Consideration of the Legislation, Codes, Standards and Regulations Required to Oversee Future Space Reactor Development

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Abstract

One of the challenges of space travel, and especially extended space travel, is the provision of on-board power. Efforts to address the issue has led to recent interest in the development of Nuclear Power Sources for use in space. This paper discusses the specific challenges of licencing and regulating nuclear power for space, and considers the implications of licensing for a UK entity looking to enter into the nuclear-space industry.

The current international treaties and supporting guidance are reviewed and considered for both nuclear and space industries. Extant national nuclear and space industry legislation is also reviewed. This allows conclusions to be drawn and recommendations to be made to account for any shortfalls identified. Further to this, specific foreign national legislation is also briefly considered in the context of a UK entity procuring a foreign launch.

International legislation is adequate to cover the nuclear-space industry, however, there are a number of shortfalls at a national level which need to be addressed to allow the industry to become viable. These relate to the regulatory relationship between the UK Space Agency and the Office for Nuclear Regulation, as well as a lack of specific nuclear-space Safety Assessment Principles. Due to the nature of international space law, and strict liability on the State, multiple licences may be required. Therefore, the identified shortfalls are generally applicable to a UK entity regardless of the launch location.

Based on the findings, the paper makes enabling and implementation recommendations for the regulatory framework and an operator respectively. The enabling recommendations require government bodies to provide detailed technical guidance and agency agreements; whereas the enabling recommendations aim to make ventures commercially viable, recommending operators define the scope of supply, logistical arrangements and relevant good practice as early as possible.

Declarations and Acknowledgements

Declaration

The work presented in this paper is entirely my own work unless referenced clearly to the contrary and no portion of the work referred to within the paper has been submitted in support of an application for another degree or qualification of this or any other university or other institute of learning.

Intellectual Property Statements

Acknowledgements

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1 Introduction

1.1 Background

1.1.1 One of the challenges of space travel and exploration is the provision of on-board power. Early, and internationally, it was recognised that nuclear power would be essential to any prolonged space programme, and nuclear power has been used in some capacity since the 1960s (see Sections 2 and 3). However, it is generally limited to low level heat generation for the purpose of maintaining instrument integrity, or low-level power, kilowatts rather than megawatts, for propulsion and generation of electricity.

1.1.2 As international ambitions for space exploration increase, and private enterprises continue to develop economically viable ways of getting to space, the provision of more power in space, megawatts rather than kilowatts, is going to be essential.

1.1.3 Concepts such as In-situ Resource Utilisation (ISRU), i.e. refuelling stations on the Moon or Mars, intended to reduce payload on outward journeys and allow further exploration, give an illustration of the extent of ambition, and levels of power that may be required.

1.1.4 There are clearly significant challenges when it comes to resources in space. The options are to utilise solar power or take a power source with you. Solar power is widely utilised, but it has limitations. It can become large and bulky when trying to generate higher power, it reduces in effectiveness as a spacecraft moves further away from the sun, and if used for ISRU, for example, would be prone to simple failure modes such as dust reducing effectiveness or stopping power production all together.

1.1.5 Taking the power source with you gives the potential for higher powers and a higher level of flexibility in application. The limitation is longevity of the power source, which is why nuclear power is such an attractive and viable way of extending the reaches of both manned and unmanned space travel.

1.1.6 The terrestrial nuclear industry is a mature, highly regulated industry with a significant amount of operational experience to draw on, including nuclear incidents and accidents over the years. As the interest and demand for nuclear power in space increases, extending to private companies, there is a need for national and international legislation and regulatory frameworks to keep up with the industry, both to enable ambitions to be met and to ensure safety.

1.2 Objectives

1.2.1 This paper has been written to support the development of the UK nuclear space programme, and therefore sets out to consider legislation and regulation relating to a UK based entity entering into the space industry with the intent of using nuclear power.

1.2.2 National and international legislation and regulations will be discussed to clearly set out the current legal framework. This will allow conclusions to be drawn on the suitability of the current framework, any gaps in that framework and the expectations on an operator or service provider.

1.2.3 The paper will then make recommendations for the purposes of the UK entity, which include pre-emptively considering and influencing future regulation to allow nuclear power in space to become a viable enterprise.

2 Technology Overview

2.1 Introduction

2.1.1 It is essential to understand the fundamentals of nuclear technology for space in order to understand the potential hazards posed during the Nuclear Power Source (NPS) lifecycle, i.e., Concept, Demonstration, Manufacture, In-service and Disposal (CADMID) cycle, including transportation and launch. Therefore, this section provides an overview of known space reactor technology to help inform later conclusions regarding necessary regulation and licencing in the UK.

2.1.2 It is also important for any historical incidents or accidents relating to NPSs to be reviewed so that lessons that can be learnt and captured. Whilst the liability for incidents and accidents is clear (see Section 3), and a specific incident is unlikely to change the law, regulation and regulatory expectation is more flexible. Regulation tends to rely on lessons learnt and relevant good practice to ensure safety and modern standards are being applied, so incidents are an important consideration in the context of this paper.

2.1.3 Two categories of NPS for space need to be considered when reviewing the technology, particularly technology that has been successfully developed or deployed to date:

a) Nuclear Fission Reactor (NFR)

b) Radioactive Power Source (RPS)

2.1.4 An NFR for space uses the same principles and is broadly similar to a terrestrial reactor. An NFR has the benefit of being able to provide significantly more power than an RPS, along with the capability to load follow. This is a clear distinction from the RPS, therefore, the choice of technology for a mission will be driven by application, rather than the two types of technologies being used interchangeably. Each are discussed in more detail in the following subsections.

2.2 Nuclear Fission Reactors

2.2.1 This subsection summarises NFRs that have either already been deployed, or are in development. The reactors considered here are by no means exhaustive, but it is important to have a conceptual understanding of the types of technology, as well as the differences to RPS technology, to provide a basis for considering regulatory requirements.

Space Nuclear Auxiliary Power

2.2.2 The Space Nuclear Auxiliary Power (SNAP) programme was run by the United States government between 1955 and 1973 and generated a number of reactor designs [1].

2.2.3 The programme developed a series of reactors, typically with a highly enriched uranium-zirconium-hydride core, cooled by a sodium-potassium alloy. The SNAP reactors operated in the thermal neutron spectrum and reactor control was provided by beryllium reflectors around the core, which were moved to vary the reflectivity, and therefore reactivity, rather than using control rods [2].

2.2.4 The SNAP-10A reactor was the only reactor from the SNAP programme to be successfully launched into orbit. A schematic of the reactor is shown in Figure 1.

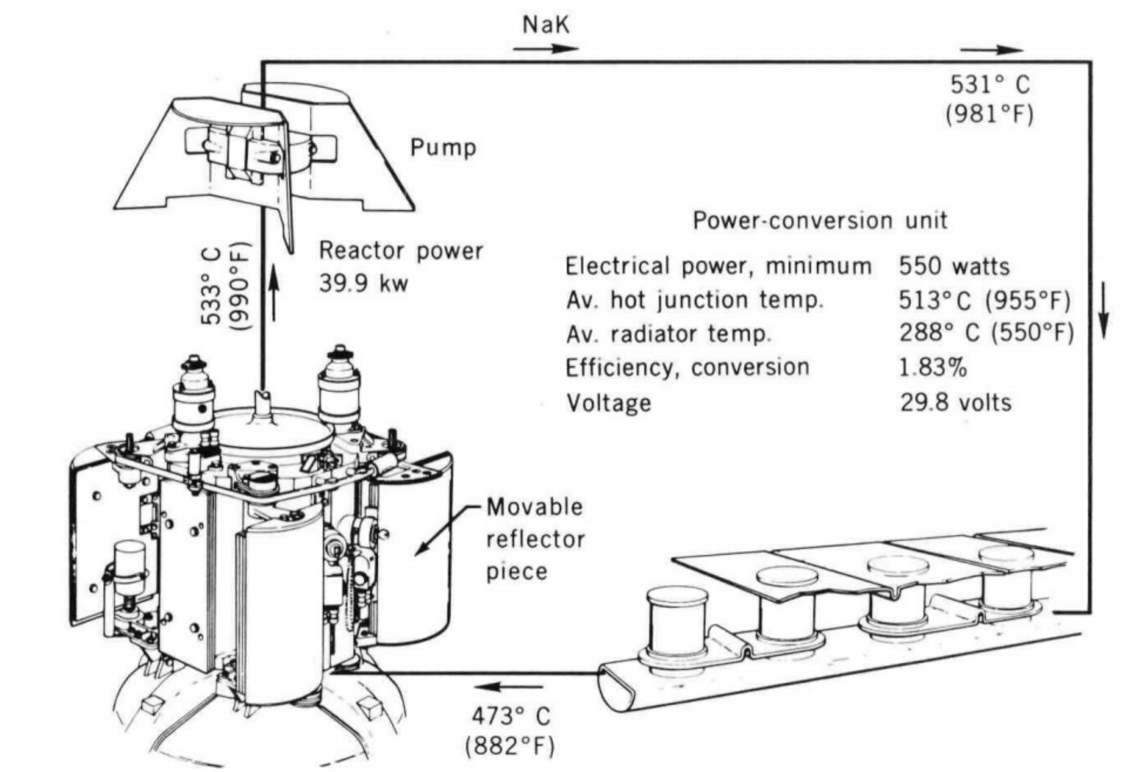

Figure 1 SNAP-10 Reactor and Power Conversion Schematic [2]

Thermionic Experiment with Conversion in Active Zone - I

2.2.5 The Thermionic Experiment with Conversion in Active Zone - I (TOPAZ-I) reactor was developed by the former Soviet Union in the 1980s and was used on their Cosmos 1818 and 1867 satellites [3].

2.2.6 The thermal reactor used thermionic fuel cells to generate electricity and a radial beryllium reflector. The reflector contained drums with segments of boron carbide that could be rotated to control the reactivity of the reactor. This maintained the core in a subcritical condition during launch and could be used to start up the reactor once in orbit [3].

2.2.7 A schematic of the TOPAZ-I design is shown in Figure 2.

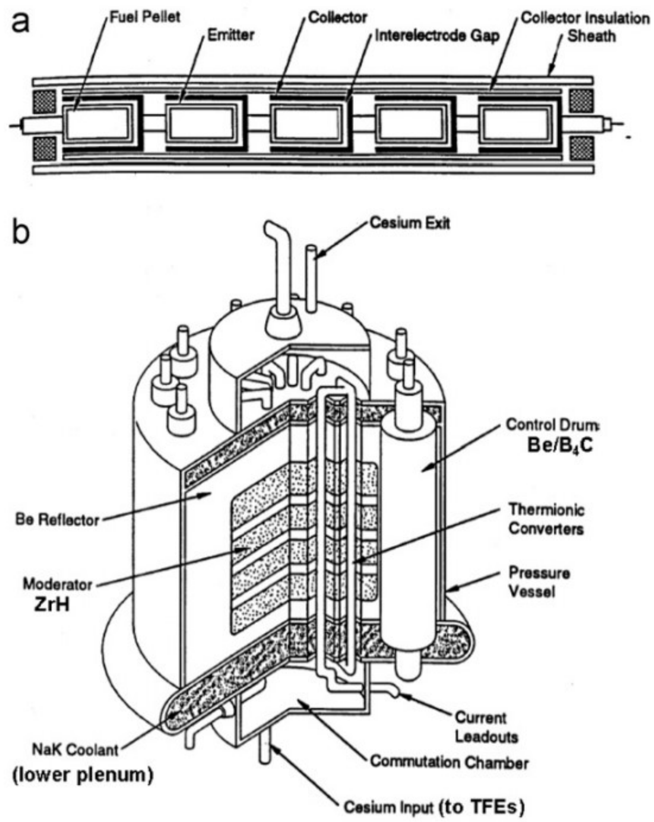

Figure 2 TOPAZ schematic: a) Thermionic Fuel Element b) Cross-section of TOPAZ – I [3]

Kilowatt Reactor Using Sterling Technology (KRUSTY)

2.2.8 The Kilowatt Reactor Using Sterling Technology (KRUSTY), is a prototypic space reactor, that has been developed by the United States National Aeronautics and Space Administration (NASA) with the intent of enabling an increase to durations in space, potentially even on planetary surfaces [4].

2.2.9 The KRUSTY uses heat pipes to transfer energy generated from fission energy via sodium as the working fluid, to a sterling engine to generate power. It has a cast uranium-molybdenum alloy core and is controlled using a boron carbide rod and beryllium oxide reflectors [5]. The configuration of the reactor is shown in Figure 3.

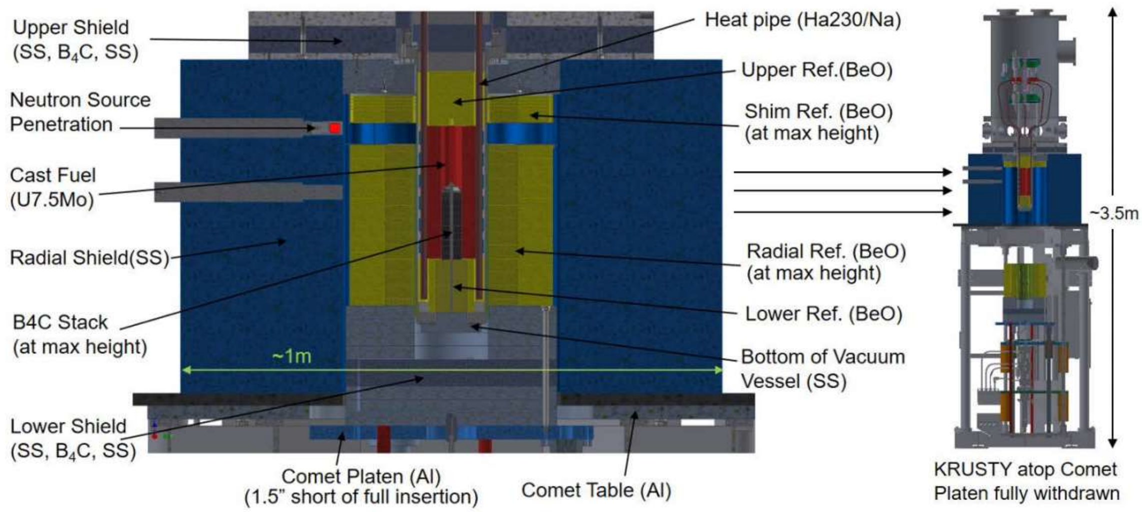

Figure 3 Configuration of the KRUSTY Reactor [5]

2.2.10 The KRUSTY reactor is a fast reactor with a negative thermal feedback coefficient which contributes to its control and inherent safety [6].

History of Deployment

2.2.11 Figure 4 provides details of the space reactor power systems that have been developed and deployed to date [6]. Other systems have either been developed and abandoned, or are currently in development e.g., KRUSTY.

	SNAP-10 US	SP-100 US	Romashka Russia	Bouk Russia	Topaz-1 Russia	Topaz-2 Russia-US	SAFE-400 US	ERATO* France
Start decade	1960s	1980s	1960s	1970s	1980s	1990s	2000s?	1980s
kWt	45.5	2000	40	<100	150	135	400	
kWe	0.65	100	0.8	<5	5-10	6	100	20
Converter	t'electric	t'electric	t'electric	t'electric	t'ionic	t'ionic	t'electric	t'electric
Fuel	$U\text{-}ZrH_x$	UN	UC_2	U-Mo	UO_2	UO_2	UN	UO_2, UN
Reactor mass, kg	435	5422	455	<390	320	1061	512	
Neutron spectrum	thermal	fast	fast	fast	thermal	thermal/ epithermal	fast	fast/ epith
Control	Be	Be	Be	Be	Be	Be	Be	
Coolant	NaK	Li	none	NaK	NaK	NaK	Na	Na, gas
Core temp., °C max	585	1377	1900	?	1600	1900?	1020	840

Figure 4 Summary of Space Reactor Power Systems [6]

2.2.12 Only two nations have successfully developed and deployed NFRs to space; US and Russia. The SP-100, Romashka, TOPAZ II, SAFE and

ERATO reactors listed in Figure 4 were developed but have not been deployed. The BUK reactor (sometimes known as Bouk or BES-5) has been deployed and uses very similar technology to the TOPAZ reactors. In all instances, there has been a significant amount of time since the last reactor was used in space, with the whole nuclear industry having move forward with respect to safety and regulation over that period of time.

Summary of NFR Technology

2.2.13 It is clear from a brief look into the available fission reactor technology that there are different reactor types, with varying power and control mechanisms. This is illustrated in Figure 4.

2.2.14 The application of technology and the specific detail of the control mechanisms may differ from a terrestrial reactor; however, the physics and the principles of safe reactor design remain unchanged. Therefore, the challenges are the regulation of those principles and ensuring adequate consideration of any additional hazards introduced by this specific application.

2.2.15 A considerable amount of time has also passed since an NFR has been launched and used in space, and some previous activity predates more recent international guidance. Therefore, further consideration of regulatory frameworks elsewhere in the world is provided in Section 6 because the assumption cannot be made that suitable frameworks are already in place.

2.3 Radioactive Power Sources

2.3.1 RPSs are typically used in thermoelectric generators or heater units to utilise the natural decay heat of radioactive isotopes. Radioisotope Thermoelectric Generators (RTGs) use thermocouples to convert the decay heat generated by a passive radioactive source into electricity. Therefore, the power supply from such a system is ‘non-variable’ because it is directly linked to the isotope decay. This drives a requirement for ancillary systems e.g. batteries, to accommodate spikes in power demand and recover potential losses when power demand is low.

2.3.2 A typical RTG arrangement is shown in Figure 5 for information.

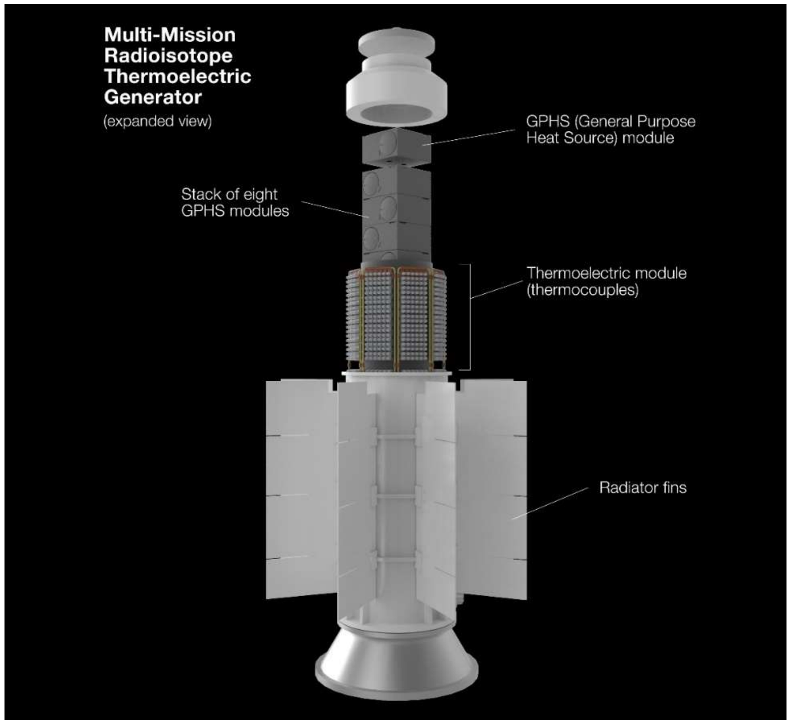

Figure 5 Typical RTG Arrangement [7]

2.3.3 The most common isotope used for RTGs in space applications is ^{238}Pu. However, studies have been carried out to assess the feasibility of other sources, for example ^{241}Am, ^{208}Po, ^{210}Po, and ^{90}Sr [8]. There are 22 isotopes that have the potential to power RTGs [9] but prohibiting factors such as cost, dose during production and power output, normally drive the use of ^{238}Pu as the most viable choice [10].

2.3.4 The specific isotope used for RTGs is not directly relevant to this study, however, consideration needs to be given to the potential hazard to either operators or the public in order to understand and determine the most suitable regulatory and safety framework. That is, the Nuclear Installations Act (NIA) covers only nuclear fuel or "*bulk quantities of other radioactive matter which has been produced or irradiated in the course of the production or use of nuclear fuel*" [11], but all ionising radiation is subject to the Ionising Radiation Regulations (IRR) 2017 [12]. This distinction and its relevance are discussed further in Subsection 4.3.

History of Deployment

2.3.5 The only country other than US and Russia, (both have successfully launched RPSs and NFRs into space), to deploy an RPS is China. There have been multiple launches containing RPSs from Russia and US [13]. China launched their Chang'e-3 in 2013, which contained RTGs and Radioactive Heater Units (RHUs) [14].

2.4 Incidents and Accidents

2.4.1 Regulation of the Nuclear Industry, particularly in the UK has continued to evolve by taking into account relevant good practice and lessons learnt from incidents across the industry and beyond, to ensure the continued improvement of safety across the industry. For example, there was an increased focus on Human Factors following the Three Mile Island incident in 1979 [15]. Then crossing over to wider learning in other industries, the Office for Nuclear Regulation (ONR) have reviewed the findings of the Grenfell Tower fire to consider lessons learnt, and the regulatory implications of those findings [16].

2.4.2 The use of RPSs for RTGs and RHUs is more common than NFRs, however, compared to the terrestrial nuclear industry, the space industry is extremely immature with regards to operational experience. Therefore, relevant good practice and lessons learnt from the terrestrial industry will need to be applied. This must be carefully considered to avoid placing overly constraining limitations on the industry, and should be utilised with the consequence of failure firmly understood, i.e. an accident in space does not carry the same consequence as a similar accident terrestrially. This could result in lesser claims being placed on a system and therefore, may mean it is not necessary to demonstrate high design tolerance to a particular failure mode, whereas it may be terrestrially.

2.4.3 There is a wealth of operational experience from the wider nuclear industry, and therefore it is not appropriate, nor necessary, to consider it all here. However, some specific examples of terrestrial relevant good practice, which have the potential to significantly hinder the UK space industry are considered later, in Subsection 5.8.

2.4.4 The incidents or accidents considered here are both those relating to re-entry of NPSs to the Earth's atmosphere and those in space. Whilst in most instances, failure in space does not present a safety concern to the general population, there would be a concern if similar missions were manned, or if common failure modes could result in similar accidents occurring during launch.

2.4.5 As the two dominant nations in the use of RPSs in space, all incidents and accidents have occurred during either US or Russian missions.

United States

2.4.6 The US has flown 27 missions with RPSs and one with an NFR [17].

2.4.7 Of those 28 flights, there have been three incidents that either occurred during launch or involved re-entry to the Earth's atmosphere; all had ^{238}Pu RTGs on board [17].

a) The Transit 5-BN-3 satellite in 1964 – The SNAP-9A RTG burnt up on re-entry to the Earth's atmosphere and dispersed plutonium in the upper atmosphere.

b) The Nimbus B-1 satellite in 1968 – The launch was aborted, the fuel container from the SNAP-19 RTG was recovered intact and reused.

c) The Apollo 13 lunar module in 1970 – The lunar module carrying the SNAP-27 RTG fell into the Pacific Ocean and has not been recovered.

Russia and Soviet Union

2.4.8 Russia or the Soviet Union have flown 45 missions with NPSs [18], 33 of those included reactor power systems. Primarily the BUK reactor, but also the similar TOPAZ-I and TOPAZ-II systems.

2.4.9 There have been three incidents with the BUK reactor on board [3]:

a) The Cosmos-945 satellite in 1977 – A failed attempt to boost the deactivated reactor into a storage orbit, resulted in the reactor re-entering the atmosphere and spreading debris across Northern Canada.

b) The Cosmos-1402 satellite in 1982 – A failed attempt to boost the reactor into a storage orbit, resulted in the satellite (including fuel) burning up on re-entry to the Earths' atmosphere over the South Atlantic.

c) The Cosmos 1900 satellite in 1987 – Orbital decay and loss of altitude resulted in early deactivation and ejection of the reactor core into space.

2.4.10 In addition to the above incidents, the Cosmos 1818 was destroyed in orbit with a TOPAZ-I reactor on board, either due to component failure or being hit while in orbit [3].

Conclusions on Incidents and Accidents

2.4.11 The legal framework, the regulatory structure and the guidance available for terrestrial reactors is mature and has taken into consideration years of experience and learning from accidents and incidents across the world. The learning has therefore filtered into regulatory expectation and licensee's own guidance and processes.

2.4.12 Further learning from the operational experience deploying NPSs in space needs to be applied to guidance and taken into consideration by regulators, to ensure that lessons are learnt and safety is maintained as the private sector increases their involvement. Clear expectations will drive designers, operators and licence holders to engrain safe practices throughout the design process and into operation.

2.4.13 Internationally the International Atomic Energy Agency (IAEA) have already published guidance [19] with that intent, and some of the principles adopted address the failure modes that led to the incidents discussed. The IAEA guidance is discussed further in Subsection 3.5. How this is applied, implemented and regulated at a national level still needs to be defined for the UK.

3 International Organisations, Treaties and Guidance

3.1 Introduction

3.1.1 This section sets out the key international conventions and treaties that form the basis of national legislation for party nations. This includes how NPSs are considered for use in space and any interfaces with terrestrial treaties. This section also gives a summary of the relevant international and European organisations that influence and act on the terms of those treaties, which extends to guidance and regulation where applicable.

3.2 International Organisations

United Nations Office for Outer Space Affairs

3.2.1 The United Nations Office for Outer Space Affairs (UNOOSA) was originally set up to service the Committee on the Peaceful Uses of Outer Space (COPUOS) in 1958. In 1993 it took the form is has today [20]. Its purpose is to help all countries develop and build their capability in the space sector [21].

3.2.2 The UNOOSA has five sections [22]:

a) Office of the Director

b) Committee, Policy and Legal Affairs Section (CPLA)

c) Space Applications Section

d) United Nations Platform for Space Based Information for Disaster Management and Emergency Response (UN-SPIDER)

e) Executive Secretariat of the International Committee on Global Navigational Satellite Systems

3.2.3 Two of the sections are of particular relevance to nuclear power in space. The CPLA, who provide organisational and administrative support for the

COPUOS and its subcommittees; and the UN-SPIDER who provide data to support disaster risk reduction [22].

Committee on the Peaceful Uses of Outer Space

3.2.4 The COPUOS was set up in 1959 to govern the use of space and was instrumental in formation of the five space treaties [23] described in Paragraph 3.3.9.

3.2.5 The COPUOS has two subcommittees; the Scientific and Technical Subcommittee and the Legal Subcommittee. Both committees meet annually to discuss their respective agendas, with the overarching mandate of *"strengthening the international legal regime governing outer space, resulting in improved conditions for expanding international cooperation in the peaceful uses of outer space*" [24].

International Atomic Energy Agency

3.2.6 The IAEA was created in 1957 as the United Nations (UN) "*Atoms for Peace and Development*" organisation [25]. Its purpose is to "*promote safe, secure and peaceful nuclear technology*" [25].

European Atomic Energy Community

3.2.7 The European Atomic Energy Community (EAEC) is a community established by the Euratom treaty (see Paragraph 3.3.1). It has the same members as the European Union and was initially set up to manage energy shortages across Europe through peaceful use of nuclear power. The EAEC also promote research and the establishment of common safety standards [26].

3.2.8 The UK's decision to leave the European Union also resulted in its withdrawal from the EAEC. Therefore, the UK passed the Nuclear Safeguards Act 2018 [27] to cover the gap left by withdrawal from the Euratom treaty. The additional shortfalls i.e. access to supplies and research, have subsequently been addressed in a trade and cooperation agreement [28].

3.3 Treaties and Conventions

Euratom Treaty

3.3.1 The Treaty Establishing the European Atomic Energy Community, or Euratom Treaty [29] was signed in 1957 with the intent of promoting research and collaboration between states party to the agreement; it also established the EAEC.

Nuclear Liabilities Conventions

3.3.2 The treaties key to driving national legislation and regulation for civil reactors are those that pertain to liability and nuclear damage. The premise of strict rather than fault liability is the basis on which regulation of the nuclear industry is built. It ensures that any victim of nuclear harm or damage need only prove causal link to an incident rather than negligence or fault. The liability also rests with the operator i.e., civil liability. There is an obligation for the operator to cover this liability financially.

3.3.3 The following conventions are of note with regard to nuclear liability, all of which set out strict liability:

a) Paris Convention on Third Party Liability in the Field of Nuclear Energy [30]

b) Brussels Convention Supplementary to the Paris Convention [31]

c) Vienna Convention on Civil Liability for Nuclear Damage [32]

d) Joint Protocol Relating to the Application of the Vienna Convention and Paris Convention [33]

e) Convention on Supplementary Compensation for Nuclear Damage [34]

3.3.4 In addition to liability during operation, the treaties also set out that liability lies with the operator of a nuclear installation for any nuclear material "*coming from or originating in his nuclear installation*" [32] until the person "*duly authorized*" [32] to operate using that material has taken charge of it.

The Radiation Protection Convention 1960

3.3.5 The Radiation Protection Convention [35] sets out the principle that every effort must be made to reduce exposure to ionising radiation to levels as low as practicable. It also sets the expectation that a maximum allowable dose, depending on the category of the worker, should be defined [36]. Dose levels in the context of this paper are considered in more detail in Subsection 5.7.

The Convention on Nuclear Safety

3.3.6 The convention on Nuclear safety (1994) [37] was convened by the IAEA and obligates all party nations to have adequate legislation and regulatory framework to ensure safety for any nuclear installations [38]. It sets out the key elements of regulation and responsibility of the licence holder with regard to safety. Regulation in the UK is discussed in Section 4.

Maritime Conventions

3.3.7 Although a different application, conventions relating to the use of nuclear power in the maritime industry show consideration of both transportation of nuclear material and of mobile nuclear power. Therefore, they may offer some insight into other mobile applications. The following conventions are of note and are summarised below to highlight key points:

a) International convention for the Safety of Life at Sea [39]

   (i) The UK is party to this convention, which drives the obligation to comply with the "*Code of Safety for Nuclear Merchant Ships*" [40]. The UK does not currently have any non-military nuclear ships, but other countries, predominantly Russia, do make use of the convention.

b) Convention Relating to Civil Liability in the Field of Maritime Carriage of Nuclear Material [41]

   (i) This convention became necessary to avoid large insurance indemnities for maritime carriers of nuclear materials, despite the provisions made for third party liabilities in the Paris and Vienna Conventions (Paragraph 3.3.3). This convention simply ensures that strict liability under either the Paris or Vienna convention remains with the operator of the nuclear installation concerned, regardless of any other conventions that may be applicable.

c) Convention on the Liability of Operators of Nuclear Ships - Brussels 25 May 1962 (not in force) [42]

(i) This convention, although not in force, sets out the strict liability similar to that of the Paris and Vienna Conventions [30][32].

3.3.8 It is clear from brief consideration of maritime conventions, that the intent is for liability of nuclear installations to remain with the operator, regardless of the mobility of such an installation, and international conventions have been put in place to ensure this is clear and agreed. Conventions pertaining to space are considered below. Similar to the maritime industry one key issue will be the transfer or agreement of liability between parties.

Space Treaties

3.3.9 There are five UN treaties on outer space, all are applicable to the space industry. However, they are not all directly relevant to the consideration of licensing, regulation and liability with regard to nuclear applications. Therefore, only the following three treaties are highlighted:

a) Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies [43]

(i) The treaty primarily acts as a non-armament treaty. However, it also very clearly sets out that the State is responsible and liable for all national space activities and damage caused.

(ii) The treaty also sets out that the liability lies with the launch State, but that the state carrying the registry of the object retains jurisdiction and control over the object.

(iii) The terms of liability set out ensured that the USSR paid damages to Canada in the incident described in Paragraph 2.4.9a) [44].

b) Convention on Registration of Objects Launched into Outer Space [45]

(i) This sets the expectations and rules relating to registration of all objects sent into outer space.

c) Convention on International Liability for Damage Caused by Space Objects [46]

(i) Clarification is provided for the term ‘launching State’, which is either the State procuring the launch or the State from whose territory the object is launched. Where two States jointly launch and object, they are jointly liable. However, agreements can be made between the two States as to the proportion of liability, on the condition that this is done without prejudice to the State sustaining damage.

Discussion of Treaties and Determination of Liability

3.3.10 Terrestrial nuclear power liability is covered by the conventions listed in Paragraph 3.3.3. All of them ensure that the operator is strictly liable for any damage caused. The State must legislate to ensure that an operating licence is granted and that financial cover is in place for any liabilities.

3.3.11 Whilst there is still absolute liability, the situation is distinctly different for the treaties pertaining to space, where liability sits with the State, or States, responsible for the launch and operation. This necessitates legislation and regulation on behalf of any State to protect its own interests.

3.3.12 However, regardless of the intricacies of where the liabilities lie, which will affect national legislation, the approach taken with regard to strict liability in the nuclear liabilities’ treaties and the space treaties, provide ‘end-to-end’ absolute liability for NPSs. That is, international law effectively ensures absolute liability throughout production of an NPS, installation into a space reactor and ground operations, hand over to an operator at the point of launch, and then operation in space.

3.3.13 Therefore, international law is sufficient to enable nuclear power to be utilised in space. So, it is a matter for national law, across multiple nations to define the remit of responsibility and draw out suitable national legislation and regulation to cover the breadth of this new application. The point of transfer of liability between parties and phases of the lifecycle should also be considered, this is discussed further in Section 5.

3.4 International Nuclear Power Source Principles

3.4.1 The UNOOSA general assembly adopted 11 principles relevant to the use of NPSs in space in December 1992 [47]. These are:

a) Principle 1 – Applicability of international law.

b) Principle 2 – Use of terms.

c) Principle 3 – Guidelines and criteria for safe use.

d) Principle 4 – Safety assessment.

e) Principle 5 – Notification of re-entry.

f) Principle 6 – Consultation.

g) Principle 7 – Assistance to states.

h) Principle 8 – Responsibility.

i) Principle 9 – Liability and compensation.

j) Principle 10 – Settlement of disputes.

k) Principle 11 – Review and revision.

3.4.2 Some aspects of these principles have already been drawn out through discussion of the international treaties and liability in Subsection 3.3. However, principles 3 and 4 are particularly pertinent to this paper and warrant further discussion. The principles are summarised here to inform later conclusions on national legislation and regulation.

Principle 3 – Guidelines and Criteria for Safe Use

3.4.3 The first point to note in principle 3 is that it requires the amount of radioactive material in space to be minimised and limited to missions which cannot be powered by other sources "*in a reasonable way*" [47]. This point relates directly to consideration of As Low As Reasonably Practicable (ALARP) in UK law, and therefore is discussed further in Subsection 5.5.

3.4.4 The principle then sets out specific goals with regard to radiation protection and nuclear safety. It goes on to specify that "*hazards, in foreseeable operational or accident circumstances, are kept below acceptable levels*" [47]. This is defined by referral to the International Commission Radiological Protection (ICRP) radiation protection objective. It also sets out specific annual dose limits for individuals in accident conditions, to be applied with the exception of "*low-probability*" [47] accidents. The definition of 'low-probability' is not provided, therefore consideration needs to be given to the definition when applying or benchmarking against the principle nationally.

3.4.5 The principle also refers to the need for systems to be safe by design, and assurance of reliability using redundancy, independence of systems, separation, and functional isolation. All of which are fundamental and well established within the terrestrial nuclear industry, and are particularly central to the methodologies set out in IEC 61513 [48], which is discussed in the context of UK relevant good practice in Subsection 5.8.

3.4.6 The principle also provides some specific criteria for nuclear reactors and for RTGs. Orbital requirements and disposal in orbit are considered, with the requirements for nuclear reactors more stringent than RTGs, defining a need for "*highly reliable operational systems*" [47] where the reactor needs to be transferred into higher orbits at end of life. Therefore, consideration of how to define and demonstrate 'highly reliable' is important. This is also considered in Subsection 5.8.

3.4.7 The fuel type, and a requirement to ensure that the reactor cannot go critical before orbit, either intentionally or inadvertently in any accident scenario, are also defined. The fuel type is specified as highly enriched

^{235}U, although it isn't clear why this is set out as a requirement, and it is likely that this could be challenged should an alternative fuel be demonstrably safe.

Principle 4 – Safety Assessment

3.4.8 Principle 4 sets out that the launch state shall ensure a comprehensive safety assessment is carried out at the time of launch and prior to the launch. This can be done through cooperative agreement with the designer and manufacturer, but must cover all phases of the mission and all systems supporting the mission [47].

3.5 International Safety Guidance

3.5.1 The IAEA publish safety standards which provide a suite of principles, requirements and recommendations as a single global reference point for nuclear safety. How these are used by member states vary [49], but the intent is that a consistent set of standards is filtered into national regulation. In the UK, the ONR benchmark the standards set out by the IAEA against their own regulatory guidance documents, the Safety Assessment Principles (SAPs) and Technical Assessment Guides (TAGs) [50]. These guides are then used by their assessors to ensure the appropriate safety standards are maintained for the duration of a Nuclear site licence holding.

3.5.2 In 2009 the COPUOS and IAEA published a safety framework for Nuclear Power Source Applications in Outer space [19]. This publication is intended to complement the "*existing national and international safety guidance and standards pertaining to terrestrial activities*" [19]. The guidance provides a consensus by COPUOS and IAEA on safety matters for NPSs, and addresses all nuclear safety related aspects to the deployment and use of NPSs in space. This includes the NPS itself, "*spacecraft, launch system, mission design and flight rules*" [19].

3.5.3 The guidance is for national use and does not form part of the IAEA safety standards. Instead, it "*provides voluntary guidance and is not legally binding under international law*" [19]. The guidance below, for governments, has been taken directly from the safety framework [19] and presented here for information, so that the context of discussion, particularly in Section 5, can be understood:

a) Safety policies, requirements and processes - Governments that authorise or approve space nuclear power source missions should establish safety policies, requirements and processes.

b) Justification for space nuclear power source applications - The government's mission approval process should verify that the rationale for using the space nuclear power source application has been appropriately justified.

c) Mission launch authorisation - A mission launch authorisation process for space nuclear power source applications should be established and sustained.

d) Emergency preparedness and response - Preparations should be made to respond to potential emergencies involving a space nuclear power source.

3.5.4 However, notwithstanding the above guidance and position with regard to liability for space (as set out in Subsection 3.3), the framework also recommends that the responsibility for safety lies with the organisation conducting the NPS mission. This is consistent with terrestrial policy, where the operator holds responsibility and also with principle 8 of the UNOOSA principles on outer space [47].

4 UK Legislation and Regulation

4.1 Introduction

4.1.1 This section looks to consider the application of current UK regulation for the nuclear and space industries and seeks to derive any changes required should the UK be the sole launch state for a reactor or RTG designed and manufactured in the UK, by a UK entity.

4.2 UK Regulators and Authorities

4.2.1 This subsection briefly describes relevant UK authorities. This will later help draw conclusions on the remit of the authorities in relation to getting NPSs to space (see Subsection 5.2). There are a number of peripheral authorities, for example the Health and Safety Executive (HSE), the Environment Agency (EA) or the Office of Rail and Road which are not included here because, whilst agency agreements might need to be put in place or modified, their role will not be a determining factor in the regulation of NPSs for space.

Office for Nuclear Regulation

4.2.2 The ONR is the UK's nuclear regulator. They are responsible for the regulation of 36 licensed sites [51] and regulate for nuclear safety, nuclear site health and safety, nuclear security, nuclear safeguards and safety of transport of nuclear material [52].

4.2.3 A point that should be made clear, and one that is explicitly set out by the ONR [51] is that the responsibility for safety lies with the duty holder. The ONR's role is to hold the nuclear industry "*to account on behalf of the public*" [51]. This approach is derived from the international treaties (see Subsection 3.3) and the UK statute (see Subsection 4.3).

Defence Nuclear Safety Regulator

4.2.4 The Defence Nuclear Safety Regulator (DNSR) is discussed here because it provides an example of a regulatory regime for a nuclear power plant that is not a 'stationary' installation.

4.2.5 The Defence Safety Authority (DSA) is the Ministry of Defence (MoD) regulator, and provides assurance for all Defence Regulations and policy on Health Safety and Environmental Protection where MoD has authority [53]. DNSR are part of the DSA and therefore have specific exemptions from statute [54]. However, the DNSR directive sets out a specific requirement to ensure that Defence regulation is "*as far as is reasonably practicable, at least as good as that required by statute*" [54].

4.2.6 DNSR do not act completely independently. The MoD statute exemptions do not apply to the Health and Safety at Work Act (HSWA) [55], therefore, the ONRs legal obligations with respect to subordinate regulations e.g., IRRs still apply in Defence applications. There is an agreement between MoD and HSE setting out the nature of the working relationship between the two regulators [56]. There is also a letter of understanding setting out the relationship between DSNR and ONR.

UK Space Agency

4.2.7 One of the UK Space Agency's (UKSA) key performance indicators is to "*protect the space operating environment and government liabilities and responsibilities under the UN space treaties.*" [57]. Therefore, UKSA has a clear regulatory role in the UK space industry. However, the UKSA's role stretches further than the nuclear regulators (ONR & DNSR) within their industry. UKSA are responsible for strategy and policy development as well as representing the UK space industry internationally. They also invest in the sector, with part of their mission being to gain 10% of the global market share by 2030 [57].

4.3 UK Legislation and Regulation for Installations

4.3.1 Some of the key statutes and regulations are briefly described here so that their application to the space industry can be considered.

4.3.2 The NIA satisfies the UK's international obligations to the Paris and Brussels conventions (Paragraph 3.3.3) and any exemptions from it must be made with the agreement of the Secretary of State and by statutory instrument [58].

4.3.3 The NIA 1965 sets the legal requirement that "*any nuclear reactor (other than such a reactor comprised in a means of transport, whether by land, water or air)*" [11] must be located on a site that holds a licence, this is granted by the ONR. This also extends to other prescribed installations which may in their purpose, processes or activities, relate to nuclear fuel and therefore, ionising radiation. The definition of 'prescribed installations' is given in the Nuclear Installations Regulations (NIR) [59]. The steps followed for granting of a licence are set out by the ONR in their licencing process guidance [60].

4.3.4 From the NIA [11] and NIR [59], the manufacture of a fission reactor 'power unit' would require a site licence, as would the manufacture of a plutonium RTG, on the assumption that the amount of plutonium constitutes a bulk quantity [61]. However, alternative materials (see Paragraph 2.3.3), as long as they are not "*matter which has been produced or irradiated in the course of production or use of nuclear fuel*" [61], would not require a site licence. Therefore, the logistical requirements, as well as the associated hazards, change depending on the technology being deployed.

Office for Nuclear Regulation Numerical Targets

4.3.5 As introduced in Paragraph 3.5.1, the ONR uses SAPs and TAGs to assess licensees. One aspect of the SAPs are numerical targets [62]. The ONR sets nine numerical targets for nuclear facilities in their safety assessment principles. These cover individual, and collective normal operational dose targets for radiation workers, employees and the public; but they also quantify the tolerable level of risk, and associated dose during an accident. The targets use a Base Safety Objective and Base Safety Level to support the assessment of tolerability of risk. However, legal dose limits are set by the IRRs [12]. Whilst the SAPs targets are only applicable on licensed sites, the IRRs set a legal limit to be applied regardless of material type or licencing arrangements. The targets [62] cover:

a) Target 1 – Normal Operation – any person on site.

b) Target 2 – Normal Operation – any group on site.

c) Target 3 – Normal Operation – any person off site.

d) Target 4 – Design Basis Fault Sequences – Any person.

    (i) On-site.

    (ii) Off-site.

e) Target 5 – Individual risk of death from on-site accidents – any person on the site.

f) Target 6 – Frequency dose targets for and single accident – any person on the site.

g) Target 7 – Individual risk to people of site from accidents.

h) Target 8 – Frequency dose targets for accidents on an individual facility – any person off the site.

i) Target 9 – Total Risk of 100 or more fatalities.

4.3.6 The targets are discussed in more detail in Subsection 5.7 to determine their applicability to the nuclear-space industry.

As Low As Reasonably Practicable

4.3.7 The HSWA [55] sets the requirement for any duty holder to ensure safety So Far As Is Reasonably Practicable (SFAIRP), which in turn means that risks must be ALARP. This principle applies across the UK for all industries, including the nuclear industry. However, there are specific aspects of the application of ALARP that are worthy of note in the context of this paper.

a) Relevant good practice – The use of 'relevant good practice' can assist duty holders in meeting their statuary obligations because consideration of feasibility, cost and risk are integral to the development of good practices. Therefore, whilst not necessarily solely demonstrating the risks are ALARP, defining and attributing relevant good practice to a specific scenario is often sufficient as long as the practices are clearly relevant [63]. Where two industries (space and nuclear) are being combined, the definition of 'relevant' will be important in defining good practice.

b) Option Selection – Consideration of options should be undertaken with the ALARP principle in mind throughout the full CADMID cycle [63]. Without this, there is a risk that 'unsafe' features or components become embedded into a design, but the cost of retrospective removal or rectification is grossly disproportionate to the risk. This is commonly known as 'reverse ALARP' and is protected against by both UKSA and ONR through a staged approval process.

4.3.8 Both aspects of ALARP drawn out above will be particularly important for any UK entity looking to launch an NPS from the UK. Other countries however, tend to have a more prescriptive approach, with thresholds for safety, or the application of codes and standards considered sufficient. This is discussed further in Subsection 5.5 and Subsection 5.8.

Design Approval

4.3.9 It is possible for power station operators to request Generic Design Approval (GDA) for a power plant design. This is not a mandatory requirement, but allows early regulatory engagement for ONR, EA and Natural Resources Wales and is intended to reduce financial and regulatory risk by resolving potential issues early in the design process [64]. The process excludes siting and any implications of operation specific to a site, but provides generic approval for a design so that the design might be 'rolled out' in multiple locations with reduced regulatory burden.

4.3.10 Notwithstanding the option to request GDA, the ONR will use hold points to permission activities throughout design and safety case development to ensure that their regulatory need is met as the design is developed and implemented. There is no mandated method of providing this assurance, but a licensee will normally set out a through-life safety case strategy to allow the regulator sight of the safety case and design at the relevant stages. TAG 51 appendix 3 [65] provides some details of the ONR expectations which align with a staged safety case submission at each stage of the CADMID cycle.

Licensed Site Locations

4.3.11 The licensing process is set out in the ONR guide for licencing Nuclear Installations [60]. The licence applicant must notify public bodies under Section 3(4) of the NIA [11], which ultimately provides the mechanism for public consultation.

4.3.12 This is not applicable for civil power stations where consultation is carried out generically and pre-emptively, and has led to sites being defined in the National Policy Statement for Nuclear Power Generation [66] published in 2011.

4.4 UK Legislation and Regulation for Transport of Nuclear Material

4.4.1 The NIA 1965 [11] sets out the third-party liability, and therefore the responsibility of a licence holder during transportation of nuclear material. However, the requirement for a licence and the application of the conditions of that licence only relate to a nuclear installation, with clear exemptions for all reactors or components of reactors being transported.

4.4.2 Regulation of transportation of radioactive material is prescriptive, and based on international regulations set by the IAEA [67]. This is different to the model used for Nuclear Installations, where the onus is on the operator to demonstrate that the risks are ALARP and the conditions of the licence have been met. The approach ensures that the same, or equivalent, safety standards are applied during international transportation.

4.4.3 There are multiple regulations relevant to the transportation of radioactive material in the UK:

a) Carriage of Dangerous Goods and Transportable Pressure Equipment [68]

b) Ionising Radiation Regulations 2017 [12]

c) Nuclear Industries Security Regulations 2003 [69]

d) Radiation (Emergency Preparedness and public Information) Regulations (REPPIR) [70]

e) International Maritime Dangerous Goods Code [71]

f) International air transport Association Dangerous Goods Regulations [72]

g) Dangerous Goods in Harbour Areas Regulations 2016 [73]

4.4.4 In addition to the regulations listed above, the devolved UK governments also have their own regulations covering any necessary temporary environmental exemptions during transportation, or specific authorisations as required [74][75][76].

4.4.5 The application of the above legislation applies to 'Class 7' goods as defined by the Agreement Concerning the International Carriage of Dangerous Goods by Road [77].

4.4.6 Transportation of radioactive material by road or rail within the UK is regulated by ONR [78], or for the defence nuclear programmes, it is the DNSR [79]. For transport by sea or air, the enforcing authority is the Marine Civil Authority or Civil Aviation Authority respectively [78].

4.5 UK Legislation and Regulation for Space

4.5.1 The Outer Space Act (OSA) 1986 [80] is the UK's legal means of meeting its obligations to the UN treaties discussed in Subsection 3.3. As well as meeting the obligations of the UN treaties, it also ensures indemnity for the

UK government, transferring some of the strict liability placed on the state by international law onto the operator.

4.5.2 The Space Industries Act (SIA) 2018 [81] makes an amendment to the OSA so that activities carried out in the UK are no longer regulated by the OSA [82]. The SIA is not yet in force [83], so it may be some time before a licence can be granted by a regulator under the SIA [84]. However, for the purposes of this paper, and noting that a licence for launch or operation of an NPS is not imminently required, the arrangements as though the SIA was in force will be considered.

4.5.3 Both Acts require the regulator (in this instance UKSA) to grant licences for specific activities. The split is dependent on the activity planned and the location of the entity carrying it out. Figure 6 provides details of the licencing requirements.

Operation	**OSA**		**SIA**	
	Procurement of launch	In-orbit operations	Procurement of launch	In-orbit operations
UK entity procuring a UK launch for a satellite			X	
UK entity operating a satellite from the UK				X
UK entity procuring an overseas launch for a satellite	X			
UK entity operating a satellite from overseas		X		
Foreign entity procuring a UK launch for a satellite			X	
Foreign entity operating a satellite from the UK				X

Figure 6 Controlling Acts for Space Licence Launch and Operations [85]

4.5.4 As can be seen from Figure 6, any activity in the UK, whether by a UK or foreign entity is regulated by the SIA. The OSA is used to ensure that the UK meets its obligations for activities carried out overseas.

4.5.5 Guidance on the application for a licence to procure a launch or to operate a 'space object' is provided by the UK government [86]. This sets out the following application process:

a) Stage 0 – Pre-application engagement.

b) Stage 1 – Application submitted.

c) Stage 2 – UKSA's assessment.

d) Stage 3 – Decision.

e) Stage 4 – Licence issued or refused.

4.5.6 During the pre-application stage, prospective licence applicants are given the opportunity to use the 'traffic light system' [86] which provides early indication of the likelihood of a licence being granted, as well as helping UKSA understand the specific risks relevant to the mission, and therefore tailor the licensing process.

4.5.7 The SIA sets out the requirement for the regulator to consult with other organisations, including ONR and EA prior to determining the conditions of granting a licence. It is likely that the level of involvement of each agency will be informed via the 'traffic light system' at the pre application stage, with further involvement at the assessment stage if required. The OSA does not contain the same requirement for consultation, but it does provide a blanket statement that a licence "*may be granted subject to such conditions, as the Secretary of State thinks fit*" [80]. Therefore, it is highly likely that the licencing arrangements will be made consistent under both Acts.

4.5.8 As the statute governing UK based space operations, the SIA also sets out the requirement to demonstrate that risks to both those involved in the operation being undertaken, and those not (i.e., the public), must be

ALARP. The OSA does not specifically reference ALARP, but does state that a licence can only be granted when the Secretary of State is satisfied that the licensed activities "*will not jeopardise public health or the safety of persons or property*" [80], the measure of this under UK law is SFAIRP.

5 Discussion Considering UK Launch and Operation

5.1 Introduction

5.1.1 This section considers UK regulation of a UK launch and operation, which will therefore be covered by the SIA. Consideration of a UK entity procuring a foreign launch is discussed in Section 6, but draws heavily on the discussion covered here.

5.2 Regulatory Interfaces

5.2.1 Section 13, Subsection 6 of the SIA [81] provides a mechanism to ensure adequate regulation through consultation on licence conditions for space ports and operators. However, currently there is a shortfall in the definition of specific regulatory roles, responsibilities and expectations with regard to NPSs and the interface between UKSA and ONR. Without a detailed agreement, any operator expected to maintain responsibility for safety during launch, as per the international policy set out by the UN [47], would be doing so without sufficient national regulatory oversight. This leaves the State, or Operator, depending on the stage at which a potential incident was to occur, with absolute liability and the burden of undertaking activities which would otherwise be carried out by a regulator, as well as leaving a gap where public assurances are expected.

5.2.2 This shortfall could be addressed with an agreement, or suite of agreements, between the UKSA and ONR. These would document the terms of granting a licence for launching and operating a spacecraft carrying an NPS, and the roles each organisation will carry out during that process. The following agreements could address the current shortfall:

a) An Agency Agreement – A legally binding document [87] that can be used to transfer statutory responsibilities. This would require ministerial approval, but would allow the competent authority to regulate as required. For example:

(i) Agreement that, where the power source for any spacecraft satisfies the conditions that would require it to be produced on a nuclear licensed site, the ONR will act on behalf of UKSA to regulate any Systems Structures or Components that contribute to nuclear safety, throughout the CADMID cycle for that NPS.

b) A Memorandum of Understanding (MoU) – A non-legally binding agreement between two parties to set out their remit and working interface. The ONR have similar arrangements with parties such as the EA, MoD and HSE already. A MoU with the UKSA may cover:

(i) The assurances sought from ONR by UKSA, and by which stage of the development process they would be required. This is considered in more detail in Subsection 5.4.

(ii) Specific detail on the 'handover' process from the manufacturer to the duty holder responsible for the launch and operation of the spacecraft through life.

(iii) Any special transport arrangements (see Subsection 5.6).

5.2.3 Having such agreements in place would provide a standing arrangement that satisfies Section 13, subsection 6d of the SIA and would provide the mechanism for meeting the guidance stated in Paragraph 3.5.3a) of this paper.

5.2.4 Aspects of existing agency agreements and MoUs may also need to be updated to account for minor changes or alterations, and take into consideration factors such as transport and environmental assessments.

5.2.5 There are alternatives to this approach, which could be similar to the DNSR model and introduce a new regulator and/or specific exemptions from statute. However, the legislation is sufficient to avoid any need for exemption, and new agencies are much more likely to introduce further complication with regard to agency agreements and working relationships. Therefore, there is no benefit to taking this approach in preference to placing an additional demand on ONR.

5.3 Fuel Type

Nuclear Fission Reactors

5.3.1 Principle 3 of the international NPS principles (see Subsection 3.4) adopted by UNOOSA sets out the expectation that highly enriched uranium is used for fission reactor systems in space; however, any variation would not change the need to manufacture such a system on a Nuclear Licensed site.

5.3.2 Therefore, regardless of the fuel type selected, a safety case will be required, which will need to consider and define the design basis for assessment, even for accident tolerant fuels or intrinsically 'safe by design' systems (this is also an expectation of UNOOSA principle 3 and 4). Therefore, further consideration of the fuel type for fission reactors is not relevant in the context of this paper.

Radioisotope Thermoelectric Generators

5.3.3 The demand for a Nuclear Licensed site for the manufacture of RTGs is not as clear as for fission reactors, as discussed in Paragraph 4.3.4.

5.3.4 The most common material used in RTGs is ^{238}Pu, which would require a licensed site for manufacture. As would ^{241}A and ^{90}S, assuming bulk quantities, due to their method of production as derivatives of nuclear fuel.

5.3.5 However, ^{210}P can be produced by thermal neutron bombardment of ^{207}B [88]. Such an activity would not require a licence under the NIA. It would only be notifiable to the HSE under the IRR [12] and REPPIR [70] due to working with ionising radiation and storing large quantities of radioactive material respectively [89].

5.3.6 Therefore, careful consideration should be given early in design development to the material being used in any RTGs. Material or fuel selection may significantly impact on the cost, timescale and logistical challenges associated with RTG production. This cannot be done without an understanding of the mission profile or demand of the NPS. Therefore, the recommendation of this paper can only be to ensure early consideration.

5.4 Approach to Licencing

5.4.1 The staged approach UKSA take to licencing [86] compares well to the steps that the ONR set out [60]. This is illustrated in Figure 7.

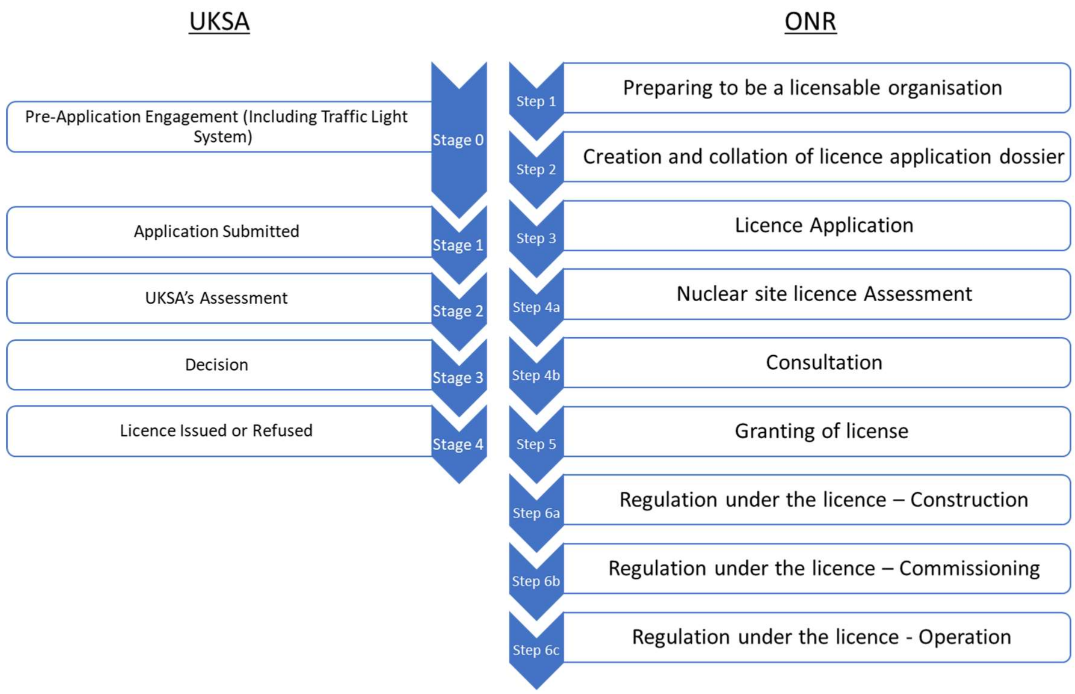

Figure 7 Licencing process mapping between UKSA and ONR

5.4.2 Whist the mapping in Figure 7 covers different applications, if the ONR support UKSA with licensing of NPSs for space (as proposed in Subsection 5.2), it is likely that a similar process will be applied.

5.4.3 Notable differences are, the need for consultation with public bodies and the additional regulation carried out through construction, commissioning and operation. This level of assessment and regulation will be required to meet international guidance as discussed in Paragraph 3.5.3c). Therefore, the approach used by the ONR is appropriate and can be 'read across' to the space industry as long as it is applied proportionately. This should be documented clearly in agency agreements and MoUs between UKSA and ONR.

5.4.4 The unknown factor is the consultation process, which has the potential to introduce significant socio-political concerns. Again, the approach is appropriate considering there is a level of public unease about the nuclear industry, and this would only be heightened by news of a reactor being launched into space, so the issue should be considered and addressed early.

5.4.5 To avoid prolonging the licence application process to the point where launching NPSs from the UK becomes economically impracticable, consultation will need to be carried out independently to specific licence application requests. That is, similar to the GDA consultation process and the consultations that supported the National Policy Statement for Nuclear Power Generation [66], generic NPS designs and locations for launching NPSs could be opened to public consultation early, locations written into national policy and designs agreed with the regulator upfront. This could extend to any licensed sites required at or near space ports to enable the space industry (see Subsection 5.6).

5.5 Mission Imperative

5.5.1 Principle 3 of the principles for NPSs adopted by the UNOOSA sets the requirement to minimise the amount of radioactive material sent into space by demonstrating no other means will do (see Paragraph 3.4.3). This aligns well with the ALARP principle applied in the UK (See Paragraph 4.3.7), and the guidance discussed in Paragraph 3.5.3b).

5.5.2 There are two aspects to addressing these principles for a UK launch. One is relatively simple, in that the operator/licence applicant will need to demonstrate that no other means of providing power is practicable for the mission being carried out. An example of this being achieved internationally is in the US for the Cassini mission. The supporting environmental assessment determined that the size of a solar panel array required for the mission would prohibit the launch vehicle taking off, clearly providing a need for a lighter alternative power source [90].

5.5.3 The second aspect is demonstrating the need to carry out the mission at all. Without something setting the national imperative for launching an NPS into space it will be very difficult to demonstrate that the risk associated with the launch is ALARP. The consultation process for siting of licensed sites, or launch sites for NPSs (as proposed in Subsection 5.4) would go some way to providing this, but a clear statement setting a national objective, would be far more effective in enabling the industry. This has been the approach taken by the US government in a recent statement from the White House [91].

5.5.4 Therefore, while the industry is in the early stages of development in the UK, it is advisable for any UK commercial and regulatory entities looking to be involved in the industry to lobby the UK government for a statement similar to that provided in the US.

5.6 Transportation

5.6.1 The regulations relating to transportation of radioactive material are clear and prescriptive. The terrestrial transportation of any NPS will need to comply with IAEA SSR-6 [67] and would be overseen by the ONR as the Enforcing Authority.

5.6.2 There may be some complexity in meeting the regulations from a technical perspective, depending on whether the NPS is transferred as a standalone unit or integral with the spacecraft being launched. This is likely to depend on the technology and whether it is a satellite or manned spacecraft being launched. However, the logistical arrangements and organisations involved, rather than developing technical solutions, will present an even larger challenge for a prospective company.

5.6.3 If the NPS is manufactured on an extant Licensed site, and either supplied as a fuel cell or assembled as a ‘power unit’, the installation of the fuel, or the ‘power unit’ into the spacecraft being launched would require a prescribed installation under the NIR 1971 [59], therefore, requiring a separate site to hold a licence under the NIA 1965 [11]. This then raises the question of how transportation of the completed spacecraft to the launch site can be carried out.

5.6.4 Without mandating that the launch site become a nuclear licensed site, which would be impractical and, most likely, disproportionate, there would need to be special arrangements made for the transportation of the completed spacecraft from the licensed site on which it is assembled, to the launch site. The IAEA regulations give provision for special arrangements, and state that "*the competent authority may approve special arrangement transport operations for single or a planned series of multiple consignments*" [67]. The ONR also provide external guidance on how to seek approval for such arrangements [92].

5.6.5 The impracticality of meeting the regulations would have to be detailed and agreement to apply alternative arrangements sought from the ONR. The ONR guidance states a requirement to submit a transport safety case in such scenarios, this provides the communication mechanism, and will include all relevant considerations.

5.6.6 It is likely, to limit risk, the ONR would seek to ensure that transportation distances were minimised. Therefore, consideration should be given to apportioning part of any future space port, or immediately adjacent land, as a licensed site.

5.7 Regulation

5.7.1 The requirement in terrestrial nuclear legislation and in the SIA to demonstrate that risks are reduced ALARP, means that it is unlikely a prescriptive approach to safety would be applied for NPSs for space regulated in the UK. As discussed in Section 4 this places the onus on the operator/licence applicant to demonstrate safety SFAIRP.

5.7.2 For any operator or licensee to be able to achieve this, regulatory expectation should be clear. This will allow operators to benchmark their own procedures and requirements against that expectation. Therefore, the ONR will need to compile SAPs that allow adequate regulation of the space industry and consider the context of application in contrast to the terrestrial SAPs.

5.7.3 This can be demonstrated by consideration of the numerical targets described in Paragraph 4.3.5. Targets will differ from terrestrial targets and will need to primarily focus on the risk to the public, as per the ICRP protection objectives referenced in principle 3 of the UNOOSA principles [47].

5.7.4 The targets relating to persons or groups on site (in this case on-board), become largely irrelevant once the point of launch is reached. This is because the doses accrued during space travel far outweigh tolerable doses to classified radiation workers. For example, NASA place a limit of 500mSv annually [93] (which is consistent with UNOOSA principle 3 [47]), compared to 1mSv in the ONR Target 1 for people working with ionising radiation. Therefore, while the presence of a radiation source on board may contribute to a person's dose uptake, setting dose targets would only act to kerb the contribution to the overall limit, as defined by the relevant space authority.

5.7.5 Astronauts are not normally classified as being occupationally exposed to ionising radiation [94], and noting the likely normal operating dose from an NPS, it seems reasonable that the introduction of an NPS shouldn't change this arrangement. There will however, be a need to minimise the dose from the perspective of mission longevity i.e., the higher the doses due to an NPS, the less time an astronaut will be able to spend in space.

5.7.6 On this basis, if the targets were to be 'read across', then all aspects relating to persons on-site can be dismissed as not applicable from the point of launch. This would exclude Targets 1, 2, 5 and 6 entirely.

5.7.7 Target 3 relates to Normal operational dose for those off site. Something that isn't a necessary consideration in space. Therefore, this would also be dismissed.

5.7.8 Target 4 sets the expectation for fault frequencies, depending on the consequence of a postulated fault. The application of this target would directly address the point raised in Paragraph 3.4.4, regarding the definition of ‘low probability’ accidents in UNOOSA principle 3, and the required reliability of systems to achieve this.

5.7.9 Targets 7 and 8 cover risk of death and accident frequency targets for anyone off-site. This is considered on a probabilistic basis and generally means multiple levels of Probabilistic Safety Assessment (PSA) need to be applied. These normally cover PSA for the reactor itself, PSA for breach of containment and PSA in the event that containment is breached. A similar approach would be reasonable and could be applied in this context.

5.7.10 Target 9 ensures that incidents beyond the design basis, i.e., lower than ‘low probability’ are considered as part of the probabilistic assessment. Again, this could be applied in this context and would drive additional measures such as accident tolerant fuel, ensuring outcomes like Nimbus B -1 (Paragraph 2.4.7b)) rather than Cosmos 945 (Paragraph 2.4.9a)), in the event of an accident.

5.7.11 Therefore, it is clear that whilst many of the principles set out in the terrestrial SAPs and TAGs could be read across to regulation for space, specific consideration and benchmarking against international guidance for space needs to be applied to provide a suitable regulatory framework.

5.8 Relevant Good Practice

5.8.1 The application of relevant good practice is essential in being able to demonstrate risks have been reduced ALARP, without having to derive a justification for tolerability of risk from first principles in every instance.

5.8.2 In most instances the application of relevant good practice will easily read across from either the space industry or nuclear industry. However, in some cases the demonstration of practices being relevant may be more difficult because of the technology being used and the cross over between industries. For example, demonstration of the integrity of control and protection systems would need to extend to cover “*highly reliable operational systems*” [47] to transfer spacecrafts into higher orbit at end of life, as per the requirements of UNOOSA principle 3.

5.8.3 Control systems are specifically covered in the ONR TAGs [95][96] and provide guidance to the ONR inspectors regarding what should be expected of a Licensee. In some cases, they also draw out the regulatory expectation of relevant good practise. When considering control systems, the TAG states "*International relevant good practice recognises the difficulty in quantifying software reliability*" [95] and refers directly to IEC 61513 [48].

5.8.4 IEC 61513 [48] provides a framework for assessing the functional safety of Control and Instrumentation (C&I) systems for a nuclear power plant. It is important in this context because the standard is widely applied across the nuclear industry, and requires detailed evaluation and assessment of systems beyond what would be applied for a conventional safety system, including those that contain commercial-of-the-shelf components. Components can be 'prequalified' but the specific application and functional requirements need to be assessed. This becomes more complex for any system or component that uses 'SMART' instrumentation or software, and has driven the development of specific tools and methods across the nuclear industry.

5.8.5 The C&I Nuclear Industrial Forum (CINIF) carries out research and develops methods for use across the nuclear industry, which can be considered relevant good practice. This is confirmed in the ONR GDA close out for the AP-1000 reactor, in which it states "*The use of CINIF's Emphasis tool for the Production Excellence of smart device justification represents established relevant good practice in the UK*" [97].

5.8.6 As mentioned previously (Paragraph 4.3.7a)), whilst the application of relevant good practice is not essential to demonstrating risks have been reduced ALARP, there is a significant amount of research and development that has led to relevant good practice in this application (see Appendix 1 (Section 10)), and providing an ALARP justification from first principles will constitute a heavy burden on any duty holder. It is likely that a similar position will be reached for the space industry because IEC 61513 [48] will be an applicable standard, but the toolset to provide specific application-based assessments will not be available.

5.8.7 For a UK entity looking to operate and launch from the UK, this aspect of relevant good practice must be a high priority consideration when developing C&I systems for NPSs in space. This is because the economic viability of developing a suitable set of tools and methods, to support the ALARP position, needs to be assessed and included in a business case or funding model.

6 Discussion Considering Foreign Launch or Operation

6.1 Introduction

6.1.1 This section is not intended to provide an in-depth review of foreign rules and regulation at a national level, but it will provide relevant information that allows recommendations to be made to a UK entity looking to procure a foreign launch, or to operate from oversees. In some cases, this will require some more detailed discussion of the applicable national regulation.

6.1.2 27 countries currently have national laws and regulations relating to the exploration of outer space [98]. However, not all of these countries have the capability to facilitate a launch. For launches not happening in the UK, the most likely launch locations are either the US or French Guiana. This is because of the likely commercial or governmental partnerships and the preferable geographical location of the launch sites (proximity to the equator). Therefore, this section primarily considers oversees launches and operations in the US or French Guiana (which is governed by French legislation).

6.2 US Regulation

6.2.1 The US has multiple agencies responsible for the regulation and licensing of space activity, with the relevant authority depending on the activity being licensed. In the context being considered here, the activity will be commercial and therefore the following agencies will be involved [99]:

a) Federal Aviation Administration (FAA) – Responsible for the licensing of launches, re-entry, space ports and related activities.

b) Department of State – Responsible for the coordination of international interactions.

c) Department of Commerce – Responsible for the Export Control of space products in the commercial sector.

6.2.2 The Office of Commercial Space Transportation is the part of the FAA that authorises licences. This is done on the basis that the activities being licensed are "*consistent with public health and safety, the environment, national security and US foreign policy*" [99].

6.2.3 The FAA apply a specific rule that defines their launch requirements under the Commercial Space Launch Act 1984 [100], which authorises them in US law as the licence provider. The FAA provide licences for all commercial launches undertaken in the US or by US entities [101] in a similar arrangement to that in the UK's OSA.

6.2.4 The specific rule the FAA apply is the Streamline Launch and Re-Entry Requirements [102]. The rule is split into four parts:

a) Subpart A – Covering detail of the licensing process and definitions of the scope of the licence.

b) Subpart B – Covering a detailed set of requirements for obtaining a vehicle operator licence.

c) Subpart C – Covering safety requirements and criteria. This covers individual and collective risk.

d) Subpart D – Covering the terms and conditions of an operator licence.

6.2.5 The rule provides a significant amount of detail on the expectations and requirements for an operator, or commercial entity looking to launch a vehicle. There are also some specific clarifications and points pertinent to this paper. In addition to the detail provided in the structure set out above, the rule states:

a) That the FAA will evaluate launch or re-entry of radionuclides on a case-by-case basis.

b) That licence applicants must provide details of type, quantity, intended use and a description of all approvals provided by the Nuclear

Regulatory Commission (NRC) for pre-flight ground operations for any radionuclides.

c) That the FAA will work closely with other federal entities to avoid duplicating regulatory effort and requirements. This will be achieved by the production of specific guidance on the topic, which also addresses the requirement set out in the Presidential Memorandum on Launch of Spacecraft Containing Space Nuclear Systems [91].

d) The principle of Equivalent Level of Safety (ELOS). This is a move to a less prescriptive regulatory approach and allows the applicant to demonstrate, by technical reasoning, ELOS for specific aspects of compliance with the rule and licensing process.

6.2.6 As indicated in Paragraph 6.2.5c), by the need to provide definitive guidance, the US has a lot of the same issues to consider as the UK (see Section 5). Ground related operations and transport will be regulated by the NRC, and the FAA the legal authority for licensing the launch, but inter-agency consultations, or further detail of expectations is still required [103]. This is despite historical operational experience of launching NPSs, which will have been considered on a case-by-case basis at the time of launch.

6.3 French Regulation

6.3.1 The regulation of space activity in France, and the territories governed by French law, is covered under the French Space Operations Act 2008 (FSOA) [104].

6.3.2 The FSOA sets out the requirement to gain authorisation from the administrative authority for space operations or launches. This applies to French, or foreign entities looking to launch from French territories, and also for French entities looking to operate or launch abroad. This arrangement is similar to the UK OSA and is in place to ensure the state obligations under international law are met and liability is transferred from the state to the operator.

6.3.3 The conditions of authorisation are also set out. Authorisation relies on demonstrating compliance with Technical Regulations. The regulations provide the following:

a) Confirmation that the Centre National d'Etudes Spatiales (CNES) are responsible for verification against the Technical Regulations and for making recommendations to the French Minister for Space regarding authorisation.

b) Specific technical regulations as follows [105]:

(i) Operator requirements for quality assurance, configuration management and management arrangements.

(ii) Details regarding the expectations for hazard studies and environmental impact assessments.

(iii) Safety objectives for launch and re-entry.

(iv) Safety objectives for uncontrolled re-entry.

(v) Requirements for the mitigation of space debris.

(vi) Requirements for the limitation of collision risk.

(vii) Policy on nuclear safety.

(viii) Environmental policy.

(ix) Launch base interface requirements specific to the Guiana Space centre.

(x) Operational emergency arrangements.

6.3.4 The policy for nuclear safety is defined by the CNES [106]. This clearly covers the requirements for all operators, foreign or otherwise, with regard to the nuclear safety expectations. It gives clarity on the expectations for nuclear safety management and safety requirements through the full CADMID cycle, including ground operations and transportation and the appointment of a Nuclear Safety Representative.

6.3.5 Therefore, France has a level of guidance that currently exceeds that of the UK and US, and can be applied commercially for the space industry.

6.4 Implications for a UK Entity

6.4.1 The technical and logistical challenges faced under French and US regulation with regard to the management of ground operations, transportation and regulatory responsibility are similar to those discussed in Section 5 for the UK. However, both have already considered how their regulatory framework can accommodate NPSs. As discussed in Subsections 6.2 and 6.3, France already has regulations in place and the US has committed to developing guidance in the near future. Therefore, some of the regulatory challenges in enabling the space industry to launch NPSs are easier to overcome than the challenges currently faced in the UK, which may drive foreign launch and operational bases for UK companies.

6.4.2 However, the nature of international space law has the potential to drive complexity into the licencing arrangements for a UK entity. Strict liability on the State means that each state involved in launch or operation in any capacity will require the entity to hold a licence granted by the applicable national authority. Therefore, a UK entity will require two licences in all of the following scenarios:

a) A UK entity procuring a launch from a foreign country but operating in the UK.

b) A UK entity procuring a launch and operating from a foreign country.

c) A UK entity launching and operating as a joint venture with a foreign entity.

6.4.3 The UK licence would be granted under the OSA as discussed in Subsection 4.5, and then by the relevant authority in the partnering nation as discussed in Subsections 6.2 and 6.3. Therefore, if any of the above operating models are being considered, then the points of discussion in Section 5 are equally applicable to a foreign launch as to a UK launch, unless credit can be taken for the prescriptive nature of a partner nation's regulation. It is unlikely that reliance on foreign regulation would be insufficient for a UK regulator [107], or government, noting the international liability legislation. However, as per the convention on international liability for damage caused by space objects (see para 3.3.11 c)), it may be possible. This would almost certainly require an update to the FAA and UKSA memorandum of co-operation that already exists [108], and require new memorandums where they do not already exist.

6.4.4 It is clear that the licencing arrangements could become complex and burdensome with the potential involvement of space regulators and nuclear regulators in multiple nations. Therefore, the scope of supply and associated liability should be considered by a UK entity looking to provide a 'power unit' for use in space.

6.4.5 If an NPS could be supplied as a component (or 'power unit') separately from launch or operation of the spacecraft, then the entity launching and operating would be the one obligated to license the activities. This would require a level of competence (an intelligent customer) in the organisation receiving such a 'power unit', and would require a commercial agreement with regard to liability, but it could significantly simplify the licencing arrangements.

6.4.6 With regard to other aspects of foreign regulation, it is not the intent of this paper to define the full scope of work that needs to be complete. The recommendations in relation to UK regulation should be progressed, and a brief summary of foreign regulation has been provided to enable and encourage early engagement of foreign regulators. This is required to ensure agreements are reached between all parties prior to significant costs being incurred, and should include discussion on the 'scope of supply' and liability that is held through commercial arrangements.

7 Conclusions

7.1 Summary

7.1.1 The international legislation relating to use of nuclear power in space has been considered, including the interface with the terrestrial nuclear industry and consideration of third-party liability. It is clear that while the international legislation does address liability for the full CADMID cycle of an NPS to be used in space, and the liability is absolute in both cases, the application of State liability in space compared to civil liability terrestrially, means that approach to national licencing is different.

7.1.2 The national legal and regulatory framework has also been considered for both the nuclear and space industry, and compared to the international conventions and guidance, to ascertain the most appropriate way for the UK to satisfy its international obligations. This identified a couple of specific examples of relevant good practice where specific technology or the application of ALARP is particularly relevant to the nuclear space industry.

7.1.3 The review has highlighted that there are currently a number of shortfalls in the UK regulatory framework. These would need to be addressed to allow the UK space industry to take advantage of nuclear power in space. The shortfalls have been highlighted throughout, but pertain mainly to the provision of regulatory expectation and inter-agency agreements. This in turn would allow any prospective duty holder to clearly develop a business case and technological capability with a high chance of being able to deploy that technology successfully. This includes clarity of responsibility for licencing and the expectations on a duty holder at each stage.

7.1.4 There are also huge logistical challenges in growing the UK nuclear space industry. The need for nuclear licensed sites and transport safety cases is fundamental to enabling the industry.

7.1.5 The potential for a UK entity to launch, jointly launch or operate from a foreign country has also been considered, with the focus on the most likely countries to provide a launch location. This has highlighted the distinct differences between the terrestrial nuclear industry and the space industry, with a requirement for multiple licences to be issued by each State involved in the launch. However, the US and France have a far more mature national regulatory framework for the use of nuclear power in space. This at least, provides some clarity on foreign expectations, and at best provides a framework that can be learnt from.

7.1.6 In the context of joint enterprises with foreign entities it will be important to consider the scope of supply and nature of the partnership to ensure that the licencing requirements are clear.

7.1.7 This paper looks to draw out pertinent recommendations for a UK entity entering into the nuclear space industry, and as such, recommendations have been made based on the discussion throughout.

Recommendations

7.1.8 The recommendations to a UK entity looking to launch and operate a satellite or spacecraft from the UK under a licence granted by the SIA can be split into two categories. The first set of recommendations focus on the legal and regulatory framework that needs to be in place to enable such operations. The second set is focused on recommendations directly applicable to a UK entity.

7.1.9 Further to the UK focused recommendations; recommendations to a UK entity looking to launch or operate from outside the UK (US or French Guiana) fall into a third category. All recommendations are presented in turn in Subsections 7.2, 7.3 and 7.4.

7.2 Enabling Recommendations for UK Regulation

7.2.1 The following recommendations are made to a UK entity, with the intent of putting focus on the shortfalls in the current regulatory or legal framework that will need to be addressed, this will generally require lobbying regulators or authorities. Therefore, this paper recommends that the entity should:

a) Lobby for ONR and UKSA to put in place Agency Agreements and MoU which clearly set out the responsibilities of both regulators throughout the CADMID cycle. This should include the conditions and arrangements for granting a licence for NPSs to be used in space. (See Subsections 5.2 and 5.4)

b) Lobby for the production of SAPs specific to the nuclear space industry so that regulatory expectations can be clearly understood and communicated. Including consideration of relevant good practice for control systems in the nuclear space industry. (See Subsections 5.7and 5.8).

c) Propose and request, to all relevant regulatory bodies, consideration of a 'GDA style' assessment that would enable a generic design to be assessed and licensed. (See Subsection 5.4).

d) Lobby the Government to provide a statement of national imperative for NPSs in space. (See Subsection 5.5).

e) Request that consultation on launch site locations (including any requirement for nuclear licensed sites) be carried out by a government body and selected sites defined in national policy. (See Subsections 5.4 and 5.6).

7.2.2 It is worth noting at this point that both the ONR and IAEA provide a mechanism for commenting on policy [109].

7.3 Implementation Recommendations (UK Based)

7.3.1 The following recommendations are made to a UK entity. The recommendations do not cover all work that needs to be carried out, but do highlight issues that will be significant, or have high importance with regard to successfully being granted a licence without prohibitive costs being incurred. Therefore, this paper recommends that the entity should:

a) Define the operational requirements and develop a clear mission profile. (See Subsection 5.5).

b) Make and justify fuel selection early, based on the mission profile and operational requirements. (See Subsections 5.3 and 5.5).

c) Consider the logistical arrangements for ground operations and transportation of an NPS 'power unit', so that a transport safety case can be developed if required. (See Subsection 5.6).

d) Develop their own arrangements and processes to ensure safety throughout the full CADMID cycle for any NPS. (See Subsection 5.8).

e) Consider the application of relevant good practice for control systems, such that tools and methods can be developed or sourced suitable for the nuclear-space industry. (See Subsection 5.8).

7.4 Implementation Recommendations (Non-UK Based)

7.4.1 The following recommendations are made to a UK entity looking to procure a launch, or operate a spacecraft containing NPSs from a foreign country (US or French Guiana). Similar to the recommendations made in Subsection 7.3, they do not cover all necessary work, but do highlight issues that will be significant, or have high importance with regard to being successful without prohibitive costs being incurred. Therefore, this paper recommends that the entity should:

a) Define the 'scope of supply' and the boundary of liability for all commercial partners. This will inform licensing arrangements. (See Subsection 5.5).

b) Engage with foreign regulators early to ascertain whether the commercial model being proposed is understood and acceptable to all parties. (See Subsection 6.4).

7.4.2 It should also be noted that all UK based implementation recommendations (Subsection 7.3) will also need to be progressed, even in the context of foreign launch or operation.

7.4.3 The recommendations presented in Subsections 7.2, 7.3 and 7.4 cover all necessary considerations with regard to licencing and regulation for a UK entity entering into the nuclear-space industry at the time of writing. Implementation of these recommendations will support the development of the UK space industry and enable nuclear power as a means of increasing the provision of power in space.

8 Abbreviations and Acronyms

ALARP	As Low As Reasonably Practicable
BUK	Also known as Bouk or BES-5 Reactor
C&I	Control and Instrumentation
CADMID	Concept, Demonstration, Manufacture, In-service and Disposal
CNES	Centre National d'Etudes Spatiales
CINIF	C&I Nuclear Industrial Forum
COPUOS	Committee on the Peaceful Uses of Outer Space
CPLA	Committee, Policy and Legal Affairs Section
DNSR	Defence Nuclear Safety Regulator
DSA	Defence Safety Authority
EA	Environments Agency
EAEC	European Atomic Energy Community
ELOS	Equivalent Level Of Safety
FAA	Federal Aviation Authority
FSOA	French Space Operations Act
GDA	Generic Design Approval
HSE	Health and Safety Executive
HSWA	Health and Safety at Work Act
IAEA	International Atomic Energy Agency
ICRP	International Commission Radiological Protection
IRR	Ionising Radiation Regulations
ISRU	In-situ Resource Utilisation
KRUSTY	Kilowatt Reactor Using Sterling Technology
MoD	Ministry of Defence
MoU	Memorandum of Understanding
NASA	National Aeronautics and Space Administration
NFR	Nuclear Fission Reactor
NIA	Nuclear Installations Act
NIR	Nuclear Installation Regulations
NPS	Nuclear Power Source
NRC	Nuclear Regulatory Commission
ONR	Office for Nuclear Regulation
OSA	Outer Space Act
PSA	Probabilistic Safety Assessment

REPPIR	Radiation (Emergency Preparedness and public Information) Regulations
RHU	Radioactive Heater Unit
RPS	Radioactive Power Source
RTG	Radioisotope Thermoelectric Generator
SAP	Safety Assessment Principle
SFAIRP	So Far As Is Reasonably Practicable
SIA	Space Industries Act
SNAP	Space Nuclear Auxiliary Power
TAG	Technical Assessment Guide
TOPAZ	Thermionic Experiment with Conversion in Active Zone
UKSA	UK Space Agency
UN	United Nations
UNOOSA	United Nations Office for Outer Space Affairs
UN-SPIDER	United Nations Platform for Space Based Information for Disaster Management and Emergency Response

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10 Appendix 1 – EC&I Research Topics

10.1.1 This appendix provides details of on-going research being carried out by CINIF. As CINIF is a privately funded research consortium, details of the output of the research are not publicly available. However, ONR provide technical input to this research, therefore details of what is being researched and support by ONR are available.

10.1.2 Due to the lack of available detail of the research output, it is difficult to assess whether a specific topic could be directly applied to the nuclear-space industry. However, in all instances, it provides an indication of how relevant good practice is being developed for the terrestrial nuclear industry. It is the determination of relevance and, if required, the development of specific practises that will need to be undertaken as future work by any UK operator or licensee.

10.1.3 All of the following information in this appendix has been taken directly (word for word) from the ONR Progress Status Report [l]. It is provided for information and is not an original output of this paper.

ONR-RRR-006: Justifying High Integrity Smart Devices (FEAST)

10.1.4 FEAST is an ongoing industry initiative sponsored by the Control and Instrumentation Nuclear Industry Forum (CINIF). Feast is investigating static analysis techniques that could be deployed to assess the software of smart devices used in safety related applications. This research project is improving the definition of relevant good practice and thus supports tests of reasonable practicability. IRR and other underlying regulations.

ONR-RRR-038: Emphasis Tool

10.1.5 EMPHASIS assessment is the preferred approach to justifying the production excellence of smart devices in the UK. The process is maturing but there remain issues to be addressed. Maintenance of EMPHASIS and improving the documentation supports ONR's core purpose of regulating the hazards arising from the UK's existing operational nuclear sites, waste storage and decommissioning facilities.

ONR-RRR-039: Field Programmable Gate Array Guidance

10.1.6 The use of Field Programmable Gate Arrays presents some novel aspects that sets them apart from more familiar programmable devices. The verification of these components is therefore an area that requires investigation in order to establish relevant good practice for the justification of their use in nuclear safety applications.

10.1.7 The objective of this research project is to explore the availability and suitability of static and dynamic analysis techniques and tools for the verification of FPGAs across the whole integrity range.

ONR-RRR-040: Effects of Neutron Irradiation from Solar Storms on C&I Equipment

10.1.8 This research project has the objective of examining the effects of neutron irradiation on the electronic components used within ground-level control and instrumentation (C&I) electronics in the nuclear industry. In particular, it is intended to consider the potentially large increases in neutron flux that could occur during extreme 'ground level events' caused by severe solar storm.

ONR-RRR-095: Agile Development Process for Smart Devices

10.1.9 Agile development process for smart devices (ADEPT) applies an approach that follows the Agile Manifesto and the 12 principles of the Agile framework.

10.1.10 Agile development process involves incremental and iterative propagation of features. Each iteration is made up of a number of phases, progressing from the requirements definition, through design, implementation and testing with a set of questionnaires that intend to be consistent with the IEC61508's software development lifecycle that demonstrates the V-model.

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