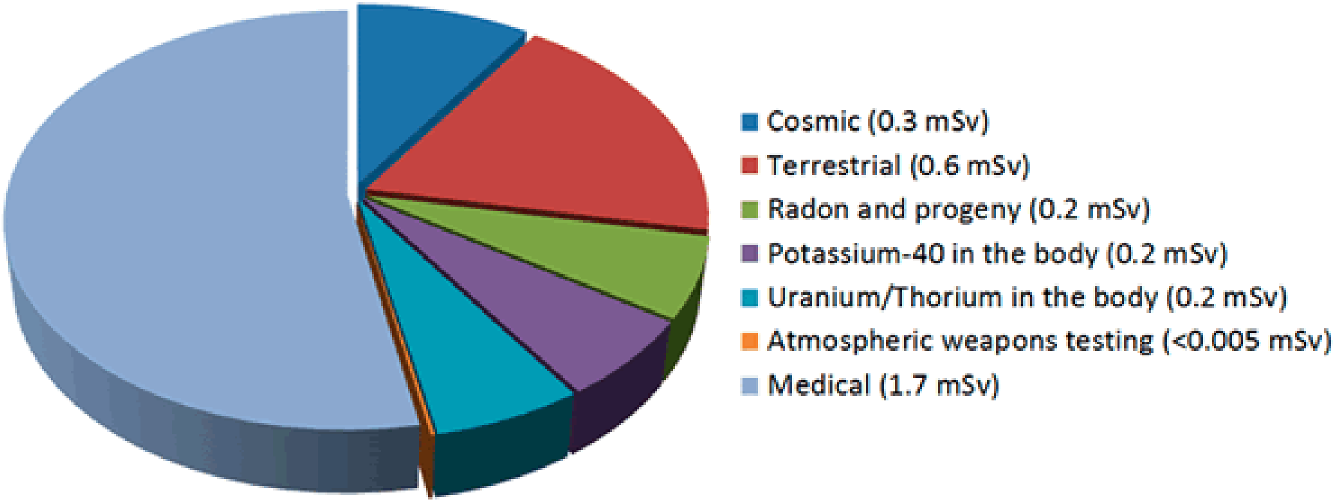
Issue 1: How much radiation exposure do Australian's receive?

Humans live in a sea of radiation, and always have.

Radioactive material that is naturally occurring surrounds the human race. In addition, there is cosmic radiation that reaches humans after being partially shielded by the atmosphere. Finally, there is radiation exposure that has been created by man.

The Australian Radiation Protection and Nuclear Safety Agency (ARPANSA) has an excellent web site that discusses the radiation exposure that Australian's typically receive.[1] The diagram below has been prepared by ARPANSA.



Average yearly radiation exposure in Australia

The diagram shows that the typical Australian received 3 mSv per year[2] of radiation exposure. It also shows that most people get half of their annual radiation dose from medical procedures, including dental X-rays, CT scans and other diagnostic or therapeutic procedures.

Workers may be involved in occupations that result in higher exposure. ARPANSA reports that the typical Australian uranium mine worker receives an additional 1 mSv per year of radiation exposure. Flight crews, especially those flying full time into and out of Australia, receive an estimated 2.2 mSv.[3] This is because of the elevation at which a commercial airliner flies.

Radiation is energy. Naturally-occurring materials such as uranium, thorium, radon and a form of potassium emit energy as they decay.

Medical procedures use radiation for diagnostic and therapeutic purposes. These procedures harness the radioactive energy for the specific medical purposes.

Nuclear material that is created in nuclear power is essentially the same as naturally-occurring radioactive material. It emits energy as it decays.

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[1] http://www.arpansa.gov.au/radiationprotection/Factsheets/is_ionising.cfm

[2] The unit of radiation exposure is Sievert. The "m" means one thousandth of a Sievert, or a milliSievert.

[3] PJ Oksanen. Estimated Individual Annual Cosmic Radiation Doses for Flight Crews. Aviation Space Environmental Medicine, Volume 69, number 7, pages 621-625, 1998. YJ Feng, et.al., Estimated Cosmic Radiation Doses for Flight Personnel. Space Medicine Engineering, Volume 15, number 4, pages 265-269, 2002.

ARPANSA reports that one of the largest potential sources of radiation exposure is inhaling radon gas. In the diagram above, radon is shown to have an annual radiation dose of 0.2 mSv. However, this exposure can be much higher – as much as 10 mSv per year.

Given that all Australian's receive these levels of radiation exposure, the obvious question is what is the consequence?

ARPANSA reports that for annual radiation doses up to 10 mSv, including doses to an unborn child, there is no direct evidence of human health effects. On the other hand, the International Commission on Radiological Protection (ICRP) and others recommended use of what is called the linear no-threshold hypothesis (LNT). This hypothesis suggests that any amount of radiation, no matter how small, may result in a cancer. Many scientific studies challenge the validity of the LNT. Empirically, the LNT would predict a much higher level of cancer than is observed. One scientific study concluded that "biological data demonstrate that the defense mechanisms against radiation-induced carcinogenesis are powerful and diverse. This is not surprising, because organisms have been subjected to reactive oxygen species from physiologic processes and environmental insults during evolution. Life is characterized by the ability to build defenses against toxic agents, whether internal or environmental."[4]

Issue 2: How Is Australian Uranium Made into Nuclear Fuel?

Australia possesses approximately 30% of the known, economically-recoverable uranium reserves in the world, estimated to be in excess of 1.7 million tonnes of uranium. Examining only Olympic Dam, it is estimated that the total reserve approaches 2.5 million tonnes of U_3O_8, or 2.1 million tonnes of total reserve.

Over the last ten years, Australia has exported between 6,000 and 9,000 tonnes of uranium per annum. Olympic Dam accounts for about 3,400 tonnes per year of uranium production, which was 6% of the global production in 2013.

The 2013 global production and consumption of uranium was approximately 60,000 tonnes of uranium.

At the current spot price of US$40 per pound, Australia's average annual production of uranium translates to between US$500 and US$700 million pa.

The spot price of uranium has, in the last 15 years, ranged from about US$7 to US$140 per pound, as shown in the Figure 1.[5]

[4] M. Tubiana et.al., Radiology, Volume 251, Number 1, pages 13-22, April 2009.
[5] Chart taken from indexmundi.com.

Figure 1. Spot Uranium Price for 15 Years

At peak production of 9,000 tonnes per annum and the peak spot price, Australia's uranium export would have a value of approximately US$2.8 billion.

Once the uranium leaves Australia, it enters the nuclear fuel cycle, as shown in Figure 2 and explained below.

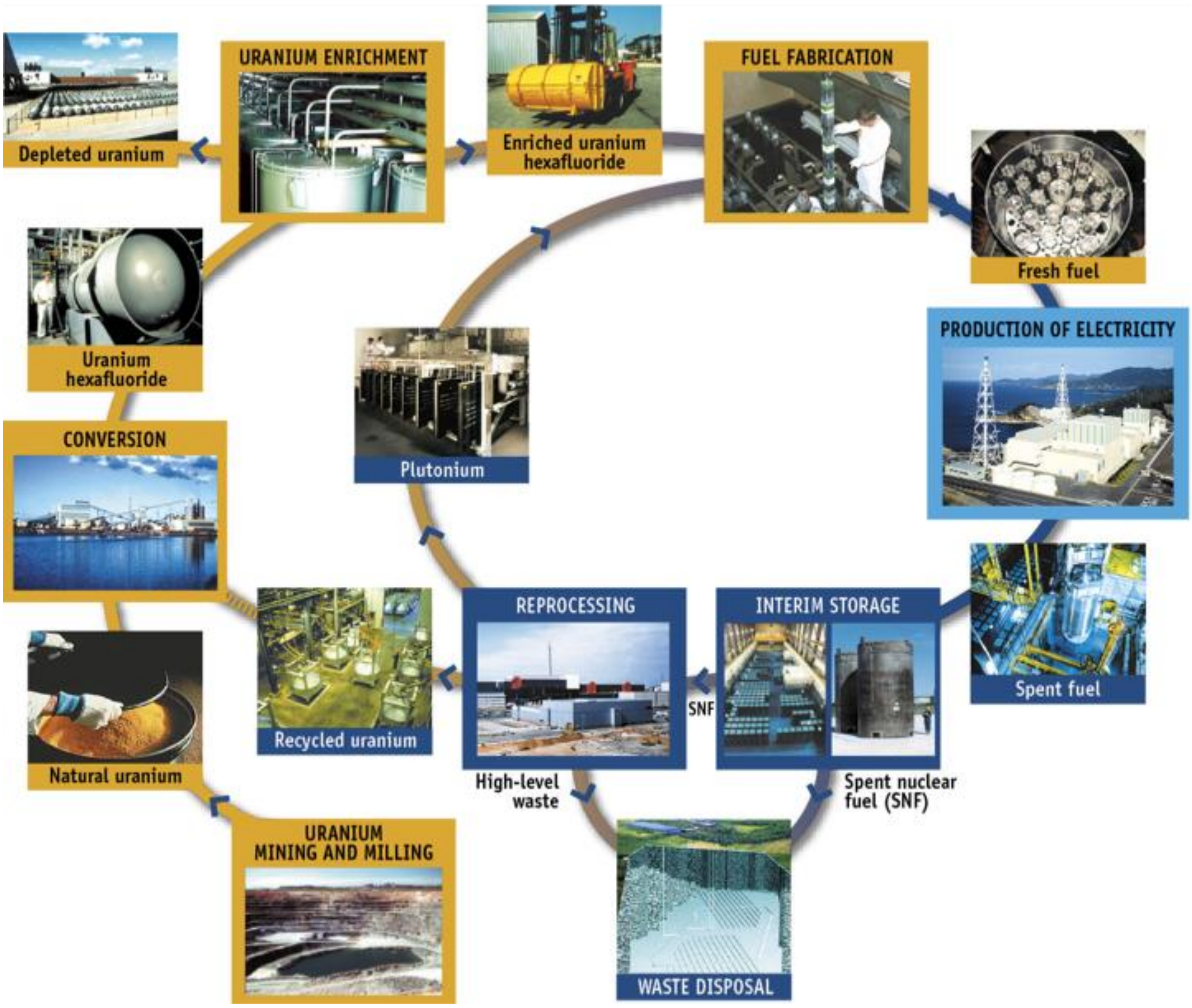


Figure 2. Nuclear Fuel Cycle

Australian uranium is produced as "yellow cake" or U_3O_8. It is shipped to a uranium conversion facility where it is converted chemically to a gaseous form, UF_6. As a gas, the uranium is processed in an enrichment plant where the concentration of U^{235} is increased from its natural content of 0.7 weight percent to a 'reactor grade' enrichment of up to 5 weight percent. This step results in a stream of depleted uranium that is stored at the enrichment plant either for future use or for disposal. The enriched UF_6 is then converted into another oxide form, UO_2, and is made into fuel.

There is a global overcapacity of facilities needed to prepare uranium for use in a reactor. The OECD has estimated that the annual contract value to convert Australia's uranium ore exports into nuclear reactor fuel is approximately US$500 million. Because there is an oversupply of these services in the world, it is probable that there will be downward pricing pressure for these services. This downward pricing pressure in turn diminishes the commercial attractiveness of building new uranium fuel production facilities in Australia due to limitations in financing. Hence, for 'front end' nuclear fuel cycle activities activities, there is a "buyers market". The scarcity in the world is in the area of post-reactor management of nuclear fuel.

Issue 3: Does Nuclear Power Reduce Greenhouse Gas Emissions?

Australia's current annual emission of Greenhouse gas is approximately 430 million tonnes. [6] Australia's current exports of uranium create an annual reduction of 240 million tonnes of Greenhouse

[6] See Trends in Global CO_2 Emissions 2013 Report, PBL Netherlands Environmental Assessment Agency, The Hague, 2013.

gases, more than half of Australia's emission. Further export of Australian uranium is perhaps the most effective way for Australia to contribute to a global reduction of Greenhouse gas emissions. The development of nuclear power reactors in Australia would add to this global reduction.

Adopting a policy of expanded uranium production and export would lead directly to a further annual reduction of 5 million tonnes of CO_2 for each nuclear power plant that is fueled with Australian uranium.

Burning coal to generate electricity releases a great deal more CO_2 to generate the same amount of electricity. The UK Parliamentary Office reports that coal releases between 30 and 160 times more CO_2 than nuclear power.

There is no single source of information that allows a direct determination of the carbon emission implications of nuclear power generation. Background information supporting the assertions is made in this description.

A Federal publication published in 2012 states that the Australian Academy of Science has reported that for every 100 tonnes of uranium exports by Australia, 4 million tonnes of CO_2 release are avoided.[7]

The export of 6,000 tonnes of uranium results in the production of 750 tonnes of enriched uranium fuel assuming that the tails contain 0.3 weight percent U-235. 750 MTU of fresh fuel produces 3.1E5 GWe-hr of electricity using a burnup of 50,000 MWth-d/MTU.

Using 800 T CO_2eq/GWe-hr as the carbon emission rate from fossil fuel consumption, the 750 MTU of fresh fuel avoids 240 million tonnes CO_2e/yr of emissions from carbon fuel consumption. This translates into 3.2 million tonnes CO_2 per every 100 tonnes of uranium exported, a value that is close to that attributed to the Australian Academy of Sciences.

The carbon emission rate for the use of fossil fuels for the generation of electricity is presented with a broad range in the literature. The UK Parliamentary Office of Science & Technology (Stephanie Baldwin, Carbon Footprint of Electricity Generation, undated) reported the information shown in the table below. This table suggests that 800 T CO_2eq/GWh is at the high range for coal consumption.

Source	Low, TCO_2eq/GWh	High, TCO_2eq/GWh
Biomass	25	237
Photovoltaics	35	58
Marine	25	50
Hydro	3	10
Wind	5	5
Nuclear	3	5
Coal	100	800
Gas	250	400

The World Nuclear Association (Comparison of Lifecycle Greenhouse Gas Emissions of Various Electricity Generation Sources, July 2011) published the table below with values of carbon emissions from various sources. This report represents values taken from 21 studies. As shown, the use of coal, lignite, oil and natural gas for electricity generation is reported as having carbon emissions ranging from 360 to 1,370 tonnes CO_2eq/GWh.

Technology	Mean	Low	High
Lignite	1,054	790	1,372
Coal	888	756	1,310
Oil	733	547	935
Natural Gas	499	362	891

[7] See Australia's Uranium Industry, Australian Government Department of Resources, Energy & Tourism, June 2012.

Solar PV	85	13	731
Biomass	45	10	101
Nuclear	29	2	130
Hydroelectric	26	2	237
Wind	26	6	124

Issue 4: Global Demand and Supply for Nuclear Reactor Fuel[8]

Broadly speaking, there are three critical services needed to convert Australia's exported uranium into nuclear fuel: conversion, enrichment and fuel fabrication. This paper provides a snapshot of global supply and demand for these services. The relevance to Australia is that there is a belief held by some that Australia should develop these facilities and receive the "value added" revenue for delivering a refined product – nuclear fuel – and not simply exporting the uranium ore.

Conversion

The first step in the fuel manufacturing process is to convert uranium ore, exported as yellowcake or U_3O_8, into a gaseous chemical form, UF_6. In 2015, the global demand for this service was for the production of 46,000 tonnes of uranium. At the same time, the annual capacity for this service was approximately 59,000 tonnes of uranium. This capacity was provided by the following facilities:

Company/Facility	Capacity Tonnes U/yr as UF6
Cameco, Port Hope, Canada	12,500
TVEL, Seversk, Russia	12,500
Cumurhex, Malvesi & Tricastin, France	15,000
Converdyn, USA	15,000
CNNC, Lanzhous, China	4,000
IPEN, Brazil	100
World Total	59,100

[8] Nearly all of the information in this paper has been consolidated from the comprehensive presentations of the World Nuclear Association. While WNA is a nuclear industry group, the information reviewed for this paper is heavily and professionally referenced, but has not been independently verified.

Thus, at the end of 2015, demand was only 83% of the available supply.

Enrichment

In enrichment, the gaseous form of uranium, UF_6, is fed into an enrichment process, usually centrifuges. The naturally-occurring uranium isotope U^{235}, which occurs in nature with a concentration level of 0.7%, is selectively concentrated to bring its resulting concentration to approximately 5%. The term that is used to measure the capacity of enrichment plants is called "separative work unit" or SWU. In 2015, nuclear reactor fuel enrichment required approximately 47 million SWU. At the same time, the global supply of this capability was nearly 59 million SWU. More production capacity is being constructed, mainly in China, so that by 2020, the annual supply will be nearly 67 million SWU, while demand is estimated to be 57 million SWU. Thus, demand is only about 84% of the total supply.

The table below summarises this information. Note all units are millions of SWU per year.

Country	Plant	2013	2015	2020
France	Georges Besse I & II	5.5	7.0	7.5
G-UK-N (a)	Gronau, Almelo, Capenhurst	14.2	14.4	14.9
Japan	Rokkaasho	0.08	0.08	0.08
USA	New Mexico	3.5	4.7	4.7
Russia	Angarsk, Novouralsk, Zelenogorsk, Seversk	26.0	26.6	28.7
China	Hanzhus & Lanzhou	2.2	5.8	10.7
Other	Various	0.08	0.1	0.2
	Total Capacity per year	51.6	58.6	66.7
	Estimated Global Demand	49.2	47.3	57.5

(a) Germany, Netherlands and the UK

Fuel Fabrication

In fabrication, the enriched uranium is converted into oxide powder and made into nuclear reactor fuel. In general, demand for "light water reactor" or LWR fuel is 7,000 tonnes of enriched uranium per year. In addition, there is a demand for 3,000 tonnes per year of fuel for "pressurized heavy water reactors" or PHWRs and 400 tonnes per year of fuel for "gas-cooled reactors" or GCRs.

Fuel fabrication services are provided at 28 facilities located in 17 countries. The total capacity of these facilities is approximately 18,000 tonnes per year. Thus demand is only 60% of the total supply.

There are some specific differences in this market, related to fuel types. Each reactor type requires a specific type of fuel. Each fuel fabrication facility has to be constructed for a specific reactor fuel type. Hence, there could be specific situations where there is more demand than supply for specific types of reactor fuels.

Summary

In broad terms, the world possesses a surplus of capacity required to meet the global demand to convert uranium, to enrich it and to manufacture nuclear reactor fuel.

Construction of these facilities is expensive, potentially billions of dollars depending on their size. The market situation – an oversupply – means that the contracts will be highly competitive, with obvious downward pricing pressure. This suggests that the return to investors in such new facilities could be low or non-existent.

Issue 5: Is It Safe to Ship Highly Radioactive Materials?

Highly radioactive materials are shipped to the highest safety standards. Highly radioactive materials, including spent nuclear fuel and solidified high-level wastes, are transported in packages deemed to be "Type B".

The International Atomic Energy Agency has established extremely difficult standards for Type B packages. These include pressure, being dropped, and surviving a fire.

Since the early 1970's, there have been over 7,000 global shipments of spent nuclear fuel and solidified high-level wastes. These shipments have been by land and sea. While there have been accidents, there has never been an accident that resulted in a breach of the container or a leak of radioactive material.

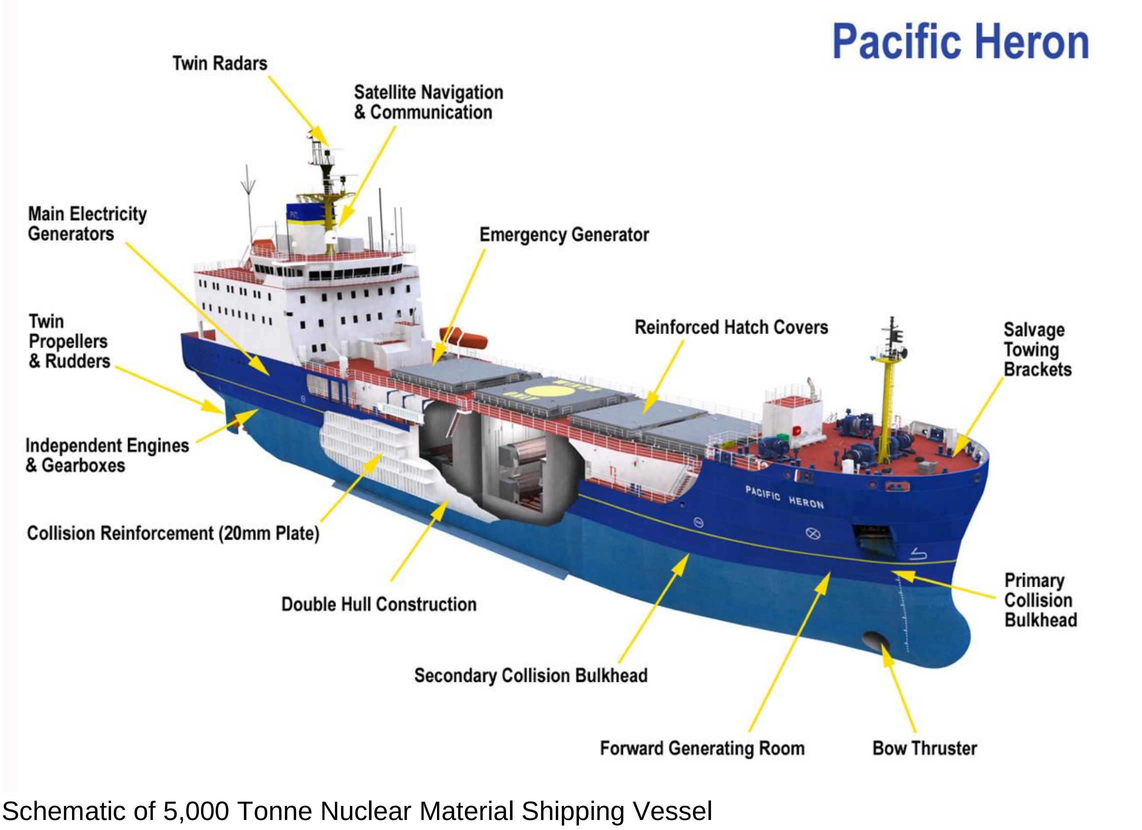
In the 1970's, Sandia National Laboratory in the United States conducted several full-scale tests of the durability of shipping containers for spent nuclear fuel. The two pictures below are from these tests. A transport was accelerated using rocket engines to 130 km/h. The transport was then crashed into an immovable concrete barrier.[9]

While the results were consistent with international safety standards – i.e., there was no breach of the shipping container – critics have discounted the scientific validity of the tests. One frequent criticism is that the test involved obsolete shipping container designs, although the industry views this as validation rather then nullification of the tests.

Shipment by sea is done in purpose-built vessels. Each are double-hulled, and have numerous systems to ensure the safety of transport. Several figures below show the typical design of these vessels.

[9] SG Durbin, et.al., Full-Scale Accident Testing in Support of Spent Nuclear Fuel Transportation, published by Sandia National Laboratories, September, 2014, publication SAND2014-17831R.


Nuclear Fuel Shipping Port, Barrow, UK



Schematic of 5,000 Tonne Nuclear Material Shipping Vessel

Loading Operations of Nuclear Fuel Shipping Cask

The question of safety has two sides to it. One is the likelihood that a shipping container will be breached and release radioactive material. The standards and experience of the industry show that this likelihood is extremely low. The other side is the consequences in the unlikely event that a breach occurs.

Transport standards focus on this point by requiring that all emergency responders who are along the paths of shipment are qualified and trained to respond to such extreme events. In addition to relying on the local first responders, transport organizations have emergency response teams that can be immediately mobilised to address such a situation.

Response starts with isolating the situation to ensure that any radioactive material that has been released is contained and isolated from the public and the environment. This process is helped by another standard – the ban of transporting highly radioactive liquids. After isolation, all radioactive material would be collected and placed into certified containers.

In addition to the extremely rigorous standards surrounding the transport of highly radioactive materials, the cleanup of radioactive materials is aided by ability to detect immediately precisely where the materials are located. This is contrasted with some toxic and hazardous chemicals that require laboratory analyses to determine their locations.

Safety may mean many things to different people. However, under any definition, the transport of highly radioactive material is very safe. The systems and standards involved ensure that the likelihood of release of radioactive material is extremely low. The standards and procedures also ensure that in the unlikely event of a release, the impact on the public and the environment will be extremely well contained.

Issue 6: What is a Nuclear Reactor?

When you stand in front of a warm fire (taking the sentiment out of the experience as scientists and engineers often do), what you are experiencing is a carbon atom being combined with oxygen by being burnt, and in the process, releasing energy. In a coal-fired power plant, the same thing is happening, except the warmth you feel at the fire is now being used to boil water. The resulting steam is used to make electricity.

In a nuclear reactor, one atom of the uranium group, U^{235}, is split into two smaller atoms and releases energy. While this energy is not the warm glow of logs burning over the fire, the energy is captured to make steam and then to make electricity with that steam.

The subject is of course more complicated than this simple sentence conveys. Nuclear power has the unfortunate history of being established initially for military purposes – for making an atomic bomb. The early-twentieth century physicists understood that fission, or the splitting of atoms, existed and that it likely released energy, but they were uncertain how to do it. In World War II, things moved rapidly from a large scale demonstration at the University of Chicago to the awful conclusion – dropping two atomic bombs in Japan.

Talking about the military application of nuclear technology in a piece about nuclear reactors seems odd. But addressing this reality is essential. Australians didn't first hear the words "nuclear" and "atomic" in the context of electricity generation or Greenhouse gas reduction. We heard them in the context of war. We continued to hear these words in the context of large-scale hydrogen bomb testing. At home, the words were eventually introduced in the context of British nuclear weapons testing at Maralinga and Monte Bello Island off the coast of WA. In the late 1990s, the French reinforced the messages that equate "nuclear" with "weapons" by doing a large underground test in French Polynesia. The North Koreans are today continuing to reinforce the validity of the synonyms.

Hence, perhaps a more obvious answer to the question of "what is a nuclear reactor" might be "a thing that is associated with war, death and destruction", rather than a stale but accurate description of that it is the fissioning of U^{235} and the capture of the resulting energy. Often, the proponents of nuclear energy proceed with bland but accurate descriptions of nuclear technology without consideration of this backdrop, of this reality. To do so, however, misses the reality of public opinion. Many people respond to the words "nuclear power" allergically. So to actually discussion nuclear power, we must address the underlying fears also.

A nuclear power plant cannot explode like a nuclear weapon! Reverting to science-speak, the physics of an atomic bomb cannot be recreated in a nuclear reactor.

What about radiation leaks from a nuclear power plant? There are two accurate answers to this query. The first is that a properly constructed and operated nuclear power plant releases less radioactive material than a coal plant does.[10] This is born out by tens of thousands of reactor years of experience throughout the world. The second answer is yes, when things go wrong, radioactive material can be released from a nuclear power plant. Three-Mile Island, Chernobyl and Fukushima are the most obvious occurrences supporting this answer. Each of these three are addressed below.

- Three-Mile Island: In the late 1970's, a US nuclear power plant in the State of Pennsylvania suffered a partial meltdown of the reactor core. There are three "take-aways" from this.
  - First: The accident was as bad as could have been feared. The internal structures of the reactor melted. However unlikely is was, it happened.
  - Second: The backup safety systems worked. The releases were contained. Yes, small quantities of radioactive material were released to the environment, but these releases were barely detectable a small distance from the reactor. The main point is

[10] Coal in nature is a carbon filter. Over the eons, water containing small quantities of uranium and thorium pass through the coal. The radioactive material is filtered out and remains in the coal. When the coal is burnt, some of the radioactive material is released up the stack. This release is not regulated by any country in the world. The result is that some coal plants release sufficient radioactive material to cause radiation doses in the population that are not allowed in the licensing of a nuclear power plant.

that the plant was designed not to fail, but also designed with the idea that things might fail, so safety systems had to be in place in this awful event. These systems were in place and worked.

- Third: The nuclear industry learned from this mistake. The industry is made of men and women, none of whom want to see a nuclear accident. Massive studies were undertaken to learn how this accident happened and how to prevent it. Nearly every plant in the world was modified once the lessons were clear. The industry learns from its mistakes.

- Chernobyl: The RBMK reactor was a stupid design, created by the Soviet Union and forced into the countries it controlled. No one outside of the Soviet Union (not even Russia today) thinks the RBMK is a good idea, although eleven of these reactors remain in operation in Russia. This reactor type grew directly out of the Cold War. It was a relatively cheap way of building a reactor to deliver electricity. The Soviet philosophy was to omit most safety and containment systems, and to make the engineers and their families live nearby, creating a built in safety system of self-preservation. This is not a philosophy embraced by anyone in the nuclear industry today. Chernobyl was and is a problem, but it is not representative of anything that goes on today with the development and operation of a nuclear power plant.
- Fukushima: The accident at Fukushima was fundamentally caused by design error. Neither Tokyo Electric Power nor the Japanese regulator anticipated that a Tsunami of that magnitude could have occurred. The reality is that preventing the event could have been achieved by a relatively modest investment to elevate the Tsunami wall and to raise the elevation of the emergency generators and fuel tanks. But in the absence of this foresight, the accident occurred. The releases of radioactive material are material and widespread. It is too early to make definitive statements on the human and environmental consequences of these releases, but early indications are optimistic. As with Three-Mile Island, the industry has made massive efforts to understand the causes and to develop means to prevent such accidents and to avoid the consequences.

These thought lead to a more pressing question. *Is nuclear power right for Australia?* As with all complex questions, there are many answers. Technically, a nuclear power plant could be safely constructed and operated in Australia, providing low-carbon energy. Commercially, it is not clear if the appropriate economic conditions exist in Australia for the construction and operation of a nuclear power plant. Advances in the development of Small Modular Reactors or SMRs may alter the economic calculus in favor of nuclear plants, but this has yet to be determined. From a regulatory perspective, ARPANSA is an excellent nuclear regulator with some experience in nuclear reactors through activities at ANSTO. Socially, it is not clear it the people of Australia are prepared to trust the institutions that would develop, operate and regulate nuclear power. This is a social question that can only be answered in time.