RECEIVED BY TIC AUG 10 1972

CONF-721109-6

Nuclear Solutions to World Energy Problems

ADVANCED GAS-COOLED REACTOR SYSTEMS

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During the past two decades considerable experience has been gained by the commercial operation of a number of different thermal power reactor systems. A large part of this experience is reported in the papers by Mr. Stolz and Mr. Kemper. The only reactor systems which have so far advanced to the stage of widespread commercial use are those of the Light Water, Heavy Water, and Uranium Metal/Magnox Gas-Cooled types. All of these are of low thermal efficiency producing heat at comparatively low temperatures which can only be utilized through the medium of low temperature steam with associated condensing systems.

In order to achieve efficiencies comparable with those attained by fossil-fired stations, gas-cooled reactors of advanced types have been developed. In the U. K. a large number of advanced CO₂ gas-cooled reactors of the uranium dioxide/stainless steel-clad fuel type are under construction, based on the very good operation of the magnox reactors and the operation of the prototype AGR at Windscale. This prototype, which has an output of 30 Mw(e), has been in operation for ten years and has satisfactorily demonstrated the integrity of the fuel and the engineering features. It has operated with a cumulative load factor in excess of 85%, making due allowance for special experimental interruptions to the program.

*Operated by the Union Carbide Corporation for the U. S. Atomic Energy Commission.

MASTER

In the continuing search for improvements in the economy and simplicity of thermal reactors, and taking consideration of environmental problems, the helium gas-cooled HTGR with particulate fuel has been developed in Europe and the U. S. A. using the integral system adopted with the later magnox gas-cooled reactors incorporating a prestressed concrete pressure vessel.

Three small prototype HTGR's have operated successfully for a number of years, Dragon (20 Mw th) commissioned in 1965, Peach Bottom (40 Mwe) commissioned in 1967, and Julich (15 Mwe) commissioned in 1967. The Julich reactor is of the pebble bed type while Peach Bottom and Dragon are the forerunners of the prismatic style of fuel. Two larger prototypes are under construction, the Fort St. Vrain reactor, a 330 Mwe HTGR using prismatic fuel which is planned to operate this year, and the 300 Mwe pebble bed reactor being constructed at Schmehausen which is planned to be completed in 1974.

Some general features to be looked for in the future reactor systems are:

- (1) application to large sizes (low capital costs);
- (2) high safety standards particularly for near urban siting;
- (3) high thermal efficiency yielding low heat rejection to the environment;
- (4) flexibility in heat rejection modes including use of dry cooling towers;
- (5) capability for energy extraction at temperatures above those utilized for the steam cycle;

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- (6) high temperature potential leading to process heat uses;
- (7) low maintenance costs and ready ability to maintain components, leading to security of investment;
- (8) on-stream refueling;
- (9) improved utilization of fuel resources;
- (10) low fuel cycle costs;
- (11) versatility in utilizing various fuel cycles;
- (12) low release of radioactive contaminants to the environment.

The HTGR illustrates particularly well the ability to meet many of the requirements and development possibilities for the future and the advent of commercial sales makes it of timely interest. It offers an orderly progression from steam-electric power generation to process heat application and to the gas-turbine as well as providing technology for a Gas-Cooled Breeder Reactor.

Many of the listed requirements involve higher temperature operation. Current prismatic HTGR designs and experience are for outlet gas temperatures up to 1400°F (760°C) with corresponding fuel temperatures up to 2280°F (1250°C). New fuel designs appear capable of significantly higher temperatures and the pebble bed reactor at Julich has already operated with core outlet temperatures of 1550°F (850°C). One way to utilize higher temperatures is through the use of a direct cycle helium turbine for energy conversion. It offers the potential for reduced capital cost because of reduced auxiliary plant requirements. Despite a high pumping power requirement, the direct turbine cycle at high helium pressure (1000 psia)

offers a high thermal efficiency. The design and development requirements for this system concentrate on turbine blading, heat exchangers, internal gas passages, valving and insulation.

Where dry cooling towers are desired, the larger temperature range over which the sensible heat is discharged from gas turbine systems is advantageous compared with the low temperatures necessary for steam condensers, so that substantial capital cost savings appear possible in addition to environmental attractions. The possibility exists for using the waste heat for district heating systems, chemical processing plant and desalting of water by distillation, thus utilizing all the heat generated by the reactor.

The HTGR fuel temperature capability potential may permit HTGR's to be used for process heat applications requiring still higher temperatures such as coal gasification and steel refining. Problems associated with PCFV and heat exchanger designs for heating the gases used in these high temperature processes are difficult, but should be capable of solution. The high temperatures may require improved structural and insulating materials.

A logical extension of HTGR gas circuit technology is to the GCFBR which offers a high breeding ratio with short fuel doubling time. Special provision is needed for emergency core cooling in the unlikely event of severe loss of primary cooling capability because of the high ratio of power density to thermal capacity. However, this appears to be feasible. The fuel pin design can utilize sodium reactor technology, although it

is considered desirable to equalize the fuel pin internal pressure to the reactor coolant circuit by a suitable coupling. Although much development is required, initial test results are favorable.

Capability to utilize many fuels effectively is another important GCR feature. The HTGR converts best when using fissile U_{233} . This suggests combining the HTGR with a breeder which produces the U_{233} in the blanket. A high gain breeder system eventually might produce both plutonium for its own expansion needs, and U_{233} for HTGR's. The low enriched uranium fuel cycle also appears attractive where highly enriched uranium is not readily available or where fuel reprocessing is not practical. The HTGR compares very favorably with other thermal reactor systems from the point of view of utilization of the world's uranium resources. This is illustrated by Table 1 which compares the weight of natural uranium required during the lifetime of the reactors normalized for the same output.

The HTGR also can function well with plutonium for fuel makeup. Since the HTGR can operate on many fuel cycles and appears compatible with breeders and other reactors, its role appears indefinitely long. Such combinations should be continuously evaluated with respect to overall power demand requirements and fuel resources.

Table 1

<u>Reactor</u>	<u>Relative Requirements of Natural Uranium %</u>
HTR - low enrichment	100
HTR - high enrichment	85 - with recycle
AGR	141
Magnox	272
SGHWR	174
PWR (Zirc)	155
PWR (stainless steel)	181

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1. INTRODUCTION

During the past two decades considerable experience has been gained by the commercial operation of a number of different thermal power reactor systems, and this has been reported in the papers by Mr. Stalz and Mr. Kemper. Of these systems the only ones which have so far advanced to the stage of widespread commercial use are the Light Water and Heavy Water Reactors and the Uranium Metal/Magnox Gas Cooled type. All of these are of relatively low thermal efficiency since they produce heat at comparatively low temperatures.

The operating gas-cooled Magnox stations have performed well in economic comparisons with fossil fuelled power stations. Information recently published by the British Central Electricity Generating Board has shown that the cost of power produced by the larger Magnox stations during 1971 was lower than that from the latest coal and oil fired plants. The published figures are shown in Table I.

Table I. BRITAIN'S CHEAPEST ELECTRICITY (1971)

	Pence per kilowatt hour	Mills per kilowatt hour
<u>Nuclear</u>		
Dungeness 'A'	0.31	7.6
Sizewell	0.32	7.8
Oldbury	0.38	9.3
<u>Coal</u>		
Ratcliffe	0.35	8.6
Ferrybridge C	0.36	8.8
Eggborough	0.37	9.1
<u>Oil</u>		
(including tax of 0.05 p/kWh)		
Kingsnorth	0.36	8.8
Pembroke	0.38	9.3
Fawley	0.41	10.0

Two advanced types of gas cooled reactors have been developed and ordered in commercial sizes. In the U.K. a number of advanced CO₂ gas cooled reactors of the uranium dioxide/stainless steel clad fuel type (the A.G.R.) are under construction. These reactors are based on the technology developed for the Magnox reactors and the data obtained from the operation of the prototype A.G.R. at Windscale.

In the continuing search for improvements in the economy and simplicity of thermal reactors, and recognizing the environmental aspects of reactor systems, the helium gas cooled H.T.G.R. with particulate fuel has been developed in Europe and the U.S.A., using the integral prestressed concrete pressure vessel design adopted for the later Magnox gas cooled reactors. A number of commercial H.T.G.R.'s are scheduled to start construction in the U.S.A. during 1974.

Three small prototype H.T.G.R.'s have operated successfully for a number of years, Dragon (20MWth) commissioned in 1965, Peach Bottom (40MWt) commissioned 1967, and Julich (15MWt) commissioned in 1967. The Julich reactor is of the pebble bed type while Peach Bottom and Dragon are the forerunners of the prismatic style of fuel. Two larger prototypes are under construction, the Fort St.

Vrain reactor, a 330MWe H.T.G.R. using prismatic fuel, which is planned to operate next year, and the 300MWe pebble bed reactor being constructed at Schmehausen which is planned to be completed in 1975.

In this paper the operating experience of prototypes and construction experience for these advanced gas cooled reactors are described, the likely requirements for thermal reactors during the next decade are reviewed and the ability of the systems to meet these requirements is assessed.

The possibility that the high temperatures produced by the H.T.G.R. will allow the eventual development of a direct cycle helium turbine for energy conversion is important, particularly where environmental conditions are such that dry cooling towers for heat rejection are required. Direct utilization of heat from the H.T.G.R. for chemical processing and desalting of water is also being studied.

2. GENERAL REQUIREMENTS FOR A REACTOR SYSTEM FOR THE NEXT DECADE

To consider the future role of advanced gas cooled reactors it is useful to set down the general features which should be sought in any reactor system for the next decade. These are:

- (1) A system which can be built in relatively large sizes (up to 2000MWe) since experience has shown that an increase in reactor size leads to genuine reductions in unit capital cost.
- (2) In many parts of the world siting near urban centers is essential and this leads to a requirement for a very high standard of safety. In particular it is absolutely essential that for any reactor system a very low level of release of radioactive contaminants to the environment can be guaranteed.
- (3) Heat rejection to the environment is becoming a serious problem in many parts of the world. A reactor system with a high thermal efficiency is, therefore, desirable and if this can be coupled with a higher temperature of heat rejection the economic use of dry cooling towers is possible.
- (4) Since the world resources of uranium are limited it is clearly necessary to develop fuel cycles which will improve the utilization of the available fuel resources.
- (5) In the past, commercial reactor systems have been designed with the sole purpose of electricity production. However, as the availability of fossil fuels deteriorates it will become economic to use nuclear reactors for process heat. To take full advantage of this possibility a high temperature potential will be required.
- (6) In addition to the features outlined above reactor operators will be interested in operational flexibility and the security of investment which results from the ability to maintain and replace defective components. The ability to refuel on-load would clearly improve the availability of the plant.

Some of these requirements have been taken into account on advanced gas cooled reactors under construction, and it is appropriate to examine the A.G.R., the H.T.G.R., and possible future developments in the light of these requirements.

3. A.G.R.

The carbon dioxide cooled A.G.R. system fulfills a number of the above requirements. Prototype operation and construction of commercial stations is as follows:

3.1. WINDSCALE A.G.R.

The prototype A.G.R. reactor constructed at Windscale commenced operation in 1962. The design output is 30MWe and the main objectives for which it was designed were:

- (1) To develop and prove the fuel under environmental conditions similar to those for commercial A.G.R.'s.
- (2) To demonstrate the compatibility of the coolant and graphite moderator to ensure adequate core life.