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ENERGY, EXERGY AND THERMOECONOMIC ANALYSIS OF THE EFFECTS OF FOSSIL-FUEL SUPERHEATING IN NUCLEAR POWER PLANTS

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Abstract—Starting with information from Indian Point 1, a full size nuclear plant with fossil-fuel superheat which was built and operated, this paper examines the effect of superheat on both energy and exergy performance, as well as on the thermoeconomics of such plants. The study finds that adding superheat to the nearly saturated steam generated by water-cooled nuclear reactors increases the amount of power generated by at least 70%, the plant efficiency by at least 16%, the plant effectiveness by at least 6%, and reduces the cost of generated electricity by at least 32%. These costs are competitive with fossil-fuel plant generated electricity. These features make fossil-fuel superheat of nuclear power plants interesting both for new plants and for retrofit of existing nuclear plants. Hardware failures which were experienced during the operation of the Indian Point 1 plant appear to be easily avoidable. The superheater accounts for the major portion of exergy destruction in the system excluding the reactor, with the extraction turbine taking second place, and it appears that optimization of their combination will lead to even better system performance. © 1997 Elsevier Science Ltd.

Exergy   Second law analysis   Thermodynamics   Nuclear power   Energy conversion   Advanced nuclear reactors   Hybrid power cycles

NOMENCLATURE

a_i = Specific exergy at state point i, $a_i = (h_i - h_o) - T_o(s_i - s_o)$ (kJ/kg)
A_i = Exergy at state point i, $A_i = m_i a_i$ (kJ)
c_e = Cost of electricity ($/kWh)
c_f = Cost of fossil-fuel ($/GJ)
C = Number of atoms of carbon in the fuel
C_o = Initial capital cost of the plant ($)
C_{nf} = Non-fuel costs of the plant (capital + O&M) over its lifetime ($)
C_u = Cost of the nuclear fuel over the plant lifetime ($)
h_i = Enthalpy at state point i (kJ/kg)
H = Number of atoms of hydrogen in the fuel
i = Interest rate on capital (%)
m_i = Mass flow rate at state point i (kg/h)
n = Lifetime of the plant (years)
N_e = Amount of electricity produced over the plant lifetime (kWh)
N_f = Amount of fuel used over the plant lifetime (GJ)
p_i = Pressure at state point i (MPa)
Q = Heat (kJ)
s_i = Entropy at state point i (kJ/(kg K))
T_i = Temperature at state point i (°C)
W = Work (kJ)
Y = Annual operation and maintenance cost ($/year)

Greek letters

ΔH_l = The lower heating value of fuel (kJ/kg)
η = Energy efficiency
ε = Effectiveness (exergetic efficiency)

Subscripts

c = Condenser
co = Condenser coolant
f = Fossil-fuel
n = Nuclear
o = Dead state
p = Pump
par = Parasitic
s = Superheater
t = Turbine.

INTRODUCTION

The energy efficiency of water-cooled nuclear power plants is in the neighborhood of 29–35%, significantly lower than that of fossil-fueled power plants, which nowadays operate at efficiencies up to about 45%. The primary reason for this low efficiency is the limitation of the top temperature of the turbine-driving steam in the nuclear power stations, which arises from nuclear fuel thermal safety considerations and the related impossibility to superheat the steam at the top pressures generated. For example, the steam in typical nuclear power plants is near saturation (slightly superheated due to pressure drops) at top temperatures of about 220–285°C, while in fossil-fueled power stations it is typically superheated up to about 540–650°C (1000–1200°F).

An obvious direction for increasing the efficiency of nuclear power stations is to superheat the generated steam by using a fossil-fueled superheater, and thus raise the steam inlet temperature to the conventional power plant levels. Such a plant, Indian Point 1, a pressurized water reactor with a 275 kWe gross capacity, was indeed designed in 1955 by the Babcock and Wilcox Company, and built by the Consolidated Edison Company of New York, at Buchanan, West Chester county, New York [1, 2]. It was commissioned in 1962 and operated until its shutdown in 1974. The plant flow diagram is shown in Fig. 1; the top steam temperature in the nuclear-heated boiler was 271°C, and at the turbine inlet 540°C at 2.5 MPa. 163 kWe of the gross electric production were attributed to the nuclear reactor (saturated steam), with the oil-fired superheater adding 112 kWe. An energy efficiency improvement of about 21% was predicted and materialized, and a produced electricity cost reduction of about 25% was predicted. The operation of this plant has proven the validity of the thermal and basic economical predictions, but it has suffered many technical failures in the reactor itself, in some of the heat exchangers, in the condenser cooling water intake system, and in the superheater. These problems, as well as lack of an emergency cooling system, the relatively small size of the plant, and the rapidly escalating fuel oil costs in the 1970s made this plant commercially uneconomical, and it was finally shut down in 1974. It appears, however, that the only failure which arose due to the nuclear/fossil-fuel hybrid nature of the plant was due to the poor integration of the superheater and turbine, which has allowed startup transients and part-load operation to cause various breakdowns of the superheater. Since steam superheater technology is well-developed, and since the superheater conditions were well within common design practice, it appears that the problems experienced were here uniquely due to poor design. Improved design and controls should easily resolve this problem.

Another externally-superheated nuclear plant, a BWR using oil for superheating, was built near Lingen, Germany [3]. The reactor thermal output was 540 MWt and of the superheater 214 MWt. The net electric power output was 240 MWe, and it achieved an efficiency improvement of nearly 33%. This plant is not in operation any longer either.

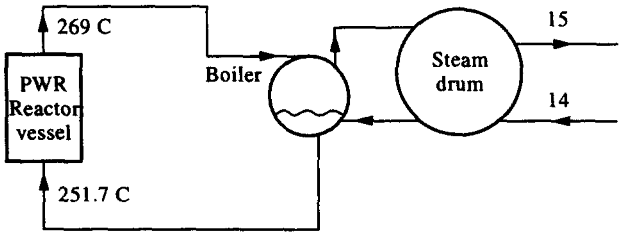
A recent comparative energy and exergy analysis of an operating boiling water reactor nuclear power plant [4] has confirmed the viability of external superheat, concluding that efficiency can be improved by incorporation of a fossil-fuel-fired economizer, superheater and reheater, upstream and downstream of the reactor vessel, respectively. Generically, guidance for the optimal use of several heat-sources/fuels and temperatures in a single plant can be obtained from exergy analysis. Since there is no evidence that the original design analyses of the Indian Point and Lingen fuel-superheated reactors involved an attempt for exergetic optimization, and since operational data on these plants is available, such a study is the subject of this paper.

Interest in this topic extends beyond nuclear power plants. Addition of external superheat to a base plant generating saturated steam was also successfully applied to other power generation systems, in which the top cycle temperature was originally well below the tolerance limit of conventional materials and devices. Some of the examples are solar power systems which use flat-plate or moderately-concentrating collectors, geothermal systems and waste-heat operated systems, all capable of producing rather low working fluid temperatures.

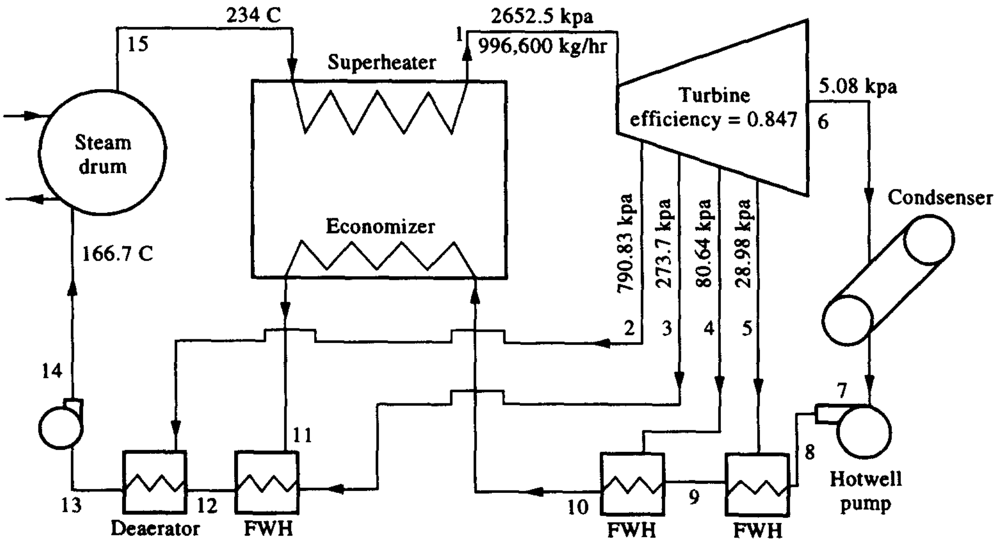
One example of this is the hybrid solar-powered/fuel-assisted Rankine cycle studied by Lior and co-workers [5, 6]. The lower temperature (here 102°C) steam generated by solar energy is superheated by internal heat-recovery and by a fuel-fired superheater to its top temperature of 600°C (corresponding to top temperatures used in conventional steam power plants, but here at just atmospheric pressure). Analysis of the cycle has shown that its efficiency at the above conditions is about 18–20%, more than double that of a power cycle operating at the solar-generated steam temperature of 102°C, impressively accomplished by the addition from the fuel source of only about 20% of the total energy. A prototype cycle, and a 30 hp counter-rotating turbine with an efficiency of 75%, were designed and built [5, 6]. It is noteworthy that solar energy can also be used to superheat the steam, by employing solar concentrators, thus avoiding the need for fuel. Similar cycles were also proposed for use with geothermal sources [7] and with automotive engines [8].

THE MODEL

As shown in the plant flow diagram, Fig. 1, The Indian Point 1 plant has a pressurized water reactor producing 585 MW of heat. It generates hot water at 269°C, 10.01 MPa, which produces



Nuclear Loop



Fossil Fuel Section of Hybrid Plant

Fig. 1. Concise flow diagram of the Indian Point 1 nuclear power plant with fossil-fuel superheat [1, 2].

steam at 234°C, 2.86 MPa, in the power system loop of this PWR. This steam is superheated in the oil-fueled superheater to 540°C at 2.5 MPa. The superheater has a capacity of 996,600 kg/h steam, and is composed of a radiant and a convection section. The hot gases exiting the superheating region then serve to preheat combustion air in a regenerative air heater, then pass through an economizer section in which they serve to provide heat to the feedwater, and finally exit through the stack. The superheated steam enters the turbine which has four extraction points, with given pressures and flow rates at each point and at the final exhaust. Three of the feedwater heaters are of the open type, and the fourth is a dearator.

Based on the plant flow diagram shown in Refs [1] and [2], it is easily determined that the turbine isentropic efficiency is 0.847. Assuming that this efficiency is valid for all turbine stages and applying enthalpy balances yields the enthalpy values of the steam at all of the turbine extraction points. This calculation was validated by the overall flow diagram data given in these papers. As stated above, the parameter varied in the analysis was the turbine inlet (same as superheater outlet) temperature T_1. The amount of heat produced by the nuclear plant, and the nuclear plant steam output pressure and temperature, were kept constant, which thus also kept constant the temperature of the water returning to the steam generator. The turbine extraction point pressures were also kept constant, although a more refined analysis would include their re-optimization for each level of superheat. Such changes in the extraction point pressures are not, however, expected to cause a major change in the conclusions of this analysis.

The energy analysis, which also assists in determining the cycle thermodynamic state conditions, is based on conventional mass and enthalpy-heat-work balances which would not be detailed here. The energy efficiency of the plant, η_{plant}, is defined as

$$\eta_{\text{plant}} = \frac{W_t - W_p - W_{\text{par}}}{Q_n + Q_f} \tag{1}$$

where W_{par} is the parasitic power consumption by the plant (exclusive of the pumping power requirement W_p), given as 19.22 MWe, Q_n is the heat rate produced by the nuclear reactor, here $Q_n = 585$ MW, and Q_f is the amount of heat supplied by the fuel to the superheater.

The effectiveness (exergy efficiency) is typically defined here as

$$\varepsilon \equiv \frac{\Sigma A_{\text{out}}}{\Sigma A_{\text{in}}} \tag{2}$$

where A_{out} are the useful exergy outputs. The dead state is taken to be $T_o = 298$ K, $p_o = 1$ atm. Exergy losses in the nuclear reactor itself are not considered in this study.

The effectiveness of the superheater, ε_s, is defined as

$$\varepsilon_s = \frac{(A_1 - A_{15}) + (A_{11} - A_{10})}{A_f} \tag{3}$$

where the exergy of the fuel oil is calculated from the correlation [9]

$$a_{\text{fuel}} = [1.0334 + 0.0183(H/C) - 0.0694(1/C)]\Delta H_l. \tag{4}$$

The effectiveness of the turbine is defined by

$$\varepsilon_t = \frac{W_t + A_2 + A_3 + A_4 + A_5 + A_6}{A_1}. \tag{5}$$

While turbine effectiveness is often defined by having only the work output, A_t, in the numerator, equation (5) assigns appropriate credit to the extraction streams which indeed are there to improve cycle performance.

The condenser effectiveness is defined as

$$\varepsilon_c = \frac{A_7 + A_{co}}{A_6}, \tag{6}$$

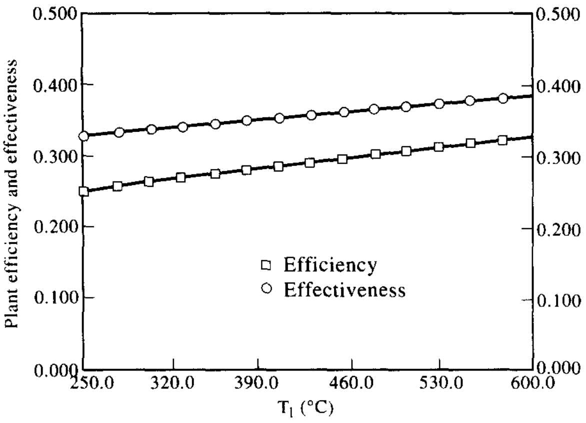


Fig. 2. Plant efficiency and effectiveness as a function of superheat.

where the exergy gain of the condenser coolant, A_{co}, is calculated by

$$A_{co} = Q_c\left(1 - \frac{T_o}{T_c}\right) \tag{7}$$

where Q_c is the amount of heat rejected in the condenser, and T_o and T_c are in K.

The overall plant effectiveness is defined as

$$\varepsilon_{plant} \equiv \frac{A_t}{A_n + A_f + A_p} \tag{8}$$

where A_n is the exergy of the nuclear heat, taken to be equal to Q_n, as explained in Refs [10, 11].

THE ANALYSIS METHOD

The steam states and flow rates at the inlet and outlet of nuclear station steam generator are assumed to be constant, and thus states 14 and 15 (Fig. 1) are given. The state at the superheater exit, 1, is set as the major variable in this analysis, and is thus prescribed. Given the original steam flow rates and pressures at the turbine extraction points (states 2–5 in Fig. 1), it is assumed that the isentropic efficiency of the turbine is constant throughout the expansion process, thus solving for the extraction point states 2–5. States 6 and 7 are also fixed by the condenser conditions. Energy and mass balances are used to compute states 8–14. Energy and mass balances, as well as combustion reaction equations are used for computing the energy distribution among the steam, stack gas, air preheater and economizer inside the superheater, thus fully defining the thermodynamic states of the entire system.

RESULTS OF THE ENERGY AND EXERGY ANALYSIS AND DISCUSSION

As seen in Fig. 2, the plant efficiency (energy) and effectiveness (exergy) increase with superheat (T_l). In the range of T_l shown, η_{plant} increases at a rate of about 7.7%/100°C, and ε_{plant} increases at a rate of about 5.2%/100°C. With no fossil-fuel supplied superheat (not shown in Fig. 2), $\eta_{plant} = 28.4\%$ and $\varepsilon_{plant} = 36.7\%$, indicating that the superheater, while increasing the power production even at low values of superheat, starts improving the plant effectiveness only when $T_l > 475$°C. This is explained by the fact that exergy destruction is higher when the highly dissipative, high-temperature combustion process [11] is used to heat lower temperature steam, and can also be seen more specifically in Fig. 3 which shows the marked increase with T_l of the superheater effectiveness, from 20% at 250°C to 45% at 600°C. The turbine effectiveness is also seen to increase, but much more moderately.

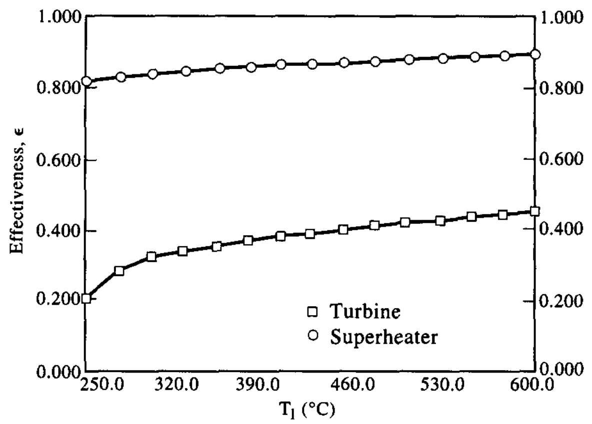


Fig. 3. Effectiveness of the turbine and superheater as a function of superheat.

From the breakdown of the exergy losses in the plant, shown in Fig. 4, one can see that the turbine and the superheater account for more than 90% of the exergy destruction in the plant. The losses in the feedwater heaters are next in magnitude, and those in the condenser and pumps are negligibly small. It is interesting to note that while the superheater is least effective at the lower values of T_1, it also destroys the least fraction of the plant exergy at these levels. This is because the amount of fuel invested in it is then least. It is also interesting to note that the turbine is the major exergy destroyer at the lower temperatures: not only is the extraction steam released without producing work, but, more importantly here, the amount of fuel used in the superheater at these temperatures is small. The crossover temperature, above which the superheater exergy loss becomes dominant, is between 300 and 325°C.

OPTIMIZATION

Different combinations of steam flows from the four turbine extraction flows would change the efficiency and effectiveness of the plant, and these combinations are likely to change with the temperature of the steam entering the turbine. To determine the maximal effectiveness that can be obtained for any given superheat, the extraction point steam flow rates were optimized.

The optimization was performed by the conjugate gradient method. This is a search method following the path along which the objective function, here the plant effectiveness, increases at the greatest rate. This path is the gradient of $\varepsilon_{\text{plant}}$ with respect to one of the extraction flow rates, it is computed numerically at chosen intervals, and the computation stops when the maximal value of $\varepsilon_{\text{plant}}$ is reached. At this point the gradient with respect to another extraction flow rate is computed, and the procedure is repeated until the global optimum (maximum) is attained.

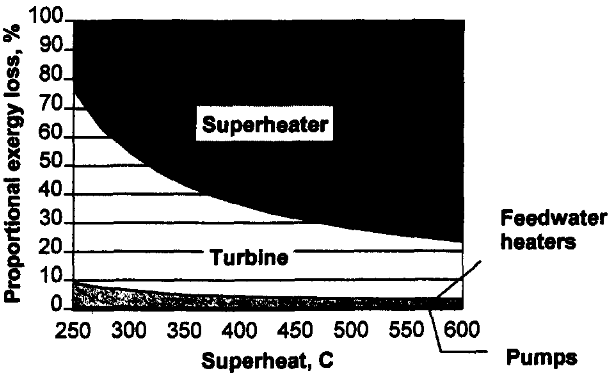


Fig. 4. Percentage exergy losses of the superheater, turbine, feedwater heaters and pumps, as a function of superheat.

Table 1. The effect of extraction streams optimization at 400 and 600°C on plant efficiency, effectiveness, and power output

T_l °C	m_2 kg/h	m_3 kg/h	m_4 kg/h	m_5 kg/h	m_6 kg/h	η_{plant} %	$\varepsilon_{\text{plant}}$ %	W_t MW
400, N	73,437	41,223	53,001	38,958	789,981	29.4	36.1	233
400, O	0	100,212	53,346	60,572	782,450	30.0	36.7	238
600, N	46,837	41,223	53,001	38,958	816,581	31.9	37.5	297
600, O	1903	91,497	45,887	53,937	803,375	32.2	46.1	299

N: not optimized; O: optimized.

The results of the optimization are shown in Table 1. Optimized extraction rates yield improvements in both plant efficiency and effectiveness, most remarkable being an effectiveness improvement of 23% at highest superheat temperature $T_l = 600°\text{C}$. Despite the benefits of internal heat recovery in the feedwater heaters, it is obvious from the table that this should not be at the expense of extracting high pressure steam. The optimization process has shown that effectiveness has increased when the same overall amount of extraction steam was taken from the low pressure extraction points.

ECONOMIC EVALUATION

An economic evaluation of the effect of superheat on the cost of electricity was conducted, using the original data of Indian Point 1, updated for the 1989–1992 period. The analysis does not include some of the less tangible economic aspects of nuclear or nuclear/fossil fuel hybrid plant costing, and is mainly oriented to estimate relative rather than absolute values.

The cost equation, based on exergy valuation, is

$$c_e N_e = c_f N_f + C_u + C_{nf} \tag{9}$$

where c_e is the cost of electricity which we seek to calculate (\$/kWh), N_e is the number of the electricity units produced over the plant lifetime (kWh), c_f is the cost of the fuel per its unit exergy (\$/GJ), N_f is the number of fuel exergy units used over the plant lifetime (GJ), C_u is the cost of the uranium used over the plant lifetime (since the nuclear part of the plant is fixed in this analysis, C_u is also a fixed value), and C_{nf} is the non-fuel cost of the plant (capital and operation and maintenance) over its lifetime. Costs of plant decommissioning at the end of its life, insurance and taxes were not included in the analysis, although at least the first one may be significant.

The amount of electricity produced over the plant lifetime, N_e, was based on plant life of 40 yr and a load factor of 0.8. Both N_e and N_f depend on the superheat level, and are so calculated. c_f for the fuel oil no. 6 for 1989 was taken as \$2.26/GJ. The cost of the nuclear fuel was given by the U.S. Department of Commerce as \$12.60/kg, and 1 kWh of heat produced by a reactor requires approximately $(7.28)10^{-6}$ kg U_3O_8. This translates into a nuclear fuel cost of \$$(2.248)10^6$/yr for the 585 MW nuclear heat supply.

The method for determining the annual value of C_{nf} was based on present worth and capital recovery factors. The equation used is

$$C_{nf} = \left[\sum_{m=1}^{n} \left(\frac{Y}{1+i}\right)^m + C_o\right] \frac{i}{1-(1+i)^{-n}} \tag{10}$$

where n is the lifetime of the plant (years), Y is the annual O&M cost, i is the interest rate and C_o is the initial capital investment.

The capital costs, included in C_{nf}, are based on the 1955 real costs for this plant as provided by [1]. These were \$106,745,000 for the nuclear plant alone and \$126,255,000 for the fuel-superheated nuclear plant. Adjusted to 1989, by using the Producer Price Index (U.S. Department of Commerce [12]), resulted in costs of \$377,123,000 and \$446,051,000, respectively. Notably, this adjustment may not take fully into account the special socio-economical circumstances affecting nuclear power plant construction, but may be adequate for comparative

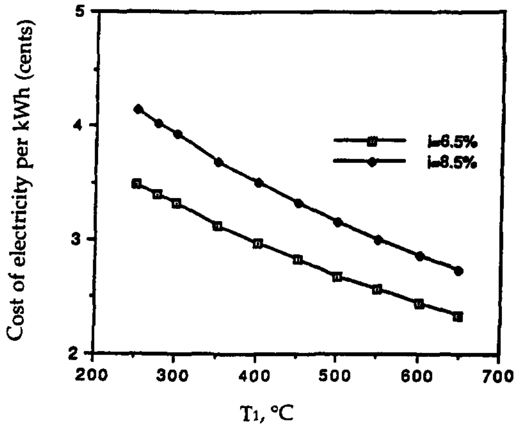


Fig. 5. Cost of electricity generation as a function of superheat, for two interest rates.

purposes. The O&M cost was estimated by the U.S. Energy Information Administration [13] to be \$0.005301/kWh in 1984 dollars, which is \$0.005946 in 1989 dollars. The same source also states that this cost is approximately constant over the plant lifetime because any deterioration in plant equipment is compensated by a rise in the learning curve. The computations were performed for two interest rates: 6.5 and 8.5%, and the electricity costs are shown in Fig. 5 as a function of superheat temperature.

As seen in Fig. 5, the cost of electricity is reduced as the superheat is increased. The reduction is significant: for example, for the interest rate of 8.5%, the change is from 0.042 \$/kWh at a superheat of 250°C to 0.027 \$/kWh at the superheat of 649°C (1200°F), a 36% reduction. For a more common top superheat temperature of 538°C (1000°F), the cost is 0.026 \$/kWh for $i = 6.5\%$, and 0.030 \$/kWh for $i = 8.5\%$. These costs are comparable to those of electricity from fossil fuel power plants [12]. It is interesting to note that the originally (1955) estimated generation costs for the Indian Point 1 plant of were 0.013 \$/kWh, 65% higher than those of conventional fossil fuel power plants at that time. The results of this study indicate that this large gap may now have been closed.

Performing the same economic analysis for the same nuclear power plant without fuel superheat, which produces 163 MWe, the cost of electricity was found to be 0.034 \$/kWh for $i = 6.5\%$, and 0.041 \$/kWh for $i = 8.5\%$. The fuel-superheated nuclear plant starts producing electricity at lower costs when the superheat temperature exceeds about 260°C.

CONCLUSIONS AND RECOMMENDATIONS

Adding superheat to the nearly saturated steam generated by water-cooled nuclear reactors increases the amount of power generated by at least 70%, the plant efficiency by at least 16%, the plant effectiveness by at least 6%, and reduces the cost of generated electricity by at least 32%. These costs are competitive with fossil-fuel plant generated electricity.

These results make such plants not only interesting for new construction, but also for retrofit, where the addition of fossil-fuel superheat to an existing nuclear power plant can produce significantly more power.

Hardware failures which were experienced during the operation of the Indian Point 1 plant, and which primarily stemmed from poor dynamic integration of the superheater with the reactor and turbine, and poor superheater design, appear to be easily avoidable. Since the superheater accounts for the major portion of exergy destruction in the system excluding the reactor, with the extraction turbine taking second place, and since these two components interact with each other, it appears that optimization of their combination will lead to even better system performance.

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