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CONSIDERATIONS FOR THE TRANSPORTATION OF SEALED SMR CORES

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ABSTRACT – Small modular reactors (SMRs) are being considered as alternatives to large nuclear power plants (NPPs) for various applications, including deployment in off-grid and edge-of-grid locations. While being based on mature technological research and operating experience from previous NPPs, the technology is still in the early stages of development and is novel by nature. As such, a number of knowledge gaps need to be addressed including packaging and transport of fuel. This work presents an introductory overview of considerations for the transportation of fully-sealed cores, which is one novelty of some SMRs designs, focusing on transport within Canada and prior to any irradiation of components or fuel.

Introduction

As an alternative to large nuclear power plants (NPPs), small modular reactors (SMRs) are being considered for various applications that include deployment in off-grid and edge-of-grid locations or where power generators need to remain below a specified power threshold, district heating, or generation of process heat. While there are a number of vendors who have expressed interest in construction and deployment of SMRs within Canada, the technology is still in the early stages of development and is novel by nature, despite being based on mature technological research and operating experience from previous NPPs. As such, there exist a number of knowledge gaps that need to be addressed, including packaging and transport of the fuel and reactor components.

The intent of this work is to present an introductory overview of considerations for the transportation of fully-sealed cores, which are being employed in a number of SMR designs for the purpose of enhancing proliferation resistance and modularity. It should be noted that the scope of this work has been limited to transport within Canada and the United States of America. International transport outside of those countries is to be addressed at a later time.

1. Current Transport Practice

Prior to discussion of factors that need to be considered for transportation of sealed SMR cores, a quick review of the governing regulations and current transport practice for nuclear material provides a convenient point of reference for comparison.

1.1 Governing regulations

The key legal instruments governing transport of nuclear material within Canada are the Transport of Dangerous Goods (TDG) Regulations [1] and the Packaging and Transport of Nuclear Substances (PTNS) Regulations [2]. The TDG Regulations set out the general requirements for shipment of hazardous materials, with radioactive substances being defined as Class 7 materials. As per the TDG Regulations, the specific requirements for transport of nuclear material are specified within the PTNS Regulations, where additional transport requirements for equipment related to the use or processing of nuclear material are also set out. Additionally, the IAEA Regulations for the Safe Transport of Radioactive Material [3] provides an international framework for transport legislation that is reviewed and updated regularly. While worthy of consideration, the IAEA regulations do not supersede the TDG Regulations or the PTNS Regulations, which are the legally binding regulations governing transport of radioactive material within Canada.

1.2 Transport packages

With regards to transport, the fundamental concept is that safety is primarily assured through the design of the packaging, which must protect the worker, the public, and the environment in all foreseeable operating and accident scenarios. Notably, it is the consignor who is predominantly responsible for ensuring safety during transport. This is partly achieved through appropriate selection or design of the transport package, which must meet certain performance requirements as set out in the regulations.

There are seven categories of packages: Excepted, Industrial (I, II, and III), Type A, Type B, Type C, Type H, and Fissile Material. These classifications are generally based on the activity and physical form of the radioactive material that would be contained within the package, with greater radioactivity requiring a more robust package. While the first three categories are considered pre-approved packages that only need to meet the general requirements and pass select tests, the latter four require certification by the Canadian Nuclear Safety Commission (CNSC) and have more stringent requirements. As per the PTNS Regulations, these requirements and the radioactive content limits for the different package types are laid out within the IAEA Regulations, with the categorization of nuclear material provided in the Nuclear Security Regulations [4].

Typically, fresh or spent fuel is transported within a Type B or Fissile Material package. While it is expected that the current transport practice and certified packages could be acceptable for SMR designs utilizing conventional fuel types (i.e. fuel rods/bundles), transport of a sealed, fully-fueled reactor core poses a number of additional challenges and represents a significant knowledge gap. The only prior experience transporting a fully-fueled core is with SLOWPOKE cores, although that scenario is not suitable for comparison given the exceptionally compact dimensions, low inventory and design power, and overall inherent safety and self-regulating nature of the SLOWPOKE design [5].

2. Transport of Sealed SMR Cores

As with current practice, the primary concern with transportation of a sealed SMR core will be demonstrating that all phases of the process can be conducted safely; from pre-shipment evaluation of functionality, to transport of the core, to confirming acceptable condition, and to the subsequent deployment on site. The following are some notable considerations arising from the overriding concern for safety, but should not be considered an exhaustive list.

2.1 Noteworthy considerations

Shipment of a sealed core will need to occur in accordance with the PTNS Regulations, and will require transport within a certified package. The total fuel inventory, level of enrichment, and fuel type will dictate the acceptable packages. It is possible that the reactor vessel itself could act as the fuel pack, but this is considered to be significantly more challenging to accomplish than use of a certified package. However, should this be the desired approach, the reactor itself would need to undergo all testing as required by the PTNS Regulations to become a certified package, and such a design decision would need to occur in the very early stages of development. Use of a package that is currently certified offers the most straightforward pathway to licensing transport of sealed SMR cores.

Regardless of approach chosen, the fundamental concept remains; safety is primarily assured through the transport package. It must be able to provide sufficient containment and shielding for all contents in all expected scenarios, and should be fully compatible with the fuel and coolant chosen for the selected SMR design. For example, additional challenges will be present should the contents include any pyrophoric materials. To address any compatibility concerns that arise from the selected fuel or coolant, alternative packaging materials to the typical stainless steel construction currently used could be suitable. However, care must be given to ensure that the candidate material has suitable pedigree and supporting analysis for use in a transport package. As might be expected, demonstrating sufficient package safety will be simplest for solid fuels and water coolant or moderator.

Physical protection of the nuclear inventory must also be thoroughly assessed. In general, “it is [currently] believed that the application of existing physical protection recommendations… remain valid and sufficient to address known concerns [6].” However, any measures of proliferation resistance that can be implemented will enhance the case for licensing of the transport package or activity. Protection from theft or radiological sabotage is the primary concern, which can partly be addressed by mechanical means or selection of inherently proliferation-resistant fuels. Utilizing lower levels of enrichment reduces the attractiveness of the nuclear inventory, and should be considered if possible. Furthermore, the back-end transport scenario warrants additional consideration as “both external (in the form of explosives) and internal (residual heat and pressure) energies may be used by the adversary to expose or damage the core [6].” This is especially important for integral reactor designs, which would contain a significantly greater number of irradiated, and possibly radiation-weakened, components.

Above all, ensuring that the fueled core remains subcritical is the paramount concern. It has to be demonstrated that under both normal transport and all postulated accident scenarios there is no possibility for a critical arrangement to be achieved. While this is possible by mechanical means such as removing control rod drives or physically securing the rods, any inherent measures of safety that can be implemented will further enhance the case for licensing of the activity. For example, the reactor could be designed such that it is only possible to achieve critically on-site during the commissioning phase by the installation of a separate component. The issue of criticality during back-end transport will also need to be thoroughly considered and addressed.

2.2 Case study: Molten Salt Reactor

As an example of how the aforementioned considerations, among others, can be addressed simply through the reactor design, consider a Molten Salt Reactor (MSR). With regards to material compatibility, it may be possible to simplify selection or design of the package through the choice of salt. Some fluoride salts are chemically stable, which allows for a wider selection of package material. That choice is broadened further by the ability to utilize Low Enriched Uranium (LEU), with as low as ~1.5% being practical. While use of LEU also has the added benefit of being relatively unattractive with regards to proliferation, that concern is further addressed by the nature of the fuel-salt mixture, which would be solid in any non-operational scenario and requires significant infrastructure to reprocess. The combination of a highly radioactive primary fuel-coolant loop and high operating temperature by design would also require special shielded or insulated cells to be utilized, improving resistance to proliferation and sabotage [7].

Criticality control is aided by both redundant features as well as the nature of the fuel. Use of flow-driven control rods that are naturally inserted unless there is forced convection of the fuel-salt mixture enhances the safety of the design in both transport and operational scenarios. It is also expected that until commissioning, the fuel mixture would be solid and located within the core such that a critical arrangement is not possible. With some of the proposed MSR salts having melting temperatures greater than 400 ^{o}C, maintaining the subcritical arrangement during transport is almost certain [8]. This also reinforces the notion that containment during any proposed accident scenarios is significantly easier to ensure, and even more so should an integral reactor design be utilized.

3. References

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