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System Design Description for GCFR-Core Flow Test Loop

W. R. Huntley

A. G. Grindell

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W. R. Huntley A. G. Grindell

Date Published: December 1980

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LIST OF ACRONYMS

ANSI	American National Standards Institute
ASME	American Society of Mechanical Engineers
BN	boron nitride
BRS	blanket rod simulators
CACS	Core Auxiliary Cooling Systems
CAMAC	Computer Automated Measurement and Control
CFTL	Core Flow Test Loop
CRT	cathode ray tube
DAS	data acquisition system
DBDA	design basis depressurization accident
DDC	direct digital controller
DEC	Digital Equipment Corporation
DOE	Department of Energy
emi	electromagnetic interference
FCV	flow control valve
FE	flowmeter
FRS	fuel rod simulators
GA	General Atomic Company
GCFR	Gas-Cooled Fast Breeder Reactor
HX	heat exchanger
IEEE	Institute of Electrical and Electronics Engineers
IVR	induction voltage regulator
LMFBR-THORS	Liquid-Metal Fast Breeder Reactor-Thermal-Hydraulic Out-of-Reactor Safety Facility
MTI	Mechanical Technology Incorporated
NEMA	National Electrical Manufacturers Association
ORNL	Oak Ridge National Laboratory
OSHA	Occupational Safety and Health Administration
PLC	program logic controller
PSS	Plant Shift Superintendent
QAPP	quality assurance program plans
RAM	random access memory
SCR	silicon-controlled rectifier

THTF	Thermal-Hydraulics Test Facility
UCC-ND	Union Carbide Corporation-Nuclear Division
UPS	uninterruptible power supply
VSFM	vortex-shedding flowmeters

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SYSTEM DESIGN DESCRIPTION FOR GCFR-CORE FLOW TEST LOOP

W. R. Huntley A. G. Grindell

ABSTRACT

The Core Flow Test Loop, which is a part of the Gas-Cooled Fast Breeder Reactor Program (GCFR) at the Oak Ridge National Laboratory, is sponsored by the Division of Nuclear Power Development of the Department of Energy. It is a high-pressure, high-temperature, out-of-reactor helium circulation system that is being constructed to permit detailed study of the thermomechanical and thermal performance at prototypic steady-state and transient operating conditions of simulated segments of core assemblies for a GCFR Demonstration Plant, as designed by General Atomic Company. It will also permit the experimental verification of predictive analytical models of the GCFR core assemblies needed to reduce operational and safety uncertainties of the GCFR. Full-sized blanket assemblies and segments of fuel rod and control rod fuel assemblies will be simulated with test bundles of electrically powered fuel rod or blanket rod simulators.

The loop will provide the steady-state and margin test requirements of bundle power and heat removal, and of helium coolant flow rate, pressure, and temperature for test bundles having up to 91 rods; these requirements set the maximum power, coolant helium flow, and thermal requirements for the loop. However, the size of the test vessel that contains the test bundles will be determined by the bundles that simulate a full-sized GCFR blanket assembly. The loop will also provide for power and coolant transients to simulate transient operation of GCFR core assemblies, including the capability for rapid helium depressurization to simulate the depressurization class of GCFR accidents.

In addition, the loop can be used as an out-of-reactor test bed for characterizing in-reactor test bundle configurations.

1. FUNCTION AND DESIGN REQUIREMENTS

1.1 Function

The Core Flow Test Loop (CFTL) will provide a test bed in which electrically powered simulators of the Gas-Cooled Fast Breeder Reactor Program (GCFR) core assemblies such as full-scale blanket assemblies and segments of fuel and control assemblies will be operated in accordance with the requirements of the Program Plan^{1.1} to obtain both steady-state

and transient data. The assemblies are planned for use in a GCFR Demonstration Plant, as designed by General Atomic Company (GA).^{1,2} A complete understanding of all CFTL functions can only be gained by perusal of Ref. 1.1 and amendments thereto.

1.2 Operating Requirements

1.2.1 Steady-state operation

Table 1.1, which specifies the steady-state operational requirements for the CFTL, is taken from Refs. 1.1 and 1.3.

Test bundle power. The CFTL will provide up to 4100 kW of electric power suitable for operation of the rods in the test bundles. Normal rod heating power will be uniformly controllable in the total array of rods and also by zones (rows of rods) from $100 \pm 1\%$ to about 0.5%. The lower limit of power controllability is required in special tests of single fuel rods with a 37-rod bundle where power will be reduced to about 300 W/rod. Maximum rod power is equal to 45 kW/rod for blanket rods and 38 kW/rod for fuel rods. The zone controls will permit skewed power operation of the test bundles at slopes ranging from 0 to ~4% per transverse centimeter (10% per in.).

Test bundle helium coolant. The CFTL will provide helium coolant to the test bundle for inlet temperatures from 260°C to 350°C (500°F to 660°F) and pressures up to 10.6 MPa (1540 psia) at mass flow rates up to 2.77 kg/s (6.1 lb/s); this flow is sufficient to remove the heat from a 91-rod fuel test bundle. The CFTL will normally operate at a helium pressure of 10.5 MPa based on recent criteria changes that raised the operating pressure from the earlier value of 9 MPa. The design pressure is 11.8 MPa (1715 psia).

The flow rate of the helium coolant will be controllable from $100 \pm 1\%$ to approximately 0.3% of design to provide the steady-state coolant flow requirements of different bundle sizes, as indicated below:

Fuel bundle	37, 61, and 91 rods
Blanket bundle	61 rods
Control rod bundle	up to 90 rods

Table 1.1. Steady-state operating requirements in the CFTL

Coolant	Helium
Design pressure, MPa (psia)	11.8 (1715)
Maximum operating pressure, MPa (psia)	10.6 (1540)
Normal operating pressure, MPa (psia)	10.5 (1520)
Minimum operating pressure, MPa (psia)	0.1 ^a (14.5)
Test bundle data	
Test bundle ΔP , kPa (psi)	278 ^b (40.4)
Inlet temperature, °C (°F)	
Nominal	320 (610)
Minimum	260 (500)
Maximum	350 (660)
Outlet temperature, °C (°F)	
Nominal	550 (1020)
Minimum	260 (500)
Maximum	593 (1100)
Maximum total helium flow, kg/s (lb/s)	3.2 (7)
Helium flow per rod	
Core maximum, g/s (lb/h)	30.5 (242)
Blanket maximum, g/s (lb/h)	27 (215)
Core maximum linear power rating, kW/m (kW/ft)	33.6 (10.2)
Axial maximum-to-average power ratio	1.21
Maximum transverse fuel power gradient, %/cm (%/in.)	4 (10)
Minimum transverse power gradient, %/cm (%/in.)	0 (0)
Maximum hexagonal duct length, mm (in.)	4500 ^c (177.2)
Total simulated fuel rod length, mm (in.)	2860 (112.6)
Simulated core length, mm (in.)	1200 (47.2)
Axial blanket length (lower end), mm (in.)	940 (37)
Axial blanket length (upper end), mm (in.)	720 (28.3)
Maximum power per fuel rod, kW	38
Nominal power per fuel rod, kW	28
Simulated radial blanket rod length, mm (in.)	Unspecified to date
Power per blanket rod, kW	45

^aTesting is limited to atmospheric pressure and above.

^bDoes not include losses at inlet and outlet of test vessel.

^cThe maximum hexagonal duct length is much longer than the fuel rod simulator lengths presently specified to allow for possible changes in GCFR core design.

Present GA Test Specifications^{1.4} call for testing a single heated rod within a bundle and for operating a bundle in the laminar and transition flow regimes at flow rates as low as 12 g/s, or about 0.4% of maximum flow rate.

Approach-to-clad melting. During the approach-to-clad melting tests (margin tests) some actual clad melting may occur. The CFTL design will accommodate this happening and provide filters, as required, to catch the debris and protect the helium circulator and flow control valves from the deleterious effects of the debris. These tests will operate far above GCFR design temperatures when bundle power remains relatively high and flow is reduced. Figure 1.1 was prepared by GA^{1.5} and shows the expected maximum clad temperatures for various combinations of coolant flow rate and rod power. It is noted that the specific rod parameters for bundle

Fig. 1.1. Bundle AG-1 maximum clad temperature. (Courtesy of GA; Ref. 1.5).

AGI shown in Fig. 1.1 may be somewhat different from the final reference design. The maximum continuous operating temperature limit shown for fuel rod simulators (FRS) with Nichrome V heating elements was provided by Oak Ridge National Laboratory (ORNL) based on test results from prototypic fuel rod simulators. Tests of the FRS have shown their ability to operate for short periods at even higher temperatures than indicated in Fig. 1.1, but the risk of rod failure is, of course, greatly increased.

1.2.2 Transient requirements

The CFTL will be designed to impose the GCFR transients on the test bundle indicated in Refs. 1.1 and 1.6.

Flow transients. The following flow-time values bound the transient flow performance that is estimated to simulate the GCFR:

1. full flow to 10% flow in 16 s,
2. full flow to 10% flow in 4 s,
3. full flow to 10% flow in 2 s,
4. full flow to 10% flow in 1 s, and
5. full flow to 5% flow at a constant rate of flow decrease of no more than 450 g/s^2 (1 lb/s^2).

Flow tolerance could not be established by ORNL until after the method of flow measurement was selected. An accuracy of $\pm 1\%$ of reading was a desired goal, as indicated in Table 3 of the Test Specification.^{1.4} The desired accuracy of $\pm 1\%$ of reading has been obtained by the successful extension of the capabilities of the vortex-shedding flowmeter (VSFM) system in lieu of conventional venturi meters. Typical change of flow with time during a reactor trip is shown in Fig. 1.2.

Power transients. The following power-time values bound the transient power performance that is estimated to simulate the GCFR:

1. full power to 10% power in 16 s,
2. full power to 10% power in 4 s,
3. full power to 10% power in 2 s,
4. full power to 10% power in 1 s, and
5. full power to 5% power at a constant rate of power decrease of no more than 2 kW/s per rod.

Fig. 1.2. Flow rate of core coolant helium and core power vs time during a GCFR reactor trip. (Courtesy of GA; Ref. 1.1).

Power tolerance will be established by ORNL after the power control and measurement systems are proof tested. An accuracy of $\pm 1\%$ of reading from 200 W to full rod power is indicated as a desired goal in Table 3 of Ref. 1.4. Tests of prototypic equipment at ORNL indicate that this goal may be obtainable. The typical change in power with time during a GCFR reactor trip is shown in Fig. 1.2.

Depressurization transients. The design basis depressurization accident (DBDA) for the GCFR is defined as a leak area of 0.05 m^2 (75 in.^2)

from a pressure of 10.5 MPa (1520 psia). In addition to the DBDA, various leak areas from 0.006 m^2 to 0.06 m^2 will be simulated to provide depressurization transients similar to those shown below:

1. operating pressure of 10.5 MPa (1520 psia) to 0.15 MPa (22 psia) in 8 min,
2. operating pressure of 10.5 MPa to 0.15 MPa in 4 min,
3. operating pressure of 10.5 MPa to 0.15 MPa in 2 min,
4. operating pressure of 10.5 MPa to 0.15 MPa in 85 s, and
5. operating pressure of 10.5 MPa to 0.15 MPa in 1 min.

These pressure-time values bound the pressure transients that are estimated to simulate depressurization accidents in the GCFR. Figure 1.3

Fig. 1.3. Coolant pressure during depressurization of GCFR from 9 MPa. (Courtesy of GA; Ref. 1.1).

shows the typical course of depressurization for several helium leak sizes with the GCFR operating at 9 MPa rather than the prescribed 10.5 MPa.

The tolerance of final pressure is ± 4 kPa (0.5 psi). Capability will be provided to vent the system to attain atmospheric pressure.

The GCFR cladding temperatures for best-estimate and conservative models of the DBDA from 9 MPa with two or three of the Core Auxiliary Cooling Systems (CACS) operating are shown in Fig. B.5 of Ref. 1.6 and are reproduced in Fig. 1.4 of this report. The CFTL will be programmed to simulate GCFR performance and depressurization during DBDA testing. As the GCFR performance/accidents are detailed, refined data will be prepared to program the CFTL to simulate reactor power, bundle inlet temperature, flow rate, system pressure, and gas composition variations during the DBDA, which will cause clad temperatures similar to those shown in Fig. 1.4.

Fig. 1.4. Maximum cladding temperature for a 0.05-m^2 (75-in.^2) depressurization accident from 9 MPa with calculational model and number of operating loops as parameters. (Courtesy of GA; Ref. 1.6).

Air may be introduced into the loop during DBDA simulations. Air content in the helium may range up to 10% by volume during the later stages of a DBDA. The present GA Test Specifications call for about 25 DBDA simulations in the entire test program.

Summary of operating requirements. A summary of anticipated loop operating requirements in both steady-state and transient operation for both the 37- and 91-rod fuel bundles is shown in Table 1.2. This table was prepared to show the range of powers, flow rates, etc., expected during operation of the CFTL. The table is based on a maximum power of 38 kW/rod and on extrapolations of a draft of the detailed specification^{1,4} for all test bundles; it is preliminary in nature. However, loop design will proceed for these ranges of test conditions because detailed test specifications are expected to be similar for subsequent refinements. The test loop will provide 4100-kW maximum capability for the bundles, and the heat sink system will have the capability to reject both this bundle heat and the circulator power. The helium circulators will provide up to 3.2 kg/s (7 lb_m/s) to the entire loop, including 2.8 kg/s (6.1 lb/s) to the test bundle.

1.3 System Configuration and Essential Features

The CFTL will consist principally of a primary loop (helium system) that will include the necessary helium circulation equipment, the test vessel, two air-cooled heat sinks, fast-acting control valves for helium, airflow dampers, a full-flow filter, and connecting piping. It will also have a variable-flow helium purification system and an impurities-injection system installed in side loops. The test vessel, which provides the pressure boundary for test bundles, will be designed for the upward vertical flow of helium coolant.

Electrical control equipment will be located as close as practicable to the test vessel. The loop itself will be designed to provide adequate flexibility for thermal expansion of the loop piping and adequately long runs of straight pipe for accurate measurement of helium flow. Adequate space will be provided for the fast-scan data acquisition system (DAS) and the control room.

Table 1.2. Summary of electric power and test pressure requirements for fuel rod bundles

	Power per rod (kW)	Pressure ^a (MPa)	37 rods 34 rods, powered bundle power (kW)	91 rods 85 rods, powered bundle power (kW)	Table numbers in GA Test Specifications, Ref. 1.4
	(1)	(2)	(3) = 34 × (1)	(4) = 85 × (1)	(5)
A. Steady-state operations					
1. Normal range, uniform and skewed power	38 ^b –0.25	10.5–5	1292–8.5	3230–21	2, 4, 8, 9
2. Transition and laminar flows, uniform and skewed power	0.7–0.205	10.5–0.2	23.8–7.0	59.5–17.4	2, 8, 9
3. Single rod, thermal mixing	38–0.3	10.5	38–0.3	To be determined	10
4. Severe undercooling, margin	38–8.4	10.5	1292–235	3230–714	17
B. Transient conditions					
1. Normal, load changes					
a. 100–10% in 30 min	38–2.8	10.5	1292–95.2	To be determined	11, 12
b. Step change, 100–90% in 20 s	38–25	10.5	1292–850	To be determined	11, 12
c. Skewed power transients	30–10	10.5	1292–340	3230–1063	12
2. Upset, reactor scram	38–2.05	10.5	1292–70	3230–174	5, 13, 14
3. Emergencies	38–1.7	10.5	1292–53	3230–145	6, 15
4. Fault, depressurization accident	38–1.12	10.5–0.15	1292–33	3230–95	7, 16

^aCore operating pressure increased to 10.5 MPa. Reference: GCFR Plant Program Project Directive No. 13/GCFR Plant Parameters, GCFR-M-2170, October 15, 1979.

^b38 kW from Table 1.1 of Ref. 1.1.

The loop will be totally enclosed in a metal enclosure that provides adequate thermal and acoustic protection for personnel. Suitable access doors will be provided for personnel entry and equipment installation.

Hoisting equipment will be provided, as required, for the installation and removal of the test vessel. The test bundles will be installed within the test vessel at a separate assembly area, and the bundle-vessel assembly will then be moved to the loop enclosure, where the test vessel will be lifted into position and the required piping and electrical connections will then be made.

1.4 Design Life

The loop will be designed to meet the requirements of the test programs outlined in the Program Plan^{1.1} and also to sustain the steady-state conditions shown in Table 1.1 and the transients indicated below:

	<u>Transients</u>	<u>Number</u>
Normal		
	Rapid power and flow increase and decrease, 5% per min (100 to 10%)	2,000 cycles
	Step power and flow increase (90 to 100%) and step decrease (100 to 90%)	2,000 cycles
	Normal power and flow increase and decrease, 3% per min (100 to 10%)	18,000 cycles
	Most rapid power and flow cycling from 100 to 10% (~50% per min)	15,000 cycles
Upset		
	Reactor trip (see Fig. 1.2)	500
Emergency		
	Slow depressurization (10.5 to 0.15 MPa)	100
Faulted		
	Programmed depressurization (10.5 to 0.15 MPa)	100

1.5 Materials

The pressure-retaining boundaries of the high-pressure, high-temperature helium circulation system will be constructed of appropriate

grades of austenitic stainless steel or Inconel alloy. The sheath for the FRS and blanket rod simulators (BRS) will be austenitic stainless steel.

The loop enclosure will be constructed of low-carbon-iron sheet metal.

The helium supply for the loop will have no more than the following levels of impurities:

Oxygen	3 ppm	Moisture	3 ppm
Nitrogen	5 ppm	Hydrogen	1 ppm
Carbon-bearing gases	1 ppm	Neon	23 ppm

1.6 Mechanical Requirements

A principal pressure boundary requirement for the CFTL is the capability to sustain the steady-state and transient operating conditions presented in Sect. 1.2 and to provide the design life indicated in Sect. 1.4.

1.6.1 Test vessel

The test vessel that provides the pressure boundary for the test bundle will utilize bolted mechanical flanges to facilitate installation and removal of individual test bundles. The flanges will provide sufficient leak tightness to retain the helium inventory with its burden of controlled impurities in order to facilitate impurity control and minimize sizes of impurities-injection devices. The test vessel, presently envisioned to be 382-mm-OD (15-in.) $\times$ 10.2-mm-thick (0.4-in.) Inconel 625, will accommodate the largest anticipated bundle, the full-sized blanket test bundle. During meltdown transients the temperature of the pressure boundary for the test vessel will be maintained at safe limits by a bypass stream of 350°C helium. This bypass or attemperating flow of helium is also used to lower the temperature of the helium coolant departing from the test bundle before the combined streams leave the test vessel. The test vessel design will permit operation of the pressure boundary up to 480°C (900°F) during all steady-state and transient operations. The line connecting the test vessel outlet to the heat-exchanger inlet and the inlet and upstream portions of the heat exchanger must sustain temperatures

associated with the depressurization transients ($<600^{\circ}\text{C}$), but this higher temperature occurs with the system at reduced pressures of 1 to 2 atm.

The attemperation helium flow used to maintain the temperature of the test vessel walls within appropriate limits will be thermally decoupled as much as practical from the test bundle to minimize the loss of bundle heat to the attemperation stream. The thermal inertia of the decoupling means will be as small as practical to minimize the amount of heat stored or given up to the test bundle during power and flow transients.

The test vessel is defined as the pressure vessel that is fixed to the piping by welds and is considered one of the components of the loop pressure boundary. The test vessel includes the 382-mm-OD pressure shell, core flow and attemperation flow inlet nozzles, inlet and exit gas plenum regions, and the gas mixer at the test vessel exit. Stainless steel mechanical flanges are attached at both the top and the bottom of the test vessel. The top flange provides experimental access to the downstream end of the bundle while the test vessel is installed in the CFTL and the helium system is depressurized.

The test bundle is removable and includes fuel rod simulators, a mechanical flange tube sheet to which the rods are seal welded, a hexagonal duct, bundle instrumentation, quick-connector leads for electrical and instrument connections, and the circular duct that guides the attemperation flow past the test bundle to the upper gas plenum of the test vessel. A new test bundle will be provided for each of six planned CFTL bundle tests. The design of the test bundle is not described in detail in this document, since this is considered part of the test program.

The test section is defined as that part of the test bundle that simulates the GCFR core assembly and does not include the test vessel inlet or outlet regions.

The CFTL will provide data acquisition equipment for structural measurements such as hanger rod axial load, duct vibration, acoustics, rod movement, and bundle distortion. The specific structural measurement equipment for a given test bundle will be described in the System Design Description for CFTL Test Bundles. An x-ray imaging system will be provided to observe deflection of both the hexagonal bundle shroud and specified individual rods, as practical.

1.6.2 Loop piping

The main loop piping will be designed for a normal flow velocity of approximately 27 m/s (90 ft/s) and for maximum velocities up to 40 m/s (130 ft/s) during DBDA simulations. It will have sufficient wall thickness to sustain the maximum design pressure of 11.8 MPa (1715 psia) and design temperatures ranging from 400°C to 590°C (750°F to 1100°F) and to accommodate all the steady-state and transient operating conditions presented in Sect. 1.2.

Seismic design of the loop piping or components will not be provided since the test loop is to be installed in, and attached to, an existing building that was not designed or constructed in accordance with current seismic requirements.

1.6.3 Helium circulators

Helium will be circulated through the loop with three gas-bearing circulators operating in series. System controls are designed to minimize the deleterious effects of helium flow and temperature transients on the helium circulators.

The helium circulation aerodynamic specifications are tabulated below. Notice that the design temperatures and pressures shown here were selected early in the project and are slightly lower than present design criteria that were arbitrarily increased for the rest of the loop. However, helium circulation equipment is capable of sustaining the maximum design pressure of 11.8 MPa (1715 psia) and design temperature of 370°C (700°F).

	9 MPa (1300 psia)	10.3 MPa (1500 psia)
Maximum flow rate, kg/s (lb _m /s)	3.2 (7.0)	3.2 (7.0)
Maximum head required, kJ/kg (ft-lb _f /lb _m)	78 (26,170) ^a	73 (24,420) ^b
Maximum outlet helium temperature, °C (°F)	350 (660)	350 (660)

^aEquivalent to 547 kPa (79.4 psi) for three circulators operating in series.

^bEquivalent to 589 kPa (85.5 psi) for three circulators operating in series.

1.6.4 Helium coolant flow control

The helium flow control system will be capable of sustaining the maximum design conditions of 11.8 MPa (1715 psia) and 400°C (750°F) and of providing the steady-state operations indicated in Sect. 1.2.1 and Table 1.1 and the transient operations described in Sect. 1.2.2.

1.6.5 Helium supply

The helium supply system will consist of a helium trailer station capable of charging the helium system volume of approximately 3.1 m³ (110 ft³) from atmospheric pressure to 4.8 MPa (~700 psia) in 1 h. A smaller makeup helium supply, located in close proximity to the loop, will supply helium to trim loop pressure during normal operation with the CFTL at operating pressure. Alternatively, the main helium supply will provide the trim function.

1.6.6 Helium purification

The concentration of impurities in the helium system will normally be controlled within the ranges given in Table 1.3 (based on Table 5.5 in Ref. 1.1) by the coordinated operation of an impurity addition station and a helium purification system. The goal is to obtain specified partial pressures of these impurities in the helium system at test-program conditions of temperature and pressure. Note that the neon concentration

Table 1.3. Helium impurities operating ranges
at a nominal loop pressure of 10 MPa

Impurity	Partial pressure range (Pa)	Impurity	Partial pressure range (Pa)
H ₂ O	2.5-850	CO	≤120
H ₂	40-8500	CO ₂	≤12
N ₂	≤120	Ne	≤230
O ₂	≤24	Hydrocarbon (CH ₄)	≤24

shown in Table 1.3 is 60 Pa higher than specified in Ref. 1.1, because as-received helium may contain this much neon, and the neon cannot be removed by the purification system. However, this amount of neon is not significant to the test program. Provisions for impurity addition will be limited to the two gaseous impurities, water vapor and hydrogen. Other impurities, except neon, will be maintained at or below the levels shown in Table 1.3, but no provisions will be made for additions of N_2 , O_2 , CO , CO_2 , or hydrocarbons.

The flow rate of impure helium through the purification system will be sufficient to process one loop volume in a maximum of 1 h. The pressure head across the helium circulators will be used to provide flow through the purification system. The system will be capable of in situ regeneration in 8 h.

1.6.7 Helium coolant heat sink

The heat added to the helium coolant by the test bundle FRS and the helium circulation equipment will be removed with heat sinks consisting of a helium-to-air heat exchanger (HX) and supporting cooling air system. One heat sink (HX-1) will be located in the main loop downstream of the test vessel and another (HX-2) in a recirculating bypass line around the helium circulators. The two heat sinks will be sized to reject heat generated in the test bundle and helium system during the specified steady-state operation of the test bundle and during test bundle power transients by convenient control of helium and cooling airflow rates. The helium inlet and outlet temperatures for the main loop heat exchanger, HX-1, will be 593°C (1100°F) and 323°C (620°F), respectively; for the circulator heat exchanger, HX-2, they will be 350°C (660°F) and 315°C (600°F), respectively.

1.6.8 Depressurization

A depressurization system will be provided to conduct the depressurization accidents at the programmed rates of change presented in Sect. 1.2.2. The depressurization will also be coordinated simultaneously with test bundle power and helium coolant flow rates, as indicated in Ref. 1.4.

Since the system volume of helium is small (3.1 m^3) and only a few (~6) depressurization accident simulations are planned for each test bundle, the vented helium will not be recycled.

1.7 Instrumentation and Control Requirements

For CFTL, conditions such as bundle power; circulator speed; helium coolant temperature, pressure, and flow; impurities; and heat sink fluid flow and temperature will be measured and controlled, indicated and recorded, and monitored for alarm and automatic action to protect the test bundle, the helium system, and other components from the damaging consequences of loss of helium coolant flow or pressure, loss of power, and other harmful changes in operating conditions.

High-speed data acquisition capability will be provided to help monitor the loop operating conditions and to record the steady-state and transient data in the quantity and manner required by programmatic needs.

Consideration will be given to the use of the high-speed data acquisition capability to provide automatic instrument calibration and verification to reduce CFTL downtime during changeout of test bundles. It may be practical to use the DAS to check the continuity and identification of and to measure the electrical resistance of bundle rod power and thermocouple circuits, and to characterize thermocouple response behavior.

1.8 Maintenance Requirements

1.8.1 Helium purification system

The helium purification system will be provided with access necessary to permit maintenance and replacement of any component.

1.8.2 Test vessel

The CFTL design will provide access and the necessary headroom and hoisting equipment capacity for convenient removal and installation of the test vessel (with the test bundle installed within the vessel) and for making, breaking, and maintaining the many connections to the test bundle power supply and the DAS. The helium pipes that connect the test vessel

to the loop piping will be cut and rewelded whenever the test vessel is replaced.

1.8.3 Components and equipment

The loop design will provide convenient access for hands-on maintenance and for the removal and replacement of the principal components and equipment such as electric power supply and control equipment, helium circulation equipment, test vessel, heat exchangers, and associated cooling air equipment, coolant helium flow control equipment, and instrumentation.

1.9 Safety Requirements

1.9.1 Loop enclosure

The loop will be totally enclosed to protect personnel from contact with high-temperature piping and components. The sheet metal portions of the enclosure will be provided with fiberglass blanket insulation to protect personnel within Building 9201-3 from the noise associated with the operation of high-velocity gas equipment systems and will comply with Department of Energy (DOE) and Occupational Safety and Health Administration (OSHA) requirements.

1.9.2 Helium pressure

The loop and the helium purification system will be protected against the consequences of the application of pressure and (coincident) temperature in excess of safe operating conditions in accordance with the requirements of Article NC-7000 of Section III of the American Society of Mechanical Engineers Boiler and Pressure Vessel Code (ASME Code).

1.9.3 Operational safety

The output of instruments that measure helium pressure, flow, and temperature; helium circulator power and speed; cooling water flow; thrust-bearing film thickness; helium impurity levels; and test bundle power will be monitored and provided with alarms and automatic control

equipment, as required, to protect the test bundle and the loop and its components against operating conditions outside established limits.

1.9.4 Missile protection

The helium circulation equipment, which will be located within the enclosure, will not require special missile protection because the circulator diffuser section has been shown to be adequate to contain impeller fragments following failure at full speed.

Helium piping will be restrained at critical locations to prevent excessive piping movement in the unlikely event of a rupture.

1.9.5 Fire protection

The CFTL will be designed and equipped with adequate fire extinguishing equipment, as required by accepted fire protection engineering practice.

1.10 Surveillance and In-Service Inspection

All equipment except the high-pressure, high-temperature components will have convenient access for maintenance, cleaning, and inspection during loop operation. The high-pressure, high-temperature components will be installed totally within an enclosure that will have access for maintenance and inspection of the components during loop shutdown. The instrument readouts, including data acquisition equipment, will be serviced on a scheduled basis. Those instruments that initiate automatic control actions and the equipment that provides the control will be interrogated periodically for proper functioning.

1.11 Codes and Standards

1.11.1 Helium system components

The components and piping in the helium circulating system will be constructed in accordance with the rules of ASME Code, Section III, Nuclear Power Plant Components, Class 1 and Class 2 Components.

1.11.2 Helium purification system

The helium purification system is an adjunct system installed in an isolable side loop of the helium circulating system; it will be constructed to the specifications of Section VIII, Division 1, of the ASME Code.

1.11.3 Electrical systems and equipment

Electrical systems and equipment will be designed in accordance with the latest issue of the following codes:

1. National Electrical Code,
2. National Electrical Code Handbook,
3. Institute of Electrical and Electronics Engineers (IEEE) Standards,
and
4. National Electrical Manufacturers Association (NEMA) Standards.

1.11.4 Instruments and controls

Instruments and controls will be designed in accordance with the following ORNL standards:

1. ORNL Instrumentation and Controls Division Design and Drafting Standards (Division Procedure IPD-5)
2. Instrumentation and Controls Division Engineers Manual
 - Part I Instrument Specifications
 - Part II Test and Evaluation Reports and Inspection
 - Part III Instrument Reports
 - Part IV Engineering Standards

1.12 Quality Assurance

The piping and components of the high-pressure, high-temperature helium loop system, which will be constructed to the specifications of Section III, Class 1 and Class 2 of the ASME Code, will meet the requirements of the ORNL Quality Assurance Program. The ORNL Quality Assurance

Program is responsive to the requirements of OR-IMD-02XX, Oak Ridge Operations Quality Assurance Standard. Quality Assurance for CFTL data gathering and retrieval will also comply with ANSI N45.2.^{1.7}

All other components and systems that may be constructed to the rules of Section VIII, Division 1, of the ASME Code will meet the requirements of the ORNL Quality Assurance Program.

Individual instrumentation and controls will also meet the requirements of the ORNL Quality Assurance Program. Redundancy and diversity of instrumentation and controller systems — utilized as indicated by dynamic analysis and experimental judgment to protect the loop and particularly the test bundle against the consequences of pressure, temperature, helium or cooling airflow rates, or test bundle power exceeding prescribed bounds — will be designed to provide for the reliability and the continuity of loop operation.

Appropriate quality assurance program plans (QAPP) will be prepared and followed for the CFTL. Three separate QAPP will be prepared as the CFTL progresses; they will cover (1) loop construction, (2) test bundle construction, and (3) loop operation. The QAPP for loop construction and test bundle construction have been issued as documents No. Q-11590-ET-001-S-0 and Q-11590-ET-002-S-0, respectively.

1.13 Interface Requirements

The proposed CFTL test site in Building 9201-3, Y-12 Plant, Oak Ridge, Tennessee, provides the site requirements indicated below. The building has sufficient space for the full-sized CFTL and a contiguous control room and data acquisition room. It also has sufficient space to accommodate fabrication, assembly, and disassembly activities for test bundles. The site accommodates the requisite lengths of piping runs needed for accurate measurement of helium flows and satisfactory control of the nozzle loadings imposed by differential thermal expansion on anchored equipment. In addition, the site has been modified to provide ample headroom and hoisting capability to remove and replace the test vessel and to handle the test vessel as it is moved between the loop and the bundle assembly area. The site accommodates the location of the

electrical and helium supplies and controls close to the CFTL helium system. The CFTL has access to 6.5 MW of the building's 40-MVA transformer. It will require a new, reliable emergency power supply of approximately 7.5 kW to permit monitoring of CFTL operating conditions and shutting down in a safe fashion in an emergency.

1.14 Environmental Requirements

During operation the CFTL will reject heat at various rates up to a maximum of approximately 4.5 MW of heat. Infrequently the helium inventory (about 25 kg) will be vented to the atmosphere. The CFTL does not contain radioactive material or toxic materials and therefore will not impose them on the environment. Thus, the overall effect of the CFTL on the environment will be minimal.

1.15 Reliability Requirements

The importance of critical-component reliability to CFTL test runs and to the overall program is recognized. It is also recognized that statistical analysis of such component reliability would be limited in scope (or nonexistent) because production quantities of CFTL critical components are small and their application is unique. Therefore, in order to ensure the highest practical degree of reliability, the best design, development, test and inspection, and quality control practices will be followed in the design, procurement, fabrication, installation, and development of such components as fuel rod simulators, coolant helium circulators, heat sinks, flow control valves, test bundle power supply and controls, and other components and auxiliary systems.

1.16 Construction and Installation Requirements

Union Carbide Corporation-Nuclear Division (UCC-ND) will be responsible for providing, at the test site, appropriate handling and processing equipment, skilled craft manpower, and the requisite supervisory and planning functions necessary to install the mechanical and electrical equipment and the instrumentation and controls that comprise the CFTL.

1.17 Test Bundle

1.17.1 Fuel rod simulator requirements

Cycling requirements for fuel and blanket rod simulators. Individual BRS and FRS will operate satisfactorily at steady-state levels up to 45 kW and 38 kW, respectively, at coolant outlet temperatures approaching 600°C (1100°F). Rod design will provide the following cycling capability:

	Number of cycles or events
Step increase and decrease in power (90 to 100% and return)	150
Rapid power change (100 to 10%) in 1 s	20
Power change (100 to 10%) and return (within minutes)	1200

Clad melting requirement for special rods. Special rods may be developed that are capable of operation up to the point of clad melting, with operation continuing for periods of several seconds after melting initiates (even though the rod is still being powered).

Rod cladding. Rods will be sheathed in 316 stainless steel, with a post-fabrication condition equivalent to 20% cold work. To ensure that the cladding is prototypic of the GCFR fuel cladding, GA will specify, purchase, roughen, and inspect all FRS tubing that will be used in CFTL test bundles.

Instrument lead access. Access for rod instrument leads will be made from the entrant end of the rod only.

Rod replaceability. Individual rod replaceability in a test bundle would be highly desirable if a practicable method can be found. However, in designs to date no reasonable method for individual rod replacement is evident.

1.17.2 Bundle power

The control of FRS power during transient operation will impose as closely as practical the same values of thermal flux and temperature on the FRS cladding as is experienced by the GCFR cladding during the same

transient. The objective is to simulate GCFR fuel rod cladding performance, which requires compensation in test bundle power operation to reflect the differences in internal structure between the GCFR fuel rod and the CFTL FRS.

2. DESIGN DESCRIPTION

2.1 Summary

The CFTL will be located in Building 9201-3 (the site building) at the Y-12 Plant in Oak Ridge, Tennessee. It will be a helium system consisting of the following components and auxiliary systems: helium circulation equipment, helium filter, flow control devices, test vessel, and interconnecting piping; helium supply, pressure control, and purification; gaseous impurities injection; appropriate heat sinks and cooling airflow control; a test bundle mounted within the test vessel and a power supply and control system for the test bundle; the instrumentation and controls for the loop; a fast-scan DAS to record test bundle data; an electronic controller to control loop operation; and a loop and bundle protection system.

The loop will have the capability to subject test bundles of electric cartridge heaters (called FRS or BRS, or merely rods or simulators) that simulate segments of GCFR core assemblies to all the operating conditions, both steady state and transient, that are anticipated for the GCFR and are presented in Sect. 1. The rods in the test bundle will simulate the geometry and heating rates of individual GCFR core assembly rods and will be arranged in the test bundle to simulate the configuration of the rods in a segment of a GCFR core assembly.

The components of the helium system will be supported and enclosed within a concrete, terra-cotta, and steel structure. The instrumentation and controls and the DAS will be located in a control room adjoining the loop. A hoist will be installed over the test vessel to assist in the installation and removal of the test vessel. All the ordinarily required utilities are already installed in the building.

The CFTL will be built in three stages to reach 91-rod bundle capacity and full transient testing capability. The staged approach was taken to achieve operational experience and performance data at the earliest time within budget constraints. Although the full capability of the CFTL is described throughout the report, Sect. 2.4 describes the partial capability that will exist for Stage Alpha and then Stage I.

2.2 Detailed Loop Description

The flow paths for the helium system and the various modes of its operation are described briefly to indicate how the functional and design requirements for the CFTL will be fulfilled. Other design features are described briefly.

Figure 2.1 presents a schematic flow diagram of the CFTL helium system showing the principal components and the interconnecting piping to aid the description of the helium flow paths and the modes of operation for the CFTL. The main path for coolant helium flow will be from the circulators (three single-stage units) through the test vessel, into HX-1, through the full-flow filter, and back to the circulator inlet to begin the same cycle again. Helium can bypass the test vessel (the main flow path) through the circulator bypass line, which includes HX-2. A bypass flow of attemperation helium will enter the test vessel separately from the test bundle helium coolant through flow control valve FCV-2 and flowmeter FE-7 and will be mixed with the helium coolant at the test bundle exit. The purification helium will flow in a separate bypass line from the circulator outlet through the purification system and then will re-enter the helium system at the circulator inlet.

During both steady-state operation and the various simulated GCFR transients, the helium coolant flow through the test bundle, which will be measured with flowmeter FE-4, will transport heat generated in the bundle to HX-1, an air-cooled heat exchanger designed to dissipate the maximum heat generation anticipated for the CFTL. The degree of mismatch that exists between GCFR reactor power and coolant helium flow rates during various transients described in the Program Plan^{1.1} will be simulated as closely as practical with programmed control of test bundle power and helium flow rate. Plans for performing the programmed control are discussed later.

As the test bundle flow is reduced to simulate a GCFR reactor trip, the circulator flow rate, which will be measured with flowmeter FE-11, will be maintained nearly constant by increasing the flow rate in the circulator bypass line. In this line HX-2 will be used to remove heat generated in the circulators and by helium circulation in the bypass during

Fig. 2.1. CFTL flow diagram.

this time. Flowmeter FE-9 will be used to assure the operators that the helium flow is being controlled as required in the circulator bypass line. Dynamic analysis indicates that the helium temperature at the circulator inlet will change less than 30°C during the simulated trip. Thus, the circulators will operate at nearly constant conditions during a simulated trip without experiencing the rapid changes in temperature and flow rate seen by the test bundle.

During steady-state operation, a small flow of attemperation helium in an annulus surrounding the test bundle will maintain the temperature of the test vessel pressure boundary nearly constant. The attemperation flow path will also be used in the approach-to-clad melting tests, during which, starting from steady-state design conditions and holding the test bundle power constant, the test bundle flow rate will be reduced and the attemperation flow rate will be increased in the same increments to maintain the total helium flow rate through the test vessel at a constant level. This will serve to protect the test vessel pressure boundary from the high temperatures in the test bundle. Also, mixing the two streams just downstream of the test bundle exit will serve to maintain the temperature of the exit helium nearly constant. Thus, the effects of the temperature and flow changes imposed on the test bundle during approach-to-clad melting will be minimized on the pressure boundary throughout the remainder of the loop.

However, during simulation of the decay heat removal portion of the DBDA with a 91-rod fuel bundle simulating the 0.065-m^2 (100-in.^2) leak, the limited flow of attemperation helium available to reduce the mixed helium exit temperature may permit the temperature of the vessel exit helium to exceed the design limit for the pressure boundary material for brief periods of time. The maximum expected temperature is greatly dependent on the final pressure level, e.g., 0.15 MPa or 0.1 MPa. If excessive temperatures occur, then special cooling features will be considered for the gas piping between the test vessel exit and the inlet to HX-1, the areas primarily affected.

The depressurization valve, FCV-50, will permit rapid reduction in the CFTL helium pressure from the maximum operating pressure of 10.6 MPa to as low as 0.15 MPa (22 psia) in as short a time as 60 s. If a final

pressure lower than 0.15 MPa is required for DBDA simulations, the venting system will have to be augmented by vacuum pumping.

Air may be injected up to 10% by volume into the loop helium to simulate the back diffusion of the containment helium-air mixture into the GCFR primary loop during a DBDA. Nitrogen was originally considered to mockup air ingress during a DBDA to minimize damage to loop components other than the test bundle. However, air would better simulate the accident at the test bundle by providing oxidation of grid spacers and rod surfaces. Dynamic analysis of the CFTL during a 91-rod DBDA simulating a 484-cm² (75-in.²) leak to a final pressure of 0.15 MPa has shown peak mixing pipe outlet gas temperatures of 634°C (1173°F) when operating at the nominal power level of 28 kW/rod. The major damage to the loop would be oxidation at 634°C (caused by ~10% air ingestion) on the inner surfaces of the gas mixer, the pipe leading to HX-1, and the inlet portions of HX-1. Oxidation of 304 stainless steel at these conditions would provide a thin, tightly adherent oxide layer during the total few hours of high-temperature operation expected during the DBDA simulations. For test bundles smaller than 91 rods, the maximum temperature after a DBDA will be less than 634°C because more attemperation flow is available for cooling purposes. Therefore, it appears reasonable to inject air into the CFTL to precisely mockup oxidation effects on the bundle structure during depressurization accidents. Severe oxidation of the full-flow sintered metal filter would also be a problem if this resulted in increased pressure drop in the helium circuit. However, this appears unlikely because the filter is located downstream of HX-1 and operates at a lower temperature of 340°C (650°F). The filter element is replaceable and could be exchanged if oxidation of the filter element caused plugging.

The gaseous impurities in the coolant helium that are required by the Program Plan will be introduced in a controlled manner through the impurity fill station. The concentrations of those impurities that may react with the helium system components in numerous ways will be maintained at prescribed levels by the operation of the helium purification system in conjunction with the impurity fill station. A mode of operation will be sought to minimize both the rate of impurity injection into the helium system and the flow of cleanup helium through the purification system.

A nominal pipe size of 168 mm (6 in., sched 80) was chosen for the helium system interconnecting piping instead of the 114-mm-OD (4-in., sched-80) size to reduce the head requirement for the circulators; the velocity heads that determine pressure loss are a factor of approximately four smaller with the larger pipe. As discussed elsewhere, there are exceptions to the use of sched-80 pipe to provide added strength or thermal shock resistance at the test vessel exit. Also, 114-mm-OD (4-in., sched-80) pipe is used in some flowmeter runs to provide higher velocities to improve flow measurement accuracy during low flow rate operation.

Helium coolant flow rate through the test bundle is regulated primarily with a valve, FCV-1, having a fast-acting hydraulic operator that is controlled automatically or manually as needed. In general, the circulator will be operated at constant speed to obtain the maximum coolant flow requirements for the specific bundle size being tested. The heat generation rate in the test bundle is regulated with an electronic controller that is also controlled either manually by the operator or automatically by a programmer-controller. The manual controls permit the operator to obtain the various steady-state operating conditions of bundle coolant flow rate and power required for the CFTL. Simultaneous, interlocked programmed regulation of the two independent controls for coolant helium flow rates and test bundle power will be provided to permit simulation in the CFTL of all the anticipated GCFR flow and power transients. The programmed regulation will also control the cooling airflow rate through HX-1 and HX-2 during transient operation to minimize the change in helium temperature at both the test bundle inlet and the circulator inlet.

The test vessel inlet will be designed to assist in attaining fully developed longitudinal flow in the test bundle flow channels upstream of the start of the heated zone, which simulates the fueled section in a GCFR fuel pin. A mixer will be designed downstream of the test vessel to mix the cooling attemperation flow from the annulus with the high-temperature helium from the test bundle. A full-flow filter will be installed in the piping downstream of HX-1 to protect loop components from debris that would be associated with an actual melting of the sheaths of the test bundle rods that may occur during approach-to-clad melting operation. The filter has been located downstream of HX-1 to permit design for the lower

temperature available there. The lower operating temperature reduces the pressure shell thickness accordingly. Also, thermal stress considerations for the filter pressure vessel during transient tests are ameliorated in this case, as compared to those of a filter location immediately upstream of HX-1.

The loop components and interconnecting piping will be made primarily of austenitic stainless steel, designed for a pressure of 11.8 MPa (1715 psia) and constructed according to the rules of Section III, Class 2 of the ASME Code as supplemented by the Proposed Codes and Standards for the CFTL.^{2.1} This will provide some margin for the operation of the Code-required pressure relief system above the maximum operating pressure of 10.6 MPa (1540 psia). The helium purification system and the test vessel will be constructed according to Section VIII and Section III, Class 1 of the Code, respectively. The design temperatures for the components and interconnecting piping will reflect their function and location in the loop. The minimum and maximum design temperatures for the pressure boundaries will be 370°C (700°F) and 590°C (1100°F), respectively.

The system components (except for the purification system) are slightly oversized in flow areas to accommodate 3.2 kg/s (7 lb_m/s) of helium at the normal operating pressure of 10.5 MPa (1520 psia) and 350°C (660°F). The purification system is sized to accommodate helium flow rates up to approximately 1 liter/s at 10.5 MPa (1520 psia). The approximate volume of the helium system is 3.1 m³ (110 ft³).

The heat sinks will be sized to accept approximately 4.4 and 0.4 MW from HX-1 and HX-2, respectively. A 4.1-MW power and control system will be provided to supply the test bundle with electricity.

2.3 Loop Performance Characteristics

Because the CFTL will be constructed to simulate power and coolant helium transients that are being anticipated in the design of the GCFR Demonstration Plant, thought was given in the conceptual design to enhance the reliable operation of the test bundle and various components of the helium system by protecting them, as practicable, from the deleterious effects of these transients.

Simultaneous and programmed reduction in test bundle power and coolant helium flow rate during simulated GCFR transients imposes sufficient mismatching to change coolant helium temperature distribution in the helium system. However, the controls of the system will be designed to maintain nearly constant the helium temperature at the inlet to the test bundle and both helium temperature and flow rate at the inlet to the circulator. The circulator bypass valve, FCV-3, will be opened to increase bypass flow rate as closely as practical to the increment at which the test bundle flow rate is being decreased, thus maintaining the flow rate through the circulator nearly constant. The flow rates of cooling air to HX-1 and HX-2 will be regulated to maintain the temperature of coolant helium at the test bundle inlet and circulator inlet as nearly constant as practical or to follow a prescribed transient.

In an approach-to-clad melting, the bundle power is maintained constant, while the coolant helium flow rate is reduced incrementally. The attemperation flow rate through the annulus that surrounds the test bundle will be increased incrementally to maintain constant the helium coolant flow rate through the main flow path. Thus both the heat load on HX-1 and HX-2 and the circulator flow will remain constant.

Results of preliminary dynamic analysis of simulating depressurization accidents indicate that there should be no significant changes in coolant helium temperature at the inlet of the circulator, which probably will be run continuously at a preset speed during depressurization.

When the CFTL is shut down in an emergency (scrammed), which will occur primarily upon unprogrammed loss of coolant helium flow to the test bundle, loss of helium system pressure, or loss of power to the circulators, the appropriate signal will turn off the test bundle power automatically and nearly immediately to protect the test bundle rods. The helium circulators and the cooling air blowers to the heat exchangers will be turned off, and the airflow control valves at the inlets to the blowers will be closed as appropriate to reduce the consequential effects of the thermal quench on the helium system components; all these actions will be performed automatically.

2.4 Capacity and Capability of Stage Alpha and Stage I CFTL

A stage construction approach to achieve 91-rod bundle capacity and full transient capability for the CFTL has been adopted formally^{2.2} by the GCFR participants: DOE, GA, Helium Breeder Associates, and ORNL. In this approach the design of the full 91-rod capacity and full transient capability for the Stage II CFTL will be completed as soon as practical. However, we will construct first a Stage Alpha CFTL and then a Stage I CFTL. The reduced capacity and capability of the Stage I CFTL will be described briefly here. In addition, the further reduced capacity and capability of the Stage Alpha will be summarized briefly also. The deferred equipment for the Stage I and Stage II CFTL will be designed, purchased, and installed as needs require and funding permits. Although the Stage I CFTL will not be equipped to simulate GCFR depressurization accidents or for on-line helium purification control, it will be able to accomplish the majority of the tests specified in Ref. 1.4 for the first CFTL test bundle, which will have 37 rods. Table 2.1 summarizes the specified tests that can be accomplished in the Stage I CFTL with a 37-rod bundle. However, only steady-state deflection of the test bundle can be observed and this by the ad hoc use of conventional x-ray source and film.

Only limited control of helium purity will be provided in the Stage I CFTL. Helium will be vented from the loop in batch-mode operation and replaced with as-received helium from the Bureau of Mines. Power skews can be simulated for a 37-rod bundle with the installed seven power zones by varying the power level in each row of rods within the bundle. However, it will be impossible to impose a row-by-row skewed power distribution on a 61-rod or larger bundle until six additional zone power supplies are installed to provide 13 zone supplies for the Stage II CFTL. Test section flows will be fully controllable for all steady-state and constant pressure transient conditions, as outlined elsewhere in this report and in the Test Specification.^{1.4} Major components being deferred to Stage II include the bypass heat exchanger, HX-2, the associated bypass line around the circulator, six zone power supplies, a spare circulator, the helium purification system, the depressurization system, the impurity addition system, the gas chromatograph, and the x-ray imaging system.

Table 2.1. Specified tests of a 37-rod bundle
that can be accomplished in the Stage I CFTL

	Number of tests	
	Stage I	Stage II
Steady-state flow, unheated	11	
Normal transients, unheated	36	
Upset transients, unheated	5	
Emergency transients, unheated	~3	
Depressurization transients, unheated		5
Steady state, uniform power	31	
Steady state, skewed power	33	
Steady state, single heated rod	82	
Normal transients, uniform power	13	
Normal transients, skewed power	25 ^a	
Upset transients, uniform power	5	
Upset transients, skewed power	3	
Emergency transients, uniform power	2	
Depressurization transients, heated		As required
Margin tests (undercooling)	36	4 ^b
Total	285	

^aOne test includes 1200 cycles at 145 s/cycle.

^bMay test to rod failure in this series.

It was believed initially that the elimination of HX-2 from the Stage I CFTL would restrict the capability to perform rapid transients simulating GCFR scrams. This was based on the purpose of the bypass line and HX-2, which is to divert the excess flow of relatively cool gas from the circulator discharge (that becomes available during simulated scrams) away from HX-1, and thus alleviate what might otherwise be a thermal shock to HX-1. However, on more careful consideration, it has been determined that because of the low total power input associated with the 37-rod bundle, HX-2 is not essential to the simulation of GCFR scrams with the 37-rod

bundle. During 37-rod bundle operation, judicious choices of circulator operating point and attemperator flow will permit operation of HX-1 at an initial temperature distribution low enough that thermal quenching of HX-1 in a scram is not a problem. Thus, the Stage I CFTL will have the capability to simulate GCFR power scrams with a 37-rod bundle. However, scrams with a 91-rod bundle will cause excessive thermal shock at HX-1 unless HX-2 is available.

Simulation of a DBDA must await installation of the deferred depressurization system during Stage II. On-line measurement and control of helium purity and adjustment of H_2/H_2O ratios in the circulating helium cannot be done in Stage I because this requires installation of the gas chromatograph, moisture monitor, helium purification, and impurity addition systems, which are deferred equipment also.

A summary of the capabilities of the Stage I CFTL is shown in Table 2.2.

The principal differences between the Stage Alpha and Stage I CFTL are (1) elimination of the test vessel-test bundle and the attemperation line, (2) reduction of heat source capacity from approximately 3 to 0.5 MW, and (3) elimination of the equipment to perform the scram transient. A simple bridge pipe to be installed in place of the test vessel will provide a closed helium circuit to permit the shakedown and performance operation of the helium circulation system, the heat sink, and the reduced heat source prior to installation of a test piece.

2.5 Loop Arrangement

Figure 2.2 shows an isometric drawing of the major mechanical components of the helium system. The helium piping and related components are mounted within a loop enclosure that is approximately 15 m long, 7 m wide, and 9 m high. The two existing exterior terra-cotta and concrete walls of Building 9201-3 form two sides of the enclosure, and the two interior walls of the enclosure will be fabricated of new metal panels. The enclosure walls protect personnel from equipment noise and from contact with the high-temperature components of the loop. Entry of personnel to the loop enclosure will be limited administratively during operation.

Table 2.2. Summary of capabilities of the Stage I CFTL

Coolant	Helium
Design pressure, MPa (psia)	11.8 (1715)
Maximum operating pressure, MPa (psia)	10.6 (1540)
Minimum operating pressure, MPa (psia)	0.1 (14.5) ^a
Test bundle data	
Test bundle ΔP (maximum), kPa (psi)	278 (40.4) ^b
Inlet temperature, °C (°F)	
Nominal	320 (610)
Minimum	260 (500)
Maximum	350 (660)
Outlet temperature, °C (°F)	
Nominal	550 (1020)
Minimum	260 (500)
Maximum	593 (1100)
Maximum total helium flow, kg/s (lb/s)	3.2 (7)
Helium flow per rod, g/s (lb/h)	30.5 (242)
Maximum core flow for 37 FRS, kg/s (lb/s)	1.13 (2.5)
Test section power total, kW	3500
Seven independent circuits, kW each	500
Maximum transverse fuel power gradient, %/cm (%/in.)	4 (10)
Minimum transverse power gradient, %/cm (%/in.)	0 (0)
Total simulated fuel rod length, mm (in.)	2860 (112.6)
Maximum power per fuel rod, kW	38
Nominal power per fuel rod, kW	28
Simulated radial blanket rod length, mm (in.)	Unspecified
Power per blanket rod, kW	45
Depressurization test capability	None
Helium purification	None
Spare circulators	None
X-ray deflection measurements	Film only, steady state only

^a Testing at slightly higher pressure (0.15 MPa) may be done.

^b Does not include losses at inlet and outlet of test vessel.

Fig. 2.2. CFTL.

The three helium circulators are located at the north end of the loop enclosure. Motor removal fixtures are provided on each circulator to allow precise removal procedures if disassembly, inspection, or maintenance is required on the circulator internals. Helium flows in series through the three circulators and can then be routed as required to the test bundle inlet via FCV-1 to the attemperatur annulus via FCV-2, or to HX-2 via FCV-3. Helium passing through either HX-1 or HX-2 rejoins at a tee upstream of the full-flow filter, and the helium then returns to the circulator inlet.

The test vessel is mounted vertically and is installed or removed by means of an overhead crane. A Grayloc mechanical flange is located at the bottom of the test vessel to permit removal, installation, and sealing of the test bundle within the test vessel. A similar flange is located at

the top of the test vessel to allow inspection of the region during installation of the test bundle and to provide access for experimental modifications as the test program evolves from one test bundle to the next.

Cooling air for both heat exchangers is introduced through the east enclosure wall. The air flows upward through the heat exchangers, and the heated air is then exhausted through the exterior enclosure walls to the atmosphere.

The relative location of the helium loop and its supporting facilities is shown in Fig. 2.3. The loop is located on the second floor of Building 9201-3. The control room is located adjacent to, and north of, the loop on the second floor. The control room will be air conditioned

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Fig. 2.3. CFTL and supporting facilities.

to provide a suitable ambient for the automatic DAS and loop controls that utilize many solid-state components. The floor space of the control room is about 19 m long by 8 m wide. The primary electric power supply, test bundle power supply, and circulator power supplies are located immediately below the loop on the first floor. Due to space limitations on the first floor, the electric equipment is closely grouped. A small mezzanine was added in the first floor equipment room to accommodate some of the required electric equipment.

A penthouse with a monorail crane and the air-handling equipment for both heat exchangers are located on the roof immediately above the loop enclosure. The roof-mounted equipment is shown in Fig. 2.3 as an exploded view with the roof elevated above true position to allow a view of the main loop equipment. The penthouse and crane are used to remove or install the test vessel. The smaller filter house and air blower for HX-2 can provide airflows up to 5.7 m³/s (12,000 cfm). The larger filter house and air blower supply up to 35 m³/s (75,000 cfm) of cooling air to HX-1.

2.6 Loop Component Design Description

2.6.1 Helium circulators

Three single-stage centrifugal circulators operated in series will circulate helium in the CFTL. The pressure-retaining boundary for each circulator will be hermetic and will be classified, designed, constructed, and stamped in accordance with the rules for a Class 2 component in Section III of the ASME Code. Each circulator rotary assembly will consist of an impeller, drive motor rotor, and journal and thrust bearings that will utilize hydrodynamic gas-film lubrication. Specification M-11590-RB-001-S-5 was prepared for purchase of the circulators.

The design requirements for the circulator pressure boundary are 11.8 MPa (1715 psia) at 370°C (700°F) for a ten-year service life. The design temperature for the circulators of 370°C was selected early in the project because of the long lead time required for circulator development and fabrication. It will be noted that the design temperature of most other components is higher because their design temperatures were selected

later and a wider operating margin was arbitrarily specified. The initial performance requirements for three circulators operating in series were 3.2-kg/s (7-lb_m/s) flow of helium and 78.2-kJ/kg (26,170-ft or 79.4-psi) head at outlet conditions of 9 MPa (1300 psia) and 350°C (660°F). The circulators will also operate satisfactorily at 3.2 kg/s (7 lb_m/s) of helium and 73-kJ/kg (24,420-ft or 85.5-psi) head at outlet conditions of 10.3 MPa (1500 psia) and 350°C (660°F). The circulator design and embodiment permit satisfactory operation at the maximum operating pressure of 10.6 MPa. The circulators are designed to withstand 100 exponential depressurizations at an initial rate of 0.7 MPa/s (100 psi/s). The circulators are also designed to withstand a decrease of inlet helium temperature of 28°C/s (50°F/s) for 1 s. The preceding design requirements meet all presently known helium flow requirements for 37-, 61-, and 91-rod fuel test bundles and for the 61-rod blanket test bundle.

Figure 2.4 shows the performance at 10.3-MPa (1500-psia) outlet pressure for an individual circulator as measured by the manufacturer, Mechanical Technology Incorporated (MTI). The performance data were obtained during performance testing with the circulator prototype. Performance data will also be obtained with each of the production circulators in a test loop at MTI. The test flow range is depicted in Fig. 2.4. The minimum operating flow line, labeled "surge line," is shown at the left of the figure. The maximum flow line, although not shown in Fig. 2.4, is about 20% greater than the design flow and permits operation of the circulator without reversal of thrust load. Operation of the circulator at higher flow rates could reverse the thrust load and probably damage the unidirectional helium-lubricated thrust bearing. The other two limits are the design speed of approximately 23,500 rpm shown at the top of the envelope and the gas bearing lift-off speed of 3000 rpm shown at the bottom. As helium density is increased above the design level (decreased temperature at constant pressure), the circulator speed must be reduced to avoid overloading the circulator motor. Similar curves calculated for other helium pressures from 4.8 to 10.3 MPa (700 to 1500 psia) indicate that below 4.8 MPa (700 psia) and above 65°C (150°F), there are no motor power limitations for operation with the envelope described by Fig. 2.4.

10.3 MPa DISCHARGE PRESSURE ; 345°C DISCHARGE TEMPERATURE

Fig. 2.4. Actual prototypic circulator performance.

Figure 2.5 shows some design features of the circulator. The austenitic stainless steel pressure vessel has an outside diameter of 560 mm (22 in.), is 1500 mm (approximately 5 ft) long, and has a wall thickness of about 30 mm (1 1/4 in.). The rotary assembly, motor stator, and cooling vessel are mounted as a unit from a blind flange and can be hermetically sealed to and also removed from the pressure vessel without cutting the loop piping. Hermetic feedthroughs are provided in the blind flange for the motor power leads, bearing position instrumentation, thermocouples, shaft speed measurement, and cooling water lines. The rotary assembly features a 185-mm-diam (7.3-in.) impeller mounted onto the 150-mm-diam (6-in.) solid-motor rotor with 100-mm-diam (4-in.) integral bearing journals.

2.6.2 Power supply for helium circulators

Individual circulators are powered by a solid-state, variable-frequency system that converts 460-V ($\pm 3\%$), three-phase, 60-Hz input power into an adjustable-frequency output with a nominal three-phase rating of 1.15 V/Hz over the range of frequencies from 0 to 400 Hz. The output power is suitable for providing stepless speed control from 0 to 24,000 rpm of the two-pole, three-phase, constant-torque motor rated 154 kW (206 hp) at 393 Hz (23,500 rpm), which drives one CFTI helium circulator and provides acceleration to 3000 rpm in 1 s for starting. In addition, the power supply is rated 250 kVA at 460-V, 314-A, and 400-Hz output to allow some margin in motor rating. The power supply consists of solid-state, full-wave rectifier and inverter sections with current-limiting and self-protecting circuitry to withstand short circuits and to shut down the power supply safely in the event of input power failure. The power supply is a complete self-contained unit, assembled and ready for operation.

The circulator manufacturer, MLI, has two specific requirements to protect the circulator gas bearings. One requirement is that the circulator rotary assembly must be accelerated to 3000 rpm in 1 s or less to minimize bearing wear during start-up. A second requirement is that power be interrupted to the circulator if the motor is started in reverse rotation, to prevent damage to the thrust bearing. A 120-tooth speed pickup

Fig. 2.5. Helium circulator for GCFR-CFTL. (By MTI)

gear with two magnetic pickups, coupled with a solid-state device developed at ORNL, provides a signal to trip the power supply if the circulator is started in reverse. The same speed pickup gear will be used with appropriate instrumentation to stop a particular circulator if its rotational speed decreases below 3000 rpm or exceeds 24,000 rpm. The instrumentation and controls for monitoring, starting, stopping, and varying the speed of the circulators will be located in the CFTL control room.

Design, fabrication, and testing of the first power supply was completed in December 1977. The completed power supply was loaned to MTI for use in development testing of the circulator prototype and the two follow-up CFTL production circulators. The power supply will then be shipped to ORNL for installation at the CFTL site.

2.6.3 Heat sinks

Each of the two heat sinks will be similar in configuration and will consist of a helium-to-air heat exchanger and the requisite blower, ducting, and controls for the cooling air. Heat exchanger HX-1, shown in Fig. 2.6, will be located downstream of the test vessel exit to reject the test bundle heat and helium circulator power to cooling air. Heat exchanger HX-2, located in the circulator bypass line, will reject circulator power during those flow transients when there will be a large flow through the circulator bypass line and a small flow of coolant helium through the test bundle. During normal operation, there will be a small flow of helium through HX-2 to maintain the bypass line near system operating conditions.

The pressure-retaining boundary of the heat exchangers will be classified, designed, and constructed to the requirements for Class 2 Piping Components in Section III of the ASME Code. The design pressure for the heat exchangers will be 11.8 MPa (1715 psia). The design temperature for HX-1 will range from 593°C (1100°F) at the inlet to 399°C (750°F) at the outlet. The inlet design temperature for HX-2 will be 399°C (750°F).

Heat exchanger HX-1 will be designed to reject a maximum of approximately 4.4 MW of heat. A forced draft of ambient air will cool a helium flow of about 3.2 kg/s (7.0 lb_m/s) to approximately 315°C (600°F) from temperatures as high as 590°C (1100°F). Heat exchanger HX-2 will be

Fig. 2.6. Helium-to-air heat exchanger, HX-1.

designed to reject 0.4 MW of helium circulator power to a forced draft of ambient cooling air while cooling a helium flow of about 3.5 kg/s (7.7 lb_m/s) at test bundle inlet temperature. Summaries of design data at 9 MPa for HX-1 and HX-2 are shown in Tables 2.3 and 2.4, respectively. The increase in maximum operating pressure to 10.6 MPa does not degrade the heat transfer capacity of the heat exchangers.

For both exchangers, ambient cooling air from outside the site building will be moved by blower and conducted in ducting to the heat

Table 2.3. Design data for heat exchanger HX-1

Design temperature, °C (°F)	593 (1100)
Design pressure, MPa (psia)	11.72 (1700)
Basis of heat load	90 FRS @ 45 kW, plus 400 kW circulator heat
Calculated full-load performance	
Heat load, MW	4.4
Helium pressure, MPa (psia)	9 (1300)
Helium inlet temperature, °C (°F)	593 (1100)
Helium outlet temperature, °C (°F)	328 (623)
Helium flow rate, g/s (lb _m /s)	3178 (7.0)
Air inlet temperature, °C (°F)	38 (100)
Air outlet temperature, °C (°F)	201 (394)
Airflow rate, m ³ /s (cfm)	24 (50,000)
Log mean temperature difference, °C (°F)	339 (611)
Overall unit conductance, W/m ² -°C (Btu/h-ft ² -°F)	104 (18.4)
Heat transfer area, m ² (ft ²)	121 (1304)
Actual fan capacity, m ³ /s (cfm)	35 (75,000)
Cooling air fan capacity margin, %	50
Weight, kg (lb)	6,400 (14,000)
Size, m (ft, in.)	
Length	2.4 (7 ft, 11 in.)
Width	2.3 (7 ft, 6 in.)
Height	1.9 (6 ft, 2 in.)
Materials	
Tubes	304 H stainless steel, 2.54 cm (1 in., sched 80 S)
Casing	304 stainless steel

Table 2.4. Design data summary for heat exchanger HX-2

Design temperature, °C (°F)	399 (750)
Design pressure, MPa (psia)	11.72 (1700)
Basis of heat load	Removal of heat input from circulators
Calculated full-load performance	
Heat load, kW	400
Helium pressure, MPa (psia)	9 (1300)
Helium inlet temperature, °C (°F)	350 (662)
Helium outlet temperature, °C (°F)	328 (622)
Helium flow rate, g/s (lb _m /s)	3493 (7.7)
Air inlet temperature, °C (°F)	38 (100)
Air outlet temperature, °C (°F)	184 (364)
Airflow rate, m ³ /s (cfm)	2.4 (5050)
Log mean temperature difference, °C (°F)	222 (400)
Overall unit conductance, W/m ² -°C (Btu/h-ft ² -°F)	59.0 (10.4)
Heat transfer area, m ² (ft ²)	30 (325)
Cooling air fan capacity margin, %	118
Actual fan capacity, m ³ /s (cfm)	5.7 (12,000)
Weight, kg (lb)	1226 (2700)
Size, m (ft, in.)	
Length	1.5 (4 ft, 11 in.)
Width	1.2 (4 ft, 0 in.)
Height	1.9 (6 ft, 2 in.)
Materials	
Tubes	304 H stainless steel, 2.54 cm (1 in., sched 40 S)
Casing	Carbon steel

exchanger; it will flow upward over the tubes and then be returned outside the building. The flow of air will be controllable with variable-speed blowers, variable vanes at the circulator inlet, and movable louvers installed in the cooling air duct at the heat exchanger.

2.6.4 Helium purification system

The CFTL must have the capability of duplicating the anticipated ranges of GCFR helium impurity levels listed in Table 1.3, except that

radioactive impurities will not be used. Since the CFTL helium will be obtained from the U.S. Bureau of Mines to the purity specifications listed in Sect. 1.5, it will be necessary to introduce gaseous impurities into the helium and then to establish the required level of impurity by the coordinated dynamic operation of the purification system and impurities-injection devices.

The pressure-retaining boundary of the helium purification system will be designed for 11.8 MPa (1715 psia) and 400°C (750°F) and constructed and stamped in accordance to the rules of Section VIII, Division 1, of the ASME Code. Preliminary inquiries made to the very few U.S. firms concerned with the production of helium purification equipment indicated that the cost for construction of the system to the specifications for Class 2, Section III of the Code would be as much as three times higher than for construction to the rules of Division 1, Section VIII. Because the purification system (1) is not subject to severe thermal transients and (2) is ancillary to the helium system and can be isolated from it with valves, it will be constructed to the rules of Division 1, Section VIII of the Code.

The performance requirements for the purification system will be a maximum of 1 liter/s of helium flow at inlet conditions of 10.6 MPa (1540 psia) maximum and 370°C (700°F) maximum. The inlet and outlet of the purification system will be connected, respectively, to the outlet and inlet of the circulator to provide flow potential. This performance should permit the mass of system helium to be processed through the purification system as fast as once per hour during a continuous 2-week period before the system requires regeneration.

Preliminary information indicates that the purification system will probably consist of regenerative heat exchangers, a "Deoxo" catalytic purifier to convert hydrogen and oxygen to water and carbon monoxide to carbon dioxide, a molecular sieve bed to adsorb the generated water and carbon dioxide, and a low-temperature adsorbent bed to remove the nitrogen, hydrocarbons, and other gases not collected in the molecular sieve.

During DBDA simulations the helium purification system will be isolated from the main loop by shutoff valves, and then air in-leakage up to 10% by volume will be added to the main loop helium. However, this

heavily contaminated helium will later be vented to the atmosphere and will not be passed through the purification system.

A summary of typical expected purified levels of helium at the exit of the purification system is shown in Table 2.5 along with comparisons of maximum impurity levels and as-received helium from the Bureau of Mines.

Table 2.5. Typical CFTL helium impurity levels

Impurity	Purified level (ppm)	Maximum loop helium impurity levels (ppm)	Bureau of Mines helium specification (ppm)
H ₂ O	<1	85	3 ^a
H ₂	3	850	1
CO	3	12	b
CO ₂	<1	1.2	b
Ne	23	23	23
CH ₄	<1	2.4	b
N ₂	<1	12 ^c	5
O ₂	<1	2.4	3

^aEight if in bottles.

^bAll carbon-bearing gases total 1 ppm.

^cAir levels may be as high as 10% for depressurization tests, but this gas mixture will not be passed through the purification system.

2.6.5 Loop evacuation and helium supply system

A mechanical vacuum pump with 25-liters/s pumping capacity will be provided to evacuate the piping system prior to charging with helium. This vacuum pump will remove residual air from the system prior to filling with helium after initial loop construction and after periods of loop maintenance, such as test bundle replacement.

The charging system to supply the CFTL with helium will consist of a manifold station, located just outside the east wall of the site building, and will accommodate one helium trailer in a space protected by concrete

block walls. The trailer will have the capacity to make four fills of the loop. Each fill is to be made from atmospheric pressure to approximately 4.8 MPa (~ 700 psia) at room temperature and is to be accomplished in 1 h. A sufficient amount of helium will be introduced into the CFTL in this manner to achieve the desired operating pressure at operating temperature.

The makeup helium system will be located adjacent to the CFTL on the second floor of the site building. Twenty bottles of helium, each containing 6.2 std m³ (220 std ft³) of gas, will be arranged in two banks of ten bottles and connected to the CFTL with suitable piping. Each bank would have the capability of supplying 1.8 kg (4 lb_m) of helium into the helium system in as short a time as 6 min with the CFTL pressure at 9.3 MPa (1350 psia) from fully charged bottles. Alternatively, the helium makeup will be supplied from the trailer.

2.6.6 Test vessel

The test vessel, shown in Fig. 2.7, will be vertical and contain a test bundle that will simulate a segment of a GCFR core element. The test vessel is about 380 mm OD (15 in.) with an overall length of about 5.8 m (230 in.). The test vessel shell will be fabricated of 10-mm-thick (0.4-in.) Inconel 625 alloy with stainless steel flanges at both the top and bottom. The vessel pressure-retaining boundary will be designed for 11.8 MPa (1715 psia) and 480°C (900°F) and constructed and stamped in accordance with the rules for Class 1 Components, Section III, of the ASME Code. The maximum temperature of 465°C (870°F) occurs in the outlet-mixer nozzle during normal full-power operation. Inconel 625 has been chosen for the 380-mm-OD pressure shell because it has much higher strength than stainless steel; thus, it reduces the wall thickness from about 22 to 10 mm. The reduced thickness is important because it will allow better definition in the x-ray examinations that are planned to observe possible bundle distortions during operation. Note that the test vessel is the only CFTL component built in accordance with Class 1 requirements. These more stringent requirements were selected because they permit a reduction in wall thickness compared to that for a Class 2 vessel, thereby improving the x-ray measurement of duct and rod bowing.

Fig. 2.7. Cross-section view of the test vessel.

Helium will enter and leave the vessel through side nozzles located, respectively, near the bottom and top of the vessel. A plenum and baffles will be designed at the bottom of the vessel to assist in obtaining fully developed flow before the coolant helium reaches the heated zone of the test bundle. A circular duct or thermal barrier inside of, and concentric with, the Inconel 625 pressure boundary and external to the test bundle will provide an annulus inside the pressure boundary to accommodate the attemperation helium flow in the vessel. The attemperation helium flow will enter the test vessel through two nozzles located 180° from one another near the bottom of the test vessel. A commercially available mixer will be designed to mix the bundle and attemperation helium flows, and thermal shock resistant linings will be located within the mixer and at the top of the vessel to reduce thermal shock to the pressure boundary during margin tests or other accident simulations.

The circular shroud will also serve as a thermal barrier between the test bundle and attemperation helium flow to minimize the loss of heat from the test bundle to the attemperation helium flow. The high-pressure seal between the test bundle rods and the vessel pressure boundary will be made with a welded joint between the cladding on each individual rod and the bottom flange, which is the tube sheet.

Deflection of the hexagonal duct and the test bundle rods will be observed with x-ray imaging techniques. Tests with a mockup of a 91-rod bundle within a simulated test vessel have shown that such techniques are feasible. Displacement of components within the test vessel can be measured by using platinum markers at specific locations on the structure as points of reference during the x-ray inspection. Bowing of FRS will be observed by placing markers midway between spacer grids on some of the rods. Also, gross failure or movement of grid spacers could be observed by this technique.

X-ray measurements will be made using both film and image-intensifying systems. The film will provide only steady-state measurements of deflection due to required exposure times of about 1 min with AA film using a 420-kV source.

An image intensifier with remote TV readout will be required for observations of deflection during transient tests of the bundles. Two

420-kV x-ray systems, including image receivers, will be located at 60° to one another and will be operated simultaneously to provide information on the spatial location of the test bundle and related components.

Appropriate integral shielding will be provided to minimize disruption of operations in areas adjacent to the loop enclosure. A precise, remotely operated positioning system will provide radial and axial movement of the x-ray systems. The positioning equipment will provide 360° rotation of the x-ray systems around the circumference of the test vessel in all planes from the bottom to the top of the test bundle, except as limited at the bottom by the attemperation flow inlet lines (see Fig. 2.7).

Demonstrations of image intensifiers have been made by several vendors on the 91-rod bundle mockup. Therefore, we will utilize commercially supplied image intensifiers and a remotely operated positioning system.

The x-ray imaging system evolved early in the design phases of the CFTL when the reference core design was unrestrained. Now that the reference design has changed to a restrained core, the hexagonal shroud and bundle movements will be much smaller than originally planned. This change in core design will require further evaluation in the use of real-time x-ray imaging of the test bundle.

2.6.7 Piping

The piping that interconnects the various helium system components, as shown in Figs. 2.1, 2.2, and 2.3, will be made of austenitic stainless steel and will be designed, constructed, and stamped, as practical, in accordance with the rules for Class 2 Piping Components in Section III of the ASME Code. The design conditions for the piping will be 11.8 MPa (1715 psia) and 399°C (750°F), except for HX-1 and the interconnecting run between the test vessel and the heat exchanger, for which the temperature will be 593°C (1100°F). An all-welded piping design will be favored for the CFTL. The piping will be subjected to the additional requirements outlined in Ref. 2.1.

The piping will be sized to minimize velocity head friction loss as much as practical, and the piping runs will be designed to provide the

upstream and downstream lengths that good design practice requires for accurate flow measurement.

The piping will be thermally insulated to reduce heat losses during high-temperature operation. Also, electric trace heaters will be required on selected sections of piping to maintain desired temperature profiles during tests utilizing very low flow rates and low power inputs, such as single rod tests, where power inputs are as low as 300 W. These design features were determined during dynamic analysis of loop behavior. Specifically, electric trace heaters are needed on the test vessel inlet line and within HX-1 to permit certain test operations.

2.6.8 Electrical distribution system

The source of electrical power for the CFTL is a 161-kV, three-phase, 60-Hz line from the Elza substation [located within a couple of kilometers (1 mile) of Building 9201-3, the site of the CFTL] to a 40-MVA, 161- to 13.8-kV transformer located outside at the southeast corner of the site building. This transformer has adequate reserve capacity for the CFTL requirements. It supplies power to the 13.8-kV switchgear within the building, which is within 50 m (175 ft) of the CFTL. A new switchgear section will be added to this existing switchgear for supplying power to the CFTL dry-type 2500-, 1000-, and 750-kVA transformers with their associated 480-V switchgear.

The two 2500-kVA transformers will supply the 13 zone power supplies that constitute the test bundle power supply.

The 1000-kVA transformer and switchgear supply 480-V, 3-phase power to the three variable-frequency power sources for the three helium circulators. The variable-frequency power sources are the means by which the speed of individual helium circulators is controlled.

The 750-kVA transformer and switchgear supply 480-V, three-phase power to a motor-control center that is the source of power for support functions such as the heat exchanger cooling fans, instrumentation power, hydraulic pumps, uninterruptible power system, control power, etc.

The power system one-line diagram, the test bundle power block diagram, and the equipment layouts are shown in Figs. 2.8, 2.9, 2.10, and 2.11, respectively.

Fig. 2.8. Power distribution system one-line diagram.

Fig. 2.9. Block diagram - arrangement of equipment and terminals.

Fig. 2.10. Power supply equipment layout, west room.

PARTIAL PLAN
PLATFORM @ EL. 925'-0"

Fig. 2.11. Test bundle power equipment layout, east room.

2.6.9 Test bundle power supply and control system

It is important to measure cladding temperature during simulated GCFR transients that change the power from as much as 100 to 10% in as short a time as 1 s. Electromagnetic interference (emi) noise is seen on the cladding thermocouples in the LMFBR-THORS test bundles that are supplied with ac electricity from a full-on/full-off, analog-controlled silicon-controlled rectifier (SCR) system. Thus, it was deemed prudent to make the CFTL power supply and control system for the test bundles the subject of study and some development effort. Both ac-to-dc (rectification) and ac-to-ac (ac) power and control systems were considered, and commercially available units of each were tested and evaluated before the ac system having linear multiple power levels was chosen for the CFTL.

The CFTL bundle power supply will require 13 of the ac systems. There will be one 500-kVA power supply (zone supply) for each of the 13 transverse rows of FRS in a 90-rod control bundle. This feature will be particularly useful in providing various degrees of slope of skewed power to the bundles.

Each zone will be supplied from one of the two 2500-kVA power transformers and associated switchgear mentioned in the preceding section. Each zone will be capable of supplying as much as 45 kW to 10 or 11 FRS in a single row. The total design capability of the 13 zones is 131 single-phase circuits to a patch panel, which will permit any FRS to be connected to any zone supply. Initially there will be circuits for supplying 91 FRS from the patch panel, with provisions to expand this to 131 connections. Also in each zone supply there will be equipment for controlling and measuring power to individual FRS and for testing and protecting each FRS.

The heart of the ac zone power supply is a specially designed transformer having secondary winding taps that provide 15 equal increments of power. There will also be an induction voltage regulator (IVR) to vary the transformer primary voltage, as required, and an SCR system to select and connect the appropriate level of transformer secondary power to the test bundle load.

The motor-driven IVR will be set manually to provide power during all steady-state bundle operations and will be programmed automatically to

provide it during the slower transients of 1 min or longer duration. In brief, during these operations bundle power will be supplied through the IVR in a "continuous voltage control mode" in which a preselected level of transformer secondary power will be locked into the zone supply circuit with the SCR system.

The SCR system can be set manually or programmed automatically to provide the appropriate level of transformer secondary power needed during IVR control of bundle power for steady-state and slow transient operations mentioned above. It can be programmed to change bundle power from as much as 100 to 10% during transients lasting as little as 1 s. During fast power transient operation the IVR is operated in a steady-state mode. In brief, the "all power-off mode" of operation will be rarely, if ever, used during transient operation of the test bundle power supply.

The transformer is air cooled and the SCRs are water cooled. A combination of current-limiting fuses and solid-state current detectors for interrupting the power supply will be utilized for their protection against surges and short circuits.

The power measurement for each FRS is accomplished with current and potential transformers feeding a solid-state watt transducer. In prototypic tests made over the entire voltage range of interest, these very accurate components have demonstrated a system accuracy in the 200-W to 45-kW range of 1% or less of reading and a time constant of 0.2 s or less to show a 63% response to a change in power.

The electrical resistance characteristics of the current-carrying circuit and the boron nitride (BN) insulation in each individual FRS will be determined as frequently as required during CFTL bundle operation. A test cabinet designed to provide these measurements will be made part of the bundle power supply system.

The individual FRS will be protected against damage from excessive electric current by the combination of a current-limiting fuse and an overcurrent and ground fault detector that will invoke the operation of a "crow bar" to blow the fuse very rapidly as necessary. In addition, a current-limiting ground resistor with a solid-state detector will be installed in the transformer secondary of each of the 13 zone power supplies.

The bundle power supply equipment and associated manual and electro-mechanical devices, solid-state processors along with the fast-scan DAS and the control computer, should not only provide the required programmatic steady-state and transient power operation of the test bundles but also protection of the FRS and the power supply from all anticipated electrical fault conditions.

2.7 Instrumentation and Controls

2.7.1 Introduction

The CFTL will be provided with instruments, equipment and component controls, and coordinated control exercised by direct digital control (DDC) to permit its operation in steady state and a variety of transient modes. It will be provided with a fast-scan DAS to record programmatic test data as required during both steady-state and transient operation. Alarms and automatic controls utilizing a programmable logic controller (PLC) will be provided to protect the loop and the test bundle against the damaging effects that operation at out-of-bound conditions of coolant helium flow and pressure, high coolant helium or rod sheath temperatures, loss of power, and out-of-bound cooling airflow can inflict. The DDC, DAS, PLC, instrument readouts, alarms, and automatic protection equipment will be located in the control room on the second floor of Building 9201-3 (Fig. 2.12) adjacent to the loop itself.

The DAS will serve the primarily passive function of collecting experimental data from loop and bundle sensors and recording these data on magnetic tape. The DAS will, however, contribute to protective interlock controls by checking limits on all acquired data and providing logical output indicating when the system deviates from safe operating conditions. The DAS will also provide sophisticated real-time and posttest data displays to aid the CFTL operators in correlating the large quantity of data received.

The DDC will provide centralized control of the helium flow control valves, FRS power supplies, and heat exchangers during steady-state and

transient operations. It will acquire measurements of FRS power and helium flow, pressure, and temperature, and it will adjust the various system actuators so that these conditions are controlled according to operator commands. The DDC will display data that are directly related to its control functions and check all controlled conditions against control setpoints and preset absolute limits so that a timely warning of control system failure may be obtained.

The PLC, a relay logic emulator, will provide the operating permissives and safety shutdown logic. It will accept binary inputs from the DAS, DDC, sensors, switches, and dedicated limit-checking devices, determine when safety shutdowns are required, and coordinate safety shutdown sequences.

The general relationship between measurement sensors and equipment and component controllers through the DAS, DDC, and PLC is presented in Fig. 2.13. In addition to the automatic programmed control of CFTL operation implied in Fig. 2.13, manual controls will be provided to permit the operating engineer to perform steady-state test programs with the CFTL without being entirely dependent on the DDC. To achieve this flexibility the power supplies and other control actuators will be equipped with manual controls or closed-loop analog controls. Key system operating conditions, including FRS zone voltages, helium flows, pressures, and temperatures, and selected FRS temperatures, will be displayed independently of the DAS or DDC using conventional control panel display equipment. A limited number of conventional strip-chart recorders will be used to provide the operators with a reliable and readily accessible graphic record of operation. The limit-checking functions of the DAS and DDC will, in some cases, be seconded by dedicated hardware-limit detectors.

The DAS is described in Sect. 2.7.4. The PLC has not yet been specified, as our interlock requirements are not yet fully defined. However, the functions of the PLC may be fulfilled adequately by any one of several commercially available relay logic emulators. Thus, we will describe briefly sensors to measure test conditions, equipment and component controls, the coordinated control of all equipment and components as exercised by the DDC, and the protective alarms and controls system.

Fig. 2.13. Principal components of control and interlock system.

2.7.2 Functional measurement and controls

Loop and bundle instrumentation and control components are shown on Figs. 2.14 through 2.18. (These diagrams represent the on-going design status and are subject to future change.) Figure 2.14 shows the test bundle and test vessel instrumentation. Figures 2.15 and 2.16 show the loop flow controls, heat exchanger controls, and circulator instrumentation. Figure 2.17 shows FRS power controls and measurements. Figure 2.18 shows the helium fill, cleanup, and impurities-injection systems. The functions of the instruments in the application diagrams are described in subsequent sections.

Fig. 2.15. Instrument application diagram for circulators and HX-2 bypass line.

Fig. 2.16. Instrument application diagram for HX-1, depressurization system, and test vessel flow measurement.

Fig. 2.18. Instrument application diagram for helium supplies, impurity monitoring, and impurity addition systems.

Helium circulator instrumentation. Instrumentation will be supplied on each circulator to measure rotor speed, motor power, bearing clearance, and selected temperatures (Fig. 2.15). Control of the rotor speed will be by manual setpoint input such as HC-27 to the variable-frequency motor power supply, which will automatically adjust the frequency of the motor supply so as to obtain the desired rotor speed. Speed feedback for this control will be obtained from the speed/rotation monitor (STS-24). The speed/rotation monitor provides two independent tachometer pulse chains from magnetic pickups (SE-24A, B) that observe the rotation of a toothed wheel attached to the rotor shaft. One pulse chain is used for feedback control of the speed; the other pulse chain is fed to a frequency/voltage convertor so that the circulator speed can be monitored by the DAS and the DDC. Comparison of the phase of the two pulse chains provides a shutdown signal (SS-24) to the power supply and to the PLC if an attempt is made to start the circulator in the reverse direction. Logic internal to the power supply provides a shutdown if rotor speed is not sufficient to maintain an adequate bearing gas film. A digital panel meter will display the circulator speed. The 60-Hz power input to the variable-frequency power supply will be monitored with a conventional watt transducer (JT-30), displayed, and recorded on the DAS. Ordinary fuses and breakers will protect the motor from overcurrent.

Capacitive displacement sensors on each circulator, such as ZE33, ZE36, and ZE39, will monitor the positions of the rotor-end journal bearing, fan-end journal bearing, and thrust bearing. Bearing positions will be displayed on three oscilloscopes (ZI-45A, B, C), one for each bearing. A hand switch (HS-45) will select which of the three circulators is to be displayed. A safety shutdown switch such as ZS-39B will be provided for low clearance on the thrust bearing only of each circulator.

Three differential pressure cells (PdT-46A, B, C) will measure the developed circulator potential over the full range of expected operation. The PdT-46A cell can be isolated from the loop piping by manual isolation valves. This system will allow the operator to observe the differential across all three circulators together. A panel indication of this measurement will be provided, with no alarm or recording functions.

Thermocouples will be provided to measure the circulator pressure vessel, motor winding, and bearing temperatures. These measurements will all be displayed on a dedicated CRT bar-graph display device (TI-61), with independent alarm and scram setpoints on each channel. Winding and bearing temperatures will also be monitored and recorded by the DAS.

Motor winding cooling water flow on each circulator will be monitored by a locally indicating device such as FI-18, and flow switches will provide alarm and scram signals if this flow falls below acceptable limits.

Helium flow measurement. The flow measurement requirements for the CFTL represent an extreme combination of rangeability, accuracy, temperature, and pressure and embrace a wide range of volume flow and density. Therefore, the measurement of helium flow was the subject of a development effort in which the candidate flowmeters that were evaluated included ultrasonic, ion deflection, vortex-shedding, and conventional venturi meters with stacked differential pressure sensors. Initial work with ultrasonic and ion deflection flowmeters did not appear fruitful, and this work was discontinued early in the project. In-depth evaluations of both venturi flowmeters and VSFM were made, and the VSFM was selected. A prototype of the VSFM was tested in air and helium at near CFTL temperature conditions and successfully demonstrated the potential for measurement of almost the entire range of CFTL helium flow rates with a single meter. The VSFM provides greater accuracy than a venturi system, with considerable savings in equipment and reduction in calibration, operating complexity, and data taking and retrieval.

In the CFTL, VSFM will be used at the four flowmeter stations: test bundle flow (FE-4), attemperator flow (FE-7), bypass flow (FE-9), and total circulator flow (FE-11). The flow measurement at the test section (FE-4) is the most difficult due to its large flow rangeability. However, VSFM will be used at all locations because of the simplicity of the equipment and its ease of operation. The frequency of vortex shedding will be measured at each flowmeter. All frequency-shedding measurements will be continuously monitored by the DAS and the DDC. In addition to frequency measurements, the absolute pressure measurement and temperature are required to compute the mass flow measurement. Resistance temperature devices will be provided downstream of each flowmeter, and an absolute

pressure measurement will be made at the inlet of the test bundle flowmeter only. The absolute pressure at the different flowmeter locations will not differ appreciably and a single pressure measurement at the location of the most critical flow measurement is deemed sufficient.

An indication of helium volume flow will be obtained directly from each vortex meter and displayed on strip-chart recorders. Circulator, attemperator, and bypass flows will be displayed together on a single strip-chart recorder. Test section flow and a representative FRS power will be displayed on a separate recorder to provide visual correlation of test section flow and power. All flow data and computed measurements will also be available to the operator through the operating terminals of the DAS and DDC.

Helium flow control. At constant circulator speed and helium pressure, the helium coolant flow rate through the test bundle, the attemperation path, and the circulator bypass, as shown in Figs. 2.15 and 2.16, will be regulated by three flow control valves, FCV-1, FCV-2, and FCV-3, respectively, equipped with fast-acting hydraulic operators. The operation of each of these valves may be either manual for steady-state conditions or programmable for both steady-state and flow transient conditions. A pneumatically actuated valve, FCV-50, will be installed in the vent line to provide control of depressurization transients, as described in the next section.

The flow control range for bundle helium coolant is too large to be accommodated with one valve. Thus the valves will be sized to accommodate the high end of the flow control range, for the large 90- and 91-rod test bundles, and appropriate valve trim will be installed, as required, to obtain flow control at the other portions of the range for the 61- and 37-rod test bundles. The valve trim will be of a single seat parabolic design in order to approximate a linear flow rate versus stem travel. Maximum seat leakage at shutoff is to be less than 2% of full flow. The valve design will include a valve stem position indicator and transducer.

The design conditions for the pressure-retaining boundary of the valves will be 11.8 MPa (1715 psia) and 399°C (750°F). The valve bodies will be designed, fabricated, and tested to the requirements of Class 2 Valve Components of Section III of the ASME Code. The valve stem will be

bellows sealed, and the valve ends will be prepared for welding. Packed stem valves may be used temporarily during Stage I operation of the loop due to the long lead time required for procurement of nuclear-grade bellows valves. However, we plan to install the bellows-sealed valves at a later time.

The three main loop control valves, FCV-1, FCV-2 and FCV-3, differ in size and flow coefficient but are identical in terms of control and actuation characteristics. Each valve actuator is supplied from a central hydraulic system with the hydraulic reservoir, pump, and high-pressure accumulator. The primary accumulator will have sufficient volume to drive each valve to a predetermined fail-safe position on loss of control signal or primary hydraulic pump. Feedback control of the valve stem position is provided and stem position is continuously transmitted (ZT-1, typical in Fig. 2.16). Diagnostic switches (not shown) warn of impending failures in the hydraulic system; low oil level, low oil pressure, and high oil temperature. The actuator control characteristics have been specified as a small signal frequency response of better than 5 Hz and a full-scale step response time of less than 300 ms.

The valves will normally be controlled from the DDC. For limited operations, a manual control station (HIC-1, typical) will allow the operator to control the valve directly. Selection of computer or manual control will be by means of a manual switch (HS-1, typical). The switch position will be monitored by the DDC so that the DDC does not attempt to control the valve (and alarm a failure to do so) while manual control is selected. Valve stem position will be indicated on the control panel and monitored by the DDC and the DAS.

Helium pressure measurement and control. Helium pressure will be measured at several points on the CFTL. The highest pressure in the loop will be seen at the test bundle flowmeter inlet (PT-5 in Fig. 2.16). The lowest pressure in the loop will be seen at the circulator inlet (PT-16 in Fig. 2.15). For test data requirements, the pressure at the test section inlet (PT-700 in Fig. 2.14) will be monitored.

The pressure transmitters will employ quartz Bourdon tube sensors, providing sufficient accuracy for the full range of CFTL pressures in a single measurement device. As it is extremely difficult to seal a vacuum

reference cell against long-term infiltration of helium at high pressure, the three transmitters will be referenced to the ambient air pressure. For precise correction of these gage pressure measurements to absolute conditions, an absolute pressure transmitter (not shown) will measure the ambient air pressure. All three loop pressure measurements and the ambient pressure measurement will be displayed by digital panel meters and monitored and recorded on the DAS. The flowmeter pressure will be monitored by the DDC for flow calculations and recorded on a strip-chart recorder.

A pressure switch at the test section flowmeter inlet (PS-5 in Fig. 2.16) will provide an alarm for high loop pressure. The DAS and the DDC will also provide alarm and trip signals if the pressure deviates from the expected operating conditions. Pressures sufficiently high to threaten the loop pressure boundary will be relieved through a rupture disk (PSE-47). A pressure relief valve (PSV-48A) provides a means of shutting off the relieving flow when a permissible pressure is reached following a disk rupture. An excess flow valve (PSV-48B) and a pressure switch (PS-48) will ensure that small leaks in the rupture disk will not pressurize the vent downstream of the rupture disk and defeat the function of the rupture disk/relief valve assembly. A break wire (ZE-47) across the rupture disk will notify the DDC and the PLC if an emergency depressurization occurs.

Test transient depressurizations will be controlled using a valve (FCV-50 in Fig. 2.16), two rupture disks (PSE-51A, B), and a sized control orifice (FE-54). The rupture disks are required to provide a positive seal against the significant seat leakage of the valve. The rupture disks will be sized to burst at a pressure differential somewhat less than the normal loop operating pressure. Prior to a depressurization test, the space between the two rupture disks will be pressurized via PV-52 and ECV-53A to a level sufficient to prevent bursting of the upstream disk. To initiate a depressurization, FCV-50 will be opened, ECV-53A will be closed, and ECV-53B will be opened. Venting of the space between the two rupture disks will cause the upstream disk to burst, followed immediately by the bursting of the downstream disk. Break wires (ZE-51A, B) across the rupture disks will notify the DAS and the DDC that depressurization has begun. Depressurization will terminate on the closing of FCV-50.

Valves FCV-50, ECV-53A, and ECV-53B will be controlled through the DDC only. No direct manual control of these valves is provided, as we would not attempt to perform a depressurization transient without the assistance of the DDC. Valve FCV-50 will be a pneumatic-piston-operated valve, with continuous positioning control. Somewhat higher speed of opening and closing could be obtained by replacing the positioner with dual solenoid valves and operating the valve strictly in the on/off mode. However, the speed of this valve is not now seen as critical, and it may be convenient to have some means available to trim the rate of depressurization determined by the control orifice.

Accidental depressurization will be avoided by replacing rupture disk PSE-51A with a blind flange during extended constant-pressure operations.

Helium temperature measurement and control. Instrumentation and control components are provided on the heat exchangers to monitor helium-side and air-side temperatures and to measure and control the flow of cooling air to produce, as constantly as practicable, the specified helium temperature at the test vessel inlet. While the two heat exchangers, HX-1 and HX-2, differ in size and mission, the instruments and controls associated with each are essentially the same. Thus, the following discussion will be centered around the main heat exchanger, HX-1, which rejects test bundle heat principally.

Helium inlet temperature, helium exit temperature, air inlet temperature, and air exit temperature will be measured, respectively, with thermocouples (TE-111, 103, 106, 107, as shown in Fig. 2.16). These measurements will be monitored and recorded by the DAS, employed by the DDC for control, and recorded on a strip-chart recorder (TR-112). Airflow will be measured, displayed on a panel indicator, and monitored by the DAS and DDC.

Three different means are available for regulating the airflow under automatic control: a variable-speed drive on the fan (SC-104), fan inlet vanes (TCV-108), and heat-exchanger exit louvers (TCV-101). Louvers on the heat-exchanger inlet (HCV-105) will be manually controlled only, being used only to shut off convective airflow during low-power tests and while the loop is inactive.

Normally the three airflow regulators will be under the control of the DDC. For steady-state operations without the DDC, the fan speed may be controlled manually (HIC-104), and the vanes and louvers may be controlled either by manual adjustment or by feedback control based on the heat-exchanger exit temperature. For a typical steady-state operation, the operator would use TIC-101 in the manual mode to hold the exit louvers open, set a convenient fan speed with HIC-104, and use TIC-108 in the automatic mode to regulate the cooling airflow.

During low-power tests it will be necessary to provide auxiliary heat inside the heat-exchanger enclosure in order to maintain the specified helium temperature at the test vessel inlet. A closed-loop controller (TIC-102) will regulate the auxiliary heater power based on the heat-exchanger air-side temperature. The air-side temperature setpoint may be set either manually or by the DDC.

Test bundle power control and measurement. Each row, or zone, of FRS in a test bundle will be connected in parallel to a zone power supply. The number of zones in a test bundle will vary from 7 to 13. Figure 2.17 shows the instrumentation and control components associated with one typical zone power supply.

While the desired result is control of FRS power, the actual control variable will be zone voltage. Two methods are available for adjusting the zone voltage: the induction regulator, which will be used for steady-state and slow transient operations, and the multitap transformer with SCR switches, which will be used for fast transient operations.

The induction regulator will be actuated through a gear chain and drive motor. Closed-loop control of the regulator shaft position (ZC-401A) is provided as an integral part of the motor power supply. During normal operations the DDC will vary the shaft position setpoint so as to obtain the desired power in the FRS. Manual control of the position setpoint is provided by a bundle master manual control station (HC-400) and individual manually set ratio stations on each zone (HC-401A1, typical). This arrangement allows the operator to set the zone power skews manually and then vary all zones together from a single control point. As in the case of the valve control, selection of manual or DDC control is by means of a manual switch. The switch position and the ratio station output will

be monitored by the DDC so as to coordinate transfers from manual to DDC control. An additional manual control station (HC-401A2), provided with the motor power supply, will allow independent manual adjustments of the induction regulators for testing and maintenance purposes.

The power in each FRS will be measured with a potential transformer, a current transformer, and a watt transducer (EE-301, IE-301, and JT-301, typical). All FRS power measurements will be recorded by the DAS, and one FRS power measurement in each zone will be used by the DDC for feedback control of the induction regulators. The power measurements used for feedback control will be displayed on the control panel, along with the multitap transformer secondary voltage (JI-409A and EI-409A2). One FRS power measurement will be displayed on a strip-chart recorder (JR-300).

The SCR controller EIC406A is an analog/digital hybrid device that will operate in closed loop to control the square of the zone voltage to setpoint. Receiving an analog setpoint proportional to power demand from the DDC, the SCR controller will sequentially select transformer taps so as to produce the desired power versus time profile. Automatic scaling circuitry within each controller will maintain the same zone-to-zone power skews during a fast transient as were initially set by the induction regulators prior to the transient. Thus the DDC will be required to provide only one setpoint signal for all of the SCR controllers. Manual control of the SCR switching (HC-401B1) is provided as an integral part of the SCR controller.

Overcurrent and leakage current detectors in each FRS circuit will gate crowbar SCRs on detection of a current fault, providing a rapid burnout of the protective fuse. A contact closure will inform the PLC that an FRS has been crowbarred. Emergency disconnection of the zone power supply will be accomplished through a solenoid-operated circuit breaker activated from the PLC.

Helium fill, cleanup, and impurities systems. The helium fill, cleanup, and impurities systems are shown in Fig. 2.18. The main helium supply is a helium trailer located outside Building 9201-3. An auxiliary helium supply of 20 helium bottles is located near the control room on the second floor of Building 9201-3. Ordinarily, the empty loop piping will be charged to an intermediate pressure level from the trailer, and the

pressure will then be increased to operating pressure by heating the loop to normal operating temperatures. The auxiliary bottles will normally be used for trimming the operating pressure to the particular level required by the specific test program. Adjustment of the helium pressure level is done manually as required with pressure regulators and hand valves. Helium flow into the loop is measured on either flowmeter FI-241 or FI-242.

Hydrogen and water vapor will be manually added as gaseous impurities to the circulating helium inventory as required by the test program. Water vapor is added to the main loop helium by flowing dry helium over the surface of heated water in a pressurized tank and then directing the saturated helium into the loop to raise the water content. A water-level alarm (LA-223) will alert the operators if the water level is too low in the water tank. A temperature alarm (TA-227) and a pressure relief valve (PSV-224) are provided to ensure that the water tank is not overpressurized due to overheating. Hydrogen addition will also be done manually by direct injection from one of two supply cylinders via PV-230. Hydrogen flow input to the loop is measured by flowmeter FI-228.

The helium purification system and gas analyzer shown schematically in Fig. 2.18 will receive the helium via a bypass line from the circulator discharge. Flow rate in the bypass line is measured by flowmeter FE-200. The components of the gas purification system will be supplied by a commercial vendor as a packaged unit in accordance with an ORNL specification. Helium flow through the purification system will be remotely started or stopped from the control room by a suitable solenoid valve (HV-205).

A gas chromatograph will be used to analyze helium impurities such as hydrogen, oxygen, nitrogen, methane, carbon monoxide, and carbon dioxide. The gas analyzer receives loop helium from the circulator discharge bypass line via a tee downstream of flowmeter FE-200. The helium pressure is reduced to near atmospheric pressure before the gas passes through the analyzer at a volume flow rate not to exceed 0.1 standard liter/min. The analyzer will be automated for unattended operation and will provide a complete analysis on a cycle time of about 20 min. The analyzer will be a commercially available unit purchased in accordance with an ORNL specification. A separate moisture analyzer will also be

purchased to provide a measure of water content in the helium. The helium that passes through the gas analyzer system is measured at flowmeter FI-206 and then vented to the atmosphere.

The gas impurity control system is being deferred to Stage II of the loop assembly. Therefore, procurement of the gas chromatograph, helium purification system, hydrogen addition system, and water vapor addition system will be delayed.

2.7.3 Coordinated control with the direct digital controller

A brief description of the equipment for and the tasks performed by the DDC is given here. The DDC will be based on CAMAC (Computer Automated Measurement and Control), an internationally standardized system of modular digital equipment. Use of this standard provides for the convenient design of a flexible and expandable system for which fully compatible, high-quality components may be obtained from a number of sources. A block schematic diagram of the DDC is shown in Fig. 2.19.

System intelligence will be supplied by a 16-bit microprocessor, Digital Equipment Corporation (DEC) LSI-11/2, equipped with 32K words of random access memory (RAM). In order to allow for the preparation and storage of sophisticated control programs, a dual-drive floppy disk system with 1-mega byte capacity will be provided. The operator interface will be standard CRT data terminal. A high-speed hard copy printer will provide permanent records of operator input and computer output. Software purchased with the system will include a real-time operating system (DEC RT-11), with libraries and programming aids for developing programs in FORTRAN, BASIC, and assembly language. FORTRAN accessible input/output routines for communication through the CAMAC dataway will also be purchased.

The CAMAC system consists of a crate, a crate controller, and process input/output modules. The crate is a mechanical housing with a prewired communications backplane (the dataway) that interconnects the modules with the crate controller. The crate controller provides the control logic required for passing information back and forth between the modules and the microprocessor. Data transmission on the dataway is 24-bit parallel, with a cycle time of 1 μ s. Thus, the dataway is capable of up to one million

Fig. 2.19. Schematic diagram of the DDC.

information transfers per second, with each transfer containing up to 24 bits of information. This information transfer rate is far in excess of what a single microprocessor can use, but it will prove helpful if additional processing capability is added in the future.

Our initial system will consist of one CAMAC crate, the crate controller, and up to 20 input/output modules. Future system expansion can proceed in three different ways:

1. The CAMAC dataway may be expanded by the addition of crates and crate controllers, allowing additional process input/output.
2. The microprocessor bus may be expanded to allow the addition of non-CAMAC computer equipment.
3. The crate controller may be extended using an auxiliary control bus, allowing additional microprocessors to be connected to the same crate. The additional processors may be LSI-11/2's or simpler devices such as the Intel 8080A.

The CAMAC input/output modules translate information between the digital logic of the microprocessor and the various analog and discrete signals associated with sensors and actuators. Modules are commercially available to suit a variety of functions and signals. The modules chosen for the CFTL incorporate sophisticated logic to handle the routine chores associated with their tasks, thus minimizing the amount of microprocessor time that must be devoted to input and output.

Analog input modules. Each analog input module can accommodate 16 channels of differential input. The module has a 16-channel multiplexer, an analog-to-digital converter, and a 16-word memory register. Logic within the module controls the multiplexer and converter, continuously scanning all input and storing the conversion results in the memory register where they may be accessed from the CAMAC dataway. Each channel is scanned once every 16 ms. Conversion resolution is 12-bits (1 part in 4096). The converter is a successive-approximation type, with an input range strap selectable for 0 to 5 V, 0 to 10 V, ± 2.5 V, ± 5 V, or ± 10 V. Inputs are single-pole filtered to 30 Hz.

Thermocouple input module. The thermocouple input module functions similarly to the general analog input module, automatically scanning

16 thermocouples and placing the temperature measurements in a memory register accessible from the dataway. Reference junction compensation and thermocouple linearization are performed within the module; the number passed to the dataway is the temperature in degrees Celsius rather than thermocouple millivolts. In addition, the module automatically checks all input against high and low limits, signalling the microprocessor when limits have been exceeded. Analog-to-digital conversion is by integration with 13-bit resolution, yielding excellent noise rejection and measurement precision. Each thermocouple is scanned once every 1.3 s.

Analog output module. Each analog output module provides eight channels of voltage output for controlling actuators. The digital-to-analog converter for each channel has 12-bit resolution and a settling time of 4 μ s. Output voltage range is selectable on each channel for 0 to 5 V, 0 to 10 V, ± 2.5 V, ± 5 V, ± 10 V. Output drive capacity is 5 mA at 10 V.

Current drives. The current driver module has no dataway interface; its function is to convert the voltage output of the analog module to 4-20 mA signals that provide superior noise immunity for field transmission to actuators.

Binary input module. Each binary input module accepts 24 contact inputs and makes the input data accessible to the dataway. Inputs are optically isolated and filtered to eliminate false signals due to contact bounce. The module informs the microprocessor when contacts change state, thus eliminating the need for the microprocessor to scan all contact inputs periodically.

Binary output module. The binary output module provides 24 optically isolated switches for transmitting status information to other devices.

Watchdog timer module. The purpose of the Watchdog timer is to provide a timely notification to the operators, the PLC, and the DAS of a failure of the CAMAC system. The Watchdog expects to receive a periodic update signal from the microprocessor via the CAMAC dataway. If this signal is not received, an audible alarm is sounded and a relay contact opens, indicating that the DDC is no longer functioning. The update period is selectable for 0.1 s, 1 s, or 10 s.

The tasks that the DDC will have to perform may be generally categorized as operator interface, flow measurement and control, helium

temperature control, and FRS power control. A general discussion of these tasks is given in the following sections.

Operator interface. The CFTL will be provided with a DDC to give the operator a convenient means to make and monitor those coordinated adjustments of power, flow, and temperatures by virtue of which the CFTL is able to simulate GCFR transients. The DDC will be programmed so that simple keyboard commands can request specific information displays, alter helium flow and airflow rates and temperature setpoints, and test section power or directly manipulate actuators. The CFTL will also be equipped with sufficient manual controls, analog automatic controls, and dedicated display hardware, so that the loop may be operated in steady state without the use of the DDC.

Transient test programs will be keyed in and stored on the DDC as setpoint versus time tabulations for the controlled variables. Interface programs will assist the operator in preparing these tabulations by interpolating between input data points, automatically calculating power skews, and determining constrained setpoints once the unconstrained setpoints have been specified by the operator. Prior to transient execution the setpoint tabulations will be presented to the operator for verification, and the DDC will check the requested setpoints to determine if they call for obvious violations of safe operating procedures. Automatic checks will be made to ensure that the DDC does not attempt to perform a transient until all requisite measurements and controls are accessible and functional. Diagnostic messages will inform the operator of control system failures, prompt the operator for missing inputs, and provide warnings of attempted misoperation.

Helium flow control. The DDC will acquire raw flow data from sensors on four VSFM, compute mass flow and volume flow measurements, and control the flow through the three helium flow control valves to setpoint. In addition, the DDC will check circulator flow against speed and issue alarm and scram signals to protect the circulator from surge and thrust reversal. Alarm and scram signals will also be issued for gross flow measurement errors and gross flow control errors.

The computation of the helium mass flow and volume flow for the four vortex meters will be the single most time-consuming task that the DDC

will have to perform. For each vortex meter, the DDC will have to read the frequency of vortex shedding and combine this measurement with pressure and temperature in a floating-point computation to determine the mass flow rate. Both mass flow and volume flow will have to be computed, at least on some of the measurement points, in order to supply the correct information for the different control and limit-checking tasks.

Closed-loop control of the CFTL flows, particularly the test section flow, has been a subject of some study. Because of the large flow range, inherent nonlinearities of the system, and required rates of change, the conventional closed-loop control technique would not produce satisfactory tracking of flow transients. This was demonstrated in early simulations of the CFTL.

However, there was considerable incentive to develop a satisfactory closed-loop controller for CFTL flows. Closed-loop control in general offers the possibility of greater precision and reproducibility than can usually be achieved with open-loop control. In the case of the CFTL, additional considerations made closed-loop control particularly desirable. With open-loop control, preprogramming of the transient tests would be extremely laborious. The specified flow versus time data for each test would have to be converted into a specification of valve stem positioning signal versus time. Repeated computer simulations and some in-loop trial and error would probably be required to achieve the desired flow transients. In contrast, the flow versus time data may be preprogrammed directly when closed-loop control is used. Finally, protective control functions designed to limit circulator flow to a safe operating region would be more difficult to implement if the flow control valves were operating open loop to follow a specified motion.

The reason that conventional closed-loop control techniques were not successful in controlling the test section flow is that the open-loop gain of the system (i.e., the ratio of measured flow to valve positioning signal) is not a constant, but varies approximately as the square of the mass flow and as the square root of pressure and temperature. The gain is, of course, also influenced by the circulator operating point and the relative positions of the bypass and attenuator valves. There is also some

degree of coupling with the power/flow ratio in the test section, as this influences the pressure drop in the test section and HX-1.

The variation in gain with mass flow can partially be compensated for by using an appropriately contoured valve plug and seat ring. However, the other factors influencing the gain cannot be satisfactorily accounted for by means of a simple process characterization curve. This rules out the use of the more common "adaptive gain" control techniques.

While the maximum rates of change in the CFTL are rather fast for a large mechanical system, events in the loop are paced rather slowly when considered from the viewpoint of an electronic digital controller. It was therefore considered possible to design an "intelligent" controller that would, while controlling the flow, estimate the system gain based on the immediate past history of flow response to valve position. A modified version of the ORCULT code,^{2,3} which accounted for valve trim characterization, valve actuator dynamics, and flow measurement noise, was used to test several prototype control algorithms. One algorithm was found that yielded quite good flow control, for both constant pressure and depressurization transients.

The flow control algorithm is computationally simple and should require no more computer time than a conventional PID control calculation. As an added bonus, simulations demonstrated that adequate control could be achieved with quite slow sampling rates, as slow as three samples per second for the fastest transients in the test specifications.

Protection of the circulator bearings requires that the circulator flow be maintained within the limits defined by the design head/flow characteristics of its aerodynamic design. One task of the DDC will be to ensure that this requirement is satisfied. A direct measurement of circulator head is not readily obtainable, and in any case is rather uninformative in the operating region approaching surge conditions. However, the circulator head/flow and head/speed characteristics may be combined to define a region of safe operation in the flow/speed domain. This region is bounded (approximately) by straight lines on a plot of flow versus speed. The DDC will acquire measurements of circulator speed and compare the calculated speed/flow ratio to preset limits. On approach of the circulators to surge or thrust-reversal conditions, the DDC will issue alarm

and scram signals, meanwhile modifying flow setpoints as required to avoid circulator damage.

In order to protect the test bundle and the circulators, early detection of failure in flow measurement and control is essential. The test section, attemperator, and bypass flow measurements will be subtracted from the circulator flow measurement, yielding a number that should be approximately zero if all flow measurements are valid. Significant errors will result in alarm and scram signals. Likewise, the flow measurements will be compared to the flow control setpoints and to the alarm and scram signals issued for large or sustained control errors. These checks should limit the consequences of failures in the flow sensors, control valves, or computer input/output modules.

Helium temperature controls. The DDC will be charged with the task of controlling heat removal from the CFTL so as to maintain a specified helium temperature at the test vessel inlet. This will be accomplished by manipulating controllers of the cooling airflow to HX-1 and HX-2. Each heat exchanger has three different controls for regulating airflow, and HX-1 has, in addition, an auxiliary electrical source to make up heat losses during low-flow, low-power tests. The controls are imposed on blower speed, vane position at blower inlet, and louver positions at heat-exchanger outlet. Regulation of the heat exchangers will require a rather sophisticated control strategy to determine the required airflow and some informed decisions to manipulate the three actuators in coordinated fashion so as to achieve that airflow.

The primary objective of the temperature control is the maintenance of the helium temperature at the test section inlet to the specified value. Unfortunately, the relationship between this temperature and the heat-exchanger actuators is rather remote. The response of the actuators to input signals, the response of the airflow to actuator positioning, the response of the heat-exchanger exit temperature to airflow, and the response of the test section inlet temperature to heat-exchanger exit temperature are all processes that will be characterized by large dead times, slow time constants, and significant hysteresis. These are the handles on the process that we must use to deal with rapidly varying heat loads as the test section power and flow are varied in accordance with the test

specification transients. Our difficulties are somewhat ameliorated by the large thermal capacity of the loop piping, which will retard the propagation of temperature upsets, but there is little doubt that maintenance of the test section inlet temperature to specifications presents a challenging control problem that we plan to resolve as indicated in the next paragraph.

The heat-exchanger exit temperature setpoint will be initially set based on an estimate of the piping heat losses and the circulator heat input. This setpoint will be modified by the test section inlet temperature error. The airflow setpoint will be generated by the combination of a feed-forward signal representing expected heat load and a feedback signal from heat-exchanger exit temperature error. The expected heat load will be calculated from the heat-exchanger inlet helium temperature and mass flow. The airflow will be controlled to setpoint using a PID algorithm, with some auctioneering logic to select the appropriate actuator for control over the present airflow range.

Control of HX-1 in the heating mode will be very similar to that in the cooling mode, except that instead of an airflow setpoint, the feed-forward and feedback signals will be used to generate a heat-exchanger air temperature setpoint. This setpoint will be passed to a conventional hardware PID controller, which will regulate the heat-exchanger air-side temperature.

In order to protect the circulators from high temperatures, the DDC will issue alarm and scram signals for loss of airflow control, high heat-exchanger exit temperature, and high circulator inlet temperature. Alarm and scram signals will also be issued for high temperature on the heat-exchanger inlet to protect the heat-exchanger pressure boundary.

Test bundle power control. The DDC will control the FRS power by directly manipulating the induction regulators on each zone for the steady-state mode of operation and by supplying a single power setpoint to the closed-loop SCR controllers for the fast transient mode of operation. Detection of large control errors will result in alarm and scram signals.

The induction regulators will be used for zone control during steady-state operations and for relatively slow transients. The DDC will monitor one FRS watt transducer in each zone, compare this power measurement to

the setpoint, and generate a positioning signal to the induction regulator. The control calculation will be a standard PID algorithm, probably performed in integer arithmetic. A sampling rate of once per second on each zone will probably be adequate for the induction regulator control.

The DDC will supply two signals to the SCR controllers: an analog setpoint signal proportional to power and a binary signal to enable/disable controller action. During fast transient operations the setpoint signal will be updated 60 times per second. At the beginning of a fast power transient, the enable signal will be sent to the SCR controllers so that they may begin switching transformer taps in response to the setpoint. At the end of the fast power transient, the disable signal will lock the SCR controllers, inhibiting further tap switching. Control of the zones will then revert to the induction regulators.

2.7.4 Fast-scan data acquisition system

A fast-scan DAS will be designed to record real-time data on tape at high speed during high-speed transients and at greatly reduced speed during steady-state operation. The magnetic tape data, principally of the transients, will be given to GA in the appropriate format for analysis and also will be subjected to detailed analyses on the large computers in the ORNL Computer Center. The system will also provide the operator with quick retrieval of data that can be displayed in suitable units on either a cathode ray tube or in Teletype. In this way the operator may scan quickly the results of a transient to choose between the necessity of performing the test run again and the opportunity of moving on with the test program. He may also supplement the conventional instrumentation with a large number of data to assist monitoring particular operating conditions, to compute a heat balance, etc.

The DAS will utilize a high-speed, 640-channel system that can take 10,000 samples of data per second. The system will also permit continuous limit checking of all input signals against programmable high- or low-alarm setpoints. Detection of out-of-limits conditions will initiate visual and audible alarms and also provide automatic safety control actions as required to protect the loop and test bundle.

The system will also permit multiple application programs to be operated simultaneously. During test operation several functions will be supported concurrently, such as loop status display, instrumentation status, and test bundle data logging and analysis. Good quality, hard-copy plots can be generated using the printer/plotter for quick-look analysis.

Functional capabilities of the DAS. The DAS performs two major functions.

Recording data. The primary function of the DAS is the acquisition and recording of data on magnetic tape from up to 640 sensors. The data sensor sampling rate can be varied from a maximum of 10,000 per second to any slower speed. The data acquired from the sensors are recorded on standard 9-track magnetic tape at 1600 bpi (bits per inch) phase-encoded. These "raw" data tapes will then be available for the conversion of data to engineering units and will be maintained in archival storage.

The system will be capable of scanning, digitizing, and recording analog signals in the ranges of 0 to ± 10 V dc. It will have a resolution of one part in 2048 and an accuracy of 0.3% of full scale, exclusive of induced electrical noise. The system will be programmed in FORTRAN language and will utilize industry-compatible magnetic tape. Appropriate signal conditioning in the form of thermocouple reference junctions, strain gage bridge completion, and excitation power supplies will be provided as required.

Limit checking. Another primary function of the DAS is to provide limit-checking capability. Limit checking consists of comparing the data acquired from the sensors to predefined limits for each sensor and taking appropriate action when abnormalities are detected. This action can range from doing nothing to setting off alarms to shutting down the test loop in critical instances.

Each sensor can have up to two limits defined for it: two high, two low, or one high and one low. For example, a critical temperature measurement could have two high limits defined: if the first limit is reached, an alarm could be activated; if the second limit is reached, the loop could be shut down.

Configuration of the data acquisition system. A block diagram of the DAS is shown in Fig. 2.20. The DAS consists of a PDP-11/34 computer

Fig. 2.20. Block diagram of DAS.

from DEC with a number of peripherals. The computer will have 124K words of nonvolatile memory; i.e., the contents of the memory will not be lost during a power failure.

Two magnetic tape drives are included to record data and to provide backup of the disks and programs. A serial line multiplexer is required to connect the various terminals to the computer. Digital input and output will be used to sense external events, set alarms, shutdown the loop, etc. If analog output is required for control functions, it will be incorporated into the digital subsystem. A paper-tape reader is required for diagnostics and transporting programs between computer systems that

are otherwise noncompatible. Two seven-million-word disk drives are provided for the operating system, application software, and other on-line data.

A total of four terminals are proposed that will include the system console, a television-type cathode ray tube for the operator's display, a storage graphics cathode ray tube for plots, and a hard-copy terminal for short printouts. An electrostatic printer/plotter will be used for listings, data tabulations, and graphical output.

The analog input subsystem will initially have input for 640 channels of analog data. This is expandable to 1024 channels with no software modifications and up to 2048 channels with considerable software modifications.

Compatibility with other computer systems at ORNL. One important feature of the DAS is its compatibility with the upgraded data acquisition system for the Thermal Hydraulics Test Facility (THTF). The CFTL DAS is functionally identical to the THTF data system and, in fact, will duplicate a good deal of the hardware and software. This duplication is desirable for a number of reasons. First, if one of the systems has a hardware failure, the other system may be able to provide temporary replacements until repairs can be made. Of course, consideration must be given to preventing the permanent disabling of the contributing system. Secondly, a very large amount of time and manpower has been invested in developing the software for the THTF. By using similar hardware, the CFTL can benefit considerably from this effort. Some "customizing" of the software will be required to meet the specific needs of the CFTL, but this should amount to a small fraction of the effort that would ordinarily be required.

2.8 Loop Interfaces

The loop interfaces with the site building are principally electrical, structural, and spatial in nature. The total maximum electrical power requirement of approximately 6.5 MVA for the test bundles, helium coolant circulators, and heat-exchanger blowers will be supplied from an installed 40-MVA transformer located at the southeast corner of the site

building. This power is available to the CFTL. An uninterruptible power of about 7.5-kW capacity will be obtained to monitor the operating conditions of the CFTL and to shut it down in a safe manner in the event that an emergency interrupts the main Tennessee Valley Authority electrical source to the loop.

A hoist of 4550 kg (5-ton) capacity will be installed at an appropriate elevation in a new penthouse above the test vessel to provide for the installation and removal of the test vessel-test bundle assembly.

The site will provide the space needed for piping runs of sufficient length to meet good practices for the measurement of helium flow, for the control room, electrical substation, and associated power controls, and for the helium purification and supply systems. The space will also be sufficient to provide for the maintenance of all CFTL equipment and systems.

Cooling water that is needed for small auxiliary heat sinks will be obtained from the site building process water supply. Anticipated process cooling water requirements are:

	Total heat loss (kW)	Cooling water flow rate [liter/s (gpm)]
1. Thirteen electrical load banks (45 kW ea)	585	4 (65)
2. Six water-cooled resistor assemblies	366	2 (36)
3. Thirteen variable ac power supplies	<600	4 (65)
4. Three helium circulators	126	3 (45) ^a

^aThe amount of cooling water for the circulators is greater than other comparable heat loads, because the allowable water ΔT is reduced to protect the motor windings.

Item 1 above will be used primarily during checkout prior to operation. Therefore, the normal cooling water flow rate during operation will be the sum of items 2 through 4, or 9 liters/s (146 gpm).

2.9 Test Bundle and Fuel Rod Simulators

The test bundles, which are discussed here only in the most general terms, will be described more completely when detail design is developed sufficiently.

The FRS and BRS for the CFTL test bundles are the subject of continuing development effort. The configuration that has been defined for the FRS, which may be seen in Fig. 2.21, is reentrant with both power leads entering at the open end. The heating element is a helically wound, variable-width ribbon made from Nichrome V alloy to provide a chopped cosine heat flux. The high-temperature portion of the rod leads will be made of nickel, and the lower-temperature portions will be made of copper. The rod cladding will be made from type 316 stainless steel roughened seamless tubing provided by GA. The current-carrying components will be insulated as required from each other and from the rod sheath with cold-pressed preforms made to close-tolerance dimensions from BN powder. Both swaged and nonswaged fabrication techniques were considered during the development effort, and the nonswaged fabrication process was selected as the reference design. One advantage of the nonswaged process is that the FRS cladding may be roughened prior to the FRS assembly. This allows the FRS fabrication process to be simpler and less costly; it further permits cold working and dimensional tolerances to be more prototypic of GCFR fuel rod cladding than is possible when swaging of the cladding is required during FRS assembly. The development effort has also shown that Inconel sheathed, type-K thermocouples (0.5 mm OD) with insulated junctions have smaller temperature measurement errors than stainless steel sheathed, type-K thermocouples for temperature measurement above 1100°C at the internal surface of the rod sheath. The effects of thermal cycling and differential expansion of thermocouples within the FRS were also evaluated before a final selection of Inconel thermocouple sheath material was made. Up to six thermocouples will be installed inside each FRS.

Two areas of development are still in progress on the FRS. Heating elements made of Kanthal A1 alloy are being evaluated for the CFTL in lieu

Fig. 2.21. GCFR-CFTL FRS.

of Nichrome V, because the Kanthal alloy has a higher melting point. Compared to Nichrome V, Kanthal would allow the FRS to operate about 50°C higher before heating element failure occurs during undercooling or margin testing. The maximum continuous operating limit for CFTL FRS with Nichrome V heating elements was determined by test operation at ORNL and is shown in Fig. 1.1 for information purposes. Also BN insulation for sheathed thermocouple junctions is being evaluated on another project because BN has greater thermal conductivity than the normal insulating material, magnesium oxide. The increased thermal conductivity of BN would provide greater thermocouple accuracy during transient operation of the rods. Both of the above development items may be incorporated in the CFTL FRS if on-going tests are successful.

The stored thermal energy in an FRS differs from that in a GCFR fuel rod at a given power and cladding temperature. To provide comparable thermal behavior between the two, it will be necessary to supply programmatically a small amount of additional energy to the FRS during a transient. A computer code is available at ORNL that can determine test bundle power during transient operation to provide thermal behavior of the CFTL FRS comparable to the GCFR fuel rod.

Present plans for the first test bundle, AG-1, call for a 37-rod test bundle with three unheated support rods. The rods will be roughened along a 1220-mm length that slightly overlaps the 1200-mm heated length. The overall length of each FRS will be 2860 mm from the bottom surface of the tube sheet to the top end of the rod. The unheated rod length upstream of the FRS heated section will be about 940 mm in length, and the unheated rod length will be 720 mm downstream of the heated length. The FRS diameter has recently been increased from 7.46 mm to 8.00 mm, and the pitch diameter is now 12 mm between the axial centerlines of adjacent rods.

A special thermocouple assembly will be used at the exit of the AG-1 test bundle to detect and measure hot streaks if they occur in the flow from the bundle. Five thermocouples are planned to be placed across the hexagonal flow passage for this purpose. Special fast response thermocouples that minimize conduction errors along the thermocouple stem will be used in this application.

3. SYSTEM LIMITATIONS, SETPOINTS, AND PRECAUTIONS

The CFTL alarms and automatic safety control action instrumentation will be designed to prevent (1) unintentional overheating of the test bundle, (2) loop damage due to component or auxiliary system failure, (3) overheating or thermal shock of the gas circulators, and (4) overheating or overpressurization of the pressure boundary. In this period of Title II design, only general statements on limitations, setpoints, and precautions can be made. The loop will be operated over a wide range of conditions to simulate GCFR accidents, and therefore the setpoints for some of the automatic safety control circuits will have to be adjusted for each test series. Frequent setpoint adjustments place an extra burden on loop operating engineers and technicians and also require the prediction of loop and bundle performance before each test series to determine the proper setpoint for each safety circuit.

The helium circulator specification limits maximum operating temperature to 350°C (660°F) and also limits short-term cooling transients to 28°C (50°F) for no more than 1 s. However, because the mass of the circulator impeller is relatively large and the sensitive bearing and motor region is relatively isolated, MTI, the circulator manufacturer, has indicated that the circulator should be able to sustain larger and faster transients in helium inlet temperature than specified. Normal heating and cooling rates will be 55°C (100°F) per hour. Dynamic simulation studies are now in progress to determine the automatic safety control actions needed to protect the circulators during simulated GCFR emergency operations as well as from failures of loop components such as FCV-1, HX-1, and HX-2 and loss of normal electric power, etc.

Protection against overheating is particularly important to the test bundle FRS because of the high heat flux and the corresponding rapid temperature rise if the helium flow is reduced or stopped. For example, the FRS temperature will increase about 180°C (325°F) per second if the helium flow is reduced to zero, whatever the cause, when the rods are being operated at the maximum heat rate of 38 kW per rod. High-temperature alarm and scram action will be provided on selected internal thermocouples within the FRS. Alarm and scram action will also be provided on helium

flow rate and the helium exit temperature of the vessel. However, in certain clad melting tests, it will be necessary to raise the setpoints of these safety circuits so that FRS cladding temperature will approach the melting point of stainless steel. Each FRS is also protected with a quick-acting ground fault interrupter circuit that can deenergize an individual FRS in the event of electrical shorting or excessive electrical leakage. If a fault is detected on a single FRS, power to the entire bundle will be interrupted.

The CFTL is operated within a shielded enclosure to reduce the noise level from the loop equipment and to prevent operator injury due to leakage of high-pressure, high-temperature helium. Entrance into the enclosure will be restricted when the loop is operating.

The fire hazard of the facility is extremely low because nonflammable helium is being circulated in the piping system, and no oil lubrication system is required for the gas-lubricated bearings of the circulators. Hydraulic fluid will be required to operate the fast-acting control valves of the main helium circuit; however, we plan to use a synthetic lubricant as the hydraulic fluid to reduce fire hazard. One fluid being considered is Fyrquel 220 (tricresylphosphate), which has a fire point of 615°C (1140°F). The only significant flammable material within the loop enclosure is the electrical insulation on the instrument and electrical wires. A cable fire could safely burn itself out without endangering other experimental facilities or the loop operators.

4. OPERATION

An operating manual will be prepared to guide all CFTL operations. It will consist of the detailed procedures required to perform each operation, or to activate a system, and the detailed checklists needed to support the procedure. Operators of the loop will be put through a training program before operations begin. Standard practice also dictates that certain emergency procedures and loop schematic diagrams be displayed at the control panel to aid operators during emergency situations. Shakedown operation will be performed with the CFTL in accordance with the operating manual to characterize the loop for programmatic operation. During the shakedown period the procedures may be revised as deemed necessary in light of experience.

Prior to the programmatic operation of the CFTL with a new test bundle and at the conclusion of significant maintenance or modification work, a "Readiness Review" will be performed.

All the test operations for an individual test bundle will be performed in accordance with its associated test program. Each test program will present the objectives and philosophy of the test series, the specific test conditions to be attained, and the test measurements to be recorded and their frequency. The test program will also provide predictions of test data and will list limits on the various test measurements that will help determine the necessity to repeat a test or the opportunity to do the next test.

The course of bringing the CFTL from an unfilled, room-temperature condition to a steady-state condition and thence, as required, to transient operation will conform to the approximate sequence of events presented in this section.

4.1 Activation of Systems

The electrical, hydraulic, and helium systems and the fast-scan DAS will be activated in accordance with the operating manual.

4.1.1 Electrical system

The electrical distribution system to supply the test bundle, helium circulators, control room, and various other systems will be the first system activated.

4.1.2 Hydraulic system

The hydraulic system will be activated to supply hydraulic fluid to the stem position operators on the flow control valves for the coolant, attemperation, and circulator bypass helium and for the coolant airflow to the various heat exchangers.

4.1.3 Helium supply system

The helium supply system will be prepared to fill the CFTL with helium. A helium trailer will be located outside of Building 9201-3 to furnish the major source of helium, and 20 helium cylinders will be installed in a manifold adjacent to the loop as an auxiliary gas supply. All helium lines will be purged of air prior to start-up.

4.1.4 Fast-scan data acquisition system

The fast-scan DAS, the DDC, and the PLC will be activated. The DAS will be used to assist loop start-up, to record loop operating and test bundle test data, and to monitor loop and bundle conditions for safe operation. The DDC will be used for loop control, and the PLC will protect the loop and bundle from casualty events.

4.2 Steady-State Operation

4.2.1 Loop filled with helium

After the supply, support, and control systems and the DAS are activated, the loop will be filled with helium in accordance with written procedures. The loop piping system will be evacuated and filled with helium to the room-temperature pressure level that will produce the required operating pressure at operating temperature. (Room-temperature filling

will maximize the number of times the loop may be filled from a helium trailer.)

4.2.2 Helium circulation established

The helium circulators will be started in accordance with written procedures. Helium circulation will be started and helium temperature and pressure will be increased toward the appropriate test conditions by using circulator power and, if required, electric loop heating. The addition or venting of trim amounts of helium may be necessary to achieve test pressure.

In the Stage I CFTL, no helium purification system is available to remove contaminants such as air, water vapor, and hydrocarbons that will evolve from the piping and component surfaces during initial high-temperature operation. Therefore, the impurities will be monitored and the helium inventory will be replaced as dictated to achieve required helium purity. In the Stage II or final loop configuration, a helium purification system will be used to remove trace impurities as they are evolved and to maintain impurity levels within desired limits of the test specification. Helium impurities will be measured with an on-line moisture monitor and by batch sampling and off-site mass spectrometer analysis during Stage I operation. The Stage II facility will have an automated on-line gas chromatograph.

4.2.3 Test bundle power supplied and test bundle heat removed

Power and coolant helium flow rates to the test bundle will be increased in matched fashion, as practical, and HX-1 will be put into operation simultaneously. Heat removal will be increased in equal increments to match bundle power, so as to maintain the helium temperature at the test bundle inlet as nearly constant as practical. The maintenance of a nearly constant helium temperature at the test bundle inlet is a key test condition in the Test Specifications.

4.2.4 Fast-scan data acquisition system utilized

When the required steady-state powered operating conditions are established, the requisite test data will be recorded in the DAS in either high- or slow-speed mode as appropriate. The software necessary to instruct the DAS to collect the data that are appropriate to a particular test will be prepared in accordance with the test program.

4.3 Transient Operations

Initiation of a CFTL transient to simulate an anticipated GCFR transient will always start from a steady-state operating condition. Some anticipated GCFR transients include, but are not limited to, (1) normal, rapid, and step changes in flow; (2) normal, rapid, and step changes in test bundle power; (3) a simulated reactor trip; and (4) a simulated GCFR accident that involves depressurization of the loop helium.

For each transient, appropriate software will be prepared for use in the program controllers to control, in closed-loop fashion, the helium flow rates to the test bundle and through HX-1 and HX-2, the cooling air-flow rates to both HX-1 and HX-2, and test bundle power. Helium pressure will be reduced programmatically as required during depressurization accident simulation. The temperature of the helium at the test bundle inlet can be trimmed as required with the closed-loop control of the circulator heat exchanger HX-2. The DAS will be programmed to record test data required by the test program at highest speed during the transient proper. Data will be taken at greatly reduced speed before and after the transient as appropriate.

4.4 Shutdown

4.4.1 Scram

It is necessary to protect the test bundle rods from high-temperature damage that can be caused during powered operation by the substantial reduction or loss of helium coolant flow to the bundle for whatever reason. Bundle cooling is affected by the leakage or venting of helium from the loop and the failure of equipment or equipment supply systems. Loss of helium will reduce helium density and consequently thermal transport

capability. Failure of a helium circulator, the circulator power supply, or one of the helium flow control valves can reduce or stop the flow of helium to the test bundle. A malfunction of one of the heat sink blowers or an airflow control valve can reduce or eliminate heat removal capability. Protective actions in general consist of automatic high-speed interruption of power to the test bundle and the circulators in proper, timed sequence and notification of the loop operators. Dynamic analysis has shown the need to protect HX-1, the test bundle, and the circulators from the rapid temperature change caused by the power scram. A scram is triggered whenever helium pressure, flow, or temperature is out of bounds. Additional scram initiation will be required for threats to the circulators, reduction or loss of cooling airflow in a heat sink, loss of instrument air supply, malfunction in the hydraulic system supplying the flow control valves, and other control system failures. About 30 categories of scram conditions have been identified to date, as shown in Sect. 5.

Two scram procedures are required, depending on the particular emergency condition. The first, called "scram A," is under the control of the DDC; it causes a controlled and relatively gentle reduction of bundle power and helium flow to reduce the effects of shutdown transients on the test bundle. If the DDC is not operational or the fault condition implies insufficient control to perform scram A, the PLC will provide a second procedure called "scram B." In scram B all the automatic actions are taken immediately; bundle and circulator power is cut off, and the helium control valves are moved to their failure positions, with FCV-1 closed and FCV-2 and FCV-3 opened to allow the coastdown flow to bypass the test bundle.

4.4.2 Normal shutdown

In a normal shutdown, the test bundle power is first reduced to zero and heat removal from the CFTL is continued until room temperature is reached. Then depressurization of the helium may be performed and the support systems secured as appropriate. (The operators may interrupt the normal shutdown procedure to achieve some intermediate operating condition desirable for the test program, e.g., isothermal operation at test

conditions of helium temperature and pressure for the test bundle inlet, or at some lower helium temperature with the helium inventory conserved.)

4.5 Unattended Operation

Experience at ORNL with the unattended operation of the Liquid-Metal Fast Breeder Reactor-Thermal-Hydraulic Out-of-Reactor Safety Facility (LMFBR-THORS) indicates that setting the test bundle power at zero while maintaining both the flow rate and the isothermal temperature of the working fluid at high ready levels minimizes the time required to achieve the next programmed set of test conditions. Thus, unattended operation procedures not only eliminate the additional time required to achieve test conditions from a room-temperature start, but they also reduce the thermal changes the loop must sustain compared to a room-temperature start. Whenever the working fluid temperature or flow rate departs from prescribed boundaries or smoke is detected within the containment enclosure, the unattended operation system automatically puts the THORS into a safe condition. It also alerts personnel in the Plant Shift Superintendent's (PPS) office, which is manned at all times, and they in turn notify the operators of the loop problem. The operators must then resolve the problem and take appropriate action.

A similar unattended-operations philosophy will be used for the CFTL. Present plans call for the CFTL to be manned during one shift a day (8 h/d), 5 d/week. On nights and weekends the facility will be placed in standby and monitored by the PSS office. In addition, consideration will be given to the utilization of the installed fast-scan DAS to permit the unattended performance of a relatively slow cycle of load changes (such as 100 to 50% power and return in 4 min). The DAS would be programmed to monitor helium coolant pressure, flow rate, transport temperatures, and test bundle power and to scram the CFTL (i.e., place it in a safe condition) whenever any of these test conditions depart from prescribed boundaries or other setpoints are exceeded.

5. CASUALTY EVENTS AND RECOVERY PROCEDURES

5.1 Scram Sequence

The CFTL will be designed to be returned automatically to a safe condition upon the appearance of out-of-bounds conditions in the test bundle or loop or the failure of the (1) electric power supply, (2) loop components, or (3) auxiliary systems. The general procedure for all casualty events is immediately to take automatic control actions to protect both the test bundle and the loop from damaging consequences of the event. Two automatic scram procedures are provided depending on the nature of the malfunction. "Scram A" is used to provide a relatively slow shutdown in which the test bundle power is ramped down with circulator flow coast-down to minimize thermal shock to the test bundle by providing a near match between bundle power and coolant flow. "Scram B" is used for those emergencies that threaten the test bundle with extreme thermal shock due to malfunctions such as a general loss of electric power, FRS crowbar action, or loss of the control system. In scram B the test bundle power and circulators are turned off immediately, the control valve on the test bundle inlet line is closed to prevent overcooling of the test bundle, and the bundle heat is removed by natural cooling through the test vessel pressure boundary. Simultaneously, the attenuator and bypass valves will fail open to predetermined positions to avoid circulator thrust reversal. The heat exchangers HX-1 and HX-2 will continue to be controlled at normal temperature setpoints after either scram A or B. After a scram, the loop helium pressure will drop from 10.5 MPa (1520 psia) to about 5.5 MPa (800 psia) as the loop cools to room temperature. The problem will be diagnosed and resolved as necessary before the loop is returned to operating status.

5.2 Summary of Casualty Events

A summary of casualty events for the CFTL is shown in Table 5.1. The casualty events have been arbitrarily grouped into five sections pertaining to circulators, pressure boundary, test bundle, and control and

Table 5.1. Summary of casualty events

Casualty event	Type of scram required
<u>I. Circulators</u>	
Underspeed/reverse rotation	A
Overspeed	A
Flow/speed ratio out of limits	A
High winding/bearing temperature	A
Thrust bearing clearance out of limits	A
Low cooling water flow	A
High helium inlet temperature	A
High HX-1 exit temperature	A
HX-1 or HX-2 airflow failure	A
<u>II. Pressure boundary</u>	
High pressure	B
Rapid pressure decrease (major leak)	B
Low tube sheet cooling airflow	A
High tube sheet temperature	A
High test vessel vertical section temperature	A
High test vessel mixer section temperature	A
High HX-1 inlet helium temperature	A
<u>III. Test bundle</u>	
FRS high temperature	A
High ground currents or short circuits at FRS	B
High bundle gas temperature	A
Continued FRS high temperature after scram A initiated	B
Continued high bundle gas temperature after scram A initiated	B
<u>IV. Control failures</u>	
Valve hydraulics failure: oil pressure, temperature, oil level	A
Gross flow measurement error	B
Gross flow control error	B
Gross power control error	B
DDC failure	B
DAS failure	A
Programmable logic controller failure	A
Zone power trip	B
Circulator power trip	A
FRS crowbar action	B
<u>V. General failure of electric power</u>	
Interruption of electric power to Building 9201-3 or the CFTL	B

power failures. The table lists the cause of the casualty and scram action required after a scram, based on on-going analysis and dynamic simulation studies. For example, if control valve FCV-1 fails closed, it will be necessary to open FCV-2 or FCV-3 as quickly as practical to ensure that the circulators continue to operate within a stable operating envelope. Similarly, loss of bundle power will require closing of FCV-1 to preclude excessive cooling of the test bundle. A consistent scram sequence using either scram A or B will be used for all emergencies with a minimum of valve repositioning after a scram occurs. The hydraulic operator system for the control valves will have sufficient stored energy in hydraulic accumulators to operate each valve to a fail-safe position after loss of the electric power.

5.3 Circulator Casualty Events

Nine different casualty events have been identified that impact each of the three circulators as shown in part I of Table 5.1. The gas bearings of the circulators are protected against operation below 3000 rpm except at start-up, and special instrumentation also precludes reverse rotation. The flow/speed ratio is constantly monitored by the DAS and DDC to ensure that the circulator is not throttled excessively, which could result in unstable surging, or conversely operated at excessive flow rates at a given speed, which can create thrust reversal. The thrust bearing clearance measurement also provides a measure of the approach to thrust reversal of the circulator, and suitable clearance limits and control action will be selected for additional protection from out-of-bounds operating conditions of the circulators. Protection against overspeed is also provided.

High temperature of the windings in any of the three helium circulators will require loop shutdown. High winding temperature can be caused by either motor overload or low flow of the cooling water that protects the stator winding insulation against thermal damage. Consequently, low-flow scram action will be included on individual cooling water flowmeters for each circulator as well as a high-temperature scram from thermocouples in each motor winding. Alarms will warn the operators of impending

trouble before scram action is initiated by either low water flow or high winding temperatures. The alarm and scram settings on both fault-sensing elements will be set at different, but fixed, levels for all modes of loop operation and will not need frequent adjustment for individual tests.

High exit-gas temperature or loss of cooling air at HX-1 is shown as a circulator threat, since this would result in excessive inlet gas temperatures to the circulators during Stage I operation. In the complete or Stage II CFTL, a loss of cooling air at HX-2 will have similar connotations.

5.4 Pressure Boundary Casualty Events

The effects of high helium pressure on the system boundaries (part II of Table 5.1) will be mitigated by the automatic operation of a three-pressure-level system that will provide alarm and scram actions prior to operation of an ASME pressure relief valve. The operators will be notified by alarm if the operating pressure reaches 200 kPa (30 psi) higher than test specification, and manual corrective measures will be taken at that time. The loop will automatically scram if the pressure reaches 11 MPa (1600 psia), and the relief valve will be set to open fully at 11.8 MPa (1715 psia) whether or not corrective action is taken by the operators. (As noted elsewhere, all components of the helium system are designed for a pressure of 11.8 MPa.) The pressure relief valve will reclose at 95% of the set pressure or at 11.2 MPa (1630 psia).

Rapid pressure decrease of the loop, while operating at constant temperature, indicates a major leak. The DAS will provide on-line, rapid monitoring of the system pressure and will call for a scram B if required. The hot helium leaking into the cell would rise to the penthouse and be discharged by at least one of two cell ventilation fans that operate continuously. However, even if the loop enclosure were unvented, the entire loop helium inventory of 175 m³ (STP) would increase the cell air temperature about 40°C and would not reduce the oxygen content of the 1000-m³ loop enclosure to unbearable levels for operating personnel.

A double-ended pipe rupture would result in an extremely rapid pressure loss. This accident has ramifications beyond the loop components

because venting capacity must be provided to prevent excessive pressure rise in the test cell enclosure. A blowout panel in an exterior cell wall provides this pressure relief protection.

The tube sheet on the test bundle is cooled by 350°C helium on the inner surface and by filtered ambient-temperature air circulated by blowers on the outer surface. These two coolants remove heat generated by the FRS electrical copper conductors that pass through the tube sheet. Calculated maximum temperatures for 7.46-mm-OD rods on 11.2-mm rod-to-rod pitch are about 380°C at 38 kW/rod and about 365°C at 28 kW/rod. The rod pitch has recently been increased from 11.2 to 12 mm, and this will reduce the calculated maximum temperature slightly. Also, the recent increase of FRS diameter from 7.46 to 8 mm will allow the use of larger copper conductors through the tube sheet, with correspondingly lower heat generation in the conductors and resultant lower tube sheet temperatures. Scram A action is provided for both loss of cooling airflow and for high tube sheet temperature.

High-temperature scram A action is also required for the pressure boundaries of the test vessel vertical section and the test vessel mixer section, and at the inlet to HX-1. Excessive temperatures at these locations would most likely be caused by the failure of FCV-2 in the closed position. Loss of helium attemperatur flow results in high mixed-gas outlet temperatures from the test vessel. A thermocouple well will be provided at the mixer outlet to allow relatively fast response to a sudden increase in gas outlet temperature.

5.5 Test Bundle Casualty Events

Test bundle casualty events are listed in part III of Table 5.1. The two primary bundle protection devices will be the internal rod thermocouples, which will warn of improper power/flow ratios, and the FRS crowbars, which will protect adjacent FRS when short circuits or high leakage currents occur within a particular rod. Crowbar action in one rod will cause the entire bundle to be deenergized in a scram B after the DAS observes the low power reading on the affected rod.

One of the most severe test bundle traumas would be failure of the inlet helium control valve FCV-1 in the closed position. The internal rod temperatures would rise $\sim 180^{\circ}\text{C/s}$ (325°F/s) during operation at maximum heat rate of 38 kW/rod after the helium flow stops. In this casualty event, a scram signal is provided by high rod temperature from one or more of the six thermocouples within each rod. The DAS will be used to initiate scram action due to the extreme speed of response required. This action will be backed up by other protective systems.

A threat to the test bundle structure is rapid quenching or overcooling whenever the test bundle electric power is interrupted by actions such as a general power failure or any other event that deenergizes the bundle. For this casualty event it is necessary to close FCV-1 immediately to preclude a cooling sequence much more severe than could occur in a GCFR, where decay heat is present in the reactor fuel. As has been noted elsewhere, whenever FCV-1 is closed it is necessary to maintain adequate flow through FCV-2 or FCV-3 to preclude putting the gas circulators into an unstable surging region of operation.

Thermocouples will also be located external to the FRS in the test bundle structure to monitor excessive operating temperatures. The set-point on this protection will depend on the type of test in progress and predicted operating temperatures.

Scram actions related to the test bundle will require a thorough check of all FRS resistance measurements and internal thermocouples to ensure that the bundle was not damaged by the casualty before operation can resume. Loss of an FRS would require a thorough evaluation to determine if meaningful data could be obtained in further testing with a particular rod deactivated.

5.6 Control Failures

Presently known control failures are listed in part IV of Table 5.1. The hydraulic actuator system will be monitored with conventional alarms on the commercially available hydraulic system package. Alarms from low oil pressure, high oil temperature, or low oil level will result in a scram A.

Measurement and control of helium flow and power input will be monitored with the DDC and DAS with suitable cross checks to provide a scram B if significant errors are detected. Operation of the DDC and DAS will be monitored by Watchdog timers to warn of impending failure of these two critical control devices.

"Programmable logic controller failure" is listed as a possible control failure leading to a system trip, and the detection of this failure is assigned to the DDC. The state of the art in programmable logic controllers is now well advanced, and the commercially available units are generally considered to be as reliable as equivalent hard-wired relay circuits. However, considering that the PLC is central to our safety protection system, it is prudent to have some safeguard against a possible failure. One possible means of guarding against this failure is to have the DDC periodically test the PLC by presenting a specific contact closure sequence to the PLC and monitoring to determine if the PLC makes appropriate responses. As the full specification of the PLC is developed, other means of limiting the effects of a PLC failure will be considered.

Also listed under control failures are "Zone power trip" and "Circulator power trip." The electrical power system will include a large number of fault-sensing devices that pertain primarily to the safety of the electrical system rather than to the safety of the CFTL as a whole. Detection of fault conditions by these devices will result in power trips that require one of our shutdown procedures. The degree to which the PLC will participate in the electrical system trip logic is still undefined, but at the least the PLC will be informed of such trip actions so that it may coordinate a uniform system shutdown.

5.7 General Failure of Electric Power

Part V of Table 5.1 indicates the scram safety action provided to guard against loss of electric power to either the control system, the test bundle, or the entire loop. An emergency uninterruptible power supply (UPS) will be provided to allow monitoring the loop conditions after a general power failure occurs. The UPS has a limited capacity, so only key instruments will be powered from this source. In addition to the UPS,

an emergency diesel generator, which automatically starts and comes on-line about 20 s after the normal electric power fails, will take over the lighting loads. Loss of all electric power to the loop will result in gradual coastdown of air blowers and helium circulators and relatively mild thermal shock to loop components because of the loop's large thermal inertia. As in all power interruptions to the test bundle, rapid closing of FCV-1 is required to prevent overcooling of the test bundle.

6. MAINTENANCE

6.1 Maintenance Philosophy

Maintenance of the loop equipment within the cell enclosure will not be done while the piping is at elevated temperatures and a normal helium pressure of 10.5 MPa (1520 psia), because rupture of a pipe, component, or circulator would endanger personnel. Minor repairs to instrumentation and controls within the enclosure will be done with the loop at or near ambient temperature, since the maximum pressure is then about 5.5 MPa (800 psia) or about half the high-temperature design pressure of 11.8 MPa (1715 psia). Maintenance will be performed by properly supervised and experienced craftsmen wearing prescribed safety clothing. The entry of personnel into the shielded enclosure of the facility is controlled by the loop operating engineer. A safety work permit and the safety equipment indicated in Table 6.1 are required for entry into the enclosure. If a gross helium leak occurs, the helium will rise to the

Table 6.1. Safety requirements

Status of loop	For enclosure entry	For opening helium system pressure boundary
System empty and at ambient temperature	Safety glasses	<i>a</i>
System near ambient temperature with pressure below 6 MPa (870 psia)	Safety glasses	Not permitted
System pressure above 6 MPa (870 psia)	<i>b</i>	Not permitted
System at full pressure; circulators at full speed	<i>c</i>	Not permitted

^a Safety glasses and gloves.

^b Full protective equipment — chrome leather suit, gloves, and head cover.

^c Maintenance not permitted, but inspection by loop operators in full protective equipment (*b*) sometimes required.

top of the loop enclosure and be exhausted by louvers and ventilation fans. Air monitors supplied by Industrial Hygiene will be used to ensure that adequate oxygen (19.5 vol %) is in the cell atmosphere before entry is permitted after a gross helium leak.

Normal maintenance of and major modifications to the CFTL will be performed in accordance with the requirements of the Quality Assurance Program for operation of the CFTL, which will be prepared prior to operation of the CFTL. Maintenance of the bundle instrumentation, DAS, and data retrieval equipment will be performed in accordance with ANSI N45.2.

6.2 Normal Maintenance Requirements

During normal operation of the CFTL, routine checks, calibrations, and preventive maintenance of the loop components, auxiliary equipment, and instrumentation are required to maximize the programmatic usefulness of the facility. A tentative checklist of the facility equipment and the required maintenance is given in Table 6.2. The checklist will be better defined as the loop design progresses. Scram circuits will be periodically tested during actual loop operation to ensure that the required safety actions occur.

6.3 Major Maintenance

Major maintenance involving opening the pressure-retaining boundary of the helium system will be performed only when the helium system is depressurized and at room temperature and the high pressure helium supply system is secured. Major maintenance will be performed by properly supervised, experienced craftsmen wearing prescribed safety clothing, using prescribed devices, and working to written procedures prepared as required.

Table 6.2. Preventive maintenance checklist

Equipment or function	Action	Maximum time between checks
1. Check alarm and scram actions		
Loop temperatures, high	Scram 	

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