ship fleet has traveled more than 100 million kilometers while loaded (and a similar distance on ballast voyages). The distance between Algeria and France being of order 1,000 km, it follows that the equivalent of 100,000 round trips has been covered.

The frequency with which Tanker Accidents, mostly due to weather, can be expected to cause interruption of supplies of LNG destined (after regasification in France) for the UK is then 30/100,000 trips and as 163 trips per year will be required to supply the UK's LNG this frequency is 0.049/year or once in twenty years. This would deprive the UK of gas for 3.125 days per round trip interrupted.

Figure 11 is an excerpt from the summary table in my Report on LNG. It shows the interruption of UK LNG supplies attributable to bad weather. The frequency of interruption is 0.0489/year but only a subset of these losses will be in storms that also interrupt other supplies of electricity, such as nuclear, windpower and the national grid itself.

Figure 18: Loss of LNG Supplies due to Tanker Accident in Bad Weather.

Source of Interruption.	Days: Duration	Per Year: Likelihood	$ Maximum Insurable Amount	Loss, bcm/day	LNG
Algeria Tanker Accident	5	0.0489	1E+08	0.026849	LNG

Combined Effects for the Storm RDS.

Figure 19 summarizes the combined effects of the storm RDS. It results in a loss of about 650 Gwe.d of electricity, with a return period of 3580 years.

Figure 19. Storm Realistic Disaster Scenario. Forecast Frequency and Losses.

STORM.	Source of Electricity	Interrupted for, days.	Loss.
RETURN PERIOD, YEARS	Wind	180	315 Gwe.d
3580	Nuclear	180	180 Gwe.d
	LNG	5	0.13 bcm.
	Grid	20	100 million connection.days.

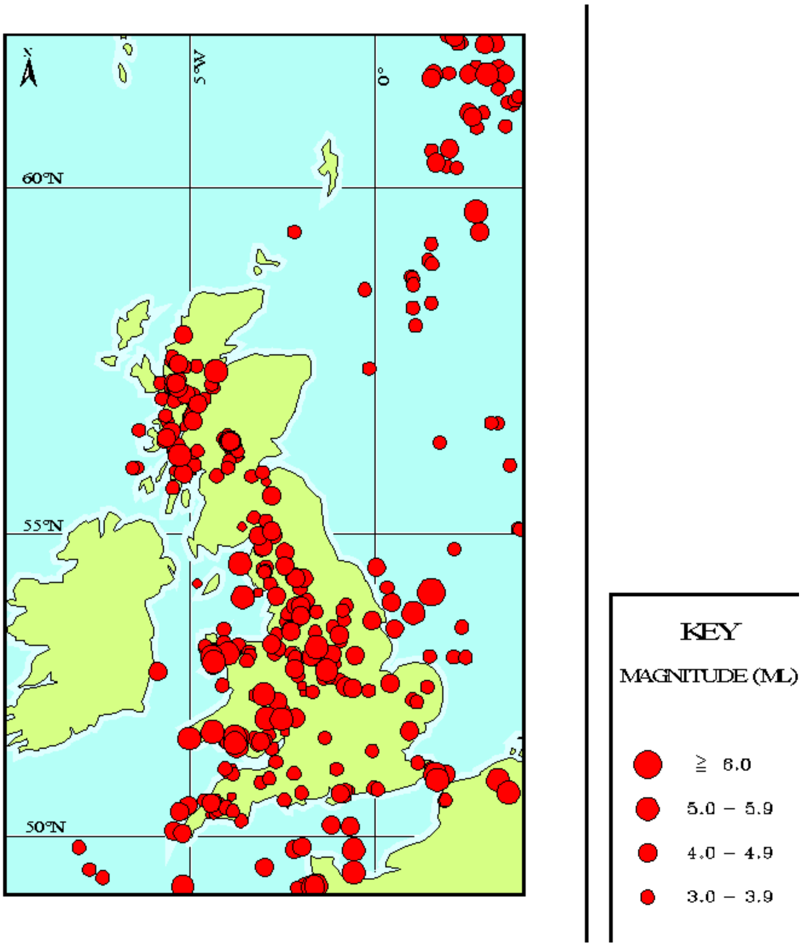
Realistic Disaster Scenario No 2: Earthquake.

Earthquake

The UK is not a country generally associated in the public mind with earthquakes. However, while the UK is nowhere near in the same league as high seismicity areas such as California and Japan, it nevertheless has a moderate rate of seismicity, sufficiently high to pose a potential hazard to sensitive installations such as dams, wind generators and chemical plants.

Figure 20: Regions of Raised Seismic Intensity, UK and Continent, The darker the yellow colour, the more seismically active the zone.

Figure 21: Earthquakes in the UK and its coastal waters.



The spatial distribution of earthquakes in the UK is neither uniform nor random. For example, in Scotland most earthquakes are concentrated on the west coast, between Ullapool and Dunoon, with the addition of centres of activity near the Great Glen at Inverness and Glen Spean, and a small area around Comrie, Perthshire, and extending south to Stirling and Glasgow. The Outer Hebrides, the extreme north and most of the east of Scotland are virtually devoid of earthquakes. For the north-west of Scotland the absence of early written records, the small population, and the recent lack of recording instruments means that there may be a data gap in the context of an apparent event in 1925, possibly near Ullapool, with magnitude probably about 3½ ML, for which there are no first-hand reports. However, many other parts of Scotland, especially south of the Highland line, are quite well-documented, at least since 1600, and therefore the lack of earthquakes is genuine.

Further south a similar irregularity is seen. If one draws a quadrilateral from Penzance to Holyhead to Carlisle to Doncaster, most English and Welsh earthquakes will be included within it. The northeast of England seems to be very quiet; almost aseismic. The southeast has a higher rate of activity, with a number of earthquakes which seem to be "one-off" occurrences. The most notable example of these is the 1884 Colchester earthquake, a magnitude 4.6 ML event which was the most damaging British earthquake in at least the last 400 years, and yet which occurred in an area (Essex) otherwise more or less devoid of earthquakes from the earliest historical period up to the present day (Musson et al 1990). There are also important centres of activity near Chichester and Dover. The former produced a swarm-like series of small, high-intensity earthquakes in the 1830s and was active again in 1963 and 1970.

Offshore, there is significant activity in the English Channel and off the coast of Humberside. Because only the larger events in these places are likely to be felt onshore, the catalogue in the pre-instrumental period is probably under-representative of the true rate of earthquake activity in these zones. Even after the introduction of seismometers, offshore earthquakes may still have gone unnoticed on account of the distance to the nearest instruments. The Central Grabens of the North Sea are now known to be active features, only because of the improvements in instrumental monitoring over the last fifteen years.

The whole of Ireland is practically free of earthquakes. This is clearly a real phenomenon and not a product of reporting - as Ware, as early as the 17th century, remarks in describing an earthquake (probably Welsh) felt in Dublin in 1534, *"... qui casus adeo rarus est in Hibernia, ut quando contingit, inter prodigia habeatur"* [loosely, which is such a rare thing in Ireland that when it happens it is considered a wonder].

Certain centres can be identified as showing typical patterns of activity. For example, the Caernarvon area of north-west Wales is one of the most seismically active places in the whole UK. Both large and small earthquakes, usually accompanied by many aftershocks, occur at regular intervals. The most recent of these larger events was the earthquake of 19 July 1984 (5.4 ML), which was one of the largest ever UK earthquakes to have an epicentre on land and had a very protracted aftershock sequence. Two further felt earthquakes have occurred there since, on 29 July 1992

(3.5 ML) and 10 February 1994 (2.9 ML). It is tempting to ascribe several early earthquakes of unknown epicentre (eg that of 20 February 1247) to this area just because it seems to be such a favoured site for large earthquakes.

In South Wales, on the other hand, although a line of epicentres of significant events can be traced from Pembroke (an earthquake in 1892) to Newport (active in 1974), only the Swansea area shows consistent recurrence, with significant earthquakes occurring in 1727, 1775, 1832, 1868 and 1906. (Given this periodicity it may be that a further earthquake in this area is due in the near future.) The Hereford-Shropshire area has also produced large earthquakes in 1863, 1896, 1926 and 1990, but none of these share a common epicentre.

The area of the Dover Straits is particularly significant because of the occurrence there of two of the largest British earthquakes in 1382 and 1580 (both of magnitude about 5¾ ML). Since 1580 the only earthquakes there have been much smaller, raising the question of whether there is a danger of another 1580-style earthquake in the near future. The area may be structurally continuous with a zone of activity running east through Belgium, in which case it could be argued that stress in this area since 1580 has been released further east. This does not rule out another 1580-type earthquake in the future, but it is impossible to estimate how soon it might occur.

In the north of England seismic activity occurs over a more or less continuous area from Leicester to Carlisle. The most prominent centres of repeating activity here are the upper end of Wensleydale (with significant earthquakes in 1768, 1780, 1871, 1933 and 1970) and to a lesser extent the Skipton area.
What is remarkable is the lack of correlation between this pattern and the structural geology of the UK.

The boundaries between areas of moderate or high seismicity and areas of very low seismicity do not correspond to any major structural feature; for instance the sharp dividing line running SE from Inverness. And the major boundaries are not clearly reflected in the pattern of seismicity either as dividing lines between zones of differing rates of seismicity nor as lineations marked by earthquakes. It seems likely that the pattern of seismicity may be influenced by the distribution of ice during the last glaciation - certainly for Scotland this appears to be the case.

The distribution of British earthquakes in time

Earthquakes are not rare in the UK, as Figure 22 shows there have been ten in March 2003.

Figure 22:This map created at Tuesday March 25 08:42:25 GMT 2003

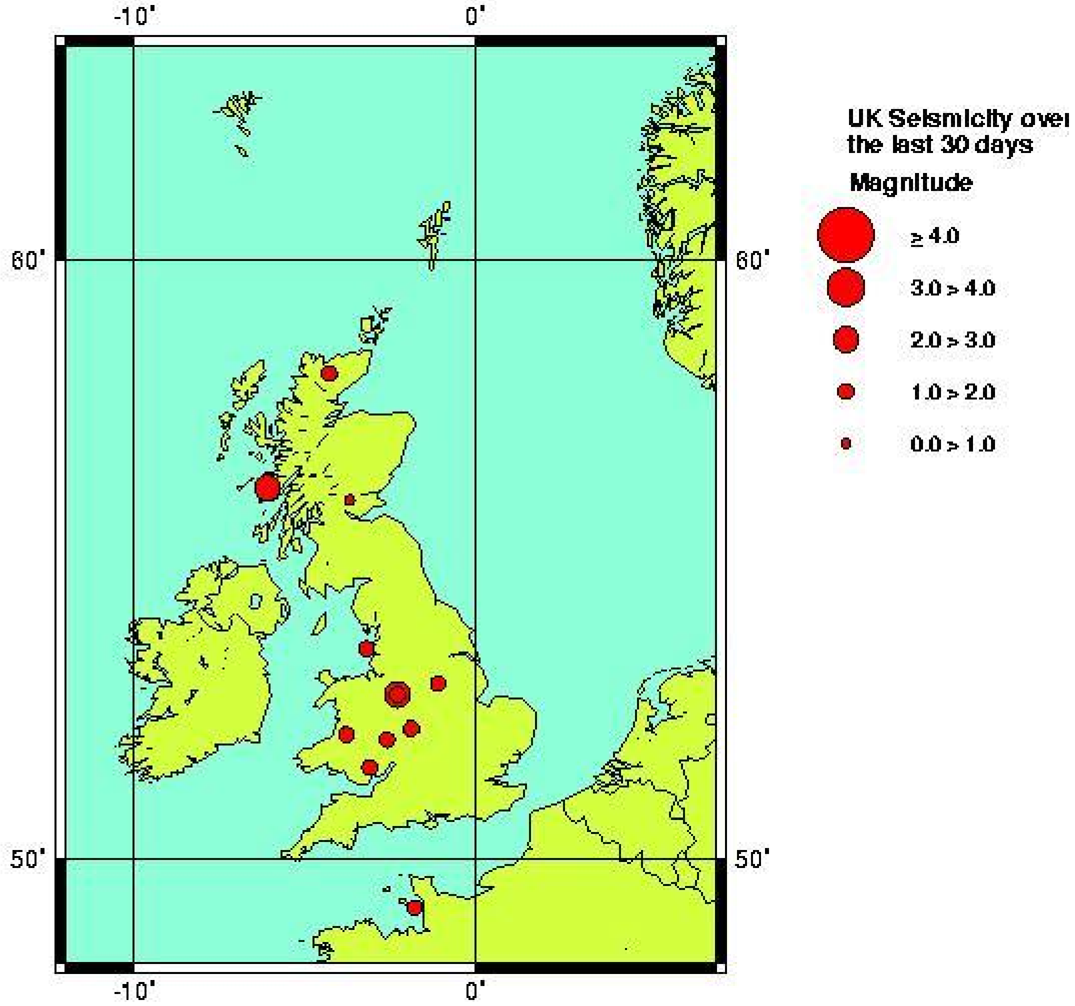
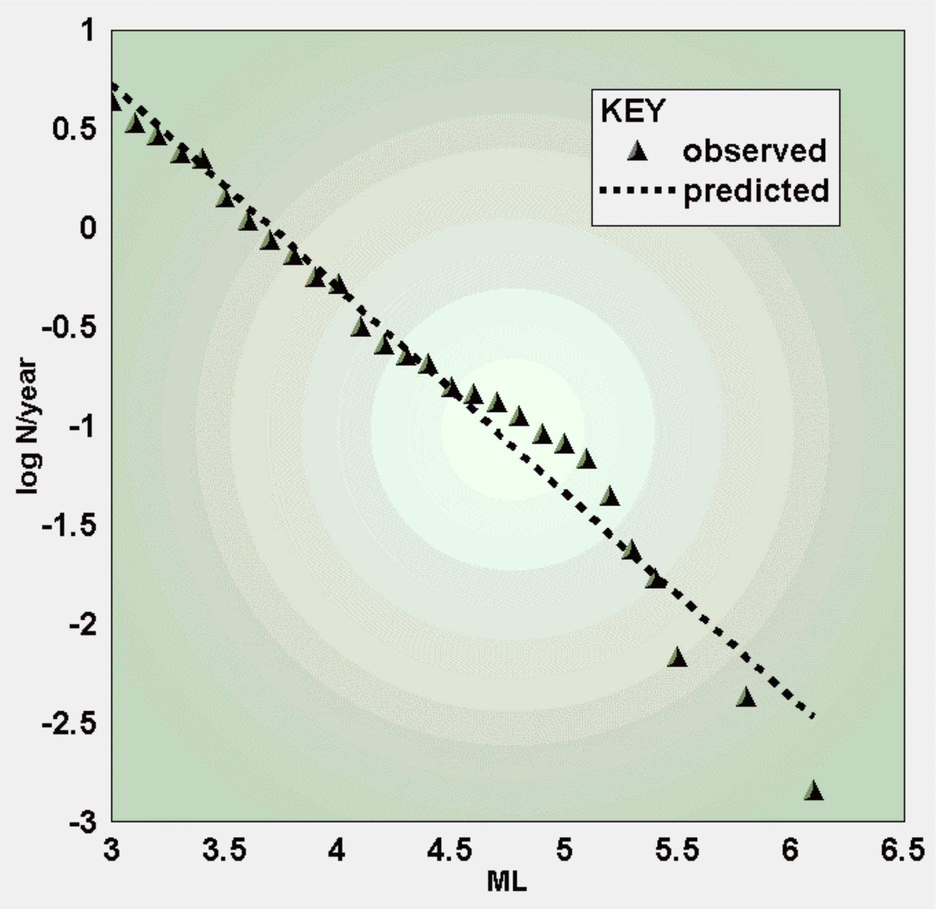


Figure 23: Frequency of Exceedance Versus UK Earthquake Intensity.



It has long been realised that larger earthquakes occur less frequently than smaller earthquakes, the relationship being exponential, ie roughly ten times as many earthquakes larger than 4 ML occur in a particular time period than earthquakes larger than magnitude 5 ML. This can be expressed by the Gutenberg-Richter formula

log N = a - b M

where N is the number of earthquakes per year exceeding a given magnitude M. The constant a reflects the absolute level of seismicity in an area, and the value of b has generally been found to be consistently close to 1.0.

This holds true for the UK for the area 10o W to 2o E and 49o N to 59o N. This deliberately excludes the northern North Sea area which is of high seismicity and completely under-represented in the catalogue before 1970 because of the impossibility of detecting smaller events in this area before that date. A least-squares regression to the UK data of Figure 23 gives the relationship

$$\log N = 3.82 - 1.03 M$$

One can therefore draw the following conclusions about average recurrence - the UK may expect:

- an earthquake of 3.7 ML or larger every 1 year
- an earthquake of 4.7 ML or larger every 10 years
- an earthquake of 5.6 ML or larger every 100 years.

Seismic hazard calculations

Seismic hazard calculations in regions of low seismicity, such as the UK, are generally based on probabilistic methodology. Probabilistic seismic hazard assessment (PSHA) uses a combination of interpreted geological and seismological data to calculate the probability that a certain level of ground motion will be exceeded, or not exceeded, in a given period of time. This methodology can be divided into three principal components as follows:

(i) Definition of a set of seismic source zones which define the geographical variation of earthquake activity. These source zones are based on the distribution of observed seismic activity together with geological and tectonic factors and represent areas where the seismicity is assumed to be homogenous; ie there is an equal chance that a given earthquake will occur at any point in the zone.
(ii) An understanding of earthquake recurrence with respect to earthquake magnitude, as described above.
iii) An attenuation relationship is required which defines what ground motion should be expected at Location A due to an earthquake of known magnitude at Location B. The rate at which the strength of shaking decreases with distance from an earthquake's epicentre varies regionally and has to be calculated or estimated. Peak ground acceleration (pga) is the measure of earthquake shaking most used by engineers in this country. However, it has two disadvantages - firstly, the attenuation of pga in the UK is very poorly known, and secondly, pga is actually not a particularly good measure of the actual expectation of damage. A useful alternative is intensity, which is an expression of ground shaking in terms of its effects. The attenuation of intensity in the UK is very well documented, and intensity is directly proportional to damage, making it a very meaningful parameter.

The intensity attenuation model used here is expressed by the formula

$I = 3.32 + 1.44\ ML - 3.34 \log R$

where ML is local magnitude and R is hypocentral distance in kilometres. The data that I have used to produce this formula are found in Musson [6] .

Seismic hazard studies in the UK in the past have been mostly single-site studies for particular installations. The first attempt to look at hazard for the UK as a whole using the PSHA methodology was conducted by Ove Arup around 1991. This study calculated hazard at eleven representative sites in the UK. Following this, a study to produce contour maps of UK seismic hazard was commissioned by the Department of Trade and Industry. In this study the computer code SUNMIC was used, which allows a "logic tree" model to be applied to the hazard, by which uncertainty in input parameters can be modelled by the inclusion of multiple choices each with a weighting value).
One of the innovations used in this study was the approach taken to source zone modelling. If several significantly different source zone models are included in a logic tree model without regard for their combined effect, the result tends to be that the conflicting source zones smear one another out into a semi-uniform distribution of hazard; meaningfulness is lost. In this study, two mutually supportive zone models were constructed; one consisted of relatively broad zones based chiefly on the general regional trends observed in the seismicity data. The second consisted of much smaller zones closely placed around sites of known large earthquakes, the size of these zones being roughly related to the degree of uncertainty in the epicentral location. The result of the combination of these two models was a hazard map in which the general areas where earthquakes might be expected to occur would have higher hazard, but within these, spots where such earthquakes had occurred in the past were picked out as having locally higher hazard values.

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[6] Musson, R.M.W., 1994a. A catalogue of British earthquakes, BGS Technical Report No WL/94/04.

Seismic hazard results

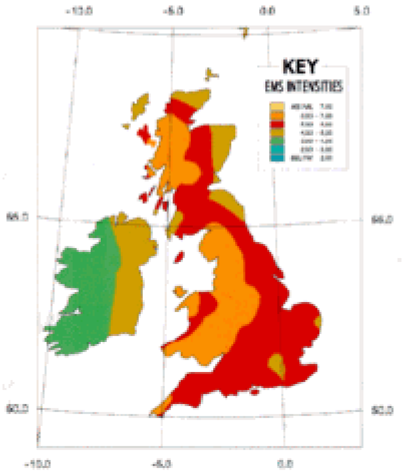
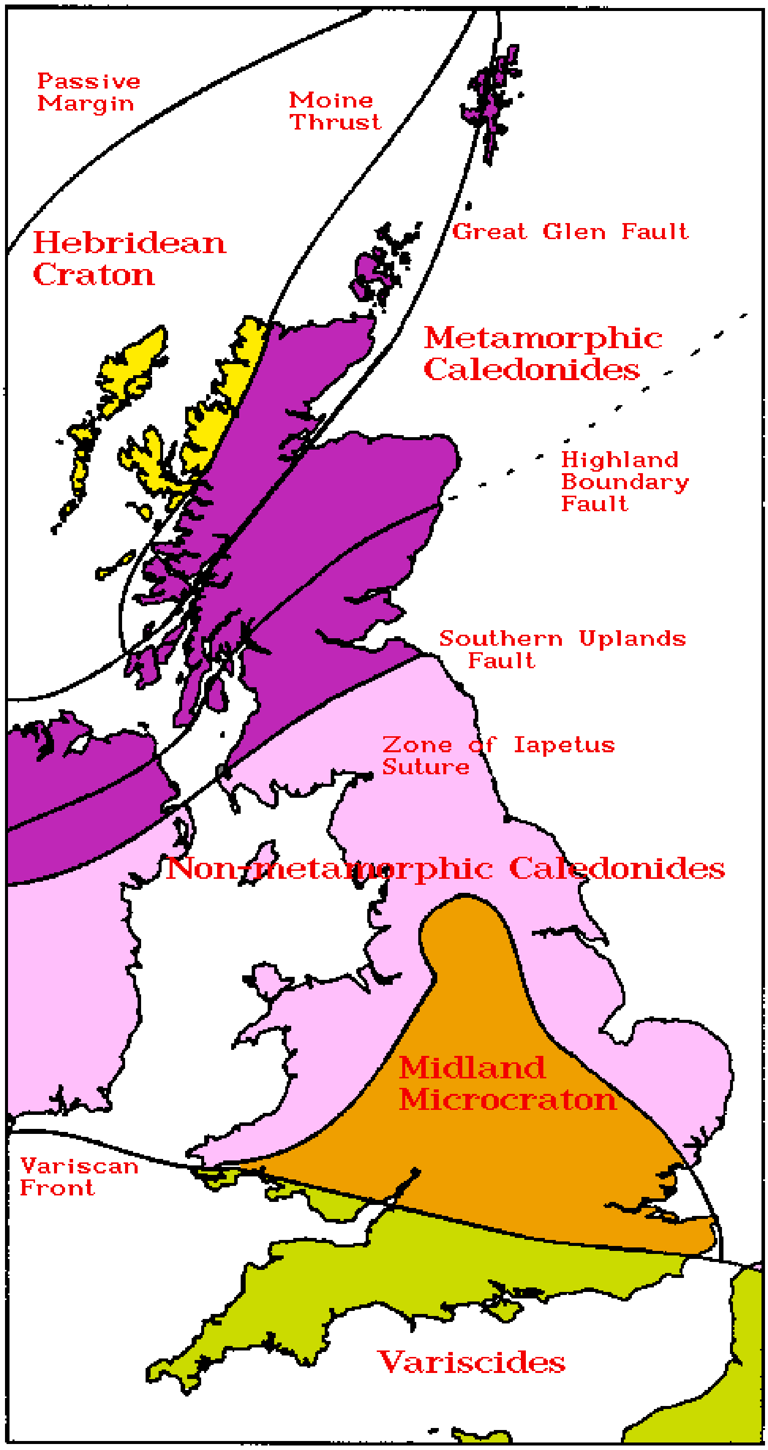


Figure 24 Seismic Hazard Map of the UK.

Figure 25: Tectonic Map of the UK, for comparison with Seismic Hazard Map.



A sample hazard map of the UK is shown in Figure 24.

The map shows intensities that are 90% likely not to be exceeded in 50 years - equivalent to a return period of 475 years.

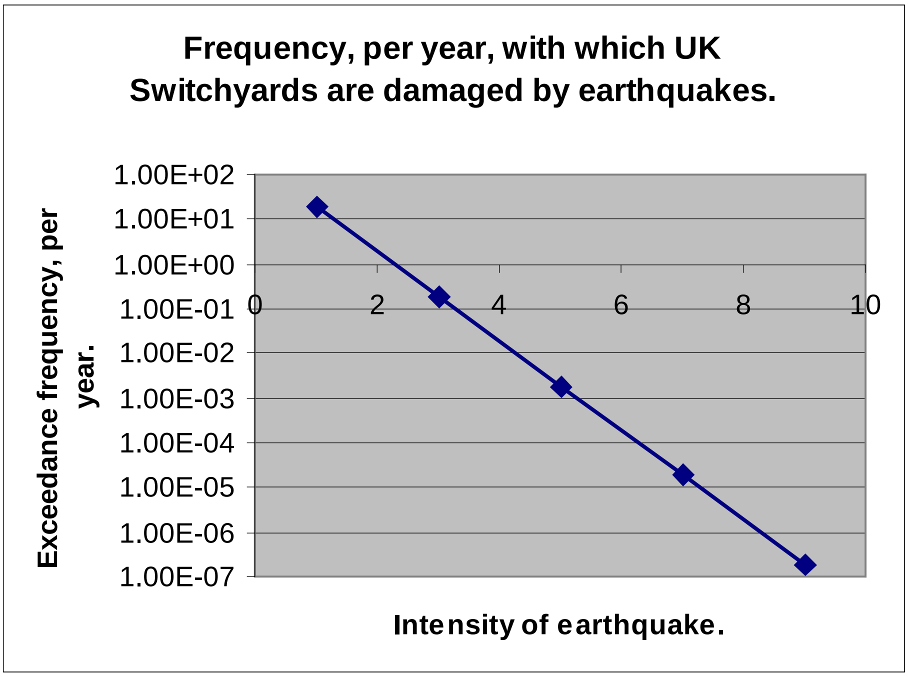
As might be expected, the areas of highest hazard parallel the areas where earthquakes have been most common in the past, but particularly those places where repeated earthquake activity has been highly localised - this localisation has a pronounced effect on the hazard calculations compared to areas where the seismicity, while high, is more diffuse and less repetitive. The zones where hazard is higher than average encompass the W Highlands of Scotland, an arc running from Carlisle to Pembroke, NW Wales and W Cornwall. The places in the UK with lowest seismic hazard are Northern Ireland (especially the western counties) and outlying parts of Scotland, including the Orkneys and Outer Hebrides.

The actual values of hazard are not particularly high, since the predicted intensity for the higher zones is only 6 EMS. In other words, even in areas of relatively high exposure to earthquakes in the UK, if a facility has a life of 50 years there is only a 10% chance that it will experience shaking equivalent to intensity 6. Moving briefly from hazard to risk, if we take as a guideline that probably less than 5% of buildings of normal construction (eg conventional brick houses) will be damaged in a place when the intensity there is 6, the probability of damage for a single house in 50 years is therefore less than 0.5%.

Seismic Interruption of Grid Connections.

The Exceedance frequency with which UK Switchyards and other transmission-structures are forecast to suffer earthquakes of various intensities is shown in Figure 26: Exceedance Frequency with which UK Switchyards will suffer earthquakes of stated intensity..

Figure 26: Exceedance Frequency with which UK Switchyards will suffer earthquakes of stated intensity.



From this analysis we arrive at the frequencies in Figure 27 for grid-disconnections due to seismic interruptions.

Figure 27: Effect of Earthquake on Grid Disconnections.

Source of Interruption.	Days: Duration of Consequent Interruption	Per Year: Likelihood	$ Maximum Insurable Amount	mean % of power lost	Million Disconnection.days
Seismic	70	0.0002	1E+08	5	70

Seismic Interruption of Gas Supplies.

The design of the equipment used to pump and distribute gas embodies the concepts of Lines of Defence, LOD. A strong LOD comprises engineered safeguards. A weak LOD includes human factors.

The frequency with which a strong LOD fails is of order 0.0001/year. The frequency with which a weak LOD fails is 0.01/year.

Seismically-Induced Minor Equipment Failure.

The scenario that I consider here is minor equipment failure due to earthquake for example.

The design of the equipment is such that the frequency with which this happens will be the frequency with which a weak Line of Defence (LOD) fails, i.e. 0.01/year, for all causes, of which earthquake is one cause.

Major Equipment Failure.

Here the scenario is that, due to internal or external events, there is a release of gas from a small fracture followed by fire that renders pumps inoperative.

The design of the equipment is such that the frequency with which this happens will be the frequency with which a strong Line of Defence (LOD) fails, i.e. 0.001/year. Again this is the failure rate for all causes of such accidents, including earthquakes.

In Figure 28 we show the frequencies for Minor Equipment failure. A small proportion of these will be due to earthquakes.

Figure 28: Frequencies with which Earthquakes and other External accidents will interrupt gas supplies.

GAS	Frequency/year	% Flow	Duration of Interruption, days	fraction of year during which flow is reduced	% of Year's flow lost	% of year's contract uk receives
Minor Equipment Failure.	0.01	0.9	10	0.027397	0.00274	0.99726

Figure 29: Combined Effects upon Gas and Grid Connections of the Earthquake with Return Period of 5,000 years.

SEISMIC	Source of Electricity	Interrupted for, days.	Loss.
RETURN PERIOD, YEARS	Gas	10	0.00274% of Year's Contract lost
5000	Grid	70	70million disconnection-days

Political Action.

Interruptions to LNG Supplies.

From worksheet "POLITICAL RISKS AND PREMIUMS" from the Workbook "LNG MASTER" the following values for Political Risks and Political Risk Insurance Premiums are taken, for Qatar. For comparison, values for Algeria and the UK are given:

Figure 30: Political Risk Indices and Insurance Premiums for Qatar, with comparative values for UK and Algeria.

	2002 Premium	2002 Political Risk.	2020 Premium	2020 Political Risk
Qatar	0.60%	24	0.72%	37
Algeria	2%	53	2%	53
UK	0.10%	11	0.08%	8

Then following the methods used above for Algeria we have:

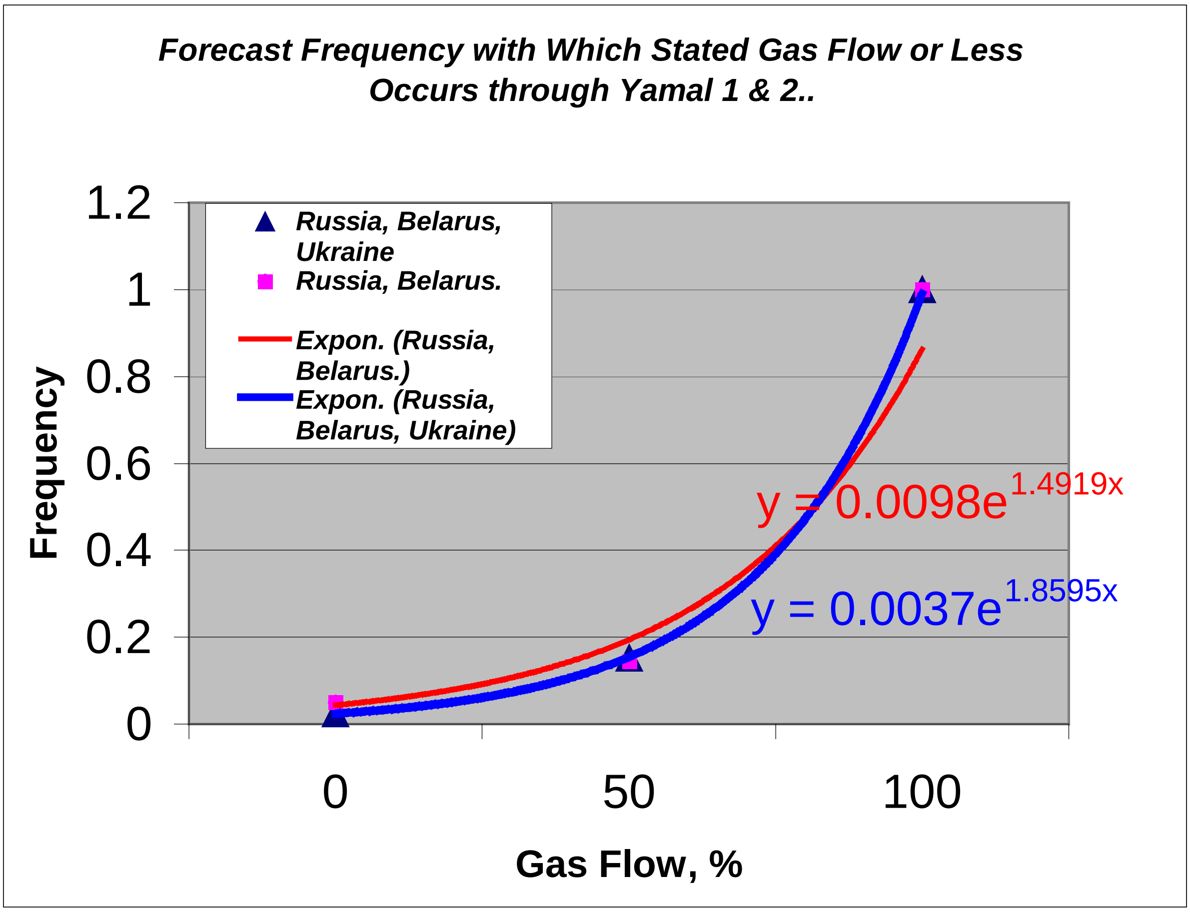
Figure 31: Political Risk of Interruption of Supplies of LNG from Qatar.

Source of Interruption.	Days: Duration	Per Year: Likelihood	$ Maximum Insurable Amount	Loss, bcm/day
Political Risk in Qatar	90	0.072	1E+08	0.026849

Interruptions to Gas Supplies.

By 2020 most of the UK's natural gas, on present forecasts, will come from Russia. The main gas reserves are in the Yamal region (Yamal means "end of the earth") and they will arrive in Western Europe via two pipelines, Yamal-Europe 1 and Yamal-Europe 2. Figure 35 shows my forecasts of the frequencies with which gas flows of various magnitudes will occur through these two families of pipelines. The flows are interrupted by political action, the frequency of which I calculate from data bases on political risk and political insurance premiums that have been formulated in the finance and insurance sectors.

Figure 32: Figure: Forecast Frequency with Which the Stated Gas Flow, or Less, will Occur from Yamal in 2020.



It is forecast that, irrespective of whether or not one of the two Yamal-Europe gas pipelines passes through Ukraine:

- There will be no Yamal gas flow to the UK for a few percent of the time.For about 15% of the time, Yamal gas will flow to the UK at 50% or less than the intended rate.

Forecasts of Interruptions to Gas from Iran and Russia.

Iran has been chosen as it has the second largest reserves of natural gas in the world, second only to Russia. Iran and Russia are making preparations to supply Europe with natural gas. However, in order to boost oil and natural gas exports from the Caspian Sea region, a number of issues will need to be addressed. During the Soviet era, all of the oil and natural gas pipelines in the Caspian Sea region (aside from those in northern Iran) were designed to link the Soviet Union internally and were routed through Russia.

From the forecast Political Risk indices and Political Risk Insurance Premiums for Iran in the years up to 2020 the following forecasts are produced, and are here tabulated and plotted together with those already presented for Russia to permit a comparison.

We shall assume that the UK imports natural gas from Russia and from Iran.

As has been explained Russia has the largest reserves of natural gas in the world and Iran has the second largest.

We have also seen that Russia and Iran are making preparations to become the world's biggest and second biggest suppliers of natural gas.

We assume that the UK imports natural gas from Iran and Russia in amounts that are proportionate to the natural gas reserves of the two countries.

This means, that of the natural gas which the UK will import from (Iran plus Russia):

- 27% will come from Iran and the balance of
- 73% will come from Russia.

Russia is keen that the gas pipelines from Iran should be routed through Russia. However Iran and its potential customers are aware that there will be a risk that Russia will then interrupt the flow of Iranian gas in order to obtain political or business advantages. There are therefore moves to install pipelines to Europe from Iran that do ***not*** pass through Russia and in the present analysis I have assumed that gas to the UK from Iran flows exclusively through pipelines that pass through countries that present a political risk small enough to be neglected compared to that evidently presented by Iran itself.

In each of the three cases in the following Table and Figure the gas-flow occurs through both of the Yamal-Europe pipelines. Each of the cases contains a forecast of the total of the flows through Yamal 1 and Yamal 2.

The three cases considered in Figure 33 and Figure 34 are as follows:

A. Gas comes to the UK through two pipelines from Russia, one via Belarus and Ukraine; the other via Ukraine,
B. It comes from Russia through two pipelines both of which are routed via Belarus or
C. It comes through three pipelines, one from Iran, the second from Russia via Belarus and Ukraine; the third from Russia via Ukraine

Cases A and B have already been considered in the earlier part of this Report and are here included for the purposes of comparison.

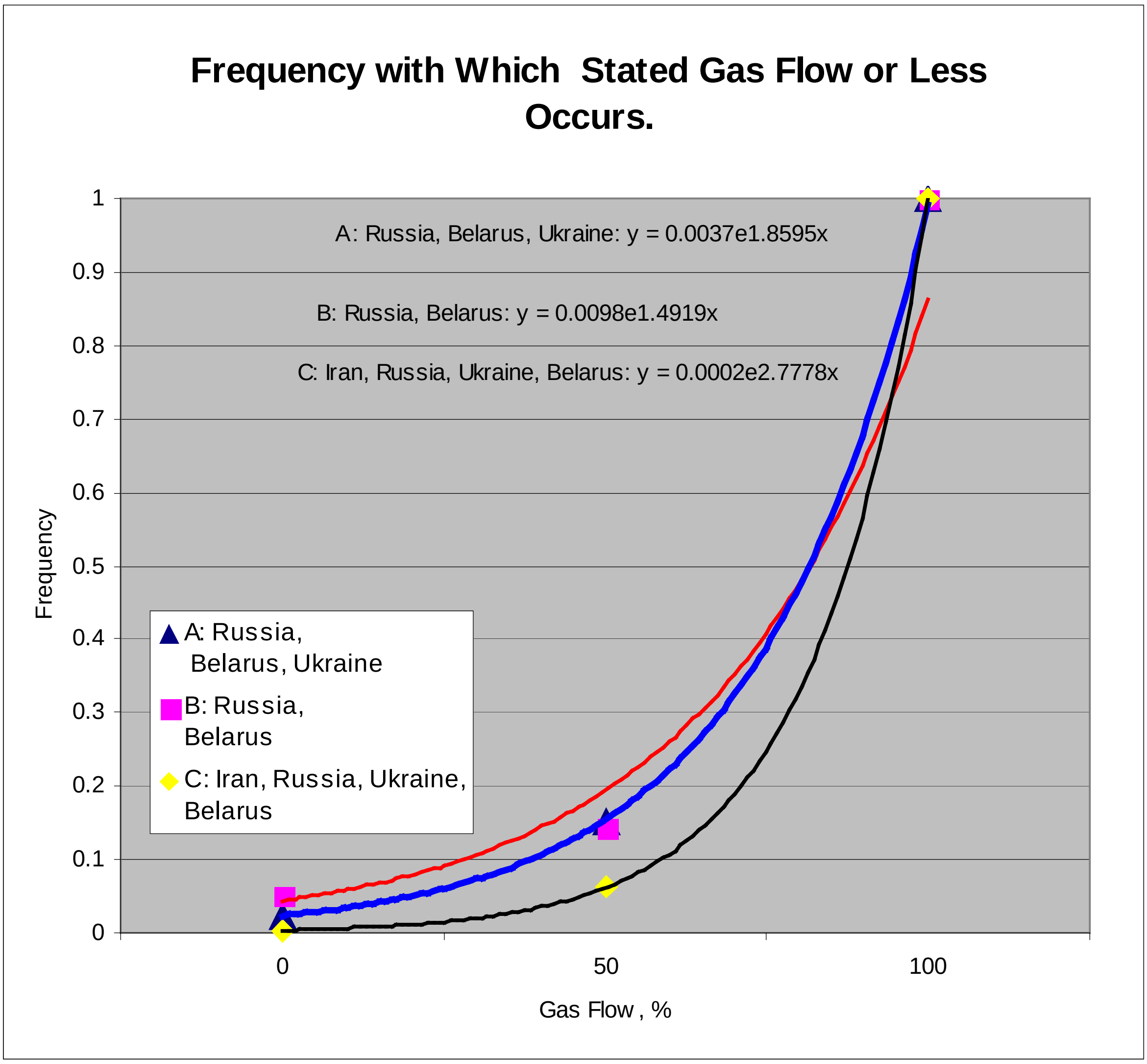
Figure 33: Frequency with which the stated % of Gas or less arrives in UK either

- **A. Through two pipelines from Russia, one via Belarus and Ukraine; the other via Ukraine, or**
- **B. from Russia through two pipelines both of which are routed via Belarus or**
- **C. through three pipelines, one from Iran, the second from Russia via Belarus and Ukraine; the third from Russia via Ukraine**

% of Flow	0%	50%	100%
A. Russia, Belarus, Ukraine	0.024256	0.151744	1
B Russia, Belarus	0.0506	0.1446	1
C Russia, Belarus, Ukraine, Iran	0.004	0.062	1

Figure 34: Frequency with which the stated % of Gas or less arrives in UK either

- **A. Through two pipelines from Russia, one via Belarus and Ukraine; the other via Ukraine, or**
- **B. from Russia through two pipelines both of which are routed via Belarus or**
- **C. through three pipelines, one from Iran, the second from Russia via Belarus and Ukraine; the third from Russia via Ukraine.**



In this analysis I have assumed that if Iran interrupts our gas supplies, then Russia will not decide to join-in. However there will be a chance that this will occur and if it does then we move towards lines A and B in Figure 34.

Thus, an Iranian-Russian task force will be in charge of negotiations on the possible participation of Russian enterprises in joint projects in the fuel and energy sector. An agreement on the creation of this group was achieved at a meeting of Russian Energy Minister Igor Yusufov and Mohammad Froozandeh, the Chairman of the Mostazafan

Foundation, on April 8th 2003. Froozandeh declared the foundation was ready for active collaboration with Russian enterprises. In particular, he mentioned concrete proposals concerning participation of Russian companies in the foundation's large projects aimed at constructing electrical power stations, modernizing thermoelectric power plants, conducting drilling activities on oil and gas fields and supplies of Russian oil and oil products to Iranian northern regions.

Figure 35: Political Risk of Interruption of Supplies of Gas from Russia and Iran.

GAS	Frequency/year	% Flow	Duration of Interruption, days	fraction of year during which flow is reduced
Political Risk in Russia, Ukraine, Belarus and Iran	0.019	0.268075	180	0.493151

Figure 36: Combined Effects upon LNG and Gas Supplies of Simultaneous Political Action in Qatar and Russia or Iran.

POLITICAL	Source of Electricity	Interrupted for, days.	Loss.	
RETURN PERIOD, YEAR	LNG from Qatar	90	2.41641	billion cu m.
263	Gas from Russia and Iran.	180	36.00	% of Year's Contracts.

Annex 1: Chronological Summary of Incidents Involving LNG Ships

1. **1964/1965** 25,500 M$_3$ *Jules Verne*
While loading LNG in Arzew, Algeria, lightning struck the forward vent riser of the ship and ignited vapor, which was being routinely vented through the ship venting system. Loading had been stopped when a thunderstorm broke out near the terminal but the vapor generated by the loading process was being released to the atmosphere. The shore return piping had not yet been in operation. The flame was quickly extinguished by purging with nitrogen through a connection to the riser. A similar event happened early in 1965 while the vessel was at sea shortly after leaving Arzew. The fire was again extinguished using the nitrogen purge connection. In this case, vapor was being vented into the atmosphere during ship transit, as was the normal practice at that time.

2. **May, 1965** 27,400 M$_3$ *Methane Princess*
The LNG loading arms were disconnected before the liquid lines had been completely drained, causing LNG to pass through a leaking closed valve and into a stainless steel drip pan placed underneath the arms. Seawater was applied to the area. Eventually, a star-shaped fracture appeared in the deck plating in spite of the application of the seawater.

3. **May, 1965** 25,500 M$_3$ *Jules Verne*
On the fourth loading of Jules Verne at Arzew in May 1965 an LNG spill, caused by overflowing of Cargo Tank No.1, resulted in the fracture of the cover plating of the tank and of the adjacent deck plating. The cause of the overfill has never been adequately explained, but it was associated with the failure of liquid level instrumentation and unfamiliarity with equipment on the part of the cargo handling watch officer.

4. **April 11, 1966** 27,400 M$_3$ *Methane Progress*
Cargo leakage reported. No details.

5. **September, 1968** 5,000 M$_3$ *Aristotle*
Ran aground off the coast of Mexico. Bottom damaged. Believed to be in LPG service when this occurred. *No LNG released.*

6. **November 17, 1969** 71,500 M$_3$ *Polar Alaska*
Sloshing of the LNG heel in No. 1 tank caused part of the supports for the cargo pump electric cable tray to break loose, resulting in several perforations of the primary barrier. LNG leaked into the interbarrier space. *No LNG released.*

7. **September 2, 1970** 71,500 M$_3$ *Arctic Tokyo*

Sloshing of the LNG heel in No. 1 tank during bad weather caused local deformation of the primary barrier and supporting insulation boxes. LNG leaked into the interbarrier space at one location. *No LNG released.*

8. Late 1971 50,000 M^3 *Descartes*
A minor fault in the connection between the primary barrier and the tank dome allowed gas into the interbarrier space. *No LNG released.*

9. June, 1974 27,400 M^3 *Methane Princess*
On June 12, 1974 the *Methane Princess* was rammed by the freighter *Tower Princess* while moored at Canvey Island LNG Terminal. Created a 3- foot gash in the outer hull. *No LNG released.*

10. July, 1974 5,000 M^3 *Barge Massachusetts*
LNG was being loaded on the barge on July 16, 1974. After a power failure and the automatic closure of the main liquid line valves, a small amount of LNG leaked from a 1-inch nitrogen-purge globe valve on the vessel's liquid header. The subsequent investigation by the US. Coast Guard found that a pressure surge caused by the valve closure induced the leakage of LNG through the bonnet and gland of the 1-inch valve. The valve had not leaked during the previous seven or more hours of loading. Several fractures occurred in the deck plates. They extended over an area that measured about one by two meters. The amount of LNG involved in the leakage was reported to be about 40 gallons. As a result of this incident, The U.S. Coast Guard banned the Barge Massachusetts from LNG service within the U.S. It is believed that the Barge Massachusetts is now working in liquid ethylene service.

11. August, 1974 4,000 M^3 *Euclides*
Minor damage due to contact with another vessel. *No LNG released.*

12. November, 1974 4,000 M^3 *Euclides*
Ran aground at La Havre, France. Damaged bottom and propeller. *No LNG released.*

13. 1974 27,400 M^3 *Methane Progress*
Ran aground at Arzew, Algeria. Damaged rudder. *No LNG released.*

14. September, 1977 125,000 M^3 *LNG Aquarius*
During the filling of Cargo Tank No. 1 at Bontang on September 16, 1977, LNG overflowed through the vent mast serving that tank. The incident may have been caused by difficulties in the liquid level gauge system. The high-level alarm had been placed in the override mode to eliminate nuisance alarms. Surprisingly, the mild steel plate of which the cargo tank cover was made did not fracture as a result of this spill.

15. August 14, 1978 124,890 M^3 *Khannur*
Collision with cargo ship *Hong Hwa* in the Strait of Singapore. Minor damage. *No LNG released.*

16. April, 1979 125,000 M^3 *Mostefa Ben Boulaid*
While discharging cargo at Cove Point, Maryland on April 8, 1979, a check valve in the piping system of the vessel failed releasing a small quantity of LNG.

This resulted in minor fractures of the deck plating. This spill was caused by the escape of LNG from a swing-check valve in the liquid line. In this valve, the hinge pin is retained by a head bolt, which penetrates the wall of the valve body. In the course of operating the ship and cargo pumping system, it appears that the vibration caused the bolt to back out, releasing a shower of LNG onto the deck. The vessel was taken out of service after the incident and the structural work renewed. All of the check valves in the ship's liquid system were modified to prevent a recurrence of the failure. A light stainless steel keeper was fashioned and installed at each bolt head. Shortly after the ship returned to service, LNG was noticed leaking from around one bolt head, the keeper for which had been stripped, again probably because of vibration. More substantial keepers were installed and the valves have been free from trouble since that time.

17. April, 1979 87,600 M_3 *Pollenger*
While the Pollenger was discharging LNG at the Distrigas terminal at Everett, Massachusetts on April 25, 1979, LNG leaking from a valve gland apparently fractured the tank cover plating at Cargo Tank No. 1. The quantity of LNG that spilled was probably only a few liters, but the fractures in the cover plating covered an area of about two square meters.

18. June 29, 1979 125,000 M_3 *El Paso Paul Kayser*
Ran aground at 14 knots while maneuvering to avoid another vessel in the Strait of Gibraltar. Bottom damaged extensively. Vessel refloated and cargo transferred to sister ship, the *El Paso Sonatrach. No LNG released.*

19. December 12, 1980 125,000 M_3 *LNG Taurus*
Ran aground in heavy weather at Mutsure Anchorage off Tobata, Japan. Bottom damaged extensively. Vessel refloated, proceeded under its own power to the Kita Kyushu LNG Terminal, and cargo discharged. *No LNG released.*

20. Early 1980s 125,000 M_3 *El Paso Consolidated*
Minor release of LNG from a flange. Deck plating fractured due to low temperature embrittlement.

21. Early 1980s 129,500 M_3 *Larbi Ben M'Hidi*
Vapor released during transfer arm disconnection. *No LNG released.*

22. December, 1983 87,600 M_3 *Norman Lady*
During cooldown of the cargo transfer arms, prior to unloading at Sodegaura, Japan, the ship suddenly moved astern under its own power. All cargo transfer arms sheared and LNG spilled. No ignition.

23. 1985 35,500 M_3 *Isabella*
LNG released as a result of overfilling a tank. Deck fractured due to low temperature embrittlement.

24. 1985 35,500 M_3 *Annabella*
Reported as "pressurized cargo tank." Presumably, some LNG released from the tank or piping. No other details are available.

25. 1985 126,000 M3 *Ramdane Abane*
Collision while loaded. Port bow affected. *No LNG released.*

26. February, 1989 40,000 M3 *Tellier*
Wind blew ship from its berth at Skikda, Algeria. Cargo transfer arms sheared. Piping on ship heavily damaged. Cargo transfer had been stopped. According to some verbal accounts of this incident, LNG was released from the cargo transfer arms.

27. Early 1990 125,000 M3 *Bachir Chihani*
A fracture occurred at a part of the ship structure, which is prone to the high stresses that may accompany the complex deflections that the hull encounters on the high seas. Fracture of the inner hull plating led to the ingress of seawater into the space behind the cargo hold insulation while the vessel was in ballast.*No LNG released.*

28. May 21, 1997 125,000 M3 *Northwest Swift*
Collided with a fishing vessel about 400 km from Japan. Some damage to hull, but no ingress of water. *No LNG released.*

29. October 31, 1997 126,300 M3 *LNG Capricorn*
Struck a mooring dolphin at a pier near the Senboku LNG Terminal in Japan. Some damage to hull, but no ingress of water. *No LNG released.*

30. September 6, 1999 71,500 M3 *Methane Polar*
Engine failure during approach to Atlantic LNG jetty (Trinidad and Tobago). Struck and damaged Petrotrin pier. No injuries. *No LNG released*