Cost Escalation in France's Nuclear Reactors: A Statistical Examination

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Summary

From the early 1970s to the late 1990s, the French utility organization, Électricité de France, constructed 58 commercial nuclear power reactors. All used the pressurized water reactor (PWR) design developed by the Westinghouse Corporation, with three different unit sizes: 900, 1,300 and 1,500 megawatts. **From the beginning of that program nearly to the end, the real per-kilowatt costs to construct these plants increased by approximately 60%.**

There is an important caveat to this finding, however, pertaining to the four units employing the largest (1,500-MW) reactor design, known as N4. Taken as a whole, **the four N4 reactors cost approximately twice as much to build, per kilowatt, as the other 54 reactors.** Their grossly higher costs are only partially reflected in the 60% figure above. From a statistical standpoint, the doubling of costs for the N4 reactors may be attributed to three factors (in declining order of importance): (i) their later sequencing, which subjected them to more chronological-related cost escalation, (ii) apparent N4-specific design or construction issues, and (iii) the loss of construction economies due to being built concurrently with very few other units.

Nevertheless, these findings, even with the caveat, are at odds with a recently published assertion that between the first reactors and the last, the real per-kilowatt costs of the 58 French reactors increased by more than a factor of three. That conclusion appears to have been based on a cursory comparison of costs of a few reactors at either cost extreme. A selective approach such as this is not a suitable method for distilling results from a large database; in that case, moreover, the comparison appears to rest on numerical imprecision. To derive my results, I have employed the standard statistical tool for analyzing large datasets: regression analysis.

Prologue

Late last year, in a chance encounter in New York City, the renowned physicist and energy expert Amory Lovins shared with me some "startling news": a researcher at the International Institute of Applied Systems Analysis in Vienna had obtained cost data for the 58 reactors built in France during that country's big nuclear power push, primarily in the 1970s and 1980s, and had found that from the start of this construction program to the finish, the per-kilowatt cost to build the French reactors had increased by more than a factor of three. "Adjusted for inflation?," I asked. "Yes, in real terms," Amory replied.

The implication was immense. France had begun and completed a hugely ambitious nuclear power construction program, second in size only to the U.S. program, in a relatively short quarter-century. Unlike the American electric utility companies, which for the most part contracted plant design and construction to architect-engineering firms that in turn tailored each project to local site and grid conditions, while struggling to keep up with continually evolving regulatory criteria, the French utility, ÉDF, and reactor supplier, Framatome, had largely standardized their reactor designs. The two organizations had also maintained a cozy alliance with government regulators, fending off citizen intervention in reactor design, siting and licensing and generally making it difficult for the public to learn about emerging design defects and operational mishaps. Yet evidently neither the ability in France to duplicate engineering and manufacturing across dozens of reactors, nor the country's compliant regulatory process and supportive political culture, had kept the nuclear power cost-escalation virus at bay. That *was* startling.

Amory suggested that I get in touch with the researcher, obtain his data, and subject it to the same statistical treatment that I had done on U.S. nuclear costs thirty years ago. At that time, I put public-domain cost data for completed U.S. reactors on a consistent basis, and then showed, through rigorous statistical analysis, that their real per-kW costs had risen almost 2.5-fold in just seven years (1971 to 1978). As I summed it up in my 1981 book, *Power Plant Cost Escalation*,[1] the increase in American nuclear costs was several times greater than for contemporaneous coal-fired plants; yet those were at least getting demonstrably cleaner, whereas throwing money at nuclear plants hadn't stopped the newest U.S. reactor, Three Mile Island Unit 2, from melting down disastrously in 1979.

The French Cost Data

The IIASA researcher was Arnulf Grubler, a PhD engineer and part-time professor at Yale with a long list of books, articles and papers on energy policy and technological change. Arnulf had dug up a 2000 report commissioned by French Prime Minister Lionel Jospin that disclosed, for the first time, France's year-by-year expenditures to begin and complete 58 pressurized water reactors (PWRs) between 1971 and 1999.

The Jospin report didn't provide *individual* reactor cost data. Nevertheless, Arnulf was able to estimate them by artfully applying "characteristic time profiles of expenditures" on the reactors, which he gleaned from reports published in the late 1970s by the French utility, Électricité de France. The ÉDF documents showed a triangular cash-flow pattern between start and completion, with the expenditure rate peaking in the middle. Applying the best-fitting cash-flow shape and, presumably, adjusting it as necessary to ensure that the sum of the expenditures assigned to each reactor matched the yearly totals in the

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[1] Power Plant Cost Escalation: Nuclear and Coal Capital Costs, Regulation, and Economics, Van Nostrand Reinhold, 1981. Available for downloading from this link: <http://www.komanoff.net/nuclear_power/>.

Jospin report, Arnulf derived what could be termed *calculated* costs for each of the 58 PWRs.

With each plant's annual expenditures thus approximated, Arnulf converted the cash flows to constant 1998 francs, using the French GDP deflator. This step adjusted the data for inflation in the overall French economy, allowing plants built at different times to be compared on a consistent cost basis — as if each plant had been built at the price levels for commodities and labor that prevailed in France in 1998. Neither the original ÉDF sector-wide cost data nor Arnulf's calculated plant-cost data included interest during construction, further facilitating comparison of costs of plants built in different periods.

In effect, Arnulf's adjustment removed general price *inflation* in order to reveal the extent of reactor cost *escalation* embodied in increases in construction inputs (more labor-hours, materials, components, engineering effort) and/or price rises for these inputs that transcended general inflation. (This type of adjustment has long been standard practice in European electricity policy analysis, but had to be introduced to the U.S. in the late 1970s by analysts from outside the electricity industry, myself included.) Arnulf then divided each reactor's constant-money construction cost by the reactor's generating capacity, in kilowatts, producing 58 data points in "constant francs per kilowatt."

Arnulf hadn't published these records, but after I contacted him, he generously shared them with me.[2] Since the data are proprietary, I reproduce them here only selectively to make key points and elucidate my statistical analysis. Given Arnulf's experience and probity, and seeing the care he took to assign the gross data to the individual reactors, I am confident that the 58-reactor database is adequately accurate.

French Reactor Costs — A Quick First Pass

The 58 pressurized water reactors built by Électricité de France from the early 1970s into the 1990s fall into three groups:

1. 34 "CP" reactors, 900 megawatts (approximate) capacity, construction of which started between late 1971 and early 1981, a 9½-year period.

2. 20 "P4" reactors of 1,300 MW capacity, whose construction started over a 7-year period from late 1977 to late 1984.

3. 4 "N4" reactors, 1,500 MW each, construction of which started over a 7-year period from early 1984 to early 1991.

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[2] The data are discussed in A. Grubler, "An assessment of the costs of the French nuclear PWR program 1970–2000," Interim Report IR-09-036, International Institute for Applied Systems Analysis, Oct. 6, 2009. Available at <www.iiasa.ac.at/Admin/PUB/Documents/IR-09-036.pdf>.

As Table 1 makes clear, the average costs of the first two groups of reactors differed only modestly, by around 20%. That is many times less than the cost difference between either group and the last, the 1,500-MW class reactors. This small group, comprising just four units, averaged 112% higher costs per kW than the 900-MW group and 76% more than the 1,300-MW group.

Table 1: French PWR Costs (in 1998 French Francs / kW)

Reactor Category	N	First Start	Last Start	Min Cost	Max Cost	Mean Cost
CP (900 MW)	30	1971.8	1981.2	5,843	7,301	**6,355**
P4 (1,300 MW)	24	1977.7	1984.8	6,627	10,163	**7,665**
N4 (1,500 MW)	4	1984.0	1991.3	10,947	17,499	**13,460**

Dates denote start of construction and are in decimal equivalents, e.g., 1971.8 denotes September 1971. Note that in mid-1998 the currency conversion rate was approximately 6.1 French Francs to one U.S. dollar.[3]

It is only a slight simplification to say that France's per-kW nuclear plant costs roughly doubled from the first 54 reactors to the last four. This apparent doubling of costs is significant, and its reasons cry out for investigation. But limiting quantitative observations to this observation would obscure important nuances within the underlying averages. It would also leave unanswered more crucial questions: the annual rate of cost escalation in the French nuclear program, and the extent of escalation for the program as a whole.

French Reactor Costs — A Second Pass

The standard statistical technique for distilling trends from a data set is "regression analysis," specifically multiple or multivariate regression analysis. Regression analysis is best described as a means of correlating an observed, dependent, "outcome" variable with one or more independent (and possibly causal) variables simultaneously. This process, which used to require specialized statistical software but can now be performed with standard spreadsheet programs, yields a formula quantifying the contribution of each independent variable to the predicted outcome. It "reports" not just the magnitude of each correlation but its statistical significance — an assessment of whether the correlation might have been a random occurrence as opposed to the more interesting alternative that it reflects a systematic relationship.

Here, the dependent variable is reactor cost (in constant money) per kW.[4] The independent variables I tested were those which I had reason to believe might be strongly

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[3] The Federal Reserve Bank of New York's "Foreign Exchange Rates Historical Search" facility at <http://www.ny.frb.org/markets/fxrates/historical/> yields, for July 1, 1998, a "noon buying rate" of 6.094 French francs for one U.S. dollar.

[4] More precisely, the dependent variable here is the *(natural) logarithm* of cost per kW. Specifying the cost as a logarithm enables the effect on costs of later construction starts (the first independent variable

correlated with reactor costs, and/or those whose exclusion might bias the correlations measured for other variables. (Note that while regression analysis renders a verdict on the validity of each possible independent variable, it cannot instruct the researcher as to which variables to test; that is up to the researcher's judgment and expertise, guided by substantive understanding of factors that might plausibly have an effect on the outcome.) Following are the three variables that met these conditions for the French reactor costs:

1. *Date of construction start* — the hypothesis being that plants begun later might have been subject to progressively more elaborate and/or stringent design criteria that raised their costs.

2. *Number of reactor construction starts in that year[5]* — the hypothesis being that building many plants at once might have allowed per-plant savings, perhaps by freezing plant designs that otherwise were changing over time, perhaps through other savings in engineering, logistics or labor.

3. *Was the reactor an N4 (1,500-MW-class) plant* — Table 1 made clear that costs for these four plants were grossly in excess of most of the others (this is strikingly apparent in Figure 1, further below.) The regression method would reveal, statistically, the extent to which their higher costs were intrinsic to the N4 class, vis-à-vis that the plants came later (factor #1) and that they weren't built in groups (factor #2).

The regression analysis is easily implemented in Microsoft Excel. Following is the table of results and a discussion of their import.

Table 2: Regression Results for French PWR Costs (per-kW, inflation-adjusted)

Variable	Impact on Costs	95% Range
1. Construction Start Date	Costs increased **3.6%** for each later year	3.1% – 4.1%
2. No. of reactors begun that year	Costs fell **5.7%** per doubling of reactor starts	3.9% – 7.4%
3. 1,500-MW (N4) Class?	**25.6%** higher cost if N4 (1,500-MW class)	15% – 37%

95% (confidence) range denotes range encompassing "true" cost impact with 95% probability. Relatively narrow ranges shown indicate a high degree of confidence that each variable is actually correlated with reactor costs. R Square value for the regression equation is 93%, indicating that the three variables together explain (account for) an impressive 93% of variation among costs of the 58 reactors.

1. *Date of construction start* — This important result is the simplest to report: for each increase in the year in which reactor construction began (i.e., for each later year), reactor costs per kW increased by an average of 3.6% (in real terms).

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discussed directly below) to be expressed as a constant percentage increase rather than as, say, a constant additive amount, which would correspond to a declining percentage over time.

[5] This independent variable was specified as the (natural) log of the number of reactors, in order to allow its relationship to costs to be expressed as a constant percentage decrease per constant percentage increase in the number. (See previous footnote for context.)

2. *Number of reactor construction starts in that year* — This result is relative rather than absolute. It says that doubling the number of plants started in a calendar year — say, building 6 rather than 3, or 4 rather than 2 — reduced the costs of all plants begun in that year by 5.7%, on average.

3. *Was the reactor an N4 (1,500-MW-class) plant* — If so, it cost 26% more than otherwise.

Together, the three factors explain the approximate doubling of costs for the N4 reactors: Because the N4 plants started construction nine years later, on average, than the CP and P4 plants, they suffered nine more years of chronologically-based cost escalation, raising their costs an average of 39%.[6] Because on average only 1.5 plants were started during the years the N4 plants started construction, versus an average of 5.7 for the CP and P4 plants, the N4's missed out on cost-cutting opportunities from mass reactor construction to the tune of 11-12% higher costs.[7] Combine these two factors with the third, the 26% intrinsic higher costs for the N4 design shown in Table 2, and the result is a 95% higher average cost,[8] more or less matching (and explaining) the roughly two-fold cost difference between the N4 plants and the earlier plants shown in Table 1.

Characterizing Cost Escalation in the French Nuclear Program

The most significant result from the regression model, in my view, is the 3.6% annual increase in reactor costs. Indeed, in a real sense the greatest value of factors two and three is to control for "confounding" factors (cost savings for multiple reactor starts, and higher costs for the N4's) so that the regression equation can reveal the "true" value of factor one, annual cost escalation.

By comparison, in my 1980-1981 analysis of U.S. nuclear power plants that were completed between late 1971 and late 1978, I measured the rate of real cost increase at 13.5% annually. That is three to four times the 3.6% per annum figure observed for the French program.[9] On the other hand, the French figure was estimated through a (regression) process that effectively neutralized the significantly higher costs for the N4

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[6] Calculated as the annual escalation factor, 1.0359, raised to the 9.35 power (the number of years between the mean construction-start date of the N4 plants and that of the other 54 plants).

[7] Calculated as the reciprocal of: 0.943 (the complement of the 5.7% cost saving per doubling of reactor starts), raised to the following power: 5.7/1.5 divided by two.

[8] Calculated as the product of the first factor, 1.39; the second factor, 1.116; and the third factor, 1.256.

[9] The 13.5%/annum U.S. finding, from *Power Plant Cost Escalation*, op. cit., especially Chapter 10, is not perfectly fungible with the 3.6%/annum result for the French reactors. The French result is apart from (i.e., controlled for) two non-chronological factors, whereas the U.S. result incorporated a half-dozen such factors. Moreover, the U.S. result, unlike the French, adjusted for inflation in construction-sector inputs such as labor, thus reducing it slightly, while incorporating (real) interest during construction, which raised it slightly. Nevertheless, even taking these differences into account, the conclusion appears robust that annual cost escalation for the U.S. reactors was three to four times as great as for the French.

plants by creating a special independent variable for those plants alone. Moreover, the 3.6%/year result for the French plants, while noteworthy, doesn't fully characterize overall cost escalation over the course of the French nuclear construction program. For that, we need to return to Arnulf's database, beginning with construction start dates for the French reactors. These are summarized in Table 1, above, and shown in Figure 1, below.

Fig. 1: Costs by Year of Construction for France's Reactors
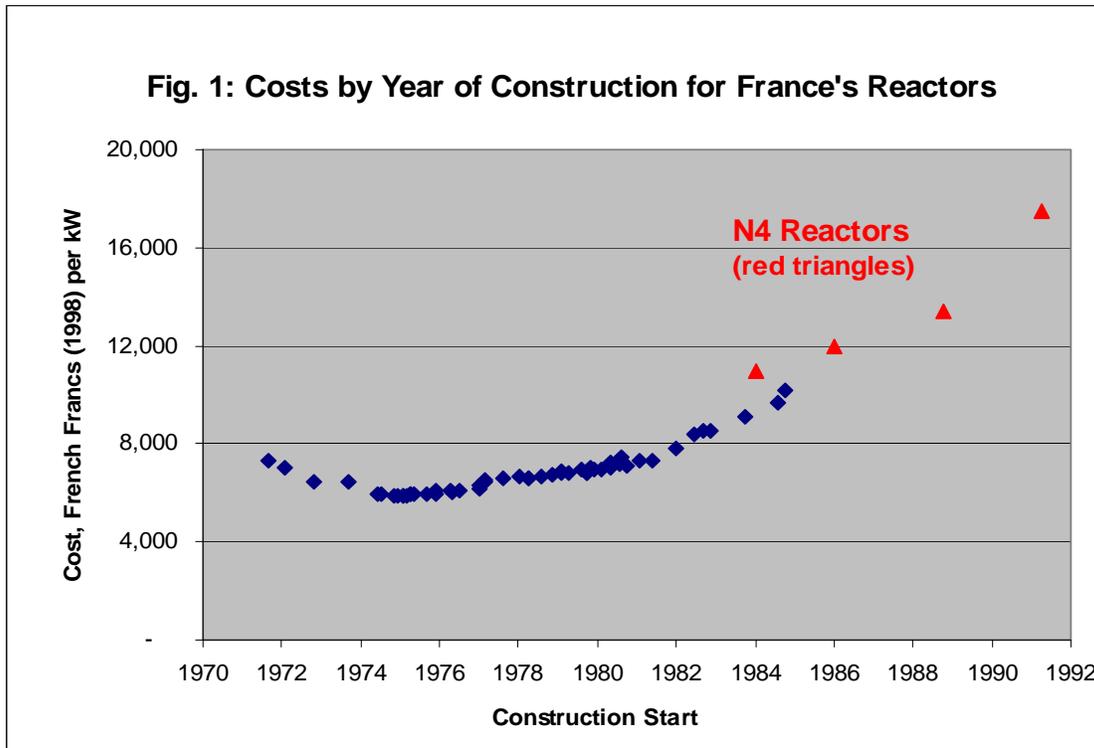
Both the table and figure make clear that 55 of the 58 reactors — all 34 CP's, all 20 P4's, and one N4 — began construction during a 13-year period, from late 1971 to late 1984, whereas the remaining three reactors, all N4's, were begun later: on the last day of 1985, in October 1988, and in April 1991. *The rate of reactor construction starts per year in the later period (covering the last three plants) was seven times less than in the later period (covering the first 55).*

The 3.6% per year cost-escalation rate was calculated on, and thus applies to, the date that construction began. Two factors militate in favor of applying it over the 1971-1984 period *and no further*: first, very few reactors — just three — were begun after 1984; second, with one exception (the first N4 unit), all of the 55 reactors that did begin construction in 1971-1984 used one of two standard designs and were built under an industrial regime characterized by concurrent construction of a large number of such standardized reactors.

The product of compounding a 3.6% annual increase over 13 years is an increase of approximately 60%. (Arithmetically, raising 1.036 to the 13th power yields approximately 1.60.) We thus summarize our regression findings as follows:

1. From the early 1970s to the late 1990s, 58 commercial pressurized water reactors, embodying three different unit sizes (900, 1,300 and 1,500 megawatts) were built in France. **From the beginning of this program nearly to the end, the real per-kilowatt costs to construct these plants grew by approximately 60%.**

2. An important caveat to this finding pertains to the four units employing the largest (1,500-MW) reactor design known as N4. Taken as a whole, **the four N4 reactors cost approximately twice as much per kilowatt to build as the other 54 reactors.** Their grossly higher costs are only partially reflected in the 60% figure above. Using a statistical simultaneous-correlation technique known as regression analysis, this doubling of costs may be attributed to three factors (in declining order of importance): (i) their later sequencing, which made them subject to more chronological-related cost escalation, (ii) design or construction issues inherent in the N4 design, and (iii) the loss of reactor economies due to their being constructed in relative isolation from other units.

Clarifying the Record

The title of this section may appear presumptuous, particularly in that the record I aim to clarify is the work of Dr. Arnulf Grubler, upon whose data I relied to construct my statistical analysis of French nuclear costs.

Yet my findings differ importantly from those in the IIASA "interim paper" that Arnulf published in October 2008,[10] a few weeks prior to my impromptu meeting with Amory Lovins in New York, as this excerpt from the abstract of Arnulf's paper shows:

> Drawing on largely unknown public records, [this] paper reveals for the first time both absolute as well as specific reactor costs and their evolution over time. Its most significant finding is that even this most successful nuclear scale-up was characterized by a substantial escalation of real-term reactor construction costs. **Specific costs per kW installed capacity increased by more than a factor of three between the first and last reactor generations built.** (emphasis added)

If by "generations" Arnulf is referring to all reactors in any of the three classes presented here in Table 1, then his conclusion which I have bold-faced above does not appear to be supported by the data. The straightforward computation of averages in Table 1 demonstrates that the four N4 (1,500-MW) reactors as a class were only a little more than

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[10] See citation in footnote 2, above.

twice as expensive to build, per kilowatt, as the thirty units comprising the first group (the 900-MW CP reactors).

But even that fact, regarding the doubling of costs, appears to give undue weight to the high costs of the N4 reactors that drew the curtain on the French PWR program in the 1990s. The truest "takeaway" from the program's costs, in my view, is that over the 13-year period in which ÉDF began construction of 55 of the 58 reactors that made up the program, real per-kW costs increased approximately 1.6-fold, i.e., by 60%. To be sure, this relative containment of costs was undercut by the significant additional cost escalation suffered by the trio of N4 reactors whose construction began after the 13-year period. Nevertheless, France's experience in building the 58 reactors as a whole stands in impressive contrast to the American reactor program, the real per-kW costs of which increased by approximately 140% (2.4-fold) over just the seven years, 1971-78, corresponding to the first phase of the French program, and probably by 400% (5-fold) from 1971 to the late 1980s.[11]

How, then, did Arnulf come to report that real reactor costs (per kW) more than tripled over the course of the French program? I'm not entirely sure, but this passage, from pp. 25-26 of his paper, may point to possible problems:

> The reference model suggest[s] a cost escalation from 4,200-4,400 to 14,500 FF98 [per kW] between the CP0/CP1 reactors constructed [completed] during 1974–1977 and the last N4 reactors constructed [completed] in the mid-1990s, i.e., by a factor of 3.4.

A glance at Fig. 1, above, which displays, in chronological order of start of construction, the per-kW costs that Arnulf provided to me for each of the 58 reactors, shows that no reactors were built for even close to the minimum level of 4,200 to 4,400 French francs per kW that Arnulf claimed in his paper. Rather, the least-cost plants cost around 5,840 French francs per kW. (All figures are in 1998 terms.)

The ratio of Arnulf's high-end figure, 14,500 French francs per kW, to the corrected low-end figure of 5,840 FF/kW, is approximately 2.5, which is considerably less than 3.4. But there is an additional correction to be made: only a single, solitary plant came in at Arnulf's high-end figure of 14,500 or more per kW, as Fig. 1 shows. Indeed, aside from that reactor, only one other unit cost more than 12,000 per kW. The ratio of 12,000 to 5,840, which is 2.05, would indicate only a doubling of costs. It appears, then, that

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[11] The correspondence is inexact because the same dates apply to construction *starts* for France and construction *completions* for the U.S. The 140% figure is referenced here in an earlier footnote, in the section "Characterizing Cost Escalation." The 400% figure is a rough estimate based on the premise that real U.S. per-kW reactor costs somewhat more than doubled from late-1970s completed plants to late-1980s plants. Combining a 140% increase and a 100+% increase yields a roughly 400% increase.

Arnulf's factor of 3.4 is an artifact of understating the low end of the cost scale and using just two data points to represent the high end.

Yet even using a more rounded (and accurate) group of endpoints invariably builds in an element of guesswork, or, worse, arbitrariness, since there is no *a priori* reason to select one group over another. Moreover, even if there were a canonical procedure for selecting the endpoints, drawing conclusions from them alone would effectively discard the intervening data, corresponding to some 50 plants — the vast majority of the sample.

The antidote is to apply regression analysis to the entire sample. In this way, every plant's cost contributes to measuring the cost trends. While there will always be an element of judgment in the analyst's choice of independent variables to be tested (and in specifying their functional forms, e.g., exponential via linear via logarithmic), at least that is transparent, and other analysts are free to test other variables. Most importantly, with regression analysis, *all* of the data contribute to estimating the influence of the independent variables on the dependent variable.

Suggestions for Further Research

This paper is a modest effort to explore the terrain opened by Arnulf Grubler's 2009 investigations into historical French nuclear power costs and clarify his results. My current interests lie elsewhere — primarily in improving urban transportation through traffic pricing, and in establishing and communicating the environmental and equity benefits of taxing carbon emissions. Following are suggestions for research by others:

1. Validate Arnulf's procedure for assigning annual French "gross" costs of nuclear plant construction to the individual reactors undertaken in those years. If this results in an altered cost database, rerun the regression model to derive corrected coefficients corresponding to the model's three explanatory factors.

2. Determine the factors that brought about the observed annual 3.6% real escalation in reactor per-kW costs reported here. Investigation of the "causes" should be at several levels, including the *engineering* level (i.e., were there design and construction changes that increased the required inputs of labor and materials?), and, in turn, identifying the factors that led to those engineering changes.

3. Determine the causes of the sharply higher costs observed for the N4 reactors. One avenue of inquiry might be the influence of the 1986 Chernobyl accident, in what was then the Soviet Union, on French regulatory criteria and, hence, reactor costs. Since no N4 reactors had been completed (in fact, two hadn't begun construction while the other two had barely started), this group could easily have been more affected than the CP (900-MW) or P4 (1,300-MW) plants. Other factors that may also have been at work should be investigated as well.

4. Improve upon my modeling of the savings from concurrent reactor construction ("factor 2" in Table 2). As noted, this variable, denoting the number of reactors begun in a given year, was included in the regression model to help isolate the true annual cost-escalation rate. However, the phenomenon of "construction start proximity" is worth investigating in its own right. It doubtless can be specified more incisively than I have done here — perhaps with a construction-start-date "radius" (e.g., "radius" of months around the start of construction in which X other reactors were also started), or with a different functional form, or by a different approach altogether. In any case, the pattern of reduced costs through building many units at once merits attention, not just through finer statistical analysis but with informed interpretation.

5. The model does not attempt to distinguish between CP and P4 reactors, or within either class, or between building reactors in pairs, quartets or sextets. Nor have I investigated possible regional variations in costs, e.g., plants built in proximity to large populations vs. small populations, or site-related differences such as inclusion of cooling towers vs. less-expensive once-through cooling systems. To the extent that any of these subgroups might be expected to have had cost advantages or disadvantages, they should be tested with appropriate variables. Similarly, researchers with greater knowledge of the French program should test their own hypotheses to explain the remaining variations in the reactors' costs.

Acknowledgments and Authorship

Charles Komanoff is an activist, energy-economist and policy-analyst. In the 1970s and 80s Charles gained prominence for deconstructing the spiraling costs of nuclear power in the United States as author-researcher and expert-witness. He subsequently "re-founded" and led NYC's bicycle-advocacy group Transportation Alternatives in the 1980s, helped found the Tri-State Transportation Campaign in the 1990s, and co-founded the Carbon Tax Center in 2007. Charles's writings include books, journal articles, op-ed essays and landmark reports such as Subsidies for Traffic, Killed By Automobile, and the Kheel Report on financing free transit through congestion pricing in New York City. He blogs about urban transport on Streetsblog and energy policy on Grist. A math-and-economics graduate of Harvard, Charles lives with his wife and two sons in lower Manhattan.

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