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An Optimal Allocation between R&D and Prototype Funding:

The Case of Generation IV International Forum's Nuclear Energy Initiative

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Abstract

National Research Council of the National Academies, *Prospective Evaluation of Applied Energy Research and Development at DOE (Phase One): A First Look Forward* (2005) proposes a cost-benefit methodology to evaluate U.S. Department of Energy's Research, Development, and Demonstration (RD&D) programs. This paper develops the methodology for nuclear energy programs. The RD&D process is analyzed in two stages with two success probabilities: (1) that the technology will transition from the R&D Stage to the Prototype Demonstration Stage, and (2) that the technology will be adopted commercially. It models discounted expected total benefits of an RD&D program as a function of the levels of funding, stage durations, the probabilities of success, and spillovers to other technologies. Project duration is an exponential function of funding. Project success is a logistic function of funding and uncertainty. Spillovers are linear functions of funding at each stage. This specification allows calculation of the marginal effects of changes in funding on discounted expected total benefits for a single technology. The paper uses this method to offer an optimal allocation of pre-prototype R&D funding in the development of the Generation IV International Forum's advanced nuclear energy systems under a specific parameterization and funding constraint.

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1. EVALUATING THE BENEFITS OF ENERGY RESEARCH, DEVELOPMENT, AND DEMONSTRATION

National Research Council of the National Academies (2005) proposes a cost-benefit methodology to evaluate U.S. Department of Energy's Research, Development, and Demonstration (RD&D) programs. Their methodology assesses a program's costs and risks and its potential economic, environmental, and security benefits. DOE's Office of Nuclear Energy, Science & Technology (DOE-NE, www.ne.doe.gov) manages several RD&D programs: Nuclear Power 2010, the Nuclear Hydrogen Initiative, the Advanced Fuel Cycle Initiative, and the Generation IV Nuclear Energy Systems Initiative. This paper focuses on the advanced nuclear power technologies being developed through the Generation IV International Forum (GIF, gif.inel.gov). GIF members include Argentina, Brazil, Canada, Euratom, France, Japan, Republic of Korea, Republic of South Africa, Switzerland, United Kingdom, and the U.S.

The primary purpose of this paper is to provide a conceptual framework for RD&D managers.[1] The paper develops a general model of the probability of technology development success with which to discount expected total benefits of an RD&D program. It uses this model to calculate an optimal allocation of funding to pre-prototype R&D under a funding constraint. It applies this model to funding the development of a Generation IV Nuclear Energy System.[2]

2. DISCOUNTED EXPECTED TOTAL BENEFITS OF DEVELOPING A TECHNOLOGY

Figure 1 outlines the stages of a technology development program. Each stage is characterized by a funding level (a cost, C, in \$100,000), a duration (T in months), a probability of successful completion (P, a percentage), and a benefit (B in \$100,000). There are three relevant periods: (1) T_1 from the start of R&D to prototype selection, (2) T_2 from prototype selection to first commercial order, and (3) T_3 from first commercial order to the dismantling of the fleet. In Figure 1, P_1 is the probability of the successful completion of R&D with a positive transition to the construction of a prototype.[3] P_2 is the probability of the successful completion of the prototype stage with the order of a commercial version of the technology. In each stage there are spillover benefits, B_1 and B_2, to other RD&D projects (on spillovers, see Foray, 2004); and there is a benefit from commercialization, B_3.

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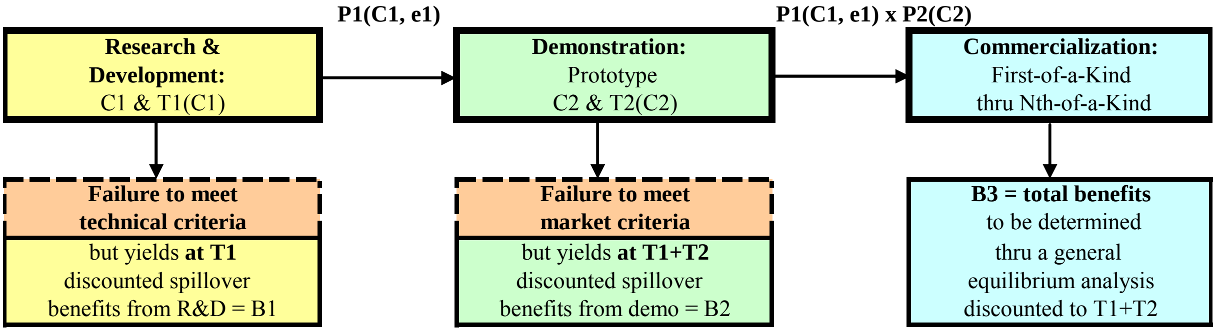
[1] See Sachon and Pate-Cornell (2004) and Dutta (1997) for approaches to similar questions.

[2] This paper focuses on programs already receiving funding; future work will examine what levels of funding might be optimally awarded to unfunded programs and the related probability of awarding funding.

[3] This is a narrow definition of success. At the R&D stage the most important result is reliable information about the technology that can be used to decide whether to build a prototype. The definition of success will be extended when portfolio effects are incorporated.



T1 = time from R&D start to prototype selection

T2 = time from prototype selection to first order

All costs and benefits are discounted to R&D start.

|<---------------- **T1** ---------------------| |<-------------- **T2** ----------------------| |<----------------------------

R&D Start **Prototype Demo Start** **First Commercial Order**

where
Pi is the probability of success at stage i (%); Ti is the duration of stage i (months);
Ci is funding (costs) for stage i (in \$100,000); Bi is benefit of achieving stage i (in \$100,000); and
e1 is error in estimating P1(C1).

Figure 1. A Research, Development, Demonstration & Commercialization Model.

Before discussing the relationships between funding, project duration, and the probability of success, an order-of-magnitude calculation is made for the total benefits (B_3) from developing one Generation IV technology discounted to the first commercial order (at $T_1 + T_2$).[4] For the purposes of planning fuel cycle facilities, EMWG (2005) assumes a deployment of 32 GWe for each Generation IV (Gen IV) technology developed. Let T_3 be 10 years from the order of the first commercial unit to the end of construction of the first 8 GW, when EMWG assumes Nth-of-a-kind cost will be achieved. Further, assume (1) an additional 8 GW is built every 5 years, (2) the life of each unit is 50 years, and (3) the average capacity factor is 90%. Each 8 GW generates 63M MWh on average each year. Discounting total annual MWh (not dollars) to the end of construction of each 8 GW is equal to the inverse of the capital recovery factor with a continuous 3% annual social discount rate and a 50-year life, i.e., 1/CRF = 25.51. The present value at the start of operation of each 8 GW is 1.6 B MWh. Each 8 GW's annual output must be discounted to the first commercial order. The discounted total benefits, B_3, at $T_1 + T_2$ would be about 3.86B MWh.[5]

Given B_3, the discounted expected total benefits of the program are

$$EB = D(T_1)\,B_1 + D(T_1 + T_2)\;P_1\;B_2 + D(T_1 + T_2)\;P_1\;P_2\;B_3\,. \qquad (1)$$

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[4] Following "Methodology for Prospective Evaluation of DOE Programs" NRC-NA (2005, pp. 19-81), the discounted expected total benefits, B_3 (including economic, environmental, and security benefits) will be determined by comparing states of the world with and without the new nuclear energy system using a general equilibrium model, such as MARKAL.

[5] 3.86B MWh=1.61B MWh x (0.7408 + 0.6376 + 0.5488 + 0.4724) Assuming T_1 and T_2 are 10 years, benefits in MWh discounted to the start of R&D would be about 2B MWh with a 32 GW deployment. Considering only the economic benefits of generating electricity, assume there is a net surplus of \$1/MWh compared to the next-best alternative, discounted benefits to the start of R&D would be about \$2B per \$1 of net surplus with $P_1 = P_2 = 1$.

The expected benefits (EB) are equal to (1) the time discounted benefits derived from R&D spillovers (B_1 starting at T_1) plus (2) the probability and time discounted benefits from prototype spillovers (B_2 starting at $T_1 + T_2$) plus (3) the probability and time discounted commercialization benefits (B_3 at $T_1 + T_2$). Both B_2 and B_3 are evaluated at the time of the first commercial order, $T_1 + T_2$, then discounted to the start of R&D. Consider each term of Equation (1):

(1) $D[t] = \exp\{-\mathbf{r}\, t\}$ and **r** is the monthly social discount rate, according to U.S. Office of Management and Budget (OMB) guidelines. So, $d\,D/d\,t = -\mathbf{r} \exp\{-\mathbf{r}\, t\}$.

(2) Project durations, T_i (in months), depend on the levels of program funding, C_i (in \$100,000), where the duration decreases with funding increases, $d\,T_i / d\,C_i < 0$.

(3) Define BCR_i as the benefit-to-cost ratio of spillovers from stage i: $B_i = BCR_i\, C_i$. These benefit streams are equivalent to a discounted perpetuity on spillovers at a return equal to the social discount rate (future work will incorporate spillover benefits into the success probabilities of technologies in the same portfolio).

(4) The probabilities of success, P_i, of stage i depend on the levels of program funding, C_i, where the probability of success increases with funding, $d\,P_i / d\,C_i > 0$ (with $C_i > 0$, and $\Sigma\, C_i = \underline{C}$, total funding). However, the relationship between P_i and C_i is not known with certainty: there is error, e_i, in specifying $P_i(C_i, e_i)$, where $d\,P_i / d\,e_i \neq 0$ and $d\,C_i / d\,e_i = 0$, i.e., funding does not change with the realization of e_i, only the probability of success changes with e_i. (For simplification, $P_2(C_2)$ is assumed to be known, e.g., Stage 2 uncertainty is resolved in Stage 1.)

Under these specifications, Equation (1) becomes

$$\begin{aligned} EB(C_1, \underline{C} - C_1) \;=\; & D[T_1(C_1)]\, C_1\, BCR_1 \\ & + D[T_1(C_1) + T_2(\underline{C} - C_1)]\; P_1(C_1, e_1)\; [\underline{C} - C_1]\; BCR_2 \\ & + D[T_1(C_1) + T_2(\underline{C} - C_1)]\; P_1(C_1, e_1)\; P_2(\underline{C} - C_1)\; B_3\,, \end{aligned} \tag{2}$$

i.e., discounted expected total benefits depend on (1) the levels of funding through its influence on stage durations, the probabilities of success, and spillovers to other technologies, and (2) uncertainties in the R&D process.

Equation (2) allows calculation of the marginal contribution to EB from funding at the R&D stage, C_1. Assuming T_i, T_j, P_i, and P_j are all independent (and holding BCR_i and B_i constant),

$$\begin{aligned} \partial EB/\partial C_1 \;=\; & e^{-r\,T_1}\, [1 - r\, C_1\, T_1']\, BCR_1 \\ & + e^{-r\,[T_1 + T_2]}\, \{ [-r\,(T_1' + T_2')\, P_1(\underline{C} - C_1) + P_1'(\underline{C} - C_1) - P_1]\, BCR_2 + \\ & [-r\,(T_1' + T_2')\, P_1 P_2 + P_1' P_2 + P_1 P_2']\; B_3\}, \end{aligned} \tag{3}$$

where $T_i' = d\,T_i/d\,C_1$ and $P_i' = d\,P_i/d\,C_1$. Section 5 uses Equation (3) to calculate an optimal proportion of R&D funding. The next section describes reasonable representations of project durations and the probabilities of success as functions of RD&D funding.

3. EXPECTED TOTAL AND MARGINAL BENEFITS OF RD&D FUNDING

It is not possible to calculate $T_i(C_i)$, $P_i(C_i)$, T_i', and P_i' without specifying the functional relationships between funding and project duration, and between funding and the probability of success. First, consider the relationship between T_i and C_i, where $d\,T_i\,/d\,C_i < 0$, i.e., the greater the funding, the shorter the duration to stage completion. Assume an exponential relationship between project duration and funding (for other duration functions see Rothwell, 1996):

$$T_i = S_i\, C_i^{\varepsilon_i}, \tag{4}$$

$$T_i' = d\,T_i/d\,C_i = S_i\, \varepsilon_i\, C_i^{\varepsilon_i - 1}, \tag{5}$$

where duration (T_i) is in months, funding (C_i) is in \$100,000, $S_i = e^{s_i}$ is a scaling factor for each stage, and ε_i is the elasticity of project duration with respect to project funding for stage i.[6] Also, $\ln(T_i) = s_i + \varepsilon_i \ln(C_i)$ and $\varepsilon_i = d\ln(T_i)/d\ln(C_i)$, the elasticity of project duration with respect to funding, e.g., if ε_i were –0.35, a 10% increase in funding would decrease project duration by 3.5%.

Second, P_i is a cumulative probability distribution that maps funding levels to probabilities of success. Assume $\partial P_i/\partial C_i > 0$, i.e., increases in funding always increase the probability of success. (This infers there are no diseconomies of scale at any funding level.) Although not mathematically necessary, to illustrate this model, the distribution function should have a closed form that is easy to differentiate. One such function is the logistic.[7] The logistic has the following simple form:

$$P_i = [1 + e^{-Z_i(C_i, e_i)}]^{-1} \text{ or } 1/[1 + \exp\{-Z_i(C_i, e_i)\}], \tag{6}$$

where Z_i is an index function of C_i, e.g., $Z_i = a_i + b_i C_i$. As C_i ranges from low levels (e.g., the smallest "Nuclear Energy Research Initiative" grant) to extremely high levels (e.g., the Manhattan Project), P_i ranges from 0 to 1 (note: when $Z = 0$, $P = 50\%$).

However, the influence of funding on the probability of success changes with the level of funding. For example, an extra million dollars will have more influence on the project success if the project is funded at one million dollars than if the project is funded at one hundred million dollars. This can be modeled by taking the natural logarithm of funding, i.e., $Z_i = a_i + b_i \ln(C_i)$.

Finally, specification error in Equation (6) can be represented as

$$P_i = 1/[1 + \exp\{-(a_i + b_i \ln(C_i) + e_i\}] \tag{7}$$

where e_i represents uncertainty in the probability of success. (In this paper e_i has a uniform distribution; in future work, e_i will be modeled with an extreme value distribution, e.g., $e_i = \exp[-\exp(\tilde{u}_i)]$, where $\tilde{u}_i$ is a randomly distributed variable and e_i is more likely to take negative values than positive values.) Taking the derivative of P_i with respect to C_i,

$$P_i' = d\,P_i/d\,C_i = (d\,P_i/d\,Z_i)(d\,Z_i/d\,C_i) = [e^{-Z_i(C_i, e_i)}][1 + e^{-Z_i(C_i, e_i)}]^{-2}(d\,Z_i/d\,C_i). \tag{8}$$

Given $e^{-Z} > 0$ and $[1 + e^{-Z}]^{-2} > 0$, if $d\,Z/d\,C > 0$, then $d\,P/d\,C$ is positive. With Equation (7),

$$d\,Z_i/d\,C_i = b_i / C_i > 0, \tag{9}$$

if $b_i > 0$ (when estimated, $b_i > 0$; see Figures 3 and 4, below).

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[6] The lowest value for C_1 is \$100,000. Dividing funding by \$100,000 yields $\ln(C_i) \geq 0$.

[7] The distribution function of the logistic is $e^Z / (1 + e^Z)$. Dividing both sides by e^Z, yields $1/(e^{-Z} + 1)$. Robustness of the results due to the choice of the logistic distribution will be explored by using alternative probability distributions and numeric techniques.

Substituting Equations (4), (5), (6), (7), (8), and (9) into Equation (3), it is possible to calculate the change in expected benefits with respect to funding levels. The next section parameterizes the model for the Generation IV RD&D program.

4. THE CASE OF DEPLOYING A GENERATION IV NUCLEAR ENERGY SYSTEM

The Generation IV Nuclear Energy Initiative provides a test case for calibrating the model described above; see DOE-GIF (2002). There are four functions to characterize the discounting of the value of technology development: (1) project durations and (2) success probabilities for (1) the R&D stage and (2) the Prototype Demonstration stage of a Generation IV Nuclear Energy System (G4NES). Appendix A presents funding estimates by the Generation IV Roadmap Committee's Water Technical Working Group for each system they were evaluating in 2002. GIF selected the Super-Critical Water Reactor (SCWR) and five other non-water nuclear energy systems for development, see below.

First, consider the specification of the relationship between project duration and funding in Equation (4). How does R&D duration change with increases or decreases in R&D funding for a G4NES technology? Assume the relationship between T_i and C_i can be approximated with S_i and ε_i in the Equation (4). For example, assume an R&D project duration is 60 months with a funding level of \$200M. Further assume that the funding manager or experts believe that the project could be shortened by 12 months with an increase in funding to \$400M.[8] Then

$$\ln(60) = S_1 + \varepsilon_1 \ln(\$200\text{M}/\$100\text{K}), \tag{10}$$

$$\ln(48) = S_1 + \varepsilon_1 \ln(\$400\text{M}/\$100\text{K}). \tag{11}$$

Solving these equations yields $S_1 = 853$ and $\varepsilon_1 = -0.347$. Figure 2 graphs this. (Least Squares or Maximum Likelihood techniques could be used with more than two points.)

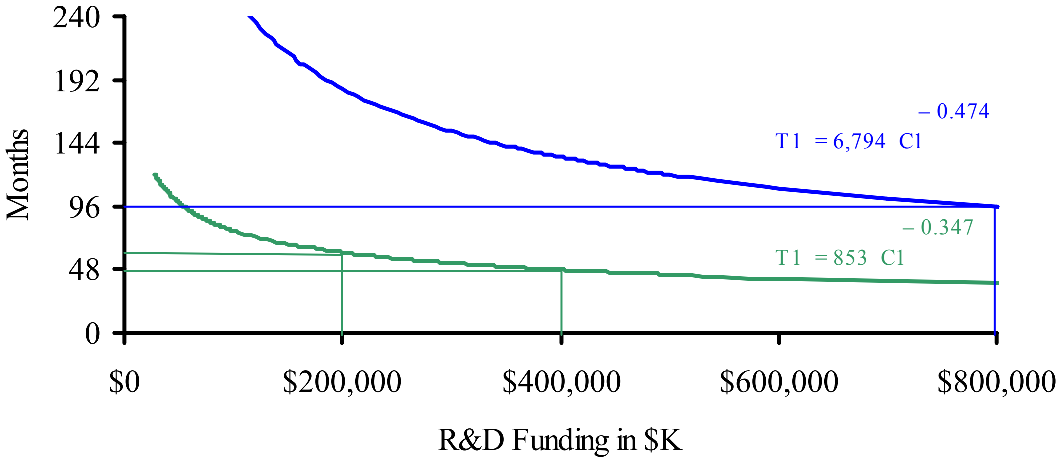

Figure 2. Exponential Relationships between R&D Funding Levels and Stage Durations.

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[8] See Chapter 4, "Expert Panel Process," in NRC-NA (2005, pp. 82-100) on eliciting expert estimates of the parameters discussed in this section.

Next, assume experts believe that with a funding level of \$800M, the **prototype** duration would be 96 months, or with a funding level of \$1.6B, the duration would be 72 months. These expectations imply $S_2 = 6{,}794$ and $\varepsilon_2 = -0.474$. See Figure 2.

Second, the parameters in Equation (6) can be specified. Define a level of funding for each stage such that the probability of success would be **50%**, i.e., where Z = 0. For example, for the R&D stage, let this funding level be \$50M; note, ln(\$50M/\$100K) = 6.215. Also, define another level of R&D funding such that the probability of success would be **90%** (Z = 2.19). For example, let this level be \$250M; note, ln(\$250M/\$100K) = 7.824. The parameters of Equation (6) can be found by solving the following set of equations:

$$0 = a_1 + b_1 6.215, \tag{12}$$

$$2.19 = a_1 + b_1 7.824. \tag{13}$$

Solving these equations, $a_1 = -8.456$ and $b_1 = 1.36$, or $Z_i = -8.456 + 1.36 \ln(C_i) + e_i$. See Figure 3. Here, e_i is uniformly distributed between –2 and +2. The uniform distribution implies an extremely wide range of uncertainty regarding the likely success of R&D at a predetermined funding level, C_1. Here, at a funding level of \$50M the probability of success could be anywhere between 10% and 90%.

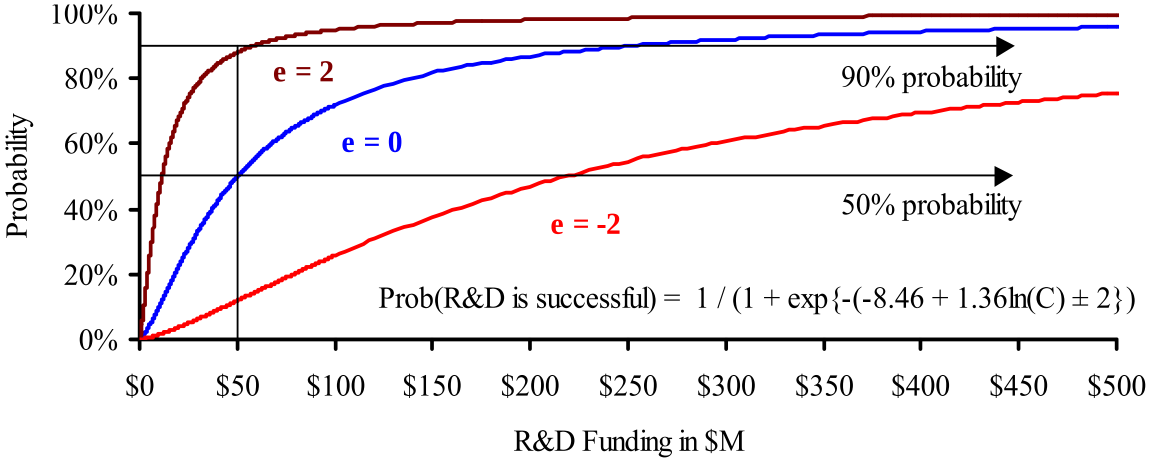

Figure 3. The Logistic Cumulative Probability Distribution for the R&D Stage.

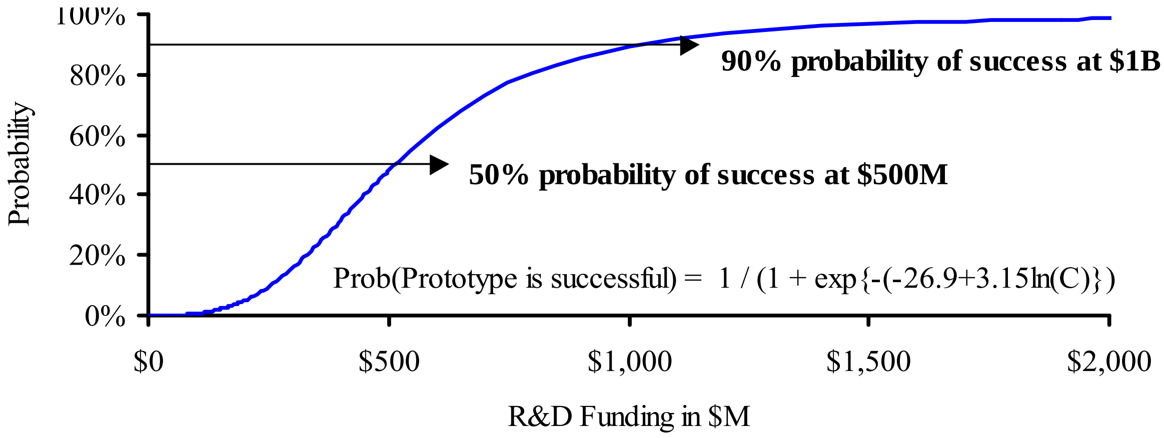

Figure 4. The Logistic Cumulative Probability Distribution for the Prototype Stage.

Similarly, appropriate values for the logistic distribution must be determined for the prototype stage. Assume that to construct the prototype such that a commercial order would be placed, a funding level of \$500M yields a **50%** probability of success, and a funding level of \$1B yields **90%** probability of success. The appropriate set of equations is

$$0 = a_2 + b_2\,8.517, \tag{14}$$

$$2.19 = a_2 + b_2\,9.210. \tag{15}$$

Solving these simultaneously, $a_2 = -26.9$ and $b_2 = 3.15$. Figure 4 illustrates this.

5. FUNDING FOR A GENERATION IV NUCLEAR ENERGY SYSTEM UNDER A BUDGET CONSTRAINT

With these parameters, EB and $\partial EB/\partial C_i$ can be calculated for one G4NES technology. Substituting parameters S_i, ε_i, a_i, and b_i into Equation (2) yields the graph in Figure 5 for $\underline{C}$ = \$1B, $BCR_1 = BCR_2$ = 25%, and B_3 = \$3.86B. Optimal R&D funding levels, C_1^*, are shown in Figure 5 for $e_1 = -2, -1, 0, 1,$ and 2. A graph of $\partial EB/\partial C_1$ is presented in Figure 6. The range of optimal R&D spending is between \$180M and \$280M for $-1 \le e_1 \le 1$. At \$250M the probability of a successful transition from Stage 1 to Stage 2 (under this parameterization) would be about 88%. Also, at \$750M the probability of commercialization would be about 79%. Therefore, at the optimal R&D allocation, $P_1(C_1^*, e_1 = 0) \bullet P_2$ = 70%.

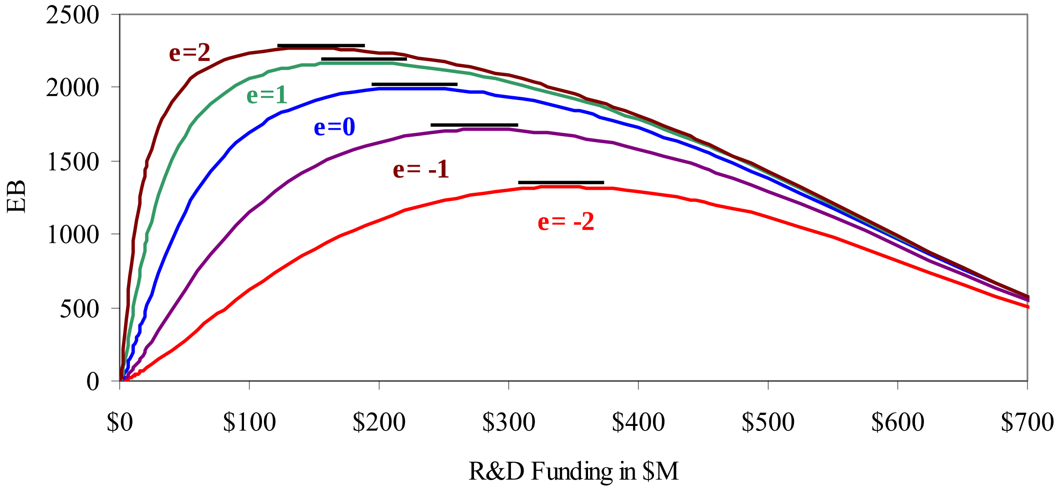

Figure 5. Time and Probability Discounted Total Benefits as a Function of R&D Funding.

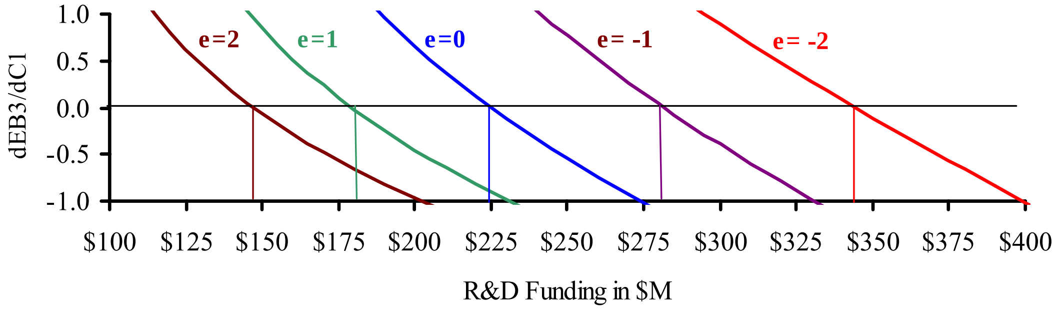

Figure 6. Derivative of Expected Benefits with respect to R&D Funding: $d\,EB/d\,C_1$.

Under the method described in Sections 2 and 3 with parameters from Section 4, an optimal allocation between R&D and Prototype Demonstration with a fixed budget of $1B varies with the size of the uncertainty in understanding the relationship between R&D funding and the probability of success for a particular technology. Therefore, more work must be done to understand and model this uncertainty.

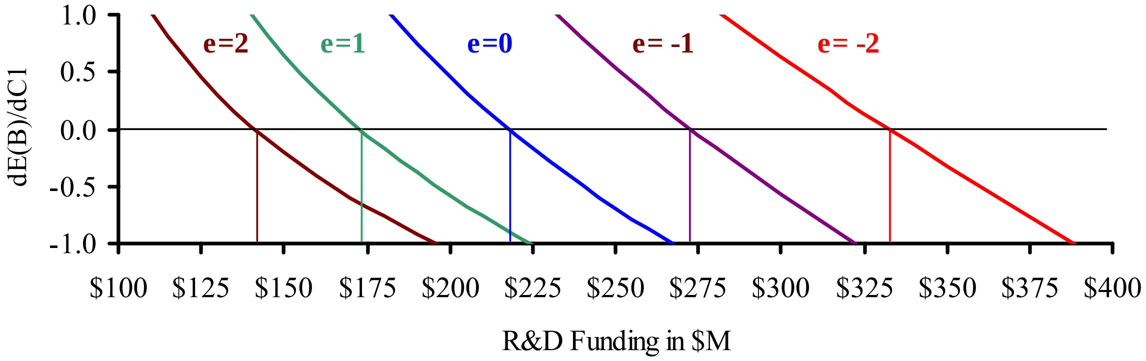

Figure 7. Derivative of Expected Benefits with respect to R&D Funding: $d\,EB3/d\,C_1$.

Finally, Figure 7 graphs $\partial EB_3/\partial C_1$. The optimal level of R&D at e = 0 decreases from $225M to $218M, i.e., an error of 3%. Therefore, Equation (3) can be approximated as

$$\partial EB/\partial C_1 \approx \partial EB_3/\partial C_1 \tag{16}$$

$$= e^{-r[T_1+T_2]}\,[\,-r\,(T_1'+T_2')\,P_1(C_1, e_1)\,P_2 + P_1'(C_1, e_1)\,P_2 + P_1(C_1, e_1)\,P_2'\,]\;B_3\,.$$

Equation (16) can be used to calculate $\partial^2 EB/\partial C_1 \partial e_1$, i.e., the sensitivity of $C_1{}^*$ to realizations of error in the estimation of R&D success.

6. FUTURE RESEARCH

This paper developed a general model of a two-stage RD&D project and adapted it to the allocation of funding in the commercialization of advanced nuclear energy systems by the Generation IV International Forum.

This model can be extended to M technologies (see Rothwell 2003a and 2003b). Within the GIF portfolio there are six technologies: the Gas Fast Reactor (GFR), the Very-High Temperature (Gas) Reactor (VHTR), the Supercritical Water Reactor (SCWR), the Sodium Fast Reactor (SFR), the Lead Fast Reactor (LFR), and the Molten Salt (Fast) Reactor (MSR). A portfolio of these technologies can be characterized by the spillover benefits from R&D and Prototype Demonstration that can be captured by other technologies in the portfolio as a function of the "distance" between the technologies (see David and Rothwell, 1996). For example, technologies using the same fuel design or reprocessing system can benefit from other Generation IV nuclear energy system successes.

Discounted expected total benefits can be calculated and compared for M technologies, EB_{im}. Portfolio performance can be simulated with random generation of e_{im} to assess various technology investment strategies. This will aid in the specification of a dynamic programming model, similar to that in Sachon and Pate-Cornell (2004). These models should give public and private investors a better understanding of the management of advanced technology research, development, demonstration, and commercialization programs, particularly in advanced nuclear energy systems.

APPENDIX A:
RD&D COSTS ESTIMATED BY THE GENERATION IV ROADMAP WATER TECHNICAL WORKING GROUP

(from TWG spreadsheets dated July 2002)

W1--Integral Primary System Reactor Concept Set (IRIS): “These light water reactor concepts are characterized by a primary system that is fully integrated in a single vessel, which makes the nuclear island more compact and significantly improves safety. All the proposed concepts are thermal reactors and make use of either LEU or MOX fuel (the scoring is for the LEU fuel version), clad with Zircaloy. (1005 MWe/3 units).

“An evaluation of the development cost of IRIS up to and including design certification yields (amounts in $M) follows: Preliminary design - 22.5, Safety by design testing - 42, SG design and testing - 31.5, Cost Estimate - 7, NRC certification - 24, System Performance Modeling - 1, Maintenance optimization - 15, SG inspection development - 5, RCP design and testing - 12, PRA - 11, Int. CRDM design and testing - 18, I&C system and control room - 34, Plant simulator - 13, Code V&V - 10, Fuel assembly - 10, Systems and equipment - 80, Building layout, civil structures - 35, Piping and Supports Analysis - 20, Equipment Qualification - 21, Construction/3D Planning Tool - 6, Configuration control - 8, SSAR - 20, and ITAAC - 5. Total - 461. It is felt that no prototype is necessary to obtain design certification. The costs reflect that a large amount of IRIS development effort is done overseas at substantially lower rates. The estimates of the development costs for the SMART, CAREM, PSRD, MRX and MASLWR reactor concepts range from $77M to $210M.” (Total estimated between $350-$550M)

W2--Large Simplified Boiling Water Reactor (ESBWR): “This is a large boiling water reactor with natural circulation in the core region, no re-circulation pumps, and highly passive decay heat removal systems. This quantitative assessment assumes that the ESBWR has a standard LEU fuel cycle. (1380 MWe/unit)

“The SBWRs are almost fully developed: R&DD should be less than $250M.”

W3--NG CANDU - With LEU Once-Through Cycle: “The next generation CANDU design is based on the standard CANDU design with horizontal pressure tubes fuelled on-line and surrounded by a low-temperature heavy water moderator. The emphasis is on improving the economics of current CANDU reactors by replacing the heavy water coolant in the pressure tubes with light water, moderately increasing the thermal efficiency, and simplifying and reducing the size of the nuclear island. (1400 MWe/2 units)-

“The NG CANDU design is an extension from the existing CANDU design basis, so that the amount of ‘new’ development and engineering is limited. In addition, the design conditions have been selected to be modest extensions of the existing R&D database for key CANDU components and materials. The NG CANDU design includes improvements in the safety and operating margins in key areas to reduce the need for expensive qualification and validation testing. A design center value of $300M is estimated excluding advanced fuel cycles. Significant development costs are anticipated for a MOX or DUPIC fuel suitable for use in a CANDU.” (Total estimated at $250-$450M).

W4--Supercritical Water Reactor (SCWR)- Thermal: "These are a class of high-temperature, high-thermal-efficiency (up to 45%), thermal neutron spectrum water-cooled reactors with a primary coolant system that operates above the thermodynamic critical point of water (374.1°C, 221.2 bar). Stainless steel clad LEU fuel is used. This concept set includes the pebble bed and CANDU versions as well as the conventional SCWR. (1700 MWe/unit).

"This concept will require significant fuel cladding and core structural materials development and testing as well as fuel bundle testing, including loop testing in existing test reactors ($300M). It will also require significant separate effects and scaled integral thermal-hydraulic safety testing ($200M). The balance of plant materials and equipment will be the same as currently used in the supercritical water-cooled fossil fired plants and will not need much development. However, a small demonstration plant will be needed to fully demonstrate the concept before full sized plants are built ($500M, assuming 1/2 the full cost of the demonstration plant is recovered with electricity sales). All that adds up to about $1 billion or more." (Total estimated as $550M-$2B).

W5--Supercritical Water Reactors - Fast Spectrum (SCWR-Fast): "These are a class of high-temperature, high-thermal-efficiency (up to 45%), fast spectrum water-cooled reactors with a primary coolant system that operates above the thermodynamic critical point of water (374.1°C, 221.2 bar). The fuel is mixed oxide (MOX) with plutonium and minor actinide multi-recycle and a core average discharge burnup of 80 MWd/kg-HM. The spent fuel reprocessing technology will be advanced aqueous. (1700 MWe/unit).

"This concept will require significant fuel cladding and core structural materials development and testing as well as fuel bundle testing, including loop testing in existing test reactors ($300M). It will also require significant separate effects and scaled integral thermal-hydraulic safety testing ($200M). The balance of plant materials and equipment will be the same as currently used in the supercritical water-cooled fossil fired plants and will not need much development. However, a small demonstration plant will be needed to fully demonstrate the concept before full sized plants are built ($500M, assuming 1/2 the full cost of the demonstration plant is recovered with electricity sales). All that adds up to about $1 billion or more." (Total estimated at $550M-$2B).

W6--High Conversion ABWR-II: "This is a reduced-moderation, fast spectrum BWR designed to use uranium more efficiently (conversion ratio near 1.0) and minimize the reactivity swing. The positive void coefficient is reduced by the use of neutron streaming assemblies and a pancake-type core. MOX fuel with minor actinide recycle is used with advanced aqueous spent fuel reprocessing. (1500 MWe/unit).

"Little development cost is needed for systems external to the core since they are same as the ABWR plants. However, new cladding materials need to be developed ($100M), and neutronics and thermo-hydraulics methods and verification experiments are needed ($200M). In addition, the fuel cycle (advanced aqueous or dry reprocessing and MOX fuel fabrication) needs further development ($500M). A demonstration plant is not needed." (Total estimated at $800M).

REFERENCES

DAVID, Paul and Geoffrey ROTHWELL. 1996. “Measuring Standardization: An Application to the American and French Nuclear Power Industries,” *European Journal of Political Economy* : 291-308.

DUTTA, Prajit K. 1997. “Optimal Management of an R&D Budget,” *Journal of Economic Dynamics and Control*, 21: 575-602.

Economic Modeling Working Group of the Generation IV International Forum (EMWG). 2005. *Cost Estimating Guidelines for Generation IV Nuclear Energy Systems*. DOE-GIF.

FORAY, Dominique. 2004. *The Economics of Knowledge*. MIT Press.

National Research Council of the National Academies (NRC-NA). 2005. *Prospective Evaluation of Applied Energy Research and Development at DOE (Phase One): A First Look Forward*. National Academies Press.

ROTHWELL, Geoffrey. 1996. “Organizational Structure and Expected Output for Nuclear Power Plants,” *Review of Economics and Statistics* 78: 482-88.

ROTHWELL, Geoffrey. 2003a. “Standardization, Diversity, and Learning in China’s Nuclear Power Program,” in *History Matters: Essays on Economic Growth, Technology, and Demographic Change,* Stanford University Press.

ROTHWELL, Geoffrey. 2003b. “Determining the Optimal Number of Prototype Systems in Commercializing New Technologies,” in *On the Diffusion of Knowledge following Disasters*, Paris: French Ministry of the Environment.

SACHON, Marc and M. Elisabeth PATE-CORNELL. 2004. “Managing Technology Development for Safety-Critical Systems,” *IEEE Transactions on Engineering Management* 51,4 (Nov.): 451-61.

U.S. Department of Energy, Nuclear Energy Research Advisory Committee, and the Generation IV International Forum (US DOE-GIF). 2002. *A Technology Roadmap for the Generation IV Nuclear Energy Systems*. http://gif.inel.gov/roadmap/

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