LA-2198
REACTORS--POWER
TID-4500 (13th Ed., Rev.)

LOS ALAMOS SCIENTIFIC LABORATORY

OF THE UNIVERSITY OF CALIFORNIA LOS ALAMOS NEW MEXICO

REPORT WRITTEN: January 23, 1958

REPORT DISTRIBUTED: June 2, 1958

TURRET
A HIGH TEMPERATURE GAS-CYCLE REACTOR PROPOSAL

By

R. Philip Hammond
Harold M. Busey
Kenneth R. Chapman
Franklin P. Durham
John D. Rogers
W. R. Wykoff

Contract W-7405-ENG. 36 with the U. S. Atomic Energy Commission

DISCLAIMER

ABSTRACT

A nitrogen-cooled graphite-moderated nuclear reactor experiment is proposed to drive a closed-cycle gas turbine power plant at 1300°F. The annular core of the reactor can be rotated inside the reflector to permit fuel loading and discharge while operating at full power. Small cylindrical fuel elements of graphite are solution-impregnated with partially enriched uranium. The fuel is recycled by incineration of the elements, chemical separation of the fission products, and impregnation of fresh graphite in a small batch process.

The unclad, uncoated fuel should permit high burn-up and simple fuel processing, but allows fission product diffusion into the gas stream. While methods are proposed for the removal of these from the gas, the long-term consequences on turbine operation are unknown. The compatibility of nitrogen gas with the fuel has been studied experimentally.

The radial movement of fuel gives a reactor with a constant power profile and no excess reactivity. The temperature is regulated by the fuel charging rate.

CONTENTS

	Page
Abstract	3
1. Introduction	7
2. Description	7
2.1 Reactor	8
Construction	8
Fuel Loading	8
2.2 Fuel Processing	10
2.3 Turbine Cycle	12
Description of Cycle	12
Control	14
2.4 Gas Clean-up System	15
2.5 Turbine Clean-out System	15
3. Discussion	15
3.1 Advantages	15
High Burn-up	16
Continuous Loading and Unloading	16
Radial Fuel Motion	16
Fission Product Recovery from Gas Stream	16
Cycle Efficiency Factors	17
a. Turbine Inlet Temperature	17
b. System Pressure Drop	17
c. Regenerator Effectiveness	17
d. Comparison with Helium Cycle	18
Availability of Turbine Equipment	18

Page

3.2 Limitations and Disadvantages 19
Use of Unclad Fuel Elements 19
Temperature Limitation 20
Scale-up 20
Containment 20
Economics 20

4. Conclusions 21

5. Recommendations 21

References 22

Appendix 25

ILLUSTRATIONS

Figure 2.1 Schematic Diagram of the Reactor. 9

Figure 2.2 Schematic Diagram of Reprocessing Unit. 11

Figure 2.3 Schematic Diagram of Closed-cycle Gas Turbine Power Plant 13

TABLE

Table I Comparison of Pessimistic Nitrogen Cycle with Optimistic Helium Cycle 18

1. INTRODUCTION

The concept of a gas-cooled, graphite-moderated power reactor has been attractive for some time.[1-19] Closed-cycle gas turbines for power plant use have been improved until they can accept 1300°F gas, at which temperature they are approximately competitive with steam turbines of comparable size. The properties of uranium-impregnated graphite have recently been thoroughly investigated at Los Alamos Scientific Laboratory, and facilities have been developed for manufacturing such materials, testing their reaction with gases, and recovering the uranium by incineration and extraction. It now appears that essentially all material-compatibility questions for this type of reactor have been resolved, and a simple fuel recovery and refabrication scheme has been demonstrated. The indicated compatibility of graphite with nitrogen coolant allows the use of presently existing air turbine-compressor equipment, instead of waiting for the development of helium turbomachinery.

2. DESCRIPTION

The plant described is rated at 20 Mw electrical output, although it would be equally attractive in almost any conceivable size. At the 20 Mw level the economic potentialities of the concept are reasonably well developed, yet the equipment required is small. For large stations partially enriched fuel would be preferred, but the example is based on high enrichment.

2.1 Reactor

Construction

The principal novelty of the reactor lies in the turret loading feature which requires that the core rotate past stationary loading ports. As shown in Fig. 2.1, the core is a graphite cylinder, 9 ft in diameter by 6-1/2 ft high. A 24 in. diameter central hole in the core forms a coolant inlet passage from which 1440 fuel channels lead radially to the outlet plenum between the core and the stationary reflector. The 3/4 in. square fuel channels are arranged in 40 levels or layers with 36 channels in each level. The tubular graphite fuel elements are about 3/4 in. o.d., 1/2 in. i.d., and 6 in. long. There are seven elements in each channel, or 10,080 in all. Each fuel element contains about 2 g of 90% enriched uranium. The core and the bottom portion of the reflector are mounted on an iron base which can be slowly revolved.

The core is surrounded on top and sides by 18 in. of stationary graphite reflector, and this is enclosed in about 12 in. of insulating refractory, then in steel or cast iron thermal shields, and finally in a steel pressure vessel to contain the 500 psi nitrogen coolant. A biological shield surrounds the vessel.

Fuel Loading

Fuel elements are loaded at the periphery of the core and moved toward the center as burn-up proceeds. A small opening in the reflector and vessel at each level allows a new fuel element to be pushed into the outermost core position in the fuel channel. A latch prevents the fuel elements from moving outward with the gas flow. (The 10 psi pressure drop across the core results in a thrust of 2.4 lb, or less, on the latch.) Rotation of the core brings each of the 36 channels in turn to the loading position.

The fuel loading mechanism could take any of several forms. Shown in Fig. 2.1 is a version consisting of a nitrogen-powered ram, which can be positioned and locked pneumatically at any of the 40 loading elevations.

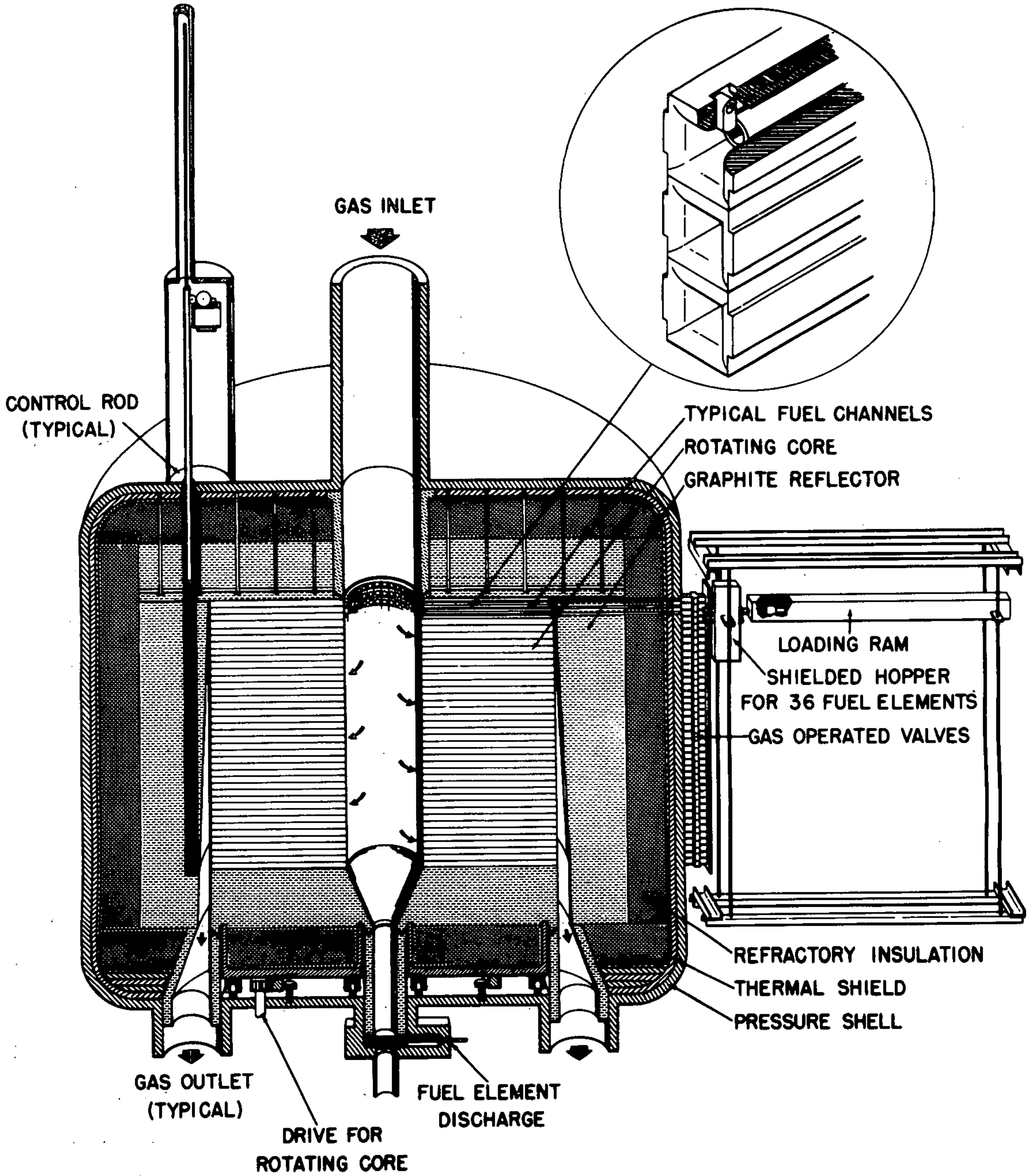


Figure 2.1 Schematic Diagram of the Reactor

A gas-tight shielded hopper carrying 36 fuel elements is attached by a crane to the ram, and thus fuel can be advanced one step in an entire level of the reactor with one opening of the port. If the burn-up obtained were 10%, an average power level of 60 Mw would require reloading about 350 elements per day, or one hopper-full every 2.5 hr. At this power and burn-up, the average service time of a fuel slug is one month.

Fuel discharge is accomplished by the loading ram. As a new fuel element is inserted it pushes the others in the channel ahead, and the inner one, most highly burned up, falls down the central plenum into a graphite or carbon-lined hopper, which is opened in synchronization with the advance of the ram. The hopper opens into a second compartment containing a screw conveyor, which crushes the fuel elements and discharges them into the incinerator and fuel processing system.

The graphite fuel channels may be subject to wear and need replacement at long intervals. The construction indicated in Fig. 2.1 is one possibility for renewal of these channels by the same general method used for the fuel elements--the new section of channel is pushed into place and displaces an inner section, which is disposed of by crushing and incineration in the fuel plant.

2.2 Fuel Processing

The crushed fuel elements discharged from the conveyor can be incinerated either by continuous or batch-type equipment. However, a full day's throughput consists of only 700 g of uranium at 10% burn-up, and less at higher burn-ups, so a batch process seems adequate for such a small plant. The process has been studied recently by Group CMB-8 at Los Alamos Scientific Laboratory and at Knolls Laboratory. The incineration step leaves uranium and fission products in the form of oxides which are readily soluble in nitric acid and form a suitable feed for solvent extraction or precipitation operations. The equipment is shown schematically in Fig. 2.2 for a mixer-settler process. The mixer-settler equipment could be any of several remotely-operable types.

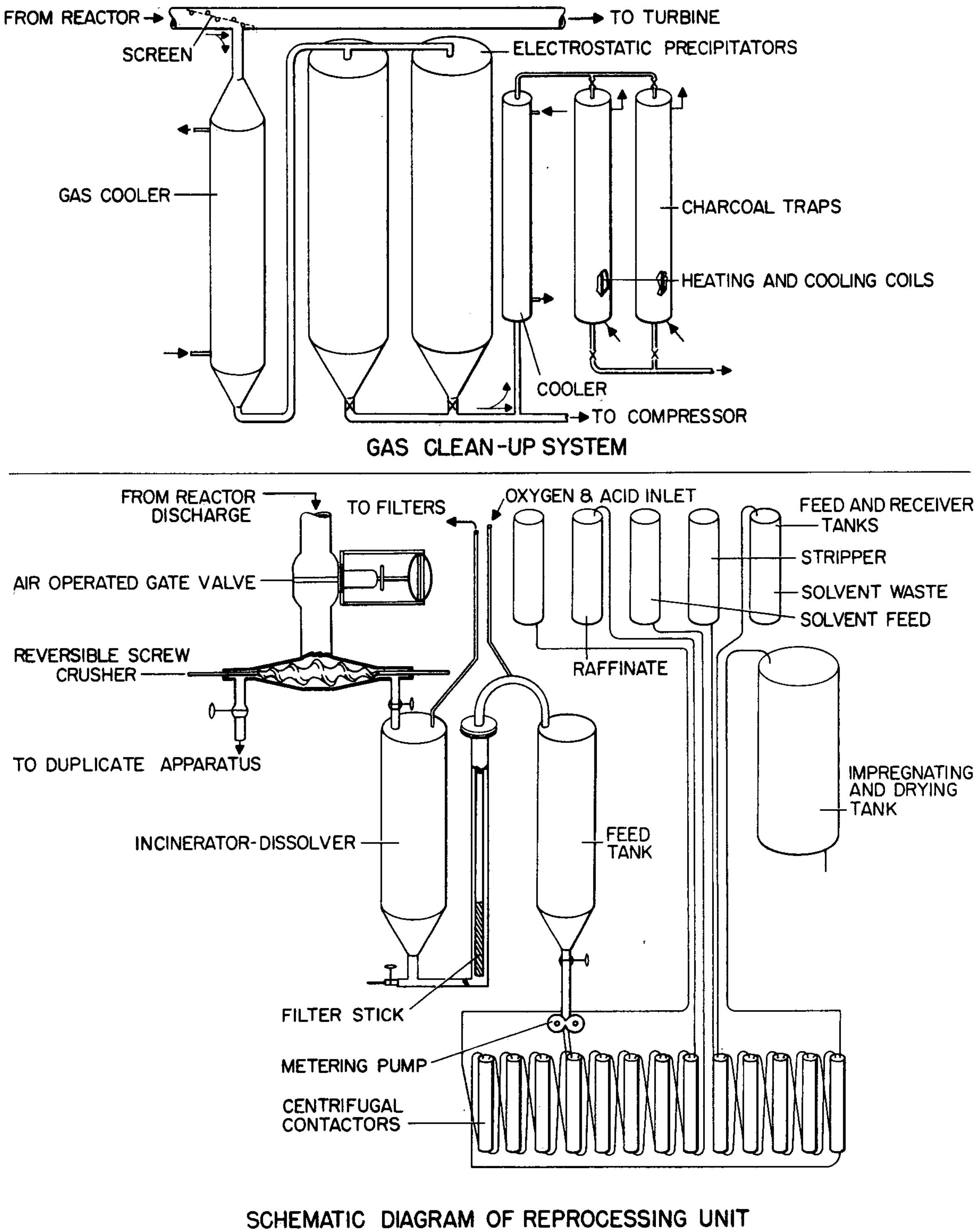


Figure 2.2 Schematic Diagram of Reprocessing Unit

After decontamination by a factor of only 10 to 20, the fuel solution would be ready for reloading by impregnation of new graphite slugs. The conditions for remote solution-impregnation of graphite have been worked out in recent experiments at Los Alamos (see Appendix) and elsewhere.

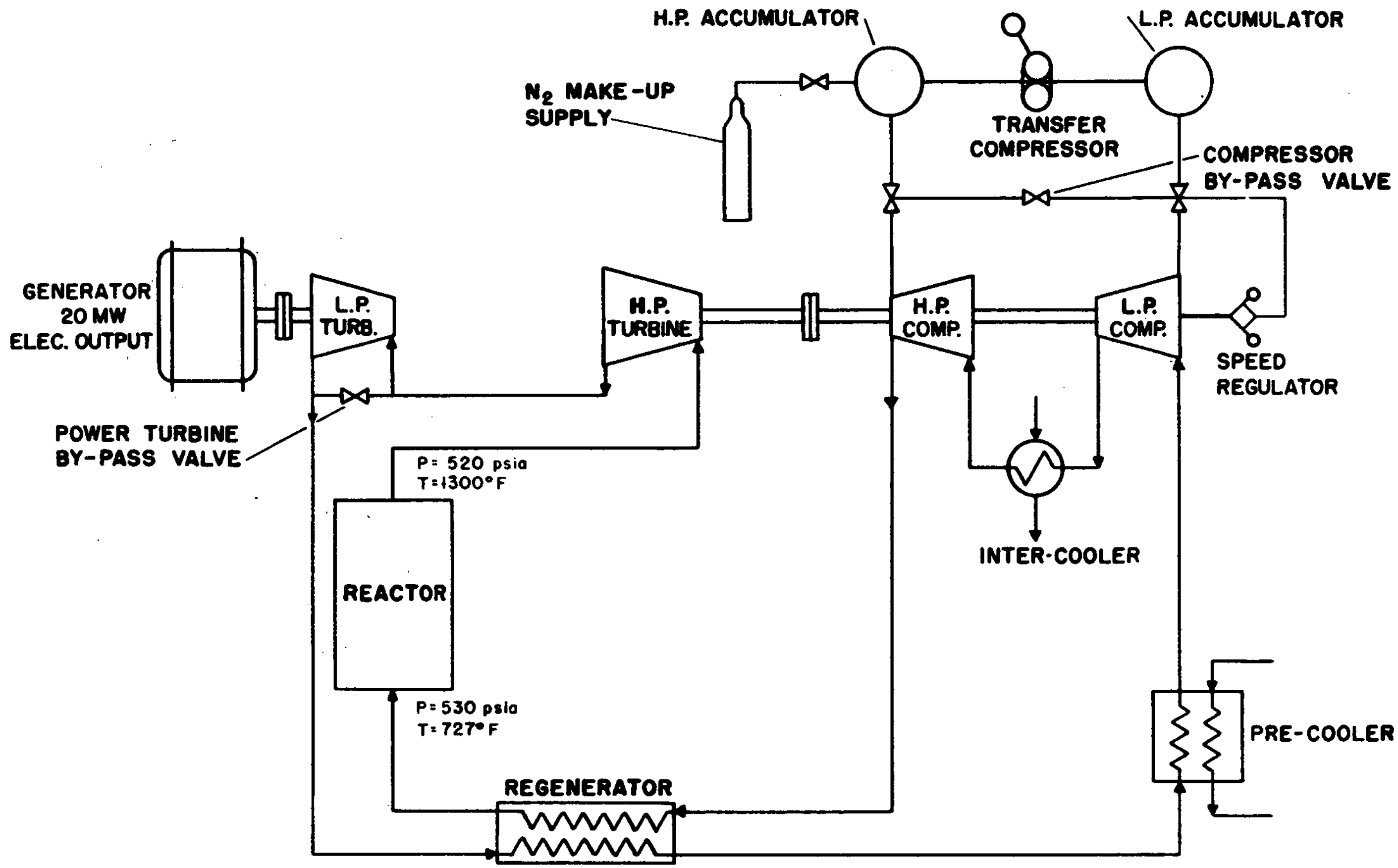
The cooling time would depend on experience with the process. If once-a-day processing were done, a cooling time of one day would be achieved with an average plant condition of about 20 kg of fuel in the reactor, 3/4 kg in fuel elements ready for loading, 3/4 kg in cooling, and 3/4 kg in process. This small inventory gives a negligible inventory charge to the plant, so that a longer cooling period or a generous reserve of fuel elements could be afforded.

2.3 Turbine Cycle

The prime mover chosen for purposes of this description is an Escher-Wyss plant of 20 Mw electrical capacity.[20] The turbine equipment consists of a two-stage compressor with intercooler driven by a high-pressure turbine and, on a separate shaft, a low-pressure turbine driving the useful generator load. A schematic diagram of the cycle is given in Fig. 2.3.

Description of Cycle

Nitrogen at 90°F and 490 psi enters the low-pressure compressor and undergoes half of the required pressure rise. It is then cooled to 90°F and enters the high-pressure compressor for final compression to 530 psi. In the regenerator, waste heat is transferred to the compressed gas and the temperature raised to 727°F. The gas then passes through the reactor and is heated to 1300°F. The heated gas proceeds to the high-pressure turbine, where enough energy is extracted to drive both stages of the compressor. The low-pressure turbine next converts the remaining available energy to useful output. The gas discharged from the turbine goes through the regenerator, where it heats the gas entering the reactor. Finally, the gas is cooled to its initial state in the precooler.



ELECTRICAL OUTPUT — 20 MW
REACTOR OUTPUT — 66 MW
N_2 FLOW RATE — 1,480,000 LBS/HR
CYCLE EFFICIENCY — 30.3%

Figure 2.3 Schematic Diagram of Closed-cycle Gas Turbine Power Plant

Control

Load changes are accommodated in two ways. Sustained changes in output are effected by varying the pressure level of the system. With this method of control, efficiency is substantially constant over a wide range of loads since the temperature differences and gas velocities within the system remain constant. The load changes are made by bleeding gas out of the system into the low-pressure accumulator or by adding gas to the system from the high-pressure accumulator.

An extremely rapid change in load can be effected by bypassing the power turbine. This method of regulation is particularly effective in guarding against overspeed, or accommodating a sudden load dump, as in maneuvering a ship propulsion plant.

The reactor has a negative temperature coefficient of reactivity and is stable to neutron transients. Control of turbine output by pressure variation, however, affects the operating temperature because of the poisoning effect of the nitrogen. The reactor temperature increases about 150°F as the power level is reduced to zero from full power. If it is desirable to maintain constant turbine-inlet temperature over the entire power range, adjustable reactivity control must be provided.

Safety shutdown or rapid control is provided by means of boron-loaded graphite rods operating in the reflector. As described below, xenon diffusing into the gas stream from the fuel elements is removed by charcoal traps, and these offer an intriguing alternative control possibility. While one trap is in operation, a duplicate would be undergoing regeneration. Storage of the xenon from this trap would provide a supply of poison which could be released into the gas stream at any desired rate for reactor control, and removed again by the operating trap.

The safety shutdown rods would need sufficient negative reactivity to enable the reactor to be brought down to room temperature (10 to 20% ΔK). The escape of all the nitrogen coolant would add another 1% ΔK, or about 200°F, which must also be added to the safety-rod requirement.

2.4 Gas Clean-up System

The experiments done with the Los Alamos Supo Water Boiler off-gas indicate that about 30% of the gross residual gamma activity will be volatile and readily escape into the gas stream.[21] In addition, solid fission products, graphite, and uranium will be present in the form of dust of unknown particle size. Coarse in-line screens are shown in Fig. 2.2 which serve only to protect the turbine against damage. The fine dust is collected in the bypass stream shown wherein the temperature of the gas is reduced somewhat and then passed through electrostatic precipitators or other collector. The pressure drop suffered is restored by a blower, if necessary, as the bypass stream is returned to the main system. An even smaller stream is diverted from the precipitator effluent to the charcoal traps. These are designed to remove xenon, krypton, and iodine almost completely from the gas stream and will handle the entire gas content of the system a few times an hour. The effluent is returned to the system by a compressor.

2.5 Turbine Clean-out System

Whatever the efficiency of the gas clean-up system, some particulate matter will be carried through the entire system. In view of recent successful experience with gas turbine plants burning powdered coal, this does not appear to be a serious problem. However, the effect of these deposits on the performance of the plant, and means of removing them, would certainly be an important objective of the experiment. The experimental plant should be designed so that the entire turbine-exchanger portion could be filled or sprayed with detergent or mild acid solution, with provision for disposing of the washings.

3. DISCUSSION

3.1 Advantages

The direct gas turbine cycle powered by an impregnated graphite reactor provides a number of attractive advantages as follows:

High Burn-up

The life of an unclad fuel element at the low loadings (<0.1 g/cc) used is fairly certain to be long, although this is unproved. The reactor operating economics and processing costs would be attractive at 5% burn-up and increasingly so as this is increased. Ten to twenty per cent burn-up would be a reasonable expectation based on the present erosion and corrosion data.[22]

Continuous Loading and Unloading

Ability to add and discharge fuel while at power adds greatly to the safety and convenience of operation. The safety feature derives from the fact that a continuously loaded reactor requires no excess reactivity for burn-out and poisoning compensation and no devices for controlling the excess. The plant factor and availability are increased as much as 5 to 10% by eliminating fueling shutdowns and the life of equipment is increased because of fewer start-up stress cycles.

Radial Fuel Motion

A feature of advantage to heat-transfer design and to reactor control is a steady-state temperature and power profile. Variations in power and temperature at different portions of the fuel at different times in the burn-up cycle are difficult to design for and require large control elements in stationary fuel concepts. In the concept shown, the fuel is loaded at the periphery of the reactor and moves slowly toward the position of highest flux in the center, where it is discharged. This radial fuel motion not only helps to reduce the central flux peak, but keeps all parts of the reactor at a steady state of temperature and power distribution.

Fission Product Recovery from Gas Stream

There is no question but that several gaseous fission products can be efficiently removed from the circulating gas stream of the plant. Iodine, xenon, and krypton have been shown to be readily handled with a bypass charcoal absorption system. The experiments mentioned with off-gas from the Los Alamos Water Boiler have produced the basic knowledge required, and other experimenters have also confirmed these results elsewhere.

The extent to which other fission products will be volatile and collectible either as gases or particulates must be determined by trial and would represent an important objective of the reactor experiment.

Cycle Efficiency Factors

a. Turbine Inlet Temperature. The usable range for this variable is 1200 to 1500°F. Most studies of reactor-heated gas turbine cycles select 1400°F as their design point. However, none of the closed-cycle machines in commercial use today operate above 1270°F. For this reason, 1300°F has been selected for this study as being a readily achievable figure. When the manufacturers of turbomachinery show that they can handle 1400°F gas, certainly the impregnated graphite reactor can produce it.

b. System Pressure Drop. The effect of over-all system pressure drop on the cycle efficiency and nitrogen flow rate is quite large. Design studies frequently allow 6 or 7% of the system pressure for the entire system pressure drop in order to show a high cycle efficiency. In this study 8% has been allowed with one quarter of it in the reactor. This is quite in line with the pressure drop realized in the air-heaters in commercial closed-cycle gas turbine plants, and certainly should be achievable in the reactor plant.

c. Regenerator Effectiveness. The effect of regenerator effectiveness on cycle efficiency is also quite marked, although it does not affect flow rate. Very high effectiveness can be achieved, 95% and higher; however, this requires large amounts of surface, is expensive, and contributes to a higher system pressure drop. Authorities in the field seem to feel that 90 to 95% can be readily achieved in practice. For this study, 80% has been selected as certainly being achievable.

An attempt has been made to select all variables on the conservative side. Even so, the net result is a very attractive cycle efficiency of 30.3%. A detailed description of this and other applicable cycles may be found in references 20, 23, and 24.

d. Comparison with Helium Cycle. The operating conditions and cycle parameters chosen for this study were overly pessimistic. This was, of course, done intentionally in order that this project, if undertaken immediately, might undergo the usual "bad breaks" and still yield the predicted performance without undue delays in obtaining equipment.

In Table I, the cycle of this study is compared to a helium cycle with a more favorable selection of operating conditions. The assumptions chosen for the helium cycle are not at all unrealistic, but are generally considered to be achievable with present technology.

TABLE I

Comparison of Pessimistic Nitrogen Cycle with Optimistic Helium Cycle

	Nitrogen	Helium
Net electrical output	20 Mw	20 Mw
Turbine inlet temperature	1300°F	1400°F
Over-all system ΔP	8%	7%
Regenerator effectiveness	80%	93%
Reactor heat output	66 Mw	49.5 Mw
Net cycle efficiency	30.3%	40.3%

Availability of Turbine Equipment

Studies[25] indicate that the power cycle is relatively unaffected by the nature of the working fluid. Helium, nitrogen, and carbon dioxide have all been shown to be usable with only minor variations in cycle efficiency, assuming, of course, that the turbomachinery and heat exchangers are properly designed for the working fluid selected. The many papers on this subject usually select helium for the working fluid because of its low neutron cross section and inert nature. These characteristics are postulated to ease the reactor design problems.

Nitrogen has been selected as the working fluid for the power plant proposed herein for exactly the opposite reason--that it eases the turbomachinery design problems. Air-cycle machinery operating today is suitable for use with nitrogen and could be adapted to the Turret reactor with a minimum of delay and developmental expense. The use of helium would reduce the reactor control problem, would result in smaller heat-transfer equipment, and would produce a higher net cycle efficiency. It is expected that Turret reactors would adopt the helium cycle as soon as practical.

Corrosion-erosion of bare uranium-impregnated graphite by flowing nitrogen has been studied experimentally at Los Alamos.[22] The tests were run with electrically heated graphite tubes at temperatures and gas flow velocities corresponding to those proposed for Turret. The conclusion was drawn that Turret fuel elements would not be appreciably attacked during at least a one-month exposure, unless some unknown radiation effect occurred.

If at some later date helium turbomachinery should prove to be available and reliable, this reactor concept can readily be adapted to a helium cycle. The important change would be that the reactor flow area, and therefore the over-all reactor size, would be somewhat reduced.

Neutron activation, normally considered to be a problem when using nitrogen in closed-cycle reactor power plants, is not important in this scheme. The assumption must be made that fission products diffuse into the working fluid and, therefore, the turbomachinery must be operated and maintained remotely. Neutron activation of nitrogen is only a minor activity compared to the fission product activity which will be present.

3.2 Limitations and Disadvantages

Use of Unclad Fuel Elements

The bare fuel elements proposed are at once an advantage and a disadvantage--they make fuel recovery and reimpregnation extremely cheap and simple, but they allow rapid diffusion of fission products into the gas stream. The gas clean-up equipment proposed is fairly certain to be effective for xenon and krypton, and probably for iodine, but just where the particulate matter will lodge in the system is uncertain. Both the amounts and particle size are unknown, and the effect on turbine efficiency, maintenance, etc., undetermined. The disadvantage of having to shield and remotely operate the entire system is severe. Clad fuel elements, on the other hand, would severely limit burn-up and make fuel recovery expensive. The operation and maintenance of a contaminated turbine is a complication which cannot be realistically evaluated without experience.

Temperature Limitation

At present the graphite-nitrogen system seems to be stable for any temperature conditions for which turbines are now available. As improved turbine equipment allows higher operating temperature, a fuel temperature might be reached (near 2500°F) where the nitrogen-carbon reaction would cause excessive fuel element erosion. If helium turbines become available by that time, the temperature limit will again be raised.

Scale-up

At the present time, closed-cycle gas turbine equipment has not been built in sizes over 12.5 Mw electrical output. Manufacturers of this type of equipment contend, however, that there are no particular limitations in going to units of much higher capacity.

Containment

A Turret reactor would require a secondary containment shell of some kind since the entire system contains radioactive gas at 500 psi. This shell might present a difficult design problem since certain operations, such as fuel charging, would have to go on inside it.

Economics

Although studies of the cost of such a reactor power plant as is proposed appear very favorable, the actual fact is that very little knowledge relative to this system will be available unless a test is made, since the necessary complexity of handling equipment is impossible to estimate in advance.

4. CONCLUSIONS

The Turret reactor operating on a nitrogen cycle offers promise of a power plant which can be built using technology and materials now available. The 66 Mw heat level, 20 Mw net electrical output version described herein is a size fully useful for economic application.

The adaptation of the reactor to a helium cycle offers promise of improved economy as technology is developed.

5. RECOMMENDATIONS

It is recommended that a small-scale complete reactor experiment be initiated immediately.

Before launching into the design of a 20 Mw, or larger, plant, some preliminary information should be obtained on the following items:

a. Reliability of the fuel charging mechanism.

b. Long-term stability of the fuel under reactor conditions.

c. Permissible burn-up.

d. Activity level throughout the entire system.

e. Effectiveness of technique for gas clean-up system.

f. Maintenance difficulties with the radioactive turbomachinery.

A 1 Mw Turret reactor using a modified open-cycle gas turbine with integral compressor could be obtained with minimum delay. The system would give no electrical output, but would provide the information required to design a complete 20 Mw electrical plant.

REFERENCES

1. F. B. Daniels, J. S. Barker, and A. F. Erwin, "Development of Heat Exchangers, Pumps and Associated Equipment for a Heat Transfer System: Interim Progress Report No. 4; March 1, 1950 to May 1, 1950," Report NP-1522, May 1, 1950 (Classified).
2. F. B. Daniels, J. S. Barker, and A. F. Erwin, "Development of Heat Exchangers, Pumps and Associated Equipment for a Heat Transfer System: Interim Progress Report No. 5; May 1, 1950 to August 1, 1950," Report NP-1732, August 1, 1950 (Classified).
3. F. B. Daniels, "Factors Involved in the Production of Atomic Power," Report MDDC-893, April 1, 1957.
4. F. B. Daniels, "High Temperature Pebble Pile," Chicago University Metallurgical Laboratory Report CF-2860 (5) (Classified) June 1945.
5. F. B. Daniels, "A Homogeneous High Temperature Power Pile Utilizing Graphite Which Has Been Impregnated with Uranium," Clinton Laboratories Report CL-FD-15, August 1946.
6. F. B. Daniels, "Importance of Chemical Processing in Determining the Design of a Power Pile and the Choice of Materials," Clinton Laboratories Report CL-FD-26 (Classified) December 1946.
7. F. B. Daniels, E. J. Murphy, G. T. Seaborg, N. E. Bradbury, and J. R. Dunning, "Proposed Research Program for 1946-47," Report AM-2706 and also listed as Report M-2781, 1947
8. F. B. Daniels, "Status of the Power Pile, March 20, 1947," Clinton Laboratories Report CL-FD-36 (Classified) March 1947.
9. F. B. Daniels, "Suggestion for an Experimental Power Reactor; An Impregnated Graphite, Nitrogen-Cooled Reactor and Gas Turbine, Using Materials and Equipment Available Now," Argonne National Laboratory Report AECD-4095, April 1950.
10. F. B. Daniels, "Suggestions for a High Temperature Pebble Pile," Chicago University Metallurgical Laboratory Report N-1668b, October 25, 1944.

11. S. Siegel, "A Study of the Performance of a Reactor for the High Temperature Power Plant," North American Aviation, Inc., Report NAA-SR-Memo-27, February 2, 1951 (Classified).

12. "Progress Report for the Month of August 1951," North American Aviation, Inc., Report NAA-SR-Memo-107, October 16, 1951 (Classified).

13. "Progress Report for the Month of September 1951," North American Aviation, Inc., Report NAA-SR-Memo-116, November 8, 1951 (Classified).

14. R. W. Dayton, E. M. Simons, C. E. Sealander, F. A. Fend, F. J. Jankowski, and J. H. Stang, "A High-Power-Density Gas-Cooled Core Reactor Configuration," Battelle Memorial Institute Report BMI-T-27, May 15, 1950 (Classified).

15. H. W. Ibser, "Low Density UO_2 Pile," Chicago University Metallurgical Laboratory Report CP-445, February 24, 1943.

16. H. E. Stevens, Jr., "Critical Mass and Critical Size of Thermal Gas-Cooled Piles," Clinton Laboratories Report MonN-389, September 25, 1947.

17. R. H. Armstrong, A. Lovoff, and L. J. Templin, "A Design Study of Two Helium-Cooled Reactors," Report TID-2508, Nuclear Science and Technology, 1A, Issue 3, December 1955, pp. 445-461 (Classified).

18. B. L. Goodlet and R. V. Moore, " Natural Uranium Power Reactor (Project "PIPPA") 1951-1952 Design Study," Great Britain Atomic Energy Research Establishment Report AERE-R/R-1955, June 1956 (Classified).

19. F. B. Daniels, "Small Gas-Cycle Reactor Offers Economic Promise," Nucleonics, 14 (3), 34-41, March 1956.

20. "Design Study--60 Mw Closed Cycle Gas Turbine Nuclear Power Plant," American Turbine Corporation Document ATC-54-12, December 1954.

21. H. M. Busey, "Composition and Decontamination of Radioactive Gas Mixtures," Nucleonics, 12 (5), 9-13, May 1954.

22. K. R. Chapman, Internal Report, "Corrosion of Graphite by Nitrogen," May 1957, Los Alamos Scientific Laboratory.

23. E. A. Sheehan and A. O. White, "Submarine Advanced Reactor Gas Turbine Cycle Study," General Electric Company Report R53GL186, September 29, 1953.

24. F. G. Hamitt and H. A. Ohlgren, "Nuclear Powered Gas Turbines for Lightweight Power Plants," University of Michigan Engineering College Industry Program Report IP-199, January 1957.

25. S. T. Robinson, "Influence of Working Fluid Characteristics on the Design of the Closed Cycle Gas Turbine," American Society of Mechanical Engineers, Paper 57-GTP-13, 1957.

APPENDIX

AQUEOUS IMPREGNATION OF GRAPHITE WITH URANIUM

In tests made to determine the quantity of uranium that could be added to graphite by simple evaporation of solutions within the graphite pores, the following method was used.

Graphite, heated to 100°C, was added to a concentrated, boiling, uranyl nitrate solution. The solution was at 120°C and 585 mm. Its freezing point was 60°C. The graphite cylinders were 13 mm in diameter and 73 mm long with a 7 mm hole along the axis. The volume of these samples averaged 8.0 ± 0.3 ml as determined by immersion in mercury (which did not enter the pores).

After boiling five minutes, the solution was allowed to cool slowly to 60°C. Next, the samples were removed from the uranyl nitrate solution, dipped in distilled water, and drained. After air-drying for 20 hours, they were placed in an air oven and heated at 66°C for another 16 hours. Finally, they were heated to 800°C for 20 minutes in a stream of helium. They were cooled rapidly in a vacuum. The weight gains are shown below.

Sample	Original Wt.,*g	Density, g/cc	Wt. after treatment, g	Gain as U_3O_8, g	Gain as U, g	Loading, g U/cc
A (blank)	12.9696	1.62	12.9671	-0.0025	----	----
B	13.1453	1.64	15.2874	2.1421	1.81	0.226
C	13.1816	1.65	15.2187	2.0371	1.72	0.216
D	12.8759	1.61	15.0765	2.2006	1.86	0.233
	Av.	1.63			Av.	0.225

*Weighed after the samples were heated to 800°C in a vacuum before impregnating.

Upon sectioning and x-ray examination it was found that the uranium was evenly distributed in these specimens. In other tests it was found that the distribution of the uranium could be controlled to some extent by leaching after the impregnation and before the samples were dried. It was also found that the quantity of uranium could be increased over the 0.225 g U/cc shown above by multiple loadings.

With dilute solutions light loadings can be reached in one soaking. Values of 0.026, 0.025, and 0.078 and 0.080 g/cc were obtained with dilute solutions on graphite samples of different densities. The loading required for the highly enriched Turret is 0.08 g/cc.

Cylinders of up to 1.5 in. in diameter have been loaded with up to 12 weight per cent uranium oxide. The distribution of uranium oxide was found to vary no more than ±0.5 weight per cent.