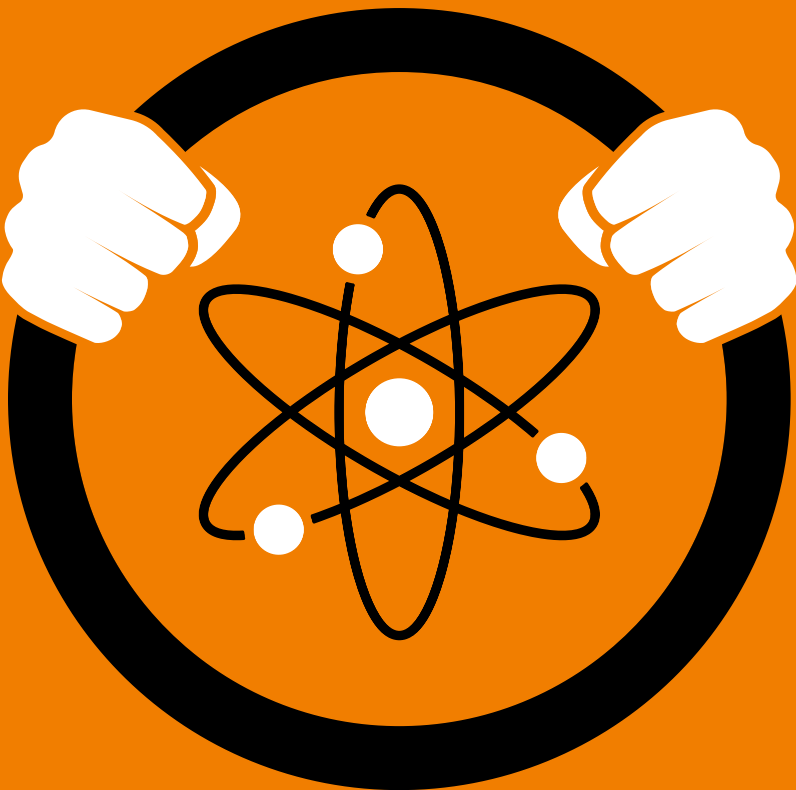
COLIN TUCKER

HOW TO DRIVE A NUCLEAR REACTOR



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To Lynette

Preface and Acknowledgements

Have you ever wondered how a nuclear power station works? This book will show you, by asking you to imagine that you're a trainee reactor operator on a Pressurised Water Reactor (PWR), the most common type of nuclear reactor in the world. It'll take you on a journey from the science behind nuclear reactors, through their start-up, operation and shutdown. Along the way, it covers a bit of the engineering, reactor history, different kinds of reactors and what can go wrong with them. This book will show you how reactors are kept safe, and what it feels like to drive one.

So what inspired me to write this book? It was a conversation about a book entitled *How to Drive a Steam Locomotive* (by Brian Hollingsworth). I was describing to a friend how the author puts the reader on the footplate of a locomotive and then gradually introduces them to the controls in front of them; what they each do; and what might go wrong. By the end of the book, it felt like you were really there. The conversation ended with me complaining about the lack of any similar book describing nuclear reactors. I have searched for such a book, but have found that most concentrate on energy policy or on nuclear accidents, with only a few short chapters on reactor operation. My experience is that often people want to know more.

So I decided to write *this* book. I hope you enjoy reading it as much as I enjoyed writing it. (I'll let you be the judge of whether or not it matches up to the original.)

As with many industries, nuclear power stations use a lot of jargon. Hopefully, you won't find this too off-putting—there is an Index at the back, which may help. Different kinds of reactors use different jargon (of course!) and you'll see that this book is heavily PWR-biased, though other reactors do make an appearance. Confusingly—especially for people new to the industry—it's not uncommon for power station equipment to have two or more different names, often used interchangeably, especially if that equipment can have different functions at different times. Examples include using the word 'Containment' instead of 'Reactor Building', 'Reactor Coolant System' for 'Primary Circuit', 'Fuel Rod' for 'Fuel Pin', etc. I've tried very hard to only use single terms in this book. To my ear, and perhaps to others who work at PWRs, that makes some of the text feel a little clumsy. Hopefully, to everyone else it will make things clearer. My advice to anyone reading this book is not to get too hung up on the jargon; it's the safe operation of the reactor that matters, not the labelling.

I want to start my acknowledgements by thanking my wife, Lynette, for encouraging me and helping me find the space and time to devote to writing this book. It's not easy to fit this sort of thing into your spare time without other things being displaced. I also need to thank my first readers, Nicholas Butt and Kevin Martin, who provided both technical and non-technical review comments which have (mostly) been addressed. It can't have been easy to read drafts of chapters when you don't have a clear idea of how it's all supposed to fit together. Their patience and perseverance were much appreciated.

I owe an enormous debt of gratitude to the staff of the UK's Sizewell 'B' nuclear power station. This has been my base for nearly 25 years, primarily working in the field of nuclear safety. Most of my experience of PWRs is Sizewell-based, and I accept that there are risks in this for an author; not every PWR is the same. I hope I've been flexible enough in what I've written for those at other PWRs (and indeed, at other reactor designs) not to feel excluded. Sizewell has a marvellously 'open' culture where I've found that I can ask questions on anything to fill gaps in my knowledge. Beyond this, I'd especially mention the support from the Management Team and from EDF Energy Corporate staff with this project. Their enthusiasm for it from the outset, without interfering in any way with its content, has made it so much more achievable.

Finally, I should mention the 'Nuclear Safety Group' at Sizewell B. Their depth of knowledge, experience, willingness to challenge, patience and rigour go a long way to keeping Sizewell 'B' as safe as it is. Their humour makes it enjoyable! This book, though ostensibly concerned with reactor operation, probably comes closest to a view of the world as it's seen from the Nuclear Safety Group. Make of that what you will…

The majority of the content of this book is my own. Where opinions are expressed—and there are a few—they are also mine, and do not in any way reflect the views or policies of EDF Energy or of any other company. That, of course, means that any errors that you find must also be mine. For these, I apologise and say ‘well done!’ if you’ve spotted one.

Personally, I find nuclear reactors fascinating. I hope you will too.

Suffolk, UK Colin Tucker
September 2019

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1

One Man and His Dog

I've heard it said that a modern nuclear power station could be operated by one man and a dog. The man would be there to feed the dog, and the dog would be there to bite the man if he touched any of the controls…

If only.

1.1 Reading This Book Won't Qualify You to Drive a Nuclear Reactor

The idea of this book is to explain how a nuclear reactor works and how it can be operated to produce power for the electricity grid. This book won't qualify you to drive a nuclear reactor. That takes a couple of years of training, including hundreds of hours in a simulator. On the other hand, this book will probably give you a much better idea of what is involved in driving one.

So, in starting this book, let's imagine that you've passed all the entrance tests for a job in the 'main control room' of a modern nuclear power station, like the one in Fig. 1.1, and you're ready to learn how it all works. Now your supervisor suggests you change reactor power. Do you have any idea what to do?

Or perhaps the computer system displays an alarm. What does it mean? Which of the quarter of a million or so different items of equipment—depending on how you count them—does this alarm refer to? Is it a problem? Will you respond using one of the few hundred controls and indications in the control room or will someone have to be sent to look at the equipment locally? Could something more significant be going on? Will you have to get

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Fig. 1.1 Part of a PWR control room

ready to shut down the plant. There'll be tens of thousands of possible alarms on a modern station, and just as many procedures to follow.

As a trained reactor operator, you'll need to be able to decide when to act quickly and when to act in a more measured way. Safety is your overriding priority as it is for anyone who drives a reactor or works at a nuclear power station. After safety, you can think about what's best for the people and the plant, but safety comes first. Despite this, you'll understand that your power station is just a factory for making electricity. Unnecessary shutdowns are going to be expensive.

I've never seen an individual book (including this one) that covers everything you'll need to know. After all, an operator has very many controls at their fingertips. This book won't take you through the function of each one, but it will show you how a competent operator works in partnership with both the physics of the reactor and with the automatic systems out on the plant.

So what would make you a successful (and safe) person to drive a nuclear reactor? Well, you're probably going to need some kind of science or engineering background; but this needn't mean a university degree. It could be from an apprenticeship, for example. You'll need the ability to learn a lot about a lot of different things, without necessarily becoming an expert in any of them. You'll need to be rigorous in following procedures, but not blindly—if something doesn't feel right, you should be the first person to stop and ask the question 'Is this OK?' You'll need to be able to move from inactivity to high-speed action very quickly, without getting bored or complacent when things are quiet. On top of all this, you'll need to be able to communicate well and work within a team.

Does all of that sound impossible to learn? It's not. There are more than 400 operating nuclear power stations in the world, and each one of them has dozens of trained operators. Think of it as being like learning to fly a passenger aircraft—it takes a lot of time (and money) to train a pilot, but there's always one there when you get on a plane. Well, usually.

1.2 What This Book Covers

This is very deliberately not a textbook. It does cover some physics—quite a lot actually, I enjoy physics—but without the maths. In the real world, we usually let the computers do the maths! As a reactor operator, it's the concepts that are going to be relevant to you, i.e. what happens to the reactor, when and why. The book includes more than a hundred diagrams and photos; these should help you understand the more complicated bits. There are a few definitions, but I hope that doesn't put you off; every industry that I know of has 'jargon', and the nuclear industry is no exception. I've included an index of all the essential terms at the back of the book, just in case you need to remind yourself of anything as you go along.

The majority of the reactors in the world, whether generating electricity or powering ships and submarines, are of a particular kind: Pressurised Water Reactors (PWRs), or the similar Boiling Water Reactors (BWRs). This isn't true of the UK where most of the current electricity-generating reactors are of a different type. However, the UK has operated one very successful commercial PWR (Sizewell B) since the 1990s, and is building more e.g. Hinkley

Point 'C', and the reactors planned for Sizewell 'C' and Bradwell 'B'. For this reason, and because that is the author's bias, this book is based around PWR operation and technology.

I'm going to use this book to explain how a PWR reactor works—what makes it run. I'll describe how, if you were a reactor operator, you'd start-up a reactor, change power levels and shut the reactor down. Once you grasp the three key concepts (see below), you'll find that this is all much easier than you might imagine. Along the way, this book is going to introduce you to some of the history of nuclear reactors and power stations. I've always found this interesting, but I also think that it makes it easier to remember the things that affect the operation of the reactor.

I'll explain how a PWR reactor is refuelled and how you tell that the reactor is ready for it. I'm also going to cover several *possible* faults that could happen to a PWR and what you, as a reactor operator, would do about them. Safety comes first, remember? Faults are going to be a big part of an operator's training, however unlikely they may be.

1.3 The Three Key Concepts

Driving a nuclear reactor is not as complicated as you might think, neither is it entirely intuitive. I'm going to suggest that there are three key concepts to understanding the operation of a PWR:

- Reactivity, or how the conditions inside the reactor affect the fission chain reaction.
- Reactor stability, the feedback mechanisms that hold it steady.
- Plant stability, what happens when you connect your reactor to the rest of the plant (and beyond).

If this book helps you to grasp these three key concepts, you'll find it easy to understand the behaviour of a PWR both in its day-to-day operation and during more challenging events.

1.4 And Finally…

If you're thinking of (or have recently started on) a career in the nuclear industry then I wish you good luck, and I hope that you'll find this book useful. If you're just keen on science and engineering, or perhaps you live near to a nuclear reactor, then I hope you'll find this book informative and entertaining.

If you want to read about energy policy and arguments for and against nuclear power stations then find another book; there are plenty out there on the politics of nuclear power. Similarly, this book contains only a brief history of nuclear power stations, and of the significant accidents that have shaped the industry. Once again, there are very many good books on these subjects already written. Instead, this book starts from the *fact* that hundreds of nuclear reactors already exist and are successfully generating electricity. Dozens more are currently under construction and will be running in a few years' time. I'm not going to try to defend these reactors in this book; I'm just going to try to explain how to drive one.

2

Physics Is Phun!

If you're reading this book, I expect it's because you have an interest in science and engineering. That's great, but the problem for me is that I don't know how much you already know. If I guess too low, you're going to feel insulted by what you read. If I guess too high, what I'm saying isn't going to make sense, and you'll lose interest.

So here's the deal: I'm going to start with some physics that I expect you'll clearly remember from school science. I'm going to use that to explain how a nuclear reactor works, and from that starting point, I'll be able to describe how to drive one… feel free to skip anything that you're already familiar with (at your own risk).

2.1 Atoms and Nuclei

You'll probably remember being told that an atom has a (small) positively charged 'nucleus' in the middle, with negatively charged electrons going around it—a bit like planets orbiting the sun. Things are a bit more complicated in the real world, but it's a good enough model for our purposes.

As an example, Fig. 2.1 is an illustration of a helium atom. Helium is one of the simplest of the chemical elements:

Helium has two positively charged particles (called protons, shown in red) in the central bit (the nucleus) and two negatively charged particles (electrons, shown in light blue) going around the outside. The two protons tell a physicist (or a chemist) that this is helium. One proton would make it hydrogen, three would mean it was lithium, four beryllium, and so on through the more

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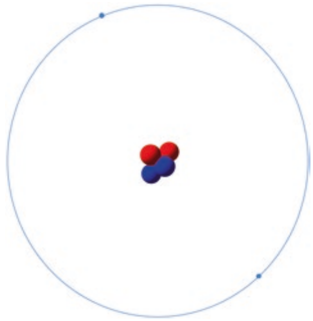

Fig. 2.1 Helium atom (not to scale)

than a hundred chemical elements that have been found or manufactured. The number of electrons is usually matched to the number of protons, and it's the number of electrons and how they are arranged that determines an element's chemical behaviour.

The two protons in our helium nucleus are positively charged so you'd expect them to push away from each other (like-charges repel, remember?). Because of this, there are also two uncharged particles (called neutrons, shown in dark blue) included in the nucleus to help glue it together. The total number of neutrons and protons is 2 + 2 = 4, so we'd call this helium-4. You can find helium atoms with only one neutron (helium-3), but they are relatively scarce on earth.

Atoms are small. Really small. You could put 100 million of them in a line, and they'd only stretch one centimetre. But atoms are enormous when you compare them to the size of the nucleus. This drawing of a helium-4 atom here is not to scale as the nucleus of a real helium atom is roughly 100,000 times smaller than the size of the whole atom. This book is mostly about what happens in the nuclei of large atoms such as uranium ('nuclei' is the plural of 'nucleus'). It's a book about nuclear physics, not chemistry, so from now on, we'll barely mention electrons. All of the drawings of atoms you see from now on will be of atomic nuclei rather than whole atoms because that's the bit that's interesting to us. If I'm lazy and call these 'atoms', don't worry about it….

So let's look at some nuclei—Fig. 2.2 shows hydrogen-1, helium-4, oxygen-16, iron-56 and uranium-235:

Hydrogen-1 is a single proton with no neutrons. Helium-4 and oxygen-16 have 2 and 8 protons respectively, i.e. they have the same number of neutrons as they have protons. Iron-56 has 26 protons and 30 neutrons (a few more neutrons than protons). By the time you get all the way out to uranium-235 with 92 protons, you find that there are 143 neutrons. This just shows that the

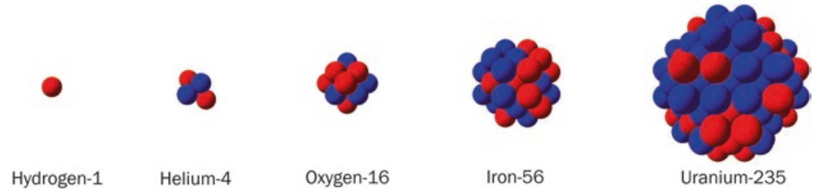

Fig. 2.2 A selection of nuclei

more protons you have in a nucleus, the progressively more neutrons you need to stick it together (this becomes important in Chap. 5 when we talk about radioactive fission products).

By the way, the chemical symbol for uranium is 'U', so I'm going to use 'U-235' instead of uranium-235 from now on; it'll be easier to read.

2.2 Fission

U-235 is not a happy atom… (OK, I mean nucleus, but that doesn't sound as good, does it?)

If you can find a way to give a U-235 nucleus just a bit more energy, it'll probably give up and split into two smaller nuclei. In physics, there are ways of doing this. For a nucleus, a simple way is to drop in another neutron—we could call this process 'neutron capture', if we wanted to be technical about it. The neutron itself won't be carrying a lot of energy, but it will release energy when it joins with the nucleus—think of the noise you get when you snap a magnet onto a block of iron, and you'll get the idea.

That extra energy makes the U-235 nucleus pretty unstable. One way to imagine this is to think of the U-235 nucleus as a large water droplet in a weightless environment such as on a space station. If you've seen any videos of these, you'll have seen how a droplet can start out spherical but if it's poked it can get squashed, stretched and even split into two droplets. If this were to happen, the two new smaller water droplets would probably just sit (float?) there. But that doesn't happen with nuclei as they are each made up of a large number of positively charged protons along with the neutrons—the electrons are a very long way away on this scale and don't really get involved. The two smaller positively charged nuclei will be pushed away from each other very strongly, accelerating to reach tremendous speed before eventually bumping into other atoms and slowing down. Their speed energy will then have been converted into heat. Most of the energy from the splitting of a U-235 atom is carried away by these smaller nuclei.

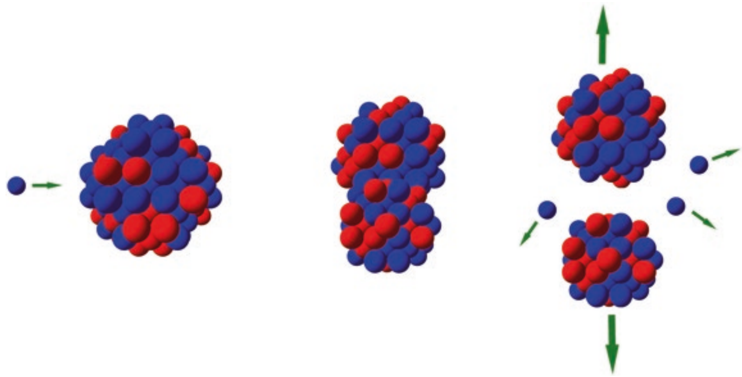

Fig. 2.3 Fission of U-235

This splitting process is called fission and is shown in Fig. 2.3. The smaller nuclei left behind are usually known as ‘fission products’. If a neutron happens to encounter a U-235 nucleus and is travelling slowly enough to be captured, it’s then very likely that fission will occur. It’s a quick process—for an individual U-235 atom it’s all over in around a millionth of a millionth of a second. But the energy released by even a single fission event is enormous on an atomic scale. It’s roughly 2.5 million times the energy that you get from ‘burning’ a carbon atom to make carbon dioxide.

That much energy could probably be quite useful if we could just find a way of encouraging these fission events to happen more often…? Helpfully, U-235 does this for us, because with every fission event we also get two or three spare neutrons. In theory, these could go on to cause more fissions, giving us a ‘chain reaction’. In practice, it’s a little more complicated.

Most uranium dug up out of the ground (natural uranium) isn’t U-235; it’s U-238 (it has three more neutrons). It’s much less likely that U-238 will fission if it captures a neutron—it’s a more stable nucleus. Unfortunately, only around 0.7% of natural Uranium is U-235. You can increase the proportion of U-235 through a process called enrichment, but that’s expensive, so most enrichment plants stop at around 4–5% U-235. (If you enrich too far the politics get tricky as you’d effectively be making the raw material for nuclear weapons; let’s not go there). That means that you’re still stuck with a lot of U-238 in your fuel, which won’t fission but can affect the reactor in other ways (as you’ll see in later chapters).

At this point, you might be wondering where all this extra energy actually comes from? Here’s the trick: if you add-up the masses (weights) of the fission products and neutrons after the fission, you find that they weigh a little less than the U-235, plus the extra neutron, that you started with. The fission process has converted some of the original mass into energy in line with Einstein's famous equation Energy equals Mass times the Speed of Light Squared ($E = mc^2$). It only takes a little bit of lost mass to give a lot of energy as c^2 is such a large number, whatever units you use. Another way to think of it is that the fission products are more tightly stuck together than the original U-235 nucleus because they are smaller nuclei and the attractive forces work better over short distances. In squeezing the nuclei together a bit tighter, a bit of spare energy is released. If you want to know more, go online and look up the physics of 'binding energy'.

2.3 Fast and Slow Neutrons

Neutrons released during and after a fission event are moving at around ten thousand miles per second. Even Physicists are happy to call them 'fast neutrons'. This matters because it makes them far less likely to be captured by a U-235 nucleus. It'd be like shooting a steel ball-bearing past a magnet at very high speed; it's not liable to be stopped. On the other hand, throw a ball bearing slowly towards a magnet, and it'll stop dead. So to encourage further fissions, we need to design a reactor that slows down its neutrons.

An excellent way to slow down fast neutrons is to let them bounce around in some material, giving up a bit of their energy (speed) with each collision. After enough collisions, the fast neutrons will have become 'slow neutrons'. Slow neutrons are sometimes called 'thermal' neutrons. This is because they will be travelling at the same speed as the atoms of the material around them, so to a physicist, they are 'in thermal equilibrium' with it.

Physics has fancy names for this process of slowing-down neutrons: it's called 'moderation', and we call the material in which the neutrons slow-down a 'moderator'. In a 'Pressurised Water Reactor' (PWR) water is used as the moderating material. Physics tells us that more energy is lost in each collision if the atoms that the neutrons collide with are of a similar size (mass) to the neutrons themselves. The hydrogen atoms in water molecules—being individual protons—make water an effective moderator. The other reactors currently in the UK actually use graphite (carbon, another relatively light atom) as a moderator. Chapter 22 briefly covers different designs of reactors, where you can see this.

Incidentally, this is one of the most frequent errors that people make when they talk about nuclear reactors: they'll describe 'control rods' as 'moderating' the reaction. To a reactor operator, the moderator is what makes your reactor run! This error makes me wince every time I hear it, but I'm probably a little over-sensitive…

2.4 Chain Reactions

Once the neutrons released by the fission have been slowed to thermal energy, they are very likely to go on to cause another fission, if they encounter another U-235 atom. But, as you've seen, most of the uranium in a typical reactor is U-238 and, unfortunately, it's pretty good at capturing neutrons as they slow down through intermediate speeds (between fast and slow). In practice, this means that if you simply take uranium and a moderating material and mix them together, nothing will happen. The U-238 will steal all the neutrons before they've had a chance to slow down.

The trick to overcoming this is to use a bit of geometry: deliberately separate the uranium fuel and the moderator. This means that fast neutrons can be produced in the fuel, will escape the fuel into the moderator, where they will then slow down before bouncing back into the fuel, finding a fresh U-235 atom and causing another fission. It all sounds a bit unlikely, but it works! This is the 'chain reaction' that powers your nuclear reactor—it's what makes it a 'reactor'—as you can see in Fig. 2.4. Understanding what affects this chain reaction is the key to understanding the physics of reactors.

At this point, you might be a little bit worried? I said earlier that two or three neutrons are released during or after each fission of U-235 (the average is around 2.4, but you'll never see 0.4 of a neutron). If there's a chain reaction going on and two or three neutrons are produced each time a U-235 atom fissions, then isn't the chain reaction going to snowball very quickly? The answer is 'No'. You're going to waste the majority of your neutrons.

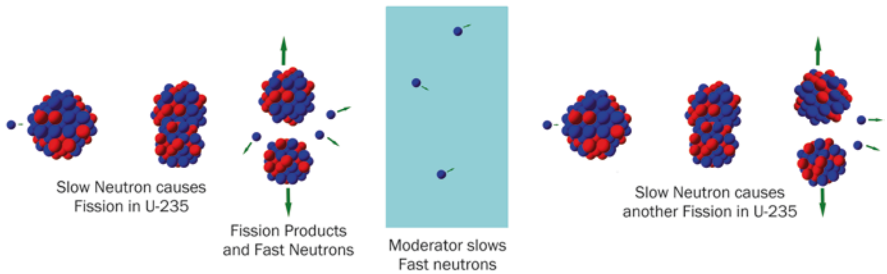

Fig. 2.4 The fission chain reaction