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And who would run, that's moderately wise,
A certain danger, for a doubtful prize?

Rev. John Pymfiel (1667-1702)
Abbreviations

PWR Pressurised Water Reactor.
TMI-2 The second of two PWR stations at Three Mile Island.
MAGNOX The earlier type of British gas-cooled reactor.
AGR The Advanced Gas-Cooled Reactor: successor to MAGNOX.
PSI Pounds per square inch.
LOCA Loss of Coolant Accident.
PORV Pressure-operated Release Valve.
NII Nuclear Installations Inspectorate.
SNUPPS Standard Nuclear Unit Power Plant System.
At Sizewell in Suffolk, the Central Electricity Generating Board is proposing to build an American Pressurised Water Reactor (PWR). This pamphlet has been written for people who want to know about the risks of the PWR and are prepared to spend a little time finding out. It is also intended for those who, knowing something already of nuclear science, wish to address meetings or lead discussions on the topic of PWR safety. So inevitably, it will be too short for some, too long for others; but it is at least hoped that everybody will be able to understand it.

Two points need to be made about it. Firstly, it deals only with the specific hazards of the PWR. Therefore, nothing is said about radioactive waste transport, reprocessing or plutonium production or other problems which the PWR, in general, shares with all other reactor types.

Secondly, it may appear that this pamphlet, which is intended to be read as a whole, is making a case for the gas-cooled reactors. No doubt, it could be so used by those who wish to make such a case; but the intention here is quite different. To understand the dangers of the PWR requires that it be compared with something: and the obvious and relevant comparison is with other reactor types. The immediate danger which confronts us is that we are about to shift to a type of power reactor which is markedly more dangerous than its British predecessors, and unproved in British experience. Such a statement may or may not suggest approval of a nuclear power programme of some sort. In the case of the present writer, it does not.

I wish to thank numerous friends and colleagues on whom this document has been tried out for accuracy and clarity of exposition. They, and I, have done their best; to the extent that I may fall short, it is not their fault but my own.

Don Arnott
All nuclear power stations contain enormous amounts of radioactivity – comparable with the amounts released by the bomb which devastated Hiroshima. Nobody, whether a supporter of nuclear power generation or not, will deny that all such nuclear power stations are potentially dangerous because of the enormous quantities of radioactivity they contain, which could be released in the event of a serious accident. It is equally impossible to deny that some reactor systems are less potentially dangerous than others.

Of all such systems, the Pressurised Water Reactor (PWR) is the most dangerous because it contains a whole complex of hazards which are in addition to those found in other types of nuclear power reactor.

This pamphlet explains why this is so. It is written in language which, it is hoped, can be understood by anybody. It is concerned solely with the dangers of the PWR. It does not deal with questions of cost, need or other economic issues, nor with the question of nuclear power in general, nor with alternative energy resources. Instead it concentrates on a single objective: the physical dangers of the PWR.

But first: What might be the consequences of an accident?
The accident most to be feared is one which leads to severe damage to the reactor core. This would result in a massive release of radioactivity from the nuclear fuel.

If all containment systems failed, there would be a large-scale release of radioactivity into the environment, which would be a danger to life. Obviously, this must be our main concern – but there is another possibility.

If the furnace of a coal or oil-fired power station breaks down, it will be shut down, the damage repaired, and the station restarted. But this is impossible with a nuclear-fired station which has suffered severe core damage, because the radioactivity released makes it impossible for human beings to approach it and repair it. And, of the two possibilities, this is the more probable, because it could be caused by a far smaller accident than one leading to a massive radiation release into the environment.

On 28 March 1979, the USA suffered exactly such an accident. It is claimed (and it is true) that relatively little radioactivity was released into the atmosphere and that nobody died or was injured immediately; it is also claimed (and this is much less certain) that nobody will be injured or die as the result of the delayed effects of the radiation released. Nevertheless, within minutes, the investment was lost: the second power reactor at Three Mile Island, TMI-2, will never work again. Moreover, the wreckage remains dangerous.

TMI-2 was a PWR. And, despite all that is claimed to the contrary, the fundamental design of the Sizewell PWR is the same. For that design involves certain risks which arise from its nature (called generic risks by the industry). They may be minimised or their consequences may be better contained. But they cannot be abolished.

The accident at Three Mile Island was described by the President’s Commission – the Kemeny Report – in its very first sentence as ‘the worst accident in the history of commercial nuclear power generation’.

Whether we are prudent to invest in a design which can become a complete write-off so quickly is a question we refer to economists. Our business here is to explain how the dangers arise. For that to be done, some scientific terms must first be explained.
Radioactivity: The whole world is built up of some fundamental building-blocks called elements, some 90 in all. Some are metals, and with one exception (Mercury) the metals are all solids. Others are non-metals and most of these are gases. The smallest particle of an element which can exist independently is called an atom, which can be split into sub-atomic particles but then loses its original identity. Most atoms of most elements are quite stable. But in the case of certain very heavy elements – notably Uranium – the atoms are so large that they are unstable. These break down spontaneously, in one or other of several ways, releasing great quantities of energy and producing smaller atoms of different elements. This is radioactivity.

The rate at which a radioactive element decays is normally constant. In practice, one measures the half-life, the time taken for half the element to decay. The half-life of Uranium is around 4000 million years, comparable with the age of the Earth as at present believed. If this process is speeded up in a controlled fashion a very great deal of energy, including heat energy, would be released in a very short time. The method for doing this is called nuclear fission.

Nuclear fission is one form of radioactive decay. An atom undergoing fission splits into two nearly-equal parts, called fission products, themselves nearly always radioactive. At the same time there is an enormous release of energy of almost every sort known: of heat, light, motion and ionising radiation (see below). At the level of a single atom, fission represents an explosion of almost inconceivable violence.

Critical mass. One part in 140 of ordinary Uranium (U-235) undergoes fission extremely easily. When it does so, it releases the very small particles called neutrons which have the power of triggering off further fissions in surrounding U-235 atoms. In a small mass of uranium most neutrons will escape; but as the mass is increased in size, a greater proportion of neutrons are retained and promote secondary fission until, when the critical mass is reached, the process becomes self-sustaining, and is called a chain reaction. What we have then is a nuclear furnace.

This may seem a difficult concept; but there are homely
parallels to help. Any fire, to be useful, must first generate enough heat to keep itself alight. And we are familiar with the coal fire which is too small to do this: too much of its heat energy is escaping, it cannot keep itself alight and so goes out. In other words, it is smaller than its critical mass.

The heat energy of any nuclear reactor arises almost entirely from U–235 fission. The remaining Uranium (U–235) plays no direct part; but it does absorb some of the neutrons generated to form plutonium.

**Ionising radiation and its dangers.** Amongst the forms of energy released in radioactive decay are various **electronically charged particles** as well as (in the case of fission only) **neutrons**, and **gamma-rays**, which resemble very energetic x-rays and have great penetrating power. These, collectively, are called **ionising radiations** because they produce intense electrical charges in their pathways through matter, whether living or dead.

To varying degrees these radiations are dangerous to all cells of all species of animal or plant. Since these cells necessarily include reproductive cells, there is also a genetic effect of radiation. The facts are well-authenticated experimentally. To the shame of humanity, the crucial experiments on human beings were done in Japan in August 1945. The results of Hiroshima and Nagasaki leave no doubt whatever that radiation causes a variety of fatal and non-fatal injuries and that amongst the former are leukaemia, anaemia and cancer, the development of which, following exposure, is always delayed. The latency period varies, depending on the type of cancer; it can be several decades.

It is necessary to assert these matters whenever possible because the nuclear industry has a tendency to suggest that because the Earth is naturally radioactive, we need not worry about increasing it. The argument is specious. Natural radioactivity too must exact its toll. What is in dispute is not the fact of radiation injury, but its extent. This is difficult to determine because the injuries caused are not specific to radiation: leukaemia remains leukaemia no matter how caused. But a danger is not abolished merely because it is difficult to define precisely.

This is all that is necessary by way of explanation and it will simplify and shorten what follows. Other matters will be explained as they arise.
A critical mass of fuel. This generates the heat, by fission. As it does so, fission products and plutonium—both highly radioactive—accumulate in the fuel and eventually necessitate its replacement. Fuel, at present, is Uranium metal (in Magnox reactors) or Uranium oxide (in AGRs and PWRs) in the form of rods which are then typically arranged in a lattice.

A Moderator. The neutrons produced in fission are travelling too fast to sustain the chain reaction. They must therefore be slowed down and the moderator does this. The moderator surrounds the fuel, and by the time the neutrons originating in any one rod have traversed it, they are of the right energy to promote fission in the nearby fuel-rod they then enter. The moderator slows the fission process slightly and is one reason (there are two more important ones which are irrelevant here) why a nuclear reactor cannot explode like a nuclear bomb. Moderators may be solid or liquid.

Control rods. These control the rate at which the reactor generates heat. They are made of somewhat unfamiliar materials such as Boron or Cadmium which absorb neutrons very easily and they can therefore be used to slow down or stop the chain reaction. They have another function. In an emergency, it is arranged that they will automatically drop into the reactor under gravity and shut down the chain reaction entirely: this is called a scram.
A Coolant. This removes the heat generated, ultimately to the turbines generating electricity. Obviously, this must flow, and is therefore either a liquid or a gas. And here arises a difference so crucial that, although we must return to it in some detail, we must summarise it here. It is this: no matter how hot a reactor may get, the coolant, if a gas, will remain a gas; but if it is a liquid, it may boil, i.e. be partly converted to gas – with drastic and sudden alteration to the operating conditions. This is what happened at Three Mile Island, though the accident was triggered by an event occurring outside the reactor itself. This dreaded possibility is known as phase-change. It is a generic defect. It can happen in the Sizewell PWR, which is cooled by water. It cannot happen in the British reactors which are cooled by a gas, Carbon dioxide.

Probably the safest type of reactor would be one in which these four essential functions are entirely separated: the moderator moderates, the coolant cools; and neither has any other function. But in some reactors, functions are combined: in the PWR, the water is both coolant and moderator. This means that in the event of phase-change, not merely one essential function is distorted, but two. The possible range of consequences of this are by no means clear; what seems clear is that the possibilities of control in an emergency are inevitably reduced if functions are inextricably combined.

Two other things are vital in reactor design. Firstly, all equipment used (other than the fuel and the control rods) must be in a form which does not, or not greatly, absorb neutrons. This principle, if violated, would interfere with the chain reaction. Secondly, the materials used must not react with each other chemically under reactor conditions: the fuel cladding, for example, must not be corroded either by the fuel it contains or by the moderator and coolant with which it is also necessarily in contact.

We shall now compare the British reactors (Magnox and AGR) with the PWR in order to see how far each has been designed to flow with the safety current rather than against it.
In a Magnox reactor, the fuel is natural Uranium clad in a Magnesium alloy (called Magnox) which gives the reactor its name. In an AGR, the fuel is Uranium oxide enriched slightly with added U–235 and the cladding is stainless steel.

In both, the moderator is graphite and the coolant is Carbon dioxide. None of these components reacts chemically with any of the others. And the coolant gas absorbs relatively few neutrons.

We now turn to the vital question of pressurisation. The reactor core is enclosed in a pressure vessel through which the coolant gas is pumped under pressure. The purpose of the pressure is to get more gas in, which increases the efficiency of heat removal, and hence of electricity generation: it does not itself increase the operating temperature.

Now, as anybody who ever blew up a balloon knows, gases can be compressed; and relatively large quantities of Carbon dioxide have to be pumped in to raise the pressure to what is required. And the opposite is true: loss of coolant gas through a leak – unless it is very large indeed – reduces pressure only slowly, thus leaving time for effective human intervention.

WRs originated in the USA where Westinghouse, though not the only manufacturers, are the best known. Their model, chosen for Sizewell, has been extensively modified. In respect of the reactor-steam generator assembly, it is important, first of all, to understand the exact status of those modifications.

In 1973, five US manufacturing companies entered into an agreement to build nuclear power plants to a common design. This is called SNUPPS (Standard Nuclear Unit Power Plant
Five such plants were ordered but only two are actually being built and they will not operate for another two years.

In Britain, a Task Force, headed by Dr - now Sir - Walter Marshall, was set up to introduce further modifications to the SNUPPS design, with the object of reducing cost and increasing safety - a combination guaranteed to raise eyebrows. The important fact to realise, however, is that the SNUPPS design has not been operationally tested anywhere in the world. So the Marshall re-design is a further modification of an already modified and untested version!

The fuel is enriched Uranium oxide clad in a Zirconium alloy called Zircaloy. The moderator/coolant is water under pressure and in that form does not react significantly with Zircaloy.

Turning once more to pressurisation, we find a situation very different from that described for the gas-cooled reactors. The reactor core is enclosed as before in a pressure vessel; but the purpose of the pressure is to raise the boiling point of the water to above 300 degrees Centigrade - three times normal - whilst preventing it from boiling by the application of pressure. This is essential, if electrical generation is to be efficient. The pressure required is around 2300 psi.

As compared with a gas, water is almost incompressible and relatively little extra has to be forced in to reach the pressure required. In consequence, even a relatively small coolant leak (known in the trade as a LOCA, or Loss of Coolant Accident) can lead to rapid and serious depressurisation. What happens then is best illustrated by reference to a device which most people know - the familiar pressure-cooker.

The pressure-cooker cooks vegetables quickly by heating them hotter than the normal boiling point of water, which is 100 degrees Centigrade at atmospheric pressure. At that temperature, there is a phase-change: the water boils and turns to steam. And no amount of extra heat will raise the temperature higher: the additional heat merely produces steam more quickly.

If now the weighted knob, typically weighing \( \frac{1}{4} \) lb, is placed in position on the pressure-cooker vent, steam can no longer escape; therefore, it is no longer generated; and the extra heat supplied raises the temperature of the water above its normal boiling point.

Most people know what then happens if the knob of the
pressure-cooker is removed too trustfully. The increase of pressure has been suddenly removed; the water inside instantly reverts to atmospheric pressure – but at a temperature several degrees above its correct boiling point. It therefore boils with explosive violence and a jet of steam escapes through the vent. When the extra heat accumulated under pressure has been got rid of in this way, things quieten down.

We can now easily understand what happens to a PWR core when there is a leak, or LOCA, somewhere in the pressurised coolant system. The pressure inside the reactor core falls rapidly and the water contained can flash into steam. And steam reacts with the Zircaloy fuel-cladding forming Hydrogen. Moreover, this reaction itself guarantees heat, thus worsening the situation. Furthermore, steam is a bad conductor of heat. The partial destruction of the fuel cladding leads inevitably to fission-product release; this was a prominent feature on the TMI–2 accident.

A direct LOCA is not the only, nor indeed the most common source of trouble. When a reactor gets too hot, it is not usually because the core has suddenly started producing more heat, but because the coolant, through some interruption in flow, is no longer removing the heat generated. In the PWR, since water absorbs neutrons, matters are arranged so that as little as possible is in the reactor at any given moment. In order to get the heat out, the coolant must be pumped through at very great speed. In fact, very nearly 19 tonnes of pressurised water per second must be pumped through the pressure vessel – which is about the volume of a medium-sized bedroom. If now a pump fails, the coolant no longer flows, and both temperature and pressure start to rise rapidly within the reactor. At this point, a pressure-operated release valve (called a PORV by the trade) opens to restore conditions to normal. Its function is strictly parallel to that of the knob on our pressure-cooker; should it fail to close, the consequences will be as described in the previous paragraph and no further description is necessary. A stuck PORV was the major contributor to the TMI–2 accident.

It is not the case that the risks of depressurisation occur only in the reactor pressure vessel. For the coolant is removed from the reactor to a heat-exchanger (in the course of generating steam for the turbines) and thence returned to the reactor to
extract more heat; and all pipes, pumps and valves associated with this circuit must necessarily operate under nearly the same conditions of extremely high pressure which are found in the reactor itself. Opportunities for leaks or other malfunctions are greater here than in the reactor itself and even transient changes can produce mechanical shock to the system. Another example from everyday life can illustrate this.

Gardeners who live in tower blocks are often aware of how an open-ended hosepipe behaves when connected to a high head of water; it writhes like a living snake. This is known as pipe-whip. And, inside the tower block, the sudden turning off of a tap can produce a shock to the pipe which feeds it, suggesting that somebody has hit it pretty hard with a mallet. This is waterhammer.

Similar phenomena can occur in the system just described in the event of malfunction. Actual physical disintegration would not be slow but violent. There is a section in the CEGB’s Preconstruction Safety Report which is headed missiles. This is not concerned, as might be supposed, with anything lobbed our way by the USSR or casually dropped by the US military aircraft which ceaselessly patrol the East Anglian skies. It refers to flying debris, mostly metallic, produced from any disintegration in the heat extraction circuits and to the problems of containing the damage it would do.

As may be imagined, a significant part of the whole design consists of systems, back-up systems and alternative systems whose function is to contain these and other hazards. There are too many of them to be described here. But in number and complexity they exceed those to be found in any other type of commercial power reactor now operating.

In fact, the whole operation is an exercise in technological brinkmanship. One example of how perverse this can become must be given. In order that the fuel rods (over 50,000 of them) can withstand, without collapsing inwards, the enormous water pressure within the reactor core they too must be pressurised. This is done by pumping Helium gas into them at the time of manufacture; which is fine unless the coolant depressurises. In that case the cladding, which is little more than 0.5 mm thick, may swell, thus distorting the fuel rod assembly. This danger is graphically known as clad-ballooning – and at the present time
the problem is not solved.

In the gas-cooled nuclear stations, the reactor itself is isolated from virtually all of the steam-generating and other equipment by a concrete vessel called the biological shield. All equipment can be serviced with the reactor on load; and, in the later Magnoxes, refuelling can also take place under load (theoretically the AGRs can also be refuelled under load, but there have been a few technical problems about that).

By contrast, in the PWR, the whole of the steam-generating equipment, the reloading equipment and much else has to be housed close-in to the reactor, the whole of it being mounted in a very large building called the containment. The name itself explains its purpose. If there is a severe accident, the whole of this equipment is liable to become severely contaminated; the containment is there in order to ensure that none of this radioactivity reaches the environment.

Therefore, as the National Nuclear Corporation observed in its evidence to the House of Commons Select Committee on Energy, the basic construction and mode of operation of SNUPPS, no matter how modified, is bound to lead to increased radiation-exposure for reactors. In fact, it is expected that this will be 2–4 times higher than for the gas-cooled reactors. There will also be increased production of radioactive waste, arising from servicing and refuelling, and itself contributing to increased operator exposure.

Mention must finally be made of the emergency procedure which will come into play should things go seriously wrong. This has been almost entirely automated with little room left for human intervention. With the example of Three Mile Island in mind, this might seem to be no bad thing – until one knows that the system to be adopted is new, untested, and has not been licensed for any PWR in the world. In fact, should it ever be brought into action, what we shall be witnessing is not an established emergency procedure but a scientific experiment to determine whether the system works or not.
So how did we get stuck with it?

Like much else in the nuclear field, the origin of the PWR is military. If, for the sake of argument, you assume that a submarine that can remain submerged without refuelling for long periods is a good thing to have, there is only one way of propelling it; that is by nuclear power. And, space being at a premium in a submarine, a small unit of high power output is needed; a small PWR provides this. And from this has grown the notion that the best power station reactor is the one which produces the most output from the smallest volume – even where space is not at a premium. The Sizewell PWR is basically a scaled-up submarine reactor. It produces enormous output in small volume (the pressure vessel containing the reactor is cylindrical and only 13 metres × 4) and not a few of its instability problems arise from that fact.

It is a commonplace in technology – and not only in nuclear engineering – that scaling-up produces problems of its own.

What about the Nuclear Installations Inspectorate?

The NII is the watchdog which oversees the operation of a nuclear power station from start-up to decommissioning; and if an entirely new type of reactor is proposed for Britain, then it must also approve the design. In theory, the NII is independent; but, in reality, it is staffed by members of the nuclear constellation. Recently, concern has been expressed about the NII being under-staffed and its employees being
under-paid. It is interesting to reflect on the degree to which it is likely to carry out these tasks – or indeed is able to.

If there is an accident leading to shutdown – or even a lesser incident – at a functioning nuclear station, NII approval is necessary before the station can be restarted. But a most peculiar position arises with new introductions, such as the PWR. For, once the NII has decided that the design is generically acceptable on safety grounds, there is thereafter no way off the hook.

For the emphasis now shifts from scientific principles to design details. And inevitably, for such a huge project, approval is given in stages with many amendments, themselves requiring approval. The advisor to Suffolk County Council, Professor Leslie, graphically describes the NII as shooting at a moving target. It is in theory possible that some insurmountable snag late-on in the development process might arise which would cause the NII to reject the whole proposal. In practice, by that time tens of millions of pounds will have been spent on development work and the pressure to solve outstanding problems at any price will have grown; there may even be the dangerous assumption that all problems are soluble. It is therefore realistic to assume that approval of fundamental design will be followed by approval of a finished power-station: this is no more than an assertion of the fact that all of us are subject to pressures from other persons and other interests.

On the PWR, the NII’s position is particularly shaky. It has had the safety factors under review for several years; and, shortly before the Three Mile Island accident, it had decided that the generic risks of PWRs, properly contained, were acceptable. Also, in its evaluation at that time, it concluded that the likelihood of a Loss of Coolant Accident (LOCA), such as subsequently happened at TMI-2, was small. There need be no implication of slipshod work in this – but it is a sharp statement about human fallibility! LOCAs, we now know, have been relatively common in the American PWR experience. To decide that British modifications can make this unstable reactor safe, to give it in effect a new lease of life when cancellations are the order of the day, is an awesome responsibility for the NII.

And this responsibility must be set against what is the most disquieting issue of all. This is the sudden change in British policy.
For thirty years, it has been British policy to start small and build larger, gaining experience on the way: from the relatively tiny Magnoxes of Calder Hall to the last and largest of them at Wylfa. A similar policy has been followed with the Fast Breeder project at Dounreay. Possibly this is why there has not been a major commercial reactor accident in Britain, or at least none which has not been adequately contained.

All this caution is now to be thrown overboard. We are to start with the second largest reactor which Westinghouse has on offer. Nuclear submarines apart, we have no operational experience; neither does the NII.

Under these circumstances, the need for an informed public determined to halt the introduction of the American PWR to Britain is overwhelming. It is hoped that this pamphlet will form a contribution to that end.

LAST YEAR,
THE CEBG SPENT £3 MILLION*
PROMOTING NUCLEAR POWER—HELP US FIGHT BACK!

You can help by raising money for our Sizewell Fighting Fund, affiliating your organisation or becoming an individual supporter. Formed in late 1979, the Anti Nuclear Campaign is the national campaign against nuclear power. The ANC seeks to build a united and broad-based movement.

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For further information, a list of our campaign materials or a bibliography on nuclear power, please write, enclosing an SAE, to: ANC National Office, PO Box 216, Sheffield S1 1BD; telephone: 0742-754691 (24 hours).

At Sizewell, in Suffolk, the CEGB wants to build a Pressurised Water Reactor (PWR) – the same type of nuclear reactor as went seriously wrong at Three Mile Island on March 28, 1979.

In this short and readable pamphlet, Dr D G Arnott, a nuclear scientist, argues that the PWR is the 'most dangerous' type of nuclear reactor. With the aid of homely examples, he explains lucidly why the PWR 'contains a whole complex of hazards which are in addition to those found in other types of nuclear power reactor.'

This pamphlet is an essential primer for the nuclear age and the author believes that 'the need for an informed public determined to halt the introduction of the American PWR to Britain is overwhelming.'

Dr D G Arnott is a former Consultant to the International Atomic Energy Agency. He is currently Scientific Advisor to the Anti Nuclear Campaign.