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Advanced micro-reactor concepts

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ABSTRACT

Nuclear power systems capable of outputting low powers (< 100 MWth) are increasingly receiving interest internationally for deployment not only as electricity production systems, capable of operating off-grid, but also as systems able to provide industrial process heat. These 'micro-reactor' concepts must demonstrate economic competitiveness with other potential solutions capable of providing similar power outputs. With this in mind, reactor technologies that offer inherent advantages associated with improved power density and simplified operation, both of which are important attributes that determine economic competitiveness, are reviewed in the context of the fundamental safety functions provided by the IAEA.

The reactor technology chosen based on the results of the review were: low vapour pressure coolants like molten salt or liquid metal; solid moderator material; and conventional solid UO_2 fuel. Initial infinite lattice neutronic studies indicated a series of positive reactivity coefficients. A finite system was also modelled using a molten salt as the coolant. When modelling the finite system the coolant temperature reactivity coefficient became negative, the void coefficient strongly negative and moderator temperature coefficient negative to weakly positive. Given that a number of reactivity coefficients were negative to strongly negative in the finite system, the weakly positive moderator temperature coefficient is not thought to be prohibitive. Thus the design should exhibit acceptable safety performance.

Whilst the importance of leakage in fast reactor cores is well known, a key outcome from this study is the strong influence of leakage on all safety related parameters for the thermal reactor designs considered here with solid moderator material. Thus it seems that safety studies for such small cores should be based on full core calculations instead of the traditional infinite lattice studies for fuel assemblies.

1. Introduction

There is an increasing interest, globally, in small reactors (< 300 MWe) that are designed to be assembled, as far as is practical, in a factory setting. These so-called Small Modular Reactors (SMRs) have been discussed extensively elsewhere (OECD-NEA, 2016; Vujićet al, 2012; IAEA, 2016). Briefly, apart from being ideally suited to customers with smaller power requirements, the benefits SMRs may offer are: increased flexibility with respect to siting; improved safety performance; reduced construction times; and reduced upfront investment requirements. The challenges facing SMRs relate to development costs; uncertainty surrounding licensing (especially for innovative technologies that regulators are less familiar with); and uncertainties surrounding economic competitiveness, in terms of cost per kWe.

Many of the SMRs have power outputs ~100 MWe, with the intention of placing multiple units together to allow for electricity production around 500 MWe and sharing of facilities (such as turbo-generator units) to reduce costs. Therefore, the primary purpose of these systems is to provide electricity to the grid. It should be noted that as power plants are grouped together, this limits siting flexibility. However, to operate systems with a small combined power output (< 200 MWe), bespoke turbo-generators would be required.

There has also been recent interest in mobile floating nuclear power plants. Two recent noteworthy examples are: the ACPR50S, which is a 60 MWe reactor, being developed for the supply of electricity, heat and desalination; and the Russian Akademik Lomonosov plant which uses two 35 MWe reactors (WNN, 1301). Besides the Akademik Lomonosov plant, several new designs are investigated for autonomous power supply in Russia (Goltsov et al, 2016).

Some SMRs are focused on producing even lower power outputs and are targeted at industrial power facilities or remote locations where there is no grid available. Furthermore, these low powered systems intend to take the safety performance benefits of many SMRs further by achieving indefinite decay heat removal. These smaller variants of SMRs are sometimes termed micro-reactors (NNL, 2014).

Micro-reactors, being a subset of SMRs, share the same challenges

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listed above but the most profound will be the issue relating to cost per kWe since micro-reactors will lose almost entirely the benefits attributable to scaling of power to improve economic performance and, if not appropriately designed, the operation and maintenance (O&M) costs could make these low power nuclear reactors formidably expensive. However, it must be remembered that for micro-reactors, the comparison should not be with large nuclear reactors but with the technologies that are often used to provide such small amounts of power, e.g. diesel generators or small gas turbines.

Unlike in the case for SMRs, where there is a broad agreement in the literature regarding power output (< 300 MWe), there is no comparable definition for micro-reactors. Given that many micro-reactors are focused around industrial power requirements and process heat applications, micro-reactors are thus defined here as having thermal powers < 100 MWth. This definition is based solely on the fact that industrial power generation units typically have outputs of up to 50 MWe (The Committee on Climate Change, 2010; Viessmann, 2015) and some advanced micro-reactors claim thermal efficiencies ~40% (Smith et al., 2008).

The purpose of this investigation was to consider what technologies are capable of taking advantage of the inherent benefits attributable to micro-reactors (easier decay heat removal) whilst also meeting the requirements related to improved economic performance (reducing capital and O&M costs).

2. Choice of technologies

For any nuclear reactor system it is vital that the system is able to demonstrate that: the fuel is adequately cooled; reactivity can be controlled; and radioactive material is confined (International Nuclear Safety Advisory Group, 1999), see Fig. 1. Meeting these multiple requirements, defined in the fundamental safety functions provided by the IAEA, always adds to the complexity, and therefore cost, of the system.

2.1. Controlling reactivity

The neutron spectrum ultimately governs the overall difficulty in achieving adequate reactivity control and the required fissile concentrations in the fuel (with the cycle lifetime being of secondary importance). With fast spectrum systems, high fissile concentrations are required due to the low fission cross-section of fissile material at high neutron energies (~1/100th compared to thermal neutron energies).

Energy production per unit volume (E) is given by:

$$E = \phi \cdot \kappa \cdot \Sigma_{fiss}$$

where ϕ is the neutron flux ($cm^{-2}s^{-1}$), κ is the average energy released per fission event (J/fission) and Σ_{fiss} is the macroscopic fission cross-section (cm^{-1}). Therefore, to achieve high energy production within a small core the choices are:

- to increase the flux level, which results in degradation/neutron damage of core materials; and/or
- to increase the fissile content, which has negative implications regarding cost of enrichment, proliferation and safety. Moreover, in the case of high concentration plutonium fuel, there is limited information regarding the suitability of manufacturing such fuel using current processes and, for uranium fuel, the 20 wt% enrichment limit must be obeyed (Glaser, 2006); and/or
- to adopt a neutron energy spectrum that favours the thermal end of the spectrum such that the integrated value of Σ_{fiss} is maximised.

A further difficulty in fast reactor systems is the inherent difficulty associated with reduced negative feedback effects, compared to LWRs, and the reactor kinetics associated with the comparably short neutron generation time. Furthermore, since high fissile concentrations are required in a fast spectrum, which almost inevitably forces designers to employ MOX fuel, with significant ^{239}Pu content, the delayed neutron fraction is reduced. Therefore, a thermal spectrum system was selected.

By operating a liquid metal, or molten salt cooled system with a thermal spectrum, some of the inherent challenges with fast spectrum systems, such as core compaction, (whereby, in a fast spectrum system, fuel densification increases system reactivity, whereas in a thermal spectrum system reactivity reduces) and sufficient shutdown margin, would be removed. Furthermore, there exists the possibility of utilising a liquid injection system to act as a diverse shutdown mechanism, which is not normally possible in fast systems due to the weak fast neutron absorption properties of almost all absorber materials in a fast neutron spectrum.

2.2. Cooling the fuel

The most important design choice that impacts heat removal aspects is the selected coolant medium. A coolant should preferably exhibit a high volumetric heat capacity (product of density and specific heat capacity) and no phase change during normal and accident conditions.[1] Furthermore, for economic reasons, the coolant should: exhibit low neutron absorption; possess a low pressure at operational temperatures; exhibit limited activation in the presence of neutrons (thereby reduce shielding requirements); be chemically compatible with core and structural materials; and have good thermal conductivity (the latter enabling high power density operation). The coolant options most reactors utilise fall into the following groups:

- Water, with light water being the preferred coolant option due to its low cost and the ready availability of the required enriched level of uranium on the open market. The main drawbacks associated with water as a coolant are the inevitable need to operate at high pressure (due to the steep vapour pressure curve) to achieve sufficiently high temperatures for electricity production, the need to use a large volume of water to achieve indefinite decay heat removal and a containment with a considerably large volume when the system pressure is high (Morozov and Soshkina, 2008). All of these drawbacks result in significant economic penalties.
- Light liquid metals, with most experience associated with sodium. The main benefits of sodium are its excellent heat transfer capabilities at atmospheric pressure and its compatibility with a variety of materials that have been well-tested in nuclear reactors, along with the extensive operational experience gained with this coolant medium (> 400 reactor-years of operation) (Merk et al., 2015). The drawbacks related to sodium are mainly associated with its chemical reactivity with air and water, the difficulty in achieving a negative void coefficient, and its opacity, which makes in-service inspection and repair (ISI&R) challenging relative to transparent coolants (Baque et al., 2013).
- Heavy liquid metals, with historic experience heavily focused on lead-bismuth eutectics (LBE). Lead-based coolants are not strongly exothermic with air or water and have very high boiling points. However, their drawbacks relate to their ability to corrode and erode materials in a nuclear reactor and their high density making ISI&R even more difficult than sodium (IRSN, 2015). LBE has a much lower melting point than other lead-based coolants but it has a significant drawback associated with the production of highly active, volatile polonium compounds. Therefore, there is an increasing interest to move away from LBE to pure lead coolants.

[1] A phase change associated with a coolant that exhibits a strong negative void effect can be an important safety-related feature associated with reactors that struggle to maintain negative reactivity coefficients under normal and accident conditions. However, this advantage needs to be considered against the disadvantages associated with impaired heat transfer once the phase change has occurred and stresses imposed on structural materials associated with the increase in system pressure.