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**Technical and Economic Studies of Small
Reactors for Supply of
Electricity and Steam**

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TECHNICAL AND ECONOMIC STUDIES OF SMALL REACTORS
FOR SUPPLY OF ELECTRICITY AND STEAM

I. Spiewak, O. H. Klepper and L. C. Fuller

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CONTENTS

	<u>Page</u>
ABSTRACT.....	1
INTRODUCTION.....	2
THE CONSOLIDATED NUCLEAR STEAM GENERATOR (CNSG).....	2
Plant Capital Costs.....	5
Operating and Maintenance Costs.....	5
Power and Process Heat Costs.....	5
Barge-Mounted CNSG.....	5
THE CONSOLIDATED NUCLEAR STEAM SUPPLY SYSTEM (CNSS).....	9
THE GENERAL ELECTRIC COMPANY INTERMEDIATE SIZE BOILING WATER REACTOR (BWR) STUDY	9
SMALL HIGH-TEMPERATURE GAS-COOLED REACTORS.....	9
COGENERATION OF ELECTRICITY AND STEAM.....	12
DISCUSSION AND CONCLUSIONS.....	12
REFERENCES.....	16

TECHNICAL AND ECONOMIC STUDIES OF SMALL REACTORS
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ABSTRACT

Several years ago conventional opinion held that nuclear power plants must be very large to be competitive with fossil fuels. This situation has changed markedly in most countries within recent years, as oil and gas supplies have become more scarce and costly. Studies have been carried out for several nuclear steam supply systems in the small and intermediate size range. Detail studies are reported of the Consolidated Nuclear Steam Generator (CNSG), a 365 MW(th) pressurized water reactor being developed by Babcock and Wilcox, as applied to industrial energy needs. Both conventional and barge-mounted nuclear steam supply systems are considered. Conceptual studies have been started of pressurized and boiling water reactors in the range of 1000 MW(th), which are envisioned for utility operation for supply of electric power and steam. Design studies of a 500 MW(th) high temperature reactor are also reported. The small reactors are expected to have higher unit costs than the large commercial plants, but to have compensating advantages in higher plant availability, shorter construction schedule and greater siting flexibility.

Studies are also reported of power cycle parameters and cost allocations for extraction of steam from steam turbine plants. This steam could be used for industrial energy, district heating or desalination.

INTRODUCTION

In the United States, the electric utility industry is responding to the shortages of oil and gas by adopting coal and nuclear energy as the fuel resources for most of the new capacity. Nuclear power plants are generally in the size range 800-1300 MW(e) [2500-3800 MW(th)].

It would be desirable for nuclear plants also to be available for the industrial sector. However, the consumption rate of individual industrial plants is much less than the capacity of the utility power plants currently supplied. One desirable arrangement is for an electric utility to generate both electrical energy for the grid and pipeline steam for nearby industries. Another solution would be to use small industrial nuclear reactors which would match the load demand of single large energy user plants, thus, avoiding the institutional problems arising from use of a single utility owned plant to serve a number of industries. Furthermore, the planning and construction of small reactors could quite likely be accomplished within about two-thirds of the time required for large central station reactors.

The United States Energy Research and Development Administration (USERDA) has sponsored a series of studies of small and intermediate size nuclear steam supply systems as reported here. These studies have been carried out by reactor manufacturers under subcontract to the Oak Ridge National Laboratory (ORNL). While the purpose of the USERDA studies has been the evaluation of industrial energy supply alternatives, the results may also be applicable to electric power supply.

THE CONSOLIDATED NUCLEAR STEAM GENERATOR (CNSG)

Work on the CNSG, Fig. 1, for nuclear ship propulsion has been underway at the Babcock & Wilcox Company (B&W) [1] since 1959. Some of the unique features of the plant design, including the once-through steam generator housed within the reactor vessel, have already been demonstrated in the Federal German Republic nuclear ship "Otto Hahn," that has operated successfully since 1969. The U.S. Maritime Commission has continued to sponsor work in the areas of design, testing, and evaluation of the CNSG concept, and current efforts are directed toward a 313 MW(th) application for propelling a 600,000 ton tanker.

The CNSG design is essentially based on current technology, [2] and relatively little development would be required for process heat applications in the 300 MW(th) power range or electric power applications of about 100 MW(e). The CNSG is an integral water reactor with the core and steam generator inside the reactor vessel, and an electrically heated pressurizer connected to the vessel externally. The CNSG emergency core cooling system is more easily designed than that of loop-type reactors because the potential pressurizer pipe break releases water coolant much more slowly than the pipe break of a loop-type reactor.

The process energy version of the CNSG is rated at 365 MW(th). It was developed for USERDA by B&W. [3] B&W believes that a first-of-a-kind CNSG can be built in 6.5 years and nth-of-a-kind schedules of 5.5 years (letter of intent to commercial operation) are achievable. Major reactor parameters are shown in Table I.

FIG. 1. CNSG ARRANGEMENT

TABLE I

CONSOLIDATED NUCLEAR STEAM GENERATOR REACTOR PARAMETERS

Reactor type:	Pressurized Water Reactor
Thermal rating :	365 MW(th)
System pressure:	15,510 kPa
Core inlet temperature:	300°C
Core outlet temperature:	319°C
Maximum thermal output (100%):	53 kW/m
Boiler feedwater temperature:	204°C
Total SG flow:	189 kg/s
Steam side design temperature:	343°C
Steam side operating temperature:	281°C
Steam side operating pressure:	4830 kPa
Electric capability:	110 MW(e)
Fuel type:	Zircaloy-clad UO ₂
Fuel life in core:	4.5 years
Refueling interval:	1.5 years.

Plant capital costs

The major cost components for the 365 MW(th) CNSG concepts are summarized in Table II, amounting to \$158 million for the electric plant and \$128 million for the process steam plant, including the reboiler. Costs have been estimated by B&W with assistance from United Engineers and Constructors (UE&C). These costs are for nth-of-a-kind plants given in 1976 dollars, including the interest during construction, but excluding escalation beyond 1976. The costs for the nuclear steam supply system remained fixed in the economics of the two options examined.

Operating and maintenance costs

The annual operating and maintenance costs (\$1976) for the two concepts are shown in Table III. The steam plant costs include an allowance for the process steam reboiler.

Power and process heat costs

Energy costs in 1976 dollars for 1983 startup of the 365 MW(t) CNSG plants are summarized in Table IV. These costs are based on a levelized fixed charge rate of 22.2% per year, representative of private industry financing. Fuel cycle costs are based on replacing about one-third of the reactor core fuel elements at intervals of 18 months. Energy costs amounted to 53 mills/kWh for the electrical energy generating plant and 371¢/10⁶ kJ (392¢/10⁶ Btu) for the process steam plant. These costs are higher than had been estimated in earlier preliminary studies[4,5] (primarily because of a rise in capital costs); however, they remain competitive with some of the coal-based energy systems under development in the United States, Fig. 2. Figure 2 illustrates the great importance of fixed charge rate in fossil-nuclear competition.

Barge-mounted CNSG

A concept for a barge-mounted CNSG is also being examined to determine the reductions in construction time and cost possibly achievable by repetitive platform construction in a shipyard. Two plant configurations were developed[6] by G. G. Sharp, Inc. - a platform-mounted plant to generate 91 MW of electrical power, and another design for the production of 137 kg/s (1.1 x 10⁶ lb/h) of steam. Hull dimensions were limited to allow passage through the locks and under bridges encountered enroute to potential operating sites located on or near inland waterways. These concepts were refined by the Newport News Shipbuilding and Dry Dock Company to determine construction costs and schedules. Methods for siting small platform-mounted reactor plants near inland waterways were examined[7] by Gibbs and Hill, Inc. Concepts and costs were developed for siting the 34-m (105-ft) wide and about 98-m (320-ft) long platforms in a floating as well as a dry mode. Site construction, including barge emplacement, was estimated at 22 months for the floating arrangement and 19 months for the dry scheme.

The barge-mounted concept was found to be more costly than the land-based concept.[3] This conclusion may not be applicable to all sites, however.

TABLE II

CONSOLIDATED NUCLEAR STEAM GENERATOR, 365 MW(th) OUTPUT
CAPITAL COST SUMMARY (10^3 US \$)

	<u>Process steam</u>	<u>Electricity</u>
Land and land rights	300	300
Structures and improvements	25,300	25,700
Reactor plant equipment	39,000	39,000
Electric plant	6,500	7,600
Turbine plant	-	20,400
Process steam reboiler	4,200	-
Miscellaneous plant equipment	<u>2,500</u>	<u>2,600</u>
Subtotal	77,800	95,600
Undistributed Costs (25%)	20,200	24,900
Contingency (10%)	<u>9,800</u>	<u>12,000</u>
	107,800	132,500
Interest during construction	<u>20,500</u>	<u>25,100</u>
Total cost in 1976 US \$	128,300	157,600

TABLE III

ANNUAL OPERATING AND MAINTENANCE COSTS (10^3 US \$)
FOR 365 MW(th) CNSG PLANTS

	<u>Steam Plant</u>	<u>Electric Plant</u>
Staff	1,400	1,660
Maintenance	530	630
Supplies	290	350
Nuclear insurance	300	300
Facility inspection fee	20	20
Administration and general	<u>240</u>	<u>280</u>
Total	2,780	3,240

TABLE IV*

SUMMARY OF LEVELIZED PRODUCTION COSTS FOR 365 MW(th) CNSG PLANTS

	<u>Steam Plant</u>			<u>Electric Plant</u>	
	<u>US 10^6\$/year</u>	<u>¢/10^6Btu</u>	<u>¢/10^6kJ</u>	<u>US 10^6\$/year</u>	<u>mills/kWh</u>
Fixed Charges	28.5	306	290	35.0	42.7
Operating and Maintenance Costs	2.8	30	28	3.2	3.9
Fuel Costs	<u>5.2</u>	<u>56</u>	<u>53</u>	<u>5.2</u>	<u>6.4</u>
Total	36.5	392	371	43.4	53.0

*Fixed charge rate: 22.2%

Costs in 1976 dollars, startup in 1983; 85% plant factor.

ORNL-DWG 76-20494

FIG. 2. ANNUALIZED PRODUCTION COSTS FOR COAL, NUCLEAR AND OIL-FIRED PROCESS STEAM PLANTS

THE CONSOLIDATED NUCLEAR STEAM SUPPLY SYSTEM (CNSS)

USERDA has supported a Babcock & Wilcox study of extrapolation of the CNSG concept upward in size to 1200 MW(th). [8] The larger reactor is called the Consolidated Nuclear Steam Supply System. The study confirmed that the CNSS would retain the schedule and safety advantages of the CNSG. Table V compares the CNSG and CNSS technical parameters.

The unit capital cost of the larger reactor for electric power production is about 63% of the unit cost of the smaller reactor. The electricity cost of the CNSS should be about two-thirds that of the CNSG. While the CNSS costs appear to be quite attractive for process heat production in dual-purpose plants, it is not likely that they would be competitive with large reactor costs for electric power production in the U.S.

THE GENERAL ELECTRIC COMPANY INTERMEDIATE SIZE BOILING WATER REACTOR (BWR) STUDY [9]

General Electric Company (GE) conducted a study for USERDA of the feasibility of intermediate size nuclear plants [300-400 MW(e)] for dual-purpose steam-power application. The method of study was by analysis of existing operating experience from small BWR plants notably the Muhleberg 306 MW(e) plant. Cost analyses were conducted on actual costs, including correction for escalation to 1976. The changes in licensing requirements were factored into the study.

It was found that small BWRs had excellent operating records and had potential for being produced economically. The key to such economic production is duplication of a standard design and through modular construction of large sectors and subsystems. Greatly reduced front end costs are envisaged with the use of one reactor designer-architect engineer-constructor team (consortium) for 10 to 20 similar units. Through this approach, the indirect costs, particularly expenses for engineering and design, might be reduced significantly below the corresponding costs for a single small unit.

An estimated comparison of small vs large plant costs is given in Table VI.

SMALL HIGH-TEMPERATURE GAS-COOLED REACTORS

Applications of small gas-cooled, pebble-bed reactors for industrial energy were evaluated in an ERDA-sponsored study [10] by the General Electric Company. This technology is based on the 40 MW(th) AVR pebble-bed reactor in Germany. That plant has operated successfully with helium reactor exit temperatures up to 950°C (1742°F), with on-line refueling. The GE study evaluated three distinct pebble-bed reactor concepts designed to furnish process energy to industry: (1) plant for the production of process steam only, (2) plant for the production of synthesis gas through methane reforming, and (3) plant for generating electricity with a helium-driven turbo-generator, in addition to producing process steam. The range of power level, 200-1000 MW(th), is compatible with the energy requirements of large chemical, petroleum refining, and primary metals plants.

Considerable amount of component development and construction of a prototype plant would be needed for the introduction of small commercial pebble-bed reactors. Assuming the project starts in 1977, prototype plant

TABLE V

COMPARISON OF DESIGN PARAMETERS
1200 MW(TH) CNSS AND 365 MW(TH) CNSG

	<u>CNSS</u>	<u>CNSG</u>
<u>Reactor Vessel Design</u>		
Design pressure, kPa	17,340	17,340
Design temperature, °C	293	293
Shell ID, m	4.62	3.99
Height inside heads, m	13.26	10.57
<u>Containment</u>		
Height/diameter, m	28.9/13.7	19.5/11.6
Design pressure, kPa	724	724
<u>Steam Generator</u>		
Total steam flow, kg/s	666	189
Steam pressure, kPa	6,450	4,830
Steam temperature, °C	280	281
Feedwater temperature, °C	227	204
Tube length, m	4.6	4.0
Tube OD, mm	13	13
Number of tubes	30,807	11,916
<u>Hydraulic and Thermal Design</u>		
Core heat output, MW(th)	1200	365
System pressure, kPa	15,510	15,510
Total core flow, kg/s	7,180	3,120
Core inlet temperature, °C	299	300
Core outlet temperature, °C	328	319
Average thermal output, kW/m	19.5	15.9
<u>Core Design</u>		
Core height (active), m	3.0	1.8
Number fuel assemblies	97	57
Number of fuel rods	21,136	11,400
Fuel rod OD/pitch, mm	11/14	11/14
Number control rod assemblies	37	17
Number control pins/assembly	16	20

TABLE VI
INTERMEDIATE BWR STUDY
TOTAL ENERGY COST ESTIMATE

	Mass-Produced 306 MW(e)	Standard 1000 MW(e)
Capital Cost	\$620/kW(e)=19.7 mills/kWh	\$560/kW(e)=17.8 mills/kWh
Fuel Cost	66¢/MBtu = 7.0 mills/kWh	58¢/MBtu = 6.2 mills/kWh
O&M Cost	\$18/kW(e)yr= 2.6 mills/kWh	\$11/kW(e)yr= 1.6 mills/kWh
Total	29.3 mills/kWh	25.6 mills/kWh

1976 US \$, 80% capacity factor, FCR= 22.2%
Plant startup mid 1980s.

startup could take place by 1987, followed by commercial plant startup around 1990.

Steam cost from the process steam plant was estimated to be about 30% more than steam cost from a CNSG of the same thermal rating. These costs do not reflect the potentially greater value of 510°C (950°F) steam from the pebble-bed reactor relative to steam of only 250°C (483°F) from the light-water reactor.

General Atomic Company (GA) has carried out a privately-funded study of an 850 MW(th) high-temperature gas-cooled reactor based on Fort St. Vrain size components.[11] They concluded that such a unit would make a very attractive energy source for industrial dual-purpose plants. The steam conditions were compatible with those of modern fossil-fueled equipment, and would therefore fit well with industrial energy applications. No costs were estimated.

COGENERATION OF ELECTRICITY AND STEAM

Cogeneration is defined as the generation of electricity and steam from a common source, where prime steam is expanded through a turbine prior to extraction for use. The electric-generating efficiency of a cycle where steam is extracted from a backpressure turbine is a function of backpressure as shown in Fig. 3. The maximum efficiency is obtained when prime steam is expanded to condenser temperature, about 38°C (100°F). Cogeneration is a fuel conserving process as shown in Fig. 4. Maximum conservation occurs at the lowest temperature (i.e., waste heat utilization). At a common industrial steam pressure (250 psi), the fuel savings from cogeneration in an LWR are about 16% and the savings in an HTGR are about 22%.

In principle, steam may be extracted from any pressure of a turbine cycle. Actually, extraction can occur most easily at turbine crossover pressure; limited additional amounts of steam can be extracted at predetermined locations on the turbine. Figure 5 illustrates the economies which are obtained by use of extraction, rather than prime steam.

DISCUSSION AND CONCLUSIONS

The USERDA studies of small- and intermediate-size nuclear plants suggest that reactors of 300-1200 MW(th) can be economically competitive with fossil fuels in the United States for industrial energy supply. The degree of industrial interest will be better known following the completion of several application studies which are under way considering specific U.S. sites, and which take into account need for interfacing with industrial plants. This includes need to consider the methods for providing backup energy supplies and their costs. While the economics of the nuclear plants appear to be favorable, there are serious questions about public acceptance and the realization of a timely construction schedule in early plants. Some of the conditions for the small nuclear plants to be successful include mass production of a standard design, a stable licensing climate and access to financing for the capital facilities. If these conditions can be met, then nuclear power could provide an important share of the industrial steam needs in addition to supplying electric power.

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FIG. 3. EFFICIENCY OF BACKPRESSURE CYCLE IN THE FORM OF ELECTRICITY PRODUCTION

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FIG. 4. FUEL SAVINGS IN A BACKPRESSURE CYCLE
COGENERATING ELECTRICITY PLUS STEAM

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FIG. 5. EXTRACTION STEAM COST RATIO AS A FUNCTION OF EXTRACTION TEMPERATURE

REFERENCES

- [1] DICKINSON, R.W., et al., Nuclear Maritime - An Economic Revival, Paper presented at Spring Meeting of the Society of Naval Architects and Marine Engineers, Williamsburg, Virginia, May 24-27, 1972.
- [2] Preliminary Safety Analysis Report, Competitive Nuclear Merchant Ship Program, Prepared for the U.S. Maritime Administration by Babcock & Wilcox, MA-940-02 (April 1974).
- [3] A Small Pressurized Water Reactor for Process Energy, Prepared by Babcock & Wilcox, BAW-1428 (June 1976).
- [4] MACPHERSON, H.G., KLEPPER, O.H., Small Reactors for Process Heat (Proceedings of the First National Topical Meeting on Nuclear Process Heat Applications) Los Alamos, New Mexico, October 1-3, 1974, LA-5795-C (CONF. 741032).
- [5] KLEPPER, O.H., Small PWR for Industrial Energy, Transactions American Nuclear Society, Vol. 19 (October 1974).
- [6] Barge-Mounted Nuclear Power Plant Study, Prepared by George G. Sharp, Inc., for the Oak Ridge National Laboratory (June 28, 1974).
- [7] Siting Study for Small Platform-Mounted Industrial Energy Reactors, Prepared by Gibbs and Hill, Inc., for the Oak Ridge National Laboratory (July 1975).
- [8] Conceptual Design Study for a Consolidated Nuclear Steam System, Prepared by Babcock & Wilcox (to be published).
- [9] Small LWR Plant Study for Process Heat Plus Power, Prepared by General Electric Company, ORNL-Sub-4380-1 (NEDC-21386) (September 1976) (to be published).
- [10] Small Nuclear Process Heat Plants (SNPH) Using Pebble-Bed Reactors, prepared by the General Electric Company for the Oak Ridge National Laboratory, GEEST 75-001 (November 1975).
- [11] Small HTGR Steamer for Industrial Process Applications, prepared by General Atomic Company, GA-A13888 (April 23, 1976).

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