CONF-760906--3

NUCLEAR DUAL-PURPOSE PLANTS FOR INDUSTRIAL ENERGY*

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ABSTRACT

One of the major obstacles to extensive application of nuclear power to industrial heat is the difference between the relatively small energy requirements of individual industrial plants and the large thermal capacity of current power reactors. A practical way of overcoming this obstacle would be to operate a centrally-located dual-purpose power plant that would furnish process steam to a cluster of industrial plants, in addition to generating electrical power. The present study indicates that even relatively remote industrial plants could be served by the power plant, since it might be possible to convey steam economically as much as ten miles or more. A survey of five major industries indicates a major potential market for industrial steam from large nuclear power stations.

1. INTRODUCTION

The results of a recent AEC-sponsored cooperative study between the Oak Ridge National Laboratory and a number of industrial participants on alternative sources of industrial energy, Anderson et al. (Ref. 1) indicate that process steam, produced in present type central station reactors, may be one of the most economical forms of process energy available with current technology. The Midland reactor plant now being built for Consumers Power Company to generate electrical power and furnish process energy (so-called dual-purpose use) to the adjacent Dow Chemical

*Research sponsored by the Energy Research and Development Administration under contract with the Union Carbide Corporation.

CONTRACT NO. W-7405-ENG-26

plant is an example of this approach applied at a very large industrial plant. Since the start of the Midland project, fossil fuels have become increasingly scarce and costly, and thus the relative position of nuclear power economics has improved. As a result, it is now believed that dual purpose reactor plants (located at sites that allow economical construction of process steam lines) can provide competitively priced industrial steam even to industries relatively remote from the reactor station. This concept might overcome one of the major obstacles to extensive application of nuclear power to industrial heat, namely the disparity between the relatively small energy requirements of individual industrial plants and the large thermal capacity of current power reactors. Thus, it may be practical to furnish process steam to a cluster of industrial plants with an aggregate electrical and process energy demand that warrants operation of a centrally-located dual-purpose reactor station. Steam conveyance distances may reach 16 km (10 miles) or more. The purpose of the present investigation was to make a preliminary economic evaluation of such an arrangement for a representative industrial site, and to predict competitive steam transmission distances. In addition, the potential U.S. market for these applications was surveyed.

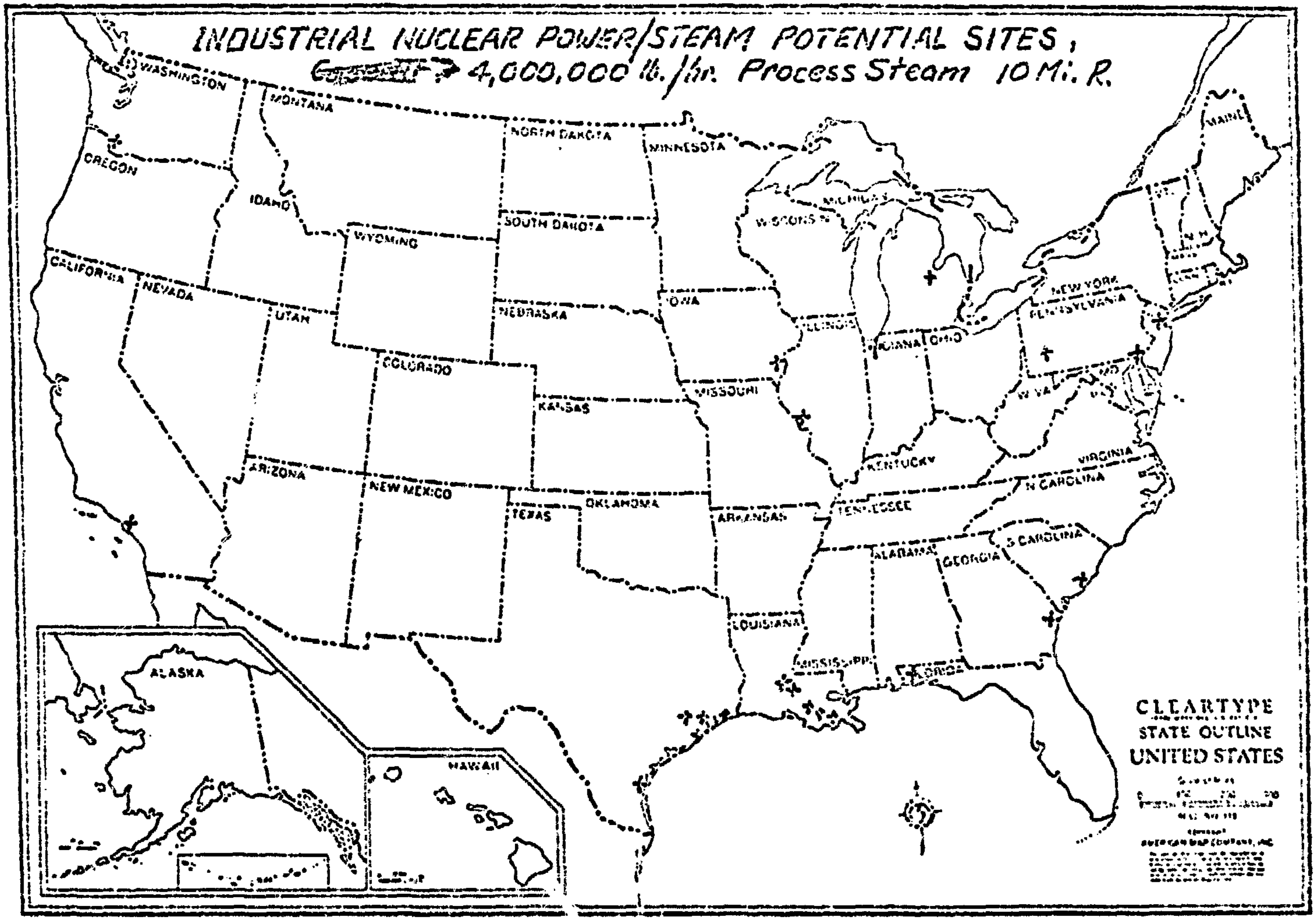
Some background data (Ref. 1) are needed to help assess the dimensions of industrial energy requirements. The industrial sector is the largest energy user in the United States, requiring about 40% of the national consumption; natural gas and petroleum furnish about 80% of industrial fuels. Roughly two-thirds of this Nation's industrial energy is consumed by the primary metals, chemicals, petroleum refining, food, paper, and stone industries. The chemicals, petroleum refining and primary metals industries are of particular interest, since these include many plants and industrial complexes with sizable energy requirements where the introduction of alternative energy sources might reduce consumption of oil and gas significantly. A breakdown of industrial energy by form, indicates that process steam is the most commonly used type, amounting to nearly 17% of the total national energy use. This is equivalent to two-thirds of the energy consumed in the United States to produce electric power.

2. POTENTIAL MARKET

The Dow Chemical Company, under contract to the Oak Ridge National Laboratory, recently completed a survey of the potential market for industrial energy supplied by nuclear reactors, Dow Chemical (Ref. 2). A specific segment of industrial process heat use was examined in detail to identify individual plant locations throughout the United States where nuclear generated steam may be a viable alternative. Five major industries have been studied, paper, chemicals, petroleum, rubber, and primary metals. Process steam applications within the industries studied involve temperatures from about 38°C (100°F) up to about 232°C (450°F). Although steam is often produced at temperatures above 232°C (450°F), the high temperature/high pressure steam is first used for electrical power generation and then extracted at lower pressures for process heat. Also, much of the steam use in the 232°C (450°F) temperature range is in turbines or reciprocating engines, driving pumps, compressors, etc. These applications may be converted to electrical drive as steam costs increase. Thus, it is estimated that at least 85% of the industrial steam heat requirements is below 204°C (400°F) and within the range available from conventional nuclear light-water reactors.

For the industries investigated, representing 75% of the total industrial steam consumption, the individual plant locations within the U.S. using steam in large quantities have been located and characterized as to fuel requirements. Figure 1 shows the 19 locations within the United States where there exists a concentrated

Figure 1.


INDUSTRIAL NUCLEAR POWER/STEAM POTENTIAL SITES,
→ 4,000,000 lb./hr. Process Steam 10 Mi. R.
WASHINGTON
MONTANA
NORTH DAKOTA
MINNESOTA
MAINE
OREGON
IDAHO
WYOMING
SOUTH DAKOTA
WISCONSIN
MICHIGAN
VT.
N.H.
CALIFORNIA
NEVADA
UTAH
NEBRASKA
IOWA
NEW YORK
PENNSYLVANIA
ILLINOIS
INDIANA
OHIO
COLORADO
KANSAS
MISSOURI
W. VA.
KENTUCKY
VIRGINIA
ARIZONA
NEW MEXICO
OKLAHOMA
N. CAROLINA
TEXAS
ARKANSAS
TENNESSEE
S. CAROLINA
ALABAMA
GEORGIA
LOUISIANA
MISSISSIPPI
FLORIDA
ALASKA
HAWAII
CLEARTYPE
STATE OUTLINE
UNITED STATES

industrial steam load of at least 504 kg/sec (4,000,000 lb/hr) within a 32 km (20 mile) diametercircle, a load that appears compatible with the power level of large dual purpose reactors. An additional 24 locations have a combined industrial steam requirement of at least 252 kg/s (2,000,000 lb/hr) within a circle of 16 km (10 miles) diameter, and 119 further locations have a combined requirement of at least 63 kg/s (500,000 lb/hr) within a circle of 64 km (4 miles) diameter. Thus there exists also a potential market for industrial energy from small reactors, MacPherson and Klepper (Ref. 3). The sites identified in the survey are listed by state in Table I.

Although the total steam load was the factor on which the selection of each plant was based, it is recognized that not all of the steam generated in a given plant may be replaceable on an economic basis. Significant steam is often produced by the combustion of "process residuals"; these materials, if not used for steam generation, may have little or no alternate value. Examples of such fuels are the black liquor and wood-waste of the paper industry, certain refinery gases of the petroleum industry, and the blast furnace gas of the iron and steel industry. To avoid neglecting this factor, estimates were developed of the nominal fractional range of steam production that is met using process residual fuels in plants within each industry. Since the amount of process residuals which are produced and used within any given plant is sensitive proprietary information, this factor has not been defined precisely for each location; for the sites included in this survey, about 87% of the steam loads shown were judged replaceable on the average. Within the limitations of the procedures used to assemble this information, it should be noted that the stated steam requirements are minimally conservative for each identified industrial concentration. This is because only the five specified industries were examined and within these industries, individual plants using less

Table I. Summary of Potential Sites for Industrial Energy Reactors

State	No. of Sites	Total Steam Load Kg/Sec (10^6 #/Hr)	Energy Use Elec. MW	Energy Use Fuel 10^{12} kJ /Day (10^9 Btu/Day)	Sites With Navigable Waterway Access
Alabama	8	(12.6)	913	(348)	7
Arkansas	3	(5.7)	174	(159)	0
California	9	(18.4)	694	(521)	6
Connecticut	1	(0.7)	8	(20)	1
Delaware	1	(2.1)	102	(59)	1
Florida	7	(11.6)	464	(328)	6
Georgia	7	(10.1)	643	(285)	6
Iowa	1	(.7)	62	(20)	1
Idaho	1	(.8)	45	(23)	0
Illinois	4	(11.0)	347	(312)	2
Indiana	3	(11.9)	2220	(336)	2
Kentucky	2	(1.5)	35	(43)	2
Louisiana	15	(45.4)	3227	(1283)	12
Maryland	2	(2.8)	298	(79)	1
Maine	6	(4.8)	201	(137)	0
Michigan	5	(18.4)	666	(238)	4
Minnesota	2	(1.5)	69	(42)	1
Missouri	2	(1.6)	50	(45)	2
Mississippi	3	(4.9)	198	(143)	1
Montana	1	(1.3)	24	(37)	0
North Carolina	6	(6.0)	207	(169)	3
New Jersey	3	(5.7)	169	(161)	3
New York	8	(8.2)	566	(231)	3
Ohio	6	(6.4)	266	(182)	3
Oklahoma	2	(2.3)	91	(65)	0
Oregon	4	(2.7)	163	(79)	2
Pennsylvania	4	(7.7)	666	(217)	3
South Carolina	3	(6.6)	332	(190)	2
Tennessee	3	(2.0)	487	(56)	2
Texas	17	(78.4)	4158	(2212)	10
Utah	2	(2.45)	228	(69)	0
Virginia	7	(6.35)	155	(179)	1
Washington	5	(4.85)	260	(137)	5
Wisconsin	2	(1.4)	58	(39)	1
West Virginia	4	(7.25)	390	(205)	4
Wyoming	3	(3.0)	74	(84)	0
TOTAL	162	319.1	18,710	8733	97

than 25 - 38 kg/sec (200,000-300,000 lb/hr) of steam were not considered. It is known that many of the identified locations have additional, but undetermined, steam requirements from plants in the categories not considered.

The electrical loads have been calculated from unit ratios relating power requirement to production capacity for each industry and major process application.

The fuel requirement is based on the total steam load adjusted for efficiency of the boiler operation as influenced by the type of fuel employed. For most of the plant sites identified, there will be additional process heat applications other than steam, and the total fuel requirement will be appreciably larger than that shown.

Because of the long lead time inherent in nuclear reactor installation, there is reason to be concerned as to whether the industrial locations identified in this study will continue to have the requisite level of steam usage as time progresses. With very few exceptions, it is expected that these locations will show an increase in steam demand over the next ten to twenty years. This conclusion is based on the following observations and reasoning.

There are three principal circumstances which could cause a given industrial location to decrease steam usage:

1. Energy conservation activity.
2. Decrease in demand for the products produced.
3. Abandonment of obsolete facilities.

Other studies, Barnes (Ref. 4), indicate that within the industries of interest here, conservation efforts can be expected to ultimately reduce energy requirement per unit of production by 10-25% from 1972 levels. This means that when total production in these plants exceed 1972 output by 10-25%, overall energy use will increase. Recent estimates, Barnes (Ref. 4), of production growth for the subject industries indicate that all except petroleum should grow from 20-85% by 1985 with a 7% growth expected for the petroleum industry. On this basis, normal growth should more than offset the conservation reduction in steam use.

3. RELIABILITY REQUIREMENTS

Modern industrial complexes include processes that become difficult to control (or where damage results) if the process heat flow is interrupted; thus, service dependability is vital to the application of alternative energy sources. This is particularly true for a nuclear unit if it supplies a large amount of process energy. Two major questions need to be addressed: First, what reliability is required by industry, and second, how can the needed reliability be provided at reasonable cost? Some preliminary results have been obtained on the first of these topics. The approach taken has been to use actual industrial energy reliability experience as a guide for estimating future requirements. Questionnaires requesting information on the characteristics and operating experience of energy supply systems were sent to about 70 major installations in the chemicals, petroleum refining, and primary metals industries. At the present time, only the returns for the chemicals industry have been analyzed. These consist of responses from 12 major users of industrial steam [in the range from 14.6 to 416 kg/s (116,000 to 3,300,000 pounds per hour)] that consume about 5.6% of the steam requirement in that industry. Natural gas represented 30% of fuel use, oil 19%, coal 39%, and other fuels 12%. Table II summarizes the results. Reserve margins at each plant were determined by subtracting the actual steam usage from the on-line capacity. From line J, it is seen that the reserve margins in eight out of the twelve plants were 80% or greater than the capacity of the largest on-line unit. This indicates that high reliability has been sought by providing a

Table II. Process steam system capacity, consumption and reliability for chemical plants in the survey

Item of data	Plant 1	2	3	4	5	6	7	8	9	10	11	12
A. Average installed capacity, 10^3 lb of steam/hr	4360	2440		1700	1200	1220	720	525	360	220	320*	300**
B. Average on-line capacity, 10^3 lb of steam/hr	3700	2320	1450	1475	1100	1155	670	500	330	212	265	280
C. Average on-line capacity, as percentage of A.	84.8	95.1	91.0	86.8	91.2	94.7	85.7	95.2	91.7	96.2	82.8	93.3
D. Average actual steam usage, 10^3 lb of steam/hr	3300	1900	1170	1160	900	917	550	480	270	175	164	116
E. Average scheduled steam usage, 10^3 lb/hr	3300	1900	1200	1230	930	917	600	490	280	175	164	116
F. Average actual steam usage, as percentage of B	89.2	81.9	80.7	78.6	80.7	79.4	82.1	96.0	84.8	82.5	61.9	41.4
G. Average safety margin, Item B - Item D	400	420	280	315	230	238	120	20	50	37	101	164
H. Average safety margin, as percentage of B	12.1	22.1	23.9	27.2	24.0	25.9	21.8	4.2	18.5	21.1	61.6	141.0
I. Largest unit on-line (i) 10^3 lb of steam/hr	430	400	200	550	250	267	125	175	100	100	125	150
(ii) avg. percentage of B	11.6	17.2	13.8	37.3	21.0	23.1	18.7	35.0	30.3	47.2	47.2	53.6
J. Safety margin as percentage of largest unit on-line (i)	93.0	105.0	140.0	57.3	100.0	89.0	96.0	11.4	50.0	37.0	80.8	109.0
K. Percent of time steam supply unable to meet scheduled requirements (E) due to equipment outages	0.8	0	2.4	9.0	0	0.8	3.8	0	0	0	0	0
L. Percent of time scheduled steam production (E) was curtailed due to nonequipment related outages	0	0.5	0	2.0	0.5	0	2.0	0	1.2	0	0	0
M. Percent of time plant was completely shut down for scheduled vacation	0	0	0	0	0	0	1.0	0	3.8	3.8	3.8	3.8
N. Total percent of time scheduled steam production was curtailed (Item K + Item L)	0.8	0.5	2.4	11.0	0.5	0.8	5.8	0	1.2	0	0	0

*Does not include 65,000 lb/hr standby boiler.
**Does not include 45,000 lb/hr standby boiler.
Note: Multiply lb/hr by 0.000126 to obtain Kg/Sec.

considerable amount of excess capacity. Production for the 12 plants was curtailed 1.9% of the time during the one-year sample period due to planned and unplanned outages, but excluding vacation periods. Unscheduled equipment outages averaged 1.4% of the elapsed time. These outages included 20 plant days of total steam loss. On the average, steam flow was reduced to 40% during outages.

This survey sample represents a small fraction of the chemical industry; however, it is believed to be representative of current reliability experience with large plants. For those applications, an energy supply system capable of meeting load demand 98-99% of the time appears reasonable. It is believed that this goal is achievable with one or more current type reactors, supplemented by fossil-fired units.

4. DESCRIPTION OF DUAL-PURPOSE PLANT

An industrially developed region near the Gulf Coast was selected to provide realistic site data. The overall suitability and acceptability of the hypothetical siting area has not been evaluated, however studies report by Anderson et al. (Ref. 1) suggest that at least from the population viewpoint, the location would be compatible with current reactor siting practice. To illustrate the effect of steam conveyance distance and flow rate on overall process steam costs, three major steam consuming plants in the area were selected as surrogate users of industrial steam. The first, a large refinery located 2.2 km (1.4 miles) from the hypothetical reactor site, generates about 700 kg/s (5.6 million pounds per hour) of steam at temperatures from 260°C to 440°C (500°F to 825°), using gas fired and heat recovery boilers. Preliminary analysis indicates that a steam flow of 315 kg/s (2.5 million pounds per hour) at 5860 kPa (850 psia), 274°C (525°F) furnished from a dual-purpose reactor could meet about 75% of the process energy requirements now obtained by burning purchased fossil fuels. An additional 190 kg/s (1.5 million pounds per hour) of steam at 274°C (525°F) was assumed required by a chemicals-plastics plant located 3.5 km (2.2 miles) from the station, replacing substantial amounts of natural gas used to fire process steam boilers. A second chemicals plant, located 3.9 km (2.4 miles) from the reactor, presented a requirement of 250 kg/s (2 million pounds per hour) of steam at 274°C (525°F), replacing 40 to 50% of the process energy provided by purchased natural gas.

Reactor Station and Process Steam Supply. The reactor station consists of two current type 3750-MW(t) pressurized water reactors, and a power conversion system. Characteristics representative of a PWR nuclear steam system are given in Table III. Process steam is furnished from a reboiler rather than from the prime steam generators since, in many applications, an intermediate heat transport system may be required to prevent the transfer of contaminants between the reactor systems and the industrial processes. For the base case, all the steam from one reactor is supplied to a 1200 MW(e) turbogenerator, while steam from the second reactor is split 54/46 between a 650 MW(e) turbogenerator and a reboiler capable of generating 755 kg/s (6 million pounds per hour) of process steam at 5860 kPa (850 psia) and 274°C (525°F). The capacity of the reboiler and the smaller of the turbogenerators could be varied to match different process steam flow rate requirements. For applications requiring power process steam pressure temperature, the smaller generator could be driven by an extraction or back-pressure turbine, with the extraction or exhaust steam going to a reboiler producing steam at more moderate conditions.

For the base case, prime steam at about 317°C (603°F) 7400 kPa (1075 psia) is supplied to the tube side of the reboilers, to generate process steam at 274°C

Table III. Design Characteristics [3750-MW(t) PWR]

Design Core Heat Output, MW(t)		3750
Nominal System Gage Pressure, kPa (psi)	15500	(2250)
Total Reactor Coolant Flow, kg/s (lb/hr)	19300	(153×10^6)
Vessel Coolant Inlet Temperature, °C (°F)	301	(573)
Vessel Coolant Outlet Temperature, °C (°F)	332	(630)
Steam Conditions at Full Load		
Flow, kg/s (lb/hr)	2000	(16×10^6)
Temperature, °C (°F)	318	(603)
Absolute Pressure, kPa (psi)	7400	(1075)

(525°F), 5860 kPa (850 psia) on the shell side. For the base case, 755 kg/s (6×10^6 lb/hr) of steam is generated in several high-pressure reboiler units of about 63 kg/s (500,000 lb/hr) capacity each. One back-up unit is needed to maintain full steam flow during reboiler maintenance. Associated with the reboilers are feedwater heaters that heat the condensate from the industrial processes before it is returned to the reboilers. It is anticipated that the reboilers and feedwater heaters would be located at the reactor station so that process steam can be furnished conveniently to a number of dispersed industrial users.

Process Steam Conveyance. Insulated steel pipes convey the process steam from the reboilers located at the reactor station to the industrial sites utilizing the steam. Assuming pressure drops of 43 to 51 kPa per km (10 to 12 psi per mile), a pipe of 0.71 m (28 in.) diameter could convey 126 kg/s (1×10^6 lb/hr) of 5860 kPa, abs. (850 psia) steam. A flow of 252 kg/s (2×10^6 lb/hr) requires a diameter of about 0.91 m (36 in.). For steam at 1380 kPa abs. (200 psia) flows of 126 kg/s (1×10^6 lb/hr) and 252 kg/s (2×10^6 lb/hr) require 0.91 m (36 in.) and 1.22 m (48 in.) diameter pipes, respectively.

5. ECONOMIC ANALYSIS

Capital Costs. The capital costs for nuclear steam electric and process steam plants were estimated in accordance with the economic ground rules shown in Table IV. Table V summarizes the capital cost for the 1200-MW(e)/3750 MW(t) steam-electric unit of the two-reactor dual-purpose station described previously. These costs were estimated with an updated version of the CONCEPT code, Bowers et al. (Ref. 5), and they are based on a two-reactor station; interest during construction is included. Values are given in 1975 dollars; escalation beyond early 1975 is not accounted for. The total cost for this unit amounts to 494 million dollars.

Table IV. Economic Ground Rules

1.	Plant Type:	PWR
2.	Environmental Systems:	All-electric power plants use mechanical draft evaporative cooling towers.
3.	Unit Size, MW(t):	3750
4.	Plant Net Efficiency, %:	32 (11250 kJ, 10,660 Btu, per kWhr)
5.	Plant Capacity Factor, %:	80
6.	Plant Location:	Gulf Coast Region
7.	Design and Construction Period:	8 1/2 years from purchase of nuclear steam system to commercial operation of first unit; 9 1/2 years for second unit.
8.	Workweek, hrs:	40
9.	Cost Basis:	Early 1975 dollars.
10.	Interest Rate, %:	8, compound.

Table V. Capital Cost for a 1200-MW(e)/3750 MW(t) PWR Plant*

	Steam Supply Plant	Turbine Plant	Total
Direct Costs (millions of dollars)			
Land and Land Rights	1	0	1
Physical Plant			
Structures and Site Facilities	40	9	49
Reactor Plant Equipment	92	0	92
Turbine Plant Equipment	0	94	94
Electric Plant Equipment	15	15	30
Miscellaneous Plant Equipment	3	2	5
Subtotal (Physical Plant)	151	120	271
Spare Parts Allowance	1	1	2
Contingency Allowance	10	8	18
Subtotal (Total Physical Plant)	162	129	291
Indirect Costs (millions of dollars)			
Construction Facilities, Equipment and Services	9	8	17
Engineering and Construction Management Services	23	18	41
Other Costs	7	6	13
Interest During Construction	73	59	132
Subtotal (Indirect Costs)	112	91	203
Total Costs (millions of dollars)			
Total Plant Capital Cost at Start of Project	274	220	494

*Costs based on a two-reactor station, 1975 dollars.

For the base case, the second reactor unit powers a 650-MW(e) turbogenerator and a reboiler capable of generating 755 kg/s (6×10^6 lb/lhr) of process steam at 5860 kPa (850 psia). The capital costs for this plant are tabulated in Table VI. The cost of the turbine plant was assumed to be directly proportional to gross electrical power output, amounting to 117 million dollars for a capacity of 650 MW(e). The reboiler plant cost was derived from preliminary data obtained for the Midland station; investment capital is expected to be directly proportional to the process steam flow rate, amounting roughly to $69,000 per kg/s (8.7 dollars per pound/hour), or 52 million dollars. The cost for the second unit in the base case configuration amounts to 443 million dollars, giving a total of 937 million dollars for a two-reactor dual-purpose station generating 1200 MW + 650 MW of electrical power and 755 kg/s (6 million pounds per hour) of process steam.

Production Costs. Table VII summarizes the levelized production costs for a two-unit dual-purpose reactor station in base-case configuration. Utility ownership was assumed for the reactor station and the associated reboilers, corresponding to an annual fixed charge rate of 15%. The operating and maintenance costs were based on costs reported by Anderson et al. (Ref. 1) for large pressurized water reactors. The reboiler plant O&M costs were obtained by appropriate modification of the turbine plant estimates. These costs are given in 1975 dollars.

The fuel cycle costs were adopted from Anderson et al. (Ref. 1) for 1984 plant startup and in terms of 1975 dollars. For a separative work unit cost of $58.64/kg ($26.60/lb) and a plant factor of 0.8, the annual expense for fuel amounts to 28 million dollars corresponding to 29¢ per million kJ (31¢ per million Btu).

Table VI. Capital Cost for a 6 Million lb/hr (850 psia) Process Steam and 650 MW(e)/3750 MW(t) Dual-Purpose PWR Plant*

	Steam Supply Plant	Turbine Plant	Reboiler Plant	Total
Direct Costs (millions of dollars)				
Land and Land Rights	1	0	0	1
Physical Plant				
Structures and Site Facilities	40	5	2	47
Reactor Plant Equipment	92	0	0	92
Reboiler Plant Equipment	0	0	26	26
Turbine Plant Equipment	0	50	0	50
Electric Plant Equipment	15	8	0	23
Miscellaneous Plant Equipment	3	1	1	5
Subtotal (Physical Plant)	151	64	29	244
Spare Parts Allowance	1	1	0	2
Contingency Allowance	10	4	2	16
Subtotal (Total Physical Plant)	162	69	31	262
Indirect Costs (millions of dollars)				
Construction Facilities, Equipment and Services	9	4	2	15
Engineering and Construction Management Services	23	9	4	36
Other Costs	7	3	1	11
Interest During Construction	73	32	14	119
Subtotal (Indirect Costs)	112	48	21	181
Total Costs (millions of dollars)				
Total Plant Capital Cost at Start of Project	274	117	52	443

*Costs based on a two-reactor station, 1975 dollars.

Table VII. Levelized Production Costs for 3750-MW(t) PWR Base Case

	1200 MW(e) (10^6 $/yr)	755 kg/s (6×10^6 lb/hr) Steam and 650 MW(e) (10^6 $/yr)	
NSS Plant			
Fixed Charges (15%)	41.1	41.1	
O&M	4.1	4.1	
Fuel Cost (1984 Startup)	28.0	28.0	
	73.2	73.2	
T-G Plant			
Fixed Charges (15%)	33.0	17.5	
O&M	1.6	1.0	
	34.6	18.5	
Annual Cost NSS + T-G	107.8	91.7	
Revenue @ 12.8 mills/kWhr	107.8	58.4	
Steam Cost		33.3	
Unit Steam Cost, ¢/10^6 kJ (Btu)			77 (81)
Reboiler Plant			
Fixed Charges (15%)		7.8	
O&M		0.4	
Annual Cost Reboiler		8.2	
Incremental Steam Cost for Reboiler (Plant Factor = 1.0) cents/10^6 kJ (Btu)			15 (16)
Steam Cost @ Reboiler, cents/10^6 kJ (Btu)			92 (97)

The required revenue from process steam was calculated by taking the difference between the annual cost and the annual revenue from the sale of electricity. The total annual production cost for the 1200-MW(e) unit is 107.8 million dollars, corresponding to 12.8 mills/kWhr. This value is not affected by the dual-purpose nature of the station and it is therefore considered a fair price for computing the revenue obtained from the sale of electricity. This income amounts to 58.4 million per year for the 650 MW(e) unit, leaving 33.3 million dollars to be obtained from the sale of steam. This is equivalent to a cost of 77¢/million kJ (81¢ per million Btu) of reactor prime steam.

The industrial processes served by the station generally require continuous full flow of process steam; thus a plant factor of 1.0 was used to arrive at the 15¢/million kJ (16¢ per million Btu) cost increment attributable to the reboiler plant. Total cost of the 5860 kPa abs. (850 psia) 274°C (525°F) process steam therefore amounts to 92¢ per million kJ (97¢ per million Btu), at the reboiler.

The cost of process steam at lower temperature was derived from cost data developed for dual-purpose LWRs. In this instance, turbine extraction steam or back-pressure steam is used to heat the reboilers that generate process steam at 100% quality. Steam costs were again obtained from the difference between total annual plant expenditures and the revenue from the sale of electrical power at 12.8 mills per kWhr.

Process steam costs over the range from 93-260°C (200 to 500°F) are shown in Fig. 2. The reboiler costs are believed to be fairly insensitive to the saturated steam pressures corresponding to this temperature range; thus an incremental cost of 15¢ per million kJ (16¢ per million Btu) was applied uniformly to allow for the reboiler cost.

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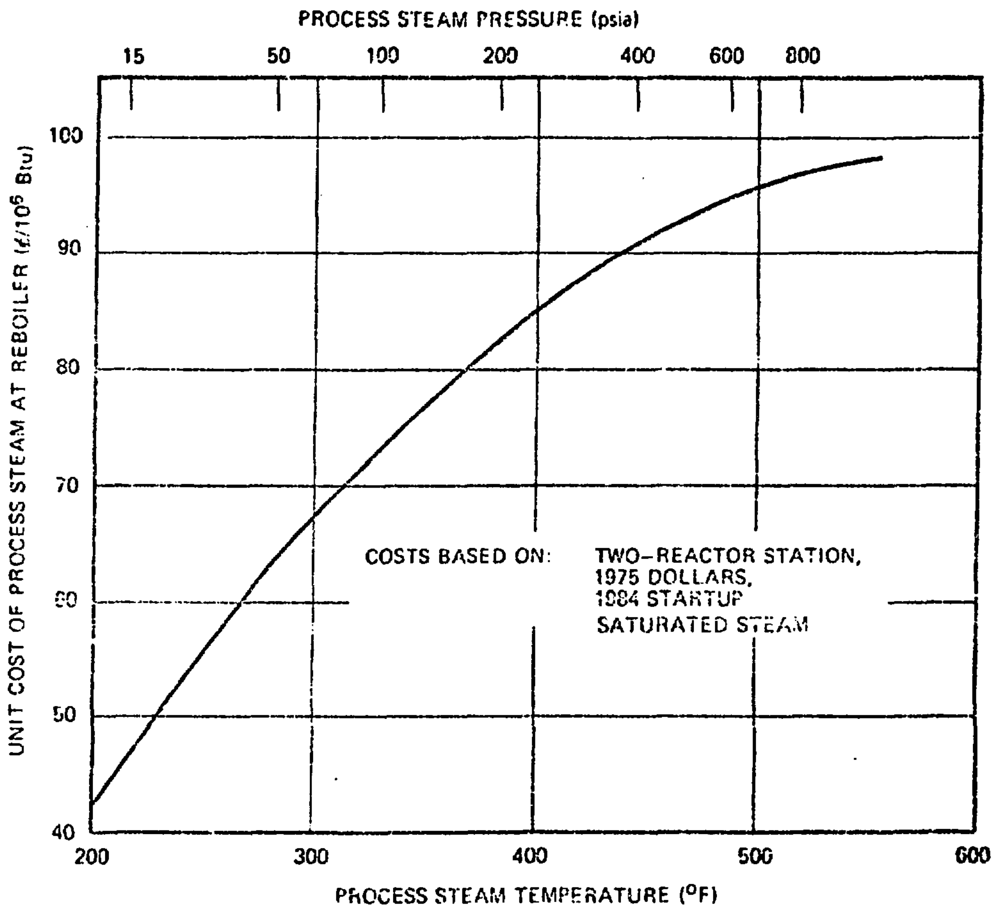


Figure 2. VARIATION OF PROCESS STEAM COST AS A FUNCTION OF STEAM CONDITIONS

Typical costs for process steam at moderate pressure, taken from Fig. 2, amount to 78¢ per million kJ (82¢ per million Btu) at 1380 kPa abs. (200 psia) and 88¢ (93¢) at 3800 kPa (550 psia). The cost of process steam varies somewhat as the flow rate is changed; this effect is not accounted for and thus the values shown ought to be used only for guidance in preliminary evaluations.

Steam Conveyance Costs. The cost of transporting process steam from a centrally located reboiler plant to the various industrial users was derived from recent data reported by Anderson et al. (Ref. 1). The pipeline capital costs for various steam pressures and flow rates are listed in Table VIII. For cost estimating purposes, it was assumed that process steam and condensate would be carried in insulated steel pipes installed above ground; the cost of land was not included in the analysis. The heat loss is estimated at about 0.3% per mile; the pipe diameters are based on a pressure drop of 80 kPa/km (12 psi/mile). The cost of a condensate return line is included in the cost estimate. For a 25% per year fixed charge rate (representative of industry ownership) and neglecting pipeline operating and maintenance costs, the fixed charge for transporting 5860 kPa abs. (580 psia) steam at a flow rate of 250 kg/s (2×10^6 lb/hr) per hour is about 4.8¢ per million kJ per km (8.2¢ per million Btu per mile). The corresponding cost for 1380 kPa abs. (200 psia) steam is 3.7 (6.3) cents; for 3450 kPa (500 psia) steam, a cost of 4.2 (7.2) cents was obtained by interpolation.

Table IX combines the steam production and transport costs, giving the cost of 1380, 3450 and 5860 kPa abs. (200, 500 and 850 psia) saturated steam delivered to industrial users located at sites up to 16 km (10 miles) from the power station. The cost of delivered process steam ranges from 78 to 191¢ per million kJ (82 to 201¢ per million Btu), depending on the particular steam pressure, flow rate, and conveyance distance.

Table VIII. Steam Conveyance Capital Cost*

Pressure (psia)	200		850	
Flow (lb/hr)	1,000,000	2,000,000	1,000,000	2,000,000
Pipe Diameter (in.)	36	48	28	36
Cost per Mile (dollars)	2,900,000	4,900,000	3,300,000	5,600,000

*Cost of condensate return lines (250°F) included; all in 1975 dollars.

Table IX. Cost of Process Steam as a Function of Conveyance Distance*

Steam Flow (lb/hr)	1,000,000			2,000,000		
Pressure (psia)	200	500	850	200	500	850
Pipeline Length (miles)						
0	82	93	97	82	93	97
.5	87	98	102	86	97	100
1.0	91	102	107	90	101	105
1.5	95	106	113	93	105	109
2.0	99	111	118	97	109	114
3.0	107	120	127	104	116	123
4.0	116	129	138	111	124	132
6.0	133	147	159	126	139	150
8.0	149	165	180	140	155	168
10.0	165	183	200	154	170	186

*The tabulated values do not include the cost of a new backup steam supply. Provision of an oil-fired standby steam supply capable of providing 25% of normal flow would increase the cost of 200 psia process steam by about 14 cents per million Btu. The corresponding values for 500 and 850 psia steam are 16 cents and 19 cents, respectively.

Delivered Cost of Process Steam. The cost of process steam delivered to the plants of the industrial customer at the hypothetical site, is tabulated in Table X. Costs range from \$0.89 to \$1.15 per million kJ (\$0.94 to \$1.21 per million Btu). The cost of a backup steam supply and of modifications needed to adapt the user's plant to reactor steam conditions is expected to be modest for most industrial plants.
Figure 3, adapted from Klepper (Ref. 7) shows the costs for several fossil based energy forms in the U.S. Gulf region. Fuel cost assumptions are listed in Table XI. Figure 3 shows that nuclear steam will be strongly competitive with other sources that may produce steam costing in the range from \$1.42 to \$2.84 per 10^6 kJ (\$1.50 to \$3.00 per 10^6 Btu). Further, in comparing the nuclear process steam costs of Table IX with the data of Fig. 3, one concludes that nuclear steam may be competitive at conveyance distances as great as 16 km (10 miles).
Savings resulting from the load pattern expected for a dual-purpose plant have not been taken credit for in the cost analysis: The process energy demand represents a sizable base load [1800 MW(t)], that should result in a larger reactor plant factor and therefore lower unit power costs than for normal electric utility service. Additionally, some "economy of scale" savings may be achievable since the combined dual-purpose energy demand may justify construction of a larger station than would be needed for producing electricity only.

6. CONCLUSIONS

A preliminary economic evaluation of a large dual-purpose reactor station designed to generate electricity and industrial steam at a hypothetical Gulf Coast site, has shown promising results. Process steam piped over distances up to 16 km (10 miles) appears economically competitive with alternative energy sources, opening up the possibility of supplying nuclear steam to clusters of nearby users. A survey of the potential market has identified 19 current industrial sites in the U.S. with

Table X. Cost of Process Steam Delivered to Industry

	Steam Cost (¢/10^6 Btu)					
	Flow 1,000,000 lb/hr			Flow 2,000,000 lb/hr		
	200	500 psia	850	200	500 psia	850
Refinery (1.4 mile)	94	106	112	93	104	108
Chemicals/Plastics Plant (2.2 miles)	101	113	120	98	110	114
Chemicals Plant (2.3 miles)	102	114	121	99	111	116

Table XI. Fuel Prices for Alternative Steam Sources

COAL

MINIMUM

EASTERN – 50¢/MBTU MINE MOUTH, 74¢/MBTU DELIVERED TO HOUSTON

WESTERN – 30¢/MBTU MINE MOUTH, 75¢/MBTU DELIVERED TO HOUSTON

MAXIMUM – $1.83/MBTU DELIVERED TO HOUSTON

NUCLEAR

U_3O_8 PRICE

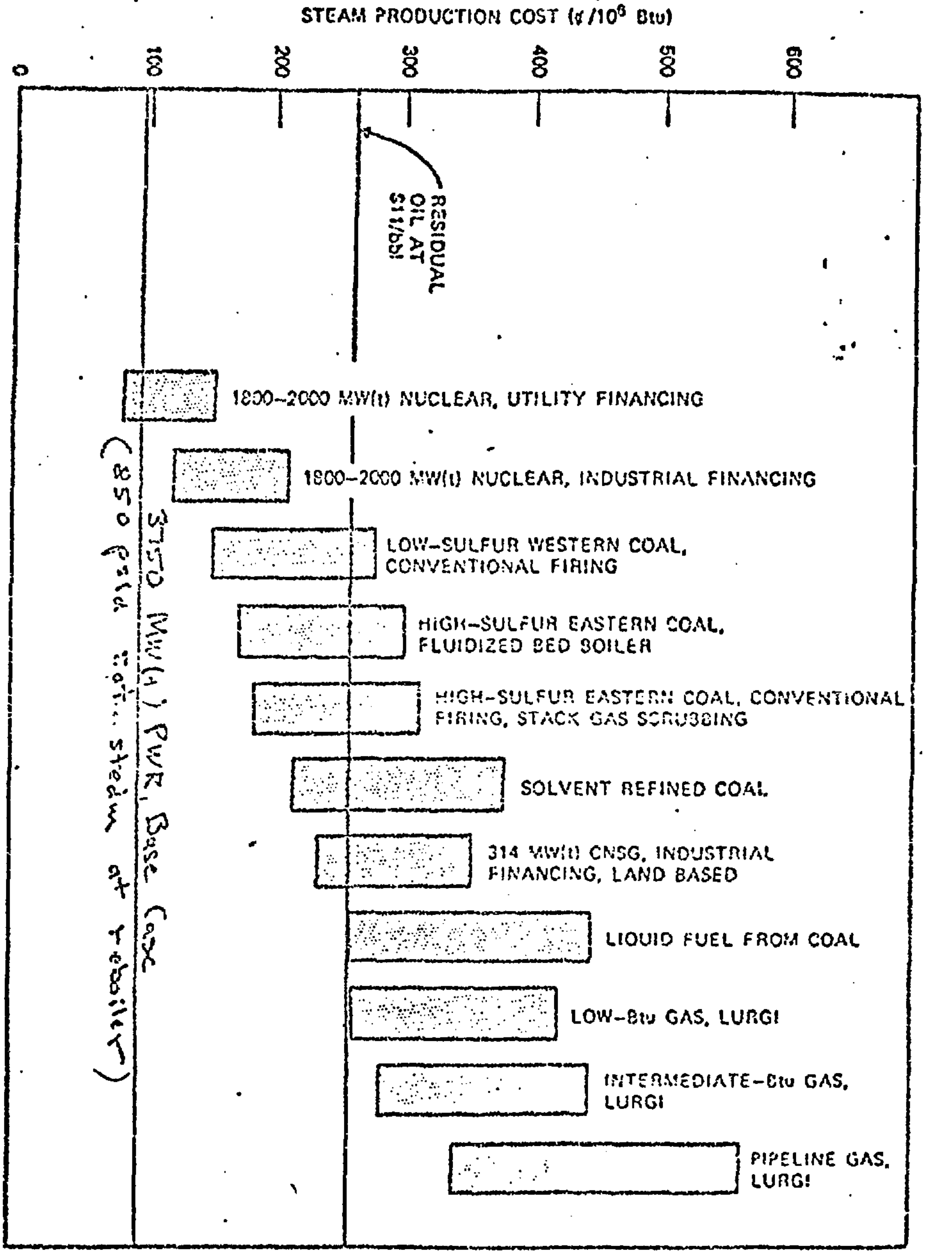
MINIMUM – $ 15/LB-U_3O_8

MAXIMUM – $100/LB-$U_3O_8$

SEPARATIVE WORK

MINIMUM – $44/SWU

MAXIMUM – $75/SWU



RANGE OF EXPECTED STEAM PRODUCTION COSTS
(U.S. Gulf region)
FIGURE 3

Figure 3

steam demands that might be met with large dual-purpose reactors. Use of process steam generated with current type reactors could reduce consumption of scarce oil and gas at these industrial sites by the equivalent of approximately 80,000 m^3 (0.5 million barrels) of oil per day.

Service continuity is vital to many industrial processes using steam. Early results from a survey of industrial process steam reliability experience suggest that one or more current type reactors, supplemented by fossil fired units, have adequate availability.

New organizational and institutional obstacles will be faced by a dual-purpose reactor project that is designed to serve groups of industrial customers. Means will have to be found for resolving these complex questions on a timely basis. Assurance that this new energy source can be brought on line on schedule is essential if the concept is to be attractive to industrial users.

7. ACKNOWLEDGEMENTS

This evaluation of large dual-purpose reactors includes valuable contributions from R. Barnes of the Dow Chemical Company, H. I. Bowers, J. G. Delene, M. L. Myers, and W. G. Sullivan (consultant) at ORNL. Special thanks are due to Mrs. G. C. Bower for the preparation of the manuscript.

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