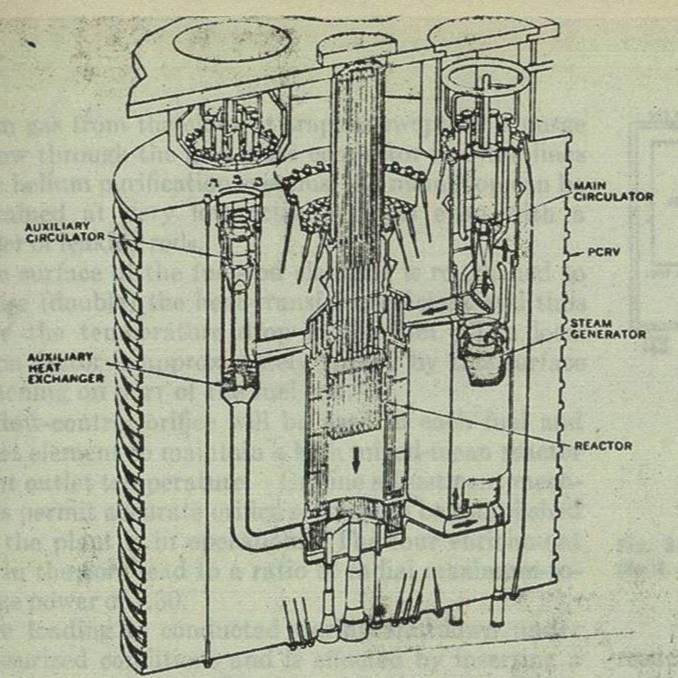


Fig. 1 300-MW(e) GCFR demonstration plant.

The primary coolant system contains three main loops, each with independent boilers and circulators, Fig. 1 (right), and three auxiliary loops, Fig. 1 (left), each with its own circulator and heat-removal system. The auxiliary loops are used for long-term shutdown cooling and as backup for the main loops. The steam generators and their associated circulators are housed in vertical cavities in the walls of the prestressed concrete vessel surrounding the reactor core. The helium coolant, at a pressure of about 1250 psia, flows downward through the core where it is heated to a temperature of 1007 F. The flow is also downward across the tube banks of the helical-coiled once-through steam generators to accommodate ~~the~~ use of upflow boiling in the generators.

The reactor outlet gas flows up through a central hole in the tube bundles, down through the resuperheater and steam generator, and up again around the boiler shells to top-mounted circulators, from which it is discharged to the reactor top plenum at a temperature of 593 F.

The three main coolant circulators each have a single-stage axial blower driven by a series steam turbine in the high-pressure steam line. Thus, a mechanically simple and very compact power source provides the necessary large circulator power (22,300 hp each), making each main loop as self-contained and independent of the others as possible. In addition, afterheat initially provides power for its own removal. Circulation for auxiliary cooling is provided by centrifugal circulators, each driven by a 500-hp electric motor.

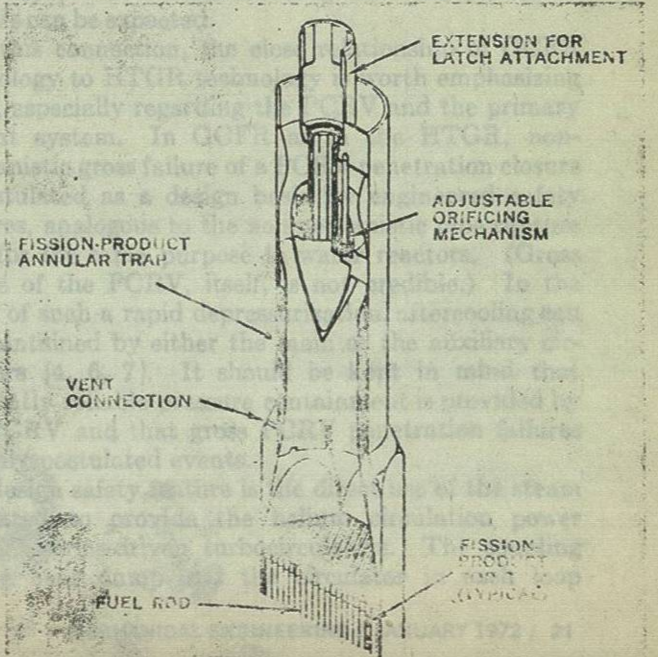
The reactor assembly contains 118 hexagonal fuel and 93 blanket elements. The elements, which are 10 ft in length and $6\frac{1}{2}$ in. across flats, are supported from a top-mounted grid plate. They are clamped to the grid plate solely at their cold ends. Irradiation-induced metal swelling will be accommodated in the design of the core by the provision of a 0.25-in. gap between adjacent elements in the active core region. Bowing due to differential swelling will be minimized by rotation of elements at partial refueling intervals. The fuel-element-to-grid-plate clamps and variable orifices of each element are actuated by external mechanisms that have drive shafts above each element through the top access plug.

Each standard fuel element contains 271 fuel rods. The fuel rods consist of annular $(Pu{-}U)O_2$ pellets within a 316 stainless steel cladding about 20 mil thick. Upper and lower axial blankets are contained in the ends of the fuel rods and consist of depleted UO_2 pellets. The blanket elements each have 127 rods of larger diameter that contain depleted UO_2 pellets.

The fuel-rod design conditions include a maximum temperature of 700 C (1292 F) at mid-thickness of the fuel cladding (including hot-spot factors), a cladding thickness ratio of 1.15, and a "smeared" fuel density within the cladding of 80 percent of theoretical density. The maximum design burnup was chosen to be 100,000 Mwd/tonne, and the maximum linear rating (with 10 percent overpower) is 13.8 kw/ft. These design parameters were selected after evaluation of existing irradiation data and are within the range now planned to be tested in the AEC's Fast Flux Test Facility (FFTF) and in the LMFBR demonstration plant programs.

The fuel rods are vented to equalize internal gas pressure to that of the reactor coolant outside the rod. This eliminates the need for a rod designed to prevent cladding creep collapse and will provide a demonstrated basis for reducing cladding thickness in later designs in order to increase plutonium production through better conversion ratio. Radiation monitors on the vent lines leading to the helium purification system provide means for detecting any leaks in the fuel rods. The fuel elements contain charcoal-filled fission-product delay traps in each of the fuel rods and also a single second-stage trap in the inlet end of the fuel element, as shown in Fig. 2. These traps are well cooled and delay the passage of the volatile and gaseous fission products long enough to minimize subsequent heat release. The arrangement permits adequate trapping for the life of the element even with several leaking rods in an element. Helium entering such a leak has, of course, no effect on reactor operation, and since the flow of vent

Fig. 2 Section through GCFR fuel-element inlet.



system gas from the element traps is swept by a purge gas flow through the grid plate connector into the lines to the helium purification systems, the main loop can be maintained at very low activity levels even with a number of leaking rods.

The surface of the fuel-rod cladding is roughened to increase (double) the heat-transfer coefficient and thus reduce the temperature drop in the film. The local friction factor is approximately tripled by this surface roughening on part of the fuel rod.

A flow-control orifice will be used in each fuel and blanket element to maintain a high mixed-mean reactor coolant outlet temperature. On-line adjustment mechanisms permit accurate orifice settings to be established while the plant is in operation. The four enrichment zones in the core lead to a ratio of radial maximum-to-average power of 1.30.

Core loading is conducted during shutdown under depressurized conditions and is effected by inserting a fuel-transfer machine through the bottom of the PCRV. This machine lowers and traverses fuel in the vacant space below the core to a single exit port leading to a transporting cask beneath the vessel structure [3]. Partial core reloading will occur at approximately annual intervals, one-third of the core being changed every year.

Reactivity control is by 27 rods in the control fuel elements, which have central channels to accommodate the rods. The control-rod drives are located above the reactor. Normal operation of the reactor, requiring a total reactivity swing of $17, including a minimum $3 shutdown margin at all times, is provided by 21 control rods, each of which is limited for safety reasons to $0.85 worth. The six shutdown rods, each having a value of $1.60, form a backup system capable of independently shutting down the reactor from any anticipated operating conditions.

Protection of the PCRV liner and ducts from neutron irradiation is provided by thermal shielding. Around the core this shielding takes the form of a replaceable inner layer of steel blocks surrounded by an annular region consisting of steel cylinders containing graphite. Cooling of the radial shielding is by a small bypass from the inlet helium.

The concrete plugs above the steam generators incorporate large central holes for circulator removal and smaller surrounding holes for steam pipes. Steam generator tube plugging can be done externally; the main penetration closure is removed only for complete removal of the steam generators.

The GCFR steam cycle is noteworthy in that resuperheaters are used following the circulator turbines. This, in effect, confers most of the advantages of normal reheat and provides steam dry enough to avoid the necessity for moisture separation in the main turbine.

Fig. 3 shows a simplified heat-balance diagram for the demonstration plant. In each main loop, hot helium (at 1007 F) out of the reactor first reheats the steam in a resuperheater, after which the helium flows into the superheater, evaporator, and economizer sections of the steam generator. It then passes through a helium circulator before it is returned to the reactor at 593 F (311 C). The main steam flow goes through a blower turbine, is returned to the steam generator to be

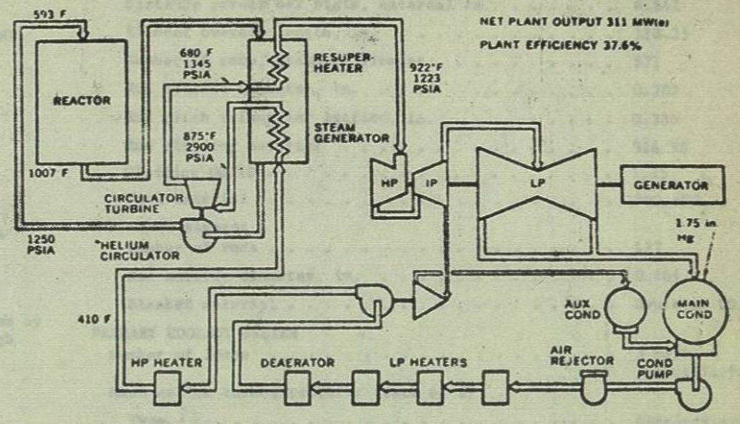


Fig. 3 Simplified heat-balance diagram for GCFR demonstration plant.

resuperheated to 925 F, and then goes to the main turbine. The net cycle efficiency of 37.6 percent leads to a net electric power of 311 MW(e) for 875 F, 2900-psi steam conditions at the superheater outlet. The steam conditions at the main turbine throttle are 922 F and 1223 psia. Further design data on the demonstration plant are given in Table 1.

Safety Considerations

A major effort has been placed on safety studies [4] and these have continued to confirm the advantages of helium as a reactor coolant. There are no possible change-of-phase problems nor are there any cladding–coolant, fuel–coolant, or steam–coolant reactions to design for; engineering for overall system safety is, therefore, eased.

An important design safety feature of the GCFR is the enclosure of the entire primary coolant system in the PCRV, thereby eliminating primary coolant ducts. Because of the conservative design bases, the highly redundant prestressing system, and the predictable, noncatastrophic failure modes, PCRVs are considered by many to have desirable safety features [5]. As design, construction, and operational experience accumulates with the 20 PCRVs both in this country and in Europe, wider understanding and acceptance of PCRVs can be expected.

In this connection, the close relationship of GCFR technology to HTGR technology is worth emphasizing again, especially regarding the PCRV and the primary coolant system. In GCFR as in the HTGR, nonmechanistic gross failure of a PCRV penetration closure is postulated as a design basis for engineered safety features, analogous to the nonmechanistic pipe rupture used for the same purpose in water reactors. (Gross failure of the PCRV, itself, is not credible.) In the event of such a rapid depressurization, aftercooling can be maintained by either the main or the auxiliary circulators [4, 6, 7]. It should be kept in mind that inherently reliable pressure containment is provided by the PCRV and that gross PCRV penetration failures are only postulated events.

A design safety feature is the direct use of the steam generated to provide the helium circulation power through series-driven turbocirculators. The coupling of the heat dump and the circulator in each loop

TABLE 1 300-MW(e) GCFR Demonstration Plant Data Summary

GENERAL	
Average breeding ratio	1.33
Maximum fuel burnup, MWd/Te heavy metal	100,000
Net electrical power, MW(e)	311
Plant efficiency, %	37.6
Steam conditions at main turbine	
Throttle pressure, psia	1223
Throttle temperature, °F	922
Condenser pressure, in Hg, absolute	1.75
Reactor coolant	Helium
Reactor coolant pressure, psia	1250
Reactor vessel and primary containment	PCRV
PCRV dimensions, ft	84 diam by 17 high
REACTOR	
Reactor geometry	
Core height, in.	39.2
Core length-to-diameter ratio	0.5
Axial blanket length, each end, in.	17.7
Reactor subassemblies	
Standard fuel elements	91
Control fuel elements	27
Radial blanket elements	93
Core volume fractions, %	
Fuel	30.1
Helium coolant	44.6
Cladding	10.0
Structure	6.0
Gaps (box interspace, control-rod channel)	9.3
Reactor heat transfer	
Helium temperatures	
Reactor inlet, °F (°C)	593 (312)
Mixed mean outlet, °F (°C)	1007 (541)
Average power density, kWt/liter of core	238
Maximum linear rating (10% overpower), kW/ft	13.8
Hot-spot cladding temperature, °F (°C)	1290 (700)
Radial maximum-to-average power	1.30
Axial maximum-to-average power ratio	1.20
Rod surface roughening	
Fraction of active core length roughened, %	75
Roughening heat-transfer multiplier	2
Roughening friction-factor multiplier	3
Maximum heat flux, Btu/(hr)(ft^2)	520,000
Core and axial blanket power fraction, %	95.55
Radial blanket power fraction, %	4.45
Nuclear characteristics (midcycle)	
Fissile core loading (Pu), kg	1320
Average fast neutron flux (E > 0.1 MeV), n/cm^2-sec	2.2 x 1
Reactor rating, MW(t)/kg fissile	0.605
Doppler constant, TdK/dT (T in °K)	-0.0032
Fuel lifetime, full-power days	750
Partial refueling cycle, yr	1
Fuel element	
Distance across hex flats, external in.	6.642
Element overall length, in.	118.25
Number of rods, standard element	271
Rod outside diameter, in.	0.282
Rod pitch triangular lattice, in.	0.386
Rod cladding material	316 SS
Cladding OD/ID	1.15
Fuel material	PuO_2-UO_2
Blanket element	
Number of rods	127
Rod outside diameter, in.	0.464
Blanket material	Depleted UO_2
PRIMARY COOLANT SYSTEM	
Number of loops	3 main, 3 auxiliary
Main helium turbocirculator (each of 3)	
Type	Single-stage axial
Drive	Steam turbine
Pressure rise, psi	60
Brake horsepower (per circulator)	22,300
Steam generators (each of 3)	
Type	Helical once-through
Heat duty, Btu/hr	8.45×10^8
Surface area, ft^2	33,400
Feedwater temperature, °F	412
Steam outlet temperature, °F	875
Steam pressure, psi	2900
Resuperheater	
Type	Helical
Heat duty, Btu/hr	1.47×10^8
Surface area, ft^2	3600
Steam temperature out, °F	925
Auxiliary heat exchanger (each of 3)	
Type	Helical, water cooled
Heat duty, Btu/hr	56.4×10^6
Surface area, ft^2	1180
Auxiliary circulator (each of 3)	
Type	Single-stage, centrifugal
Drive	Electric motor
Brake horsepower (per circulator)	500
TURBINE GENERATOR	
Type	TC6F-23
Speed, rpm	3600
Gross electrical output, MW	316
SECONDARY CONTAINMENT	
Type	Reinforced concrete
Inside diameter, ft	114
Height, ft	176
Atmosphere	Air
Equilibrium pressure, atm, absolute	2

increases the reliability of cooling. The GCFR turbocirculators are similar in concept and in many details to the HTGR turbocirculators.

The primary system is designed to operate with a limited amount of steam inleakage and the effect on reactivity is negative.

The use of pressure-equalized fuel rods also has important safety benefits. Most important is the elimination of fuel failure modes due to cladding collapse from high external pressure (at start of irradiation) or due to cladding deformation or rupture from internal fission-gas pressure (later during irradiation).

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