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THE ORNL GAS-COOLED REACTOR

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ORNL-2500
Part 1
Plant Design

Contract No. W-7405-eng-26

THE ORNL GAS-COOLED REACTOR

By

The Staff

of the

Oak Ridge National Laboratory

DATE ISSUED

April 1, 1958

OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee
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THE ORNL GAS-COOLED REACTOR

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SUMMARY REPORT

INTRODUCTION

In September 1957 the Atomic Energy Commission undertook as part of its Reactor Development Program a serious study of gas-cooled reactors for power production. The purpose of this study was to present to the Congress a specific set of conclusions concerning the possible role of gas-cooled reactors in the United States together with a set of recommendations which would constitute a national program for gas-cooled reactor development.

In order to evaluate the individual studies made by Kaiser Engineers, Hanford, and the Oak Ridge National Laboratory, it is necessary, first of all, to understand the historical development of the American attitude on gas - cooled reactors. The very first U. S. studies of gas-cooled reactors were in connection with the plans for plutonium production at Hanford. In the early days of the Metallurgy Laboratory at Chicago, after the chain reaction had been demonstrated experimentally, the design program was based on the utilization of gas cooling for plutonium production. It was only after the painstaking work of the group under the direction of Eugene Wigner that it became apparent that natural-uranium, graphite- moderated, plutonium-production reactors could be successfully water cooled. Since it was possible to utilize lower temperatures and conventional materials in a water cooled system, the original plan to build gas-cooled plutonium-production reactors was set aside. It must be emphasized that the gas-cooled reactor design work at Chicago was carried out in a thoroughly responsible fashion and the plans for gas cooling were only laid on the shelf when it became completely clear that water offered a surer route for achieving large scale production of fissionable material. Since 1943 there has been only one other serious study of gas-cooled reactors for power production, the ill-fated Daniel's Power Pile project at Oak Ridge immediately following the war.

Generally speaking, gas-cooled systems have received hardly more than casual attention because the early studies seemed to indicate that it is difficult to achieve sufficiently high-power densities in these reactors

to be interesting. This notion has remained firmly planted in American nuclear energy thinking up to the present time.

The present studies are, we believe, the most up-to-date, and thorough going studies which gas-cooled reactors have had in the U. S. during the past twelve years. As a result of the British success with gas-cooled systems, a sufficient technology now exists on which to base firm estimates of the present performance and future potential of gas-cooled systems. In the light of twelve years additional experience we now know that the popular notion of the limitations and economics of gas-cooled reactors are not adequately true in detail to permit rejecting out-of-hand gas-cooled reactors for power production.

It is the purpose of this report to establish in detail the basis for these general conclusions and to summarize the Oak Ridge National Laboratory phase of the gas-cooled reactor program. The Atomic Energy Commission requested that the Oak Ridge National Laboratory make the results of this study available on April 1, 1958 with an early construction date in mind.

AIMS OF OAK RIDGE NATIONAL LABORATORY STUDY

The classical argument against gas-cooled reactors has been that gases are such poor heat transfer media, when compared with liquids, that gas-cooled reactors will have very low-power densities and hence high unit capital costs. It has always been recognized that natural-uranium-fueled gas-cooled stations have very low fuel and operating charges associated with them as has been borne out by the experience in the British stations. One obvious way of achieving a substantial improvement over existing gas-cooled reactor stations is to employ partially enriched uranium as the fuel for such reactors. It is certain that the utilization of enriched fuel will reduce the capital costs of a gas-cooled station, but it is not obvious in advance how the utilization of enriched fuel affects the economics associated with the fuel cycle itself. The Oak Ridge National Laboratory study phase of the program reported herein deals exclusively with designs of reactors utilizing enriched uranium.

The Atomic Energy Commission specified that the Oak Ridge National Laboratory enriched gas-cooled reactor design (GCR-2) must be based on existing technology in order that it could be constructed immediately if a decision were made to do so. It should be recognized that the restriction of early construction places the partially enriched system in an unfavorable light in comparison with the natural system since all of the British and French experience with natural-uranium reactors serves to strengthen the natural-uranium design and permit a high degree of plant optimization. In addition to undertaking the detailed design of a reactor for immediate construction, it was thought necessary to attempt to evaluate the future potential of gas-cooled reactors as compared with other reactor types which are presently part of the U. S. reactor development program. To this end the Laboratory has undertaken various experimental studies to explore the prospects of utilizing alternate materials which, if successful, would grossly simplify the design or significantly improve the performance of enriched gas-cooled reactors.

CONCLUSIONS

The Oak Ridge National Laboratory offers the following conclusions which constitute the opinion of the Laboratory on the basis of the work done through April 1, 1958 on the Gas-Cooled Reactor Program.

1. Adequate technology exists today in the U. S. on which to base construction of gas-cooled reactors either of the natural-uranium or the enriched-uranium variety in the very near future. The experience available to us through the British power program gives us a high degree of assurance that gas-cooled, natural-uranium reactors can be built in a very straightforward fashion. The only significant difference between the natural-uranium and the enriched-uranium systems is in the fuel element proposed for the enriched reactors. There is more experience available using UO_2 than for any other possible fuel material of interest in high temperature applications. It is

impossible, at this time, to state categorically that UO_2 will operate under the precise conditions specified in this study. Nevertheless, all of the experimental data available to date indicate that the fuel element proposed will perform more than 50% longer than required to meet the specifications of the design outlined herein.

2. An enriched gas-cooled reactor of the GCR-2 type will produce cheaper power than a natural-uranium plant. This follows from the large reduction in capital costs achieved by enriching the fuel combined with the fact that no serious penalty is paid in increased fuel costs as a result of fuel enrichment.

3. Gas-cooled reactors are at the present time technologically competitive with the best available pressurized-water reactors. This conclusion is based on our estimate of the degree of advancement which has been achieved in general gas-cooled reactor technology both in the U. S. and abroad, coupled with the observation that a very large fraction of the cost of a gas-cooled reactor plant is devoted to components which represent current practice in the steam power industry. In this important respect, gas-cooled reactor systems utilize modern power practice more closely than any other reactor.

4. On the basis of recent paper studies, it appears that gas-cooled reactors are economically competitive with pressurized-water reactors in the U. S. There is no firm operating experience available with either large-size gas-cooled or pressurized-water reactors. Accordingly, it is necessary in drawing this conclusion to resort to available design studies of both types made on a comparable basis by a single group.

5. There are a large number of ways in which the performance of gas-cooled reactors can be substantially improved beyond that predicted in this report for the GCR-2. In order to convert

these possibilities into reality, it will be necessary to undertake a research and development program in addition to a gas-cooled reactor construction program. The principal improvements which can be achieved are, of course, in fuel element performance and lifetime. The additional possibility exists of constructing high-conversion ratio systems which would further improve both the fuel economy and the fuel utilization. The Laboratory believes that with respect to the important consideration of development potential both gas-cooled reactors and pressurized reactors have substantial potential to be realized in the future and there does not seem to be at this time any fundamental reason for selecting one type for development to the exclusion of the other.

REACTOR DESIGN

There are three fundamental limitations on any gas-cooled reactor which must be considered in detail in the design of such a power plant.

1. The basic limitation on the reactor itself stems from the ability of the fuel element to perform over its required lifetime under the operating temperatures and pressures. It is necessary in undertaking a first reactor design to provide a larger margin of engineering safety than would be required once some specific operating experience has been obtained with a given reactor system. Further, future development of improved fuel elements will certainly lead to increased confidence in the predictions of fuel element integrity and lifetime under operating conditions.
2. A second important limitation arises from the chemical behavior of the system of gas, coolant and moderator. Of particular interest here is the oxidation of graphite by CO_2 which sets an upper limit on the gas temperature which can be achieved in a CO_2-cooled graphite reactor. It is likely that further research will eventually succeed in increasing our confidence, that the materials

presently under consideration can be operated at the required temperatures for sufficiently long times, or that the materials can be altered so as to increase their reliability and improve their performance.

3. Once the materials have been selected the final limitation on reactor performance results from practical considerations of how large a pressure vessel can be field constructed, stress relieved and tested. As time goes on, the capability of the fabrication industries to produce larger diameter and thicker walled pressure vessels, assembled at the site, will improve the economic picture of gas-cooled reactors. From the reactor performance point of view, there will always be an incentive to increase the physical size or the pressure level of a given reactor, thus permitting one to extract more power from a single unit. Accordingly, the present capabilities of the pressure vessel fabricators play an important role in the final design of such a system.

It should be recognized in attempting to judge the development potential of any reactor system, gas-cooled or otherwise, that it is impossible to predict with any degree of certainty how successful a research program will be in providing for improved reactors in the future. The only possible predictions of the success of such research are necessarily based principally on previous experience. With this in mind, the Laboratory indicates its belief that there exist substantial prospects for improving the performance of gas-cooled reactors beyond that assumed in the GCR-2.

A perspective section through the proposed plant is shown in Fig. 1. Figure 2 gives details of the reactor design.

The site selected for the study is one which is typical for U. S. power plants, and which meets the nuclear requirement for remoteness, as well as the practical requirements of water transportation, a supporting power network, good construction conditions and an adequate labor force. The most important deviations from standard gas-cooled reactor practice, represented by the GCR-2 design, are as follows:

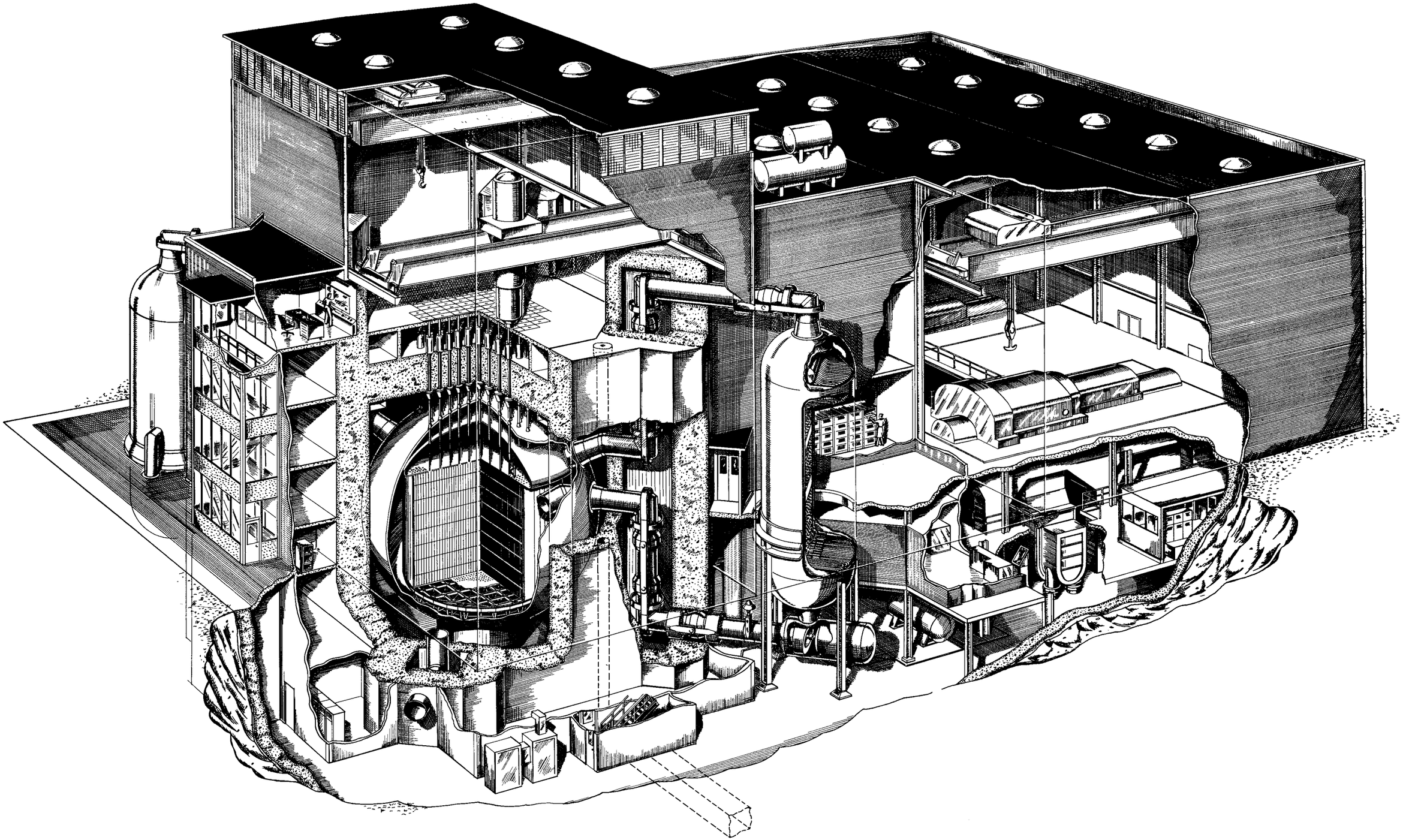

Fig. 1. Cutaway Perspective of ORNL Gas-Cooled Reactor Plant (GCR-2).

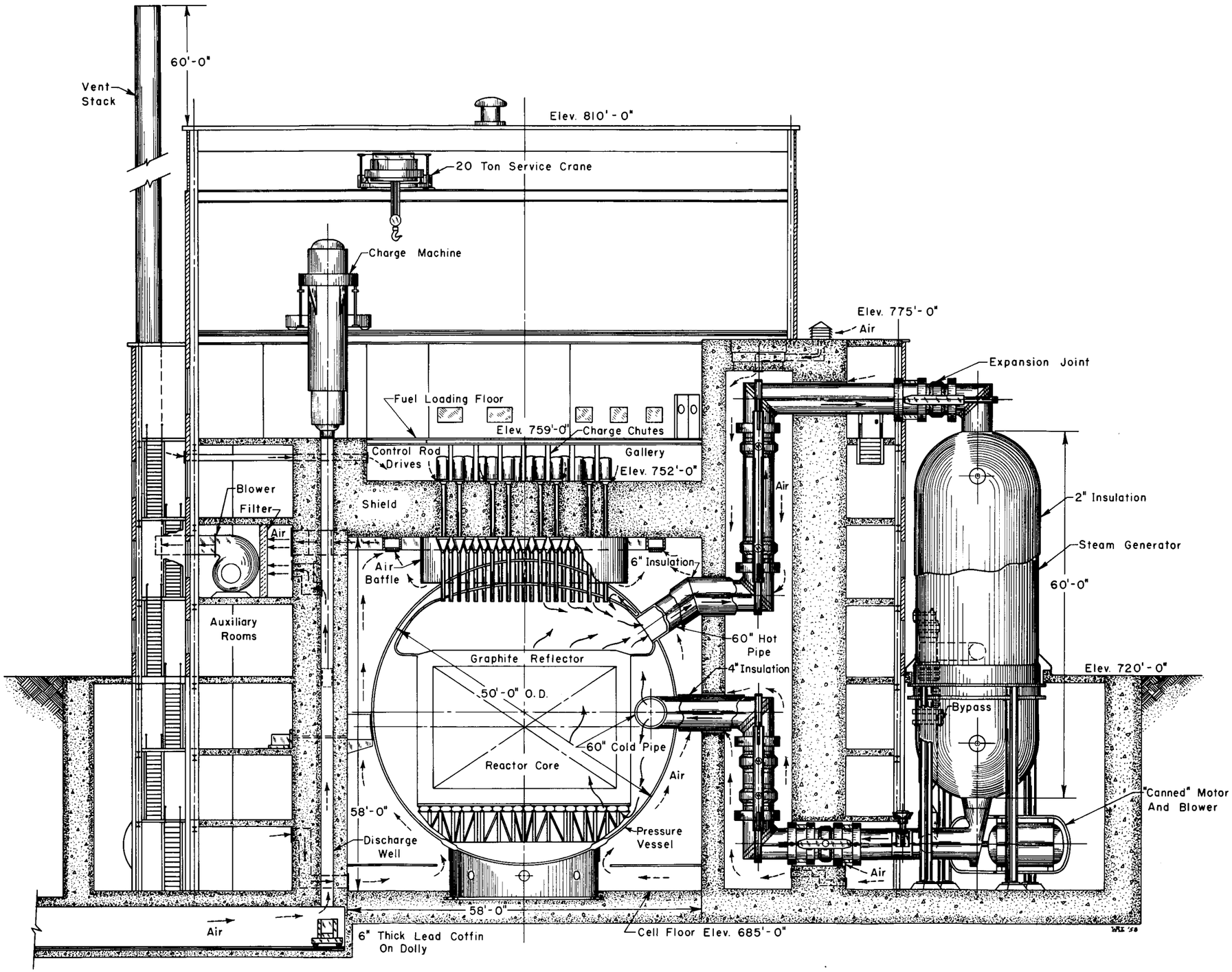

Fig. 2 Sectional View Through Reactor and Reactor Bay (ORNL – GCR-2).

1. Utilization of stainless steel capsules as the cladding for the fuel.
2. Utilization of enriched UO_2 as the fuel material.
3. Utilization of helium as the cooling gas.

There are, in addition a large number of engineering novelties introduced into the design, none of which markedly changes the comparison between the GCR-2 and any other gas-cooled reactor. It is worthwhile, however, to draw specific attention to the effects of the three important changes.

1. The principal virtues of stainless steel as a structural material are two in number.
   a. Because of the excellent high-temperature strength of stainless steel, it is possible to raise the temperature of the reactor exit gas, thus improving the over-all heat transfer and thermodynamic performance of the system.
   b. There is no catastrophic oxidation between stainless steel and the important coolants which could initiate a graphite fire.
2. The utilization of enriched fuel is not merely a matter of counteracting the nuclear poisoning effect of stainless steel. Rather the use of enriched fuel has several other important consequences.
   a. The enriched fuel design permits the utilization of UO_2 which is a superior fuel material to natural uranium metal. Uranium dioxide does not suffer the mechanical deformation characteristic of uranium metal in the low-temperature range. At higher temperatures, UO_2 retains most of the fission product gases which are produced without undergoing severe distortion, as does the metal.
   b. By enriching beyond the level required for criticality, it is possible to obtain enough excess reactivity so that the nuclear poisoning effect of the Pu^{240} which is produced can be overcome to the point where Pu^{240} begins to behave as a fertile material through the production of fissionable Pu^{241}. The effect of this over-enrichment is to increase the reactivity lifetime to such an extent that the over-all fuel costs of the

enriched gas-cooled reactor become comparable to those of a natural-uranium gas-cooled reactor. In the past the principal argument for building enriched gas-cooled reactors has been to achieve reductions in capital cost. It has always been presumed that the fuel costs associated with enriched systems would be considerably higher than in natural systems. The GCR-2 study indicates that there is no substantial fuel cost penalty associated with a properly designed enriched reactor system.

c. The principal economic effect of enrichment is to reduce the over-all capital cost by permitting operation at higher specific power levels. The investment costs/kw fall substantially as the power density of a given sized system is increased, since the capital cost of a large fraction of the over-all power plant is independent of power level.

d. Graphite-moderated, gas-cooled reactors in which the fuel is either natural uranium or only very slightly enriched uranium exhibit a positive moderator temperature coefficient of reactivity for exposures in excess of roughly 1000 Mwd/Tonne. This is an important design consideration in both the British and French reactor plants. By enriching the fuel so that the absorption competition between plutonium and U^{235} is shifted, it is possible to maintain a slightly negative moderator temperature coefficient over the entire lifetime of the fuel.

3. It is recognized that the use of stainless steel imposes a severe nuclear penalty on the system which can best be offset by raising the exit gas temperature of the system. Once the design temperature is substantially higher than the levels in use at Calder Hall and Marcoule, the whole materials system based on CO_2 is suspect, in virtue of the chemical reactions between CO_2 and graphite. In order to circumvent this problem, helium was selected for the coolant in the GCR-2.

If helium were universally available, it would undoubtedly be the standard coolant for such reactors. The chemical inertness of

helium makes catastrophic oxidation of the capsule material, as well as the graphite, almost impossible since only impurities enter into such reactions. Thus, the character of the principal maintenance problem, location and replacement of leaking fuel elements, is greatly simplified.

It is the opinion of Oak Ridge National Laboratory that it would be desirable as part of a gas-cooled reactor program to develop a reactor which uses CO_2 as coolant since helium is not available on the world market at the present time. It is further the opinion of the Laboratory that it is crucially important that the first gas-cooled reactor constructed in the U. S. be of advanced design with respect to the present British Central Electric Authority Plants. It is suggested that the minimum design specification for such a plant should be to achieve 1000°F gas temperature. Since it has not yet been demonstrated that graphite and CO_2 are chemically compatible at temperatures in the neighborhood of 1000°F, Oak Ridge National Laboratory recommends helium as the coolant for the first gas-cooled reactor.

The high cost of helium imposes an engineering requirement on the design for much-improved leak-tightness over the Calder Hall performance. It is the opinion of Oak Ridge National Laboratory that adequate leak-tightness can be assured by proper design. An over-all system helium-leakage loss of 1% per day, which is more than ten times higher than is achieved in present practice in large gas systems, would result in an increase in net power cost of only 0.05 mills/kwh.

The basic design of the GCR-2 power plant is predicated on conventional power-station practice insofar as possible. The plant is designed for base-load operation, with the provision of load-following ability. The reactor is designed to produce a gross thermal power output of 687 Mw. The turbine-generator plant will produce a gross electrical power of approximately 250,000 kw at a turbine heat rate of 9458 Btu/kwh. With a net efficiency of 32.8%, the net electrical power output of the power plant is 225 Mw. The

optimization studies described in Parts 2, 3, and 4 of this report were the bases for the selection of the nuclear power plant design. It should be emphasized again that the conventional portion of gas-cooled reactor power plants utilizes modern steam power practice. Accordingly, the Laboratory believes that it should be possible to construct such plants with a smaller contingency factor than is currently in the vogue for stations utilizing other reactor types. The capital costs of the GCR-2 are summarized in Table 1. The total direct costs are $47,904,700. The indirect charges when added to the direct costs give a total estimated plant cost of $83,627,300. The indirect charges used were specified by the Atomic Energy Commission and have been applied to each of the gas-cooled reactor designs in order to achieve direct comparability of the final costs.

The over-all cost of producing power has been divided in conventional fashion into fixed and operating charges.

Fixed charges include:

1. Capital charges against the cost of the power plant, computed at 14% per year.
2. Capital charges against interest on construction funds (interest computed at 6% per year during construction; capital charges computed at 14% per year).
3. Capital charges against fuel fabrication costs for the first core, computed at 14% per year.
4. Interest charge on initial value of in-pile fuel inventory, computed at 4% per year.

Operating charges include:

1. Fuel burn-up cost, less plutonium credit.
2. Cost of recovering fissionable material from spent fuel ($12.40/kg U).
3. Cost of fabricating replacement fuel elements ($30.90/kg U).
4. Interest charge on fuel inventory held up outside reactor.
5. All other operating and maintenance costs.

Among the important assumptions made in the cost analysis are the following:

1. Annual charges against the fixed investment in the plant (exclusive of fuel inventory) are 14% of the investment. This rate includes return

TABLE 1

CAPITAL COSTS ORNL GCR-2 EXCLUDING FUEL ELEMENTS

Land and land rights	$ 450,000
Structures and improvements	7,695,000
Reactor system	19,414,700
Steam system	3,349,000
Turbine generator plant	12,030,000
Accessory electrical equipment	4,091,000
Miscellaneous power plant equipment	875,000
Direct Costs Subtotal	$ 47,904,700
Indirect Costs (15% of Direct Costs)	$ 7,185,700
Subtotal	$ 55,090,400
Escalation at 6%/yr from 1-1-58 to 7-1-60 on direct costs and indirect costs	8,263,600
Subtotal	$ 63,354,000
Contingency (20% of direct costs and indirect costs and escalation)	12,670,800
Design - including contingency (12% direct costs and indirect costs and escalation)	7,602,500
TOTAL COST	$ 83,627,300

to the investors, corporate income tax, amortization of principal, ad valorem taxes, and insurance.

2. Annual interest, or rental, charges for the fuel are 4% of the initial value of the fuel. This rate is firmly established by the Atomic Energy Commission.

   It should be emphasized that this low arbitrary interest rate which has been specified by the Atomic Energy Commission strongly influences any decision based on the relative economics of gas-cooled reactors. The comparison of large-fuel inventory systems typified by the GCR-2 with the more compact highly enriched systems which have low-fuel inventories is partially dependent on the interest charges assumed to apply to the fuel. If the interest rate were significantly higher than 4% it could influence such comparisons.

3. Plant load factor is 0.80. It is assumed that this plant would be a base-load plant.

4. A value of $12/g is assigned to the plutonium content in spent fuel. This is an approximate value established by the Atomic Energy Commission as the worth of plutonium as a reactor fuel (without regard to its isotopic composition). It is possible that a lower figure would be more realistic if the value of plutonium is to be determined exclusively for thermal reactors.

5. It is assumed that progress payments which will be necessary as construction proceeds are equally spaced over the construction period, 14% of the appropriate capital cost must then be added to the annual fixed costs of the plant.

6. It has been assumed that construction costs rise 6% per year. For a three-year construction period from 1959 to 1961, an average end escalation date of mid-1960 was chosen, in view of the uniformly spaced progress payments assumed previously.

It is of interest to compare the GCR-2 design with recently constructed fossil fuel plants of approximately the same thermal rating. A relative analysis of the GCR-2 and such plants is presented in Table 2. Table 2 lists an escalated cost column for each of the fossil fuel plants which takes account of the increase in construction costs since the date of construction

COMPARISON OF COST AND PERFORMANCE DATA FOR TYPICAL COAL-FIRED POWER PLANTS* WITH CORRESPONDING DATA FOR THE ORNL GCR-2

Plant Designation (ORNL or Electrical World)	GCR-2†	303(218)		304		305	
GENERAL DATA							
Total generator rating - Mw	252	262		275		230	
Date of construction	1958	1954		1955		1954	
Thermal efficiency, over-all	32.8	32.48		37.22		33.98	
Steam pressure, psig	950	900 and 1450		2050		1475 and 1825	
Steam temperature, initial superheater °F	950	950 and 1000		1050		1010	
(Reheat) °F	---	1000		1000		1010	
Plant factor, %	80	80.85		87.7		89.4	
INVESTMENT DATA ($/kw)	(Base)	(Base)	(Escalated)**	(Base)	(Escalated)**	(Base)	(Escalated)**
(310) Land	3.12	0.43	0.43	4.93	4.93	0.49	0.49
(311) Structures and improvements	53.33	35.27	44.70	40.02	47.70	33.56	41.20
(312) Boiler or reactor plant	157.60	60.62	76.70	52.82	63.00	64.72	81.90
(314) Turbine generator plant	83.25	39.24	49.70	38.07	45.40	42.20	53.40
(315) Acessory elect. system	28.32	7.51	9.51	9.75	11.64	12.88	16.31
(316) Miscellaneous plant equipment	6.06	1.53	1.94	1.97	2.35	2.00	2.53
TOTAL	331.68	144.60	182.98	147.56	175.02	155.85	195.83
Total, less reactor or boiler	174.08	83.98	106.28	94.74	112.02	91.13	113.93
COST OF ENERGY (mills/net kwh)							
Fixed Charges							
A. Plant costs	7.42	2.93	3.86	3.353	4.43	3.319	4.48
B. Computed at (%)	14.0	13.6	14.0	12.61	14.0	15.0	14.0
C. Fuel inventory at 4%	0.76						
D. Fuel element fab. at 14%	0.38						
TOTAL Fixed	8.56	2.93	3.86	3.35	4.43	3.32	4.48
OPERATING COSTS (mills/net kwh)							
Wages (including supervision)	0.38	0.25		0.38		0.18	
Water, lubrication, supplies	0.25	0.03		0.15		0.004	
Maintenance	0.26	0.15		0.21		0.066	
Total, operating and maintenance (excluding fuel)	0.89	0.43		0.74		0.25	
Fuel	1.73	2.78		2.73		2.97	
Total operation (including fuel)	2.62	3.21		3.47		3.22	
Total cost of energy	11.18	6.14	7.07	6.82	7.90	6.54	7.70

*Base data for coal-fired plants from "Electrical World," (October 7, 1957).

**All costs except land and operating costs were escalated to a 1958 base at 6% per year compounded semiannually. and fixed charges were computed at 14% for an 80% load factor.

†The GCR-2 data herein differ from those quoted in ORNL-2500, Sections I and II. This results from a last-minute change of ground rules for economic evaluation of the various gas-cooled reactor designs. The AEC requested these changes in order to achieve comparability between reports.

of these plants. Although the GCR-2 is not competitive with these modern steam plants, it should be noted that the GCR-2 is at least as competitive as recent studies have shown the best pressurized-water reactors to be.

During the course of the GCR-2 design study it became apparent that it would be possible to improve the over-all plant performance by changing certain important parameters. Unfortunately, the press of time did not allow for incorporating these changes into the present design. Three improvements which would probably be included in a future plant optimization are:

1. Increase the steam pressure to 1,400 psi.
2. Increase the power density, and hence the over-all thermal rating, by boosting the pumping power per channel.
3. Reduce the hot-spot allowance of 300°F by approximately 35°F as indicated from recent detailed performance calculations.

The over-all result of making all of these improvements would be to increase the thermal power level of the system from 687 Mw to more than 1100 Mw and to reduce the unit power cost by approximately 2 mills/kwh.

RECOMMENDATIONS

On the basis of the study presented herein, the Oak Ridge National Laboratory offers the following recommendations to the Atomic Energy Commission pursuant to their request that we appraise the present state of gas-cooled reactor technology and offer recommendations on how best to implement the technical results of the study.

1. The U. S. should initiate early construction of a substantial gas-cooled power reactor of the partially enriched type, typified by the GCR-2 design.
2. The first gas-cooled reactor should be designed to produce approximately 1000°F gas. If Oak Ridge National Laboratory were asked to design such a reactor at the present time, helium would be selected as the coolant gas in order to have as large a margin of engineering safety as possible in the design. It is, however, not proper in our estimation to insist that helium be the coolant.

The choice of coolant should be left to the designer who should guarantee to produce the specified gas temperature in the operating reactor.

3. The Atomic Energy Commission should also initiate immediately a program to construct a small gas-cooled reactor of an advanced type, following perhaps one year of intensive research and development in materials, which would provide the technological basis for the advanced system. It is too early to specify the single most fruitful direction this research program should follow. The research program should include investigations on how to raise, and hence improve, the steam conditions, as well as how to improve the over-all fuel economy by increasing the conversion ratio. In general, the specification for this experimental reactor should be that it provide a sound basis upon which to build a second generation of gas-cooled reactors which represent a significant improvement over the GCR-2 type.

4. In undertaking gas-cooled reactors, the Atomic Energy Commission should recognize that it is adding not simply one reactor but rather a whole new technology to the framework of the civilian power reactor development program.

5. Finally, it should be generally recognized that the ultimate goal of reactor development in the U. S. must necessarily hinge on our ability to utilize efficiently the raw materials on which nuclear energy power production is based. To this end, the Oak Ridge National Laboratory believes it would be imprudent to inject gas cooling into the development program at the expense of the development of any of the long range and ultimately important reactor concepts. If it is impossible for fiscal reasons to superpose gas cooling on the existing reactor development program, then the Laboratory recommends that the Atomic Energy Commission undertake gas cooling only at the expense of those short-range reactor-development programs which are presently part of the over-all Commission reactor development program.