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REPORT OF THE OBJECTIVES AND PLANS

FOR THE AEC'S CIVILIAN POWER

GAS COOLED REACTOR PROGRAM

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BACKGROUND

Historical

Studies on gas cooled reactors in the United States began in the mid 1940's with investigation at Oak Ridge of the Daniel's Pile Concept. This project was dropped after completion of the preliminary design because of the uncertainties involved in the concept at that early stage of reactor development. No further work on gas cooled reactors for civilian power was undertaken until 1957.

In the meantime, work was begun in the late 1940's and early 1950's on gas reactors for aircraft and rocket propulsion systems. This work evolved into the direct cycle aircraft propulsion program, and the Rover and Pluto programs. Much of this work is classified and will not be discussed in this paper. However, it should be mentioned that a considerable body of high temperature gas cooled reactor technology, involving a wide variety of materials and working fluids, has been generated in these programs. In general, this technology is not of direct use in the civilian power program because of a number of major differences in application conditions. This technology does, however, serve as valuable background to the civilian power program, and has been made available on a need-to-know basis.

During the early 1950's an aggressive program in gas cooled reactors for central station power was undertaken in the U.K. This development was centered on natural uranium fueled, magnox clad, CO₂ cooled reactors. The first reactor of this type began operation at Calder Hall in 1956, and several additional plants of this type have since been constructed at a number of different sites. Subsequently, work was also begun on the development of more advanced gas cooled reactor systems: (1) the UK's slightly enriched fueled, stainless steel clad, CO₂ cooled system known as the Advanced Gas Cooled Reactor (AGR), and (2) the UK-OEEC's high temperature, enriched uranium-thorium fueled, graphite clad, helium cooled system known as the Dragon Project.

In 1957, the AEC re-examined the gas cooled reactor concept as a power producer. A series of evaluation and design studies led to the conclusion that natural uranium plants of the Calder Hall type are not economically attractive for the US, and that the most promising immediate approach to a more economic reactor of the graphite moderated type was through the use of slightly enriched fuel clad with stainless steel. Additional studies, conducted by the AEC and by private industry, pointed up attractive features of various other types of gas cooled reactors.

The Civilian Gas Cooled Reactor Program was established during 1957 and 1958 when work was approved or initiated on the Pebble Bed Reactor Experiment (PBRE), Turret, Heavy Water Moderated Gas Cooled Reactor (by ECNG-FWCNG), Experimental Gas Cooled Reactor (EGCR), and the Peach Bottom-High Temperature Graphite Reactor (PB-HTGR). Work was begun in 1956 on the Army Gas Cooled Reactor Program and in 1958 on the Maritime Gas Cooled Reactor (MGCR) Program. The above projects (except for PBRE and ECNG-FWCNG which have been terminated) have continued to the present and are now in various stages of development. Because of the importance of BeO moderation to the over-all gas cooled reactor program, the original MGCR program has been altered in its scope to become the Experimental Beryllium Oxide Reactor (EBOR), now under construction at NRTS, which is expected to make important contributions toward evaluation of this concept for various possible applications.

Technical

The features of gas cooled thermal reactors which make them attractive as potential producers of economic power are as follows:

1. High Conversion Ratio. The moderators most commonly considered for gas reactors (graphite and BeO) are highly efficient. The coolant has low neutron absorption. Finally, it is possible to consider using no fuel cladding or low cross-section ceramic cladding in gas reactors. All these features result in good neutron economy, and make possible a very high conversion ratio,
2. High Temperature. Gas reactors are capable of providing the outlet temperatures required for the most modern steam plant conditions. Gas reactors also appear appropriate for improved power cycles that might be developed, such as gas turbine, magnetohydrodynamic or thermo-ionic. Any of these improved cycles require extremely high temperatures which appear to be most readily attainable in gas cooled reactors,
3. High Fuel Burnup. Certain gas reactor fuel is generally capable of high burnup because its high conversion ratio results in retention of reactivity after long exposure. Two Peach Bottom prototype fuel elements have been irradiated successfully at reactor operating conditions in the GAIL in-pile loop in GETR and the second element will be withdrawn late this year after a burnup of approximately 50,000 MWD/ton has been reached. Excellent fuel particle integrity has been demonstrated at ORNL with the irradiation up to 280,000 MWD/ton of loose, pyrolytic-carbon-coated, fuel particles at temperatures of 1500 to 1700°F. Further work is underway to incorporate these particles in a matrix without damaging them in the fabrication process,

4. Power Density. Gas reactors have classically been considered as low power density systems. However, recent advanced designs have minimized this factor by: (1) combining fuel with the moderator to permit the entire core to contribute to heat transfer, (2) use of high temperature all-ceramic fuel, and (3) use of higher gas coolant pressures, and
5. Large Units and High Plant Availability. Requirements for 500 MWE power plants are common at this time, and in the 1970s the trend will be to somewhat larger sizes. Gas reactors are easily capable of construction in large sizes because the relatively thin-walled, steel, pressure vessels can be readily field fabricated. In Europe the trend is toward prestressed concrete vessels which also permits large sizes.

There are a number of technical problems and uncertainties which require additional investigation to demonstrate the full potential of thermal gas reactors as outlined above. These problems and uncertainties vary in importance from concept to concept, but are discussed briefly in a general way below:

1. Safety considerations. Uncertainties related to safety aspects of our gas cooled reactor projects have resulted in the addition of certain expensive components such as emergency cooling in the EGCR and a back-up shutdown system in the PB-HTGR. Additional data and operating experience with these reactors may show that this added complexity is unnecessary on future reactors or that less expensive techniques are possible,
2. High Cost Components. Certain components of the EGCR such as pressure vessel, charge and service machines, and shaft seals have been much more expensive and difficult to fabricate than anticipated. Other components such as the heat exchanger cost less than anticipated. New design approaches are necessary to reduce or eliminate the cost of these more expensive components,
3. High Fuel Fabrication Cost. Coated particle, graphite matrix fuel is currently comparatively expensive to fabricate. The chief factor causing this high cost is the newness of the technology. Although a low fuel cycle cost is still possible because of high burnup, high conversion ratio and high thermal efficiency; the largest single cost component in the cycle is fabrication. Reductions in this area can be reasonably expected in the future and will result in significant cost savings,

4. Irradiation Damage of Graphite. Fast neutron irradiation of graphite at high temperature results in significant shrinkage of the permanent moderator over long periods. Current reactor concepts have been designed to accommodate this problem. However, development of a more stable graphite would simplify reactor design and an R&D program is underway to develop improved types of graphite,
5. Helium Impurities. Sufficient data is not yet available to definitely specify the tolerable level of impurities in the helium. This is not a significant problem in the EGCR because of low graphite temperatures. However, in graphite fueled reactors, excessive water in-leakage may result in increased transport of graphite out of the core into colder regions of the reactor. The designers are aware of this potential problem but its magnitude can only be fully demonstrated by reactor operation, and
6. Coolant Leakage. Helium coolant leakage specifications have been established for the EGCR and PB-HTGR and their operation will demonstrate the magnitude of this problem.

PROGRAM OBJECTIVES

Over-all

The Commission's recent report to the President on the Civilian Nuclear Power Program concludes that "the nuclear power program should continue on an expeditious basis and the program should include the following specific objectives:

1. The demonstration of economic nuclear power by assuring the construction of plants incorporating the presently most competitive reactor types;
2. The early establishment of a self-sufficient and growing nuclear power industry that will assume an increasing share of the development costs;
3. The development of improved converter and, later, breeder reactors to convert the fertile isotopes to fissionable ones, thus making available the full potential of the nuclear fuels; and
4. The maintenance of a U. S. technological leadership in the world by means of a vigorous domestic nuclear power program and appropriate cooperation with, and assistance to, our friends abroad."

The Gas Cooled Reactor Program, as set forth herein is designed to meet or contribute to each of the specific objectives established for the Civilian Power Program in the "Presidential Report for 1962". Steps toward the first and second objectives have already been taken with the construction of the Peach Bottom-High Temperature Gas Reactor (PB-HTGR) concept, which is one of two gas cooled power reactors being built in the US. It is currently at a developmental stage where its potentially low fuel cycle cost in larger sizes and high thermal efficiency have led to development and design by General Atomic on scaling the plant from 40 MWE to larger sizes. Empire State Atomic Development Associates, Inc. (ESADA) is currently sponsoring jointly with GA the development work and engineering evaluation of a large scale 500 MWE HTGR plant at a total estimated cost of \$8,700,000. A decision by the utility industry to construct a second and larger HTGR such as this would further the first objective. Current private sponsorship of work by ESADA and GA has furthered the second objective.

Studies indicate that, as the size of the HTGR is increased from the 40 MWE for Peach Bottom, to 500 and to 1000 MWE sizes, conversion ratio increases from 0.5 to 0.80 to 0.90 respectively appear possible. This would meet the Commission's third objective for improved converters. Preliminary indications from the TARGET study indicate that, in large plants using BeO in the graphite fuel element, the conversion ratio could be over 1.0; however, this is accomplished at the expense of increased fuel cycle costs. The Thermal, Advanced Reactor, Gas Cooled, Exploiting Thorium (TARGET) concept indicates a potential for breeding in thermal, gas cooled reactors and could also contribute to meeting the Commission's third objective.

Helium coolant has potential possibilities for fast U-Pu reactors because it is highly transparent (to neutrons) and therefore won't degrade the neutron spectrum or contribute to a temperature or power coefficient to any significant degree. In addition, its chemical inertness permits a wide choice of materials and attainment of high temperatures. Finally, an indirect (gas to steam generator) or possibly direct power cycle (closed cycle gas turbine) might be used to achieve high thermal efficiency and a simplified power loop system. Thus the fast gas cooled reactor could contribute to the Commission's breeding objective and have the advantage of an attractive doubling time over the thermal gas breeding system.

Finally, our gas cooled program is contributing its share to the AEC's fourth objective in terms of our domestic program efforts and the cooperative arrangements with our friends abroad.

Technical

The technical objectives for the Gas Cooled Reactor Program can be listed under near and long term goals. Under the near term goal category we have the following objectives for gas cooled reactor power plants to be constructed and operated by utilities:

1. Economically competitive in sizes ranging from about 150 up to 1000 MWE.
2. High conversion ratio systems.
3. Thermal efficiencies ranging from 40 to 50%.
4. Reactor coolant at 1400°F.
5. Supercritical steam cycles.
6. An integrated fuel recycle (U^{233} - U^{235} with U^{235} or Pu makeup)
7. Demonstrations of the safety aspects.

The objectives of the program defined as long term goals are as follows:

1. Economically competitive in sizes up to 2000 MWE
2. Economic breeding with gas cooled thermal and/or gas cooled fast reactors.
3. Direct cycle gas turbine system combined with a steam cycle.
4. Thermal efficiencies of 50 to 60%.
5. Greater independence from cooling water requirements - remote sites and highly industrialized areas where river water consumption is or will be overtaxed.
6. Coal gasification capability with 2000 to 2500°F reactor coolant.

PROGRAM ACTIVITIES

The current civilian power program is directed at investigating certain types of gas cooled reactors and at solving the major technical problems common to reactors of this type. There are also related programs within AEC and industry which contribute to the gas cooled effort in important areas of the technology. A description of each project and directly related activity is discussed briefly below:

1. EGCR

This reactor, which is being built at ORNL, is a 21.9 MWE, 84 MWT plant. The original function of the EGCR was to provide a flexible facility for the long range development of gas reactor systems for central station power production. Directed to this end, the core

was designed to permit operation with a variety of metal clad fuel element designs, helium coolant which permits eventual outlet temperatures up to 1200°F and provisions for future installation of in-pile loops which will permit limited testing for both clad and unclad fuels and a variety of gases at temperatures up to 1800°F.

The reactor can be generally described as a modified Calder Hall type, which has vertical fuel channels in a graphite moderator. However, the EGCR uses higher temperature materials such as stainless steel clad UO_2 fuel and helium coolant to permit more attractive performance than possible with the Calder Hall type reactor. Helium gas at 300 psi and 500°F enters at the bottom of the reactor, passes up through the fuel channels, then out at 1000°F through ports at the top of the pressure vessel and on to a heat exchanger where steam is generated. The gas leaving the heat exchanger returns to the reactor through electrically driven blowers. Fuel elements consist of a seven rod bundle with UO_2 pellets in the cladding and the bundle is contained within a graphite sleeve. The fuel is loaded and discharged during reactor operation by a fuel handling machine operating through ports in the bottom of the reactor vessel. A service machine is used at the top of the reactor for servicing the loops and control rods and to assist in fuel handling in case of malfunction in the normal fuel handling procedure.

Construction completion is scheduled in late 1964 with full power operation after mid-1965. Due to higher than anticipated costs for major equipment such as the pressure vessel and charge and service machines, and due to cost increases in other areas such as engineering and instrumentation, the plant is estimated to cost about \$51 million rather than the originally estimated \$30 million. The R&D program for the reactor is essentially complete except for life tests of reactor materials and certain components.

The EGCR will be operated as an experimental reactor to obtain performance information on helium containment and cleanup; gas cooled reactor components such as circulators, control rods, valves, fittings, etc.; graphite moderator performance; collapsed metal clad fuel behavior; on-stream fuel handling; and other miscellaneous areas of technology. The EGCR uses materials and components whose performance will contribute significantly in the exploitation of the gas cooled reactor concept.

2. Graphite Fuel Development

The gas cooled program is now mainly oriented to the development of improved all-ceramic fuels to obtain high temperature, long burnup and good neutron economy for high conversion systems. Since the intensive development on any concept must be first based on successful fuel performance, this activity is of primary importance to the gas cooled reactor program. It furnishes the basic fuel development and testing support for all aspects of the gas cooled reactor program.

At the inception of the civilian gas cooled program, ORNL was assigned the task of supporting EGCR construction and investigating improved gas cooled reactor concepts. Since the various concepts all involved different types of fuels, they could only be intelligently compared by testing the various fuel concepts involved. These included SS clad UO_2 , beryllium clad UO_2 , $BeO-UO_2$, UC_2-ThC_2 in graphite and others. Such a large scale fuel testing program required the construction of extensive fuel irradiation facilities and this construction program is just now being completed with the activation of the ORR-2 loop and the new ORNL hot cells. As a result of a recent decision to emphasize coated particle, graphite matrix systems, most of these fuel test facilities are being utilized for this type of fuel. A listing of these ORNL irradiation facilities is given below:

Name	Description
LITR Capsules	Small, inexpensive static capsules for initial screening work
ORR pool side sweep	4 reflector capsules capable of $2\frac{1}{2}$ " diameter fuel specimens
ORR "8-ball"	In core sweep capsule for high burnup rate tests
"B-9" and "C-1" Capsules	Small flexible capsules for accelerated tests of loose coated particles
MTR-48 Capsule	For fuel tests requiring higher flux than available in ORR.
ORR-1 Loop	Gas cooled loop for metal clad fuels
ORR-2 Loop	Gas cooled loop capable of testing unclad fuel and obtaining fission product plateout data.

Congressional authorization is being sought by the Commission to participate with the West Germans in their Potato Bed or AVR project. The Commission proposes to develop and procure a graphite fueled core for testing in this reactor. A primary activity at ORNL in the next few years will be development, testing, procurement, and operation of a US manufactured core in the AVR reactor. Personnel will be assigned to participate in the AVR operation.

As soon as the ORNL facilities are available, fuel screening tests will begin in support of the TARGET program. This program will utilize the GAIL loop for final prototype proof testing of fuel. The Thorium Utilization Program at ORNL is developing the basic techniques for recycling thorium based fuels. It is planned that the graphite fuel development irradiation facilities will also be utilized to carry out tests of fuel fabrication concepts developed for recycling fuel.

3. PB-HTGR

This reactor, which is being constructed at Peach Bottom, Penna., on the Conowingo Pond, is a 40 MWE, 115.5 MWT plant. It is a prototype thermal reactor employing highly enriched uranium as fissile material; Th as fertile material; graphite as moderator, cladding, structure and reflector; and 300 psi helium as coolant. This system, having a net plant efficiency of 34.7% will operate at a reactor coolant temperature high enough (1380°F) so that full advantage can be taken with the high temperature steam cycles and turbines developed for modern, conventional, coal fired plants thus providing future capabilities of over 40% net efficiency in large HTGRs.

The PB-HTGR reactor core is made up of 822 fuel elements, each about 12 feet long and $3\frac{1}{2}$ inches in diameter, arranged in a vertically oriented, close-pack array. There is no additional moderator, but the core is surrounded by a graphite reflector. The fuel element consists of cylindrical fuel compacts, which are contained in a low permeability graphite sleeve. The fuel compacts consist of uranium and thorium carbide, in the form of particles coated with pyrographite, dispersed in a graphite matrix. The helium coolant enters the core at 654°F, flows up through the cusps between the fuel elements and leaves the core at 1380 F. A helium purge stream enters the fuel element at the relatively porous upper reflector piece and flows downward around the fuel compacts, sweeping fission product gases out of the space between the fuel compacts and the graphite sleeve. The mixed gases then pass through an internal fission product trap, out the bottom of the fuel element and through a manifold

system to a set of external fission product traps. Clean helium from the external trapping system is then returned to the primary coolant stream.

This project, is a joint venture of the AEC and private industry in the R&D, design, construction and operation of an advanced gas cooled reactor. Under contracts with the Commission, General Atomics is performing pre-construction and later post-construction R&D, and Philadelphia Electric Company is constructing and will later operate the plant for a period of five years. The Commission is funding the R&D program up to a maximum of \$14.5 million, and will waive up to \$2.5 million in fuel use charges. Construction is being funded by Philadelphia Electric and the HTRDA utilities group. The plant is being designed and constructed for Philadelphia Electric by Bechtel Corporation for a fixed price of \$24.5 million. The nuclear steam supply system for the plant is being furnished by General Atomic Division under a sub-contract with Bechtel.

The pre-construction R&D program for this project is essentially complete; reactor design is over 90% complete; and reactor construction, which started in early 1962, is about half complete. Completion of reactor construction is scheduled for mid-1964 with full power operation in late 1964. The first core will be discharged after 3 years of power operation.

The PB-HTGR is expected to provide valuable operating experience on all-ceramic core using pyrographite coated fuel particles capable of high temperature and burnup, homogeneous fuel-graphite moderator structures, high temperature helium coolant, vented fuel with fission product removal and trapping, U^{235} -Th fuel cycle, and componentry. Each of these features is significant in the successful exploitation of the thermal gas cooled reactor concept needed in order to meet the high conversion objective set forth by the Commission.

4. Private Construction and Operation of Additional Gas Cooled Reactors.

In order to demonstrate economic nuclear power for gas cooled reactors and to provide early establishment of a self-sufficient and growing nuclear power industry, it will be necessary to assure the construction and operation of increasingly larger plants of this type in U. S. utility grids. The Commission hasn't solicited this type of reactor as yet under its Modified Third Round Assistance program; however, unsolicited proposals embodying the confidence of the proposers would be given serious consideration by the Commission.

5. TARGET

The over-all "Thermal, Advanced Reactor, Gas Cooled, Exploiting Thorium" program includes a design study effort to specifically define the design parameters for a 1000 MWE plant; continued fuel development and testing in GAIL loop; R&D on selected improved components; and design, construction and operation of a prototype TARGET reactor.

The technical characteristics of the TARGET plant are currently envisioned as follows:

Power	- 1000 MWE
Steam Cycle	- 3500 psi, 1050-1000-1000
Net Efficiency	- over 46%
Gas Circulator Drives	- Gas turbines
Reactor & Primary Circuits	- All housed in a pre-stressed concrete vessel
Conversion Ratio	- .90 to 1.0
Fuel	- Advanced designs utilizing U-233 recycle

At the present time, effort in the TARGET program is confined mainly to General Atomics. The non-vented coated particle fuel development program at ORNL, cited previously, will contribute to the TARGET program. With completion of the TARGET design study this Fall, it is anticipated that certain subcontractors will be brought into the program to carry out R&D on turbocirculator and reactor vessel designs necessary for the TARGET prototype.

6. Fuel Recycle Program for Gas Cooled Reactors*

To attain a high conversion ratio for maximum utilization of our thorium resources in gas cooled reactors using thorium as fertile

* This activity is conducted under DRD's base program for recycle of thorium bearing fuels. Under this Thorium Utilization Program at ORNL emphasis is currently being placed on recycle technology for the Spectral Shift and HTGR high converter reactor systems. Design of a Th-U Fuel Cycle Development Plant is underway at Oak Ridge and initiation of construction is planned for the near future.

material, it is necessary to develop suitable processes for the reprocessing and refabrication of the U-233-Th carbide, graphite matrix type fuel. Since recycle of the U²³³-U²³⁵ fuel is our goal, investigations based on both U²³⁵ and Pu as makeup are required.

A program is currently being carried out under the Thorium Utilization Program at ORNL to investigate the reprocessing of pyrolytically coated carbide fuels in a graphite matrix. Dissolution leach studies on graphite fuels indicate that fuel pretreatments by burning the graphite rather than grinding is best from an over-all fissionable material recovery standpoint. The Sol-Gel refabrication technique developed for oxide fuel has been tried with some initial success on the preparation of U-Th carbide particles.

ORNL has only recently initiated development of the necessary technology required for recycling in gas cooled reactors using carbide fuels in a graphite matrix. Conceptual flow sheets for the processes involved in reprocessing and refabrication have been developed but much remains to be done.

7. Fast Gas Cooled Reactors

This activity is in its initial program planning stage. Therefore, the first undertaking is to establish concept feasibility and potential for economic operation and high breeding gain. The initial work will be an over-all concept analysis and study supported by certain exploratory fuel development work. No comprehensive program will be established until the initial evaluation and fuel test data is obtained. This concept can lean heavily on the component, materials and coolant technology work already being performed under the various thermal gas cooled programs. Therefore, it is not envisioned that a large new independent program will be required initially but rather a supplement to the existing programs covering those areas which are unique to a fast gas system.

8. Related Activities

a. Foreign Exchange Agreements

Specific programs for exchange of information have been set up between the EGCR and the UK's AGR, between the PB-HTGR and the UK-OEEC sponsored Dragon project and between the German BBC-Krupp pebble bed reactor and our pebble bed fuel development program and EBOR project. These exchange programs

are proceeding satisfactorily, and have proven to be very useful to all parties. These agreements have included exchange of reports, visits by individuals and small groups, exchange conferences, and a limited number of cooperatively conducted experiments.

b. Materials Work

An extensive program for the investigation of graphite is being carried out at Hanford. The Hanford group has been carrying out investigations on irradiation damage to graphite in high temperature gaseous environments, graphite oxidation (including burning), and graphite permeability - all of these are of particular interest to gas cooled reactors.

A program is underway at Battelle Memorial Institute to conduct basic fuel and materials investigations of coated particle fuels for reactor use. These studies are investigating a variety of possible coating materials, coating methods, and particle size ranges, and include the testing of coated particles furnished by outside suppliers.

c. Reactor Physics

Current plans call for a new high temperature critical facility to be constructed at Hanford. This facility will enable us to obtain more precise information on U^{233} thorium-graphite systems at actual operating temperatures.

d. Nuclear Safety

HTGR reactor designs use a heavily loaded core to obtain minimum fuel costs. Such a core has an over-all negative temperature coefficient because of the strong Doppler component. However, future plants with more lightly loaded cores which are desirable for breeding or near breeding have greater uncertainty as to over-all temperature coefficient. For this reason, it appears desirable to construct an excursion facility to fully investigate the transient characteristics of HTGR reactors.

e. Commercial Reprocessing of Graphite Fuels

There are no firm plans established for industry's entry into this activity; however, ORNL technology on reprocessing this fuel and on their recycle development program to be demonstrated in the Kilo-rod and the Th-U Fuel Cycle Development Facilities should be forthcoming in the next several years. The commercial

construction and operation of HTGR type reactors will provide the impetus to industry to provide the necessary fuel reprocessing and refabrication facilities.

Summary

The US civilian power gas cooled reactor program has made considerable progress since its inception in the late 1950s. Gas reactors having technical features of high conversion ratio, high temperature, high fuel burnup and capability of construction in large sizes make them very attractive as potential producers of economic power in the very near term. The operation of Peach Bottom-HTGR and EGCR in late 1964 and 1965 respectively will contribute significantly in the successful exploitation of the best thermal gas cooled reactor needed to meet certain objectives set forth by the Commission.

Since the new graphite fuel concept already promises very low fuel cycle costs along with reactor coolant conditions that can exceed current practice, it is my belief that the concept provides a long term potential that promises some very exciting possibilities.