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Comparative economic analysis of the Integral Molten Salt Reactor and an advanced PWR using the G4-ECONS methodology

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ABSTRACT

The assessment of economic viability of a new reactor concept is crucial particularly during the early stages of its concept development. The G4-ECONS methodology provides a standardized top-down estimate of electricity cost and parametric sensitivities, not specifically targeted toward an accurate prediction of the final cost when deployed, but rather seeking an approximation of cost variations relative to other systems. This study presents an analysis of the Integral Molten Salt Reactor (IMSR) concept in comparison with a consistent analysis of an advanced PWR reactor (represented by AP1000). Estimation of levelized unit electricity costs, as well as sensitivity analyses to the discount rate and uranium or SWU prices, are presented using this methodology.

1. Introduction

The goal of this study is to provide a comparison of a top-down estimation of electricity cost between a molten salt reactor (MSR) design and a modern advanced PWR. It does not aim to provide an accurate estimate of the MSR's levelized unit of electricity cost (LUEC), but rather, to generate a standardized comparison to a modern PWR's LUEC estimate using openly available information and sources. By consistently using the same methodology for a PWR and the MSR, the goal is to help reasonably establish the relative economic viability and competitiveness of the MSR concept.

The methodology herein employed was developed by the Economic Modeling Working Group (EMWG) of the Generation IV International Forum (GIF) in order to integrate economic evaluations in the early stages of the Generation IV design development and to help to guide the economic goals established by the GIF. Early developmental stages call for a simplified cost estimating methodology suitable for various kinds of nuclear systems. The methodology is described in detail in the *Cost Estimating Guidelines for Generation IV Nuclear Energy Systems* (The Economic Modeling Working Group Of the Generation IV International Forum, 2007) and implemented in the G4-ECONS software package available from the OECD Nuclear Energy Agency in Paris (The Economic Modeling Working Group Of the Generation IV International Forum., 2008).

Cost estimations of three versions of the Integral Molten Salt Reactor (IMSR) and the Advanced Passive PWR (exemplified by AP1000) are presented in this article. The IMSR is a modular graphite-moderated MSR burner with an unconventional safety system. Three versions of IMSR with different power levels (32.5 to 291 MWe) are being developed by a Canadian company Terrestrial Energy Inc. According to the company the reactors are expected to be ready for commercial deployment by the early 2020's. Therefore, the AP1000 was chosen as a reference Generation III + design which is expected to be a competitor of the IMSR in a future market. It should be emphasized that the published IMSR data necessary for economic calculations are scarce which necessitated approximations and using data from other relevant sources. Therefore the IMSR costs estimates are rough approximations and the respective results are preliminary.

2. Methodology

The *Cost Estimating Guidelines for Generation IV Nuclear Energy Systems* is a document created by the Economic Modeling Working Group (EMWG) of the Generation IV International Forum (GIF). The purpose of this document is to provide a standardized cost estimating protocol for assessing and comparing future energy systems. It provides a set of assumptions, code of accounts (COA), cost estimating guidelines and it is accompanied by the G4-ECONS software

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(Generation IV Excel Calculation of Nuclear Systems), which is a Microsoft-Excel-Based model designed on the basis of the above noted guidelines.

The model employs relatively simple, though fundamental, economic algorithms which give the user the opportunity to avoid country-specific economic factors such as taxation, cost-accounting, depreciation or capital cost recovery methodologies. The basic assumptions of the model include constant-dollar levelized annual cost, cash flow levelization, capital and financing costs repaid over the operating life of the plant or constant annual electrical production over the life of the plant.

The calculated LUEC, or levelized unit product cost (LUPC) for other energy products such as hydrogen, consists of four main components: recovery of capital (including financing costs), non-fuel operation and maintenance (O&M) costs, fuel cycle costs, and funding of decontamination and decommissioning (D&D) costs, as illustrated within the flowchart presented in Fig. 1, and described in the subsections that follow.

2.1. Recovery of capital

The total capital cost (TLCC) consists of two components: overnight cost (COVNT) and the interest during construction (IDS). The overnight costs consist of direct and indirect costs which are partitioned by COA system, owner's cost and contingency.

The interest during construction is the portion of the TLCC which depends on the duration of the plant's construction together with other front-end activities, their timing and the discount rate. This model uses a simple quarter sine-wave function (S-curve) approximation for cumulative expenditures over the project's front-end. The model converts the TLCC into annual amortization ($M/year) by multiplying the TLCC by the simple fixed charge rate (CRF) described by Eq. (1):

$$CRF = i/[1-(1+i)^{-L}], \quad (1)$$

where i is the annual discount rate and L is the plant operating lifetime in years.

2.2. Non-fuel operation and maintenance costs

The annual nonfuel O&M costs are split into specific COA categories. The O&M contribution to the LUEC is the annual O&M costs divided by the annual electrical production in kilowatt-hours.

2.3. Fuel cycle cost

The fuel cycle cost calculation assumes that all the fuel reloads during the plant operation are identical, in other words, it assumes to have reached an operational steady state referred to as an "equilibrium cycle". The fuel cycle's contribution to the LUEC is simply a sum of the annualized "constant dollar" cash flows of all fuel cycle steps divided by the annual electricity production in kilowatt-hours. The first fuel load is added to the total capital cost in this calculation. The model provides three fuel cycle scenarios: the open fuel cycle, partial recycle, and total recycle. However, only the open (i.e., "once-through") fuel cycle was used in calculations presented in this paper.

2.4. Decontamination and decommissioning cost

The D&D costs are annualized in a similar way like the TLCC. The annual payment into the sinking fund is a constant dollar lump sum estimate of what is required at the end of plant life as D&D costs according to regulatory requirements (CDD) multiplied by the sinking fund factor (SFF), as described below by Eq. (2):

$$SFF = i/[(1+i)^{L}-1], \quad (2)$$

where i is the annual discount rate and L is the plant operating lifetime in years.

3. Considered reactor designs

3.1. Reference LUEC for system 80 + PWR

Some test applications were carried out during the G4-ECONS (Version 1.0) development with results presented in The Economic Modeling Working Group Of the Generation IV International

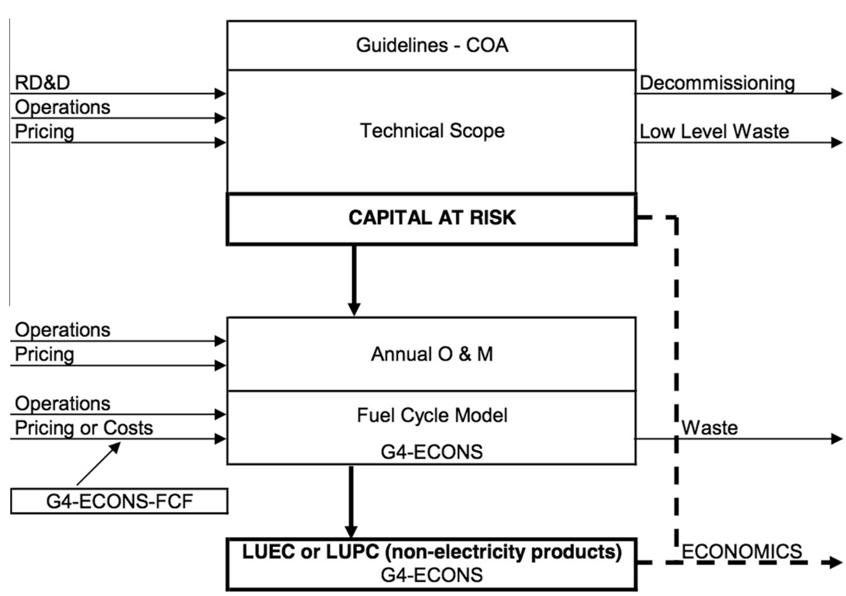

Fig. 1. Structure of the integrated nuclear energy economic model (INEEM) (The Economic Modeling Working Group Of the Generation IV International Forum, 2007).