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COST ESTIMATING ISSUES IN THE RUSSIAN INTEGRATED SYSTEM PLANNING CONTEXT

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Paper Presented at the

Fourth International Conference on Nuclear Engineering
New Orleans, LA

March 10-14, 1996

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Cost Estimating Issues in the Russian Integrated System Planning Context

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ABSTRACT

An important factor in the credibility of an optimal capacity expansion plan is the accuracy of cost estimates given the uncertainty of future economic conditions.

This paper examines the problems associated with estimating investment and operating costs in the Russian nuclear power context over the period 1994 to 2010. Investment costs in the nuclear power sector covered the following areas:

- safety upgrades to existing power plants
- decommissioning older reactors at the end of service life
- completion of partially completed power plants
- repower a newly completed nuclear power plant as a fossil fueled plant
- construct evolutionary reactors available for licensing in the year 2001

Fuel and non-fuel variable costs for evolutionary reactors as well as existing nuclear power plants were estimated.

Estimation of the costs of safety upgrades required that upgrades be identified. The basis for the identification was that after the completion of upgrades, Russian reactors had to operate "at levels of safety acceptable to the West." In practice this meant that upgrades would conform to those defined in a March 1994 report to the International Users Group (IUG) of Russian Designed Reactors to the World Association of Nuclear Operators (WANO); the implementation of containment/confinement system for RBMK and VVER-440/230 and certain additional upgrades which were referred to as "beyond WANO."

Decommissioning costs were estimated on two bases: a Russian approach and a U.S. approach. The Russian approach is based on long-term safe storage of the plant until the time of fuel dismantling (SAFSTOR). The U.S. approach was characterized by full plant dismantling following decontamination without a safe storage phase. Estimates for both the U.S. and Russian approaches included an allowance for social costs in accordance with Russian laws and practice.

The Energy Economic Data Base (EEDB) developed by Raytheon Engineers and Constructors (RE&C) was used to estimate supply options, safety upgrades and decommissioning costs. Estimates were initially based on U.S. material and labor costs. These costs had to be converted to Russian costs as they were expected to evolve over the planning horizon. Conversion factors were supplied by the Energy Research Institute of the Russian Academy of Science. They agreed in many aspects with conversion factors developed independently by Raytheon from data compiled by U.S. firms doing business in Russia. All costs were denominated in 1994 USD.

BACKGROUND

The system planning study from which this paper is derived was conducted in the period November 1993 to November 1994. The objective was to formulate a least cost capacity expansion plan upon which an investment schedule for the further development of Russia's electric power system would be based. While many diverse issues had to be resolved in this planning study, this paper is narrowly focused on the nuclear sector.

At the beginning of 1994 there were nine nuclear power plants (NPPs) with 29 power units in Russia. Their total installed capacity was 21 GW(e) or 10.6% of total generating capacity. These NPPs produced some 118 trillion watt-hours (118 TWh) of electric energy.

Power reactors in commercial operation were of several types:

- RBMK, a graphite moderated, pressure-tube, low enriched reactor rated 1000 MW(e), designed for on-line refueling;
- VVER-440/230, a first generation pressurized water reactor rated 440 MW(e);
- VVER-440/213, a second generation pressurized water reactor also rated 440 MW(e); and a
- VVER-1000, a second generation pressurized water reactor rated 1000 MW(e)

Several variants of these reactors were also in operation. In addition to a 600 MW(e) liquid metal-cooled (BN-600) reactor connected to the Ural grid, four small (12.5 MW(e)) water-cooled graphite-moderated channel type (EGP-6) reactors operated isolated from the grid in the Far Eastern part of Russia.

The breakdown of total installed capacity is given in Table 1.

TABLE 1. STRUCTURE OF THE RUSSIAN NUCLEAR POWER SECTOR ON JANUARY 1, 1994

Reactor Type	Number of Units	Share in Total Capacity, %
RBMK-1000	11	51.8
VVER-1000	7	33.0
VVER-440	6	12.2
BN-600	1	2.8
EGP-6	4	0.2

A set of options for the development of the nuclear sector which was included in the Terms of Reference (TOR) for the study was provided to the planners by the United States and Russian governments. They were to consider these and only these options although others were conceivable. The cost estimates of these options would provide the data on the nuclear sector needed by the integrating model, i.e., the formal structure to be used for determining the optimal capacity expansion plan.

The options to be studied were the following:

- Option 1. Provide safety upgrades to RBMK and first generation VVER-440 reactors to allow operation until the end of the reactors' service life at a safety level acceptable to the West.
- Option 2. Decommission RBMK and VVER-440/230 reactors. Kursk-1 and Novovoronezh-3 are the representative nuclear power units (NPPs) for this option.
- Option 3. Repower partially completed Rostov-1, VVER-1000 reactor, as a fossil fueled plant.
- Option 4. Complete the partially completed Kalinin-3, VVER-1000 reactor, with safety upgrades to allow operation at reduced levels of risk.
- Option 5. Provide safety upgrades to operating VVER-1000 and VVER-440/213 reactors to provide for operation of these reactors at reduced levels of risk.
- Option 6. Build new evolutionary NP-500 power plants.

The expression "level of safety acceptable to the West" is mentioned in Option 1 above and is employed in the TOR. In this study, this is assumed to be a level of safety of Russian NPPs that could satisfy the demands of potential investors. A major objective of the study is to estimate the cost of safety upgrades for Russian NPPs so that they may achieve that level.

GENERAL ESTIMATING APPROACH

Cost estimates were based on the RE&C's EEDB. EEDB cost data models are quantity (materials and installation hours) driven reflecting the specific design features of U.S. power plants. These design features are represented by a set of technical data models. An EEDB model of an 1144 MW(e), Four-Loop PWR NPP was selected as the basis for estimating the cost of safety upgrades to RBMK and VVER reactors as well as the completion of Kalinin 3. The cost of construction of the innovative NP-500 reactor was based on an EEDB model of a 587 MW(e) Two-Loop PWR NPP.

The estimate of direct costs for repowering Rostov-1 is based on actual cost experience of Burns and Roe for repowering the Zimmer plant in the U.S. The cost of major equipment items was verified by obtaining price quotations from U.S. manufacturers. Total direct costs were further verified by scaling estimated costs of a fossil plant of similar design in the EEDB. Good agreement with Zimmer was obtained. Indirect costs were estimated on the basis of RE&C experience incorporated in the EEDB.

CONVERSION OF U.S. BASED ESTIMATES TO A RUSSIAN BASIS

The EEDB methodology reflects U.S. construction practices, wages, equipment costs and commodity prices. Thus, it is necessary to establish adjustment factors for converting the economic conditions reflected in the EEDB to Russian economic conditions and construction practices. This study utilized two sets of U.S. to Russian adjustment factors:

1) One set of factors was developed by RE&C cost estimators based on the following assumptions:

- The cost of engineering services reflects an average U.S. rate of \$35/hour (January 1994) excluding overheads and profit.
- Russian engineering costs are based on the Ernst & Young Moscow Salary Survey of January 1994.
- Social costs normally provided for in Russia, such as housing, medical care, schooling, etc., are not reflected in any comparisons of costs.
- The factors for equipment and materials (other than concrete and structural steel) assume that the Russian economy will continue to change in the direction of market based pricing and will eventually be as competitive as the world market.
- Concrete and structural steel are assumed to be higher in cost due to demand of infrastructure and housing construction.
- It is assumed that the Kalinin 3 Station construction data reflects typical construction manpower staffing levels and that no major "off-site" construction is included.
- Construction labor cost comparison assumes that the relationship between average labor cost and cost of construction labor will remain the same as in the past (construction 30% higher).

The adjustment factors thus arrived at are provided in Table 2.

2) Adjustment factors also developed by the Energy Research Institute of the Russian Academy of Sciences. The factors applicable as of January 1, 1994, are as follows:

Equipment	0.5 x U.S.
Material	0.7 x U.S.
Labor Cost	0.1 x U.S.

Contingencies were added to the base construction cost (BCC) estimate to ensure a pre-selected confidence level of "no-cost-overflow," i.e., that the BCC plus the contingency will not be exceeded. It reflected the uncertainty of the estimator of the BCC. In this respect it is only partially analogous to contingencies which are included in a bid for, say, a construction contract, where the contingency reflects an element of uncertainty but is strongly constrained by anticipated competition from other bidders.

Contingencies ranged from a high of about 35 percent to a low of 15 percent with the remainder in the range of 25 to 30 percent. While contingencies remain largely subjective, the EEDB provides guidelines and procedures for arriving at contingency values.

TABLE 2. FACTORS FOR CONVERTING U.S. BASED COST ESTIMATES TO A RUSSIAN FEDERAL BASIS

	Conversion Item	Comment	Factor
1	Equipment	This assumes that manufacturers will be at least as competitive as the world market.	0.70
2	Commodities: • Concrete • Steel • Other	This assumes that the pressure of infrastructure and home construction will keep price of concrete and steel high. Other commodities will adjust to world market.	1.00 0.55 0.70
3	Productivity of Direct and Indirect Labor	A comparison of Kalinin 1 and 2 total project man-hours to the EEDBE indicates a factor of 2.7, however, unusually heavy front loading and an extended gap between completion of units indicates unusual circumstances. Therefore, use 2.5.	2.5
4	Professional Services (Based on "Unloaded" Rates) -	It is assumed that this sector of the labor market will most readily adapt to a more independent employment approach and be less dependent on government or industry support.	0.15
5	Construction Labor	This factor is based on a highly speculative value for average labor cost in Russia of 256,000 Rb/mo. The result is an adjustment factor of 0.04. In order to be conservative it was increased to 0.10. Cost of housing, food, health, education, day care, and other labor subsidies are specifically excluded.	0.10

SAFETY UPGRADES TO RBMKs AND VVERs

It was assumed that a "level of safety acceptable to the West" could be achieved by implementing the following:

- 1) those upgrades developed by Russian engineers for the International Users Group (IUG) of Soviet Designed Reactors and published in a March 1994 report prepared for WANO;
- 2) the implementation of containment/confinement systems for RBMK-1000 and first generation VVER-440/230 reactors, and

- 3) certain additional upgrades not included in 1) and 2) above and referred to hereafter in this report as "upgrades beyond WANO."

The major measures for the safety enhancements of these nuclear power plants have been categorized on the basis of the specific plant elements which they address, namely:

- Integrity of the primary loop
- Reduction of control transients
- Integrity of the containment/confinement
- Protection from fires
- Accident management
- Methods, studies, and procedures

Additional safety upgrades beyond WANO considered by Russian and American engineers were assessed. These are summarized below. A majority of them are presently included in Russian plans for safety upgrades. Some are currently being implemented at various NPPs.

- Upgrades to cope with "Station Blackout"
- Provisions to safely manage Anticipated Transients Without Scram (ATWS)
- Interactions between the plant and the grid (measures to protect the plant from transients or functional degradation on the grid)
- Additional safety upgrades that address common cause failure
- Environmental qualification (assurance that the capability of safety-grade equipment and certain other systems and components function as required under accident conditions)
- Performance of a comprehensive set of accident analyses that will support current safety upgrade proposals and identify additional upgrades, if any
- Additional fire protection measures
Addressing long-term cooling capabilities.

The above set is not comprehensive, nor does each upgrade apply to all reactor types. Some of these upgrades require engineering studies only; others require engineering studies which may or may not provide a rationale for additional construction or equipment installation. Some studies have been completed and assessments of required physical upgrades have been made. The cost of upgrades were not included in the study estimated in the evaluation stage.

The containment function is not explicitly referred to in the recommendations for the IUG. For the purposes of this study, three containment functions were conceptually designed and costed. These were 1) a U.S. style containment system for RBMK and VVER-440/230 reactors, 2) a jet condenser pressure suppression system of Russian design and a metal confinement structure over the operating floor for RBMKs and 3) a jet condenser pressure suppression system with an improved seal for the existing reactor cavity dome without additional confinement for the VVER-440/230 reactor.

The construction of a U.S. style containment at either an RBMK or a VVER-440/230 would be very difficult because it would require: 1) extensive safety-related equipment relocation; 2) a new Seismic Category I structure to house the relocated equipment; 3) demolition of part of the existing rectangular reactor building to

make way for a cylindrical containment; and 4) incremental tunneling and reinforced concrete and steel liner placement beneath the reactor building to provide a containment mat and a continuous final fission product barrier (liner).

The jet condenser design proposed for the RBMK-1000 and VVER-440/230 reactors will accommodate larger size pipe breaks compared to the original design basis. For VVER-440/230 the jet condenser would be effective for the large LOCA according to the Russian experts. For the RBMK-1000 this same conceptual design should be able to withstand the loss of one pipe manifold. The VVER-440/213 reactor design incorporates the bubbler condenser tower designed for the large break LOCA and, therefore, does not require any additional work.

DECOMMISSIONING

The U.S. approach to decommissioning Russian nuclear power plants was developed as a hypothetical case, on the basis of nuclear regulation, financial conditions and the technology base existing in the U.S. This resulted in differences between the base construction costs of Russian and U.S. approaches to decommissioning. Because of fundamental differences between the U.S. and Russian approaches, direct comparison of the respective cost-estimates should be undertaken only with extreme caution so as to avoid incorrect conclusions.

The Russian approach to the decommissioning process with data provided by Russian experts formed the estimating basis for this study. This approach is analogous to the approach with long-term safe storage of the plant until the time of final dismantling (SAFSTOR).

The Russian approach is based on Russian studies tempered by maintenance, repair, and replacement experience. As such, it reflects decommissioning procedures that regulatory and utility organizations find acceptable in Russia today.

The specifics of the approach to decommissioning in Russia lie with the current GAN decision which states that the reactor is considered to be in operation as long as spent fuel remains at the unit. Consequently, the unit operational staffing must be maintained at a 100 percent of normal operational staffing level and there is a significant time lag between the unit shutdown and the beginning of decommissioning. An allowance for social costs, in accordance with Russian laws and practice, was included in the decommissioning costs.

The U.S. approach, included this study at the request of the U.S. experts, is merely for the purpose of comparison. This approach is analogous to a process characterized by decontamination followed by immediate full plant dismantling (DECON). Its inclusion was to serve as a "What-If" (what if the U.S. Approach could be applied to Russian nuclear power plant decommissioning).

For RBMK-1000 and first generation VVER-440 NPPs there is a need to install a waste processing/storage facility. A direct impact cost which pertains to RBMK-1000 alone is the need to build a spent fuel storage prior to actual decommissioning. This is a consequence of the insufficient size of an on-site spent fuel storage facility to accommodate the decommissioning process. The costs of those facilities were accounted for in both the Russian and U.S. approach to decommissioning.

The approach to the assessment of socio-economic costs was the same for both approaches. The cost drivers considered in this study for the estimate of socio-economic costs are as follows:

- Staffing levels at the units during normal operation
- Staffing levels at the unit during various decommissioning phases
- The duration of the decommissioning broken down into phases
- Town site demographics
- Costs of retraining and relocating staff made redundant by decommissioning
- Continued compensation for redundant workers
- Allowance for living accommodations at new location

The extent of the social obligation considered in this study is identical in large measure with those proposed by the Russian Government for social programs for workers in coal and strip mines and mining towns that were stated for shutdown. It is also similar to the social guaranties and compensation given to workers laid off from enterprises named in labor legislation and in the Russian law on "Employment of the Populace in Russia."

For social costs, 50 percent of workers and townspeople that would be displaced by decommissioning were assumed to be transferred to other facilities. This assumption was based on expectations of the Russian experts. The transferred people were assumed to be provided with moving expenses only. The other 50 percent were assumed to be provided with additional benefits, such as retraining, severance pay and apartment allowances. One notable exception pertains to early decommissioning. All personnel and prorated town's people displaced at the reactor shutdown time (Phase 1 only) are assumed to receive full benefits.

Note that substitute heat sources for district heating may be required when NPs are shut down for decommissioning. Such costs associated with decommissioning, have not been estimated in the JPNAS.

Not considered in this study is the construction of additional generating capacity at the site or in the vicinity of a decommissioned reactor unit. This scenario will mitigate or completely eliminate the socio-economic cost.

Two decommissioning scenarios are considered for each reactor type:

- Planned - reactor is shut down at the end of service life (ESOL)
- Early - reactor is shut down 5 years prior to EOSL

RUSSIAN APPROACH

The duration of activities and their manpower resource requirements formed the basis for the present estimate. The Russian experts developed the definition of the decommissioning phases, their duration, the outline of activities for each of the phases and the man-power requirements for each activity. The total decommissioning period is divided into three sequential phases: preparation for decommissioning, preparation for SAFSTOR and SAFSTOR itself.

The cost estimation assumed the following breakdown of activities into phases:

Phase 1 (the phase duration is 5-8 years):

- Integrated engineering and radiological studies to develop the decommissioning plan including the schedules and logic which incorporates resource needs (people, programs and hardware)
- Assessment of the actual physical condition of structures, systems and equipment (SSE)
- Development of SSE modification packages for SAFSTOR
- Resolution of the licensing issues
- Software development (procedures, programs and plans)
- Construction of liquid and solid radwaste processing facilities; processing of accumulated operational radwaste
- Construction of spent fuel facility (RBMK-1000 only)
- Decontamination of equipment and facilities
- Site characterization study is performed to address physical and radiological inspection

Phase 2 (the phase duration is 5 years):

- Disassembly of equipment and systems (excluding the reactor vessel)
- Localization of reactor in place
- Processing of liquid and solid radwaste
- Facility decontamination and preparation for use as temporary storage
- Storage of radwaste

The U.S. approach is based on the results of U.S. studies tempered by the evolutionary effects of actual experience. As such, it reflects decommissioning procedures that regulatory and utility organizations find acceptable in the U.S. today. Social costs of decommissioning were assessed in the same way for both the U.S. and Russian approach.

The U.S. approach to decommissioning Russian nuclear power plants was developed as a hypothetical case, on the basis of nuclear regulation, financial conditions and the technology base existing in the U.S. This resulted in differences between the base construction costs of Russian and U.S. approaches to decommissioning. Because of fundamental differences between the U.S. and Russian approaches, direct comparison of the respective cost-estimates should be undertaken only with extreme caution so as to avoid incorrect conclusions.

REPOWERING A PARTIALLY COMPLETED NPP

An assessment of repowering Rostov-1 as a fossil fueled unit was included in the study. The Rostov site was initially planned as a four-unit VVER-1000 NPP, however, the plant construction has been discontinued. Unit 1 is approximately 95 percent complete, while Units 2, 3, and 4 are only about fifty, ten, and five percent complete respectively. The site, installed systems and equipment have been maintained by the plant staff since construction at the plant was halted.

This assessment was premised on the maximum use of the equipment already installed. The basic concept involves producing supercritical steam in fossil fueled boilers to drive high pressure topping turbines. The exhaust steam flow from this system is cooled so as to match inlet conditions of the turbine of

the partially completed nuclear unit. The combined output of the generators driven by the topping turbines and those driven by the turbine of the partially completed nuclear plant is approximately 1500 MW(e). Thus, the repowered plant provides a total generating capacity of approximately 150 percent of the VVER-1000. To implement the repowering, substantial development of fossil fuel resources and railroad capacity may be required. Site development for coal storage and ash disposal are also needed. The impact of additional capacity on the grid was not assessed.

COMPLETING KALININ 3

This option involves completing the construction of Kalinin-3, a VVER-1000 plant, which is reportedly 75 percent complete. If this option is exercised, construction will be restarted after a period of relative inactivity. This period of inactivity was assumed to be at least two years in duration; long enough to require some rework of certain plant systems and structures. It is reasonable to assume that the plant will be completed, not strictly as designed but will incorporate safety upgrades to permit operation at reduced levels of risk.

FUEL COSTS

Three scenarios of the prices for nuclear fuel are suggested: minimum price scenario, average price scenario and maximum price scenario. The basic assumptions for all scenarios are as follows:

- Due to the existence of large stocks of extracted uranium in various forms in Russia (low-enriched uranium, enrichment tails, high-enriched uranium, reprocessed uranium) price escalation for nuclear fuel over the whole period of the study need not be considered.

Thus, it is sufficient to determine the price for only one reference year of the study, e.g., 1994.

- The model of the fuel cycle is as shown above. Thus, there are six components in the price of nuclear fuel: 1) the cost of yellow cake (U_3O_8), 2) the cost of the conversion to UF_6 , 3) the cost of the separative work unit (SWU), 4) the cost of fuel fabrication, 5) the cost of long-term fuel storage off-site and 6) the cost of the final encapsulation and disposal of nuclear fuel.
- All the prices are calculated on the assumption that the raw material is natural uranium with the assay of 0.71% in uranium-235.
- The uranium-235 content of enrichment tails is assumed to be 0.3%.
- The price of nuclear fuel is determined on a unit-by-unit basis depending on the enrichment of the fuel used.

The set of prices in the OECD/NEA study [OECD/NEA] is used here as the basis for the formulation of various fuel prices scenarios.

For the maximum price scenario all costs are the prices characteristic of long-term contracts of major producers in the world market as assessed in Reference [OECD/NEA].

- The cost of fuel fabrication is assumed to be half of the price of those characteristic of long-term contracts. The coefficient of 0.5 is used here to reflect the differences between the Russian and world market conditions. The value of the coefficient roughly corresponds to the general ratio between the U.S. and Russian costs bases as found by WG #3 in its studies.

For the average price scenario it is assumed that the costs of U₃O₈, conversion to UF₆ and SWU are the prices in the world unrestricted market served mainly by the CIS countries including Russia. For the minimum price scenario the price of enriched uranium is assumed to be zero. This reflects the fact that a very large stock of enriched uranium, including highly enriched uranium, exists in Russia. Although the level of enrichment of a portion of such stocks is less than required for reactor fuel, assuming a zero cost for enriched uranium remains a reasonable basis for establishing a least cost. The prices of fuel fabrication, long-term storage and final fuel disposal are assumed to be as in the average price scenario.

NON-FUEL OPERATING COSTS

Non-fuel O&M costs were derived on the basis of applying the U.S. Department of Energy (DOE) methodology using input staffing tables provided by the Russian experts for each reactor type. Tending to distort such costs is the fact that when a unit at a Russian NPP is shut down its staffing costs are charged against operating units.

CONCLUSIONS AND OBSERVATIONS

Estimating capital and operating costs of nuclear power plants is technically feasible. Uncertainties arise, from a lack of knowledge of construction practices and labor productivity among other things. The need to factor in the cost of safety upgrades to meet criteria loosely defined as to achieve levels of safety "acceptable to the West" or "acceptable to international financial institutions" imposes an additional conceptual burden on estimators. When estimates are performed in the context of capacity expansion planning where alternative generating technologies must be considered, it is important that estimating assumptions and practices be consistent for all candidates generating plants. Estimates of decommissioning costs in Russia are extremely uncertain given the general lack of solid experience both in that country and the United States.

ACKNOWLEDGMENT

Work described in this paper was performed under Contract DE-AC02-76CH00016.

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