APPROACHING THE DEVELOPMENT OF A UNIVERSAL MOLTEN SALT FAST REACTOR FOR WORLDWIDE DESTRUCTION OF HIGH-LEVEL NUCLEAR WASTE

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ABSTRACT

Earlier work has demonstrated that the molten salt nuclear reactor in all its various forms appears to be the most suitable system for general worldwide use. To a large extent, this arises from its natural outstanding safety characteristics. Prominent among these is the high negative coefficient of reactivity which arises not only from thermal expansion of the effectively near incompressible nature of the fuel-coolant itself but from the exceedingly useful characteristic that gaseous fission products are voided immediately in the fuel-coolant to give an immediate strong negative feedback effect in reactor control. The future seems clear to embark on a massive expansion of nuclear fission using this improved technology. One purpose of this is to give us our main energy source, which is electrical power, generated from a basic source which can, if necessary, exclude the use of fossil fuels completely and thus avoid further adverse effects on our climate. The scientific evidence is more than just suggestive that the world is getting far too close to a dangerous runaway form of GHG emission which could send our civilisation back to the Stone Age. Yet major manufacturing nations such as Japan and Germany are seriously considering a return to using fossil fuels instead of nuclear fission. Japan has experienced the reality of Fukushima and Germany, equally conscious of the safety of its densely populated nation, is well aware of the risks of reactors which use water in the reactor core. Added to this is the need to have technology for reprocessing spent nuclear fuel safely. Pyroprocessing of spent fuel has shown much promise and is ideal for eliminating long-lived actinide nuclear waste in a fast neutron spectrum molten salt reactor. The problem is one of choice, namely that any fast reactor can destroy long-lived nuclear waste and the greater experience we have with lead-bismuth fast reactors suggests that in some ways this is the more attractive approach to use in fuel reprocessing. It is recommended that the lead cooled fast reactor may be preferable initially until more experience, particularly with pyroprocessing, is gained with molten salt reactors.

Keywords: molten salt fast reactor, global warming, Pb/Pb-Bi eutectic reactors.

1 INTRODUCTION

As climate change worsens there is a need for an expanded nuclear fission power industry to reduce our dependence on fossil fuels. The situation has been reviewed recently (Boothroyd [1]). In summary, it was concluded that wind and solar power can only make a limited contribution to our energy needs. Commercialisation of fusion power is still far away in the distant future. Despite this nuclear fission power has a history of success and can be increased enormously to satisfy our needs without contributing much to global warming. This is also an opportunity to adopt the most modern available technology.

1.1 The danger of runaway planetary warming

This has also been examined in Fig. 1 of an earlier paper (Boothroyd [2]) which is easy to download for personal scrutiny. This diagram from Dunlop [3] shows Earth's history of temperature variation in the last 50 million years. Up to about 5 million years ago the Earth has enjoyed an acceptably cool temperate climate. Today CO_2 emissions are edging the natural temperature fluctuations of Earth's climate closer to 2°C above the previous average.

WIT Transactions on Ecology and the Environment, Vol 246, © 2020 WIT Press
www.witpress.com, ISSN 1743-3541 (on-line)
doi:10.2495/EPM200091

The main problem is that much of our methane is locked safely away in the Earth's crust, but this locked methane can be released as a gas if temperature rises even slightly [4]. Methane is 100 times more potent as a greenhouse gas (GHG) than CO_2, when first released. Of particular concern are the large sources of methane which can be released from decomposition of methane hydrates from cool underwater deposits and permafrosts. This positive feedback effect of global warming could easily result in higher temperatures such as those existing more than 40 million years ago Boothroyd [2, Fig. 1]. We should not be deceived by the fact that methane has a much shorter life in the atmosphere than CO_2 as it decomposes to CO_2 and water by chemical reaction with the hydroxyl (OH) radical. We know that over a 20 year period methane is still 84 times worse on average than CO_2 on a mass for mass comparison. This natural decomposition rate of methane is far too slow to prevent methane from causing runaway global warming.

It is also of concern that some nations are investigating the possible exploitation of this methane hydrate source of energy. In the present author's opinion this should be outlawed. These methane hydrate (aka clathrate) deposits are under intensive research at present. Nevertheless the theoretical models for calculations resulting from this research are of dubious accuracy and it seems very dangerous to interfere with an unstable potential source of GHG which may be more than 100 times greater than that of traditional sources of fossil fuels such as from coal and oil [4]. There is another statistical fact which should be of concern to us. Since the start of the industrial revolution in 1790 the atmospheric CO_2 concentration has risen by 41% but the concentration of methane has risen nearly 4 times as much. The explanation for this is uncertain and debateable.

2 TARDINESS IN ADDRESSING GLOBAL CLIMATE CHANGE

It is a reality which is to be expected. In a democracy it is a hard task politically to impose change on an electorate when it involves risk, especially risk of reduced living standards. We need to reduce our GHG emissions and most people would accept this but this will inevitably entail a risk of a significant reduction in living standards. Economic growth is part of the dogma of modern politics. The alternative view hardly gets a mention [5], [6]. It is this scenario which seems to be bringing us to the brink of runaway global warming. From this line of reasoning it makes sense to provide for a solution which can be implemented in a very short interval of time. By its nature, however, a solution based on a sudden increase in nuclear power seems to be especially inappropriate: nuclear reactors are notorious for the length of time needed for construction, which is typically about 10 years. Yet there has been much interest recently in the nuclear industry in small modular reactors which can be factory-fabricated and assembled on site as a kit of parts [7]–[9]. It is advantageous to "nest" many modular reactors together to give a power plant of the desired size.

The original molten salt reactor (MSR) used at Oak Ridge, USA in 1960 worked well for 4 years without trouble. It is rumoured that, on Friday afternoon, reactor shut down was just a matter of ensuring that the reactor was non-critical by pumping a small part of the fuel-coolant into a separate tank. On Monday morning the fuel-coolants in the 2 tanks were still molten and the fuel-coolant was pumped back into the reactor core until the reactor went critical again. In Boothroyd [10], such a simple thermal neutron spectrum reactor was shown to have wide application in many different situations and it would be very safe to use. Can we manufacture and use such modular reactors as an emergency form of power at sufficient speed without having a lengthy regulatory procedure?

www.witpress.com, ISSN 1743-3541 (on-line)

3 A PANIC SCENARIO

On the basis of the lack of action regarding climate change, let us presume that we suddenly come to realise that we have acted far too slowly in addressing the climate change problem. We might reasonably expect many world-wide changes to stir us into action viz:

- Coal-fired power stations and other industrial plant using fossil fuels may have to be shut down before the end of their natural lifespan. Industries emitting bulk CO_2, such as cement manufacture, will need to be integrated with other industries such as those using CO_2 as a feedstock for making synthetic organic chemicals.
- Fuel for all private transport may well have to be made unavailable by international agreement. Everyone without a bicycle will have to walk to work, coping with overstretched public transport. A lucky few may have foldable electric scooters but these scooters really need to be redesigned with a view to using them in a redesigned public transport system [11].
- Air conditioning is likely to become illegal both domestically and commercially. At the very least government licensing to ensure it is solar powered and time-controlled is reasonable.
- The availability of solar photovoltaic panels and associated equipment may become in short supply.
- Loss of life and property in low-lying coastal regions is likely to becomes a regular occurrence.
- Bushfires, drought, dangerous storms and floods are expected to become more frequent and extreme.
- Electrical power cuts can be expected to be so frequent that it becomes near impossible to use refrigeration to store food.
- Air travel will probably be limited by using heavy taxation.
- Unemployment due to business failures is likely to worsen. Food supplies can be expected to dwindle worldwide in a climate adverse to our present agricultural methods. This can finally be expected to lead to mass starvation causing civil unrest worldwide.

Such issues will become a worsening problem area of responsibility for the United Nations (UN) who are already very concerned about climate change. Our only hope seems to be that the UN will be able to keep the peace and help to steer us through these difficult times (see Sections 7 and 8. Nevertheless, it appears that the other main factor in saving our society is maintaining our energy supplies and this is where nuclear fission power can come to our aid.

4 REACTORS SUITED TO DESTROYING HIGH-LEVEL NUCLEAR WASTE

The neutron is remarkable in exploring the nature of nuclear reactions because, having no electric charge, it can penetrate deeply into an atom. When it does so it can react in various ways often by forming a compound nucleus. The neutron can also be scattered by the nucleus, either elastically or inelastically or it can be absorbed by the nucleus to form a new element after ejecting surplus energy by radioactive decay. Alternatively, it can cause the nucleus to break apart into 2 (or very unusually, into more) fragments with much release of energy. We call this fission and each fission usually releases 2–3 fast-moving neutrons as well which can be used to perpetuate a chain reaction. The relative probability of these events depends on the kinetic energy of the incident neutron and on the atom itself. Atoms with an odd number of nucleons (aka neutrons plus protons) are particularly weakly bound together and undergo fission easily. Examples of such atoms used in nuclear fuels are U^{235}, U^{233}, Pu^{239}, and Pu^{241}. The thermal (low energy) neutron reactor described in Section 2 provides a much higher probability of causing fission because the neutron spends more time in the vicinity of the nucleus. The time spent by a neutron near an atomic nucleus is therefore inversely proportional to its velocity at these low speeds. Conversely, at higher neutron energy, nuclear reactions take place mainly in resonances. These resonances can be seen in Boothroyd [12, Fig. 2] where the dips in the spectra curves show the energy levels where the resonances occur. The larger fission rate of neutrons near resonances cause this local negative blip in the neutron flux. Calculating neutron flux levels in reactor design is a well-covered field and has important features. For example, as the fuel gets hotter the thermal agitation of the fuel atoms increases the effective bandwidth of the resonance slightly thus changing reactivity slightly. This is known as Doppler broadening. Further details [13] are in a very comprehensive reference (Hwang [14]), the author of which has worked in this area for 44 years. Fig. 2 of Boothroyd [12] is a theoretical prediction but this would be found to agree closely with experimental measurements.

We describe these relative probabilities as nuclear reaction cross-sections. Mathematically, we imagine the atom to be like a target with a certain area allocated to each of these probable reactions. This target model is very realistic in the physical sense and gives calculated results which agree closely with reality. This unit of target area used in these calculations is called "the barn" and one barn equals 10^{-24} cm^2 [15], [16].

Nuclei with even numbers of nucleons such as U^{238} and Pu^{240} are much sturdier and will only undergo fission with fast (energy, exceeding 1 Mev) neutrons. These fast neutrons are not "moderated" in velocity by the elastic collisions with light atomic nuclei which are used in moderators for producing slow neutrons in a "thermal" reactor. These reactors without moderators are called fast reactors and can burn up more fuel than "thermal", i.e. moderated neutron (slow) reactors. Natural uranium only contains 0.7% of the isotope U^{235} which is the only fissile isotope able to use slow neutrons. The 99.3% remainder of natural uranium is isotope U^{238} which is only fissile using fast neutrons.

In slow (thermal) reactors the conversion of U^{238} to fissile Pu^{239} is limited because neutrons lose their energy quickly in these moderated reactors and the conversion cross section to form Pu^{239} is low at the high neutron energy levels compared with the cross sections at low thermal levels. The neutrons are moderated in energy too quickly to have an appreciable chance of meeting an atom while still a high energy neutron.

The net result is that thermal reactors can, at best, only use 5% of fuel before the fuel has to be reprocessed [15]. Reprocessing involves chemically removing the parasitic fission products which waste neutrons by absorbing them to no useful effect. The remaining extracted mixture of uranium and fissile Pu^{239}, with a little Pu^{241}, is then converted to new mixed oxide (MOX) fuel for new fuel elements (mixed plutonium/uranium oxide fuel made after processing). These fuels can be reprocessed many times so theoretically all fuel is consumed eventually. This is also true of the minor actinides produced from consuming U^{238} and plutonium by continual neutron irradiation described by eqns (1) and (2).

One of the "tricks of the trade" which theoretically can get rid of almost all of the dangerous minor actinides in nuclear waste as well as all the plutonium isotopes is to add the lighter isotope U^{233} to the fuel mix in the last burn-up stages. Because of its low atomic weight U^{233} cannot absorb sufficient neutrons via eqns (1) and (2) to be able to form actinides. Meanwhile nearly all the previously existing minor actinides and plutonium isotopes (also known as actinides) get burned up safely by fission. Actually U^{233} is a poor fuel for fast reactors because its absorption and fission reaction cross section are low compared with those of U^{238} and other plutonium fuel isotopes. This low cross section of U^{233} helps it to do its clean-up job.

U^{233} is obtained from irradiating Th^{232} in another reactor and is normally only used as a fuel in thermal reactors.

4.1 Burning up the dangerously radioactive minor actinides

Fuel which has been used in a reactor for a long time has an increased content of transmuted elements formed by neutron absorption. The generation of actinides is described by the general eqns (1) and (2):

$$_{a}X^{b} + {}_{0}n^{1} = {}_{a+1}Y^{b+1}. \tag{1}$$

After a very long time in the reactor, a further fast neutron may react with Y according to

$$_{a+1}Y^{b+1} + {}_{0}n^{1} = {}_{a+2}Z^{b+2}, \tag{2}$$

which describes a further stage of transmutation.

A 3rd and 4th stage of transmutation is possible but these are negligible in calculations. These new elements are Y generated from element X and new element Z comes from Y. Note that there may be a small number of intermediate radioactive decays before X becomes Y and Y becomes Z. These transmuted atoms with atomic numbers in the range 93–100 are called minor actinides. The most important of these are the isotopes of Curium (242–248), Neptunium 237 and Americium 242–243. These minor actinides emit strongly ionising particles (a health hazard) and have very long radioactive half-lives much longer than the fission fragments which have shorter half-lives. These long lived actinides remain a major health hazard for many thousands of years unless they are burnt up in a fast reactor. The minor actinides are easily burned up as fuel in fast reactors like the main actinide isotopes of Plutonium.

These actinides cannot become fissile fuel in a thermal reactor such as that described in Section 2. We can conclude that these actinides with their long half-lives are the most dangerous part of nuclear waste. Only in a fast reactor, with high energy neutrons, can these actinides be destroyed by fission.

Thus, apart from being able to burn up more fuel, the fast reactor is essential to burn up dangerous long-lived minor actinides. By managing a fast reactor and processing advantageously, the final waste consists only of short half-life fission products with little contamination from plutonium and the minor actinides. In the industry this separation of fuel from fission product waste is called "partition and transmutation" often abbreviated to "P-T". This fission product waste is reasonably safe for handling and disposal after 300 years of storage. Nevertheless the volume of the final waste is small enough to be manageable such that it can be vitrified economically and placed in thin-walled stainless steel drums and stored in an old salt mine where there is no water seepage. This waste is actually a valuable source of rare elements and it would be expected to be re-used by our descendants 300 years later when the fission products with their short half-lives have decayed away nearly completely. The development of the complicated chemical processing techniques needed to extract these minerals from the safe waste is a task for these later generations.

In an earlier paper (Boothroyd [12, p. 236], it was suggested that the quality of our future nuclear waste might not satisfy our descendants and a carousel type cleaner using a linear proton accelerator could be used to improve the quality of the waste. Very recently the present author has come across an undated but important paper [17] also suggesting that a sub-critical reactor powered by a linear proton accelerator was described to improve the quality of nuclear waste. Cleaning up nuclear waste is a developing field of technology and refs [18]–[24] provide more recent details.

5 STORING NUCLEAR WASTE OR RECYCLING IT?

Many scientists are appalled by the huge amount of spent nuclear fuel elements from thermal reactors now held in storage. At the present time it is much less expensive to store this inconvenient waste rather than reprocess it [20]. Yet if we were to increase this stored waste by a factor of 100, the average person would be unaware of this. All this presumes that we can control acts of terrorism. Up to the present time this has been successful. Fortunately, high-level nuclear waste is compact and needs little space even though it is extremely dangerous.

It is part of human nature that we usually act according to our prejudices and not on the basis of rational reasoning. This applies to our attitude towards radioactivity which we have good reason to fear. Yet we could easily live in a world which has more than 100 times as much stored nuclear waste as now exists. Most people would be unaware of this and it is concluded that we can use huge numbers of the reactors described in Section 2 for decades and store the waste using current methods. Obviously great care is needed in storing the waste but this is all part of an established technology.

As distinct from this fear of radioactivity many people have a blasé attitude towards global warming. We are accustomed to variations in climate which are often severe. Such variations about a constant mean temperature are normal and can be tolerated usually. What is not normal and is extremely dangerous for us is a mean temperature which varies one way or the other at a constant rate.

The conclusion is simple enough. We can live with nuclear waste at 100 times the present level but our worldwide civilisation will collapse completely if the mean temperature of our planet is just 10°C above the present level. The other conclusion which follows is that a vast increase in safe nuclear power reactors does not present a serious waste problem like fossil fuels. We can expect to have at least 30 years to work out how to control nuclear waste to our best advantage. This is enough time. We can do this and it is not particularly difficult.

Thus it is concluded that there is no urgency in processing a large increase in nuclear waste. It follows that there is no constraint necessary in the large number of reactors described in Section 2.

6 CHOICE OF REACTOR SYSTEMS FOR RENDERING WASTE HARMLESS

Any fast reactor can be used for the destruction of harmful nuclear waste. The most widely-studied fast reactor and the type in which we have the greatest experience is the sodium cooled reactor [15]. Sodium, or a sodium/potassium mixture, is an excellent coolant with a low parasitic neutron absorption cross section. It also has low viscosity for easy pumping, and a high thermal capacity and conductivity for effective heat transfer. Moreover, it can be pumped magnetohydrodynamically by a completely sealed pump which has no shaft seals to leak or bearings to malfunction. Nevertheless sodium and potassium metal will burn almost explosively in air and when in the presence of water. For this reason, the sodium fast reactor is not considered suitable by the present author for a much expanded and safer nuclear world.

6.1 The ideal reactor for processing nuclear waste

In the longer term there seems little doubt that the fast molten salt reactor (FMSR) is the best choice for treating nuclear waste. This is mainly because the most modern method of processing spent nuclear fuel is the pyroprocessing {aka electrometallurgical) method [18], [19], [21]–[24] of performing P-T. Pyroprocessing also handles the spent fuel as a molten salt so it is reasonable to consider only a future MSR because it is the only reactor which can incorporate automatic on-line electrometallurgical fuel reprocessing, The older methods of fuel reprocessing using chemicals dissolved in water such as in the PUREX process used very large and cumbersome equipment. Pyroprocessing equipment is small and compact and relatively easy to install close to a fast reactor core.

However the only MSR which has ever been built is the original MSR at Oak Ridge, USA. All other studies have only been desk designs, sometimes with limited hardware. It seems that we still have many basic questions to ask ourselves, For example several molten salt recipes have been suggested [12, Fig. 2] but which of these, if any, are suitable for pyroprocessing and P-T?

The conclusion is that we are still far from any ability to design, let alone to build, a full size FMSR because we have not yet acquired the necessary practical experience and indeed much of the necessary fundamental knowledge at this stage [16].

Yet if we are to propose to a whole world society that the answer to global climate change is a massive increase in the number of nuclear reactors then we have little option but to start serious work solving the nuclear waste problem. For this we need access to working reactors which already exist.

There seems to be a consensus in the nuclear industry that there is an insufficiency of materials testing reactors so this would influence our decision about our choice of an existing nuclear reactor system to help us develop the fast MSR The nuclear material testing reactor at Petten in the Netherlands has recently completed important preliminary work for the MSR system. However, the Petten reactor is an old reactor and we also need a reactor which can be used to help us with developing a system for burning up long-life waste.

6.2 A compromise: the lead cooled fast reactor

By contrast with the MSR the lead cooled fast reactor has a very convincing and sizeable history [15], [25], [26]. As might be expected, fast lead cooled reactors came into existence due to military interests. Several Soviet submarines were powered by this type of reactor. In a similar way to the history of the American submarine pressurised water reaction, using water coolant and moderation, military development led to the lead cooled reactor for civil purposes in Russia. The lead cooled fast reactor has excited much interest even in America. The Westinghouse corporation intends to market its own design. What is of particular interest is that this type of reactor is ideal for burning up the minor actinides.

In some ways the lead cooled fast reactor resembles the MSR. The reactor vessel has an open top and works at atmospheric pressure. Molten lead is an excellent coolant both for its nuclear and thermal properties, such as a low melting point and high boiling point. Bismuth can be used to lower the lead melting point by forming a Pb/Bi eutectic. However this raises costs: lead is cheap and plentiful and Bismuth is rare and expensive. Both coolants are safe but using Bismuth produces Polonium which is a very toxic nuisance. Nevertheless, the LFR has one drawback for MSR researchers in that any experiment we wish to carry out must use encapsulated fuel. There seems to be no possibility of using lead coolant and nuclear fuel together so that we can develop on-line fuel processing with this system. However, many experiments we need to help us develop an MSR can be carried out in lead-cooled reactors. Also, much of the development work for actinide burning can be carried out with a lead cooled fast reactor which can also make a start on reducing the backload of spent fuel elements which need reprocessing. The LFR seems to have a promising future but in the present author’s opinion it seems likely to become outdated eventually and displaced by MSR systems.

Compared with thermal reactors all fast reactors have much smaller cores with internal dimensions of a metre or so. This is mainly because they run on more expensive enriched fuels and there is nothing else in the reactor core except fuel and coolant. For maximum economy the reactor is designed to operate at a very high rate of heat emission. In LFRs this is limited by the heat transfer rate though the fuel element walls. MOX fuel element pellets have a low thermal conductivity. Later fast lead cooled reactors use mixed nitride U/Pu fuels which have better thermal conductivity but the pellets are prone to swelling under high irradiation. MSRs by comparison do not have this problem because the fuel and coolant are mixed as a common fluid. This is another advantage of the MSR system.

7 FINANCING NUCLEAR WASTE

Supposedly there is unlikely to be any serious financial problem supplying the small modular reactors described in Section 2. The sale of mass-manufactured articles in demand by the public arena is a matter for private enterprise. As with all mass-produced products legal requirements apply and these will be more comprehensive than in other areas of normal commerce.

Financial problems are completely different regarding the disposal of nuclear waste. The best offer which can be made to commercial developers interested in nuclear waste disposal is a rather tenuous suggestion that after 300 years or so, nuclear waste might be worth purchasing for profitable use.

Yet inevitable public demand for a technology for safe nuclear waste disposal cannot be ignored if this source of energy is to predominate. As yet we do not have comprehensive answers to the task, The fast MSR seems to be the most promising system, yet we do not even have a FMSR built to the development stage. We have a host of unanswered questions regarding different technical alternatives. Consequently it seems that we cannot acquire necessary significant investment unless it is from public funds. Allied to this need is the hard fact that the whole problem of climate change is likely to end up, rather too quickly, as a huge UN responsibility.

Perhaps the time is ripe for the UN to raise its own taxation revenue. This was suggested rather tentatively in an earlier paper [2] which recommended the introduction of a Tobin tax on all international monetary transactions. Almost inevitably this will invite dissent from at least one of our major nations and this may well be a nation which can use its UN veto to dismiss such a suggestion, Presumably this would be the time for the rest of the UN to apply total trade sanctions against such a member for using its veto improperly. There are also other arguments which can be mustered in support of a Tobin tax administered by the UN. Money is often merely transferred internationally by those with skill in such matters just to cream off profits. It is suggested that subtle and clever enterprises skilled in making money out of nothing have no real value in our troubled world.

8 THE SOCIAL ENGINEERING OF A WORLD-WIDE PROBLEM

If, as seems likely, we have to face a crisis over the climate change issue, then, as a personal opinion, our only hope seems to be that the UN could be the only way to find a solution. One might think that the UN has no power. It does not possess its own army and it can only talk. We might think the situation is hopeless. Our national political leaders and their delegates talk quite a lot but don’t seem to achieve much. Can the UN be any better? Hopefully it can. The UN is an embodiment of ourselves and, with regard to climate change, the enemy is also ourselves in a collective sense. There can be no other enemy, real or imagined. It is fortunate that the UN lacks its own army. Resorting to fighting would be a disaster for us all.

In reality the UN which is also an embodiment of our need for peace and security, has enormous power in the form of trade sanctions. Sanctions can be applied by individual nations but real powers of persuasion come from the sanctions of many, preferably all, nations. Because our world is a globalised world of commerce, no nation, however large, can stand up to the power of universal trade sanction. It is nevertheless a weapon, like any other, which must be used with discretion. American sanctions against Japan seemingly could have precipitated Pearl Harbour.

Somehow, we have to find a recipe for cooperation, a realisation that we are all involved: a genuine compassion for all our neighbours, both near and far; and a mutual sharing of blame for our misfortune. A typical example of likely conflict is the disaster awaiting several richer nations losing their overseas markets for fossil fuels. Their inevitable pleas for help may be just as convincing and desperate as the abject poverty levels in some of our much poorer developing nations.

It is arguable and of concern that our modern world now seems to lack the capacity to cooperate meaningfully. The impending departure of the UK from the European Union (EU) is a case in point. The only writer on the Brexit saga, known to the present writer, who uses relevant facts and figures to argue his case is Boyle [27]. Elaborating on this [27] approach one might wonder if the resurgence of nationalist interests in EU is the root cause of the Brexit tragedy. Germany [28] seems determined to revert to using its massive coal reserves whereas one might expect it, as a highly industrialised and science-based nation, to be in the forefront of new nuclear technology. Its more agricultural neighbour France, with almost no fossil fuels, is very active in nuclear research and determined to outlaw the petroleum driven car as soon as possible. Presumably, this is partly and largely to avoid the high future cost of imported petroleum fuels. Is all this evidence of prioritising nationalistic interests to the detriment of the common good in EU? If the EU cannot sort out the Brexit problem, it bodes badly for the UN who seemingly will have to sort out the climate change problem. The latter problem is far more difficult than Brexit and likely to promote much acrimony.

In time of war, which we all deplore, allies all become brothers. When the war is over old comrades go back to competing with each other and resurrecting old quarrels. It seems reasonable to suggest that a concerted effort to reduce use of fossil fuels in favour of nuclear power should be treated as though it was a wartime problem, if only to get international cooperation..

There are many other social engineering aspects which are relevant but many of these are outside the scope of this paper. One further consideration seems to stand out as important.

8.1 Entering our role as climate control engineers.

Earth's climate is controlled by a large variety of natural processes which for most of the time balance each other out in a harmonious manner. In fact our influence on climate is small but significant. Expressed in energy transfer terms our anthropogenic influence is only about 5% of the total natural energy transport effects which take place.

GHGs (and water vapour is the most important GHG) are essential. If we had no GHGs the average temperature of Earth would be a very cold –18°C and not a pleasant 15°C. Without GHGs our planet would probably have never developed life, certainly not life in all the varied forms we know.

Because we have become so active as Earth's dominant species and because our activities are so large, we can now control our climate. Our knowledge of the science is rather basic but it is good enough to show us what to do. At present we need to slow global warming down which is a massive task, perhaps needing us to generate 50% of our electricity by nuclear fission and not 11% as at present. If, as has happened in the past, we enter another ice-age then we should do the opposite and generate additional GHG. If we ever attempt to colonise other planets such actions would probably be necessary on a massive scale. We have some manufactured GHGs which are very potent. Obviously if we wish to engineer an alien atmosphere on this scale, much caution is needed and the same is true for making changes to Earth's atmosphere.

9 CAPITALIST ENTERPRISE OR SOCIALISM TO MAKE PROGRESS?

It is concluded that in order to get a nuclear fission remedy for climate change we have to use the enterprise of capitalism with our right hand and the methods of left wing socialism with the other hand. Perhaps there is also a lesson to be learnt from this? We have to share our lives together and we also have to solve our problems with each other and be receptive of different approaches to the matter in hand.

Finally it seems to be appropriate to emphasise that the opinions in Sections 6–8 are only personal viewpoints. The reality is that we depend on a body of many experts to make decisions. This is an area where we are well endowed, By way of example a 2017 conference on fast reactors and related fuel cycles at Ekaterinburg in the Russian Federation was attended by as many as 700 delegates. Equally encouraging regarding well-qualified personnel is a surprising number of young technologists wishing to work in the specialised field of MSRs.

10 CONCLUSIONS

10.1 Management matters

10.1.1

It seems that there is only one reasonable way to save our civilisation from the effects of fossil fuel induced climate change. Preserving our grid electricity supplies seems to be vital and necessary and this implies a much greater proportionate contribution from nuclear fission power. Other problems such as different forms of transportation and recycling of waste etc. can all be dealt with if electricity supplies can be kept sufficient and reliable. It is also recognised that nuclear power and climate control need to be organised and administered by the same corporate body. The diversity of consequent problems to be faced indicate that only the UN can fill this role.

The UN, with appropriate financing, can access independent specialist bodies such as IAEA, the U.S Dept of Energy and climate specialists etc. on a consultant basis and these organisations could report to a newly formed organisation which, for want of a name, we might know as the UN Subordinate Secretariat for Nuclear Energy and Climate change.

10.1.2

Concomitant with 10.1.1 we have the pressingly urgent problem of climate change which is also an issue affecting all nations but also differently. This is also a most difficult matter which is best addressed by a body with the welfare of all nations at heart. Again the UN seems the appropriate choice.

10.1.3

Concomitant with both 10.1.1 and 10.1.2 is the suggestion that adverse climate change can only be reversed significantly by increasing the nuclear fission component of power generation from its present level of 11% to a value approaching a figure more like 50%.

10.1.4

It follows that it is logical in delegating these considerable extra burdens of responsibility, that the UN should be granted the right to raise its own revenue through taxation. The Tobin tax is suggested. This is not a suggestion for a form of world government but a suggestion that important international relationships may be tackled in the most suitable way by a management model similar to that employed by the EU. Ideally the EU is an organisation where adjacent nations choose to agree freely to work together harmoniously for the common good.

10.2 Technical matters

10.2.1

The danger of runaway global warming suggests that contingency plans are necessary to prevent this at all costs. At the very least, the following countermeasures are considered essential:

a) The universal modular thermal reactor described in Section 2 and elsewhere [10] should be at a fully tested and reliable status as a matter of urgency.
b) Appropriate manufacturers should be pre-organised and re-tooled to manufacture parts for the internationally-available modular reactor at short notice. This is so that component manufacture can be put into effect quickly.

10.2.2

The coordination of all FMSR research and development needs to be undertaken by a centralised body. The backlog of necessary basic development work is delaying introduction of FMSRs.

10.2.3

In the absence of sufficient present progress in FMSR technology, the much more advanced LFR can be used to replace much of this deficiency by advancing the correct disposal of accumulated and new nuclear waste.

10.2.4

Sub-critical reactors are also not being considered adequately to their full potential. For example, conversion of the reactor in point (a) in Section 10.2.1 to use Thorium based fuel instead of Uranium based fuel would give us a cleaner-operating reactor. As an example of possible progress, there are some grounds to suspect that U^{233} can be made from Thorium using a device similar (but much larger) to that reported in Boothroyd [12, Appendix III]. This would be an easy way to avoid the Protactinium residence time problem.

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