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**Gas Core Reactor Power Plants
Designed for Low Proliferation Potential**

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CONTENTS

ABSTRACT	1
I. INTRODUCTION	1
II. CONCLUSIONS	2
III. TECHNOLOGY STATUS	2
IV. RECOMMENDATIONS	2
V. MIXED FLOW REACTOR POWER PLANTS	3
A. 200-MWth Mixed Flow Reactor	3
1. Vortex Flow	3
2. Fuel Region Characteristics	4
3. Reactor Configuration	6
4. Major Power Plant Subsystems	7
5. Reactor Neutronics	7
6. Salt Blanket Processing	8
7. Fission Products	10
a. Fission Product Cleanup	11
b. UF_6 Separation and Purification	11
c. Helium Purification	12
d. Uranium Inventory	12
e. Alternative Processing Systems	13
8. Power Extraction	13
a. Primary Flow Loop	13
b. Heat Exchangers	14
(1) High-Temperature Heat Exchangers	14
(2) Low-Temperature Heat Exchanger	15
(3) Regenerative Heat Exchanger	16
c. Secondary Helium Loop	17
d. Helium Coolant Loop	18
e. Cycle Performance	19
9. Moderator	19
10. Inventory	20
B. 2 500-MWth Mixed Flow Reactor Power Plant	20
1. Vortex Flow	20
2. Fuel Region Characteristics	20
3. Reactor Configuration	21
4. Major Power Plant Subsystems	21
5. Reactor Neutronics	21
6. Salt Blanket Processing	21
7. Fission Products	21
8. Power Extraction	21
9. Moderator	22
10. Inventory	22
C. Conclusions About Mixed Flow Reactors	22
VI. PLASMA CORE REACTOR POWER PLANTS	22
A. Closed Cycle Helium Gas-Turbine Plasma Reactor Power Plant	23

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CONTENTS (cont)

1.	Vortex Confinement - - - - -	23
2.	Fuel Region Characteristics - - - - -	24
3.	Cavity Structure - - - - -	24
4.	Radiant Energy Transfer - - - - -	25
5.	Reactor Configuration - - - - -	26
6.	Major Power Plant Subsystems - - - - -	27
7.	Reactor Neutronics - - - - -	27
8.	Salt Blanket Processing - - - - -	27
9.	Fission Products - - - - -	28
10.	Power Extraction - - - - -	28
11.	Moderator - - - - -	29
12.	Inventory - - - - -	30
13.	Conclusions About the Closed Cycle Gas-Turbine Plasma Reactor - - - - -	30
B.	Transmission Cell Plasma Reactor Power Plant - - -	30
1.	Vortex Confinement - - - - -	30
2.	Fuel Region Characteristics - - - - -	30
3.	Cavity Structure - - - - -	31
4.	Radiant Energy Transfer - - - - -	31
5.	Reactor Configuration - - - - -	32
6.	Major Power Plant Subsystems - - - - -	32
7.	Reactor Neutronics - - - - -	32
8.	Salt Blanket Processing - - - - -	32
9.	Fission Products - - - - -	32
10.	Power Extraction - - - - -	32
11.	Moderator - - - - -	33
12.	Inventory - - - - -	33
13.	Conclusions About the Transmission Cell Plasma Reactor - - - - -	33
VII.	SUMMARY OF PHYSICAL CHARACTERISTICS - - - - -	33
VIII.	FAILURE CONSIDERATIONS - - - - -	33
IX.	PLANT LAYOUT - - - - -	35
	ACKNOWLEDGMENTS - - - - -	36
	REFERENCES - - - - -	36

FIGURES

1.	Flow patterns in mixed flow reactor. - - - - -	3
2.	Gas temperature (top) and density in mixed flow reactor. - - - - -	4
3.	Tangential velocity and angular momentum in mixed flow reactor. - - - - -	4
4.	UF ₆ (top) and helium mass flow rates in mixed flow reactor. - - - - -	5
5.	Mixed flow reactor fuel mixture outlet temperature. - - -	5

FIGURES (cont)

6.	Mixed flow reactor cross section. - - - - -	6
7.	Conceptual reactor configuration. - - - - -	6
8.	Major power plant subsystems of mixed flow reactor. - -	7
9.	Mixed flow reactor breeding ratio. - - - - -	8
10.	Mixed flow reactor critical mass. - - - - -	8
11.	Salt blanket processing. - - - - -	9
12.	²³³ U time history in 200-MWth mixed flow reactor breeder blanket. - - - - -	9
13.	Fission product removal. - - - - -	11
14.	Mixed flow reactor power extraction loop. - - - - -	13
15.	²³³ U time history in breeder blanket of 2 500-MWth mixed flow reactor. - - - - -	21
16.	Flow pattern in plasma reactors. - - - - -	23
17.	Cavity structure of closed cycle gas-turbine plasma reactor. - - - - -	24
18.	Spectral transmission of quartz. - - - - -	25
19.	Radiated power. - - - - -	26
20.	Cross section of closed cycle gas-turbine plasma reactor. - - - - -	26
21.	TWOTRAN geometry of closed cycle gas-turbine plasma reactor. - - - - -	27
22.	Breeding ratio and critical mass of closed cycle gas-turbine plasma reactor. - - - - -	27
23.	²³³ U time history in breeder blankets of both plasma reactors. - - - - -	28
24.	Power extraction loop of closed cycle gas-turbine plasma reactor. - - - - -	29
25.	Transmission cell of plasma reactor. - - - - -	31
26.	Cavity structure of transmission cell plasma reactor. - - - - -	31
27.	Breeding ratio and critical mass of transmission cell plasma reactor. - - - - -	32
28.	Plant layout. - - - - -	35

TABLES

I.	Estimated Composition of Power Extraction Fluid - - - -	10
II	High-Temperature Heat Exchanger Specifications - - - -	15
III.	Low-Temperature Heat Exchanger Specifications - - - -	16
IV.	Regenerative Heat Exchanger Specifications - - - -	17
V.	Uranium Inventory of 200-MWth Reactor - - - -	20
VI.	Power Loop Characteristics of Mixed Flow Reactors - - -	22
VII.	Fissile Inventory in 2 500-MWth Mixed Flow Reactor - - -	22
VIII.	Fissile Inventory in Closed Cycle Helium Gas- Turbine Plasma Reactor - - - - -	30
IX.	Fissile Inventory of Plasma Reactor in Transmission Cell Configuration - - - - -	33
X.	Physical Characteristics of Gas Core Reactors - - - -	34

**GAS CORE REACTOR POWER PLANTS
DESIGNED FOR LOW PROLIFERATION POTENTIAL**

Compiled by
Luther L. Lowry

ABSTRACT

This study was made to see whether gas core nuclear power plants could provide adequate power while maintaining a low inventory and low divertability of fissile material. Four concepts were examined. Two used a mixture of UF_6 and helium in the reactor cavities, and two used a uranium-argon plasma, held away from the walls by vortex buffer confinement. Power levels varied from 200 to 2 500 MWth. Power plant subsystems were sized to determine their fissile material inventories. All reactors ran, with a breeding ratio of unity, on ^{233}U born from thorium. Fission product removal was continuous. Newly born ^{233}U was removed continuously from the breeding blanket and returned to the reactor cavities. The 2 500-MWth power plant contained a total of 191 kg of ^{233}U . Less than 4 kg could be diverted before the reactor shut down. The plasma reactor power plants had smaller inventories. In general, inventories were about a factor of 10 less than those in current U.S. power reactors.

I. INTRODUCTION

Los Alamos Scientific Laboratory (LASL) was asked by the International Security Affairs office of the U.S. Energy Research and Development Administration (ERDA) to examine the features of a gas core reactor which would minimize concern about illegal diversion of fissile material. The principal objectives were:

- Low fissile material inventory
- Low fissile material divertability
- Minimal fissile material transportation

It was further suggested that relatively low power output would be acceptable if the

power plants were intended for use in developing countries, because their cities may have a relatively small number of dwellings and multiple power plants might be preferred because of the lack of integrated power nets. Whenever possible, design decisions were made to enhance meeting these objectives.

LASL enlisted the aid of United Technologies Research Center (UTRC) because of their extensive knowledge of gas core reactors. They have performed theoretical and experimental work on gas core reactor propulsion systems continuously since 1958 under Corporate, United States Air Force and National Aeronautics and Space Administration sponsorship.

II. CONCLUSIONS

Although we have examined only the fundamental power plant functions and have not tried to find engineering solutions to the many practical problems, we believe the gas core reactor can meet the "low proliferation potential" objective remarkably well.

The principal ways in which unauthorized access to fissile material can be attained are by:

1. Hijacking.
2. Surreptitious diversion with or without user country cooperation.
3. Treaty abrogation and overt disassembly of the power plant.

Resistance to the first method is very high as the gas core reactor can sustain itself at a breeding ratio of one. The only occasion for fissile material transport throughout the entire 30-yr reactor life is delivery of the initial charge (191 kg for the 2 500-MWth mixed flow reactor down to 45+ kg for the transmission cell plasma reactor).

We estimate that less than 4 kg could be diverted from either of the mixed flow reactors by the second method, and less than that from the plasma reactors.

The third method would provide the largest amount, the entire inventory. However, the entire inventory is comparatively small, one-tenth or less of that in current U.S. power reactors.

III. TECHNOLOGY STATUS

Experimental and theoretical methods for studying nuclear criticality, neutron use, and reactor nuclear performance, dynamics, and control are available.

Fluid mechanical vortex confinement of UF_6 at high enough densities to sustain nuclear criticality has been demonstrated experimentally.

Techniques for injecting UF_6 into confined vortex flows are being developed. Equipment is being designed and built for reactor experiments to refine fuel injection and buffer gas flow control so that UF_6 deposition on cavity surfaces will be limited to levels that do not restrict long-term operation.

Experiments are in progress to define cycles for on-site continuous fuel reprocessing. Although more information on uranium compound chemistry at high temperature and pressures is needed before operation of a large-scale processing system, the results are encouraging.

IV. RECOMMENDATIONS

Because gas core reactors seem to offer power generating plants that physically deny the opportunity to divert fissile material, either overtly or covertly, to weapon production, and because they would use the available ^{235}U far more efficiently, a vigorous R&D program should be undertaken to fully establish their technical feasibility and provide engineering design data. This program should support, even to the extent of requiring the same time schedule, R&D of the plasma reactors -- even though it appears that the technical problems are more difficult than those in the mixed flow reactor. The plasma reactor payoffs are greater. The fissile inventory is lower, and temperatures are higher. Proliferation risk is even lower, and efficiencies are higher -- possibly to 65%. Further, the high-intensity thermal radiation from the plasma reactor may find application in MHD and in generation of hydrogen or other fuel gases.

The first step should be definition of this vigorous R&D program. It should include:

1. A broadened investigation to further define the characteristics of gas core reactor power plants designed for minimal proliferation risk.

2. Definition of the key technological programs necessary for development of power-producing reactor systems.
3. Definition of the fuel cycle characteristics of a gas core sustainer reactor.
4. Evaluation of the safety aspects of the gas core reactor system, including waste product removal and handling.
5. Definition of remote maintenance requirements.
6. Comparison of power extraction and energy conversion alternatives.
7. A plan and schedule for reactor and power plant development and demonstration.

Furthermore, the current experimental program should be accelerated and broadened to allow a sustained high-temperature reactor test with UF_6 temperatures of approximately 1 000 K as soon as possible. Parallel out-of-reactor experiments should be run to provide engineering design data on high-temperature UF_6 materials compatibility, heat exchanger technology, and fuel circulation and reprocessing system performance.

V. MIXED FLOW REACTOR POWER PLANTS

The heart of the gas core reactor is the gas cavity where the fuel and other gases flow in a stable pattern. In the mixed fuel reactor, this pattern is generated by injecting the UF_6 and helium mixture into the cavity through a full-length slot in its peripheral wall. Figure 1 illustrates the flow pattern. The flow enters tangentially to establish a vortex in the cavity. Most of the flow leaves the cavity through the perforated plate at its back. The rest spirals inward and leaves the cavity through a central hole at the bottom. This spiralling flow stays in the cavity longer than that removed through the peripheral wall and, therefore, is heated to a higher temperature. The flow is designed to keep the temperature of the gases in the cavity below that at which the UF_6 dissociates significantly (about 2 000 K). Adjusting the injection and exhaust flow rates

Fig. 1. Flow patterns in mixed flow reactor.

keeps the exhaust gas temperature compatible with the thermal requirements of the high-temperature heat exchanger (HTHX) that is part of the reactor energy extraction system.

A. 200-MWth Mixed Flow Reactor

1. Vortex Flow

Detailed fluid mechanics calculations were made for a mixed flow reactor cavity 1 m in diam by 4.35 m long. A two-dimensional axial symmetric theory of confined, viscous, jet-driven vortex flows which incorporates the effects of heat addition was adapted for the calculations. The basic fluid flow equations for the primary vortex flow are coupled to the end-wall boundary layer equations by the requirements for continuity of mass flow. The analysis method is described in Ref. 1. In confined vortex flows, primary mass flow enters and

leaves the end-wall boundary layer to satisfy the boundary layer momentum equations. Also, the angular momentum of the primary flow decreases whereas the secondary (end-wall boundary layer) flow increases. Interaction of the primary and secondary flows produces a complex three-dimensional flow in the vortex chamber. Results of these calculations are shown in Figs. 2 and 3. Figure 2 shows the radial distribution of temperature and total UF_6 and helium density. Note that the maximum cavity temperature is about 1575 K on the centerline ($r = 0$), whereas the wall temperature drops to about 500 K. Also, the density at the wall is about three times that at the center, a condition that provides a very stable flow pattern. The variations in tangential velocity and vortex angular momentum are shown in Fig. 3. The tangential velocity

Fig. 2. Gas temperature (top) and density in mixed flow reactor.

Fig. 3. Tangential velocity and angular momentum in mixed flow reactor.

risks steeply between the wall and the centerline and is greatest, 6.5 times its wall value, at a radius of about 7 cm. It drops to zero at the cavity centerline. This is a typical variation of a radially inward vortex flow pattern. The relative decrease in angular momentum is shown in Fig. 3b. Angular momentum is reduced by viscous losses and interaction of the primary flow with the end-wall boundary layer flow.

2. Fuel Region Characteristics

This reactor has a critical mass of only 45 kg. The heat capacity of this amount of UF_6 is small and, if UF_6 were the only gas flowing through the cavities, very high flow rates would be required to convectively transfer the quantity of power needed. However, the heat capacity of the

flowing gases can be increased by adding helium. This greatly reduces the total mass flow rate through the cavities. In this reactor, we added about 99 atm of helium to the 0.6 atm provided by the UF_6 to get the heat capacity needed to remove 200 MW at rather low mass flow rates. The total cavity pressure was then 100 atm and the mass flow rate was 68.4 kg/s.

To determine the UF_6 and helium flow rates required, we developed a simple calculational model using the following assumptions. Total cavity pressure is constant at 100 atm. The cavity contains a hot region with an average temperature, T_H , defined as the injected flow that leaves through the end-wall exhaust ports (through-flow) and an annular, cool region with an average temperature, T_C , defined as the injected flow that leaves through the perforated plate. The interface of these two regions is at 0.75 times the cavity outer radius. UF_6 and helium were assumed to behave like ideal gases. Exhaust gas temperatures of both regions are defined so that the average temperature of each region is the numerical average of the injection and exhaust gas temperatures. Fission energy deposition is proportional to the local uranium density, and UF_6 and helium weight flows are proportional to individual gas densities in each region.

Calculated results for a single cavity are given in Figs. 4 and 5. The power output per cavity is 25 MW. The fuel mixture is injected at 500 K. Figure 4 shows parametric curves for 1 000 and 1 500 K average hot region temperatures. They show, in both the hot and cold regions, the variation of UF_6 and helium mass flow rates with average cold region temperature. Given cold region temperatures of 600-800 K, the smallest total mass flow rate is at 800 K. Choosing the parametric average temperature of the hot region as 1 000 K, we read the following flow rates. UF_6 : hot region, 1.31 kg/s; cold region, 2.13 kg/s. Helium: hot region, 2.41 kg/s; cold region, 3.92

Fig. 4. UF_6 (top) and helium mass flow rates in mixed flow reactor.

kg/s. This gives 9.77 kg/s as the total mass flow rate out of the single cavity.

After the effluent flows leave the cavity, they are mixed and flow on through the HTHX outside the reactor pressure vessel. The temperature of this mixture strongly influences the efficiency of the helium gas turbine circuit which is the

Fig. 5. Mixed flow reactor fuel mixture outlet temperature.

high-temperature section of the power extraction cycle. The manner in which the effluent temperature varies at hot region average temperatures of 1 000 and 1 500 K as the cool region average temperature varies between 600 and 800 K is shown in Fig. 5. For an average cold region temperature of 800 K (peak of 1 100 K) and an average hot region temperature of 1 000 K (peak of 1 500 K), the effluent temperature is 1 225 K.

3. Reactor Configuration

Figure 6 shows a cross section of the final mixed flow reactor configuration. Each of the seven cylindrical cavities is 1 m in diam and 4.35 m long. They are lined with a nickel-aluminum plating about 75 μ m thick to prevent fluorine corrosion² and are embedded in a beryllium moderator. The beryllium web between the central cavity and the outer ones (web 1) is 6 cm thick, as are the webs between adjacent cavities in the outer ring. The web between the outer cavities and the salt blanket (web 2) is about 15 cm thick. With 15 cm more of beryllium at both top and bottom of the reactor, the total beryllium weighs about 24 metric tons.

The molten salt breeding blanket is at least 20 cm thick, and, with this same

Fig. 6. Mixed flow reactor cross section.

thickness at the top and bottom of the reactor, the salt weights 65 metric tons.

The molten salt is contained in a composite woven graphite-fiber graphite-impregnated box with 1-cm-thick walls. Outside this, and on the top and bottom as well, is a wall of 30-cm-thick interlocking graphite blocks. The total graphite weighs about 58 metric tons.

The entire reactor is encased in a 20-cm-thick carbon steel pressure vessel to retain the 100-atm internal pressure.

Figure 7 is a cutaway view of the reactor. The UF_6 and helium mixture enters the distribution manifold at the top of the reactor vessel, flows through the seven cavities, and is collected in a high-temperature discharge manifold at the bottom. The mixture leaves the reactor vessel and flows through the heat exchangers and circulator. All parts of this loop that are exposed to the high-temperature UF_6 are made of nickel or nickel alloy.

Fig. 7. Conceptual reactor configuration.

A second helium loop, free of UF_6 , controls the temperature of the beryllium moderator and the molten salt. This helium enters the header space at the top of the reactor vessel, flows down through coolant channels into the lower header space, and leaves the pressure vessel to go to a heat exchanger.

4. Major Power Plant Subsystems

Figure 8 diagrams the major subsystems.

The power extraction subsystem takes energy from the heat exchanger in the primary flow loop. This allows the secondary fluid, helium, to be free of fission products.

The fission product removal loop bleeds a small part of the UF_6 and helium mixture from the primary loop, extracts the fission products, and returns pure UF_6 and helium to the fuel mixture.

The moderator coolant flows not only through the moderator but also through a low-temperature heat exchanger (LTHX) to extract additional energy from the primary loop. It then flows through a steam cycle heat exchanger (not shown) that allows use of this energy.

The molten salt process loop is, again, a bleed system that takes out a small fraction of the salt to recover the newly born ^{233}U .

5. Reactor Neutronics

The initial guess at the reactor configuration was much like that shown in Fig. 6, except that a right circular cylinder was assumed for the outer surface of the beryllium. The neutronic calculations for the mixed flow reactor were made using the continuous energy Monte Carlo code, MCNK.³ The LASL master Monte Carlo library⁴ provided the continuous energy neutron cross sections.

A series of runs were made with both $^{235}UF_6$ and $^{233}UF_6$ as the fuel gas. The physical parameters varied were the gas density, web 1, and web 2. (Web 1 is the beryllium thickness between adjacent cavities and web 2 is that between the outer edge of the outer cavities and the graphite box that contains the molten salt.)

Figure 9 shows both ^{235}U and ^{233}U breeding ratios vs beryllium mass. A ^{235}U breeding ratio of one cannot be achieved.

Fig. 8. Major power plant subsystems of mixed flow reactor.

Fig. 9. Mixed flow reactor breeding ratio.

The best we could do with this configuration of materials was about 0.8. (The failure to achieve a breeding ratio of one with ^{235}U does not mean that this reactor cannot start without ^{233}U . As the breeding product is ^{233}U , the reactor could be started on ^{235}U and it would simply take a little longer to generate a critical mass of ^{233}U which, as Fig. 10 shows, is smaller than the critical mass of ^{235}U .)

The ^{233}U breeding ratio curve shows that a ratio of one corresponds to a beryllium mass of about 24 metric tons. Figure 10 shows that at 24 tons the ^{233}U critical mass is about 45 kg and that of ^{235}U is about 70 kg.

A one-dimensional transport code, ONETRAN,⁵ was used to estimate how moderator temperature affects critical mass. The difference in critical mass was about 4 kg at moderator temperatures of 300 and 1 000 K in the 200-MWth mixed flow reactor.

6. Salt Blanket Processing

In this study, we are using Oak Ridge National Laboratory (ORNL) work on the breeder blanket for the molten salt breeder

Fig. 10. Mixed flow reactor critical mass.

reactor (MSBR). Their currently preferred salt composition⁶ for the single-fluid reactor is $^7\text{LiF-BeF}_2\text{-ThF}_4\text{-UF}_4$ with mole fraction concentrations of 71.7-16-12-0.3, respectively. For the gas core breeder blanket, we remove the uranium and increase the thorium. The composition is then $^7\text{LiF-BeF}_2\text{-ThF}_4$ with concentrations of 70-16-14 mole %. We have set the salt blanket thickness at 20 cm, about three diffusion lengths for absorption of thermal neutrons, so 95% of the neutrons that enter the salt are absorbed. Furthermore, with a 14% thorium concentration, 96% of these are absorbed in the thorium.

ORNL developed two methods for extracting the newly bred ^{233}U from the salt.⁶ One, the bismuth contact method, extracted the ^{233}Pa , the mother of ^{233}U . It was held in a tank while it decayed to ^{233}U (half-life of 27.4 days). Early extraction of the protactinium is important if the salt runs through the reactor core where it is exposed to a high neutron flux, because both the pregnant mother and a neutron

would be lost if the protactinium were to absorb a neutron. In the gas core reactor, this is not so likely, because the breeding blanket sees only the leakage neutrons. Therefore we chose to use only the second ORNL method of ^{233}U extraction, direct fluorination of the ^{233}U .

Figure 11 diagrams the salt blanket processing. About 4 liters of salt per minute is valved into a fluorination column, where about 90% of the ^{233}U is removed as gaseous UF_6 . The salt then passes to a second column where it is exposed to hydrogen gas to remove fluorine and reduce dissolved UF_6 back to UF_4 . Next, ThF_4 is added to the salt to replace the thorium converted to ^{233}U . The salt is then filtered to remove corrosion products and is returned to the blanket.

As Fig. 11 shows, UF_6 leaves the fluorinator and flows through a bed of sodium fluoride (NaF) particles. This bed, at 500 K, does not adsorb the UF_6 but it does remove volatile fission product fluorides that may be generated in the blanket. The stream of UF_6 and F_2 is then cooled to 300 K and passed through a second bed of NaF where the UF_6 is adsorbed. The effluent fluorine gas, free of UF_6 , passes to a caustic scrubber for treatment before being released through a charcoal filter. Hydrogen from the purge column is also treated there.

Fig. 11. Salt blanket processing.

The NaF bed loaded with UF_6 is replaced by valving in a regenerated bed. The loaded bed is then regenerated by heating to 500 K and purging with a small flow of helium to remove the UF_6 . The desorbed helium and UF_6 are passed through a bed of MgF_2 (not shown in Fig. 11) to remove residual fission products and then are mixed, pressurized, and injected back into the salt.

Extraction of ^{233}U from the salt requires a concentration of 100 ppm or more.⁶ At reactor startup, there is no ^{233}U in the blanket so the reactor has to run on an "auxiliary bottle" until enough has formed. The 200-MWth mixed flow reactor, whose salt blanket weighs 65 metric tons, requires 6.5 kg of ^{233}U . So at least 6.5 kg must be kept in the salt throughout the reactor's operating life. Figure 12 shows the ^{233}U in the blanket at various times (t_0) at which extraction could start. The equilibrium value of 6.5 kg is attained if extraction is started at 72 days. The other

Fig. 12. ^{233}U time history in 200-MWth mixed flow reactor breeder blanket.

curves indicate the sensitivity of the equilibrium value to t_0 . Note that the maximum amount of ^{233}U in the blanket exists at t_0 . After extraction starts, the amount falls to approach its asymptotic value of 6.5 kg. While the reactor is being sustained at 200 MWth for 72 days, 14.4 kg of uranium is consumed. Thereafter, it resides in the blanket and the auxiliary bottle is empty. Thus the need to support the reactor until enough ^{233}U has built up to allow efficient extraction adds 14.4 kg to the fissile inventory of the 200-MWth reactor.

7. Fission Products

In the gas core reactor, the fission products are born in the gas and are carried with it as it leaves the reactor cavity. In the mixed flow reactor, the hot gases that leave the cavity flow through manifolds, piping, heat exchangers, and circulator, all of which become deposition sites for the radioactive fission products.

We expect that some of the UF_6 will dissociate in the cavity because of fission recoils, collisions from thermal motion, and nuclear radiations. This fluorine will combine with the metallic fission products to form fluorides. Table I shows our estimate of the composition of the working fluid mixture. On the basis of boiling points, we have divided the fluorides into five qualitative classes: gases, and volatile, mobile, intermediate, and refractory fluorides. With a knowledge of the temperatures in the system, this estimate will provide a first approximation to the places in the loop where the fission products will deposit.

The working fluid will leave the reactor cavities at about 1 225 K and, after transferring much of its energy through the heat exchangers, will return to the cavities at about 500 K. This suggests that the gaseous and volatile fluorides, and, perhaps the first three mobile ones, will stay in the working fluid and continue to circulate until they are extracted by the fission

TABLE I
ESTIMATED COMPOSITION OF
POWER EXTRACTION FLUID

	Mole Fraction
Helium	0.992
Uranium hexafluoride	0.008
Fission Fragments	8.1×10^{-6}
Kr	0.3×10^{-6}
Xe	1.6
I	0.2
Br	0.5
Total Gaseous	2.4×10^{-6}
SeF_6 (236 K)	0.04×10^{-6}
MoF_6 (308 K)	1.6
TeF_6 (309 K)	0.4
Total Volatile Fluorides	2.0×10^{-6}
SbF_5 (423 K)	Tr
NbF_5 (509 K)	0.02×10^{-6}
RuF_5 (523 K)	1.1
ZrF_5 (873 K)	2.6
SnF_4 (978 K)	0.02
Total Mobile Fluorides	3.7×10^{-6}
CsF (1 524 K)	7.0×10^{-9}
RbF (1 663 K)	3.0
Total Intermediate Fluorides	10.0×10^{-9}
RaF_2 (2 410 K)	0.12×10^{-9}
Y F_3 (2 500 K)	0.07
CeF_3 (2 573 K)	0.05
NdF_3 (2 573 K)	0.01
PrF_4 (2 600 K)	0.02
LaF_3 (2 600 K)	0.08
SrF_2 (2 762 K)	0.16
Total Refractory Fluorides	0.5×10^{-9}

NOTE: Normal boiling points are shown in ().

product cleanup system. The rest of the fluorides will probably deposit in the heat exchangers. Thus, about 68% of the radioactive atoms will stay in the loop until extracted and 32% will deposit in the heat exchangers and piping. These numbers are very approximate as the deposition is influenced by many things besides temperature. Moreover, the decay of a particular species

will change its chemical nature and, possibly, its affinity for a particular location.

In designing the reactor outlet piping, we conceived a battery of replaceable getter pads to capture the intermediate and refractory fluorides. If 2-mil nickel wire formed a getter whose area was the same as that of one heat exchanger, it would take about 37 kg of nickel, a negligible quantity. We further estimated that if all the fission product fluorides were deposited uniformly over the surface of one heat exchanger, its thickness would grow by less than one mil per year. This is a comforting general number, but it is quite unlikely that deposition would be uniform. More likely, a lumpy or dendriform structure would result. This is an effect that would require experimental investigation.

a. Fission Product Cleanup

During normal power plant operation, part of the circulating working fluid is withdrawn, purified, and returned to the reactor. The system is designed to prevent such buildup of gaseous impurities that reactor poisoning or condensation of volatiles becomes excessive.

The technology for separating UF_6 from the primary coolant and subsequently purifying it is from the MSBR development program at ORNL. Helium purification technology is like that used by General Atomics in their helium cooled reactor, the present design being based on a modified version of the Ft. St. Vrain helium purification system.

The purified UF_6 is returned to the primary coolant system as a liquid. The purified helium gas is free of radioactivity and chemical impurities except for neon. The coolant cleanup system will keep impurities in the primary coolant at approximately the levels shown in Table I.

b. UF_6 Separation and Purification

Figure 13 is a process flow diagram of the fuel loop cleanup. The power

Fig. 13. Fission product removal.

extraction fluid with its fission product contaminants is withdrawn from the fuel loop at approximately 0.01 kg/s for UF_6 and helium separation and purification. The slipstream pressure is reduced from 100 to about 1.5 atm. The UF_6 and helium stream is first passed through a high-temperature bed (500 K) of sodium fluoride (NaF) pellets where most of the volatile fission product fluorides are absorbed. The stream is then cooled to 300 K and passed through a low-temperature bed of NaF pellets that adsorb the UF_6 and the few remaining metal fluorides. The helium, containing xenon, krypton, bromine, iodine, tritium, and other gaseous contaminants, passes through the filter to the helium purification system.

When the bed is loaded with UF_6 it is valved out and a regenerated bed of NaF pellets is valved in. The bed loaded with UF_6 is regenerated by heating it to 700 K, which drives off the UF_6 as a gas along with small amounts of TaF_6 . A small stream of helium is purged through the bed to help strip the UF_6 . The UF_6 passes through a fixed bed of MgF_2 to absorb the TaF_6 . Then it is filtered, pressurized, and cooled to produce purified liquid UF_6 that may be recycled to the reactor.

Fission products are removed from the system by replacing the high-temperature adsorption bed and MgF_2 bed. The used beds containing fission products adsorbed on NaF

or MgF_2 pellets are sealed and shipped to storage or another waste-processing facility.

c. Helium Purification

Helium leaves the UF_6 adsorber at 300 K and flows to one of two parallel adsorption systems that include high- and low-temperature charcoal adsorbers for fission product removal. The adsorption systems are alternated between active adsorption and inactive holdup and decay cycles.

Helium, at 300 K, enters the high-temperature adsorber from the UF_6 separator.

The adsorber contains activated charcoal impregnated with potassium. It removes "condensable" metallic fission products, including iodine, by chemisorption with the potassium.

The helium is then cooled in a regenerative gas-to-gas exchanger to about 90 K against returning cold helium. The cooled helium passes through the low-temperature adsorber which removes the noble gases (krypton and xenon) and impurities such as nitrogen and hydrogen (and tritium). All these impurities, except hydrogen and tritium, are removed completely.

The gas is cooled in the adsorber to about 80 K by liquid nitrogen, which removes decay heat generated in the adsorber, sensible heat due to the temperature difference across the gas-to-gas exchanger, and heat leaking into the low-temperature system. The cold, purified helium is then rewarmed in the gas-to-gas exchanger.

The purified helium is filtered to remove any dust, compressed, and transferred to a hydrogen removal section, which consists of a regenerative exchanger, two hydrogen getters in parallel, and a filter. The hydrogen removal section uses titanium sponge to remove hydrogen and tritium. Operating temperature of the getter is about 650 K. The entering helium is heated to 630 K in the regenerator by the hot helium, and then passes through one of the titanium hydrogen getter units. The other unit is on standby. Titanium absorbs H_2 as a solid

solution. External electric heaters on the units keep the sponge at the desired operating temperature. Leaving the unit, the helium passes through the regenerator where it is cooled to 350 K, filtered, and recompressed for distribution to various users. A hydrogen getter is removed from service for regeneration when a hydrogen breakthrough is indicated, and is replaced by the standby getter unit.

Two identical charcoal adsorption systems connected in parallel are provided. During normal operation, one system is on-stream, supplying clean helium to the primary coolant system. Other equipment normally in service includes a purified-helium compressor and the hydrogen removal section, including a hydrogen getter.

A purification system is kept on stream for six months (unless there is prior breakthrough of the adsorbers), after which the standby system is placed in service and the spent system is removed. The spent system remains in this status for several months to permit decay of the accumulated activity, most of which is in the low-temperature adsorber. System cycle time can be as short as two months without affecting the decay period. During the decay period, the low-temperature adsorber is kept at its normal temperature by cooling with liquid nitrogen to remove decay heat.

d. Uranium Inventory

The only significant volume of uranium held up in the fission product processing loop is that in the cold (300 K) NaF bed, where the UF_6 must be entrapped to separate it from the helium. The NaF bed is about 30 cm in diam by 100 cm long. At the flow rates used, it fills up in about 40 min. and contains about 10 kg of uranium. Then, a second bed is valved in and the first is regenerated. This operation should be analyzed to find the best scheduling for minimal fissile inventory.

The uranium inventory in the fission product cleanup loop is not a function of reactor power. It depends only upon the

regeneration frequency and volume of the NaF bed.

e. Alternative Processing Systems

Extracting and purifying UF_6 by distillation may prove a simpler, more economical means of UF_6 and helium processing. If a significant part of the primary coolant stream must be processed owing to more stringent fission product specifications, distillation would probably be the preferred scheme. Distillation purifying of UF_6 from spent nuclear fuels has been demonstrated in the laboratory. Distillation of UF_6 derived from uranium ores has been a conventional production technology since 1959.

In a distillation system for the gas core reactor, the stream to be purified would be fed to the middle of a distillation column as a vapor. Most of the fission product fluorides would be removed as a concentrate from the bottom of the column. The fission product fluoride may be removed from the concentrate by aqueous wash, the residual UF_6 being returned to the column for further purification. The UF_6 and more volatile fission product fluorides (AsF_5 ,

TeF_6 , MoF_6 , and BrF_5) are condensed and fed to a second column where redistillation produces purified UF_6 as a bottom product and a distillate fission product fluoride over head.

8. Power Extraction

The power extraction system for the mixed flow reactor concept has been analyzed. The principal means of power removal is by convection, as all the hot gases leave the reactor cavities and flow through the heat exchangers. Figure 14 shows the principal components of the power extraction system and its interfacing with the reactor. The system consists of three interconnecting closed-loop flowing gas circuits, the primary flow loop, the secondary helium loop, and the helium coolant flow loop.

a. Primary Flow Loop

The primary flow loop is the flowing gas stream in which the fission energy is first deposited within the reactor fuel cavities. The mixed flow reactor is considered to be operating at 200 MWth, of which 175 MW is removed in the heated fuel

Fig. 14. Mixed flow reactor power extraction loop.

stream as it flows through the seven-cavity configuration shown in Fig. 6. The fuel stream enters the cavity at 500 K and is heated to 1 225 K. The total weight flow of UF_6 and helium in this loop is 68.4 kg/s, 24.1 of UF_6 , and 44.3 of helium. The total pressure in the cavity is 100 atm, of which the UF_6 partial pressure is approximately 0.6 atm.

The primary fuel stream leaves each fuel cavity, is manifolded in a toroidal ring, and is brought out through the pressure vessel. The flow then enters the HTHX where it transfers part of its energy to the secondary helium loop. The fuel enters the HTHX at approximately 1 225 K, the reactor exit temperature, and leaves at 775 K. The fuel stream then passes through the LTHX in this loop where the residual power carried out of the cavities is transferred to the helium coolant loop. The fuel temperature is reduced from 775 to 483 K as the fuel flows through the LTHX. The HTHX and LTHX transfer 109 and 70 MW, respectively. The 1-atm pressure drop in the fuel flow through each heat exchanger was determined (see Sec. on Heat Exchangers) in a series of design calculations of HTHX and LTHX sizing, and a 6-atm pressure drop between cavity injection and exhaust pressure was assumed. An axial compressor is also included in the primary flow loop to recompress the fuel from 95 atm at the LTHX exit to 103 at fuel cavity injection. The compressor work at the reference flow rate is approximately 4 MW. After the flow is recompressed, a slip stream is withdrawn from the main flow to feed the fission product cleanup loop.

b. Heat Exchangers

Design calculations were performed to size the three principal system heat exchangers, the HTHX, LTHX, and regenerative heat exchanger (REGHX). Their locations are shown in Fig. 14. All heat exchangers were assumed to be constructed alike. The basic element is concentric tubing, each tube being thick enough to

withstand the maximum design operating pressure of 100 atm. The heat exchangers are of the counterflow type with inlet and exit plenums for both the hot gas that flows in the inner tube and the cool gas that flows in the annulus between the concentric tubes. The arrangement of tubes is housed in an evacuated containment vessel to insulate them against heat loss to the exterior environment. An analytical model was used to determine the length and number of tubes required to transfer a given quantity of power and to provide a specified pressure drop in the gas flowing in the inner tubes. Convective heat transfer coefficients of both gases were evaluated using average gas properties at the operating temperatures specified for a given heat exchanger. The flow wanted in such devices is turbulent, which tends to enhance heat transfer but induces pressure losses.

(1) High-Temperature Heat Exchangers

The HTHX receives the mixed fuel effluent flow from the fuel cavities. This flow passes through the inner tubes of the concentric tube arrangement. The tubes are a nickel or nickel alloy to resist corrosion by the hot UF_6 , and are 0.89 mm thick with a 9.5-mm o.d. The operating temperatures for the fuel at reference conditions are 1 225 K at inlet and 775 K at exit; the pressure is approximately 100 atm. Helium gas also at approximately 100 atm flows in the annulus between the concentric tubes. The helium temperatures are 693 K at inlet and 1 000 K at the exit. (This is the hot gas that drives the turbine.) The outer tubes are also 0.89 mm thick but have a 14.3-mm o.d. The results of calculations performed to size this heat exchanger are given in Table II. For a flow rate of 68.4 kg/s, the variation in heat exchanger size depends on the allowable pressure drop through the tubes. For fuel flow pressure drops of 0.25, 1.0, and 2.0 atm, the tube lengths are 3.8, 4.4, and 4.8 m, respectively, and the corresponding numbers of tubes

TABLE II
HIGH-TEMPERATURE HEAT EXCHANGER SPECIFICATIONS

Basic Element and Plenums

(Reference design is for inner tube pressure drop of 1 atm.)

Parameter	UF ₆ + He in Inner Tubes			He in Outer Tubes		
Inlet gas temperature (K)	1225	1225	1225	693	693	693
Outlet gas temperature (K)	775	775	775	1100	1100	1100
Tube o.d. (cm)	0.9525	0.9525	0.9525	1.429	1.429	1.429
Tube thickness (cm)	0.089	0.089	0.089	0.089	0.089	0.089
Gas weight flow (kg/s)	68.4	68.4	68.4	51.3	51.3	51.3
Pressure (atm)	100	100	100	100	100	100
Pressure drop (atm)	0.25	1.0	2.0	0.54	2.16	4.32
Flow velocity (m/s)	24.8	49.0	68.8	23.3	46.2	64.8
Power transferred (MW)	109	109	109	--	--	--
No. of tubes	7830	3956	2819	--	--	--
Tube length (m)	3.8	4.4	4.8	--	--	--
Heat exchanger effectiveness	0.845	0.845	0.845	--	--	--
Heat exchanger area (m ²)	885	523	405	--	--	--
UA of heat exchanger (MW/K)	1.07	1.07	1.07	--	--	--
Mass of ²³³ U contained (kg)	4.90	2.90	2.25	--	--	--

are 7 830, 3 956, and 2 819. Also shown for the HTHX at these reference conditions is the total quantity of ²³³U contained. (We assume that the inlet and exit plenums contain the same amount of ²³³U as the tubular structure.) The total quantities are then 4.90, 2.90, and 2.25 kg, respectively. The HTHX reference design incorporated into

the power extraction system is the configuration for which the fuel flow frictional pressure drop is 1 atm. This heat exchanger transfers 109 MW of power.

(2) Low-Temperature Heat Exchanger

The LTHX follows the HTHX in the mixed fuel effluent flow circuit and,

as in the HTHX, the fuel flows through the inner tube of each basic element. The tubes are also made of nickel alloy for corrosion resistance. The inner tubes are 775 K at inlet and 483 at the exit, and the operating pressure is also approximately 100 atm. Helium gas from the coolant flow circuit forms a counterflow in the annulus between the concentric tubes. The operating temperatures of the helium flow are 321 K at inlet and 596 at the exit. (This is the loop that will drive the steam cycle generator.) The outer tubes are 0.89 mm thick and have a 14.3-mm o.d. Specifications are given in Table III. For fuel pressure drops of 0.25, 1.0, and 2.0 atm, the tube lengths are 1.8, 2.1, and 2.3 m, respectively, and the corresponding numbers of tubes are 3 984, 2 026, and 1 449. The quantity of

^{233}U contained in the LTHX is 1.9, 1.1, and 0.90 kg for fuel effluent flow frictional pressure drops of 0.25, 1.0, and 2.0 atm, respectively. As before, these quantities of contained ^{233}U include the amounts in the plenums. In this design, the fuel flow frictional pressure drop is 1 atm and the power transferred by this heat exchanger is about 70 MW.

(3) Regenerative Heat Exchanger

The REGHX is used in the secondary helium gas turbine flow circuit to increase the cycle efficiency. It, too, is constructed of concentric tubes. The helium leaving the gas turbine flows through the central tubes and then, in a counter direction, through the outer tubes after having been compressed to about 100 atm.

TABLE III
LOW-TEMPERATURE HEAT EXCHANGER SPECIFICATIONS

(Same reference design as Table II.)

Parameter	UF ₆ + He in Inner Tubes			He in Outer Tubes		
Inlet temperature (K)	775	775	775	321	321	321
Outlet temperature (K)	483	483	483	596	596	596
Tube o.d. (cm)	0.9525	0.9525	0.9525	1.429	1.429	1.429
Tube thickness (cm)	0.089	0.089	0.089	0.089	0.089	0.089
Weight flow (kg/s)	68.4	68.4	68.4	49.3	49.3	49.3
Pressure (atm)	100	100	100	100	100	100
Pressure drop (atm)	0.25	1.0	2.0	0.41	1.6	3.3
Flow velocity (m/s)	30.6	60.2	84.2	22.5	44.3	62.0
Power transferred (MW)	70	70	70	--	--	--
No. of tubes	3984	2026	1449	--	--	--
Tube length (m)	1.8	2.1	2.3	--	--	--
Heat exchanger effectiveness	0.64	0.64	0.64	--	--	--
UA of heat exchanger (MW/K)	0.41	0.41	0.41	--	--	--
Mass of ^{233}U contained (kg)	1.9	1.1	0.9	--	--	--

The tubes are stainless steel, 0.5 mm thick with a 6.3-mm o.d. The outer tubes are 0.89 mm thick with an 11.0-mm o.d. The operating temperatures of the flow in the inner tubes are 725 K at inlet and 429 at the exit; the outer annular helium flow has an inlet temperature of 397 K and an exit temperature of 693. The results of calculations made to size the REGHX are shown in Table IV. The helium flow rate is 51.3 kg/s. For pressure drops of 0.25, 1.0, and 2.0 atm in the helium flowing in the inner tubes, the tube lengths are 7.0, 8, and 8.7 m, and the corresponding numbers of tubes are 19 978, 10 034, and 7 119. The REGHX has an inner flow frictional pressure drop of 1 atm, and it transfers 79 MW of power within the secondary helium gas turbine flow circuit.

c. Secondary Helium Loop

The secondary helium flow loop receives heat from the primary fuel flow loop through the HTHX (Fig. 14). The helium counterflow enters the HTHX at 693 K and leaves at 1 100. A helium weight flow of 51.3 kg/s is required to remove the 109 MW of heat. The helium flow then enters the helium gas turbine.

The turbomachinery for the gas turbine part of the energy extraction cycle in the mixed flow reactor could be similar to that for a 50-MWe unit designed to operate at a turbine inlet temperature of 1 023 K now being developed in Oberhausen, Germany.⁷ For the mixed flow system, the turbomachinery is installed in two separate pressure vessels. The low-pressure turbine housed in one vessel drives the electric generator through a gear box at 3 600 rpm. The high-pressure turbine drives the compressors

TABLE IV
REGENERATIVE HEAT EXCHANGER SPECIFICATIONS

(Same reference design as Table II.)

Parameter	He in Inner Tubes			He in Outer Tubes		
Inlet temperature (K)	725	725	725	397	397	397
Outlet temperature (K)	429	429	429	693	693	693
Tube o.d. (cm)	0.635	0.635	0.635	1.11	1.11	1.11
Tube thickness (cm)	0.051	0.051	0.051	0.089	0.089	0.089
Weight flow (kg/s)	51.3	51.3	51.3	51.3	51.3	51.3
Pressure (atm)	30	30	30	100	100	100
Pressure drop (atm)	0.25	1.0	2.0	0.61	2.4	4.9
Flow velocity (m/s)	13.2	26.3	37.0	23.7	47.2	66.5
Power transferred (MW)	79	79	79	--	--	--
No. of tubes	19978	10034	7119	--	--	--
Tube length (m)	7.0	8.0	8.7	--	--	--
Heat exchanger effectiveness	0.9	0.9	0.9	--	--	--
Heat exchanger area (m ²)	2770	1610	1230	--	--	--
UA of heat exchanger (MW/deg K)	2.47	2.47	2.47	--	--	--

which are housed in the second pressure vessel. The compressors would operate at a higher speed to provide good aerodynamic efficiency. Detailed design of turbomachinery for the mixed flow system is beyond the scope of this study. However, the state of the art of helium turbines and previous high-temperature gas-cooled reactor technology indicate that it is definitely feasible to develop efficient turbomachinery for the mixed flow system operating conditions.

Electric power is required for the electric motors that drive the axial compressors used in both the primary fuel loop and the helium coolant loop. This total of 6 MW of power can be obtained from the system's electric generator. To increase the efficiency of the gas turbine cycle, a REGHX, a precooler process heat exchanger (PPHX), and a series of compressor intercooler heat exchangers (NTC) were added to the power extraction gas turbine loop. The REGHX was sized as were the HTHX and LTHX in a series of design calculations. The design chosen has 1-atm pressure drop in the hot helium flow through the central tubes. A 2-atm pressure drop was calculated for the cool helium flowing in the outer tubes of the basic REGHX element. This also is a counterflow heat exchanger. Pressure drops of 1 atm across the PPHX and 0.5 atm across each NTC were assumed. The turbine and compressor efficiency was assumed to be 0.9, as was the REGHX effectiveness. The helium gas-turbine cycle was investigated to give a maximum loop temperature of 1100 K at the entrance to the turbine and a minimum loop temperature of 327 K at the entrance to the compressor section. Calculated gas cycle efficiencies of one-, two-, three-, and four-section compressor configurations were 0.33, 0.38, 0.41, and 0.42, respectively. For the multisection compressor configurations, intercooling between compressor sections was included, so that the temperature into each compressor section was 327 K. An

efficiency gain of about 0.08 can be expected in going from a single- to a three-section compressor. Therefore, a three-section compressor with two intercooler heat exchangers has been incorporated into the power extraction system gas turbine cycle. The turbine for the helium gas turbine reference design accomplishes 100.5 MW of work of which 56.2 is required to drive the three-section compressor, so 44.3 MW of electric power is generated. The REGHX maintains 79 MW of heat in the cycle loop, whereas the PPHX rejects 27.3 MW and the NTCs reject 37.5 MW.

d. Helium Coolant Loop

The helium coolant loop receives heat from the primary fuel flow loop by way of the LTHX, as shown in Fig. 14. The helium is flowing counter to the fuel flow in the LTHX which it enters at 321 K and leaves at 596. A helium weight flow of 49.3 kg/s is required to remove the 70 MW of heat. After the flow leaves the LTHX, it passes through the moderator to remove the 25 MW of power deposited there by neutron and gamma radiation. The temperature in the helium coolant flow rises from 596 to 694 K. The flow then proceeds to a breeding blanket heat exchanger (not shown) to remove the 6 MW of heat deposited in the blanket by secondary nuclear radiation. The temperature in the flow rises from 694 to 718 K. An axial compressor in the helium coolant loop recompresses the flow from 94 to 100 atm, the pressure at the LTHX inlet. The compressor work at the 49.3-kg/s flow rate is approximately 2 MW. Heat removed from the helium coolant loop by a steam cycle heat exchanger (SCHX) represents approximately 103 MW of heat to be delivered to a steam turbine cycle. The steam turbine cycle acts as a bottom cycle in the context of the complete mixed flow reactor power extraction loop. To determine overall system power output and efficiency of the power extraction system, we assume that the steam cycle efficiency is 0.34 which implies that the steam cycle generates 35 MW of electrical power.

e. Cycle Performance

The summary results for the combined helium gas turbine and steam cycle power extraction loop in the mixed flow reactor can be determined from the individual cycle performance discussed above. The net electric power from the helium gas turbine loop is 44.3 MW. This is reduced to 38.3 MW to account for the 6 MW of electric power required to drive the axial compressors in both the primary flow and helium coolant loops. The net power from the steam cycle is 35 MW, resulting in 73.3 MW total net power from the reactor. The combined overall cycle efficiency of the reference reactor operating at 200 MW_{th} is, therefore, 0.0366.

The mixed flow reactor power extraction cycle described above has not been optimized for maximum overall efficiency. Somewhat greater efficiency might be achieved through further study of cycle alternatives.

9. Moderator

As Fig. 6 shows, the beryllium moderator occupies the region between the fertile molten salt and the seven reactor cavities. For the moderator cooling analysis described here, neutrons and gamma rays, released at fission, are assumed to be deposited uniformly within the moderator components so that the absorbed energy per unit mass of beryllium is constant. As 12.5% of the energy released from the fission process will be deposited in the moderator, the moderator must be cooled to remove the 25 MW deposited in the beryllium. As Fig. 14 shows, the moderator is cooled by helium gas flowing in a coolant loop at 49.3 kg/s. The moderator inlet temperature of 596 K was determined by the requirements of the LTHX used to extract heat from the primary fuel loop. The cooling sequence for the closed-cycle helium coolant loop, as shown in Fig. 14, is LTHX, moderator, and breeding blanket before heat exchange through the SCHX.

The moderator consists of three major components (lower, upper, and side sections). Its total mass is approximately 24 metric

tons. The upper and lower sections have a mass of approximately 5 metric tons each; the side section, a mass of approximately 14 metric tons.

Ten per cent of the moderator volume was assumed to be coolant passages through which the helium coolant flows. The convective heat transfer, number of coolant channels, channel diameter, and film temperature difference between the beryllium and helium in each of the three components were calculated. The results indicate that a cooling sequence of lower, upper, and side sections gives average temperatures of approximately 700 K. The upper and lower sections have 8660 coolant channels, each 20 cm long and 1 cm² in cross section. The resulting fluid flow velocity is 7.6 m/s, and the calculated film temperature difference between the beryllium and helium is 78 K. The side section has 790 coolant channels that extend the entire 4.35-m length of the fuel cavities, and each has a 4-cm² cross section. The resulting helium flow velocity is 20.8 m/s, and the calculated film temperature difference between the helium and beryllium is 30 K. For a given cooling sequence, the calculated bulk average temperatures in the lower, upper, and side sections are 684, 704, and 695 K, respectively. The total bulk temperature in the helium flow through the entire moderator increases from 596 K at the inlet to 694 K at the exit. The bulk helium temperature increases through the upper, lower, and side sections are 19.5, 19.5, and 59 K, respectively.

There are 113 coolant channels per unit cavity in the side moderator section. They are located around each cavity in two 3-cm-wide rings. There are 56 coolant channels uniformly spaced within the inner annulus and 57 in the outer annulus. The minimum web thickness between any two cavities is 6 cm. The most coolant channels that could be placed in the inner annulus is approximately 190. The channels in the upper and lower moderator sections

have approximately 3.2-cm center-to-center spacing. This arrangement will give approximately uniform heat flux per unit length in each coolant channel throughout the moderator.

The ratio of convective heat flux in individual side coolant channels to that in the lower and upper ones is 0.76. However, because the upper and lower moderator sections contain approximately seven times as much beryllium per unit length as the side section, the corresponding heat deposition per unit length is approximately seven times greater in the upper and lower sections. Thus, channels are required in the upper and lower sections.

We calculate that the moderator section can be cooled with helium gas well enough to provide a bulk moderator temperature of approximately 700 K with a 10% coolant volume and a helium flow rate of 49.3 kg/s.

For the reference reactor configuration, the partial pressure of the UF_6 in the fuel cavity is approximately 0.6 atm. From the variation in the radiative energy absorption coefficient of UF_6 ,⁸ and the cavity temperature variation (Fig. 2), the thermal radiation heat load to the cavity moderator wall was calculated to be approximately 26 kW per cavity resulting from the spectral radiation intensity emerging from a nonhomogeneous optical path. This heat load is small because the optical depth for radiant heat transfer as viewed from the moderator wall is small, so only the thermal radiation from the cool outer part of the fuel cavity is incident upon the moderator surface.

The convective heat transfer from the cavity moderator wall by the flowing gas in the cavity also was estimated. Turbulent boundary layer analysis⁹ indicates that approximately 2.3 MW of heat could be removed convectively from each cavity wall to give a moderator wall surface temperature of 700 K and a gas flow free stream temperature of 500 K. Thus, the convective

heat transfer from the cavity wall to the fuel gas should be greater than the thermal radiation heat load to the wall, which should cool the moderator wall further and remove some of the energy deposited by nuclear radiations.

10. Inventory

We can now add the amounts of ^{233}U in the various subsystems of the 200-MWth mixed flow reactor power plant (Table V).

B. 2 500-MWth Mixed Flow Reactor Power Plant

Although a 200-MWth power plant may be suitable for export to towns of 50 000 or so homes, we may want to know the characteristics of a reactor whose power output is comparable to that of nuclear power plants now used in the U.S. We therefore scaled the 200-MWth reactor up to 2 500 MWth.

1. Vortex Flow

The flow pattern in the cavities of this higher powered reactor is the same as before. The velocities are higher, but the cavity geometry and modes of injecting and extracting of the fuel mixture are unchanged.

2. Fuel Region Characteristics

To transfer this added power without increasing the cavity temperature, the thermal capacity of the gas and its flow rate must be increased. The thermal capacity was increased by increasing the amount of helium in the fuel mixture, its partial

TABLE V
URANIUM INVENTORY OF
200-MWth REACTOR

45 kg	Total in cavities
4	Heat exchangers
16	Piping
2	Circulators
10	Fission product cleanup loop
<u>14</u>	Auxiliary bottle
91 kg	Plant total

pressure was increased from 100 to 650 atm. The flow rate was increased from 68 to 625 kg/s.

This may not be the best approach to increasing the power. It was just an obvious one that required no changes in reactor materials or configuration.

3. Reactor Configuration

The dimensions and configuration of the cavities, moderator, breeder blanket, and graphite reflector required no changes to go from 200 to 2 500 MWth. The pressure vessel would have to be strengthened to retain the 650-atm internal pressure, and the circulators would have to be enlarged to provide the increased mass flow.

4. Major Power Plant Subsystems

The subsystem configurations and functions would be the same as for the 200-MWth reactor, but some would have to be enlarged to increase output.

5. Reactor Neutronics

As there were no changes in reactor configuration or materials, there were no changes in neutronics. The breeding ratio and critical mass are the same at both the high- and low-power levels. The only nuclear change is the increased fission rate.

6. Salt Blanket Processing

The salt blanket processing loop configuration is the same for the high- and low-power levels. Flow rates would have to be increased to meet the higher demand for new fuel.

Because of the changes in power level, the ^{233}U takes less time to build up to the 6.5-kg equilibrium value. Figure 15, the time history of the ^{233}U in the salt blanket, shows that the processing can begin in about 42 days. Other processing start times are given to indicate sensitivity.

7. Fission Products

The increased fission rate demanded of the 2 500-MWth reactor increases the uranium mass flow rate only very slightly. In both reactors, the need to maintain a

Fig. 15. ^{233}U time history in breeder blanket of 2 500-MWth mixed flow reactor.

critical mass imposes a uranium mass flow rate of 16.2 kg/s. The need to maintain 2 500 MW requires injection of an additional 0.029 g/s, which hardly alters the uranium mass flow rate. Note that 625 kg/s is the total mass flow rate. Most of it is helium; only 16.2 kg/s is uranium.

All the 0.029 g/s of injected ^{233}U is fissioned and flows through the loop as a 12.5-fold increase in fission product density. This may require more frequent service or enlargement of the fission product absorber and traps. However, the UF_6 inventory in the fission product removal system is not increased.

8. Power Extraction

The power extraction system of the 2 500-MW mixed flow reactor power plant is identical in configuration and function to that of the 200-MWth Plant. However, a thermal analysis was required to size the components of this higher powered system.

The helium pressure had to be increased to 650 atm to get adequate thermal capacity in the working fluid. Higher powered circulators had to be used to give a mass flow rate of 625 kg/s. The heat exchangers had to be enlarged to accommodate the higher heat transfer rates. The number of pipes in the HTHX had to be increased to 6 178, and they had to be lengthened to 8.5 m. The number of tubes in the LTHX had to be increased to 3 098, and they had to be lengthened to 3.85 m. The increased volume of the heat exchangers and circulators increased the fissile inventory in the power loop to 31 kg from 22 kg.

Table VI compares the sizes of the power loop elements in the two mixed flow reactors.

9. Moderator

The moderator cooling system was not analyzed for the 2 500-MWth reactor as it does not influence the fissile inventory.

TABLE VI
POWER LOOP CHARACTERISTICS
OF MIXED FLOW REACTORS

	200 MW	2 500 MW
Cavity pressure (atm)	100	650
Cavity residence time (s)	3	1.5
Total mass flow rate (kg/s)	68	625
HTHX-Q (MW)	109	1 365
Tube length in HTHX (m)	4.4	8.5
Number of tubes	3 965	6 178
HTHX-Delta p (atm)	1.14	11.1
^{235}U mass in HTHX (kg)	2.9	8.8
Pipe radius (cm)	20.3	20.3
^{233}U mass in piping (kg)	15.3	15.3
Delta p per 10-m pipe (atm)	0.024	0.29
Dynamic head (atm)	0.12	2.13
Total loop delta p (atm)	3.4	39
LTHX-Q (MW)	66	829
Tube length in LTHX (m)	1.84	3.85
Number of tubes	1 896	3 098
LTHX Delta p (atm)	1.39	12.8
^{233}U mass in LTHX (kg)	0.9	3.2

TABLE VII
FISSILE INVENTORY IN 2 500-MWth
MIXED FLOW REACTOR

45 kg	Total in cavities
12	Heat exchangers
16	Piping
3	Circulator
10	Fission product cleanup loop
<u>105</u>	Auxilliary bottle
191 kg	Plant inventory

10. Inventory

Table VII gives the fissile inventories in the various subsystems of the 2 500-MWth reactor power plant.

C. Conclusions About Mixed Flow Reactors

The UF_6 and helium reactor appear capable of providing a range of powers if a few changes in subsystem design are made. However, no significant reactor design changes are required. The fissile inventory is small compared to that in present power reactors, and susceptibility to surreptitious diversion of fissile material is less than 4 kg.

VI. PLASMA CORE REACTOR POWER PLANTS

Two plasma core reactors were designed and analyzed like the mixed flow design. That is, all subsystems were sized for suitable function and fissile inventory.

The impetus for examining the plasma reactors was their promise of higher efficiencies and additional applications. They turned out to have a lower fissile inventory as well. Because they operate above 5 000 K and transfer their energy by thermal radiation, they could be put to the following uses.

1. High-thrust, high specific impulse rocket propulsion.
2. Advanced closed cycle, gas-turbine driven, electrical generation.
3. Photochemical or thermochemical processes, such as dissociation of hydrogenous material to produce hydrogen.

4. MHD power conversion for generating electricity.

We examined two plasma reactor configurations, one designed to drive a closed cycle helium gas turbine, the other to provide a high thermal radiation flux into a working fluid channel for use in applications (1), (3), or (4), above. Both reactors use vortex confinement to keep the hot gases ($> 5\,000\text{ K}$) from the cavity walls, and both provide a way for radiant energy to get to the working fluid.

A. Closed Cycle Helium Gas-Turbine Plasma Reactor Power Plant

1. Vortex Confinement

Figure 16 shows the flow in the plasma cavity. As in the mixed flow reactor, gas is injected through the longitudinal slit just to the right of the perforated screen, but this time the gas is pure argon. The

Fig. 16. Flow pattern in plasma reactors.

molten uranium is injected through ports in the end wall at about 75% radius.

The argon spirals axially toward the cavity end walls. Part of it is removed from the cavity through annular slots in the end walls near the cylindrical wall. The rest along with the entrained fission products and gaseous uranium, is removed through ports at the center of each end wall. It is then cooled by mixing with low-temperature argon to achieve an equilibrium temperature of about $1\,500\text{ K}$. At this temperature, the uranium liquifies and is separated from the argon centrifugally. It is then pumped back into the cavity fuel region. The remaining argon effluent is cooled further outside the pressure vessel and pumped back into the cavities to drive the vortex. Analyses and measurement of vortex flow characteristics pertinent to plasma core reactor fuel confinement are reported in Refs. 1 and 10-17.

The argon is injected at 500 atm to produce a swirling flow with high densities and high tangential velocities near the wall. When these conditions are right, there is a sharp boundary between the buffer zone and the fuel cloud. For this boundary to exist, the thickness of the diffusion boundary layer at the outer edge of the fuel cloud must be less than the distance between the fuel cloud and the wall.

The thickness of the diffusion boundary layer at the edge of the fuel cloud is a function of the local axial velocity and turbulence level of the flow. A 1-cm thickness would require an axial velocity of 20 cm/s near the end walls.^{18,19} Because the density between the fuel cloud and the wall increases by about a factor of 5, the velocity would be expected to decrease by the square root of 5, or 2.24, to provide a constant axial dynamic pressure. The corresponding axial velocity of the argon adjacent to the wall would be 8.9 cm/s .

Both theory^{1,19} and experiment^{10,12} have shown that the tangential velocity at the wall must be significantly greater than the axial argon velocity to establish laminar flow at the fuel cloud. The vortex injection area necessary to produce a flow pattern with good confinement characteristics, laminar recirculation cells, is 90 cm^2 .^{21,20} The corresponding tangential injection velocity of the argon is 360 cm/s , or about 18 times the maximum axial velocity of 20 cm/s .

2. Fuel Region Characteristics

The critical mass of this seven-cavity reactor is 36 kg of ^{233}U , and the total fuel cloud volume is $1.84 \times 10^6 \text{ cm}^3$ (fuel cloud radius is 0.85 times the cavity radius), so the average uranium density is 20 mg/cm^3 . For a total cavity pressure of 500 atm , the density of the argon buffer gas at the edge of the fuel cloud is 65 mg/cm^3 . Thus, the fuel density is only 31% of the argon density at this location.

The gases within the fuel cloud are considerably hotter than those at its edge. A temperature distribution²¹ analysis gives the temperature at the cavity centerline as $28\,000 \text{ K}$. It also gives 350 atm as the partial pressure of the ^{233}U and associated electrons in the fuel cloud and 150 atm as the partial pressure of argon there. The average total (^{233}U and argon) density in the fuel cloud is 23.3 mg/cm^3 , only 36% of the argon density at its edge. From fluid mechanics analyses and experiments,^{1,11-13,16} we believe that these densities will provide a highly stable flow pattern.

The volume flow of argon passing through the cavity, the argon mass flow rate (1.6 kg/s) divided by the argon density at the edge of the fuel cloud (0.665 g/cm^3), is $24.6 \times 10^3 \text{ cm}^3/\text{s}$. The resulting average argon dwell time, the 0.36-m^3 vortex volume divided by the argon volume flow rate, is 15 s . If the average fuel dwell time is three times the average argon dwell time, as in some fluid mechanics tests,^{11,14} it would be approximately 45 s . Because the mass of ^{233}U in each cavity is 5.14 kg , this fuel residence time would correspond

to a ^{233}U mass flow rate of 114 g/s or a total of about 0.8 kg/s in all seven cavities.

3. Cavity Structure

The cavity structure is designed to accommodate radiation transfer. The transparent wall (Fig. 17) is separated into three segments made of circumferential quartz tubes fused into a single structure. The tube segments are connected to a solid structure that contains coolant entrance and exit flow manifolds and the injection slot and manifold for the argon buffer gas. Design of the transparent structure was based on prior studies and experiments^{18,20,22} which indicated that the transparent wall could operate at $800\text{--}1\,000 \text{ K}$ because at these temperatures the effects of ionizing radiation damage anneal rapidly and high optical transparency can be expected. The optical transmission of high-purity quartz at room temperature and at $1\,073 \text{ K}$,²³ shown in Fig. 18, is a remarkable match with the spectrum of a $5\,000 \text{ K}$ blackbody. Such a spectrum emits 5% of its energy at wavelengths greater than $2.5 \mu\text{m}$ and only 0.03% at less than $0.2 \mu\text{m}$. These wavelengths correspond closely to the transmission cutoff wavelengths of quartz, as shown in Fig. 18.

Fig. 17. Cavity structure of closed cycle gas-turbine plasma reactor.

Fig. 18. Spectral transmission of quartz.

Thus, the primary source of heat deposition in the transparent wall will be infrared radiation at wavelengths greater than about 2.6 μm . The fraction absorbed in the wall will have to be removed by a coolant flowing in the wall tubing. We made no detailed engineering analysis of wall-cooling requirements, but comparison of the expected heat loads with those examined during the nuclear light bulb rocket engine program²² indicates that cooling of the transparent wall is definitely possible.

Thirty-six quartz tubes with 0.5-cm-thick walls of 5-cm i.d. are located in an annulus around the reactor cavity. The zones within the annulus but outside the tubes are filled with quiescent helium at the same pressure as the reactor cavity.

Because the 0.5-cm-thick quartz tubes can withstand more than 500-atm differential pressure, the working fluid need not be run at the reactor cavity pressure (500 atm). In sizing the power extraction system, we chose 98 atm as the pressure in the working fluid. With this pressure and a total cross-section area of 515 cm^2 in the working fluid tubes (allowing for a 13% blockage by the graphite fins), the working fluid flow velocity was 140 m/s.

The limit on helium working fluid outlet temperature is determined by the upper limit on the quartz operating temperature. For the reference design, which has uncooled tubes, we chose a maximum helium temperature of 1 200 K. If internally cooled

quartz tubing were used, the helium outlet temperature could be higher, perhaps as high as 1 500 K. If still higher outlet temperatures are desired in advanced systems, use of finned graphite in isolated working fluid channels or helium seeded with carbon particles to absorb the thermal radiation²⁴ seems feasible.

Radiant heating of particle-seeded gases to high temperature has been proven feasible. A stream of tungsten-seeded argon flowing in a quartz tube was heated to a bulk temperature of 4 515 K by thermal radiation from an external dc arc.

At the assumed helium exit temperature of 1 200 K, the enthalpy rise in the helium from a 794 K inlet temperature is 2.12 MJ/kg. Dividing the 500-MW total radiated power by this enthalpy rise shows the helium flow rate to be 237 kg/s for all seven cavities together, or 33.8 kg/s per cavity.

4. Radiant Energy Transfer

Figure 17 illustrates the design of the cavity for the closed cycle helium gas turbine plasma reactor. Note that it is smaller than the mixed flow reactor cavity. Its diameter is 0.5 m rather than 1.0, and its length is 1.85 m rather than 4.35. The dashed circle in the figure represents the interface between the buffer zone and the fuel cloud. The cavity wall is quartz tubing, and the working fluid flows down the quartz cylinders containing the graphite fins. The space between the cylinders and the transparent wall contains helium that can be used to control the temperature of the quartz.

The hot fuel cloud transfers its energy by radiation to the graphite fins where it is picked up by the working fluid. About 85% of the energy released in fissions is transferred in this manner.^{18,21} The rest is either convected away by the effluent gases or deposited in the moderator and salt blanket by neutrons and gamma rays. Previous studies^{25,26} indicated that the uranium fuel region is opaque to the optical radiation generated within it. The thermal

radiation is, at the temperatures and pressures of interest to plasma core reactors, in approximate thermodynamic equilibrium with the fuel cloud. Therefore, the effective fuel radiating temperatures correspond closely to the local temperature at the edge of the fuel cloud. The heat flux radiated by this surface is the power radiated divided by the surface area, or 3.0 kW/cm^2 . This value is equivalent to the heat flux radiated by a blackbody at 4 780 K. It is estimated that surface reflection at the transparent walls and reradiation from the working fluid region will return about 1% of the outward directed energy to the fuel cloud. The loss would be made up by running the reactor at 4 950 K. This approximate blackbody behavior of the plasma reactor is important because small temperature rise causes a large increase in radiation rate. Further, this increase can be achieved without increasing cavity size or fissile inventory. Figure 19 shows the radiated power variation with temperature. Note that the radiated power goes from 500 to 2 500 MW as the fuel cloud's outer surface goes from 4 780 to 7 150 K.

5. Reactor Configuration

Figure 20 is a cross-section view of the final seven-cavity configuration of the closed cycle helium gas-turbine reactor. Each cylindrical cavity is 0.5 m in diameter

Fig. 19. Radiated power.

Fig. 20. Cross section of closed cycle gas-turbine plasma reactor.

by 1.85 m long, and each is surrounded by a 20-cm-wide annulus that contains the quartz tubes through which the working fluid flows. The seven assemblies are embedded in a beryllium moderator. The beryllium is, again, 6 cm thick between adjacent cavities (web 1) but now 20 cm thick between the outer cavities and the breeder blanket (web 2), as well as at top and bottom. The beryllium weight is now 11 metric tons, down from 24 tons for the mixed flow reactor. The reduction is, of course, caused by the smaller cavity diameter.

The breeder blanket and graphite reflector were kept at their former thicknesses which are determined more by the neutron absorption properties of the salt than by the moderating conditions of the beryllium. However, the reduced cavity radius reduced the salt mass dramatically. It is 21 metric tons, instead of 65.

The steel pressure vessel thickness is raised to 50 cm from 20, because the internal pressure of the reactor is now 500 atm. We used steel simply to get a feeling for the size. The answer is not critical to the conclusions about proliferation resistance.

6. Major Power Plant Subsystems

The loop that circulates the uranium back through the cavities no longer contains a heat exchanger, as the energy is transferred directly to the working fluid by thermal radiation. The loop still has a volume, of course, of piping, fuel injectors, and circulators that add to the inventory of fissile material. However, this volume is only about one-third that in the fuel loop of the mixed flow reactor.

The molten-salt processing and moderator coolant loops are essentially the same as in the mixed flow reactor.

We did not develop a detailed configuration of the fission product cleanup loop for this reactor.

7. Reactor Neutronics

To establish the breeding ratio and critical mass for the closed cycle helium gas-turbine plasma reactor, we made a series of survey runs on a single plasma cavity to find how sensitive these quantities are to cavity radius and moderator thickness. We used a one-dimensional transport code, ONETRAN.⁵ Runs for the full seven-cavity configuration (Fig. 20) involved varying the thickness of beryllium webs 1 and 2 by use of a two-dimensional code, TWOTRAN.²⁷ The geometry, including the web locations is shown in Fig. 21. The figure also shows the relationship between the physical and calculational geometries for the two-dimensional calculation.

Figure 22 shows the results of these calculations. The breeding ratio and critical mass have been plotted together to facilitate locating the critical mass. As indicated, a breeding ratio of unity can be obtained with a web 2 thickness of about 20 cm of beryllium. (A web 1 thickness of 6 cm had been selected previously as optimal.) At 20 cm, the critical mass curve reads 36 kg.

All calculations were carried out using a moderator temperature of 1 000 K.

Fig. 21. TWOTRAN geometry of closed cycle gas-turbine plasma reactor.

8. Salt Blanket Processing

The system configuration and the processing techniques for extracting ²³³U from the breeder blanket are the same for the plasma reactors as for the mixed flow reactors. There is, however, a difference in fissile inventory that results from the

Fig. 22. Breeding ratio and critical mass of closed cycle gas-turbine plasma reactor.

^{233}U concentration and power level requirements. (This is discussed in more detail in the section on salt blanket processing for the 200-MWth mixed flow reactor.)

In all reactors, the ^{233}U concentration must be at least 100 ppm for efficient extraction, so the quantity of ^{233}U present varies with the salt mass. For the closed cycle gas-turbine plasma reactor power plant, the salt mass is 21 metric tons. One-hundred ppm then means 2.1 kg.

Figure 23 shows the time history of ^{233}U in the blanket for various times (t_0) at which extraction could start. The equilibrium value of 2.1 kg is attained if processing starts on the 43rd day.

9. Fission Products

Because of the lack of time, we did not examine the methods for fission product removal from the plasma reactors in enough detail to allow us to size equipment. Therefore, we cannot say anything quantitative about the fissile material inventory in this loop.

Fig. 23. ^{233}U time history in breeder blankets of both plasma reactors.

As already mentioned, the argon is separated from the uranium centrifugally after the uranium is liquified. It seems likely that all but the volatile, inert fission products will be dissolved in the uranium.

A number of processes for extracting fission products from uranium should be examined, including vacuum volatilization, oxidative slagging, and electrorefining²⁸ and UN precipitation from molten U-Sn.²⁹

10. Power Extraction

We devised a power extraction system for the plasma core reactor in which the principal means of extracting power from the fuel would be by thermal radiation. The energy is absorbed by finned graphite rods encased in quartz tubes (Fig. 17) that surround the fuel region. (This allows the working fluid to operate at a pressure significantly different from that in the reactor.) Helium gas flows in the quartz tubes to cool the finned graphite rods convectively. Figure 20 is a cross-sectional view of all seven cells. The power extraction system is shown in Fig. 24. (Note that there are no heat exchangers in the fuel loop of the plasma reactor, a situation that reduces the fissile inventory.) This system has a helium gas-turbine cycle similar to that in the mixed flow reactor. The gas turbine is a two-shaft, multistage turbine. One shaft drives the helium compressors; the other drives an electric generator. A REGHX, a PPHX, and NTCs are incorporated in the system to increase cycle efficiency. Because of the temperature limitation on quartz, the helium outlet temperature for the uncooled quartz tube configuration is limited to 1 200 K.

The power extraction cycle assumes a turbine inlet temperature of 1 200 K and a minimum compressor inlet temperature of 320 K. Gas-cycle performance in a reactor that delivered 500 MW of power to the helium working fluid was calculated. Pressure drops in all system components were assumed to be 2% of the component inlet pressure.

Fig. 24. Power extraction loop of closed cycle gas-turbine plasma reactor.

Turbine and compressor efficiency was assumed to be 0.9, as was the effectiveness of the REGHX. The 320 K compressor inlet temperature permits use of a dry cooling tower for heat rejection; however, no specific heat rejection components were selected or evaluated.

Cycle performance for the system shown in Fig. 24 was calculated using two-, three-, and four-section compressors. Each had intercooling between individual compressor sections so that the inlet temperature to each section was 320 K. We recommend use of a three-section compressor with a total pressure ratio of 3.1 to 1.

These results indicate that the plasma core reactor power extraction system should perform as follows. For a 500-MW power input to the helium working fluid, the turbine produced 443 MW of power. Of this, 214 MW was used in the compressors, leaving 229 MW for the electric generator, which was assumed to be 0.89 efficient. The precooler and intercooler heat exchangers reject 128 and 14.3 MW, respectively. The amount of heat maintained in the helium loop by the regenerator is 513 MW. The required helium weight flow is 237 kg/s, and the overall cycle efficiency is 0.448.

This plasma reactor will require turbomachinery advances like those planned for the high-temperature gas-cooled reactor. Nickel superalloys may perform adequately up to about 1 500 K, but above that, internal cooling may be required. For 1 500-1 900 K, titanium-zirconium molybdenum blade material, small quantities of titanium and zirconium improve the molybdenum ductility at the operating temperature.^{30,31} Successful performance of turbine blades made of these materials may require extremely pure helium in the power loop to avoid changes in their physical properties.

11. Moderator

Figure 20 shows the closed cycle gas-turbine plasma reactor. In addition to that shown, there is 20 cm of beryllium on the top and bottom. We assume that the energy is deposited uniformly throughout the moderator, the amount being 12% of the fission power, the result of neutron and gamma-ray interactions.

The moderator is cooled by a flow of helium gas as in the mixed flow reactor. The gas could be supplied from a separate loop or, as this working fluid is pure helium, the working fluid itself could cool the beryllium before it enters the annuli

around the cavities. The latter approach would serve to preheat the working fluid.

The moderator consists of three major components (upper, lower, and side sections) as in the mixed flow reactor. The total moderator mass is about 11 metric tons. The upper and lower sections have a mass of about 1.6 metric tons each; the side section, about 7.8 metric tons. The helium coolant flows through passages that occupy 10% of the total moderator volume. We calculated the convective heat transfer, number of coolant channels, channel diameter, and film temperature difference between the beryllium and helium in each of the three components. A cooling sequence of lower, upper, and side moderator sections produces average temperatures of about 800 K. The upper and lower sections each contain 4 670 coolant channels, 20 cm long with 1-cm^2 cross-sectional area. The 237-kg/s helium mass flow used in the calculation is the mass flow of the working fluid (without preheating). The resulting flow velocity in the coolant channels is 15.6 m/s. The associated film temperature difference between the beryllium and the helium flow is about 41 K. In the upper and lower moderator sections, the 1-cm^2 coolant channels are arranged in a matrix of 3.2-cm spacings.

There are 2 560 coolant channels in the side section of the moderator, each 1.85 m long and 1 cm^2 in area. The film temperature difference is 25 K, and the helium flow velocity is 28.5 m/s.

The coolant channel arrangement gives an approximately uniform heat flux per unit length in each coolant channel throughout the moderator. The ratio of convective heat flux per unit length in the side, upper, and lower sections is 0.97.

For the assumed cooling sequence, the calculated bulk average temperature of the lower, upper, and side sections is 790, 797, and 801 K, respectively.

These results indicate that the moderator sections can be cooled adequately with helium so that a bulk moderator temperature

of about 800 K is maintained with a 10% coolant volume and a helium flow rate of 237 kg/s.

12. Inventory

We can now list the fissile inventory in the various subsystems of the closed cycle gas-turbine plasma reactor power plant (Table VIII). The critical mass of this reactor is smaller than that of the mixed flow reactor. Also, the quantity of fissile material held in the fuel flow loop is smaller, 7 kg compared to 22.

13. Conclusions About the Closed Cycle Gas-Turbine Plasma Reactor

This reactor appears to offer higher energy conversion efficiency at even lower fissile material inventories than do the mixed flow reactors. However, it requires advances in areas such as vortex confinement, high-temperature turbines, and materials that can withstand long-term exposure to thermal radiations.

B. Transmission Cell Plasma Reactor Power Plant

1. Vortex Confinement

The fluid mechanics and fuel confinement aspects of this cavity configuration are identical to those described for the closed cycle gas-turbine reactor power plant.

2. Fuel Region Characteristics

Because this reactor has a critical mass of 16 kg and a total volume of 1.57 x

TABLE VIII
FISSILE INVENTORY IN CLOSED CYCLE HELIUM GAS-TURBINE PLASMA REACTOR

36 kg	Total in cavities
3	Separator
1	Fuel injection ducts
1	Piping
2	Circulator
	Fission product cleanup loop
22	Auxiliary bottle
65+ kg	Plant total

10^6 cm^3 in the fuel clouds of its six cavities (see Fig. 25), the average fuel density is 10.2 mg/cm^3 . The density of the argon buffer gas at the edge of the fuel cloud is 43.5 mg/cm^3 . The average fuel density is, therefore, only 24% of the argon density in this region. The gases are hotter than those in the reactor designed for use with a closed cycle gas turbine, because of the highly reflecting surfaces in this cavity (see section on Radiant Energy Transfer). Other studies²¹ estimate the centerline temperature in this reactor to be 35 000 K. They also estimate the partial pressure of the fuel and its associated electrons to be 270 atm and the partial pressure of the argon and its associated electrons within the fuel cloud to be 230 atm. The average total density within the fuel cloud is 13.3 mg/cm^3 . This is only 31% of the argon density at the edge of the fuel cloud. Previous experiments and studies^{1,10,11,13,15} indicate that we can expect high stability in this flow pattern.

3. Cavity Structure

Figure 26 shows the design that allows the radiant energy to flow out of the cavity into a common working fluid channel (see Fig. 25). The dashed line, again,

Fig. 25. Transmission cell of plasma reactor.

Fig. 26. Cavity structure of transmission cell plasma reactor.

represents the interface between the fuel cloud and the buffer zone and, again, the argon buffer gas is injected through the longitudinal slits, whereas the molten uranium is injected through ports in the end wall.

The cavity walls are coated with highly reflective aluminum. This covers 88% of the wall surface. The other 12% is used for a radiation transmission cell that carries the thermal radiation out of the cavity. It, too, is coated with aluminum to reduce losses by absorption.

The transmission cell is closed by quartz windows. The space between them is filled with helium or argon to balance the pressures between the cavity and transmission cell. The optical transmission characteristics of the transmission cell are analysed in Ref. 30.

4. Radiant Energy Transfer

The total outward directed flux at the surface of the fuel cloud is determined by the total net power radiated, the wall reflectivity, and the total fuel cloud surface

area. With a net radiated power of 500 MW, a reflectivity of 0.91, and a total radiating surface area of $1.69 \times 10^5 \text{ cm}^2$, the outward directed heat flux is 14 kW/cm^2 . The highly reflective cavity liner alters the radiant heat transfer process from that in the closed cycle gas-turbine plasma reactor and gives a higher outward directed heat flux. Fourteen kW/cm^2 is the heat flux that would be obtained from a 7 050 K blackbody. Of the 500 MW of radiated power, 221 MW was found³⁰ to be absorbed in the cavity liner and 279 MW was incident on the transmission cell inlet plane. The power delivered to the central working fluid channel is estimated to be 185 MW, given a cell transmission of 0.66.

5. Reactor Configuration

Figure 25 shows the cross section of the final configuration of the transmission cell plasma reactor. The cavities are 0.5 m in diam by 1.85 m long as in the first plasma reactor. In this transmission cell reactor, there are only six cavities arranged so that they pour their radiation into a common working fluid channel.

Again, the cavities are embedded in a beryllium moderator whose thickness between and around the cavities is as in the first plasma reactor, 6 cm between adjacent cavities and 20 cm between the outer cavities and the salt blanket. But now, because there is no working fluid annulus immediately around each cavity, the diameter of the beryllium cylinders is smaller and the total beryllium mass reduces to about 8 metric tons. The salt blanket also reduces to about 16 metric tons.

The pressure vessel thickness is about the same because the internal pressure is still 500 atm.

6. Major Power Plant Subsystems

The power extraction loop is unspecified in the transmission cell configuration of the plasma reactor power plant. Its form would depend upon the specific application. All other loops would be the same as in the closed cycle gas-turbine reactor power plant.

7. Reactor Neutronics

The breeding ratio and critical mass of the transmission cell plasma core reactor were, again, determined by TWOTRAN runs. As before, web 1 was held at 6 cm while web 2 varied. The resulting curve, Fig. 27, shows that a unity breeding ratio is achieved at a web 2 thickness of 20.6 cm of beryllium. But now the critical mass is considerably lower, 16 kg, because of elimination of the void caused by the presence of the working fluid annulus in the gas turbine design.

8. Salt Blanket Processing

Again, the system configuration and processing techniques for extracting the ^{233}U from the breeder blanket are the same as for the other reactors. There is a small difference, however, in the time at which processing can start. This time depends on the salt mass, which is now 16 metric tons. The equilibrium value of the ^{233}U is, therefore, 1.6 kg. Figure 23 shows that this value is attained if processing starts at $t_0 = 42$ days.

9. Fission Products

The fission product extraction problem is the same in both plasma reactor designs.

10. Power Extraction

Power extraction loops were not specifically defined and analyzed, so no power generation performance figures are available for the transmission cell configuration of the plasma reactor power plant.

Fig. 27. Breeding ratio and critical mass of transmission cell plasma reactor.

However, quantitative figures for the radiant energy delivered to the working fluid channel were given in the section on radiant energy transfer.

Incorporating a working fluid channel in the design permits transport of high-temperature gases to MHD conversion equipment outside the reactor, thus preventing the conversion equipment from compromising the neutronic design. The pressure in the working fluid channel must be low because the electrical conductivity of the fluid decreases rapidly with increasing pressure. Thus, the working fluid channel structure must be able to withstand differential pressures of essentially 500 atm. The intense thermal radiation flux entering the working fluid channel may be useful for activation of various photochemical processes. One of importance to the energy problem is production of hydrogen for use as a nonpolluting fuel. Direct photolysis of water requires narrow ranges of photon energies in the uv region (wavelengths less than 200 nm). This makes broad-spectrum sources less attractive unless they can produce other forms of energy at the same time.

However, there may be a stepwise process for hydrogen production which can be driven by the thermal spectrum from the plasma reactor.³⁰ It involves, first, photodissociation of Br_2 in water to form HBr and O_2 . Next is photodissociation of I_2 in the presence of HBr to form HI and IBr . These products then undergo thermal dissociation to release H_2 , Br_2 , and I_2 .

11. Moderator

Calculations to size the moderator cooling system were not made for the transmission cell configuration of the plasma reactor since no specific power extraction system was chosen.

12. Inventory

The ^{233}U inventory of the transmission cell configuration of the plasma reactor power plant is shown in Table IX.

TABLE IX
FISSILE INVENTORY OF PLASMA REACTOR
IN TRANSMISSION CELL CONFIGURATION

16 kg	Total in cavities
3	Separator
1	Fuel injection duct
1	Piping
2	Circulator
	Fission product cleanup loop
22	Auxiliary bottle
45+ kg	Plant total

The critical mass is the only difference in the inventories of the two plasma reactors.

13. Conclusions About the Transmission Cell Plasma Reactor

This reactor has the lowest inventory of all the designs examined. With its high thermal radiation flux, it may provide a different way to generate a versatile energy source through photochemistry

VII. SUMMARY OF PHYSICAL CHARACTERISTICS

Table X shows the physical characteristics of the four gas core reactor power plants studied.

VIII. FAILURE CONSIDERATIONS

The gas core reactor differs from those that use solid fuels. This fact introduces some new failure modes and eliminates others. A few of the more important are as follows.

A failure in the primary fuel loop piping or the pressure vessel would release UF_6 , helium, and a mixture of fission products to the primary shield room. This thick-walled room would be sized to reduce the gas pressure to a low value, possibly below 1 atm. The wall might have pumping and flushing ports so the room could be cleaned largely by external operations.

Stability of the flow pattern within the reactor cavities might be important to

TABLE X
PHYSICAL CHARACTERISTICS OF GAS CORE REACTORS

	Mixed Flow	Mixed Flow	Plasma Turbine	Plasma Transmission Cell
MWth/MWe	200/80	2 500/1 000	590/200	590/300
Cavity diam (m)	1	1	0.5	0.5
Cavity length (m)	4.35	4.35	1.85	1.85
No. of cavities	7	7	7	6
Be cross web (cm)	6	6	6	6
Be outer web (cm)	20	20	20	20
Be top and bottom (cm)	20	20	20	20
Be mass (tons)	24	24	11	8
Salt thickness (cm)	20	20	20	20
Salt mass (tons)	65	65	21	16
Graphite thickness (cm)	30	30	30	30
Graphite mass (tons)	58	58	26	19
Pressure vessel thick- ness (cm)	20	150	50	50
Pressure vessel height (cm)	9	11	9	9
Pressure vessel diam (m)	4.6	6.6	4.5	3.9
Critical mass (kg)	45	45	36	16
Fuel	UF ₆	UF ₆	U metal	U metal
Fuel mixing gas	Helium	Helium	Argon	Argon
Cavity press. (atm)	100	650	500	500
Fuel temperature (K)	1 200	1 200	5 000	5 000
Mass flow rate (kg/s)	68	625	237	237
Energy extraction by	Convection	Convection	Radiation	Radiation
Working fluid	UF ₆ /He	UF ₆ /He	Helium	Helium
Plant fissile inventory (kg)	91	191	65+	45+

reactivity control. Sensitivity of reactivity control to variations in flow characteristics and to loss of circulation needs theoretical and experimental investigation.

The pipes that carry the cavity effluent to the heat exchangers pass through the plenum that distributes the moderator helium coolant to the channels in the beryllium. A pipe rupture at this point would contaminate the coolant with fission products. But, as this is a closed loop system at the same pressure as the fuel

loop, no physical damage or external contamination should be expected. Decontamination would be required, however, to allow repair of the ruptured pipe.

Radiation intensities have not been estimated but they would probably be high enough, because of both fission product plate-out and induced radioactivity, to prohibit hands-on repair in some parts of the system. Development of remote maintenance and repair capabilities will be required.

The classical "loss-of-coolant and core meltdown" failure does not apply to the gas core reactor. Because the core is already gaseous, the response to loss of circulation probably would be to dump the fuel gas into the two large tanks provided for temporary fuel gas storage during maintenance shutdown. In addition, the reactor has a negative temperature coefficient that would decrease reactivity as the temperature increased. We have not estimated the magnitude of this coefficient but it must be negative.

"Decay heat" failure should not be a worry either in the gas core reactor. The fission products are most concentrated during normal operations. If they have not melted anything under these conditions, they will do even less thermal damage during a failure that distributes them more widely. Sensitivity of reactivity control to loss of circulation can be illuminated by theoretical and experimental investigation.

IX. PLANT LAYOUT

Figure 28 is a conceptual layout of a 200-MWth mixed flow gas core reactor power plant. The reactor, primary loop components, gas-handling equipment, and other supporting equipment are in a leaktight cylindrical reinforced concrete secondary containment building. Wings, or extensions of the secondary containment, house the UF_6 and helium cleanup system, molten salt breeder blanket reprocessing system, and general purpose maintenance hot cells.

Mechanical and electrical equipment, maintenance areas, operating areas, and the power generating equipment are arranged around the perimeter of the secondary containment facility.

The highly radioactive components, reactor, NTHX, LTHX, getter, and circulator are isolated from the rest of the equipment by heavy shielding walls. This area is shielded to improve accessibility to adjacent areas and equipment. This inner shield

Fig. 28. Plant layout.

also protects against fission product leakage from the contaminated UF_6 and helium primary loop system. If sealed, it provides a third barrier to fission product release analogous to the triple barrier afforded by the fuel pin, reactor vessel, and secondary containment of a commercial LWR.

Provision for direct maintenance of the primary loop components is not shown. Access to the equipment is from overhead by removal of shield slabs. Removal by the overhead crane and replacement of any component that fails may be the most economical solution. Some provision for handling small items in nearby hot cells is shown in the layout.

Circulators are shown whose drive systems are protected from the circulator by drive extensions through the shield walls. This concept assumes use of shaft seals capable of preventing UF_6 and fission product leakage.

Access to the reactor internals is also from overhead. If the reactor were opened, the interior would be exposed to air and moisture. Considerable care is required to first purge the reactor of volatile fission products before maintenance, and clean it of oxygen and moisture before recharging the system with UF_6 and helium.

Surrounding the primary loop and outside the shield is auxiliary equipment such as vacuum and helium-transfer pumps, valves, controls, compressor motors, piping, manifolds, sample stations, instrumentation, and other such support equipment that is normally relatively free of fission product contamination, but which could become contaminated if there are equipment failures.

A number of hot cells are shown in the area to be used for routine analysis, some small-scale operations, and maintenance of small equipment.

Large helium storage tanks are shown in separately shielded areas. If the

primary loop were vented to the storage tanks, they would become contaminated and be a source of background radiation. The complete inventory of UF_6 and helium is held in these tanks during shutdown for repair or maintenance when the primary loop has to be depressurized or evacuated. Having these tanks shielded permits more access to the secondary containment structure.

Helium and UF_6 cleanup and processing and breeder blanket reprocessing are remote operations that use relatively small-scale piping, valves, and equipment. These operations are assumed to be conducted and maintained by conventional hot cell techniques and handling equipment, and an extensive hot-cell facility is shown. A remote system is also assumed for waste handling, processing, and packaging. Ultimate disposal of radioactive waste off-site in international waste repositories is assumed. The alternative would be to provide for long-term disposal on-site.

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