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Worldwide Nuclear Generation – History and Future

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I recently assisted in the preparation and acquisition of relevant slides for a power point presentation on Nuclear Energy by Gwyn Evans. This paper is an attempt to summaries some of the thoughts of a concerned non-nuclear engineer looking in from the outside.

Early History

During World War 2 all nuclear research in Britain, the USA, Canada, Russia and Germany focused on developing the atomic bomb. It was however realised that a nuclear fission reactor could be used as a heat source for the generation of electricity.

The Atomic Energy Commission of USA in 1946 authorized the construction of Experimental Breeder Reactor I at a site in Idaho. The reactor generated the electricity on December 20, 1951 to light four 200 watt bulbs.

In June 1954 the world's first nuclear powered electricity generator began operation at the Institute of Physics and Power Engineering in Obninsk. The reactor was water-cooled and graphite moderated.

The Queen in 1956 opened the first two dual purpose reactors at Calder Hall at Windscale (later Sellafield). The reactors were fuelled by natural uranium, moderated by graphite and gas cooled.

The AEC in the USA started up a Pressurised Water Reactor in Shippingport in 1957.

Reactor types used by country

The PWR employed by the USA used enriched uranium oxide fuel and was moderated and cooled by ordinary (light) water. This continues to be the USA standard.

Canadian reactors used natural uranium fuel and heavy water as a moderator and coolant. The refined version is still used. Canada was the main source for heavy water during the search for an atomic bomb.

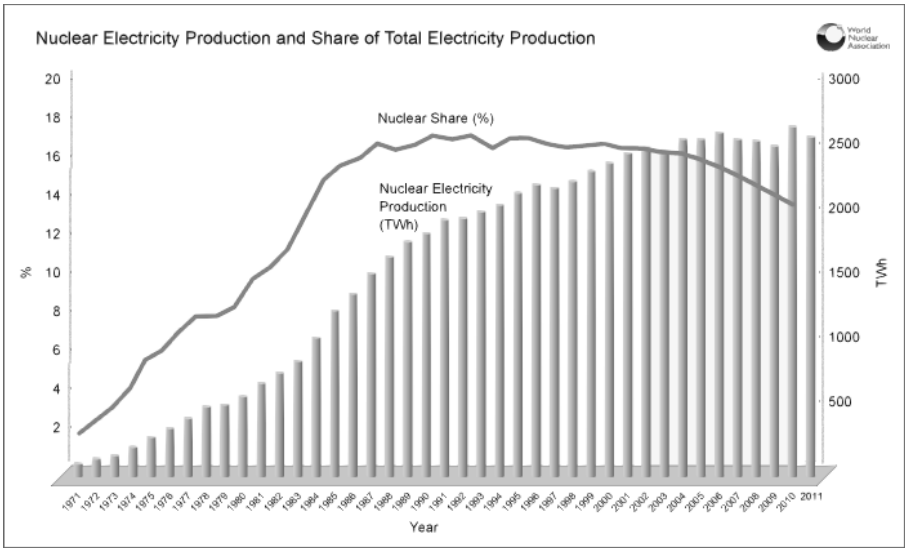
The USA had a virtual monopoly on uranium enrichment and Britain chose to use natural uranium metal but moderated by graphite, in a series of gas cooled reactors. The first of these 50 MWe Magnox types, Calder Hall-1, started up in 1956 and ran until 2003. However, after 1963 (and 26 units) the Advanced Gas-Cooled Reactor (using enriched oxide fuel) was employed. Now however PWR design is accepted.

France started out with a gas-graphite design similar to Magnox and the first reactor started up in 1956. Commercial models operated from 1959. It then settled on three successive generations of standardised PWRs, which was a very cost-effective strategy.

In Russia the AM-1 (Atom Mirny -- peaceful atom) reactor was water-cooled and graphite-moderated. It served as a prototype for other graphite channel reactor designs including the Chernobyl-type RBMK (high power multi channel reactor) reactors. In 1964 a Boiling Water Reactor (BWR) was installed And a PWR known as VVER (water cooled power reactor) power station was built. This type has developed into the current standard.

In Japan both Boiling Water Reactors BWRs and PWRs are used.

In BWRs, the heat generated by fission turns the water into steam, which directly drives the power-generating turbines and the electrical generator connected to them. In PWRs, the heat generated by fission is transferred to a secondary loop via a heat exchanger (steam generator), where the steam is produced and drives the power-generating turbines. In both BWRs and PWRs, after flowing through the turbines, the steam turns back into water in the condenser. The water required to cool the condenser is taken from and returned to a nearby ocean, river, or water supply.



The adjacent graph illustrates the rapid growth in the early years 1970-1987 then a period when the nuclear share of the all types of generated electricity is maintained up to 1996 and the current period where the share is falling.

There is little doubt the that the turning points in the graph are influenced by three major incidents that have occurred.

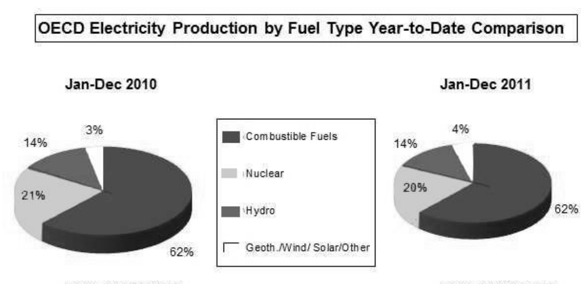
1) **The Three Mile Island** accident was a partial nuclear meltdown which occurred at the Three Mile Island power plant in Dauphin County, Pennsylvania, United States at 4 a.m. on Wednesday, March 28, 1979.
2) **The Chernobyl Disaster** occurred on 26 April 1986 when operators of the power plant ran a test on an electric control system of one of the reactors.
3) **The Fukushima Disaster** is a series of equipment failures, nuclear meltdowns, and releases of radioactive materials at the Fukushima I Nuclear Power Plant, following the Tōhoku earthquake and tsunami on 11 March 2011

One can clearly see the influence of the first two reflected in the graph of the share of the nuclear generation and The Fukushima disaster is already showing up as a downturn in the total nuclear energy production never mind the effect on the % share.

The amount of electricity generated by nuclear power plants worldwide fell by just over 4% in 2011, primarily due to reactors being idled in Japan following the Fukushima accident and Germany's reflex reaction to close its older units

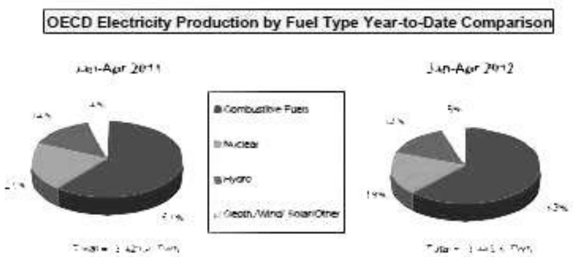
Total nuclear electricity generation in 2011 was 2518 TWh, 4.3% less than the 2630 TWh generated in 2010, according to figures from the International Atomic Energy Agency (IAEA). Generation had increased in 2010 following three consecutive years of decline.

Comparison of total electricity generation by fuel in the years 2010 and 2011 for all OECD countries is shown in the two pie charts below



The nuclear component has reduced by 1% and the Geothermal + Solar + Wind has increased by roughly the same amount.

The reduction is even greater when we look at the first quarter of 2012 in comparison with that of the first quarter in 2011



Here the reduction is 3% compensated for by an increase in fossil fuels and renewables.

With Germany opting out of nuclear altogether and the influence of Chernobyl and Fukushima on other countries we need to look at current projects and new reactors that will be installed in the next decade to see what the likely outcome will be. A detailed look at the three accidents is given in the Appendix.

The following table shows by country 63 new reactors currently being installed. This is presented together with the number of reactors online at present in those countries.

Globally in the period 1996-2009 43 reactors were retired and 49 started operation.

Country	***Reactors Under Construction***	***Reactors On Grid***
China	26	15
Russia	10	33
India	7	20
Canada	3	17
Japan	3	50
South Korea	3	23
Pakistan	2	3
Slovakia	2	4
Taiwan	2	6
Argentina	1	2
Brazil	1	2
Finland	1	4
France	1	50
USA	1	104

This has been prepared from a count of projects where the concrete base for a reactor has been installed or major reconstruction work has commenced.

In July 2012 there were 433 nuclear reactors in the world connected to the grid, of which 104 were in the USA, 58 in France, 50 in Japan, 33 in Russia, 23 in South Korea, 20 in India, 17 in Canada, 16 in the UK, 15 in the Ukraine, 15 in China and 10 in Sweden. Other countries had less than 10.

China and Russia are scheduled to have the greatest increase. The number of reactors being retired at the end of their lives is estimated at 60 compared with the 63 new ones.

Future Nuclear Generation

Up to now I have tried use only facts and factual evidence.. In looking towards the future out of necessity personal opinion and speculation enters and must play a part.

Most nuclear development is now likely to occur in the far east, however the countries where early development was greatest, are entering into an era when their current nuclear reactors have to be replaced

The UK now is in the situation that it must obtain a more reliable power source in addition to the renewables if it is not to run into a period of supply rationing by cuts. The two alternatives are either power stations using fossil fuel or new nuclear power stations.

“Horizon” a company formed by German interests was expected to redevelop sites at Wylfa and Oldbury but with the German withdrawal from nuclear the company is up for sale.

Two contenders for this sale are on the one hand the French company Areva with China Guangdong and on the other Westinghouse & State Nuclear Power Technology Corporation SNPTC of China.

EDF Energy is the main contender for the Hinkley Point C in the first instance using Areva.

It is a very different situation from the days when Britain was at the forefront of nuclear development. All that technical knowledge and engineering skill has been lost

Nuclear Fission suffers from a basic drawback – there is no instant switch off. This means we have a beast that we cannot kill when it goes on the rampage - the standard solution since pre historic times to the problem. In normal controlled circumstances it takes at least an hour using the graphite as the modulator to achieve a reduction of 99% from full output - cooling still being required to prevent heat build-up.

The word modulator is rendered somewhat irrelevant by a quirk of nature. The moderator slows down the speed of the neutrons released in the reactor but neutrons travelling freely at high speed are a 1000 times less likely to sustain nuclear fission than neutrons travelling at a more moderated speed. Further reduction will slow down neutron and fission further.

The Chernobyl Explosion that lifted the roof off the reactor building was probably caused by this feature as the control rods were inserted to bring the reactor under control.

I do speculate whether there is not some method of poisoning or killing the reactor that renders it of no further use as a heat generator and which has not been developed because nobody likes killing the golden goose. This is something that must have been considered, though without the realisation that the lack of it may cause the end of all nuclear fission reactors.

The new generation of Nuclear Power Reactors, whilst fundamentally operating on the same PWR type cycles as the earlier types, have had considerable changes in the auxiliary circuits and also in the structural strength of buildings and components. A high degree of redundancy is employed

It is worthwhile considering Station Black-Out (SBO). This means no electricity from any source. This happened in Fukushima Daiichi power station. Cooling water pumping into the Reactor Pressure Vessel ceases, temperature and pressure rises. Pressure must be released through vents. Vents are operated by DC and compressed gas. Vents release radioactive material outside, operators are loath to do this and delay. Rising pressure causes leaks, the melting core is exposed and hydrogen is generated, escapes and causes explosions.

In the Fukushima incident the earthquake caused damage which was controlled by the existing safe guards but the tsunami destroyed the backup diesel supplies and the battery facilities.

New Generation Nuclear Stations

How do the new generation Nuclear Power Stations cope with these conditions? The drawings on the next page show details and locations of some of the plant associated with such a station

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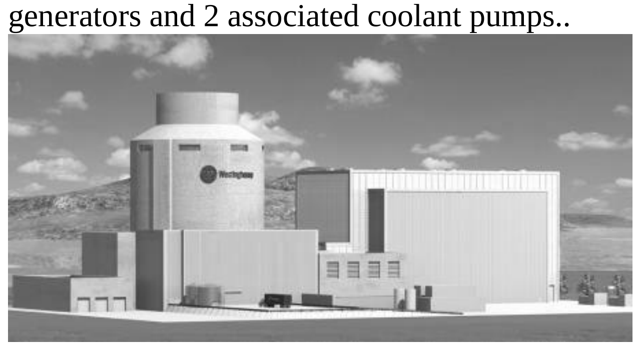
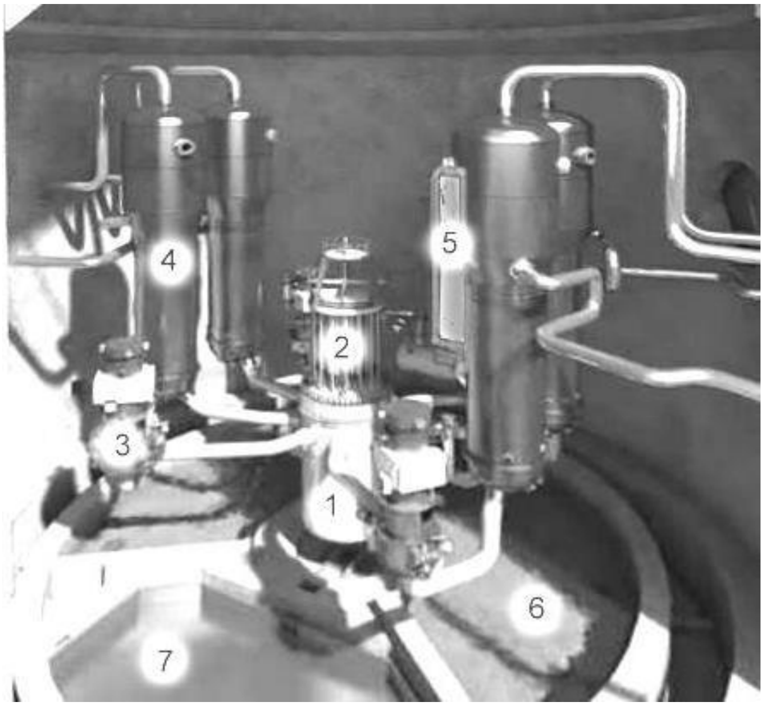
The Westinghouse AP 1000 with an output of 1154 MWe has a Containment Cooling Water Tank at the top of the building and uses 2 steam generators and 2 associated coolant pumps..



Westinghouse AP 1000

The Areva EPR 1600 MWe power plant details have been used in the preparation of the drawings. Use has been made of information and pictures obtained from their UK Website

Areva EPR



Inside the Reactor Building Shell
1 Reactor Pressure Vessel (RPV)
2. Control Rods
3 Coolant Pump (4 in total)
4 Steam Generator (4 in total)
5 Pressurizer
6 In-containment Cooling Water
7 Core Melt Container Location in case of accidents

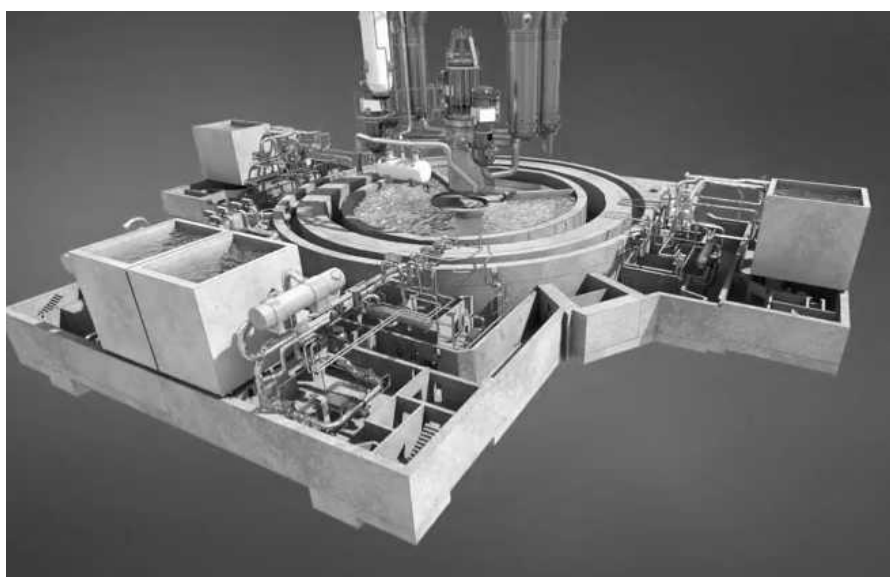
The RPV is shown without the concrete retaining shell which further protects it and the surrounding environment. The in-containment cooling water is used for cooling the core when core melt has occurred should an accident occur.

The steam generators are heat exchangers between the heat from the reactor and the steam for the turbines. The reactor building is protected by a 1.3 m thick concrete inner shell that separates it from all other buildings.

There are a number of other buildings in addition to the Reactor building such as the used fuel storage building, four emergency buildings for safeguard systems, two buildings with emergency diesel generators, the turbine building and an auxiliary building.

The 4 safeguard buildings

Each of the four safeguard buildings contains a large cooling water tank and control equipment enabling a shutdown of the reactor working at full rated output of 1600MWe to 99% of that heat output within 60 minutes or so. Each is capable of acting independent of the others – two are within the outer 1,3 m thick outer shell of the reactor building with the other two located outside it. Each of the four safeguard buildings contains a large cooling water tank.



This enables a shutdown of the reactor working at full rated output of 1600MWe to 99% of that heat output within 60 minutes or so. Each is capable of acting independent of the others – two are within the outer 1,3 m thick outer shell of the reactor building with the other two located outside it.

All the buildings bar the turbine building and the emergency diesel generator buildings are mounted on the same concrete raft foundation with the heavy equipment mounted close to the ground to ensure stability during earthquakes.

The two buildings with emergency diesel generators each contain 3 generators, two of which are of one type and on which is different in order to avoid common faults. Each can supply the electricity needed by any of the safeguard buildings to be fully operational should the external power fail. They are protected against flooding and earthquakes.

The main control room housed on top of one of the buildings can switch to battery power if electricity is lost for instruments and some basic control functions. Also a remote control room is provided for emergencies.

Conclusions

The lack of a capability to shut down a nuclear fission reaction instantaneously is costing us dearly in redundant plant – massive housing and a complex construction to be managed. . The result is a building site where competing manufactures and contractors are present and have to be controlled and scheduled. Failures to comply lead to inevitable delays and prove to be costly.

Only the Chinese appear to be capable of building a nuclear station ahead of schedule and at a more economic cost. Perhaps they will solve our workload problems for us

At the same time the current designs appear to cater for virtually any unlikely circumstances that can occur. However none of the three nuclear accidents would have happened if the operators of the plants had been reliable and could be trusted. The politicians in all the cases were placed in a position of making decisions they could not handle.

Perhaps what is called for is the presence on site of a second control room that can override the main control room and shut down the reactor. This room would be run not by the operators but by a man or organisation (nuclear health and safety) with full access to all metering and operating procedures and whose sole responsibility is to shut down the plant when the need arises.

With that thought this paper concludes.

Biographies:

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Westinghouse AP1000
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United States Nuclear Regulatory Commission – Three Mile Island Accident
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U-Tube – Chernobyl Disaster - What Really Happened
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Fukushima Daiichi – American Nuclear Society Committee Report
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Appendix – The Three Main Nuclear Accidents

Three Mile Island – Chernobyl –Fukushima

Three Mile Island

The accident began with failures in the non-nuclear secondary system, followed by a stuck-open pilot-operated relief valve (PORV) in the primary system, which allowed large amounts of nuclear reactor coolant to escape. The mechanical failures were compounded by the initial failure of plant operators to recognize the situation as a loss-of-coolant accident due to inadequate training and human factors, such as human-computer interaction design oversights relating to ambiguous control room indicators in the power plant's user interface. In particular, a hidden indicator light led to an operator manually overriding the automatic emergency cooling system of the reactor because the operator mistakenly believed that there was too much coolant water present in the reactor causing the steam pressure release.

The scope and complexity of the accident became clear over the course of five days, as employees of Met Ed, Connecticut state officials, and members of the U.S. Nuclear Regulatory Commission (NRC) tried to understand the problem, communicate the situation to the press and local community, decide whether the accident required an emergency evacuation, and ultimately end the crisis. The NRC's authorization of the release of 40,000 gallons of radioactive waste water directly in the Susquehanna River led to a loss of credibility with the press and community.

Chernobyl

The Chernobyl nuclear power plant is located in Ukraine, 20km south of the border with Belarus. At the time of the accident, the plant had four working reactors.

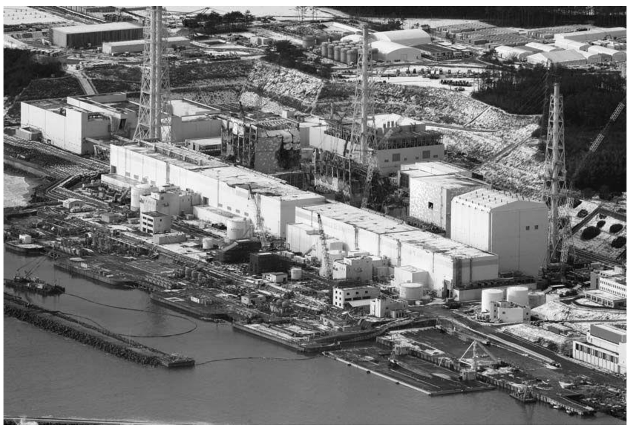
The accident occurred on 26 April 1986 when operators of the power plant ran a test on an electric control system of one of the reactors. The accident happened because of a combination of basic engineering deficiencies in the reactor and faulty actions of the operators: the safety systems had been switched off, and the reactor was being operated under improper, unstable conditions, a situation which allowed an uncontrollable power surge to occur. This led to a cascade of events resulting in a series of explosions and consequent fires that severely damaged the reactor building, completely destroyed the reactor, and caused the release of massive amounts of radioactive materials over a ten-day period.

Russia, Ukraine, and Belarus have been burdened with the continuing and substantial decontamination and health care costs of the Chernobyl accident.

Fukushima Disaster

The Fukushima nuclear disaster consisted of a sequence of equipment failures, nuclear meltdowns, and releases of radioactive materials at the Fukushima I Nuclear Power Plant, following the Tōhoku earthquake and tsunami on 11 March 2011.

All Japanese NPPs have seismic instrumentation systems that shut down the reactors when a significant earthquake occurs, and when the earthquake occurred, these systems functioned normally for all units. Following the earthquake, all the safety systems, including on-site emergency electrical power, operated as designed. It was the subsequent tsunami that caused the major damage. 4 of the NPPs affected managed to close down by March the 15th but the Fukushima Daiichi NPP with 6 reactor units was severely affected.

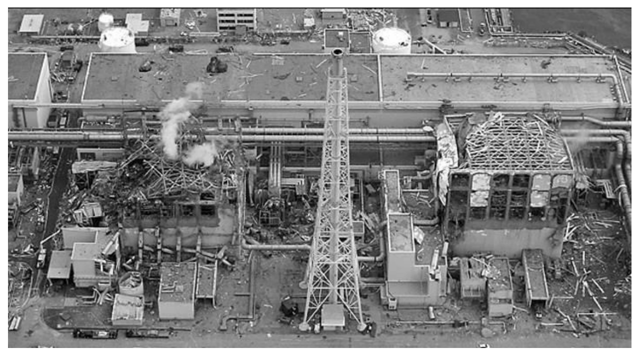


At the time of the earthquake, Units 1, 2, and 3 were operating at rated power level. Unit 4 was in a periodic inspection outage, and large-scale repairs were under way. Unit 4 fuel had all been relocated to the Spent-Fuel Pool (SFP) in the reactor building. Units 5 and 6 were also in a periodic inspection outage, but the fuel remained in the reactor core area of the Reactor Pressure Vessel (RPV), and the reactors were in a cold shutdown condition.

The earthquake brought Units 1, 2, and 3 to an automatic shutdown because of the high seismic acceleration. The off-site power supply was also lost because of damage to the transmission towers from the earthquake. For this reason, the Emergency Diesel Generators (EDGs) for each unit were automatically started up to maintain the function of cooling the reactors and the SFPs. Normal reactor cool down and decay heat removal functions were under way.

About 45 minutes after the earthquake, the tsunami arrived with an estimated maximum wave height of ~15 m, which was much larger than the seawall at 5 m. All the EDGs (except for one air-cooled EDG at Unit 6) stopped when the tsunami arrived. Specifically, the tsunami submerged the seawater systems that cooled the EDGs and the electrical switchgear. The result was that all AC power supply was lost at Units 1 through 5.

Units 1 through 4 were significantly damaged by the tsunami and subsequent actions. Clearly there was no attempt to cater for a tsunami of the size that arrived.
It is also clear that in the some of the decisions taken to deal with the unplanned for situation did cause further problems.



When off-site and on-site AC power are lost, a station black-out (SBO) occurs. This left only systems designed to cope with the loss of water supply to the reactor pressure vessel by relieving the increasing pressure by venting.
DC power and compressed nitrogen (or air) are needed to open and close valves and operate the control systems, as well as provide power for instrumentation that the operator needs in order to take appropriate actions.

The operators had no rehearsals of what to do if a SBO, occurred time was lost and the pressure in a reactors rose above maximum working resulting in leaking through joints. As the cores became exposed hydrogen was produced that escaped through leaks and caused explosions on the site.
Fukushima and Chernobyl were rated at severity 7 on the International Nuclear Event Scale while Three mile island was rated at a severity of 5.