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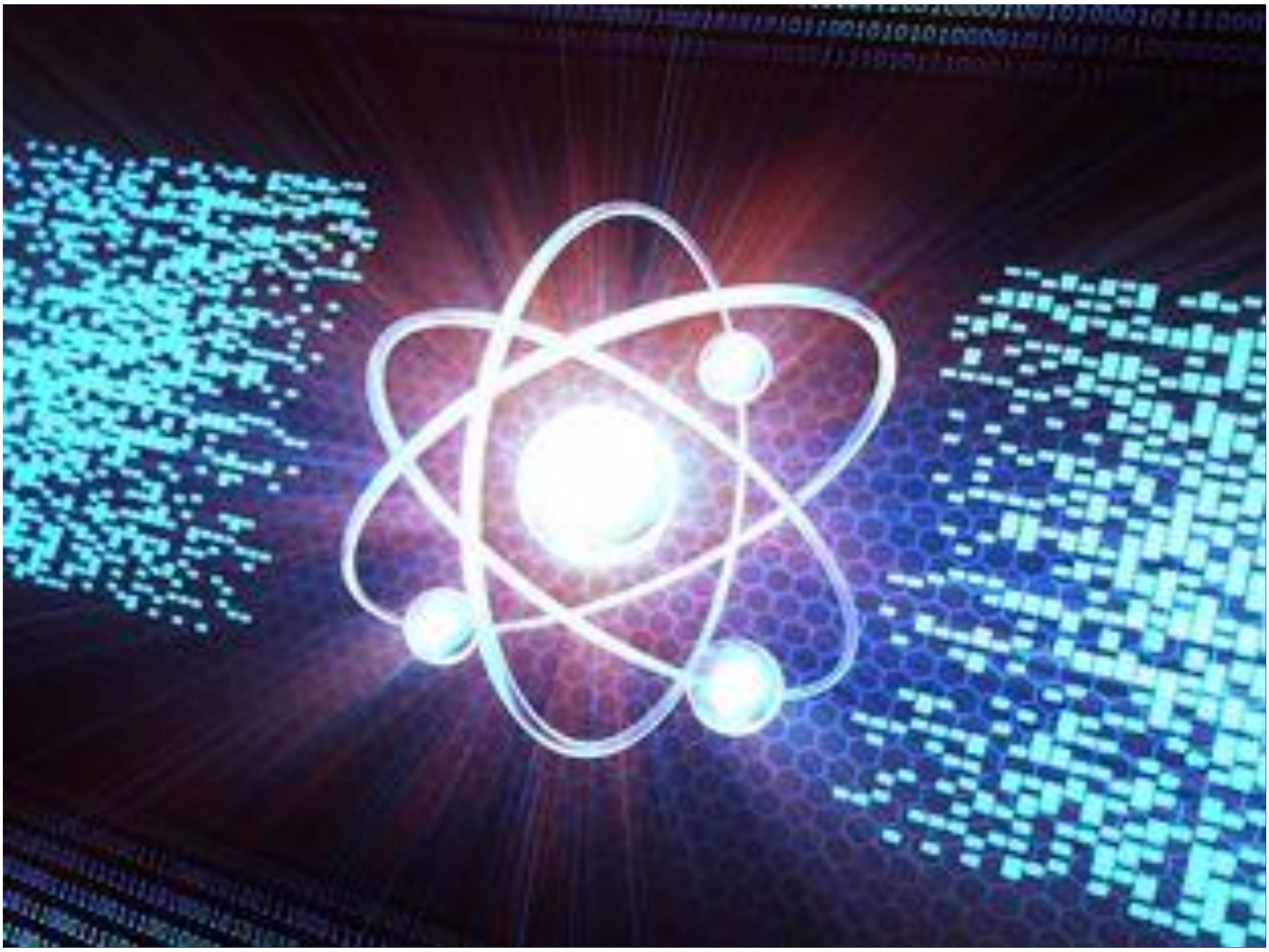
Blueprint for Future Nuclear Power
November 2020



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Blueprint for Future Nuclear Power

by

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Summary

Blueprint for Future Nuclear Power

The primary purpose of this paper is to suggest how today's nuclear waste can be used as future nuclear fuel and how this could reduce the timescales and impacts for management of existing and future waste arisings. Nuclear fission power is widely seen as desirable, if not essential, for addressing global climate change mitigation but there is a need to move the technology beyond the limitations of current designs and practice. Large Light Water Reactors with a once through fuel cycle make up most of the world's nuclear power fleet, and although these reactors have supplied a large proportion of the world's carbon-free electricity over the past six decades, they have a low thermodynamic efficiency for electricity generation, leave a legacy of spent fuel requiring long-term storage and only use approximately 1% of the uranium mined to fuel them. A critical disadvantage of nuclear power, as currently applied, is that its radioactive wastes cannot be resolved without decades of delay before a permanent solution is applied. This leads to understandable concerns that "nobody knows what to do with the waste".

The technical methods to overcome those shortcomings have been known about since the very beginning of the nuclear age. Fast neutron reactors, for example, have the potential to utilise a far higher proportion of the uranium than current thermal neutron reactors. Much technical progress has been made on individual parts of the problem, but there is a need to integrate these developments into a concerted effort to "do nuclear power better". The plan needs to involve more than just better reactors - those improved reactors also need to be integrated with better nuclear fuel cycle and radioactive waste management. Whether the reactors remain in-situ with the user or are returned to a host country at the end of life, the nuclear residues within them will need to be addressed.

The long-term hazard of waste from nuclear power, as currently applied, is a barrier to the expansion of the technology's deployment – particularly because the associated responsibilities extend beyond the time horizon of most commercial companies. The idea of recycling nuclear waste to reduce its long term hazard is not new (and indeed the extensive worldwide experience with the subject will be able to inform future work), but the objective we propose is to split spent nuclear fuel into two streams, one which can be recycled as new nuclear fuel and the other being "fission product canisters" which can conform to standards of "low level waste" suitable for shallow burial, and be disposed immediately without committing future generations to guarding them on the surface and then emplacing them in deep burial facilities at some distant future date. "Just in time" methods can be used to avoid accumulating large stocks of hazardous nuclear materials. With careful design this can be achieved economically and it is reasonable to require that waste from future nuclear projects should be immediately and fully resolved in this way.

There is also a need for nuclear power to be available for additional uses and for a wider population of consumers. To achieve that it must be deployed simply, without requiring sophisticated technical capability within the consumer's country and without leaving behind waste management and guardianship issues when the deployment is finished. Nearly all nations safely enjoy the benefits of aviation, but the majority rely on just a few countries for special capabilities such as constructing airliners. A similar pattern needs to develop with nuclear power. All this must, of course, be accomplished with adequate safety, nuclear safeguards and physical security.

This blueprint for future nuclear power presents a means in due course to address the worldwide legacy of spent nuclear fuel. The vast majority of material in this spent fuel has potential value as recycled fuel – only a tiny proportion of spent fuel is truly "waste". The potential locked up in the world's existing spent fuel (together with stocks of depleted uranium) represents at least 100 years of mankind's total energy needs. The resource will last much longer than that if nuclear power is used in conjunction with other low carbon energy sources.

1 Overcoming Barriers to Development and Deployment of Nuclear Power

Nuclear fission power is widely seen as desirable, if not essential, for mitigating global climate change, because of its demonstrated characteristics of continuous electricity generation and effectively zero carbon dioxide emissions. Until commercial nuclear fusion systems become available, nuclear fission may be considered the principal controllable and non-fossil-fuel energy source. Nuclear reactors can be used for many other purposes besides electricity generation, such as water desalination or hydrogen generation.

There is no a-priori reason for nuclear power to be expensive relative to other energy sources – if deployed efficiently it requires very little resources of land, material or labour. The current cost barriers are primarily related to issues such as complex design, high initial investment, uncertainty over the costs of disposal of long lived-wastes, lack of vibrancy of the industry and absence of opportunity for learning and improvement through replication and evolution.

There are differing views about the role that nuclear fission should play in the medium to long term future. There are those who believe it will not be necessary at all, those who believe it will provide a stop-gap for carbon-free energy until other sources take over and those who believe its advantages of simplicity (compared with nuclear fusion) and controllability and intensity (compared with renewable energy) will ultimately prevail. The history of development of nuclear fission has demonstrated that its inherent advantages can easily be squandered by inefficiencies. Waste management is, and could easily remain, one of those inefficiencies.

Internationally the focus of technical development is on new reactor designs, but the industry needs to remember that radioactive waste[1] and its associated longevity are widely perceived as a critical disadvantage for the technology. That perception stifles investment in the technology as a whole. The industry urgently needs to develop appropriate methods to address this issue.

This document sets out some principles by which that could be done in a practical and economic manner. What is proposed is not new but is a synthesis of developments which have already been successfully demonstrated. We point out that the adoption of these principles will provide additional benefits by making nuclear power available for additional uses and additional customers.

2 Widening the Use of Nuclear Reactors

The proper resolution of the issue of delayed waste management will potentially allow a much wider variety of commercial companies to use nuclear reactors than at present and hence permit a much wider range of activities. The management of wastes can be done for those companies by a smaller number of specialist organisations that are equipped to recycle the reactors and their associated fuel.

Examples of the types of the activities which could take place are given in Figure 1. This list is not intended to be exhaustive. The ability to produce hydrogen is a key advantage, whether through electricity production and water electrolysis or through thermochemical water splitting.

It should be noted nuclear reactors are well suited to complement other low carbon energy sources. For example, they can be used to generate power at high geographical latitudes where solar energy is inefficient.

[1] This paper is concerned with radioactive waste – where the term “waste” is used without other qualification, it refers to radioactive waste

More generally, stored heat from reactors can be used to provide extra electricity to stabilise grid demand and make up for the intermittency of other low carbon sources of electricity.

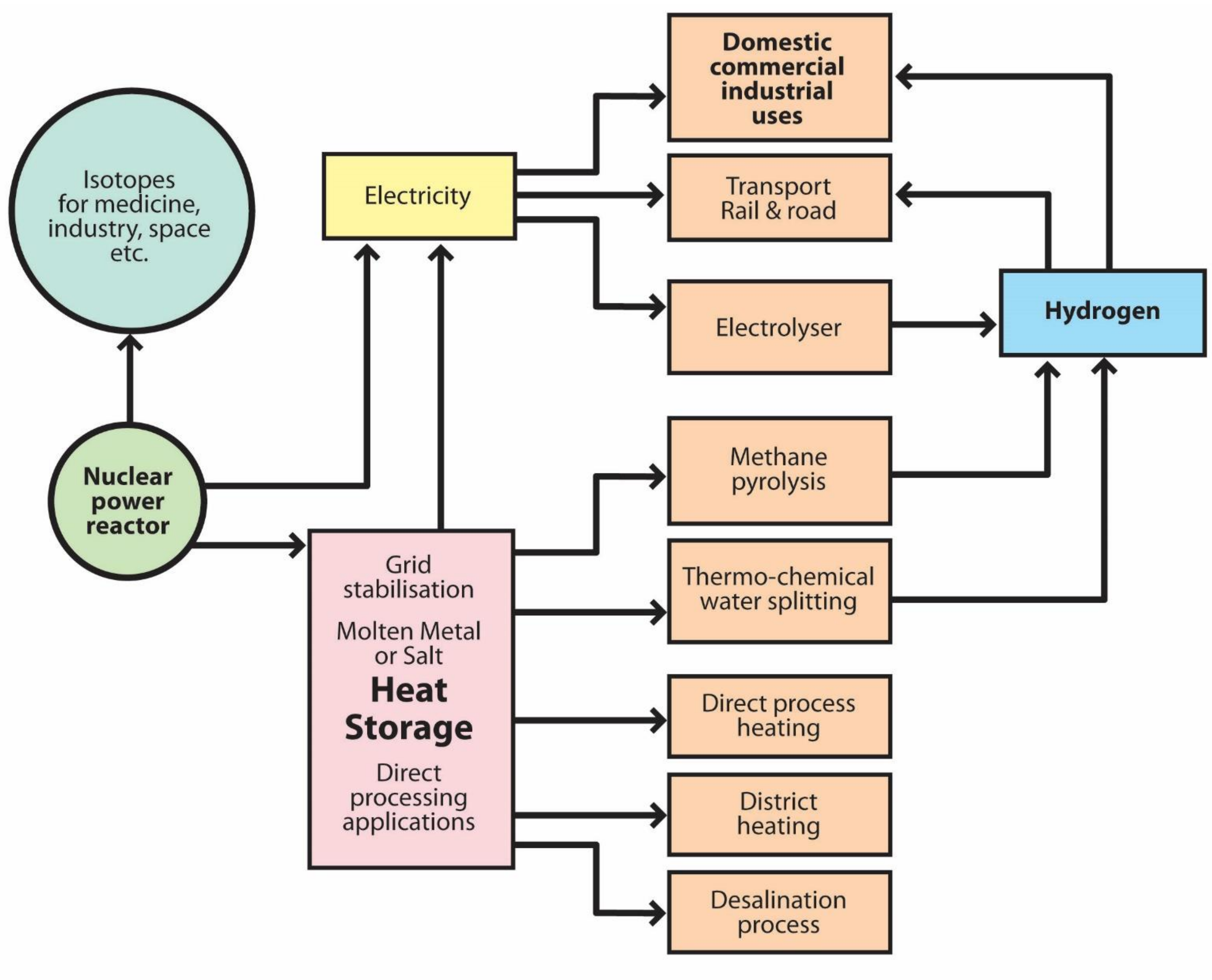

Figure 1- Applications of Nuclear Reactors

We will now discuss the reactor types that might be used in conjunction with this blueprint.

3 Future Generation IV Reactor Types

For the past two decades, the Generation IV International Forum (GIF) has co-ordinated R&D into the viability, safety and performance potential of next generation reactor systems. GIF has selected six reactor technologies for further R&D work, comprising the gas cooled fast reactor, lead cooled fast reactor, molten salt reactor, supercritical water-cooled reactor, sodium cooled fast reactor and very-high-temperature reactor. These reactor concepts were internationally selected from nearly a hundred alternatives in 2002. The selected

options are more applicable to large-scale power generating facilities but not limited to these. It was identified that by using fast neutron reactors and advanced fuel cycles it may be possible to significantly reduce the footprint of deep geological repositories for the disposal of ultimate waste [Ref 1]. The present Blueprint for Future Nuclear Power seeks to extend this approach.

4 Smaller Reactors

In the first phase of nuclear power up to the present time it was assumed that large reactors offered the best economics, because of economies of scale relating not only to the physical equipment but to the costs of complying with licensing and regulatory requirements. The downside was that opportunities for learning through replication and evolutionary improvement were limited. Nuclear power facilities last a very long time and only a few large units are needed to provide a whole country's power supply. Large units are constructed on site in different locations meaning that each project can suffer "first of a kind" construction delays and cost overruns. The substantial period and cost of construction cause challenges in financing the projects.

Because of that there is now much attention being focussed on a new generation of smaller reactors often using modular designs which could be built in larger numbers in a factory and transported to where they will be deployed. A key supporting feature is that the new designs can incorporate inherent safety features which have the potential to simplify not only the design itself but also the licensing and regulatory process associated with it.

The ability to transport the reactors for installation also allows (in principle) the reactors to be returned to the originator after deployment. It follows that the recipient nation or organisation could thereby enjoy the benefits of nuclear reactors without having to deal with issues of long-term hazardous materials. That is a key enabler to making the technology available to a far wider consumer base.

There are now many small reactor designs [Ref 2] in various stages from concept through to actual operation, from which will in due course emerge the strongest candidates. Many of the designs are based upon existing LWR technology, but the new designs also include a number of fast neutron reactors, which (because of their harder neutron spectrum) are far more efficient at "fissioning" their fuel, hence making better use of the fuel and causing less long-lived waste than the LWR designs. Fast neutron reactors will ultimately be the key to recycling not only their own fuel, but recycling the legacy spent fuel from other reactors.

The advent of smaller reactors does not in any way detract from the validity of larger reactors, which may remain more appropriate for applications such as base-load electricity generation for large electricity grids.

There is a need for nuclear power to be available for additional uses and for a wider population of consumers. To achieve that it must be deployed simply, without requiring sophisticated technical capability within the consumer's country and without leaving behind waste management and guardianship issues when the deployment is finished. Nearly all nations safely enjoy the benefits of aviation, but the majority rely on just a few countries for special capabilities such as constructing airliners. A similar pattern needs to develop with nuclear power. All this must, of course, be accomplished with proper safety, nuclear safeguards and physical security. The transportable nature of smaller reactors provides a lead-in to a more general business model that would work towards this overall objective. We call this "Hub and Satellite" Nuclear Power.

5 "Hub and Satellite" Nuclear Power

"Hub and Satellite" nuclear power represents a business model based on leaving no long-term hazardous legacy at the satellite stations – which is more or less essential for a major expansion of the nuclear power customer base. Just as with the aviation industry, a single or a small number of organisations can act as the

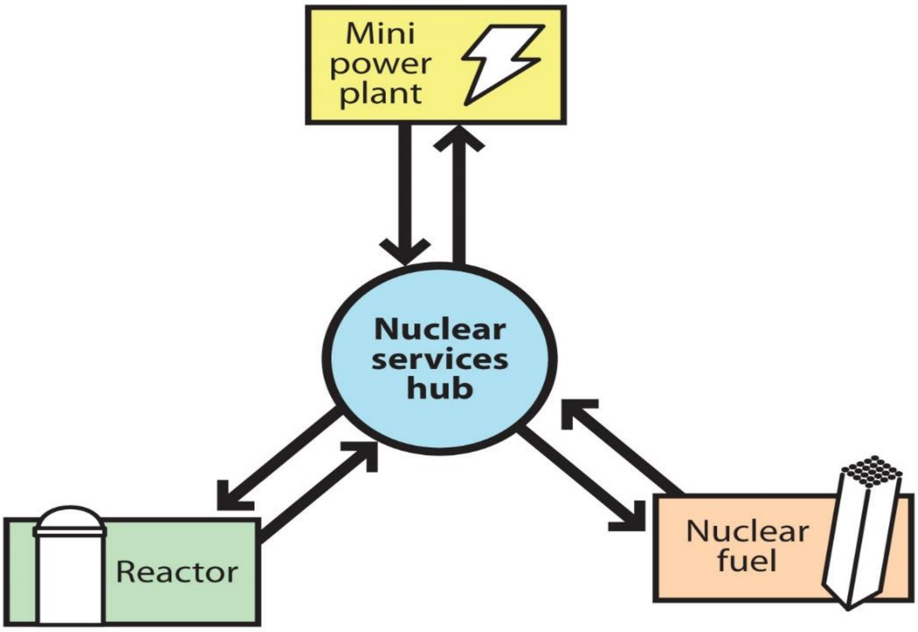

Figure 2 - Hub and Satellite Nuclear Power

hub supplying the specialist nuclear services and the satellite nations can receive and benefit from the nuclear facilities. The satellites must each have a necessary minimum of internal facilities and capabilities, just as satellite aviation countries must have airports, air traffic control and an appropriate regulatory base.

There are three potential models to operate nuclear power in this way, depending on the size of the installation. Either the nuclear fuel is transported to and taken away from reactors constructed and fixed at the satellite location, or the reactor containing its fuel is transported to and from the satellite site. Finally, for very small installations the fully integrated electricity generating capability (a mini power plant) can be transported to and from the satellite.

There are already manifestations of each of these alternatives either established or planned – for example the nuclear fuel reprocessing services that have operated in the UK and France at Sellafield and La Hague respectively, the Russian barge-mounted nuclear plant [Ref 3] and the design study for small nuclear generating plants which could be airlifted to disaster zones [Ref 4].

The Hub and Satellite concept has important implications for economics. The large number of reactors implied by the concept allows cost savings to be achieved by replication and mass manufacture, whereas the centralisation of the waste management means that the cost of the complex operations of recycling fuel and dispositioning wastes can be spread over a large number of reactors.

6 Waste – The Current Vulnerability of the Nuclear Industry

The longevity of the hazard of spent nuclear fuel (SNF) and high-level waste (HLW)[2] has posed many challenges - technical, presentational and political - for the nuclear industry and it hampers the development and deployment of nuclear power. It is untrue to say, “Nobody knows what to do with nuclear waste”, because there are technically acceptable solutions (principally deep burial with engineered barriers in stable geology). However, because of residual uncertainties about the evolution of waste over very long periods of time, and heat generation in the short and mid-term, there is little current long-term disposition of SNF or HLW happening. One example of unresolved waste is surface storage of spent fuel in pools, which require human-supervised systems to operate properly. A large proportion of the world’s spent fuel is in that condition. Much of the rest is stored in air-cooled shielded storage casks, which still require a future permanent solution (e.g. deep burial).

The safest form of long-term management of nuclear materials is not to have them in storage at all. This can be achieved by separating out what is truly waste for immediate disposal and recycling the rest through “just-in-time” procedures which do not accumulate materials in long term storage.

Because of its longevity unresolved waste creates an institutional problem for organisations, which must take the responsibility for the waste in the long term. Few organisations can guarantee to last that long. In the United States, this problem was supposedly resolved by the Federal government taking on the long-term responsibility of spent fuel in return for a fee charged to the electricity utility. So far, the government has required payments from industry but not resolved the problem. By taking the responsibility for the problem the US government has not forced the providers of nuclear power to find other ways to resolve their waste issue, and has sustained a once-through fuel cycle which is tolerated despite the shortcomings of its implementation.

In order to demonstrate proper sustainability to the public, the facilities for generating nuclear power (and supporting activities) should ideally be removed or decommissioned to completion within a short time from them ceasing to operate. Besides being consistent with principles of intergenerational equity this makes best use of existing knowledge, expertise and resources. Transport of spent fuels and radioactive wastes has been accomplished safely and securely for decades and is not a barrier to this approach. No further actions should be required of future generations which gain no further benefit. Improved nuclear power needs to achieve that goal by **recycling** those components of fuel, which cause the long-term hazard, into new nuclear fuel. Uranium (lightly enriched or depleted in the ^{235}U isotope) may be added or removed from the cycle for material balance purposes. This is shown in Figure 3.

7 Proposed Treatment of Waste

The irreducible waste of the nuclear process (principally fission products rather than minor actinides) is only a small fraction of spent fuel, and this fraction is also responsible for most of the troublesome heat generation. If this fraction is separated, the generated heat (or the fission products themselves) could potentially be **used** with proper design. Whether or not the heat is used, the fission product fraction itself can be allowed to stay

[2] High-level waste is commonly considered to be the mixture of mainly fission products and residual actinides arising from conventional PUREX reprocessing of SNF. This aqueous mixture is usually evaporated to slurry, stored and then vitrified for potential geologic disposal. By contrast, SNF contains all fuel and other actinides generated by irradiation as well as fission products. Various separation or partitioning methods may give rise to differing products for recycle and wastes for disposal.

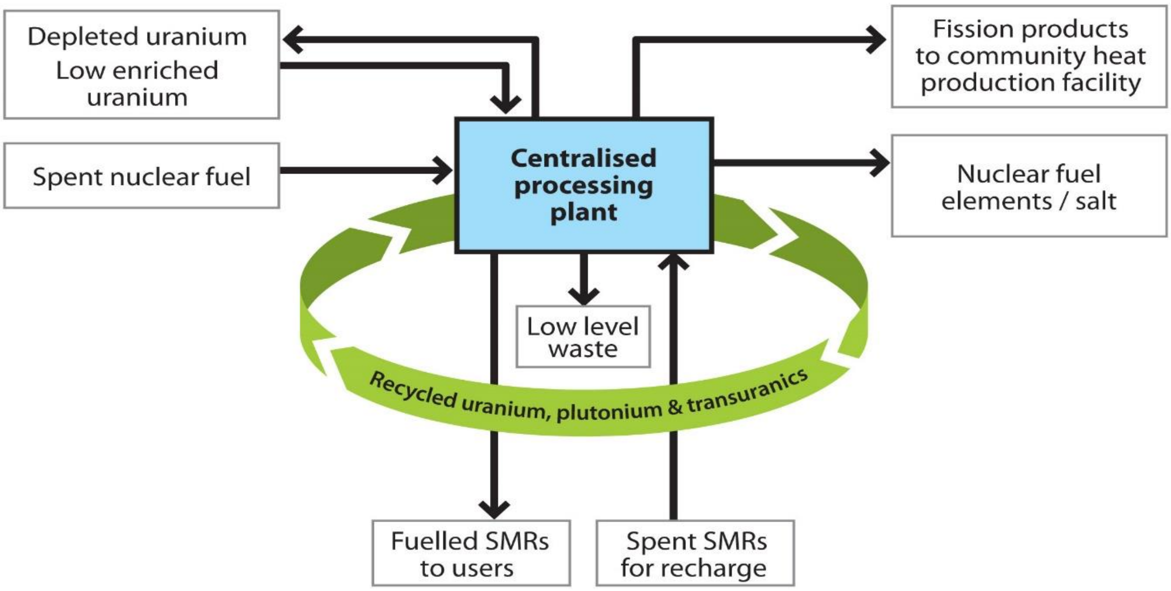

Figure 3 – Sustainable Nuclear Power without Long Term Waste

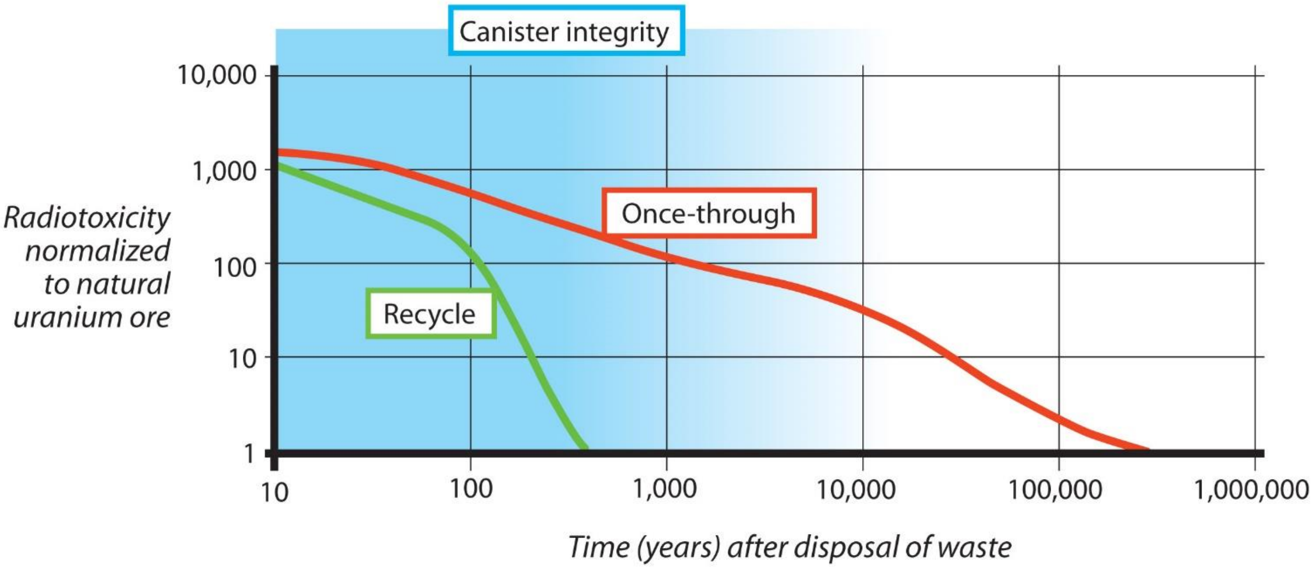

Figure 4 - Radiotoxic Hazard as a Function of Time

(Information for Figure 4 derived from Ref 5. Note that recycle of uranium, plutonium, and transuranics leads to the waste hazard falling to "natural uranium ore" levels in about 500 years - less than the life of the canister which contains the waste)

where it is without further human intervention when the use is finished. That is because the hazard will decay to essentially harmless levels before the physical containment (e.g. canister) fails. Examples of uses are radioisotope thermal electric generators for space probes based on ^{90}Sr, or heat sources for remote communities in Polar Regions.

However efficient a recycling scheme is, it cannot eliminate all waste. Waste which is described as "low level" in United States terminology can generally be managed through existing shallow-burial facilities [Ref 6]. Figure 3 also includes the option, technically relatively straightforward to deliver, to remove uranium originating from spent fuel for fissile/fertile material balance purposes (see later discussion). Such removed uranium can, of course, be re-enriched in commercially available facilities and fed back in.

The process will also lead to radioactive gases, which can be managed in conventional ways by temporary storage and release or immobilisation.

8 Nuclear Physics Requirements

The nuclear physics characteristics of fuel recycled in this way need to be carefully addressed, but it is possible in principle to combine recycled fuel with enriched or depleted uranium in schemes with thermal and fast neutron reactors. Meeting nuclear physics and material balance requirements is far easier with fast reactor as opposed to thermal reactor systems.

A primary requirement is to balance the ratio of fissile and fertile constituents of the fuel. For thermal reactors the fissile ratio will continuously fall as the reactors operate and therefore must be adjusted. For fast reactors the ratio may increase or decrease depending on the breeding gain of the reactors. Fast reactors can also be employed for the role of "incinerating" problematic species that can build up in the fuel cycle.

It might be thought that the only way of increasing the fissile to fertile ratio is by adding fissile material, but the same effect can also be achieved by extracting uranium (as shown in Figure 3). That is far preferable for security considerations.

A key material to support the early stages of recycling schemes is "HALEU", or High Assay Low Enriched Uranium. Internationally recognised standards place a limit of 20% enrichment of the ^{235}U isotope of uranium to protect against illicit use for nuclear weapons purposes. Most reactors are currently supplied with approximately 5% ^{235}U, but HALEU (up to 20% enrichment) is extremely useful to achieve material balance for recycling schemes. The US Department of Energy has recently contracted with Centrus Energy Corporation for production of HALEU [Ref 7].

9 Separation to recover values

The objective is to achieve separation of fission products so that the hazard decay of the packages follows the green curve above in Figure 4 (instead of the red curve for spent fuel itself). Note that the difference between the green and red curves in Figure 4 arises from constituents which can be recycled. Fission product isotopes which have very long half-lives but cannot conveniently be recycled (such as ^{129}I) do not contribute to hazard in excess of the level of natural uranium ore.

Spent nuclear fuel needs to be divided into two streams, one which is principally fission products and the other, which is a mixture of uranium, plutonium and minor actinides. Much progress has already been made

with development of separations of the type required. The design of early nuclear reactors was generally not tightly integrated with the design of downstream plants for the processing of irradiated fuels and treatment of wastes. The PUREX process for separating spent fuel into uranium, plutonium and HLW achieved quite wide applicability and commercial maturity because of its capability to be adapted to many different fuel types (e.g. Sellafield, UK and La Hague, France).

Over decades, many processes have been explored and developed for the separations of fissile and non-fissile materials from irradiated fuels including solvent extraction, fluoride volatility, plasma flame, molten halide electrorefining, fractional crystallisation, etc [Ref 8]. While earlier processes such as PUREX were designed for “pure” uranium and plutonium products more recent ones have concentrated on the separation of an actinide stream adequately partitioned for recycle to fast neutron reactors for power production and/or minor actinide incineration together with a fission product waste stream for near term waste management. This latter approach does require remote[3] fabrication of recycled fuels, using methods such as electrorefining and casting metallic fuel (ANL) [Ref 9], electrowinning co-deposition of MOX with vibropak fuel (RIAR) [Ref 10] and simplified PUREX with gel precipitation fuel (JNC). The integration of reactor/fuel irradiation, reprocessing, remote fabrication and recycle to fast reactor is complex, but it has been achieved by both the ANL integral fast reactor and its associated fuel cycle in the USA and by the RIAR BOR60 reactor and its associated fuel cycle in the Russian Federation, albeit that such operations have not yet reached the commercial maturity of PUREX reprocessing.

Two principal products will come out of the plant as shown in Figure 3 one which is material suitable for nuclear fuel and the other, which is a potentially useful source of heat but with no very long-term hazard associated with it.

The aim of the separation should be to achieve simplicity and to receive, process and export materials using “just in time” practices to avoid building up large amounts of material in storage. The physical amount of nuclear fuel consumed in a nuclear reactor is very small by industrial standards. The processing of it should be appropriately nimble and small scale.

Figure 3 shows how existing SNF (spent nuclear fuel) and depleted uranium can potentially be incorporated into the process of recycle. The vast majority of material in SNF has potential value as recycled fuel – only a tiny proportion of the SNF is truly “waste”. The potential locked up in the world’s existing SNF (together with stocks of depleted uranium) represents at least 100 years of mankind’s total energy needs. The resource will last much longer than that if nuclear power is used in conjunction with other low carbon energy source[4]

10 Ideas for sustainable use of fission product waste

If use is to be made of the materials or heat generation from fission product waste, then a suitable demand must be identified commensurate with the supply.

The use of ^{90}Sr for radioisotope electric generators is already established (the Russians use it [Ref 11]) but it is doubtful that gamma-emitting isotopes can be used in electric generators. Gamma irradiators based on ^{137}Cs are also established, but not on a large scale. Neither of those applications could fully utilise the supply. In passing, it should be noted that the processing plant would potentially provide access to ^{237}Np, which is a component of SNF. By neutron irradiation in a reactor ^{237}Np can be converted to ^{238}Pu - the superior

[3] “Remote” refers to avoidance of direct human contact during the process on account of radiation hazards

[4] Uranium fission releases approximately 24TWh/t thermal energy. Assuming 50% efficiency of electricity generation that equates to 12TWh electricity per metric ton. Global energy use is 150,000TWh/year, equivalent to 12,500 tonnes per year of uranium. Current depleted uranium stocks are approximately 1.6M t.

radionuclide for radioisotope generators. There are reports that worldwide shortage of ^{238}Pu is seriously threatening to curtail long-distance space exploration [Ref 12].

The most flexible use (i.e. demand-supply matched) for fission products would seem to be a heat source for district heating in a remote location. The source would be of the order of single numbers of MW (perhaps up to about 10MW maximum), suitable for a small community of a few hundred people. If fission product canisters (with contents according to the green curve of hazard decay of Figure 4) were placed in an underground pool with heat exchange to the surface, the resulting output of hot water could supply reliable and continuous district heating to homes in those remote communities, akin to supplying geothermal energy but at a location of choice rather than being limited by geographical constraints of availability. Obviously, the most appropriate locations would be Polar Regions – e.g. Northern Canada, northern Scandinavia or Russia.

For safety the underground pool would need a heat sink path to the surrounding ground in the event of the heat exchange system failing. This must operate passively without the need for human intervention.

Constant heat output would be maintained at the desired level, compensating for radioactive decay by adding extra fission product canisters to the pool on a periodic basis. That would be useful for matching the output from a processing plant. At walk-away time, the facility would be allowed to move to passive heat exchange to the ground immediately surrounding the fuel pool. After a hundred years or so the facility would no longer be significantly heat generating and after a few hundred years any radioactive hazard would be effectively gone.

The use of generated heat is obviously at best a small benefit because of the small scale of heat available. Nevertheless, it may be significantly useful in a local application and really important for presentational purposes because it represents nuclear waste having value rather than being just waste.

11 International Initiatives

The ideas presented here are not new, but merely a focussing of objectives which have been there almost since the inception of the nuclear industry. In the USA, there has been only intermittent development of nuclear fuel recycling since the days of President Carter. Whilst there is re-invigoration in the USA as a result of the strength of the National Laboratories, other countries (particularly Russia Japan, France and China) are further developing partitioning initiatives of this type. The UK has historic capabilities in this field, but these have become depleted with the shutdown of various facilities at Dounreay and Sellafield. France has very significant capability, as has The Siberian Chemical Complex in Tomsk, the RIAR in Dimitrovgrad and various surrounding Russian institutes are active as a centre of development of some of these ideas, and they have the skilled people and facilities to do the relevant work.

France's nuclear research agency, Commissariat à l'énergie atomique (CEA), indicated in September, 2019 that "industrial development of fourth-generation reactors is not planned before the second half of this century." Significant R&D, development and design work is required to enable full Gen IV reactor and fuel cycle facilities, including those for waste management with adequately short radioactive decay period, to be introduced. This period of development will allow the time for such an industry to be created using fast neutron reactors that can meet the technical requirements and specifications for the whole cycle. Nevertheless, there is nothing to stop this timescale being accelerated if there is an initiative to supply sufficient development resources and industrial sponsorship.

Incremental improvements in full-scale Gen III reactors (sometimes referred to as Gen III+ type) are expected in the shorter term and there may be early deployment of small and medium scale reactor types of new concept design such as Moltex, GE-Hitachi, Terrestrial Energy, ARC, Leadcold, NuScale, Holtec, etc. The

new concept designs based on fast neutron flux are normally intended to reduce unit costs and may be leaders in establishing the principles of this Blueprint for Future Nuclear Power.

12 Conclusions

Nuclear power is a desirable, if not essential, low carbon source of energy for mankind. It is flexible and has many applications, in particular it can provide continuous power to support other intermittent low carbon energy sources.

Current management of high-level radioactive waste requires extensive delay between the waste being generated and its disposal, which restricts deployment of nuclear power. Dealing with radioactive wastes promptly should be seen as a discipline required for all new nuclear projects.

This Blueprint presents a means to recycle current stocks of spent nuclear fuel and depleted uranium using recycling methods, which have already been demonstrated individually but need to be coordinated.

The Blueprint also describes how this can be achieved in a way which is complementary to the international GIF initiative already underway.

Integrating the new waste strategy with new reactor designs in a “Hub and Satellite” model would enable new companies to use nuclear reactors for new customers and new purposes.

Waste recycling could be done in a centralised facility to support new reactor designs.

Use of the “Hub and Satellite” model is economically efficient and would allow for a wider global distribution of nuclear power with benefits for mitigation of Climate Change.

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Acronyms

ANL	Argonne National Laboratory
GEN III	[Definitions of these reactor concepts can be found at
GEN 111 +	[https://www.amacad.org/sites/default/files/academy/pdfs/nuclearReactors.pdf
GEN IV	[
GIF	Generation IV International Forum
HALEU	High Assay Low Enriched Uranium
HLW	High Level Waste (typically used to refer to residues from LWR spent fuel after uranium and plutonium have been extracted)
JNC	Japan Nuclear Cycle Development Institute
LWR	Light Water Reactor
MOX	Mixed (Plutonium/Uranium) Oxide Fuel
RIAR	Research Institute of Atomic Reactors
SNF	Spent Nuclear Fuel
PUREX	Plutonium Uranium Redox Extraction – commonly used for Nuclear Fuel Reprocessing
SMR	Small Modular Reactors