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CONSTRUCTION COST GROWTH FOR NEW DEPARTMENT OF ENERGY NUCLEAR FACILITIES

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ABSTRACT

Cost growth and construction delays are problems that plague many large construction projects including the construction of new Department of Energy (DOE) nuclear facilities. A study was conducted to evaluate cost growth of large DOE construction projects. The purpose of the study was to compile relevant data, consider the possible causes of cost growth, and recommend measures that could be used to avoid extreme cost growth in the future. Both large DOE and non-DOE construction projects were considered in this study. With the exception of Chemical and Metallurgical Research Building Replacement Project (CMRR) and the Mixed Oxide Fuel Fabrication Facility (MFFF), cost growth for DOE Nuclear facilities is comparable to the growth experienced in other mega construction projects. The largest increase in estimated cost was found to occur between early cost estimates and establishing the project baseline during detailed design. Once the project baseline was established, cost growth for DOE nuclear facilities was modest compared to non-DOE mega projects.

1.0 INTRODUCTION

This year (2014) marks the 100th anniversary of the opening of the Panama Canal. Most people consider the canal to be an engineering triumph, but it was a failure for cost engineers.[1,2] After their success in building the Suez Canal, the French were confident that they could connect the Atlantic and Pacific Oceans with a canal through Central America. In 1876, they created *La Société Internationale du Canal Interocéanique* to undertake the project. In May 1879, an international engineering congress was convened in Paris to discuss the proposed canal. The engineering congress estimated that the canal would cost $214 million. On February 14, 1880, the estimated cost was revised downward to $168.8 million. The estimate was revised again on February 20, 1880 and March 1, 1880. The final preconstruction cost estimate was $120 million. The time required to complete the canal was also revised downward from 10 years to 6 years.

Fig. 1. Construction work on the Culebra Cut of the Panama Canal (1907).

The French envisioned a sea-level canal through Panama and began construction of the canal on January 1, 1881. However, the job was more difficult and costly then they had expected. The French suspended work on May 15, 1889 after competing approximately 40% of the project and spending $235 million (about $7.6 billion in 2013 dollars). The US purchased the land for the canal on June 28, 1902 and took possession of the French assets on May 4, 1904. When the US took over the construction of the Panama Canal, no decision had been made as to whether the canal should be a lock canal or a sea-level canal. Congress finally ratified the lock-based scheme in late 1905. The US spent an additional $375 million (about $8.3 billion in 2013 dollars) to complete the Panama Canal. The first official transit of the Panama Canal took place on August 15, 1914. The French and Americans spent a total of $610 million (about $15.9 billion in 2013 dollars) over 33 years to complete the Panama Canal. The total cost of building the Panama Canal was 2.9 times the original estimate and 5.1 times the final preconstruction estimate. The actual construction time for the Canal was about 18 years, which was about twice the original estimate and three times the revised estimate.

Cost growth is an increase in the cost of a project above the estimated cost. The history of cost growth for the Panama Canal is not very different from many large contemporary construction projects. The Department of Energy (DOE) has experienced cost growth and construction delays of a similar magnitude for constructing new nuclear facilities. The DOE canceled several high-profile nuclear-facility construction projects because of excessive cost growth. Several reports from the General Accounting Office have criticized DOE for not following established standards for cost estimation.[3,4] These reports have fueled the perception that DOE and its contractors have done a poor job of estimating and controlling the construction costs of new nuclear facilities. This concern is reflected in a recent letter from Congressmen Howard McKeon and Mike Rogers to the Secretary of Energy.[5]

Los Alamos National Laboratory (LANL) undertook a study to determine whether the perception that DOE and its contractors have done a poor job of estimating and controlling costs is justified. In particular, we have attempted to answer the following four questions.

- Is the problem of extreme cost growth unique to DOE nuclear-facility construction projects?
- Is the problem of extreme cost growth unique to nuclear-facility construction projects?
- What are the underlying problems that cause extreme cost growth?
- How can DOE and its contractors avoid extreme cost growth?

To answer these questions, we examined data from large civilian construction projects including commercial nuclear power plants in the United States and DOE nuclear facilities. We also reviewed numerous reports and evaluations of cost growth for large construction projects. By combining our own independent analysis with the insights of others, we developed a better understanding of cost growth for DOE nuclear facility construction costs.

2.0 CIVILIAN MEGAPROJECTS

A mega construction project requires huge physical and financial resources to complete. In this review, we define a megaproject as a construction project with a total cost in excess of $800 million in 2013 dollars. In this section, we will discuss non-DOE civilian megaprojects with a focus on the oil and gas industry.

2.1. Gas-to-Liquids Plants

A gas-to-liquids (GTL) process converts natural gas into liquid fuels. Currently, six large plants are operating or near completion. Several other propose GTL projects are in various stages of planning. GTL processes enable countries like Qatar and Nigeria, which possesses large quantities of stranded natural gas, to covert their resources into diesel and jet fuel that can be easily shipped and sold worldwide. GTL projects are in some ways similar to DOE nuclear projects. Like many DOE nuclear facility construction projects, a GTL plant is existing technology involving few significant innovations. Also, like DOE nuclear facilities, the owner, designer, and contractor are likely to have limited experience because only a few operating plants exist.

2.1.1. Gas-to-Liquid Plant Data

Table 1 is a summary of existing and proposed GTL projects based on the Fischer-Tropsch process.[*] The plant cost index listed in the table is the *Chemical Engineering* Plant Cost Index (CE/PCI). The location factor is based on a 1980 reference;[6] and is, therefore, only approximate. The location factor, although dated, suggest that construction coast are nearly the same for all GTL plant locations except Nigeria where construction cost are much more expensive. The final column gives cost of the plant in 2013 dollars corrected for location.

Figure 2 is a plot of the location-corrected capital cost in 2013 dollars as a function of plant capacity. The data can be fitted to a curve with the following form, which is a straight line on a log-log plot.

$$Cost = A \cdot (Capacity)^n \quad \text{, where} \tag{1}$$

A and n are empirical constants. This equation is linear on a log-log plot. All plants in Table 1 except the Oryx Plant in Qatar lie within ±30% of the "best-fit" curve through the data, which suggest that the Oryx Plant is an outlier. The capital cost of the Oryx Plant is a factor of 3 less than the correlation, which is curious considering that Oryx Plant should be similar to the Mossel Bay GTL Refinery that was built 15 years earlier. Both plants have a similar capacity and the South African company Sasol was a key player in both projects. However, the scope of the two plants is very different.

- The Mossel Bay Plant was a grass-roots project located in an area with no other petrochemical facilities (see Fig. 3a). The Oryx Plant is located in Ras Laffin Industrial City and it is part of a larger gas-processing plant (see Fig. 3b).
- Because the Oryx Plant is part of a larger complex, it required fewer supporting facility than the Mossel Bay Plant, so it occupies a smaller area (See Fig. 3).
- The Mossel Bay Plant produces gasoline, diesel, distillates, and alcohols from wet natural base. The Oryx Plant produces diesel, distillates, and oxygenates from low sulfur, dry natural gas.

Table 1. Existing and Proposed Fischer-Tropsch GTL Plants

Plant	Location	Startup Date	Product Capacity (bbl/day)	Actual or Estimated Cost (billion $)	Plant Cost Index	Location Factor	2013 Actual or Estimate Cost (billion $)
Mossel Bay GTL Refinery	South Africa	1992	36,000	$4.0	358	1.14	$5.5
Bintulu GTL Plant	Malaysia	1993	12,500	$0.85	359	0.80	$1.7
Oryx GTL Plant	Qatar	2007	34,000	$1.2	525	1.10	$1.2
Palm GTL Plant	Qatar	Canceled	154,000	$18.0	525	1.10	$17.7
Pearl GTL Plant	Qatar	2012	140,000	$19.0	567	1.10	$17.3
Escravos GTL Plant	Nigeria	2014	34,000	$10.0	568	2.00	$5.0
Oltin Yol GTL	Usbekistan	2017	38,000	$3.2	567	0.82	$3.9
Sasol GTL Plant	Louisiana	2018	96,000	$12.5	567	1.00	$12.5
Westlake GTL Plant	Louisiana	Canceled	140,000	$20.0	567	1.00	$20.0

[*] Several US companies are considering building GTL based on the Mobil methanol-to-gasoline process. These proposed plants are small (less than 1500 bbl/day) and use a different technology, so we did not include then in the compilation.

Based on the available reports, the other GTL plants listed in Table 1 are more similar to the Mossel Bay Plant than the Oryx Plant in that they grass-roots plant that required a significant investment in facilities and infrastructure outside of the battery limits. Hence, they lie on the same cost curve as the Mossel Bay plant.

For chemical plants, the exponent *n* in Eq. (1) is typically between 0.6 and 0.8. When the Oryx Plant is excluded, the exponent for the GTL plants in Table 1 is 0.97, which indicates a nearly linear relationship between cost and capacity. A linear capacity-cost relationship implies that no economy of scale exists.

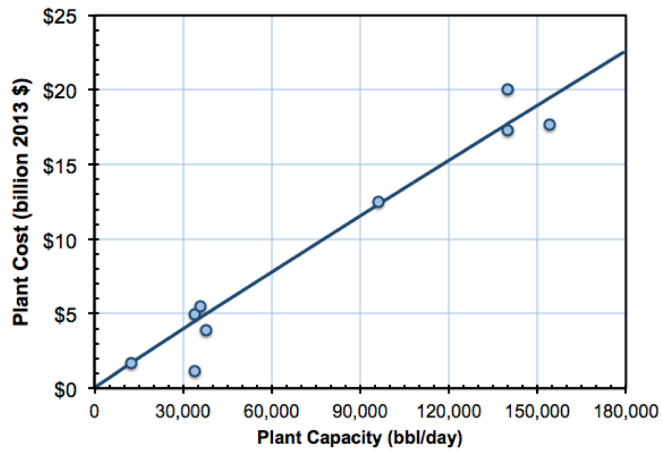

Fig. 3. Plant cost as a function of product capacity for Fischer-Tropsch GTL plants.

Table 2 is a summary of recent GTL projects. Four of the five projects listed in the table experienced significant cost escalation. The Escarvos GTL Plant in Nigeria is expected to cost 5.9 times the original estimate when it is completed in 2014. Two large GTL projects were canceled when the estimated cost increased significantly. The cost increases as well as uncertainty in future oil and natural gas prices have cause some analysts to label GTL projects as risky ventures.[7,8]

2.1.2. Discussion of Gas-to-Liquid Plant Data

The precise reasons for the large cost growth in four of the five projects listed in Table 2 is difficult to determine because the details of project costs are not available in the open literature. At best, we can only speculate about the causes. The correlation illustrated in Fig. 2 indicates that the cost of Fischer-Tropsch GTL plants are reasonably consistent when corrected for inflation and location. The eight GTL projects in Table 1 involve different locations and different contractors over a 22-year period. Execution problems

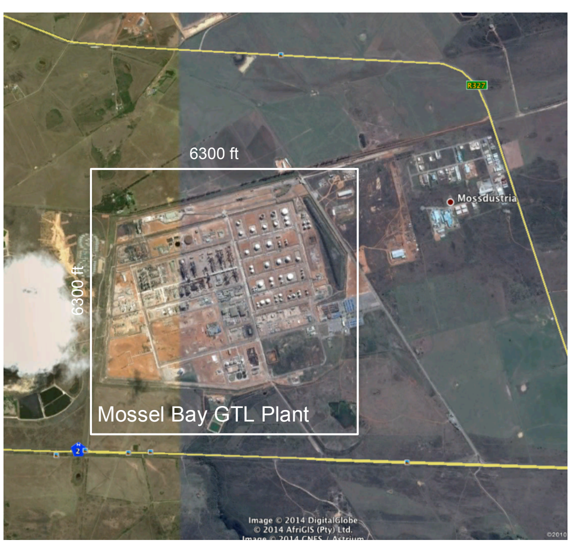

Fig. 3a. Satellite image Mossel Bay GTL Plant in South Africa. The area of the image is approximately 2.5 miles x 2.5 miles.

Fig. 3b. Satellite image of Oryx GTL Plant in in Qata. The area of the impage is approximately 2.5 miles x 2.5 miles.

Table 2. Cost estimates for gas-to-liquids plant construction projects

Plant	Location	Capacity (bbl/day)	Initial Estimate		Revised Estimate		Final Cost	
			Date	Estimate	Date	Estimate	Date	Estimate
Oryx[9]	Qatar	34,000	Nov 2003	$850 million	Jun 2006	$1.2 billion	–	–
Escravos[10]	Nigeria	34,000	Apr 2005	$1.7 billion	2011	$5.9 billion	Mar 2014	$10 billion
Palm[11]	Qatar	154,000	Jul 2006	$7 billion	Feb 2007	$18 billion	Canceled	
Pearl[8]	Qatar	140,000	Feb 2007	$5 billion	2007	$18 billion	Nov 2011	$19 billion
Westlake[12]	Louisiana	140,000	Sep 2013	$12.5 billion	Dec 2013	$20 billion	Canceled	

would vary in terms of cause and impact on cost. If execution problems were the cause of cost growth, then cost data would be less consistent, which would manifest itself as scatter in Fig. 2. The lack of scatter in Fig. 2 suggests other causes for the cost increases. We speculate that the increases are result of poor initial cost estimates.

The limited data available suggests that the extreme cost growth experienced during the construction of the Escarvos GTL Plant (see Fig. 4) was the result of a poor initial cost estimate. The Escravos Plant inside the battery limits is similar to the Oryx Plant. Both are based on Sasol GTL technology, both process dry natural gas, and both have the same product capacity. The initially reported cost estimate for the Escravos Plant appears to be based on experience with the Oryx Plant with some adjustment for location and inflation. Based on the location factor in Table 1, it appears that the estimate did not include an adequate adjustment for the Central African location. Also, adequate allowances may not have been made for utilities and other support facilities outside of the GTL plant battery limits. Finally, construction delays are endemic in Nigeria.[13] Delays have most likely added to the total plant cost.

When the initial cost estimates for the Palm and Pearl Plants were made, two GTL plants were operating and one was nearing completion. However, the Palm and Pearl Plants were also more than 4 times bigger than any of the three existing plants. Early cost estimates for these plants were extrapolations from a very limited set of data; and therefore, cost estimates for these two projects were likely to be inaccurate. The initial estimate for the Westlake GTL Plant was probably an order-of-magnitude estimate, which corresponds to na Association for the Advancement of Cost Engineering (AACE) International Class-5 cost estimate. A Class-5 estimate has an accuracy of +100% / -50%. The revised estimate was about 60% greater than the initial estimate. This difference is within the margin of error for Class-5 cost estimate, and therefore, does not represent cost escalation.

2.2. *Cost Growth for Civilian Megaprojects*

As illustrated by the Panama Canal and the more recent experience with GTL plants, cost growth is often a fact of life for megaprojects. Merrow et al.[14] studied cost growth for large civilian construction projects that included refineries, chemical processing plants, mineral extraction projects, civil infrastructure projects, and nuclear power plants. This study only included fixed capital assets as opposed to

Fig. 4. Artist conception of the Escravos GTL Plant in Nigeria.

the development of new aircraft. Although this study is old, the problem of cost growth for mega projects has not been solved as illustrated by recent experience with GTL plants; so insights gained from the Merrow analysis are valuable for understanding cost growth.

Deviations from the estimated cost occur because the cost estimate was faulty, the project execution was faulty, the project changed, and the macroenvironment assumed by the estimator changed. Cost estimates tend to be optimistic because the usual practice in the engineering and construction industry is to assume a zero cost for things not readily apparent.[†] Poor project definition at the time an estimate is made is the most important source of faulty cost estimates.[14] Blunders during execution can cause cost growth, but they are less important than other aspect of the project such as technology selection and project definition.[15] Change in the project or change of scope is any discretionary change in the size or configuration of a project. The macroenvironment is the political, economic, and cultural environment of a project, and it includes the legal system, labor practices, and safety and environmental regulations.

Merrow performed a statistical analysis of data from 47 megaprojects. A megaproject was a project with a cost greater than $800 million in 2013 dollars.[‡] The authors of the study defined cost growth as the increase in cost from the cost estimate at the beginning of detailed design to the end of construction.[§] Table 3 contains a summary of statistics for the projects that Merrow included in his study. This summary shows that cost growth is the norm for megaprojects. A final construction cost that is 2 or 3 time the initial estimate is not unusual.

Merrow found that deviations from the estimated cost are the result of faulty cost estimates, the macroenvironment, or both. They identified four areas that had the greatest impact on cost growth – regulation, ownership, innovation, and infrastructure.

Regulation – According to Merrow, the most important predictor of cost growth and schedule slippage for megaprojects is the extent to which the project encounters regulatory constraints. Regulations by themselves should not cause cost growth or schedule slippage. Regulations are a part of the macroenvironment. Changes in regulations during construction can result in cost growth Regulations also can be a source of faulty cost estimates. Problems occur when the effect of regulations on cost and schedule are not factored into the original estimates. Most regulator problems are related to environmental protection, public health and safety, and restrictions on labor and procurement. On the average, refinery construction projects encounter the least number of regulator problems while nuclear reactors encounter the most. The average cost growth due to regulator

Table 3. Summary of data used in the study by Merrow et al.[14]

Project Category	Mean	Standard Deviation	Minimum	Maximum	Number of Projects
Refineries	1.63	0.52	0.99	2.54	12
Process Plants	1.67	0.68	0.98	3.22	16
Mineral Extraction	1.99	0.86	1.27	3.71	7
Civil / Transport	2.14	1.26	0.97	4.53	6
Nuclear Plants	2.57	0.67	1.63	3.41	6
All Projects	**1.88**	**0.80**	**0.97**	**4.52**	**47**

† Cost estimates may be purposely biased low to convince the person making the funding decision to proceed with a project that he would otherwise reject. Deliberately underestimating costs is more likely at the early stages of a project than the latter stages. We did not consider deception as a contributor to cost growth in this study.

‡ The definition of a megaproject in the original study was projects costing over $500 million in 1987 dollars.

§ According to current DOE practice, beginning of detailed design corresponds to CD-2 and completion of construction corresponds to CD-4.

problems range from 20% relative to the baseline for a refinery to 130% for a US nuclear power plant completed before 1988.

Innovation – Technological innovation is usually defined as being on the "cutting edge" of putting science into practice, but modest and subtle changes from current practice can cause problems that lead to cost growth. Doing something different requires an extrapolation of the cost data and experience base, which results in less accurate estimates. Merrow found that incorporating technological innovation into a megaproject is likely to result in cost growth. Innovation includes a plant or process that involves any first-of-a-kind technology, new materials, or new construction techniques. A current example of a DOE project involving first-of-a-kind technology is the Pretreatment Facility at the Hanford Waste Treatment Plant (WTP). A process or project being the largest of its kind is not by itself an innovation that contributes to cost growth. Merrow found that the average cost growth relative to the baseline was 59% for projects that use new materials or construction methods and 42% for projects that use first-of-a-kind technology.

Ownership – Ownership is part of a project's macroenvironment. Whether a project is private, public, or mixed affects cost growth. On average, cost growth for public projects is 20% greater than private projects. Mixed ownership projects are the worst with an average cost growth that is about 40% greater than private projects. Public projects tend to have fewer regulatory problems than private projects, which moderates the overall cost growth. When other factors, such as regulatory prolems, are taken into account, projects in which the public sector is either the owner or an equity partner experience substantially more cost growth than private-sector projects. Merrow determined from his statistical analysis that public ownership results in an average cost growth of 59% relative to the baseline.

Infrastructure – Megaprojects often require extensive infrastructure development. Failure to adequately account for infrastructure needs is a source of errors in a cost estimate. Infrastructure can be divided into two categories – project-related facilities and permanent facilities. Project-related facilities are temporary infrastructure used to support the project, such as a temporary ready-mix concrete plant. Permanent facilities are infrastructure, such as roads or pipelines that are needed to maintain operations of the facility. Merrow found that permanent facilities are associated with increased cost growth and project-related infrastructure was associated with reduced cost growth.

Merrow derived the following empirical equation for cost growth from a statistical analysis of his data.

$$\begin{aligned} Cost\ Growth = 1.04 &+ 0.78 \times (number\ of\ regulatory\ problems) \\ &+ 0.56 \times (if\ a\ publicly\ owned\ project) \\ &+ 0.59 \times (if\ new\ materials/construction\ methods\ used\ ) \\ &+ 0.42 \times \left(if\ \text{first-of-a-kind}\ technology\ used\right) \\ &+ 0.29 \times (number\ of\ perminanent\ infrastructure\ items) \\ &- 0.53 \times (number\ of\ temoprary\ infrastructure\ items) \end{aligned} \quad . \qquad (2)$$

This equation accounts for 80% of the variation in the cost growth for the 47 projects summarized in Table 2.

2.3. Summary of Megaprojects

This survey shows that cost growth from the beginning of detailed design to the completion of construction is the norm for both private and government megaprojects. Cost increases of 100% are expected and much larger cost increases are not unusual. The main causes of cost growth appear to be faulty cost estimates and problems arising from the project's macroenvironment of which regulatory problems are the biggest contributor.

3.0 COMMERCIAL LIGHT WATER REACTORS

Commercial nuclear reactors in the US are subjected to a similar regulatory environment and public scrutiny as DOE nuclear facilities. Historically, cost escalation has been a problem for commercial nuclear reactors. To gain insight into possible causes of escalation of construction costs for DOE nuclear facilities, we examined cost data for US commercial light-water reactors.

3.1. Commercial Reactor Data

We obtained the data for commercial nuclear reactors from a variety of sources. Data on reactor type, key dates, thermal power, and cooling method is from Ref. 16. Costs for most reactors completed before 1979 is from a Rand Corporation report on nuclear power.[17] References 18 and 19 were the primary sources for the cost of reactors completed after 1979. References 17, 18, and 19 did not contain cost data for all US commercial nuclear reactors. We obtained the cost of the reactors not listed in these references from miscellaneous internet sources.

For some sites with multiple reactors, we could only obtain the total construction costs for the site. In these cases, we estimated the cost of individual reactors by dividing the total cost by the number of reactors on the sight. We assumed that the construction time was the time between the issuance of the construction permit and the initial reactor criticality.

We considered three inflation indices in our evaluation of commercial reactor cost data – the consumer price index, the producer price index, and the CE/PCI. These three indices may diverge for short periods of time, but their long-term behavior is very similar. The average rate of inflation from 1960 to 2013 is between 3.3 and 3.4% for all three indices. We chose the CE/PCI in this study because it measures the increase in the cost of building large, complex industrial plants.[**] We compiled the data for the CE/CPI from back issues of *Chemical Engineering* magazine.

We assumed that the interest rate during construction was 1 percentage point greater than the average prime interest rate during construction.[††] Historical data for the prime interest rate is available at the Federal Reserve's website.

3.2. Analysis of Data

We examine the general trends in the cost and construction time for commercial nuclear reactors by plotting the data as a function of the date of the first nuclear criticality (see Fig. 5). We expressed cost in terms of actual dollars per kilowatt thermal power (kWt). Actual dollars represent the actual cost of building the power plant without an adjustment for inflation. Our convention of expressing cost as dollars per kilowatt thermal power differs from most compilations, which express cost as dollars per kilowatt electric power (kWe).

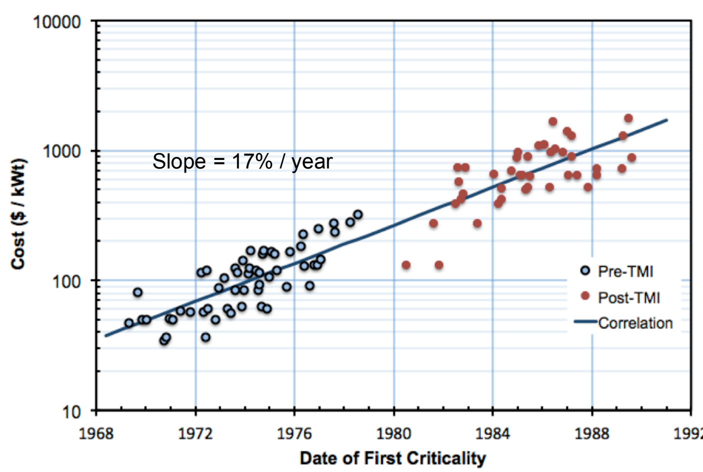

Fig. 5. Commercial nuclear power plant costs as a function of the date of the first criticality.

[**] The Handy-Whitman nuclear power plant construction cost index is a better measure of inflation than the CE/CPI, but access to the Handy-Whitman database requires a paid subscription of $970 per year. Therefore, we used the CE/CPI as a less costly alternative in this analysis.

[††] The typical utility has a Standard and Poor's bond credit rating of BBB+ and a Moody's rating of Baa. Historically, the interest rate for a Baa rated bond has been about 1 percentage point greater than the Federal Reserve's prime interest rate.

Figure 5 shows that the construction costs for a commercial nuclear power plant increased with time. Furthermore, the plot shows that the Three Mile Island (TMI) accident did not cause a change in the general trend of increasing costs. The rate of increase in the cost per kilowatt was about 17% per year. The average inflation rate over the same period was 5.1% per year, so the cost of building a nuclear power plant consistently increased at a rate significantly greater than the general rate of inflation. Mooz also observed that the cost of constructing a nuclear power plant in the US increased faster than the general rate of inflation.[17]

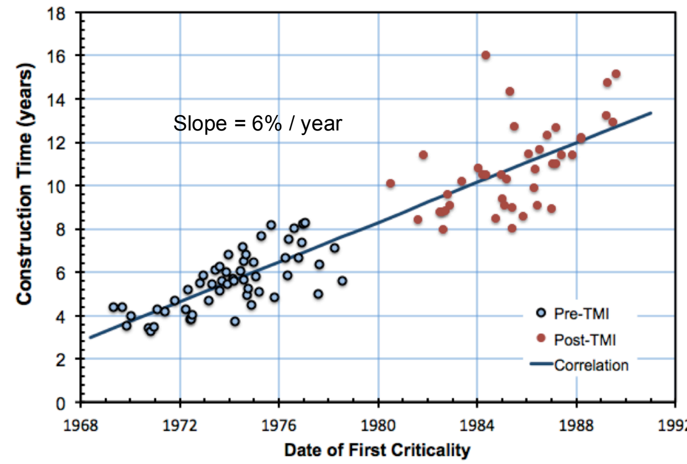

Fig. 6. Construction time for commercial nuclear power plants as a function of the date of the first criticality.

The time required to construct a nuclear power plant also increased with time as shown in Fig. 6. As with construction costs, the general trend of increasing construction time did not change after the TMI accident. However, the variability about the trend was greater after the TMI accident than before. The standard error for the trend line was 2.5 years after the TMI accident and 1.4 years before. Increasing construction time results in increased escalation due to inflation and increased financial charges, which increases the total reactor cost.

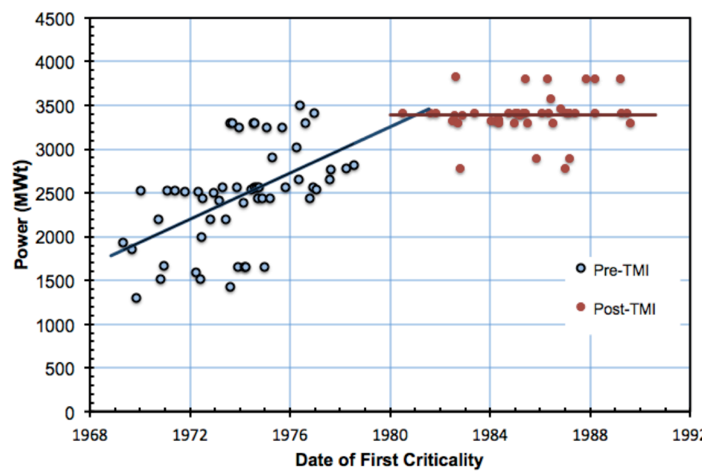

Fig. 7. Commercial nuclear reactor thermal power as a function of the date of the first criticality.

Another factor that distinguishes the pre-TMI-accident reactors from the post-TMI-accident reactors is size. Figure 7 shows thermal power as a function of the date of first criticality. Prior to the TMI accident, the average reactor power was increasing with time. The average capacity of nuclear power plants completed after the TMI accident was approximately 1 GWe.

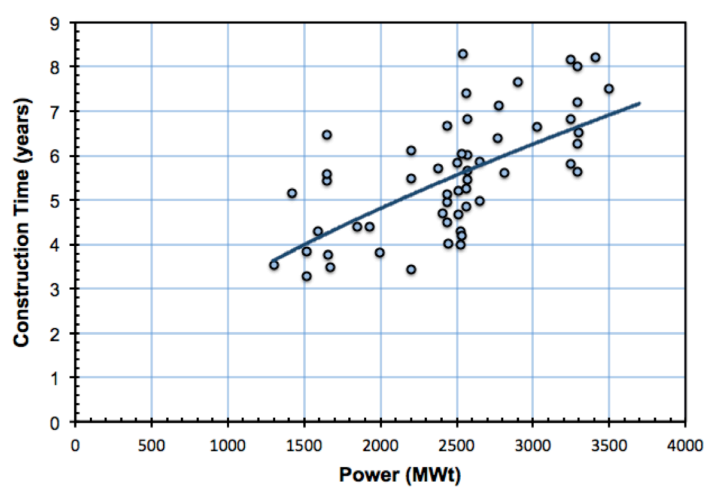

Fig. 8. Construction time for commercial nuclear power plants as a function of thermal power.

Increasing the size of the reactors should moderate the increase in construction costs because there should be an economy of scale. Mooz found no significant economy of scale in is statistical analysis of cost data.[17] Johnson and Ready, however, concluded that cost varies with power to the 0.55 power.[18] Data from reactor completed prior to the TMI accident may provide may help explain why these two studies reach different conclusions concerning economy of scale. Figure 8 shows construction time data for nuclear power plants completed before the TMI accident as a function of thermal power. During this period, construction time generally increased with reactor power. Increased construction time results in increase escalation and increased financial costs, which could mask the benefits of greater economy of scale.

3.3. Economic Model of Escalation

Because it is difficult to untangle competing effects that influence cost, we developed an econometric model of reactor costs in an attempt to account for variations in reactor power, construction time, interest rates, and inflation. The model expresses cost as a function of four factors.

$$C = C_o \cdot F_{inf}(t_s) \cdot F_{esc}(t_s, t_c) \cdot F_{int}(t_s, t_c) \quad , \qquad (3)$$

where C_o is the cost of the nuclear power plant in \$/kWt at the reference date, t_o; F_{inf} is the inflation multiplier accounting for the increase in cost from the reference date to the start of construction, F_{esc} is the escalation multiplier accounting for inflation during construction, F_{int} is the interest multiplier accounting for the accumulation of interest on construction loans during construction, t_s is the date of the start of construction, and t_c is the date of the completion of construction. For this analysis, the reference date is 1965. The cost of nuclear reactor at the reference date is a function of power and type of cooling system.

$$C_o = C_{ref} \cdot \left(\frac{P}{P_{ref}}\right)^n + C_{ct} \cdot B \ , \qquad (4)$$

where C_{ref} is the cost of the reference reactor in \$/kWt, P is the reactor thermal power in MW_t, P_{ref} is the reference reactor thermal power in MW_t, n is an exponent, C_{ct} is the cooling tower cost, and B is a function whose value is 1 if the reactor has cooling towers and 0 if the reactor has no cooling towers. We set the thermal power of reference reactor 3800 MW_t, and we assumed the exponent to be -0.45 based on the Johnson and Ready study.[18] C_{ref} and C_{ct} are empirical parameters determined from the data. The inflation multiplier, F_{inf}, has two factors – the base inflation rate as determined by the CE/PCI and a special nuclear power plant component accounting for cost increases above the base inflation rate.

$$F_{inf} = \left(\frac{I_{CE/CPI}(t_s)}{I_{CE/CPI}(t_o)}\right) \cdot e^{r \cdot (t_s - t_o)} \quad , \qquad (5)$$

where $I_{CE/CPI}(t)$ is the CE/CPI at t and r is the rate at which the construction costs for a nuclear power plant increase above the base rate of inflation. The parameter r in Eq. (5) is and empirical parameter determined from data.

F_{esc} and F_{int} in Eq. (3) depend on the construction spending as a function of time. We assumed the following function for construction spending.

$$g(t) = \frac{1}{2} - \frac{1}{2} \cdot \cos\left(\frac{\pi \cdot (t - t_s)}{t_c - t_s}\right) \quad , \qquad (6)$$

where $g(t)$ is the fraction of construction completed prior to time t and t_c-t_s is the total time required to complete the construction project. Equation (6) gives approximately the same results as the correlation in Ref. 18. It also agrees with the construction spending profiles in Refs. (20) and (21).The escalation multiplier F_{esc} for the reactor is determined from the following integral.

$$F_{esc} = \int_{t_s}^{t_c} e^{(r + r_{inf}) \cdot (t - t_s)} \cdot dg(t) \quad , \qquad (7)$$

where r_{inf} is the average rate of inflation during construction. The average rate of inflation is based on the CE/PCI. Integrating Eq. (5) gives the following expression for F_{esc}.

$$F_{esc} = \frac{\pi^2}{2\cdot\left(\pi^2+\left(r+r_{inf}\right)^2\right)} \cdot \left(1 + e^{\left(r+r_{inf}\right)\cdot\left(t_c-t_s\right)}\right) . \quad (8)$$

A similar expression can be derived for the interest rate factor, F_{int}.

$$F_{int} = \frac{\pi^2}{2\cdot(\pi^2+R^2)} \cdot \left(1 + e^{R\cdot(t_c-t_s)}\right) , \quad (9)$$

where R is the interest rate.

The model contains three adjustable parameters – C_{ref}, C_{ct}, and r. We evaluated these parameters using a nonlinear least-squares fit of the model to data for 97 commercial nuclear power plants in the US. The model accounts for 87% of the variance in the cost data. The fitted values for C_{ref} and C_{ct} are \$106/kWt and \$5.9/kWt respectively. C_{ct} is 6% of C_{ref}, which indicates that cooling towers have not been a major contributor to the overall cost of a nuclear power plant. The fitted value for r is 10.7%, which indicates that the cost of constructing a nuclear power plant between 1965 and 1989 increased at a rate that was much greater than the underlying rate of inflation. A more detailed analysis of the data reveals no evidence that the TMI accident changed the rate of increase.

3.4. Discussion of Data for Existing Nuclear Power Plants

The TMI accident in 1979 is often viewed as a turning point in the US nuclear power industry. Public support and utility company interest in nuclear power began to decline after the TMI accident. Cohen compared the cost of nuclear power plants completed in the early 1970s to those completed in the 1980s and noted a drastic increase in cost.[22] By comparing pre-TMI and post-TMI accident costs, the author seems to imply that increase in the cost of constructing a nuclear power plant after 1979 was a result of increased regulation in response to the TMI accident.

The data plotted in Figs. 5 and 6 and the results of our econometric model do not support the claim that a dramatic increase in nuclear power plant construction cost occurred in the aftermath of the TMI accident. Costs were increasing before the TMI accident and continued to increase after the accident. Regulatory creep, the continual increase in number and strictness of rules and standards, is the likely cause of increase in nuclear power plant costs between 1965 and 1990. For example, Section III of the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code, Rules for Construction of Nuclear Facility Components, expanded from one volume when it was first published in 1963 to 12 volumes in the current edition. The entire ASME code currently consists of 28 volumes. Mooz[17] and Cohen[22] both noted the impact of regulatory creep on nuclear power plant construction costs.

Cohen[22] noted the variation in the cost of nuclear power plants completed after 1979. He postulated that this variation was the result of differences in way different companies managed of the changing regulatory environment. Cohen asserted that companies that were effective in anticipating and managing the changing regulations were able to complete their projects at a much lower costs than companies that did not effectively manage the changes. This hypothesis is consistent with Merrow's findings concerning the impact of regulations on cost growth,[14] but Cohen did not provide any supporting evidence.

3.4. Escalation of Advanced Reactor Designs

The AP-1000 reactor, which is illustrated in Fig. 9, is Westinghouse's advanced reactor design. Four AP-1000 reactors are currently under construction in the US. Construction of Summer Units 2 and 3 began on March 9, 2013. Three days later, construction began on Vogtle Units 3 and 4. The cost estimates for the advanced reactor designs have increased dramatically since 2000, as shown in Fig. 10. In 2000, the construction costs for the advanced reactor designs were slightly over \$1000 / kWe. The sources of these early estimates were vendors (i.e., Westinghouse and General Electric) and advocates of nuclear power.

These parties had an interest in promoting optimistic estimates of the cost of building a new nuclear power station.

After the design certificate for the AP-1000 reactor was issued on January 27, 2006, several US utilities began to consider building new nuclear power plants. The prospect of signing a multi-billion dollar contract forced the utilities as well as the vendors to make more inclusive, more accurate cost estimates. When owner costs, such as land, cooling towers, switch yards, interest during construction, were included in the analysis, the utilities found that the total project cost were much greater than the earlier vendor estimates.[23] The increase represents an increasing degree of realism as the prospects of actually constructing a plant increases.

The increasing realism and accuracy are not the only reason the estimated cost of new nuclear reactor is increasing. Real cost growth is also occurring. Figure 11 plots cost estimates for proposed new reactors with the data for existing nuclear reactor that shown previously in Fig. 5. The data, although limited, indicates that the cost of a nuclear power plant is still increasing but at a lower rate than in the past. When we applied the model described in the previous section to the data for the proposed new reactors, we found that cost are increasing at a rate of 0.7 percentage points greater than the general rate of inflation.

This result is not surprising. From 1997 and 2007 the Handy-Whitman index for all steam plus nuclear generating plants increase at an average rate of 4.1% per year while the consumer price index increase at an average rate of 2.4% per year.[24] Labor costs have also increase faster than the general rate of inflation. Based on data from the Bureau of Labor Statistics, the average rate of increase in the cost of labor for manufacturing and construction was 0.5 percentage points greater than the general rate of inflation between 1979 and 2013.

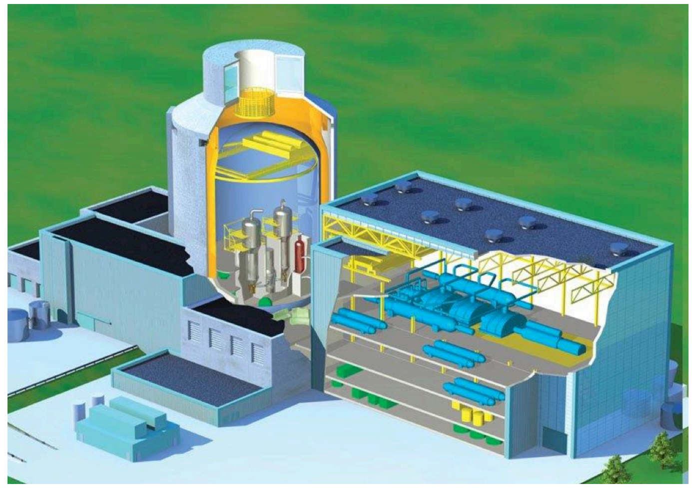

Fig. 9. A cutaway diagram of an AP-1000 nuclear power plant.

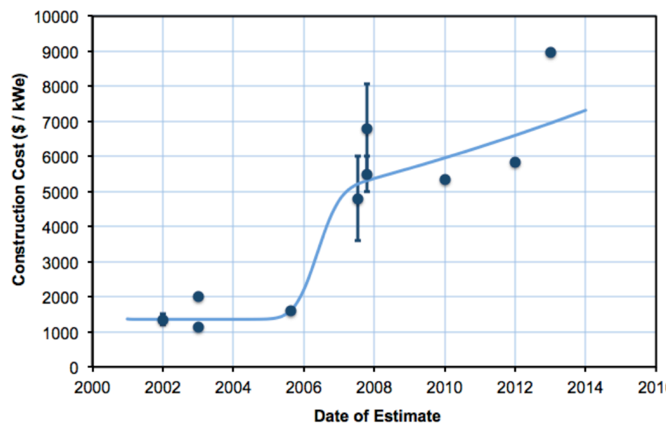

Fig. 10. Cost estimates for advanced nuclear reactor designs as a function of time.

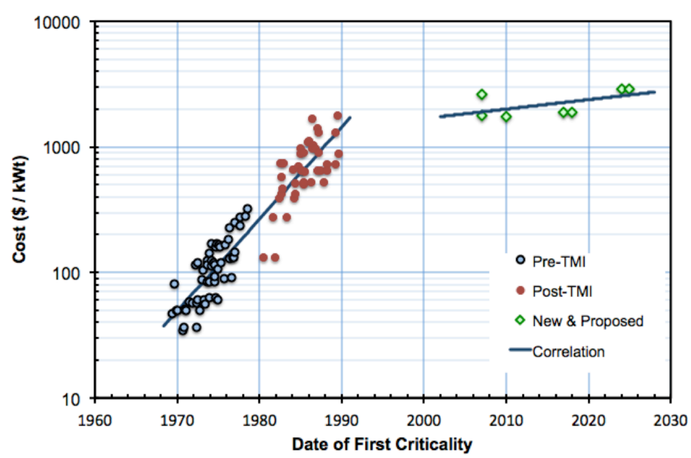

Fig. 11. Commercial nuclear power plant costs as a function of the date of the first criticality including current construction and proposed plants.

3.5. *Summary of Light Water Reactors*

The cost of building a light-water reactor in the US historically has increased faster than the general rate of inflation. The cost increases were substantial both before and after the TMI accident in 1979. The average rate of increase was about 10 percentage points greater than the CPI. Cost escalation for the advanced reactors currently under construction has moderated, but cost are still increasing faster than the generate rate of inflation. Based on the limited data available, cost is increasing at about 0.7 percentage points greater than the CPI.

The high rate escalation for nuclear power plant construction is most likely due to regulatory creep. In the 1960s, nuclear power was new; and because of the potential magnitude of the hazards, a new regulatory regime was required. The newness of the technology and regulatory regime resulted in an evolving set of rules that drove cost higher. In 1989, the US Nuclear Regulatory Commission (NRC) established a new more efficient process for licensing nuclear power plants (10 CFR Part 52). The new process provides for certification of standardized designs, early site approval, and combined construction and operating licenses. The new licensing process should reduce uncertainty and minimize regulator creep. Furthermore, now that the regulatory regime for light-water reactor construction and operations is well established, future changes to the regulations are likely to be moderate.[‡‡] Hence, cost increases for new nuclear power plants currently under construction are projected to be much less than plants constructed in the 1960s and 1970s. However, this alternative regulatory regime has not been fully exercised; so its effectiveness in reducing cost growth has not been demonstrated.

4.0 *LARGE DEPARTMENT OF ENERGY PROJECTS*

The primary purpose of this review was to examine and understand cost growth of DOE nuclear facility construction products. In the previous sections, we examined cost growth for a nuclear and non-nuclear megaprojects. We examined cost growth data for 11 large DOE nuclear and radiological facilities using data from DOE budget requests, General Accounting Office (GAO) reports, and miscellaneous news reports.

4.1. *Facility Summaries*

4.1.1. *Defense Waste Processing Facility*

The Defense Waste Processing Facility (DWPF) immobilizes high-level nuclear waste at the Savannah River Site for storage and ultimate disposal. The original estimate for the total project cost was $1.53 billion and the planned hot startup date was first quarter 1991.[25,26] By 1992, the total project cost increased to $1.87 billion and the hot startup date was moved to November 1992. Finally, radioactive operations began in March 1996 and the total project cost was $2.47 billion. DWPF experienced significant delays and increased costs as a result of problems with the technology.

Fig. 12. Defense Waste Processing Facility (DWPF).

4.1.2. *National Ignition Facility*

The National Ignition Facility (NIF) is a laser-based inertial confinement fusion research device, located at the Lawrence Livermore National Laboratory. DOE approved the project in January 1993 with an estimated cost of $1.1 billion and a 2002 completion date.[27] An addition $1.0 billion was allocated to the Inertial Confinement Fusion (IFC) Program for

[‡‡] If the US pursued the construction of commercial fast reactors or gas-cooled reactors, there would be a period of developing regulations, which would result in large cost growth for these new reactor types.

research and development in support of NIF. Construction began in May 1997. In 2001, the project was re-baselined and $1.2 billion dollars was moved from the ICF program to NIF.[28] The new estimate for total project cost was $3.45 billion of which $1.35 billion represented a real increase over the initial total project cost plus research and development cost. The new completion date was estimated to be 2008. NIF was dedicated in May 2009 with a total project cost of $3.50 billion.

Fig. 13. National Ignition Facility.

4.1.3. MOX Fuel Fabrication Facility

The Mixed Oxide (MOX) Fuel Fabrication Facility (MFFF) is a 600,000 ft^2 facility that will combine plutonium oxide with uranium oxide to produce MOX to burn in light water nuclear reactors. DOE approved the MFFF mission in 1997 (CD-0), and they approved conceptual design in 1999 (CD-1). In 2000, the total estimated cost, which is only the cost of the structure, was $383 million; and the estimated completion date was third quarter 2005.[29] DOE approved the start of construction (CD-3) in April 2007. At that time the total estimated cost was $3.23 billion, the total project cost was $3.63 billion, and the estimated completion date was third quarter 2014. In February 2014, the estimated total project cost increased to $7.68 billion, and the completion time was delayed until November 2019.[30] Currently (April 2014), MFFF is approximately 70% complete.

Fig. 14. MOX Fuel Fabrication Facility.

4.1.4. Hanford Waste Treatment Plant

The Hanford Waste Treatment Plant (WTP) has a long and complicated history. The initial plan in 1989 was to treat only part of the 57 million gallons of waste from nuclear fuel reprocessing that is stored in 177 underground tanks at the Hanford Site.[31] Construction was to have started in 1991, and the estimated cost was $920 - 965 million.[32] In 1991, DOE revised the scope of the project to include treatment of the waste in all 177 waste storage. In 1995, DOE embarked on a new approach to treating the waste at the Hanford Site known as "privatization." The plan was to bid a fixed-

Fig. 15. Hanford Waste Treatment Plant

price contract to build a plant and process the waste. DOE approved the mission (CD-0) in 1996, and they approved the conceptual design (DC-1) in 1998. The estimated cost was $6.9 billion including operation of the plant. By 2000, the estimated cost had increased to $16 billion. The contractor at this time was British Nuclear Fuels Limited (BNFL) Because of cost growth, DOE abandoned the fixed-price contract in 2000 and replaced BNFL with Bechtel National, Inc.

The current WTP project began in 2000 with an estimated cost of $4.3 billion and an estimated completion date of 2011. BNFL's preliminary design (CD-2) was approved in 2000, and construction was approved in 2002 (CD-3). The WTP would consist of four major structures plus supporting facilities. The major structures are the Pretreatment Facility, the Low Activity Waste Facility, the High Level Waste Facility, and the Analytical Laboratory. Construction was started before detailed design was substantially completed. In 2005, the total project cost was estimated to be $5.78 billion.[33] In 2006, the baseline cost estimate was revised to $12.3 billion with a completion date of 2019.[31] A 2011 DOE Headquarters review reached the conclusion that $800 - 900 million additional funds would be needed to complete WTP. In May 2013, the estimated cost of WTP had increased to $13.4 billion and an additional $2 - 3 billion will likely be needed to address technical problems in the Pretreatment facility.[31]

4.15. WTP Pretreatment Treatment Facility

The Pretreatment Facility is the largest and most expensive structure in the WTP. This 490,000 ft^2 facility accounts for about 44% of the total WTP cost. Also, the most serious technical problems at the WTP involve the Pretreatment Facility. Therefore, we singled out this structure for independent consideration. In 2003, the estimated cost of the Pretreatment facility was $1.9 billion. When a new WTP baseline was established in 2006, the cost of the Pretreatment Facility grew to $2.3 billion. The most recently available cost estimate for the Pretreatment Facility is $4.9 billion, which was made in 2009.

4.1.6. Pit Disassembly and Conversion Facility

The Pit Disassembly and Conversion Facility (PDCF), which was to be located at the Savannah River Site, was designed for dismantling excess nuclear weapons pits and preparing plutonium oxide suitable for use in MOX fuel. DOE initiated the project in 1997. Preliminary design was completed in 2003. The initial cost estimate for this 230,000 ft^2 was $347 million. The estimated cost grew to $4.8 billion in 2011. DOE suspended the project due to budgetary constraints.

4.1.7. Chemistry and Metallurgy Research Building Replacement

The Chemistry and Metallurgy Research Building Replacement (CMRR) at LANL was intended, as its name implies, to replace the aging Chemistry and Metallurgy Research Building. The facility was to have consisted of two buildings – the Radiological Laboratory, Utility, Office Building (RLUOB) and the Nuclear Facility (CMRR-NF). DOE authorized the mission need (CD-0) in July 2002 and approved the conceptual design (CD-1) in May 2005.[34] The target cost at CD-1 was $850 million with $164 million for RLUOB. The cost range was $745 - 975 million with a completion date between 2013 and 2017.[35] Detailed design and construction of RLUOB were approved in October 2005 (CD-2 and CD-3).[36] The RLUOB structure was completed in June 2010 and equipment installation was completed in 2013. Detailed design and construction of the 403,600 ft^2 CMRR-NF were to be approved in stages beginning with the infrastructure package in March 2011 and ending with the balance of project package in March 2014.

Fig. 16. An artist's rendition of the Chemistry and Metallurgy Research Building Replacement.

However, CMRR-NF was plagued with problems and delays. Modifications to the seismic design added $500 million to the price tag and delays added another $1.2 billion.[35] By April 2010 the cost estimates had increased to $3.7 - 5.8 billion with a completion date of 2020. In response to the large cost growth, the National Defense Authorization Act for fiscal year 2013 stated that CMRR shall not exceed $3.7 billion. Since 2013, DOE has delayed the start of CMMR-NF construction by at least 5 years.

Fig. 17. Salt Waste Processing Facility

4.1.8. Salt Waste Processing Facility

DOE built DWPF to vitrify concentrated high-activity waste at the Savannah River Site into a stable form and the Saltstone Facility to immobilize and dispose of low-activity decontaminated salt waste. To effectively use these facilities for disposing of liquid radioactive waste, DOE needed additional capability for separating and concentrating high-activity constituents from the salt waste. The Salt Waste Processing Facility is a 142,000-ft^2 structure that will provide this capability. This mission need for SWPF (CD-0) was approved in June 2000 and conceptual design (CD-1) was completed in 2004.[37] The initial estimate of total project cost was $438 million with a third quarter 2009 completion date. Preliminary design was completed (CD-2) in 2007 and detailed design was authorized. DOE authorized construction (CD-3) in the fourth quarter of 2008. At that time the estimate of total project cost had increased to $899 million and the completion date was moved out to 2011. In 2012, the total project cost was estimated to be $1.34 billion and the completion date was estimated to be 2016.

4.1.9. Highly Enriched Uranium Materials Facility

The DOE built the 140,000-ft^2 Highly Enriched Uranium Materials Facility (HEUMF) to consolidate highly enriched uranium (HEU) storage at the Y-12 complex in Oak Ridge, Tennessee. In 2001, the estimated cost of this facility was $181 million with a 2005 completion date.[28,29] When the approved performance baseline (CD-2) was authorized in 2004, the estimated total project cost was $251 million.[38] HEUMF was completed in 2008 with a total cost of $581 million.

4.1.10. Uranium Processing Facility

The Uranium Processing Facility (UPF) was to be a replacement for aging HEU processing and component manufacturing at the Y-12 complex in Oak Ridge. DOE approved the mission for the UPF (CD-0) in December 2004. At that time, the estimated cost of this 350,000-ft^2 facility was $800 - 1100 million with a 2012 startup date.[39] When preliminary design was completed (CD-1), the cost of UPF had grown to $1.4 - 3.5 billion and the startup date was moved to 2018. In 2010, the CD-1 estimates were updated to $4.2 - 6.5 billion and the startup date was moved to 2022. The US Army Corps of Engineers (COE) performed an independent cost analysis in 2011. They estimated that the facility would cost $6.5 – 7.5 billion if an optimal construction schedule were followed that would lead to completion of the facility in 2023. If budget constraints delayed completion of the UPF

Fig. 18. Highly Enriched Uranium Materials Facility.

until 2034, the COE estimated that the costs would increase to $10.3 - 11.6 billion. The GAO reported that the National Nuclear Security Administration (NNSA) directed the site contractor, Babcock and Wilcox, to use the estimated cost to construct the HEUMF as the basis for the UPF cost estimate.[39]

Fig. 19. Artist's conception of the Uranium Processing Facility

4.1.11. LANL Transuranic Waste Staging Facility

The LANL Transuranic (TRU) Waste Staging Facility will be a staging facility for newly generated waste destined for the Waste Isolation Pilot Plant (WIPP). This facility will replace a number of existing buildings and fabric domes. The cost estimate based on the conceptual design was $85 million with a range of $71 - 124 million, and the target completion date was 2015.[40] The final cost of the facility is expected to be $96 million.

4.2. Summary of Facility Data

4.2.1. Facility Cost Data

Figure 20 summarizes the cost estimate histories for the 11 facilities described in the previous section. The evolution of the cost estimates for a DOE project follows a pattern similar to the cost estimates for nuclear power plants shown in Fig. 10. The initial cost estimate is low. After the initial estimate is made, cost estimates will fluctuate or grow slowly for some period of time. Eventually, a point is reached in the evolution of a project at which a large increase in the cost estimate occurs. After the large increase has occurred cost growth continues at a more moderate rate.

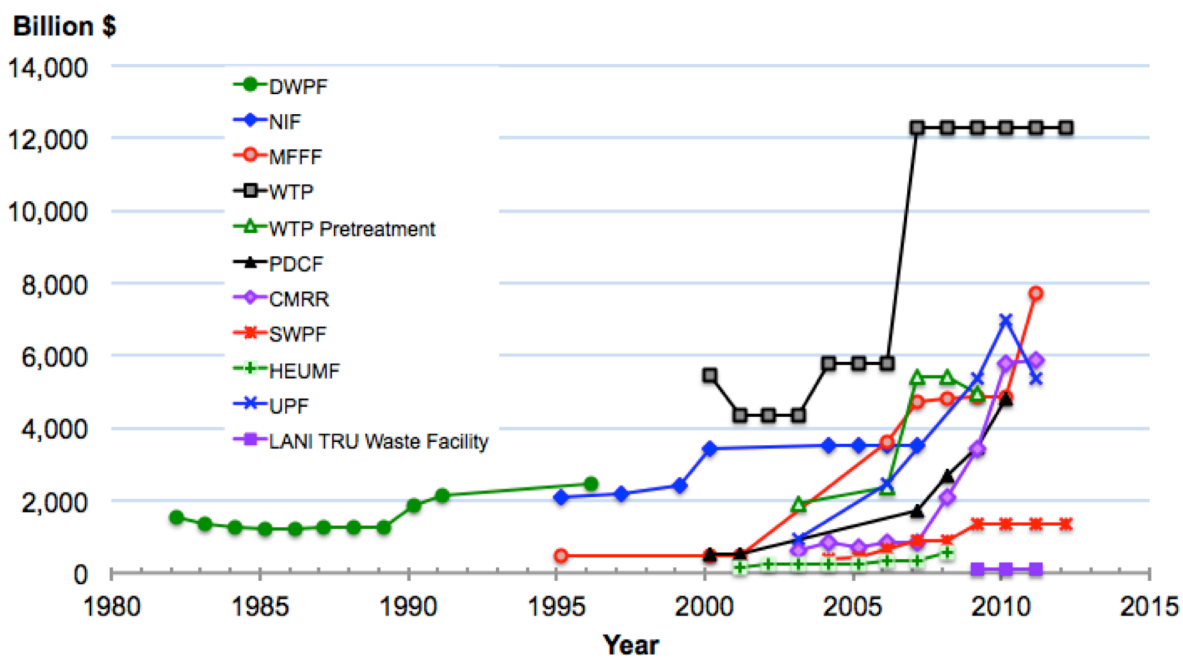

Fig. 20. Cost estimate histories for DOE Projects.

For DOE projects, the large increase in estimated cost occurs when the project baseline is established (CD-2). Cost growth once the baseline has been established is comparable to that experienced for other private and public megaprojects. The period from CD-2 until the completion of the project corresponds approximately to the period spanning from the beginning of detailed design to completion of the project, which was the period considered in the Rand Corporation's study of cost growth for megaprojects.[14] Figure 21 shows the final cost or most recent cost estimate plotted as a function of the baseline cost estimate at CD-2. PDCF, CMRR, and UPF are not shown on this plot because they had not progressed beyond CD-2. Figure 21 also shows lines represent the mean, minimum, and maximum cost growth from the Rand study. The figure shows that cost growth for new DOE nuclear facilities after the baseline is established is similar to the cost growth experience in other megaproject.

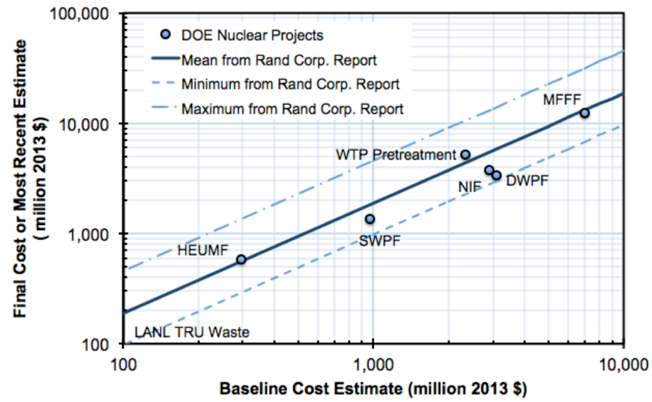

Fig. 21. Final cost versus baseline cost estimate for new DOE nuclear facilities.

Cost growth between the initial estimate and the establishment of a project baseline is large. Figure 22 is a plot of the project baseline or most recent estimate if the baseline has not been established as a function of the initial estimate. The lower line in the figure represents perfect initial estimates (i.e., baseline = initial estimate). The average cost growth for the six projects shown in Fig. 22 is about a factor of 6. The data can be represented by a power-law relationship.

$$C_{baseline} = 0.043 \cdot C_{initial}^{1.75} \ , \qquad (10)$$

where $C_{baseline}$ is the baseline cost estimate in million dollars and $C_{initial}$ is the initial estimate in million dollars. The correlation coefficient (r^2) for Eq. (10) is 0.86. According to this correlation, the ratio of baseline cost to initial cost is given by the following equation.

$$\frac{C_{baseline}}{C_{initial}} = 0.043 \cdot C_{initial}^{0.75} \ . \qquad (11)$$

The ratio of baseline to initial cost estimate measures the escalation that occurs prior to establishing the baseline. This ratio increases with the magnitude of the initial cost estimate, which implies that cost growth during the initial phase of a DOE project tends to be greater for large projects than small projects.

Figure 23 shows real cost growth for new DOE nuclear facilities from the initial or earliest available estimate to the final cost or most recent estimate. Real cost growth is the increase in cost above the general rate of inflation. We divided the projects into two categories – those with moderate cost growth

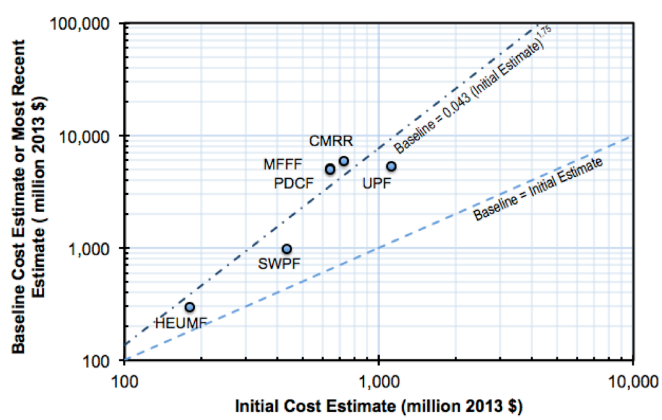

Fig. 22. Baseline cost estimate versus initial cost for new DOE nuclear facilities.

and those with extreme cost growth. We defined moderate cost growth as cost growth that is typical of other industries or an increase of less than 300% from the initial estimate. Extreme cost growth is a cost growth atypical of other industries. For facilities that experienced moderate cost growth, no statistically significant change in the accuracy of the initial estimate with time (r^2 = 0.16). For facilities that have experienced extreme cost growth, the magnitude of the cost growth is decreasing with time. However, caution must be exercised when interpreting Fig. 23. MFFF construction is approximately 70% complete while construction was never started for PDCF, CMRR, and UPF. The trend in Fig. 23 may be indicative of project maturity rather than improvements in the initial cost estimates.

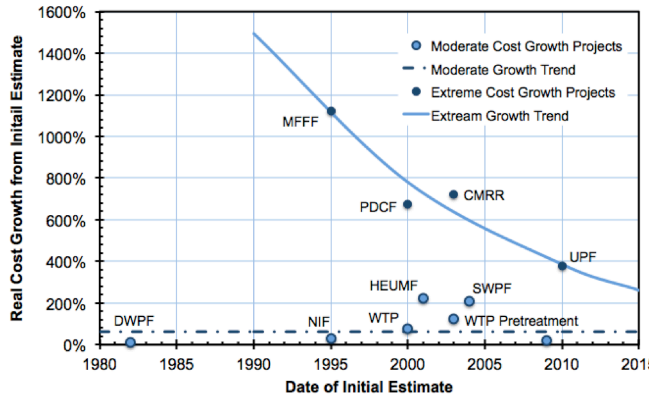

Fig. 23. Total cost growth for new DOE nuclear facilities.

Early cost estimates (AACE International Class-4 and -5 estimates) are based on empirical models. The cost of a building is often expressed a cost per square foot of floor space. Floor space data was available for 7 of the 11 facilities listed in Section 4.1. Figure 24 is a plot of the cost of these seven facilities as a function of gross floor area. These data are best represented by as simple proportionality, which is a straight line with an intercept of zero. The slope of this line is $13,200 per square foot in 2013 dollars, and the correlation coefficient (r^2) is 0.79. This simple model implies that the cost of a DOE nuclear facility per square foot is constant, which is reasonable because the cost of a building per square foot of floor area is only a weak function of the total floor area.[41] Furthermore, the cost per square foot of large facilities that hold or process nuclear materials does not depend of the buildings specific function (i.e., laboratory, manufacturing, or storage). The uncertainty in this simple model is ±65%, which makes it appropriate for an AACE International Class-5 estimate.

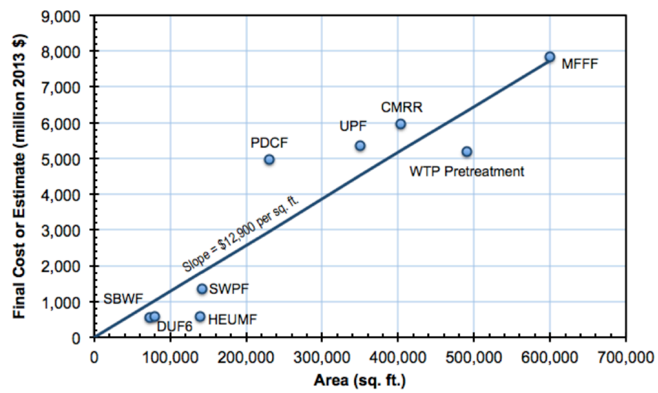

Fig. 24. Cost of a new DOE nuclear facility as a function of floor area.

4.2.2. Construction Time and Delays

Figure 25 shows construction time as a function of total construction cost for GTL plants, US commercial nuclear power plants completed prior to the TMI Accident, and recent DOE nuclear facilities. As expected, construction time increases with the cost of the facility. This relationship can be represented by the following correlation.

$$\theta = \alpha \cdot C^{0.25} \quad , \qquad (12)$$

where θ is the construction time in years, C is the construction cost in million 2013 dollars, and α is a constant that depends on type of facility. The figure shows that nuclear power plants take twice as long to build as a GTL plant with the same costs. A GTL plant has a much greater degree of modularity than a nuclear power plant, which allows a greater fraction of the construction tasks for a GTL plant to be accomplished in parallel. New DOE nuclear facilities require about twice as much time to construct as a commercial nuclear power plant. Budgetary constraints are the most likely reason that construction time for DOE nuclear facilities require longer than construction time for other facilities with comparable cost. The amount of work that can be accomplished on a DOE project in a given year is limited by the available funds and not schedule constraints.

Schedule slippage and delays are another reason DOE construction projects require more time to complete than other projects with comparable cost. All new DOE nuclear facilities experience require more time to compete than initially estimated. Figure 26 shows the schedule slippage relative to the initial estimate of the completion date. The increases in construction times are significant ranging from 2 to 16 years.

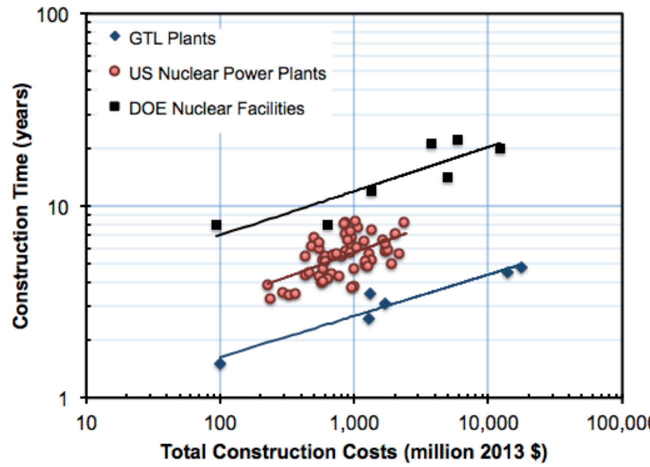

Fig. 25. Construction time as a function of cost.

Lengthy construction schedules and delays increase the cost of new facilities as a result of additional inflation and schedule inefficiencies. The COE evaluated the impact of increased construction time on total cost for the UPF. They considered two scenarios – an optimum schedule and a budget constrained schedule. Total construction time for the optimum schedule was 13 years. In the budget-constrained case, the maximum annual spending was assumed to be $500 million, and the construction time increased to 25 years. Figure 27 shows the spending profiles for these two scenarios. The cost estimate was $ 6.5 - 75 billion for the optimum scenario and $ 10.3 - 11.6 billion for the budget-constrained scenario. This difference translates into an average escalation rate of 6.6% per year. The average annual increase in the consumer price index since 1980 has been 3.0%. Cost increases due to extending the UPF schedule are greater than the general rate of inflation.

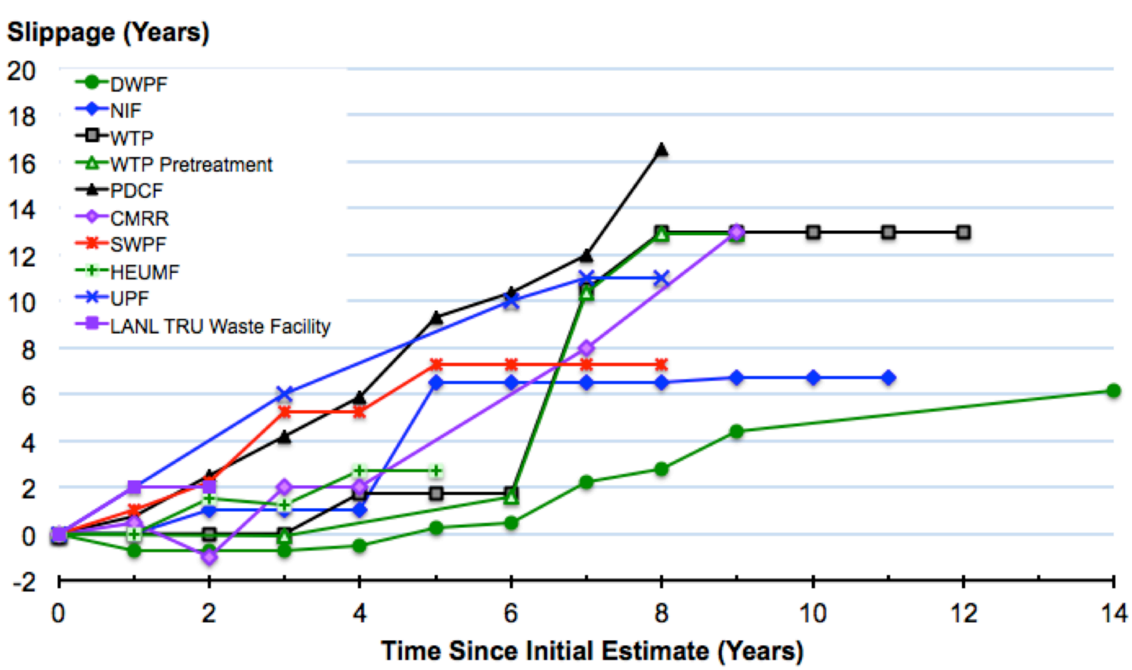

Fig. 26. Increase in the estimated construction time as a function of time since the initial estimate.

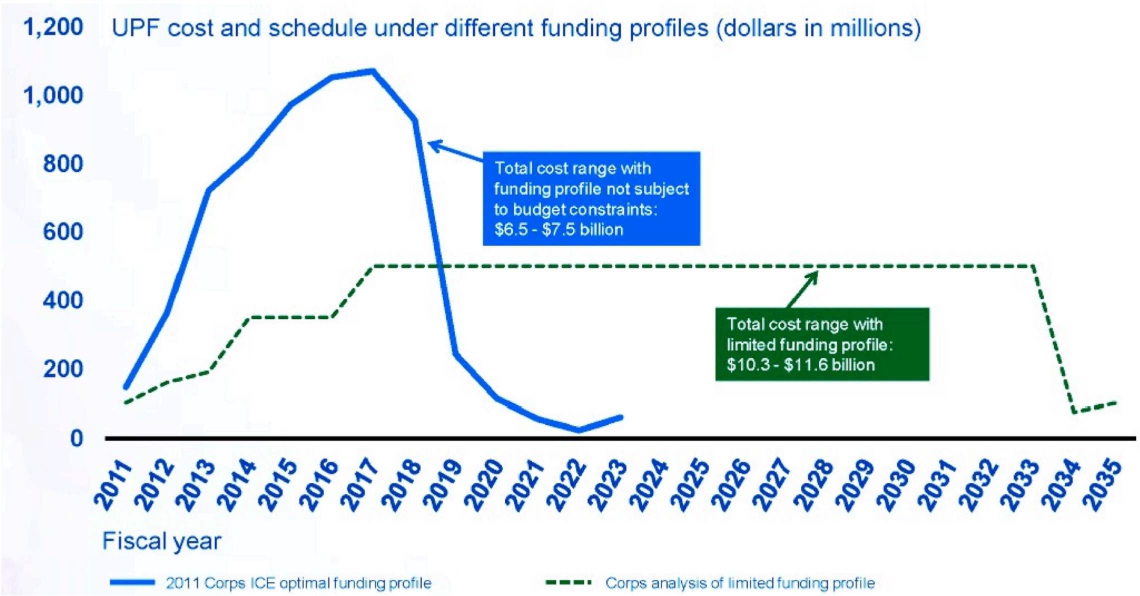

Fig. 27. UPF construction spending for optimum schedule and budget constrained schedule.[39]

4.3. Discussion of DOE Cost Data

To understand sources of errors in cost estimates for new DOE nuclear facilities, it is useful to consider estimates made after CD-2 separately from estimates made before CD-2. Cost estimation methodology used after CD-2 differs from the methodology used before CD-2. Also, the sources of errors and cost growth after CD-2 differ from sources of errors and cost growth before CD-2.

4.3.1. Post CD-2 Cost Growth

In this section, we consider how cost growth from CD-2 to CD-4 for a DOE nuclear facility compares with cost growth during the corresponding period in the design and construction of a non-DOE project. Our basis for evaluating cost growth is the results of Merrow's study.[14] To make this comparison, we need to determine the factors in Eq. (2) that are appropriate for a DOE nuclear facility.

According to Merrow,[14] the primary source of cost growth for large DOE nuclear facilities should be regulatory problems during detailed design and construction. Merrow noted that nuclear reactors encounter more regulatory problems during construction than other megaproject. He also noted that government-owned enterprises encounter fewer regulator problems than privately owned enterprises. According to Merrow's analysis, a government owned nuclear facility should experience fewer regulatory problems during design and construction than a privately owned nuclear facility. Therefore, we assumed that the number of regulatory problems that a DOE nuclear facility construction project encounters between C-2 and C-4 is less than a nuclear reactor but greater than a petrochemical plant.

Other important factors in Eq. (2) are ownership of the facility, inovation, and infrastructure. Merrow identified public ownership as a significant contributor to cost growth, and DOE facilities are publicly owned. Use of new technology, new materials, and new construction techniques contribute to cost growth. Most DOE nuclear facilities do not involve new technology, new materials, or new construction techniques; so we neglected factors related to innovation in our cost growth comparisons. Exemptions to this generalization exist of which the WTP Pretreatment Facility is the notable example. Because new DOE nuclear facilities are being build on existing sites, infrastructure should not be a major contributor to cost growth.

According to the correlation developed by Merrow (Eq.2), the expected cost growth after CD-2 should be between 100% and 230% of the baseline cost estimate. Cost growth for new DOE nuclear facilities is relatively relative to this range. Of the seven facilities plotted in Fig. 21, six have an overall cost growth less than 100%. The worst case is the WTP Pretreatment Facility which as experienced a 120% cost growth to date. Cost growth for new DOE nuclear facilities is also modest when compared with the GTL plants listed in Table 2. The cost growth for these GTL plants is between 40% and 490%. Cost growth for new DOE nuclear facilities is also modest when compared with nuclear power plants. For plants completed before 1988, the average cost growth was about 160%.[14] Cost growth for the Votgle Nuclear Power Plant, which was completed in 1989, was 590%.

Once the project baseline has been established, DOE is generally no better or worse at controlling cost growth for new nuclear facilities than other industries are at controlling cost growth for megaprojects. While growth is undesirable and every practical means should be taken to minimize it, we could identify no problem that is unique or special to DOE.

4.3.2. Pre CD-2 Cost Growth

Often, early cost estimates for new DOE nuclear facilities are overly optimistic. Cost growth from the initial estimate has exceeded 600% for several proposed projects. Overly optimistic early estimates are not unique to DOE. Figure 10 shows that early cost estimates for advanced nuclear reactor designs were also overly optimistic.

Errors in the early cost estimates do not necessarily imply incompetence on the part of the estimators. The word “estimate” implies uncertainty. Cost estimates can be either high or low, but for a variety of reasons they are usually low. We identified three likely causes for low initial estimates for new DOE nuclear facilities – faulty base-cost estimate, underestimating escalation, and inadequate contingency.

Faulty Base Cost Estimate – The base cost estimate is the best estimate of the cost without allowances for inflation, errors and omissions, and project risk. The “bottom-up” approach to cost estimation favored by engineers and the construction industry tend to be overly optimistic.[14] During the early stages of a project, when the degree of project definition is low, many aspects of the project may not specified or readily apparent. When such methods are used, items that are not readily apparent to the estimator are usually fixed at zero, which results in a biased estimate. For example, early cost estimates for advanced nuclear reactor designs did not include owner costs, such as land and the switch yard, which resulted in underestimating the ultimate cost.

Early cost estimates are most often AACE International Class-5 and Class-4 estimates.[42] Class-5 estimates are based on empirical models, judgment, and analogy. Class-4 estimates are based primarily empirical models. Large DOE nuclear facilities are typically one-of-a-kind installations with no analog in the private sector, including nuclear power plants. These large nuclear facilities are often beyond the realm of experience, and early cost estimates based on empirical correlations and experience are extrapolations. The lack of data and relevant experience can result in large errors.

Under Estimating Escalation – Escalation is the amount added to the estimated base cost to provide for procurement at a future date.[41] Escalation accounts for inflation, and the adjustment to the base estimate to account for inflation depends on the underlying inflation rate and the time required for completing the project.

The National Nuclear Security Administration (NNSA) specifies the annual inflation rates that are to be used to determine cost estimates.[42] Figure 28 shows that the cumulative escalation based on the inflation rate set by the NNSA was approximately the same as the actual CPI for the five year period beginning in 2002. For this same period, the Producer Price Index, the Chemical Engineering Building Index, the CE/CPI, and the Handy-Whitman Index for power plants increased faster than the consumer price index. As discussed in Sections 3.2 – 3.4, construction costs for nuclear power plants built in the US have historically increased faster than the CPI. Also, as noted in Section 3.4, the Employment Cost Index increases faster than CPI. The comparisons indicate that the escalation rate for new DOE nuclear facilities is generally underestimated.

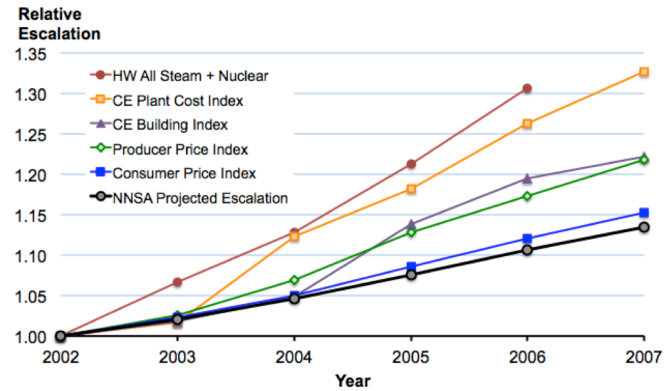

Fig. 28. Cumulative cost escalation for various cost indices.

Figure 26 shows that the initial estimates for completion dates for new DOE nuclear facilities are optimistic. Making an overly optimistic estimate of the completion date is the same as under estimating the construction time. Underestimating construction time results in underestimating escalation, which results in underestimating cost. Underestimating construction time may be due in part to a failure to account for budgetary constraints in the early phases of a project. Figure 25, also suggests that underestimating construction time could be the result of a biased cost estimation methodology. The combination of underestimating the escalation rate and construction time will result in low cost estimates.

Inadequate Contingency – The AACE defines cost contingency as "an amount added to an estimate that experience shows will likely be required." This amount may be derived from a statistical analysis of data or by applying experience gained from similar projects. Contingency usually does not include a change in scope or unforeseeable major events.[43] The amount of contingency will depend on the status of the design. Cost contingency is greater during the early stage of a project when the degree of project definition is low than it is during the latter stages of a project. Various organizations have recommended project contingency allowances. Typical values are 50% for early planning and 40% for conceptual design.

Contingency is often viewed as "padding" the estimate – a way to avoid the work needed to develop accurate estimates.[44] DOE has stated that contingency "is not to be used to avoid making an accurate assessment of the expected cost."[45] In an effort to remove padding, contingency is often limited to a fixed percentage of cost. NNSA has established contingency benchmarks. For AACE Class 5 estimates, the contingency benchmark is 20 - 30% for normal conditions and up to 50% for experimental or special conditions.[42] The NNSA states that the benchmarks are "intended to ensure the appropriateness if the contingency included in any project." Although the NNSA advocates a project specific, analytical approach to determining contingency, this statement concerning appropriateness discourages the use of larger values for contingency.

It is generally agreed that the median cost estimate is best for project management and control.[44] Base cost estimates tend to be biased. The most obvious reason for this bias was discussed earlier in this section. In the absence of specific information, the costs of items that are not readily apparent when the estimate is made are assumed to be zero. Another subtle source of bias also exists. Estimators typically use the most likely values when making point estimates. If the distribution of errors is skewed, the most likely value is not equal to the median. If the uncertainty in the estimate is large, as is the case for estimates made in the early stages of a project, the distribution of errors will be skewed and the most likely value of the cost may be much less than the median cost.

If the earliest cost estimates for the 11 facilities considered in this study were unbiased (i.e., the median error is zero), the probability that all would be less than the ultimate cost would be about

0.05%. Therefore, we conclude that these early estimates are biased, which suggests that the DOE and NNSA recommendations for contingency are inadequate. The DOE Office of Waste Management found that the contingency costs recommended in the various technical standards are inadequate if the project involves a process.[46] For a conceptual design phase of a project involving a process, they recommend a contingency cost of 70 – 110% of the base cost estimate.

To evaluate the importance of these three factors that affect the accuracy of early cost estimates, we made independent cost estimates for CMRR and UPF using only the data that was available at the time the initial estimates were made and NNSA's guidance concerning escalation and cost contingency. To determine the sensitivity of the estimate to escalation rate and contingency, we estimated the cost using alternative assumptions for escalation and contingency. The escalation rates were based on the CE/PCI and a cost contingency based on the Office of Waste Management's guidance.[46] The results are given in Table 4.

Our independent cost estimates for CMRR and UPF are greater than DOE's initial estimates. However, these estimates are still much less than the most recently available DOE cost estimates. When NNSA's assumptions for contingency and escalation were used, the estimate cost were approximately 1/5 of the most recent DOE estimate. The alternative assumptions yield results that are about 50% greater than the results obtained with the NNSA assumption, but the increases are not large enough to explain the large estimation errors. The cost estimates obtained with the alternative assumptions were approximately 1/3 the most recently available estimates.

The results in Table 4 indicate that, although inaccurate estimates of escalation and contingency have a significant impact on the cost estimate, they cannot account for the large errors in DOE's initial cost estimates for CMRR and UPF. The major source of error appears to be faulty base cost estimates. These initial estimates are AACE Class-5 estimates, which are derived primarily from empirical correlations. Because data is needed to benchmark the methodology, the cost estimates are, for the most part, unreliable extrapolations. This conclusion is consistent with the data plotted in Fig. 23, which shows that the magnitude of extreme errors in the initial cost estimates have been decreasing with time. As time passes, more relevant data and experience become cost available; and this additional data can be used to improve cost estimates.

Although DOE has been criticized for doing a not following accepted cost estimation practices, the large errors in the initial cost estimates for new DOE nuclear facilities appears to be the result of our lack of knowledge rather than a failure to follow cost estimating protocols.

Table 4. CMRR and UPF cost estimates based on data available when the initial estimates were made.

	CMRR		**UPF**	
Base Cost Estimate (million $)	830		720	
Assumptions	NNSA	Alternative	NNSA	Alternative
Cost Contingency (% of Base)	30	90	30	90
Escalation Rate (% per year)	2.65	4.0	2.65	4.0
Total Project Cost (million $)	1300	2000	1100	1700
Initial DOE Estimate (million $)	600		950	
Latest DOE Estimate (million $)	5860		5350	

It would be naïve to assume that cost estimates were deliberately made low to convince the funding agency to proceed with a project that they would otherwise reject as too costly or that cost estimators may be exposed to extreme management pressure to make optimistic cost estimates. However, we found no evidence that these practices are commonplace within DOE or other organizations.

5.0 CONCLUSIONS

5.1. Findings

Cost growth is a problem endemic to mega construction projects and not a problem that is unique to DOE. In analyzing cost growth, it is useful to divide a project into two phase – cost growth that occurs prior to establishing the project baseline (CD-2 for DOE nuclear facilities) and cost growth that occurs after the project baseline has been established.

Once the project baseline has been established, cost growth for new DOE nuclear facilities is no better or worse than other mega construction projects in both the private and public sector. While growth is undesirable and every practical means should be taken to minimize it, we could identify no problem that is unique or special to DOE.

Cost growth prior to CD-2 is large for new DOE nuclear facilities. Recent experience with advanced nuclear reactor designs suggests that this problem is not unique to DOE. However, the extent to which it is a problem in other sectors is not known. The primary cause of cost growth prior to CD-2 is inaccurate cost estimates due to a lack of relevant data and experience to needed to benchmark estimates. Other causes of cost growth are underestimation of escalation and inadequate contingency. Underestimation of escalation is the result of underestimating the rate of escalation as well as underestimating the construction time. The former is the result of using a CPI-based index rather than a more appropriate construction cost index. The latter is the result of a lack of relevant data for benchmarking early construction time estimates. Inadequate contingency is the result of a lack of relevant data as well as NNSA guidance, which discourages the use of large contingency factors for early estimates.

Early cost estimates are inherently inaccurate because of the low degree of project definition and because of limitations on the statistical models used for AACE Class-4 and -5 estimates. However, the large errors in early estimates for new DOE nuclear facilities pose problems. Early cost estimates are used to decide whether to initiate a project or to proceed to the next phase of the project. Underestimating cost can lead to the approval of a project that is ultimately too costly to complete. This failure wastes time and resource and delays consideration of alternatives. Underestimating the cost during the early stages of a project also feeds the unnecessary perception that DOE and DOE contractors are doing a poor job of controlling construction costs.

5.2. Recommendations

Cost growth for new DOE nuclear facilities, once the project baseline has been established, is typical of other mega construction projects, but matching the performance of other enterprises should not be an excuse for not trying to improve performance. Merrow found that faulty execution of a construction project is not a major cause of cost growth.[14] Efforts to reduce cost growth, therefore, should focus on improving the baseline cost estimate. Based on our review of DOE construction cost data and the observations and analyses of others, the following measures could improve baseline cost estimates and reduce cost growth.

> <u>Use an appropriate escalation rate</u>. Historically, the cost of nuclear facilities has risen faster than the CPI. Cost estimates could be improved by using an escalation rate appropriate for nuclear facilities rather than the CPI-based rate recommended by DOE.

Factor in the impact of budgetary constraints. Constraints on DOE's budget prolong the construction of new DOE nuclear facilities, which increases escalation and reduces the efficiency of construction activities. A realistic assessment of the impact of budgetary constraints is needed when establishing the project baseline.

Anticipate possible regulatory problems. Merrow[14] identified regulatory problems that arise during construction as a major source of cost growth for megaprojects. Regulatory problems can be minimized by thoroughly addressing existing regulations and anticipating regulatory changes prior to establishing the project baseline.

Account for the impact of new technologies. Merrow[14] found that cost growth was greater for project that used new technologies, new materials, and new construction techniques. The impact and risks of new technologies and schedules needs to be considered when establishing the project baseline.

Cost growth from the initial planning estimates to the establishment of the project baseline is unacceptably large. The cause of cost growth prior to establishing the project baseline is inaccurate initial estimates, so efforts to reduce cost growth from the initial estimate should focus on improving the accuracy of cost estimates made early in the life of a project. The following measures could improve the accuracy of early cost estimate.

Compile and analyze cost information for similar projects. Early cost estimates are typically based on empirical models and data. Therefore, the collection and analysis of cost data for similar project is imperative. Relevant data includes other DOE nuclear facilities. Figure 24 indicates that all DOE nuclear facilities are relevant. The database should include similar projects from other sectors. The regulatory environment should be a factor when considering whether a non-DOE project is applicable.

Define project scope and requirements more thoroughly at the start of the project. To avoid underestimating as a result of errors of omission, project scope and requirements need to be defined thoroughly before the initial cost estimate is made.

Add an appropriate contingency cost. Adding contingency to a cost estimate should eliminate bias. The initial cost estimates for new DOE have been consistently low by large margins suggesting that NNSA contingency benchmarks are inadequate. These benchmarks should be disregarded in favor of experienced-based contingency derived from data for similar projects. Projects involving new technology or materials will require additional contingency. Contingency costs of up to 100% of the base cost estimate should not be considered excessive for the initial cost estimate of a project involving new technology. However, extreme contingencies (i.e., over 100%) should be viewed as an indication of problems with the base cost estimate.

Use an appropriate escalation rate. Early cost estimates are more sensitive to escalation rate than the base line cost estimate because the time until the completion of the project is longer when the initial estimate is made. Use of an escalation rate appropriate for nuclear facilities is important for initial cost estimates.

Factor in the impact of budgetary constraints. Budgetary constraints affect project schedule, which in turn affects the total escalation for the project. Anticipated budgetary constraints should be factored into early cost estimates to ensure the added cost of a prolonged schedule is, in part, accounted for.

5.3. Modular Construction

Modular construction has been suggested as a means for reducing and controlling the cost of new DOE nuclear facilities. Modular construction means constructing several smaller facilities instead of a single large facility. Our analysis indicates that modular construction will not reduce cost but it may improve cost estimation. As an illustration, consider the "Big I" reconstruction project.

The Big I is the junction of Interstates 25 and 40 in Albuquerque, NM.[47,48] The reconstruction of this interchange took place from 2000 – 2002, and it was the largest public works project ever undertaken in New Mexico. The project included 45 new bridges, 10 reconstructed bridges, 4 miles of sound walls, and 111 lane-miles of paving. The initial budget for the project was $222 million, and the project was completed for $293 million, a modest 32% cost growth. This award-winning project is considered a model of good project management. The Big I reconstruction was not a single project but a collection of smaller projects executed simultaneously. Each part of the project was within the realm of road-construction experience, so it was possible to obtain accurate estimates for the cost of each bridge, each section of sound wall, and each mile of paving. Therefore, an accurate estimate of the overall cost could be obtained.

Breaking a new nuclear facility into several smaller modules will not have a big impact on total cost because the cost is approximately proportional to the floor area of the facility. However, the smaller modules may be closer to the existing experience, so the cost estimate for several smaller modules should be more accurate than the estimate for a single large facility. The available data support this conclusion. The percentage cost growth increases with the size of the facility [see Eq. (11)], which implies that cost estimates for smaller facilities are more accurate than larger facilities.

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