COST OF ELECTRICITY FROM MOLTEN SALT REACTORS

ECONOMICS OF NUCLEAR SYSTEMS

TECHNICAL NOTE

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The cost of electricity is estimated for a molten salt reactor based on evaluations at the Oak Ridge National Laboratory (ORNL) and compared to the ORNL pressurized water reactor and coal plant estimates of the same pre-1980 vintage plants. The results were 3.8, 4.1, and 4.2 ¢/kWh for the molten salt reactor, pressurized water reactor, and coal. Surprisingly, such cost estimates have never before been published for the molten salt reactor.

Three decades ago, a decision was made to discontinue the molten salt reactor (MSR) experiment, which had been operating quite successfully at the Oak Ridge National Laboratory (ORNL), and to stop further development of the MSR. This reactor was different from other reactors. It could be fed by any of the fission fuels—uranium, plutonium, or thorium—but it operated best on thorium and could refuel on-line so as to continuously remove dangerous fission products while burning up actinides, even those from other sources. The program developed enough information to credibly evaluate and estimate the cost of electricity (COE). Surprisingly, the project researchers documented the detailed capital cost estimate and operating costs for a 1000-MW(electric) commercial plant but never used these costs to determine the cost of MSR-generated electricity. One reason was that the MSR was in an early stage of development. The purpose of this note is to make available the estimated COE based primarily on evaluations contained in early ORNL reports and values from elsewhere.

A detailed cost breakdown and description was given for a conceptual design of a 1000-MW(electric) MSR, as well as equal size pressurized water reactor (PWR) and coal plants.[1] All three were for commercial "*n*'th-of-a-kind" plants. The MSR was fueled with thorium and denatured ^{235}U. The research and development needed on the MSR was estimated at $700 million (1978 dollars) in addition to reactor construction projects.[1] Delene[2] also compared 600-MW(electric) PWR and natural gas fired plants, but these, for the sake of brevity, are not included here because they were not done on a common basis with the MSR. To determine the COE generated by these reactors, we need to know the operating costs and the amortized capital cost. Some, but not all, operating costs were given for the MSR in the referenced document. The annual capital charges can be computed based on the capital costs, using a capital charge factor of 0.1 recommended by Delene[2] [see Eq. (1)]. The results are shown in Table I.

The COE in constant (noninflating) dollars is given by a simplified formula recommended for comparison studies by Delene. Life cycle costs are averaged over the life of the plant from construction to decommissioning. The capital charge portion of COE is computed in Table I from the first term in Eq. (1), as follows:

$$\mathrm{COE} = \frac{C \cdot i + \mathit{fuel} + \mathrm{O\&M} + \mathit{waste\ disposal} + \mathit{decom}}{P_e \cdot 8760 \cdot C_f} \ , \quad (1)$$

where

COE = COE in dollars per megawatt hour or cents per kilowatt hour

C = capital cost in dollars

i = fixed capital charge rate, typically 10%

fuel = annual cost for fuel

O&M = annual cost for operations and maintenance and similarly for waste disposal and decommissioning

P_e = net electrical power capacity of the plant

C_f = capacity factor.

The capacity factor C_f is taken as 0.9 for the MSR to account for the reduced downtime because of its on-line fueling feature and 0.8 for the PWR and coal cases. There are 8760 h/yr. To convert costs quoted in one year's dollars to those in another year, we use deflation factors. For example, to convert 1978 dollars to 2000 dollars, multiply by 2.43; to convert 1993 dollars to 2000 dollars, multiply by 1.17. If the capacity factor for the MSR increases from 0.9 to 0.95, its COE becomes 3.65 ¢/kWh. The net plant efficiency was 44% for MSR and coal and 33% for PWR.

The operations and maintenance (O&M), fuel and decommissioning costs from Delene[2] for coal and PWR are based on two 600-MW(electric) plants in the case of coal and one

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TABLE I
Economic Parameters

Item	1978 dollars			2000 dollars		
Direct costs, millions of dollars	MSR	PWR	Coal	MSR	PWR	Coal
Land and land rights	2	2	2	5	5	5
Structure and improvements	124	111	245	301	269	594
Reactor plant equipment	180	139	−−−	437	337	−−−
Turbine plant equipment	100	113	88	243	274	213
Electric plant equipment	54	44	31	131	107	75
Miscellaneous plant equipment	17	13	11	41	32	27
Main condition heat rejection	14	22	14	34	53	34
Total direct costs	491	444	391	1191	1077	949
Indirect costs						
Construction services	75	70	39	182	170	95
Home office engineering services	53	53	16	129	129	39
Field office engineering services	34	30	10	82	73	24
Total indirect costs	162	153	65	393	371	158
Total capital cost, millions of dollars	653[a]	597[a]	456[a]	1584[a]	1448[a]	1106[a]
Cost/kWh, ¢/kWh						
Capital	0.83[b]	0.85[b]	0.65[b]	2.01[b]	2.07[b]	1.58[b]
O&M	0.24[c]	0.47[d]	0.33[d]	0.58[c]	1.13[d]	0.80[d]
Fuel	0.46[c]	0.31[e]	0.71[f]	1.11[c]	0.74[e]	1.72[f]
Waste disposal	0.04[g]	0.04[g]	0.04[d]	0.10[g]	0.10[g]	0.09[d]
Decommissioning	0.02[c]	0.03[d]	−−−	0.04[c]	0.07[d]	−−−
Total	1.58	1.69	1.73	3.84	4.11	4.19

[a]From Ref. 1, p. 152.
[b]From Eq. (1), capital charge = 0.1, capacity factor 0.8 for PWR and coal and 0.9 for MSR.
[c]From Ref. 1 for annual cost used in numerator of Eq. (1).
[d]From Ref. 2.
[e]From Ref. 2, uranium at \$65/kg; the 0.74 doubles at a uranium cost of \$260/kg.
[f]From Ref. 2, coal at \$1.45/MBtu in 1993 dollars.
[g]Taken as 0.1 ¢/kWh in 2000 dollars.

1200-MW(electric) evolutionary light water reactor for the PWR case. We are ignoring the differences due to size for our 1000-MW(electric) examples. The capital cost evaluations were done on a common basis for the three options and are expected to be more reliable than the fuel and O&M costs, which were not done on a common basis.

We conclude that the COE generated by an MSR is competitive with other sources based on the old but comprehensive evaluations. Using the same methodology, the COE is 7% lower than that for water reactors and 9% lower than that for coal plants. The information in this note is based on the three options as defined in 1978 and does not include current safety, licensing, and environmental standards, which will impact costs, as will CO_2 sequestering and increased hazardous air pollutants for coal. The low COE, along with the MSR's many other potential advantages, suggests that stopping the development of the MSR might have been a mistake and that restarting the program should be considered. These advantages include the ability to burn thorium, the ability to burn most of its own actinide wastes (and some wastes from other plants), the ability to continuously add fuel and remove fission products, and the ability to provide an alternative to the plutonium cycle with its association with nuclear weapons. The fuel cycle is near to being closed, and fuel is burned with high conversion efficiency (near breeder). More recent studies are available.[a,b] Again, it is emphasized that the MSR is a conceptual design several decades old. A new evaluation of the MSR is strongly recommended based on current safety, licensing, and environmental standards and comparisons made to alternative power plants.

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[a]The concept of the MSR has been advanced by a series of publications on a small reactor [7-MW(electric)] called mini-Fuji and a mid-size reactor [155-MW(electric)] called Fuji-II by K. Furukawa; see Ref. 3.
[b]More information on the MSR is available on the Internet at (http://home.earthlink.net/~bhoglund/) and (www.moltensalt.org).

REFERENCES

1. J. R. ENGEL, H. F. BAUMAN, J. F. DEARING, W. R. GRIMES, E. H. McCOY, and W. A RHOADES, "Conceptual Design Characteristics of a Denatured Molten-Salt Reactor with Once-Through Fueling," ORNL/TM-7207, Oak Ridge National Laboratory (1980).

2. J. G. DELENE, "Advanced Fission and Fossil Plant Economics—Implications for Fusion," *Fusion Technol.*, **26**, 1105 (1994).

3. K. FURUKAWA et al., "Small MSR with a Rational Th Fuel Cycle," *Nucl. Eng. Des.*, **136**, 157 (1992).

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