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Gas-Cooled Reactor Programs

Gas-Cooled Fast Reactor Program

**Progress Report for Period
January 1, 1980,
Through June 30, 1981**

Paul R. Kasten

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National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road, Springfield, Virginia 22104
NTIS price codes—Printed Copy A10 Microfiche A01

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ORNL-5808
Distribution
Category UC-77

Contract No. W-7405-eng-26

GAS-COOLED REACTOR PROGRAMS

**GAS-COOLED FAST REACTOR PROGRAM PROGRESS REPORT
FOR PERIOD JANUARY 1, 1980, THROUGH JUNE 30, 1981**

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Date Published: September 1981

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Uri Gat and P. R. Kasten, *Gas-Cooled Fast Reactor Program Prog. Rep. Jan. 1, 1974, Through June 30, 1975*, ORNL-5119.

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Uri Gat and P. R. Kasten, *Gas-Cooled Reactor Programs Gas-Cooled Fast Reactor Program Annu. Prog. Rep. Dec. 31, 1978*, ORNL-5560.

Uri Gat and P. R. Kasten, *Gas-Cooled Fast Reactor Program Annu. Prog. Rep. Dec. 31, 1979*, ORNL-5675.

FOREWORD

Since the national Gas-Cooled Fast Breeder Reactor (GCFR) Program was terminated in 1980 and carryover funding is being expended in FY 1981, this is the last progress report for the GCFR program at ORNL until its reinstatement. We anticipate that the work being documented here will be helpful in future program planning.

The present Gas-Cooled Reactor Programs (GCRP) at ORNL began about 1957 when the Atomic Energy Commission (AEC) undertook a serious study of gas-cooled reactors (GCRs) for power production. The purpose was to present to the Congress a specific set of conclusions and recommendations concerning the use of GCRs in the United States. This led to the establishment of the GCRP at ORNL in 1956 and adoption of the Experimental Gas-Cooled Reactor (EGCR) Project by the AEC. In addition to the EGCR project, the early GCRP included studies of advanced gas-cooled reactors, particularly those of the pebble-bed type. A few years later, in 1963, gas-cooled fast breeder reactor studies were initiated and consisted of reactor physics and gas-coolant heat transfer fluid flow analyses. This work began when W. D. Manly was director of the GCRP. In 1964, the GCRP was split into three parts, and Myer Bender became responsible for the GCFR work. Soon after that, the GCFR effort was merged into the Advanced Gas-Cooled Reactor (AGCR) Program under the direction of D. B. Trauger. The GCFR effort at that time (1965) included heat transfer and heat removal studies, safety analyses involving reactor transients, and fuel fabrication and fuel irradiations. The GCFR designs on which these studies were based were those developed by General Atomic Company (GA), the prime mover of the GCFR program, and throughout the years close coordination has been maintained between ORNL and GA. In 1966, the EGCR program was terminated, and the AGCR program became the Gas-Cooled Reactor Program (GCRP) at ORNL with D. B. Trauger as director. At that time the GCFR program at ORNL initiated postirradiation examinations of fuel and continued work on fuel capsule fabrication, reactor physics analysis, heat transfer fluid flow studies, and afterheat removal studies. However, by 1969 the scope of effort had contracted to that of fuel development.

In 1970 P. R. Kasten became director of the GCRP; the GCFR program consisted of fuel fabrication activities, fuel capsule irradiations, design of new fuel capsules, and irradiations of fuel in the Oak Ridge Research Reactor (ORR) and in the Experimental Breeder Reactor (EBR-II). In 1972 the GCFR effort expanded into steam generator modeling studies, and in 1973 planning for the Core Flow Test Loop (CFTL) was initiated. The CFTL was initially considered an out-of-reactor test facility for evaluating fluid flow heat transfer relations within the GCFR core. In 1975 the fuels work (fabrication, irradiation, and postirradiation examinations) was moved to Argonne National Laboratory. At the same time, the ORNL GCFR effort expanded into the areas of prestressed concrete reactor vessel (PCRV) closures and GCFR shielding and reactor physics. Increasing emphasis was placed on the CFTL effort, particularly on the ability to develop a facility that met expanding fuel testing needs, including an understanding of the mechanical interactions that could take place within the simulated fuel elements and evaluation of rapid

depressurization events. Work in the three areas of PCRV closures, reactor shielding and physics, and the CFTL has continued until this time. All of these areas are pertinent to the High-Temperature Gas-Cooled Reactor (HTR) Program, and the associated expertise will be applied to that program. Specifically, the PCRV closures work will become part of the HTR PCRV program; the shielding and physics efforts will be appropriately reoriented to HTR shielding and physics; and the CFTL (renamed the Component Flow Test Loop) has been dedicated to the HTR program for use in developing and testing HTR components and related systems.

Although the GCFR program has been terminated, the documentation of the expertise and results developed in the various GCFR areas (as represented by this and previous progress reports) and the transfer of pertinent technology areas to the ongoing HTR program will serve to assist in efficient reinstatement of the GCFR program at a future date.

Paul R. Kasten

SUMMARY

1. COMPONENT FLOW TEST LOOP

The Component Flow Test Loop (CFTL) is a high-temperature, high-pressure, out-of-reactor helium circulation system designed to supply helium at controlled conditions to an appropriate test vessel or component of the gas-cooled reactor program.

In September 1978 construction of the CFTL was divided into two stages. For the Stage 1 CFTL, which was to have been the initial construction goal, the test section power was halved to approximately 2.5 MW, and the bypass cooling system was deleted. A limited capability to perform fast coordinated transients with test section power, helium flow, and heat removal was retained.

In mid-1979 the U.S. and German designs for the Gas-Cooled Fast Reactor (GCFR) converged on the upflow core. The change from the downflow to the upflow core slowed the progress of the Stage 1 design.

Late in FY 1980 on the closeout of the GCFR program, the Stage 1 CFTL was converted to the current Stage Alpha version. For the Stage Alpha CFTL the test section power was further reduced to 0.5 MW, and the steady state mode of operation was adopted. In May 1981 the GCFR Core Flow Test Loop (CFTL) was renamed the High-Temperature Gas-Cooled Reactor (HTGR) Component Flow Test Loop (CFTL) and was dedicated to the development and testing of components and systems for the HTGR program.

At the beginning of 1980, the major efforts of the analysis task were devoted to the implementation of computational procedures for the thermal-flow analysis of the CFTL bundle. Analyses were needed for specification of the bundle instrumentation and for the preoperational calculation of anticipated conditions in the bundle. The goals of the analysis work were to prevent unanticipated damage to the test bundle by making on-line reductions of the data for comparison with pretest calculations and to provide experimental data as the basis for verification of the computational procedures to be used in licensing. To make the computational procedures provided by the General Atomic Company (GA) operational on the ORNL computing system, it was necessary to truncate the coding to include only that segment applicable to the CFTL analysis. This truncated version was used to evaluate experimental conditions in a 12-rod, channel-centered Kernforschungszentrum, Karlsruhe (KfK), bundle and to participate in the Sixth Benchmark Meeting in September 1980. This participation was very helpful in confirming the attributes and deficiencies in the truncated code.

A structural analysis method was developed at ORNL, which was applicable to the 37-rod AG1 bundle. This method used a transfer matrix to proceed stepwise from the fixed end of the bundle to find a solution for reactions and deflections at each intersection of the members.

A cooperative experiment in an existing loop at KfK was completed in the spring of 1981 to determine the performance characteristics of the surface roughening that had been specified for the AGI bundle. The major efforts during the past year have been devoted to the preparation of adequate reports covering these efforts so that the information and procedures will be available for future use.

The Title II design and the construction of the Stage Alpha CFTL were completed except for the procurement of two helium flow control valves and the preoperational testing and Title III design activities for completion of construction. These activities should be completed during the first half of FY 1982.

The Stage Alpha CFTL consists of three helium circulators connected for series operation, the main heat sink and heat exchanger (HX1), two vortex shedding flowmeters, a full-flow helium filter, and a test section consisting of a straight section of pipe replacing the Stage 1 test vessel. These components were fabricated at various places and were assembled in Building 9201-3, Y-12 Plant, to form the pressure boundary of the CFTL helium circulation system. All the components were connected appropriately with piping, and downward flow through the test section was provided. Appropriate power supplies were installed. Instruments and controls, adequate for steady state operation and for the protection of the CFTL during emergencies, were installed.

Procurement, testing, and installation of the helium circulators were completed. Procurement, initial testing, and installation of the 0.5-MW zone power supply having power transient capability from 100 to 0% in time periods ranging from 1 s to 30 min were completed. Procurement, full-load testing, and installation of the variable-frequency power supplies for the three helium circulators were completed. Fabrication, calibration, and installation of the vortex shedding flowmeters were completed. Field instruments and controls, control room equipment and cabinets, and conduits and cable trays were purchased, assembled, and installed, and the associated wiring circuits were completed. A sophisticated control system (not commercially available) for programming the unique power transient capability of the 0.5-MW zone power supply was designed, fabricated, tested satisfactorily, and installed. Design, purchase, and installation of the interlock circuits and logic emulator necessary to protect the CFTL from damage during emergencies were completed. A substantial amount of construction acceptance testing was completed. Utility software programs were prepared to provide operator control of the data acquisition system and to yield system status on request. Documentation was furnished to permit programmers to prepare new programs on the data acquisition system with minimal guidance from Instrumentation and Controls Division personnel.

The design of the 37-rod test bundle AGI was approved by the bundle design review team. Appropriate instruments were selected for making the required measurements of bundle structural effects. Thermocouples appropriate to measurement of the temperatures of bundle internals, bundle instruments, bundle flow duct, and helium in bundle interstices and at

bundle inlet and outlet were selected. A differential pressure system was designed to obtain bundle pressure-drop information. The x-ray-imaging technique was selected for observing movement of bundle components during operation. Specifications were prepared for microphones and accelerometers to characterize acoustic and vibrational characteristics of flowing helium and the bundle. Locations of all the test bundle instruments were established. Development efforts for the 8-mm-diam fuel rod simulator (FRS) for bundle AGI and for the brazing techniques for attaching electrical connectors to the FRS were taken to logical stopping points and halted. The reliability of the center nickel electrode, which appears to be the limiting factor in FRS reliability, is reduced by the very slow formation of B-Ni eutectic; GCFR closeout precluded completion of the development of suitable MgO preforms to eliminate the B-Ni eutectic phenomenon associated with the use of BN preforms. The brazing technique for attaching electrical conductors between the power supply leads and the FRS terminals was proof-tested satisfactorily. Efforts to produce small-diameter thermocouples having suitable reliability for the FRS in bulk material lengths approaching 60 m (200 ft) were concluded satisfactorily.

The design documents for the CFTL are listed in Appendixes 1 through 5, which also identify their respective storage file points.

The procurement documentation is stored and maintained in Building 9201-3, Y-12 Plant, by the Experimental Engineering Department in the Engineering Technology Division of ORNL. Limited quantities of spare parts for the Stage Alpha CFTL and materials and equipment purchased for the Stage 1 CFTL are stored in cages A and B in Building 9201-3, Y-12 Plant, by the Experimental Engineering Department.

Some parts for test bundle AGI were fabricated by GA, were delivered to, and are stored at ORNL (see Sect. 1.4.5).

2. GCFR SHIELDING AND PHYSICS

The radial blanket and shield experiment was performed at the Tower Shielding Facility to verify the radiation transport methods and nuclear data used for the design of the radial blanket and shield for the proposed 300-MW(e) GCFR. The experimental configurations consisted of partial to full mockups of the GCFR Conceptual Shielding Configuration I extending from the inner surface of the thorium blanket, through the inner and outer radial shields, and into a portion of the PCRV. The completed postanalysis showed that a capability exists for accurately predicting (1) the neutron transmission through thick UO_2 and ThO_2 blankets and laminated shields containing steel, graphite, and boronated graphite; (2) the gamma-ray heating rates within the configurations; and (3) the neutron spectra beyond the configurations.

The outer radial shield of the GCFR consists of several interwoven pieces of graphite, separated by voids and enclosed in stainless steel envelopes. It was therefore desirable both to (1) study the effects of neutron streaming through shield heterogeneities typical of those that might be present in the actual shield and (2) provide a benchmark against

which the analytical methods used to design the shields could be tested. Analysis of the experiment was performed with both the DOT discrete ordinates code and the MORSE Monte Carlo code. The DOT results and the measurements agree within 20%, with some notable exceptions. In general, the MORSE results and the measured results are in poor agreement, but curtailment of the GCFR program will not permit a detailed investigation of the reasons.

The exit shield experiment simulated that portion of the plenum shield that comprises the upper part of each fuel assembly. It is identified as the exit shield because it provides a helium exit path from the core while providing protection for the components in the plenum above the core. The experiment mocked up seven GCFR core assemblies, and different configurations varied in placement of the control rod mockup within the subassembly. Three of the configurations were analyzed with the DOT discrete ordinates code, and one of the configurations was analyzed with the MORSE Monte Carlo code. Agreement between the measurements and the calculations is generally good, and we concluded that the exit shield configurations could be calculated adequately. The overall conclusions of the experiment were that the GCFR exit shield would be highly effective in protecting the components in the upper plenum region and that the shield would not be compromised by control rod penetrations.

Analysis of the shielding design for the preliminary upflow GCFR (Conceptual Shielding Configuration II) was completed and documented. Both localized and global Monte Carlo and discrete ordinate calculations were performed on flow-through shield designs for Conceptual Upflow Shielding Configuration III. Documentation of these calculations discusses several items that could have a potentially major impact on the shielding design.

3. GCFR PRESSURE VESSEL AND CLOSURE STUDIES

The third in a series of small-scale closure model tests was conducted during this reporting period. The 1:20-scale model represented a redesign of the central core cavity closure plug. The primary objectives of the test were to demonstrate structural performance and ultimate load capacity of the closure plug. Secondary objectives included obtaining data on crack development and propagation and on mode of failure of the composite structure.

Prominent features of the 1:20-scale central core cavity model included a close-pitched array of 55 penetration tubes, 44 segmented gusset-bearing-plate assemblies, and intermeshed reinforcing steel. Linear scaling of model dimensions and duplication of mechanical properties of the materials from prototype to model were accomplished in all aspects except one. Analysis indicated that the penetration tubes would fail from overload before failure of the structure as an entity if all mechanical properties were duplicated. Rather than increase the wall thickness of the penetration tubes, a higher strength material was substituted. This permitted both a valid overload test and a monitoring of realistic strains at the ligament area of the top penetration surface.

The closure model, which was designed for a maximum cavity pressure (MCP) of 10.08 MPa, was initially tested by applying ten pressurization cycles from essentially no load to the MCP with strain and deflection data obtained during each cycle. This was followed by pressurization cycles of 32.8, 41.3, 58.4, and 79.3 MPa. At a pressure of 79.3 MPa, an end-cap on a penetration tube developed leaks and the test was terminated.

An inelastic analysis was conducted to provide an estimate of the ultimate strength of the closure plug and to determine the potential mode of failure. At a pressure of 57.92 MPa, the analysis was terminated because of large displacements incurred from extensive liner yielding rather than because of structural failure. The very conservative analytical results indicate that improved constitutive relations are required for concrete.

1. CORE FLOW TEST LOOP

J. P. Sanders, A. G. Grindell, and R. E. MacPherson

1.1 INTRODUCTION — J. P. Sanders and A. G. Grindell

At the beginning of 1980 the staged approach¹ to the construction of the Core Flow Test Loop (CFTL) in the Gas-Cooled Fast Reactor (GCFR) Program was being implemented. The Stage 1 CFTL was being constructed to have only a 37-rod test bundle capacity and limited transient capability. It was to have been followed by the construction of Stage 2, which would have had a full 91-rod bundle capacity and full capability to simulate GCFR transients. The scope of the Stage 1 CFTL program included (1) construction of the CFTL; (2) construction of test bundles to simulate GCFR core assemblies and to simulate in the CFTL their operation under conditions anticipated for the GCFR; (3) development tasks supporting the design, construction, and operation of the CFTL and associated test bundles; (4) analysis work to support the design, construction, and operation of the CFTL and the test bundles; and (5) acquisition and analysis of test data taken during test bundle operation.

Near the third quarter of 1980, ORNL was requested to close out its GCFR program and a previously prepared closeout plan was implemented. The plan required the cessation of GCFR-related activities and completion of the design and construction of a Stage Alpha CFTL, including its adaptation to the programmatic test needs of the High-Temperature Gas-Cooled Reactor (HTGR) Program. In this adaptation, the Stage Alpha CFTL would be used to acquire and evaluate data taken on thermal performance, pressure-drop characteristics, and design and safety margins for HTGR parts and components to assist design and licensing activities.

The GCFR closeout included three activities: First, design drawings, specifications, equipment, systems, and materials were identified in lists that are appendixes to this report; the items were stored for retrievability. Second, formal reports were prepared to document important development activities. Third, all activities for the test bundles that simulate GCFR fuel assemblies were halted except two that were continued

to a logical stopping point and halted. Testing was performed on two fuel rod simulators (FRSs) for which fabrication had been completed at the time of the closeout order. A mockup to develop brazing techniques for joining electrical connectors to FRS terminals was ready at the time of the closeout order, and tests with it were completed.

Figure 1.1 presents an artist's view of Stage Alpha CFTL and indicates the principal components and systems installed. By comparison with the Stage 2 CFTL, some items of equipment that have been eliminated from the Stage Alpha include: heat exchanger number two (HX2) and the associated bypass line around the helium circulators, the helium flow control valves, the test vessel that was to have contained the GCPR test bundles, the helium purification system, and the depressurization system. For Stage Alpha, the data acquisition system (DAS), the direct digital controller (DDC), and one of the 13 zone power supplies were installed but not connected functionally.

Production of the two helium circulators in addition to the prototype was completed by Mechanical Technology Inc. (MTI). All three circulators met design requirements and, additionally, were operated satisfactorily at a helium inlet temperature of 450°C (850°F) compared with the design value of 340°C (650°F).

Calibration of the vortex shedding flowmeters (VSPMs) was completed satisfactorily at the Colorado Engineering Experiment Station.

The system design description for the CFTL was completed and distributed. It treats the Stage 2 CFTL having a full 91-rod bundle capacity and full transient capability; it also indicates briefly the differences that distinguish the Stage 2 CFTL from the Stage 1 and the Stage Alpha CFTL.

The CFTL was subjected to four quality assurance audits during this sesquiannual report period. Two audits were conducted by the quality assurance coordinator for the ORNL Engineering Technology Division, one by the lead auditor for the ORNL Quality Assurance Program and one by the Standards and Quality Assurance Division of the U.S. Department of Energy, Oak Ridge Operations (DOE-ORO). The general tenor of comments from all the audits indicates that the quality of the CFTL work is satisfactorily assured.

Fig. 1.1. Stage Alpha CFTL.

The Title II detailed design for the mechanical and electrical disciplines was completed during the first quarter of 1981, and, for the last portion of the instrumentation and controls discipline (the alarm and protection system), the Title II design was completed in June 1981.

Construction of the Stage Alpha CFTL was essentially complete when all activities were halted by a strike by the Y-12 craft unions. However, we anticipate completing the construction craft activities during the third quarter of 1981 and the preoperational testing, Title III as-built drawings, and shakedown during the first half of FY 1982.

On May 29, 1981, all the equipment and systems of the GCFR-CFTL were dedicated to the needs and uses of the HTGR program. The name was changed to HTGR Component Flow Test Loop; the acronym CFTL will be retained.

1.2 IMPLEMENTATION OF ANALYTICAL PROCEDURES FOR PRETEST CALCULATIONS, DATA REDUCTION, AND DATA PRESENTATION — J. P. Sanders, J. C. Conklin, G. E. Giles,* S. A. Hodge, C. A. Sady*

1.2.1 Introduction — J. P. Sanders

The principal effort under the analysis task has been directed toward the implementation of an analytical procedure to serve as the basis for both design calculations and calculation of anticipated conditions in the test section before operation. General Atomic Company (GA) had developed a procedure (primarily as a basis for the design of the GCFR) for the analysis of the flow and thermal conditions in a bundle of roughened rods.

This procedure was based on the COBRA code, which had originally been developed at Hanford for light-water-cooled reactors. Before the period covered by this report, a version of this procedure, modified for the GCFR, had been provided. Considerable effort was required to make that version of the code operational at ORNL. In January of 1980, GA provided a subsequent modification that was so different that implementation had to be performed again.

As an alternative to implementing the entire procedure, the computation was truncated so that only those segments required for the CFTL

*Computer Sciences Division, UCC-ND.

analysis effort remained, which made the task tractable. This truncated version, designated COBRA/ CFTL, was used as the basis for most of the work describe here.

In addition, as a consequence of the assignment of a graduate student under the Oak Ridge Associated Universities (ORAU) fellowship program, a version of the SAGAPO code, which had been written at Kernforschungszentrum, Karlsruhe (KfK), was available to ORNL. This version of SAGAPO was used to generate a pseudodata tape that was provided to GA for use in establishing procedures for verification of its computational design procedures. The SAGAPO code also provided typical anticipated conditions in the AGI bundle; this information was used as the basis for specification of the instrumentation in the bundle.

Another computational procedure, FLAC, had been provided by GA. This procedure was used to evaluate the flow conditions at the inlet to the bundle.

The ORAU fellow also generated a comprehensive evaluation of an available method of correlating the performance of roughened surfaces. The application of these methods led to a test of the actual surface roughening specified for the CFTL rod. The following sections describe this application and the subsequent incorporation of the method into the computational procedure.

1.2.2 Application of $R(h^+)$ and $G(h^+)$ Functions — S. A. Hodge

An extensive review was made of methods for determining friction factors and Stanton numbers for flow past artificially roughened surfaces. This work was supported by ORAU under its graduate fellowship program. The results of this work were published as a dissertation at the University of Texas and as an ORNL report.²

To test the application of the $R(h^+)$ and $G(h^+)$ factors, which were recommended for the reduction of experimental data and the application of this data to analysis, the SAGAPO computational procedure³ was adapted to the ORNL computer system and to the computational needs for the analysis of the CFTL bundle.

The final modifications to the SAGAPO code were completed in January 1980; this version of the computational procedure provided a

determination for the thermal-flow conditions in the CFTL bundle under steady state conditions. These modifications to the code included

1. conversion of the code to SI units,
2. adaptation of the code for calculation in a one-sixth symmetric sector of the 37-rod CFTL bundle, and
3. special accommodation to print output of rod wall and channel gas bulk temperatures plus bundle pressure at the axial distances from the bundle inlet corresponding to the thermocouple and pressure tap locations of the CFTL.

This computational method was used to generate a pseudodata tape for use by GA personnel in developing analytical procedures for verifying their computational techniques. The method was also used to provide typical values at all instrument locations in the CFTL bundle for the entire range of flows in the test plan. This information was supplied to the Instrumentation and Controls Division for use in specifying related instrumentation and in formulating the software for the data acquisition system (DAS). The results for the full-flow calculation from this code are presented graphically in a published report⁴ that describes the planned location of test bundle instrumentation in the CFTL AGI bundle.

A report⁵ was prepared for presentation at a GCFR Heat Transfer Specialists Meeting in Berkeley, England, September 1980. The report described a proposed method for the determination of the required parameters for the particular roughness to be used in the CFTL. Examples were given of the application of these methods to both transitional and fully rough flow by use of experimental results taken from the literature. Highlights of the report follow.

The friction factor and Stanton number applicable to flow past a particular roughened surface are functions of the velocity profile width (the distance between the rough surface and the surface of zero shear in the adjacent flow). The nature of this functional dependence can be revealed in relatively simple experiments, in which the roughness of interest is machined on the surface of a test rod and exposed to axial flow in a series of annular geometries. These annular geometries are formed by placing the test rod successively at the center of a series of smooth tubes of varying diameter so that the velocity profile width is varied.

A prototype CFTL roughened cladding is scheduled to be tested in this manner. The methods, which will be used for determination of the parameters A and $R(h^+)$ in the universal friction law for rough surfaces and the corresponding parameters A_H and $G(h^+)$ for the law of heat transfer, are developed and discussed. Application of the proposed methods is illustrated by use of experimental results for other roughened surfaces taken from the literature.

The method formed the basis for determining parameters for the CFTL rod in an existing experimental loop at KfK in Germany. The experiment is described in Sect. 1.2.4.

1.2.3 Travel to Specialists Meeting on GCFR Heat Transfer and Benchmark Meeting — J. P. Sanders and S. A. Hodge

Details of the Fifth GCFR Heat Transfer Specialists Meeting have been published.⁶ This meeting was held in Wuerenlingen, Switzerland, May 14–16, 1979. The meeting was followed by the Benchmark-IV Meeting, at which results of the same calculation by various computational procedures were compared. This meeting was followed by the Benchmark-V Meeting, December 13–14, 1979, at KfK in Karlsruhe, West Germany.

Continuing in this series of meetings, the Sixth GCFR Heat Transfer Specialists Meeting was held at the Berkeley Nuclear Laboratories, England, September 15–17, 1980. This was followed by the Benchmark-VI Meeting at Windscale Nuclear Power Laboratories, England, September 18–19, 1980. Both J. P. Sanders and S. A. Hodge represented the CFTL analysis task at these meetings.

Following the meetings, J. P. Sanders visited the Federal Institute for Reactor Studies (EIR) at Wuerenlingen, Switzerland, to obtain information on its continued operating experience with the AGATHE loop. He then visited KfK at Karlsruhe, West Germany, to obtain information on its experimental determination of the fundamental characteristics of roughened surfaces.

S. A. Hodge went from the meetings in England directly to KfK to initiate the experimental evaluation of parameters for the specific roughening of the CFTL rods. He remained at KfK for two weeks to coordinate these activities.

1.2.3.1 Sixth GCFR Heat Transfer Specialists Meeting — J. P. Sanders and S. A. Hodge

Three papers were presented at the Sixth GCFR Heat Transfer Specialists Meeting, sponsored by the OECD-NEA Coordinating Group on Gas-Cooled Fast Reactor Development. The paper by S. A. Hodge⁵ described methods for determining the coefficients for application of the laws of friction and heat transfer to the CFTL. The paper presented by J. P. Sanders⁴ described the location of instrumentation and the anticipated experimental values for the CFTL AGI bundle. A third paper was prepared by J. C. Conklin and presented by J. P. Sanders, which concerned a computational procedure, RODCON, to determine the effect of thermal conduction in the rods of a bundle such as the CFTL AGI bundle. This paper is contained in a published report.⁷

A total of 67 papers were presented in seven sessions at this meeting. The papers ranged from excellent comprehensive reviews of both experimental and analytical programs to preliminary data from the most recent tests at the installations represented.

Several papers from the European community contained information of particular interest to the CFTL analysis effort. Dr. L. Meyer of KfK presented the results of recent experiments with rough rods in annular geometry. He confirmed that, for fully rough flow, the slope of the dimensionless velocity profile Δ was less than 2.50. This conclusion had been developed from data reported previously.² Dr. Meyer found that this value of the slope increases as the flow decreases and enters the transition zone between fully rough and hydraulically smooth flow. Meyer's finding supports the previous conclusions by S. A. Hodge.

Dr. Dalie Donne of KfK presented results of experiments with three-dimensional roughness tested in annular geometry. He reported a remarkable improvement in heat transfer performance for this configuration over the two-dimensional roughness studied previously. However, a question still existed as to whether or not the transformation procedure used for analysis of these high-friction-factor roughnesses was valid.

S. Cevolani of KfK discussed improvements that he had introduced in the SAGAPO code and presented the basic correlations employed in the current version of the code. These improvements include a circumferential conduction option for the rods and the shroud and an option for radiative heat transfer within the bundle. These features were not available in the version of the code that had been adapted for the CFTL at ORNL.

Dr. K. Rehme reported the results of experiments by Mr. Hassan at KfK to determine the effect of spacers on the Nusselt number at the rod wall. These experiments were conducted for both laminar and turbulent flow and include results for smooth as well as roughened rods. The experimentally determined ratio of the Nusselt number in the vicinity of a spacer to the Nusselt number for undisturbed flow was shown to be represented by a linear increase from unity at a point one equivalent diameter upstream of the spacer to a maximum at the spacer midpoint, followed by an exponential decay. These findings required that the model for the spacer effect on the Nusselt number in the ORNL version of both SAGAPO and COBRA/CFTL be changed.

1.2.3.2 Benchmark Meeting — S. A. Hodge and J. P. Sanders

The purpose of the benchmark meeting was to allow the participants to compare the predictions of the respective calculational procedures with experimental data. The participants did not have access to the experimental results before the meeting, so the benchmark exercise provided a good opportunity for comparison of the relative attributes of the various codes.

For the Benchmark-VI Meeting, KfK performed the calculations with the SAGAPO code, EIR used the CLUHET and SCRIMP codes, and ORNL used a modification of the COBRA code, designated COBRA/CFTL. This was the first meeting in which ORNL actively participated. In the past, the GCFR program in this country had been represented by GA, and its calculations had been performed with a different modification of the COBRA code. The COBRA/CFTL code differed from the version used by GA in that it (1) was specifically designed for CFTL calculations, (2) operated in SI units, and

(3) was capable of computations involving simultaneous fully rough, transitional, hydraulically smooth, and laminar flow in the various channels of the bundle.

Three roughened rod bundle experiments were proposed for analysis by the participants in this benchmark meeting. The first was a 12-rod, channel-centered bundle flow experiment provided by KfK at two different operating conditions. For both cases, the helium flow was in the laminar range. In the first set of conditions, the bundle was symmetrically heated, and in the second set, a severe power tilt was obtained by heating only six rods on one side of the bundle.

The COBRA/CFTL prediction of the experimental results for the first set of conditions was very satisfactory; both calculated pressure drops and rod wall temperatures agreed well with experimental values. However, discrepancies in the COBRA/CFTL analysis appeared when comparison was made with data from the set with power tilt. This comparison indicated that several changes should be made in the code:

1. The code must be modified to represent circumferential conduction in the shroud. The predicted shroud temperatures on the heated side of the bundle were much too high; those on the unheated side were too low. The COBRA/CFTL was the only code represented at the benchmark meeting not having this capability.

2. The effect of bundle spacers on the rod wall Nusselt number is overpredicted by the correlations in COBRA/CFTL. This was caused by a coding error, because the intended correlations were the same as those used in SAGAPO, which correctly predicted the Nusselt numbers.

3. The code must be modified so that the Reynolds number for flow in the wall and corner channels are computed by use of the coolant viscosity at the average temperature of the bordering sections of the edge rod and shroud wall. The coding did not consider the shroud temperature in the averaging process; this resulted in a Reynolds number that was too low and a friction factor that was too high in the edge channels.

4. Although not a feature of the coding, we learned that the user's input must be modified when there is asymmetric heating and low flows. When calculations were performed for the second set of KfK data,

COBRA/CFTL produced a "numerical heating," which introduced more heat into the coolant than was transferred from the rods. Subsequently, G. Giles of ORNL identified the remedy by reducing the user-supplied convergence criterion for the channel cross-flows.

Identification of these changes in the coding and formulation of the input for COBRA/CFTL illustrated the great value of the benchmark process. It is difficult to envision how these discrepancies could have been otherwise identified.

The KfK experiment also indicated that turbulent mixing occurs to a significant extent following each spacer even though the overall bundle flow is laminar. This effect was modeled in both the SAGAPO and COBRA/CFTL pretest calculations; these two codes approximate this aspect of the experimental results very well.

This benchmark meeting indicated that the code SAGAPO was most consistent in accurately predicting the experimental values. The SAGAPO code is limited to steady state application, and it has a much more detailed analysis methodology than the other codes have. It is capable of computations with the bundle structure divided into channels, subchannels, and sub-subchannels.

The calculated values of COBRA/CFTL were generally very good, although several discrepancies (discussed previously) indicated the need for a limited amount of code modification. The COBRA/CFTL code has transient analysis capability and, as such, should not be expected to perform calculations in as much detail as would the steady state only code, SAGAPO.

At the conclusion of the meeting, it was agreed that a final detailed summary and comparison of the experimental results to calculated values should be assembled for each of the test bundles. Each participant agreed to make a final submission of calculated values within the following two months.

The modifications in COBRA/CFTL were made according to the points indicated above, and the calculations for the 12-rod bundle were again performed following the benchmark meeting. The results were provided to KfK in both the required tabular and graphical manners. Subsequently, an

overall comparison of the corrected calculations was provided by KfK. This presentation indicated very good agreement between the values determined from COBRA/CFTL and the experimental data points.

1.2.4 The CFTL Prototypic Rod Experiment — S. A. Hodge and L. Meyer*

An experiment for the purpose of establishing a set of pressure-drop and heat-transfer correlations for use in CFTL bundle analysis was completed at KfK, Karlsruhe, West Germany, in February 1981. The experiment involved both heated and unheated axial flow of air past the roughened cladding surface of a CFTL rod prototype in a series of annular geometries, each formed by central location of the rod within a smooth outer tube shroud. The experiment comprised three series of tests with the 7.8-mm-diam CFTL rod located within smooth outer shrouds of 20-, 16-, and 13-mm diameters, and was performed at KfK under the direction of Dr. L. Meyer at no cost to the ORNL CFTL task. The associated test data were received at ORNL on February 17, 1981.

The data analyses for this experiment were conducted at ORNL through use of the computer code AURIS, obtained from KfK and subsequently modified as necessary to satisfy the ORNL analysis requirements. The ORNL method involves graphical comparison of the experimental and analytical results for flow in the three different outer shrouds. A report has been prepared⁵ describing both the method of data reduction and the results of this experiment.

The roughness parameter $R(h^+)$ for the CFTL rod is 4.45 in fully rough flow with a corresponding velocity profile slope A of 2.56. These parameters were determined from the test results for isothermal flow and can be used for determination of the friction factors for isothermal flow within the various channels of the proposed CFTL rod bundle.

Experimental results also show that the effect of temperature in reducing the friction factor is dependent on the diameter of the test shroud. There is no discernible effect for the test runs in the 13-mm-diam shroud, a small effect for the runs in the 16-mm-diam shroud,

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and a large effect for the 20-mm-diam shroud tests. The actual dimensions of the channels in the proposed CFTL bundle fall between those modeled by the 13-mm and 16-mm shrouds. It is therefore believed that use of the isothermal friction factors in pressure-drop calculations for heated flow in the CFTL bundle will yield satisfactory results.

Correlations for calculating roughness parameters $G(h^+)$ and A_H in fully rough flow were also established from analyses of the test runs with heat transfer from the rod. These parameters are used in the COBRA/CFTL code for calculating the Stanton numbers for flow within the various channels in the roughened section of the proposed CFTL bundle. The extent of the transition zone, in which the flow regime changes from turbulent fully rough to turbulent hydraulically smooth, was clearly discernible from the test results. These results show that this zone extends over the range of roughness Reynolds numbers h^+ from 3 to 20. Correlations for determining the roughness parameters $R(h^+)$ and A , which are functions of h^+ in the transition zone, were established for use in this range.

The ratio of the friction factor to the Stanton number becomes independent of the velocity profile width in the transition zone. It is therefore convenient to determine the Stanton number directly from this ratio once the friction factor has been calculated. Correlations for the ratio of the friction factor to the Stanton number in the transition zone were also established as a result of this experimental and analytical work. This effort is described in detail in a published report,⁸ the abstract of which follows.

The friction factor and Stanton number for flow past a roughened surface are determined by the parameters A and $R(h^+)$ of the universal law of friction and the parameters A_H and $G(h^+)$ of the universal law of heat transfer. The methods used for experimental determination of these parameters for the particular roughness and rod diameter proposed for use in the Core Flow Test Loop (CFTL) are presented, and recommended values for use in CFTL bundle flow analysis are prescribed.

1.2.5 Implementation, Evaluation, and Development of Computation Procedures for Thermal-Flow Analysis - J. P. Sanders

The computational procedure supplied by GA for the preoperational and pretest calculation of anticipated thermal-flow conditions in the CFTL

bundles was based on the COBRA code.⁹⁻¹⁰ This code was written at the Battelle Northwest Laboratories (BNWL) in Richland, Washington, for the thermal-hydraulic analysis of water-cooled reactor cores. The code was developed on a Control Data Corporation (CDC) computer system. Because of its intended use for water-cooled reactors, the computational procedure had many subroutines designed specifically for that application. For example, subroutines to determine the thermophysical properties of water were included in the coding together with subroutines to determine the characteristics of two-phase flow.

Although the entire COBRA code is written in the FORTRAN symbolic language and therefore is theoretically transportable to other computer systems, significant problems arise in making this transition unless the authors of the coding are careful to use a universal subset of the symbolic language.

The COBRA code was chosen by GA for its thermal-flow analysis of the GCFR bundle on the basis that the code had been accepted for use in calculations used in the licensing process for light-water reactors. Therefore, GA took the complete COBRA code and added those computational features necessary to apply the code to a bundle of artificially roughened rods cooled by helium.

The additional computational procedures required involved a representation of the performance characteristics of the roughened surfaces, treatment of varying types of subchannels formed by combinations of surfaces representing the roughened rods and the smooth duct wall, treatment of the different size hanger rods, and representation of the spacer grids. On the other hand, much of the original coding contained in COBRA, particularly that related to two-phase flow, was not required for the calculations for the GCFR bundles.

An additional complication was introduced by GA's use of a UNIVAC computer to modify for the GCFR application. Again, features were added to the symbolic program that were available only on the software of that particular system.

Our application of the supplied computational procedure required the use of the IBM computer, which had significant differences in both hardware configuration and system software from those of the UNIVAC and the

CDC systems. For example, the IBM computer is a 32-binary-bit, hexadecimal-based word system; the UNIVAC is a 36-binary-bit, octal-based word system; and the CDC is a 60-binary-bit, octal-based word system. Differences in the number of significant equivalent decimal digits in a word affect the results obtained from numerical procedures such as those contained in COBRA. Finally, the system software and the FORTRAN compilers on the three systems have important differences that create major problems in transforming the COBRA computational procedure to the IBM system. Because the IBM system has a more limited subset of features, the transfer of procedures for the IBM system to either the UNIVAC or CDC computers is a relatively simple task.

Implementation of the COBRA computational procedure, as modified by GA for the GCFR, was at a turning point at the beginning of 1980. A previous modification of COBRA, designated COBRA*GCFR, had been delivered to ORNL and, after considerable work, had been modified to be operational on the IBM system. At that time, a new version, designated COBRA*BMV, was provided by GA. This designation indicated that this version was developed to perform the calculations for the benchmark-V Meeting. The features contained in COBRA*BMV, in contrast to the features of COBRA*GCFR, were the addition of subroutines to determine the effect of heat transport by radiation in the bundle and by thermal conduction in the rods.

As indicated in previous sections, a version of SAGAPO had been made operational at ORNL. The SAGAPO code is steady state only, and COBRA is a steady state and transient code. It is also significant that SAGAPO was originally written at KfK, which has an IBM computer system; this made the implementation of SAGAPO a much simpler task than the implementation of COBRA and its derivatives.

After a significant amount of work, we concluded that the implementation of COBRA*BMV as a total computational package would be prohibitive, both in cost and time. Therefore, we decided to extract only those sections of COBRA*BMV that were required for application to the analysis of the CFTL bundle and to make these operational on the IBM system by revising those sections of coding. This made the task tractable in terms of available manpower and money.

The truncated version of the COBRA*BMV coding was designated as COBRA/CFTL. This truncation process was completed by May 1980, and test calculations indicated similar output for sample problems executed with the earlier version. For convenience, changes were made to the coding to meet the specific needs of the CFTL design calculations and preoperational performance calculations.

The COBRA/CFTL code was used to produce the results submitted to the Benchmark-VI Meeting (Sect. 1.2.3). Use of the procedure to perform these calculations verified its performance in some areas and indicated need for further modifications.

As final verification of this computational procedure, a subcontract was provided to GA in FY 1981 to execute comparison calculations with their COBRA*GCFR (the name reassigned to a subsequent modification of COBRA*BMV) and the COBRA/CFTL on the UNIVAC system. The resulting report¹¹ presented the results of these calculations and essentially documented COBRA/CFTL by giving exceptions to existing documentation for COBRA*GCFR.¹²

1.2.5.1 RODCON — Thermal Conduction Supplemental Analysis for COBRA/CFTL — J. C. Conklin

During low-flow situations, the subchannel boundary conditions around the surface of the fuel rod simulator (FRS) can vary significantly from different bulk gas temperatures in the surrounding channels and from varying heat transfer coefficients. A rod thermal conduction computer code, CIRCON,¹³ was written by GA specifically for the GCFR fuel rod; this subprogram was incorporated into the COBRA coding. The CIRCON code was found to be inapplicable to CFTL use, because the model lacked sufficient detail to represent properly the CFTL rod internals. In addition, the circumferential heat flow path at the angles of 0° and 360° was not complete. An alternate subprogram, RODCON, has been developed at ORNL to determine the internal temperature distribution in the FRS when it is subjected to differing boundary conditions at the perimeter of the rod. The RODCON subprogram has been written in a general fashion so that any axisymmetric internal rod geometry having an arbitrary number of azimuthal divisions with any set of consistent units can be used.

The RODCON subprogram used an implicit formulation with respect to time and, as such, is unconditionally stable. The subprogram employs a numerical scheme to solve the governing equations of rod internal heat transfer. The choice minimizes the computer storage and computer operations so that the computer costs for the use of RODCON are reduced. The RODCON subprogram was inserted into the COBRA/CFTL computational procedure implemented at ORNL.

Subsequent efforts were made to verify the performance of the RODCON subroutine. The approximations used for the development of RODCON limit its use for accurate calculations to the CFTL rod geometry. Specifically, a rod geometry with a relatively low value of thermal conductivity and a relatively high value for heat generation near the center of the rod will cause errors in calculated temperatures at or near the rod center. These errors will vanish as the distance from the rod center increases.

Neither of these limiting conditions appears for the CFTL rod geometry. However, if significant detail is needed near the center, say for a nuclear fuel rod, improvements in the finite differencing scheme have been identified and can be implemented.

This subroutine has been documented⁷ in conjunction with the subprogram implemented in COBRA/CFTL to determine the effect of heat transport by radiation within the bundle.

1.2.5.2 Incorporation of Radiant Heat Transport in COBRA/CFTL -- J. C. Conklin

The radiation heat transfer subroutine RADIAT developed by GA has been modified slightly for use in COBRA/CFTL. This modification consists of interfacing the common variables of RADIAT and COBRA/CFTL and of substituting appropriate constants for use with SI units.

The RADIAT subroutine requires use of a procedure called HOTTEL, written by GA. The HOTTEL procedure converts bundle geometry and surface properties into "grey body view factors," which can represent all radiation incident on a surface, including multiple reflections. The method of solving the system of equations has been changed from matrix inversion to Gaussian elimination. This change in solution method has decreased computer time and cost by 2 orders of magnitude.

If the surface emissivity remains constant, HOTTEL needs to be exercised only once for each bundle. However, if the emissivity is a strong function of surface temperature, multiple runs of HOTTEL will be necessary.

A report has been prepared,⁷ which documents the work at ORNL to represent the effects of rod thermal conduction and radiation in the thermal-flow analysis of the CFTL bundle. The abstract for the report follows.

RODCON and HOTTEL are two computational methods used at ORNL to calculate thermal and radiation heat transfer for the Core Flow Test Loop (CFTL) analysis efforts.

RODCON was developed at ORNL to calculate the internal temperature distribution of the fuel rod simulator (FRS) for the CFTL. RODCON solves the time-dependent heat transfer equation in two-dimensional ($R\theta$) cylindrical coordinates at an axial plane with user-specified radial material zones and surface conditions at the FRS periphery. Symmetry of the FRS periphery boundary conditions is not necessary. The governing elliptic, partial differential heat equation is cast into a fully implicit, finite-difference form by approximating the derivatives with a forward-differencing scheme with variable mesh spacing. The heat conduction path is circumferentially complete, and the potential mathematical problem at the rod center can be effectively ignored.

HOTTEL is a revision of an algorithm developed at the General Atomic Company (GA), San Diego, California, to be used in calculating radiation heat transfer in a rod bundle enclosed in a hexagonal duct. HOTTEL uses geometric view factors, surface emissivity, and surface areas to calculate the grey-body or composite view factors of a finite geometry including multiple reflections.

1.2.5.3 Implementation of the COBRA/CFTL — S. A. Hodge, G. E. Giles,* G. A. Sady,* and C. B. Baxi†

The COBRA*BMV version of the COBRA program, which was received at ORNL from GA in January 1980, was made operational on the IBM computer at ORNL in a truncated form. This shortened version of the original code was created by eliminating all symbolic statements that reference water, steam, plate-type fuel, coolant properties other than helium, and other

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aspects of the calculations that were not required for analysis of the CFTL. In addition the "roll option" was eliminated. This option reduced the amount of computer memory required by the calculation; it was particularly important for those computer systems that have a limited amount of fast core storage.

At least for the steady state calculation for the CFTL, this option was not required for the IBM computers at ORNL. Because of differing charge rates for computer resources at ORNL, the roll option was not cost effective. Because of a rather involved code structure that permits the roll option, it is very difficult to isolate the coding that might produce computational problems.

The resulting code, designated COBRA/CFTL, was significantly shorter and consequently more tractable and amenable to forthcoming modifications necessary for application of the COBRA methodology to the CFTL bundle. These modifications permit evaluation of the flow regimes within the various types of bundle subchannels at low flows. In general, it affords a closer modeling of the CFTL design.

The following significant modifications were made in the COBRA/CFTL coding to adapt it for the needs of the CFTL analysis:

1. The original COBRA coding used the Dittus-Boelter correlation for calculating the heat transfer coefficient in the case of laminar flow; this equation is not applicable for laminar flow. The coding was modified to incorporate the laminar flow correlations used in the SAGAPO code;³ this correlation computes the Nusselt number as a function of the radius ratio of the equivalent annulus and the Graetz number.

2. The COBRA/CFTL was modified to print the values of the roughness Reynolds number h^+ and the slope A of the universal law of friction for each channel at each axial node. Without this information, the flow regime existing at the various positions cannot be determined.

3. The Stanton number for the central channels was calculated in the original coding by the Dipprey and Sabersky "Heat Transfer Similarity Law," which is not applicable to annular geometry.² This has been replaced by the relation obtained by solving the universal law of heat transfer for the Stanton number.

4. The original coding assumed a constant slope of 2.50 for both the universal law of friction and the universal law of heat transfer. It has subsequently been recognized that these slopes have values other than 2.50 for flow past roughened surfaces and that the values vary with the roughness Reynolds number at low flow. Accordingly, COBRA/CFTL was modified to accept the functional dependence of these slopes as input.

5. The original coding contained an error in the calculation of rod surface temperatures when the option for the consideration of circumferential conduction in the fuel rod cladding was selected. With this error, the cladding surface temperature at a specified node is calculated by use of the coolant bulk temperature and the film heat transfer coefficient at the node but with the heat flux at a point half the distance back to the previous node. This mismatch of heat flux with heat transfer coefficient and coolant temperature has been corrected in COBRA/CFTL.

6. In the original coding, input parameters directed the code to use correlations either for laminar flow or turbulent flow. A subsequent decision process was built into the code so that, depending on the value of computed variables, the proper correlation would be selected. A final modification was made so that, for those cases in which the specified flow was so low that flow would be laminar throughout the bundle, a parameter could be specified to override these internal tests and decrease the computational time.

7. The effect of the grid spacers on the Nusselt number in laminar flow was introduced. The correlation was taken from the result of experiments at Karlsruhe conducted in support of the Benchmark-VI Meeting and supplied in the test specifications for the meeting.

8. Within the turbulent range, flow past roughened surfaces can exist in either the fully rough, the hydraulically smooth, or the region of transition between these two states of flow. Modifications to COBRA/CFTL were made to allow the user to provide a complete model of the variation of both velocity profile slope and intercept $R(h^+)$ in the transitional region of flow as functions of the roughness Reynolds number h^+ . In addition, internal tests within the code can select the basis for calculation as either the hydraulically smooth or transitional regime

within a given channel at low flows by comparing friction factors computed under each assumption with regard to velocity profile slope variation between the two.

With these modifications, COBRA/CFTL can establish the regime of flow within each channel over the complete range from fully rough to laminar based on comparison of computed friction factors. This is important because previous studies² showed that, under conditions of low flow in roughened bundles contained within smooth duct walls, fully rough flow can exist in the central channels concomitant with transitional or hydraulically smooth flow in the wall and corner channels at the same axial level.

Two of the discrepancies in the COBRA/CFTL modeling discovered during the Benchmark-VI Meeting were corrected. The internal correction in the coding concerned the effect of bundle spacers on the Nusselt numbers at the roughened surface. The second correction required only a change in the input to override some of the "built-in" convergence criteria for the iterative loops.

The benchmark calculations for laminar flow in the channel-centered, 12-rod bundle (for which data was provided by KfK) were repeated, and the results were submitted to KfK for the publication of an overall comparison with the various computational procedures involved in the benchmark meeting. These results showed excellent agreement between the calculated values and the experimentally determined points.

To make certain that no errors had been introduced during the process of truncation and modification of the COBRA computational procedure as supplied by GA, a subcontract was placed with GA during FY 1981 to execute comparison calculations over a wide range of flows by use of both their computational procedure and COBRA/CFTL. It should be remembered that the complete computational procedure, redesignated as COBRA*GCPR, provided by GA could not be made operational on the IBM computer system at ORNL. On the other hand, it was a relatively simple task to implement COBRA/CFTL on the UNIVAC computer system at GA. This is a result of the differences in both hardware and software between the two systems and of the fact that COBRA/CFTL was derived from COBRA*GCPR to maintain compatibility. Because the COBRA*GCPR code had already been documented,¹² it was possible to provide adequate documentation for COBRA/CFTL by citing the differences between the two computational procedures.

Input data were prepared for three cases to be executed with both COBRA*GCFR and COBRA/CFTL and included in the code documentation. These cases were analytical models of a one-sixth section of the CFTL AGI bundle. The flow regimes represented were

- Case 1: Fully rough flow throughout the bundle
- Case 2: Transition region between fully rough and hydraulically smooth flow
- Case 3: Transition region between hydraulically smooth and laminar flow.

The results for Cases 2 and 3 show that the lower Reynolds number flow regimes exist in the wall and corner channels of the bundle concomitant with the higher Reynolds number regimes in the central channels. The desire to model the simultaneous existence of different flow regimes was a primary reason for the development of COBRA/CFTL. The results reported by GA were generally as follows:

Case 1 (fully turbulent flow)

- Close agreement in pressure drop
- Close agreement in flow distribution
- Close agreement in coolant temperatures

Cases 2 and 3

- Good agreement in pressure drop (~5%)
- Good agreement in flow distribution
- Good agreement in coolant temperatures
- Large disagreement in rod surface temperatures

The main reasons for the disagreement in rod surface temperature in Cases 2 and 3 seemed to be caused by differences in the spacer enhancement correlations in the two codes.

A report¹¹ was prepared to provide details of this comparison; the abstract of that report is

The COBRA/CFTL code has been developed by Oak Ridge National Laboratory (ORNL) for thermal-hydraulic analysis of simulated gas-cooled fast breeder reactor (GCFR) core assemblies to be tested in the core flow test loop (CFTL). The COBRA/CFTL code was obtained by modifying the General Atomic code COBRA*GCFR.

This report discusses these modifications, compares the two code results for three cases, which represent conditions from fully rough turbulent flow to laminar flow. Case 1 represented fully rough turbulent flow in the bundle. For this case, the agreement between the two codes results for the pressure drop and coolant temperature calculations was within 1%. The agreement for the interior channel rod temperatures was within 3%. However, the wall channel rod and shroud temperatures differed by up to 8.5% and 23%, respectively. Cases 2 and 3 represented laminar and transitional flow regimes. For these cases, the agreement between the pressure drop and coolant temperature calculations was within 5%. However, the rod surface temperatures varied by as much as 25% due to different spacer enhancement correlations and a different definition of start of heating locations in the two cases. The reasons for the differences are discussed in detail in the report.

The required input for the COBRA/CFTL code, a sample problem input-output, and the code listing are included in the appendixes.

1.2.6 CFTL Structural Analysis — J. P. Sanders and W. G. Dodge*

A computer program was developed for determining the thermoelastic deformations of the CFTL fuel assembly test bundle. A satisfactory iteration procedure was developed to yield solutions for the axial deformation in the rods for all conditions of sliding, locked, and buckled rods. Appropriate algorithms were added to determine the lateral deformations and corresponding spacer interaction forces resulting from transverse thermal gradients in the rods.

This method for the structural analysis of a 37-rod bundle with the AGI geometry was completed and presented to CA in January 1980. This computation was based on a matrix-transfer method, which represented the interactions at the spacer-rod and spacer-duct contact points. The procedure has been designated as FASAP. To facilitate development of the programming, it was written in the BASIC symbolic language for the Tektronix-4051 minicomputer. Subsequently, the program was rewritten in the FORTRAN symbolic language, which is compatible with the IBM system at ORNL.

*Union Carbide Corporation, Nuclear Division.

Development of this FORTRAN version for performing structural analysis of the 37-rod CFTL AGI bundle was successfully tested for a number of trial cases. The program appeared to execute very efficiently; it required about 5 s of computational time per load step when executing in double precision.

A report describing the basic formulation on which the computational method is based is to be published.¹⁴ Solution techniques of the coefficients of the resulting equations are also given. Finally, a flow chart is included, which indicates the stepwise progress of the solution through the bundle assembly. A listing of the symbolic program and a sample set of input are also included in the report.

1.2.7 Specification of Instrumentation for the AGI Bundle — J. P. Sanders

A report that specifies the location of instrumentation planned for the AGI bundle has been issued.⁴ Included in the report are locations of thermocouples (TCs) (both internal to the FRS and in the gas stream), of pressure taps through the duct wall, and of markers to be used by x-ray-imaging techniques to determine structural response of the bundle.

This presentation represents the combined efforts of a large number of members of the CFTL project. R. W. McCulloch, who was responsible for the manufacture of the FRS, provided information concerning the placement of the TCs in the FRS, and S. P. Baker of the Instrumentation and Controls Division performed all the fundamental work on the x-ray-imaging techniques. Baker and W. G. Dodge performed the analysis necessary to determine the optimum location of these markers. P. G. Herndon and others of the Instrumentation and Controls Division at ORNL provided information on the available instrumentation and associated uncertainties in measurements. Staff members assigned to the Thermal Hydraulic Test Facility (THTF) made helpful suggestions about bundle instrumentation on the basis of operational experience from their loop. Coordinating the specification and installation of instrumentation was the responsibility of H. C. Young, and the required engineering drawings were provided by the Engineering Division, UCC-ND. The abstract of the report that describes this instrumentation is

The placement of instrumentation within the Core Flow Test Loop (CFTL) AGI test section to meet the following objectives is described. The objectives are threefold: (1) to provide values for the evaluation of the performance of the test section, (2) to compare the experimental data with values determined by pretest calculations to indicate the approach to conditions that can lead to a bundle failure, and (3) to acquire data during testing that will form a data base for subsequent use in the verification of computational procedures used in the licensing of the Gas-Cooled Fast Reactor (GCFR). Anticipated values for the various instruments have been determined by using the computational procedure SAGAPO modified for the AGI geometry. These results are used as the basis for the specification of differential pressure cells and the range of readings anticipated from the thermocouples. A part of the results for the full-flow, full-power case is presented.

1.3 DESIGN AND CONSTRUCTION OF THE LOOP — H. C. Young and C. W. Collins

In early 1980 the Stage 1 CFTL,¹⁵ designed to provide 37-rod test bundle capacity and limited transient capability for operating test bundles simulating Gas-Cooled Fast Reactor (GCFR) core assemblies, was proceeding on schedule. On cancellation of the GCFR, CFTL efforts were redirected toward constructing a simpler loop having only steady state operating capabilities. In addition, although design of the 37-rod test bundle AGI was completed, fabrication of the bundle was not initiated, and fabrication of the associated test vessel was canceled.

Capabilities of the modified loop, renamed the Stage Alpha CFTL, were directed toward testing High-Temperature Gas-Cooled Reactor (HTGR) components. As indicated in Fig. 1.1, Stage Alpha consists of three helium circulators connected in series, the heat exchanger (HX1), two vortex shedding flowmeters, a full-flow helium filter, and a straight section of pipe in place of the test vessel. All the components are connected appropriately with piping and downward flow through the straight pipe test section provided. In addition, Stage Alpha comprises the ancillaries including the helium supply systems; the loop pressure relief, vent, and evacuation systems; and a cooling air system for HX1. The data acquisition system (DAS), the direct digital controller (DDC), and one 0.5-MW zone power supply (ZPS) are also part of the loop.

During the report period, development of particular loop components and equipment was completed, fabrication and procurement of all components and equipment were completed, and the loop was completely assembled and pressure-tested.

Three 250-kVA solid state variable-frequency power supplies (VFPSs) for the helium circulators were delivered, operated in place at design point with a dummy load, and installed. The single ZPS was purchased, load tested at ORNL, and installed.

Utility software was prepared for the DAS to obtain general-purpose data acquisition capability. Cable trays of sufficient size and quantity were installed to accommodate Stage Alpha requirements and to provide some expansion capabilities. Instrumentation and controls were installed to protect (1) the loop from the deleterious effects of excessive pressure and temperature and from the loss of power and (2) the circulators from misoperation. Equipment was installed to protect the loop during unattended operation in an isothermal fluid flow mode only.

Installation of all the components and systems for the Stage Alpha CPTL was nearly complete when the work was interrupted by a strike by the Y-12 craft union.

1.3.1 Mechanical Equipment and Systems - H. C. Young and C. W. Collins

Revisions to the design drawings to accommodate the change from the Stage 1 to the Stage Alpha were completed. Fabrication and installation of all the principal components and piping subassemblies were completed, and the loop boundaries were tested satisfactorily to the 14.6-MPa (2125-psig) pressure required by the code. Design and installation of the helium supply and the evacuation systems were completed.

A roll-up door was selected to complete the containment for the loop. The electric-motor-operated door is 7.3 m (24 ft) high and 4.3 m (14 ft) wide. To protect the door from damage by excessive helium pressure in the containment volume that may accompany a large rupture in the pressure boundary, a blowout panel was installed at the loop in the east exterior wall of the site building. A relief pressure of 960 Pa (20 lb/ft²) was selected to protect the door from damage.

Design drawings and specifications for the CFTL mechanical components and systems are listed in Appendix 1. Those that apply to the Stage Alpha CFTL are identified in the lists.

1.3.1.1 Heat Removal Equipment and Systems — H. C. Young and C. W. Collins

Fabrication¹⁶ and pneumatic pressure testing of the helium-to-air HX1 shown in Fig. 1.2 was completed, and the code stamp for ASME Section III, class 2, was applied. The completed heat exchanger, the first component to be set in place in the CFTL, is shown in Fig. 1.3.

The filter house, duct work, blower, and the variable-speed drive for the blower, which compose the cooling air system for HX1, were installed and checked functionally and are shown in Fig. 1.4.

Fig. 1.2. Heat exchanger 1 (HX1) being readied for transport.

Fig. 1.3. Heat exchanger 1 (HX1) installed in the CFTL site in Building 9201-3, Y-12 Plant.

Fig. 1.4. View of forced air cooling system for heat exchanger 1 (HX1). Filter house, top left; blower, right foreground; penthouse for 5-ton crane, center.

1.3.1.2 Piping and Equipment — H. C. Young and W. R. Clark

The design, specifications, and calculations for the piping and the helium filter¹⁷ were evaluated by the CFTL Design Review Team and determined to comply with design requirements and to be adequate for the intended service.

The 159- and 100-mm (6- and 4-in.) pipe subassemblies for the CFTL were prefabricated at the ORNL X-10 shops. Each of the 16 subassemblies and the vortex shedding flowmeter (VSPM) runs were nuclear part (NPT) stamped as ASME Code, Section III, class 2, components.

All piping and components were installed in the CFTL, and about 43 field welds were completed. The welding was performed by the Y-12 crafts to the intent of the ASME code, with welder qualification procedures and inspection procedures identical to those required for ASME Code, Section III, class 2, assemblies. In addition, a manufacturing plan and controlled drawings were prepared and used for the installation activities.

The entire loop was then pneumatic-pressure-tested to 14.6 MPa (2125 psig) with nitrogen. A 30-tube nitrogen trailer, filled to 12.4 MPa (1800 psig), was used to pressurize the 2.9-m^3 (100-ft³) system to about 11.7 MPa (1700 psig). A hydraulic-driven booster compressor was used to raise the system pressure to the test pressure.

Installation of the three circulator pressure vessels and interconnecting piping are shown in Fig. 1.5. In the left foreground is the full flow helium filter.

Fig. 1.5. Installation of the helium circulators and the full-flow filter at the CFTL site in Building 9201-3, Y-12 Plant.

The rupture disk and relief valve for the loop vent system were installed. The system to provide the controlled venting required for the performance of depressurization tests was not installed for the Stage Alpha CFTL.

1.3.1.3 Helium Circulator Prototype — H. C. Young

The original performance tests with the circulator prototypes were completed by Mechanical Technology Inc. (MTI) in March 1979. Modifications were made to the loop at MTI to permit supplemental test operation at higher motor power.¹⁸ The purposes of the supplemental test were to

1. determine the maximum motor drive capability as defined by a motor winding temperature of 190°C (375°F), somewhat lower than the indicated limit of 220°C (428°F), the motor saturation limit, or the current limit of 350 A for the solid state VFPS,
2. obtain test loop flow capability to 120% of design flow by reworking the loading valve,
3. conduct a head-flow performance test with the existing vaned diffuser over the maximum stable flow range on constant speed lines of up to 23,500 rpm (the original specified design conditions were met at 21,150 rpm),
4. repeat above with a vaneless diffuser designed to change the surge limit toward lower flow,
5. conduct depressurization tests at rates of 0.34, 0.68, and 1.0 MPa/s (50, 100, and 150 psi/s),
6. conduct a heat soak-back test with a vertical stand-pipe reservoir installed in the circulator cooling water line, and
7. conduct mixed gas test (90% He and 10% air by volume) at 100-kPa (1-atm) loop pressure.

The supplemental tests were completed in March 1980, and the only limitation on operating at 23,500 rpm was the 350-A maximum current limitation of the 250-kVA VFPS. This power supply is one of three purchased by Union Carbide Corporation, Nuclear Division (UCC-ND) from Servo-Optics, Dallas, Texas, and is fully capable of continuous operation at the maximum specified circulator design conditions at 10.3 MPa (1500 psia), which were

met at 21,150 rpm at about 180 kW. At the 350-A limit of the power supply, the circulator motor input was 209 kW at 23,500 rpm, yet the motor winding temperature was less than 143°C (290°F), compared with a continuous rating of 220°C (428°F) for the stator insulation.

The surge limit of the original vaned diffuser was at about 65% of the design flow at 21,150 rpm. Although this limit was acceptable, a broader flow range could make control of the CFTL valves less demanding. Mechanical Technology Inc. predicted that operation with a vaneless diffuser could reduce the surge limit to less than 50% of design flow with a loss in the circulator-developed head of about 7%. Actual supplemental performance tests indicated that, although the vaneless diffuser did not materially reduce the surge limit, it did cause an approximate 16% loss in the circulator head. Mechanical Technology Inc. reanalyzed the diffuser design and concluded that meeting the predicted lower surge limit with minimum head loss would require a redesigned vaneless diffuser having considerably more diffuser length. We considered this neither practical, economic, nor necessary for our circulator requirements and advised MTI to use the original vaned diffuser.

During the initial performance tests in March 1979, the stem position of the depressurization valve in the MTI test loop was not adjustable, and all depressurization tests were conducted at the full-open valve position. This resulted in an initial loop depressurization rate of 2 MPa/s (300 psi/s) at 10.3 MPa (1500 psia). The specified rate was 0.68 MPa/s (100 psi/s). If the circulator thrust bearing survived the higher test rate, the lower specified rate would appear to be less severe. The reed valves that equalize the motor cavity pressure and the impeller inlet pressure actually vent to the discharge pressure. Lower depressurization rates could therefore possibly result in almost as high a motor cavity pressure as do the faster depressurization rates (but for a longer duration) and thus produce an equally high thrust load for a longer time. Depressurization tests were repeated during the supplemental tests at initial rates of 0.34, 0.68, and 1.0 MPa/s (50, 100, and 150 psi/s), and the thrust bearing performed satisfactorily.

In the original heat soak-back tests to determine maximum motor winding temperature after a simulated failure of the circulator cooling

water supply, the motor cooling jacket was permitted to boil dry. During supplemental tests, a header tank was installed, and thermal convection cooling water flow was established during the heat soak-back test with normal water supply valved off. The motor winding temperature did not exceed the temperature rating of the insulation in either case.

In March 1981 at the conclusion of performance testing of the two follow-on production circulators, the circulator prototype was reassembled and satisfactorily operated to 454°C (850°F).

The pressure vessel and base assembly for the circulator prototype were delivered to the CFTL site on March 26, 1981. The rotary assembly for the prototype was shipped with the rotary assemblies for the two production circulators on April 1, 1981. The circulator pressure vessel was installed in the CFTL, and the entire test loop was pneumatic-pressure-tested at 14.6 MPa (2125 psig) on April 22, 1981. The circulator rotary assemblies were installed in mid-June 1981.

1.3.1.4 Production Circulator Activities — H. C. Young

A letter subcontract was issued to MTI in May 1979 to permit its initiating procurement of circulator materials. After several months of auditing the Phase II contract for the circulator prototype and of price negotiations, a fixed-price contract¹⁹ for fabrication and testing of two production circulators, known as Phase III, was formally placed with MTI in September 1979. At that time MTI gave us a delivery date of January 1981, contingent on our supplying the motors and pressure vessels on a timely basis. Despite delays in our providing the motors and vessels, MTI completed fabrication and testing of the two circulators to the originally specified conditions, plus an additional test of each unit at 454°C (850°F), and shipped the circulators to us on April 1, 1981.

The circulator subassemblies furnished to MTI by UCC-ND were all delayed to some extent by various fabrication difficulties, as indicated in Table 1.1.

The motor stators, one of which is shown in Fig. 1.6, were supplied to MTI on schedule; however, MTI noted a waxy material on the stator laminations. The stators were shipped to Oak Ridge, inspected, manually

Table 1.1. Schedules for some circulator components

Component	Date ordered	Date promised	Date delivered	Supplier
Motor stator (2)	December 1978	August 1979	August 1979 ²	Electromotive Engineering, Inc., Los Angeles, Calif.
Motor rotor (2)	April 1979	February 1980	July 1980	Y-12 Plant, UCC-ND, Oak Ridge, Tenn.
Pressure Vessel (2)	January 1979	March 1980	August 1980	Ionics, Inc., Bridgeville, Pa.
Ceramaseal feed-through (6)	January 1979	September 1979	July 1980	Ceramaseal, Inc., New Lebanon, N.Y.
Circulator (2)	May 1979	January 1981	April 1981	Mechanical Technology Inc., Latham, N.Y.

²Incorrectly baked out, stators were originally shipped to Mechanical Technology Inc. (MTI), then shipped to Union Carbide Corporation, Nuclear Division for vacuum bakeout and returned to MTI in April 1980.

PHOTO 6343-80

Fig. 1.6. Motor stator for CFTL helium circulator. This stator is pressed into a motor cooling vessel assembly provided with cooling water passages. The class C insulation on the stator has a continuous rating of 220°C.

cleaned, and finally baked in a vacuum furnace at 230°C (450°F) for 4 h. The waxy material was determined to be a release coating used by the stator manufacturer to prevent resin or shellac from adhering to the core and structural components during the vacuum pressure impregnation of the resin. The stator specification required a vacuum bakeout; however, the manufacturer misunderstood the instructions of our electrical engineer representative and apparently omitted the final bakeout of the stator assemblies.

We now believe a similar situation occurred with the stator for the circulator prototype, which was subcontracted directly by MTI to Task Corporation. Former employees of Task Corporation established a new company, Electromotive Engineering, Inc., which subsequently produced the two stators for the production circulators. Posttest inspection of the circulator prototype revealed a sootlike deposit on the colder surfaces in the motor cavity.²⁰ This sootlike deposit was believed to have volatilized from the stator insulation. The deposit was not found in the two production circulators at the conclusion of a test program similar to the prototype tests.

Three fabrication problems caused delays in producing the motor rotors shown in nearly complete condition in Fig. 1.7. These problems included (1) heat-treating the AISI 4340 rotor while maintaining the specified hardness, (2) gun-drilling 28 precision 9.5-mm-diam (3/8-in.) axial holes around the circumference of each rotor to accept beryllium-copper conductor bars, and (3) induction-brazing the beryllium-copper conductor bars and end rings. Each problem was resolved adequately as it was brought into focus by Y-12 shop management. However, this serial approach to the resolution of difficult anticipated problems and the priority of other shop work led to the delay in motor rotor delivery mentioned above.

The fabrication by Ionics, Inc., of the two pressure vessels (one of which is shown in Fig. 1.8) started out very smoothly, and it appeared that the vessels would be delivered on schedule. However, a subcontract by Ionics, Inc., for machining the water passages in the motor cooling vessel failed, and finding a second machining source caused considerable delay. During pressure-testing of the vessels, Ionics, Inc., broke one

PHOTO 6322-80

Fig. 1.7. Motor rotor for CFTL helium circulator. Beryllium-copper end rings have been induction-brazed to the 28 axial beryllium-copper conductor bars in the AISI 4340 solid rotor. Two nonmagnetic cold-worked 17-4 PH rings will then be shrink-fitted over the beryllium-copper rings to accommodate stresses at 24,000 rpm.

PHOTO 7307-81

Fig. 1.8. Pressure vessel for CFTL helium circulator. This is an ASME, Section III, Class 2, vessel with a design pressure of 11.7 MPa (1700 psig).

Ceramaseal power feedthrough and had difficulty seal-welding another feedthrough, causing delays that seemed out of proportion to the problems, which were resolved subsequently.

Three different configurations of Ceramaseal feedthroughs are required and are seal-welded into each vessel closure head. These are (1) the power feedthrough shown in Fig. 1.9 with three 13-mm-diam (1/2-in.) copper conductors for transmitting electrical power to the circulator motor, (2) a seven-probe feedthrough for the bearing capacitance probe signals, and (3) a feedthrough to accommodate eight internal thermocouples. The feedthroughs were purchased from Ceramaseal, Inc., by UCC-ND and were welded into the vessel heads by the vessel manufacturer. The delivery date promised by Ceramaseal, Inc., slipped repeatedly. When

PHOTO 7344-81

Fig. 1.9. Three-conductor power feedthrough manufactured by Ceramaseal, Inc. This feedthrough is seal-welded into the vessel head on the CFTL helium circulators and carries three-phase electrical current through the vessel pressure boundary to the enclosed circulator motor. The feedthrough operated satisfactorily at 360 A at 480 V.

parts were found to be damaged on receipt or were broken in handling, literally months were required to place repair orders, after which the promised delivery was about 20 weeks.

The production circulator contract at MTI proceeded well, considering the delays in our supplying components to MTI. A thrust bearing failed during a depressurization test of rotary assembly 3. Fabrication of a replacement bearing was completed in about two months. This did not cause a proportional delay in the program, however, because during that period rotary assembly 2 was put together and performance tested at the specified 343°C (650°F) conditions, and rotary assemblies 1 (the prototype) and 2 were tested to 454°C (850°F) under an addition to the contract.

Table 1.2 summarizes the total costs and overall time to design (Phase I), to fabricate and test a prototype circulator (Phase II), and to produce and test two production circulators (Phase III). Phases I and II of the contract with MTI were on a cost-plus-fixed-fee basis, and Phase III was a fixed-price contract with MTI.

Table 1.2. Cost and duration of CFTL circulation contract

Description	Contract phase	Duration	Cost (thousands of dollars)
Circulator design	I	June 1975–December 1976	217
Prototype circulator	II	January 1977–April 1979	896
Supplemental tests ^a	II	March 1979–April 1980	54
Production circulators (2)	III	May 1979–April 1981	1,062
Total			2,229
<i>Phase III cost breakdown</i>			
Motor stators (2)			56
Motor rotors (2)			137
Pressure vessels (2)			215
Ceramaseal feedthroughs (11)			19
Circulator parts and assembly and test by MTI (2)			619
Additional testing to 450°C (850°F)			16
Total			1,062

^aSee Sect. 1.3.1.3 of this report.

Under Phase II MTI subcontracted the fabrication of the motor, the design and fabrication of the pressure vessel for the circulator prototype according to ASME Code, Section III, class 2, and the design and fabrication of a circulator test loop for use at MTI. Union Carbide Corporation, Nuclear Division loaned a variable-frequency power supply to MTI for the duration of the test program at MTI.

Union Carbide Corporation, Nuclear Division provided MTI with two each pressure vessels, vessel heads, motor rotors and stators, and Ceramaseal feedthroughs for the Phase III production circulators; MTI provided all parts for the rotating units and assembled and tested all rotary assemblies in the pressure vessel for the circulator prototype that remained in the MTI test loop from the earlier prototype testing. Rotary assemblies 2 and 3 were inserted into their respective vessels to ensure a correct fit. Circulator pressure vessels 2 and 3 were then shipped to the CFTL site in advance of other circulator parts so that they could be welded into the loop piping to maintain our piping installation schedule.

The plan was that one complete circulator rotary assembly would be ordered as a spare. However, because of budgetary problems, ordering spare circulator parts was not possible. During initial operation in the canceled Stage 1 CFTL, two circulators operating in series would have provided the necessary pressure rise for the test with the (also canceled) 37-rod test bundle AG1, and the third installed circulator would have served as a spare. This spare-part philosophy must also serve the Stage Alpha CFTL.

1.3.1.5 Evacuation, Helium Supply, Purification, and Impurity Injection -- H. C. Young and W. R. Clark

The loop evacuation system²¹ was installed. It consists of a mechanical rotary-type vacuum pump, a high-vacuum sliding gate valve with electropneumatic operator, a length of flexible piping, and two ball valves of 100-mm (4-in.) pipe size arranged in series to isolate the vacuum pump from the high-pressure operation of the helium system.

Two helium supply systems, one from an outdoor helium trailer and the other from a 20-bottle makeup manifold, and a pressure control station have been installed and pressure-tested to 20.7 MPa (3000 psig). Each

supply system is provided with a 5- μ m particle size filter. The filters were fabricated with 40-mm-diam (1 1/2-in.) filter cartridges purchased as spares for the loop full-flow helium filter.

The helium purification and impurity injection system are not part of the Stage Alpha CFTL and have been deferred.

1.3.1.6 Test Vessel — W. R. Clark

The design and analysis for the test vessel²² and an independent review of the design by the CFTL Design Review Team were completed. All vessel material was procured, and fabrication was started but was canceled by the GCFR closeout. The material is stored for future use.

Grayloc closure flanges of the 400-mm-diam (16-in.) pipe size for the two ends of the test vessel were delivered in January 1981. Parts of one of the closure flanges are shown in Fig. 1.10. The flanges

Fig. 1.10. Grayloc butt weld hub and blind hub and clamps, 400-mm-diam pipe (16-in.) for CFTL AGI test bundle. One blind hub would be used as bundle tubesheet.

were ordered in March 1979, and original delivery was requested by December 1979. The flange material is type 316 austenitic stainless steel specified to ASME Code, Section III, class I, requirements.

Grayloc would not guarantee the specified ~~maximum~~ acceptable leak rate of 1×10^{-6} std cm^3/s He. The mass spectrometer helium leak test was performed by UCC-ND with a Grayloc representative supervising initial assembly of the flange seal ring. The measured leak rate was 1×10^{-10} std cm^3/s with the flange studs torqued to 275 kg-m (2000 lbf-ft).

1.3.1.7 Building Facilities — H. C. Young and W. R. Clark

The building modifications,²³ construction, and installation of the structures and services to support the CFTL were completed.

A traveling chain hoist and support bridge were set in place in the loop area for installing the helium circulator rotary assemblies into the pressure vessels. Additional steel beams were installed in the ceiling of the CFTL test site to support the loop pipe hangers.

A 4.3-m-wide (14-ft) by 7.3-m-high (24-ft) motor-operated, roll-up door was ordered for the CFTL loop enclosure and is scheduled for delivery in September 1981. The bolts in a blowout panel in the enclosure were modified to provide a reduced relief pressure of 960 Pa (20 lbf/ft²) to prevent damage to the roll-up door.

Construction of the control room was completed, and the control room air conditioner was installed and checked for operation. Installation of the ventilation system to remove heat from electrical equipment on the first floor was completed and the system checked for proper operation.

Construction of a penthouse and installation of a 4500-kg (5-ton) electric hoist were completed. This hoist will be used for handling future ~~air~~ vessels and test specimens.

Installation of the air-cooling blowers, duct systems, and filter houses for HX1 and HX2 was completed.

Installation of the conduit and electrical cables to the blower motor for HX1 was completed, and the blower motor, variable-speed drive, and air flow damper were checked for proper operation.

1.3.2 Electrical Equipment and Systems — R. B. Biggs

Design, purchase, and fabrication of electrical equipment, systems, and cabinets for the Stage 1 CFTL, which were progressing on schedule when notification of the GCFR closeout was received, were halted. The effort was redirected toward the requirements of the Stage Alpha CFTL.

Electrical equipment, systems, and cabinets are reduced considerably for the Stage Alpha, compared with the Stage 1; only one ZPS was installed, compared with seven for Stage 1. The uninterruptible power supply was not installed. The three VFPSs for the helium circulators were installed and operated. The various ancillary systems for heating, ventilating, and air-conditioning the control room, the motor centers, and associated controls were installed and checked for proper operation. The substations, which were installed in 1979, were energized and checked for proper operation.

Appendix 2 presents listings of the drawings and specifications prepared for the CFTL electrical systems. Those that apply to the Stage Alpha CFTL are identified. Retrievability information is provided also.

1.3.2.1 Primary Power Distribution System — C. F. Holloway and E. M. Lees

The primary power system,²⁴ which consists of four substations supplied from 13.8-kV breaker 1337E in the second floor breaker control room, was installed in 1979.

During the report period, breaker 1337E was closed to energize all four substations, each of which consists of a 13.8-kV-line disconnect switch, a 13.8-kV to 480-V transformer, and associated main and feeder breakers. The secondary voltage for all substations was measured at 480 V, as specified. All breakers were closed and tripped satisfactorily at least three times. The trip devices for all the 480-V breakers were load-tested satisfactorily at the Y-12 electrical shop.

The secondary output of substation 7ED was changed to provide 460 V to match more nearly the requirements of the VFPSs for the helium circulators. Substation 7EB, 2500-kVA, was deenergized because it is not scheduled for use in Stage Alpha.

1.3.2.2 Test Bundle Power Supply and Control — R. B. Biggs, C. F. Holloway, and T. L. Hudson

The design work of the test bundle electrical systems²⁵ for the Stage Alpha CFTL was completed. The construction work was completed except for making the wire-to-wire checks of the electrical circuits. This work, which would have been accomplished by June 30, 1981, was interrupted by the Y-12 craft strike. It will be completed on the return to work by the craft forces. The prototypic zone power supply,²⁶ consisting of the induction voltage regulator and the special 500-kVA transformer, was delivered, operated satisfactorily, and installed in the Stage Alpha.

The design work for the Stage 1 and Stage 2 CFTL was completed with the exceptions noted in Appendix 2, which lists the drawings and presents their status.

The status of the fabrication of the Stage 1 cabinets, which was halted in accordance with the GCFR closeout instructions, indicates:

1. Seven fuse breaker cabinets were completely fabricated. One cabinet was installed in the Stage Alpha CFTL, and the others were stored.
2. Other cabinets and electrical systems stored in uncompleted conditions include (1) the patch panel, (2) the current transformer cabinets, (3) the overcurrent detector cabinets, (4) the silicon-controlled rectifier (SCR) crowbar cabinets, and (5) the pulse transformer cabinets.
3. The cable trays for the Stage 1 CFTL were purchased and stored temporarily in Building 9201-3, Y-12 Plant.

All cabinets and materials not utilized for the Stage Alpha CFTL are stored either in Building 9201-3, Y-12 Plant, or in the Y-12 Stores Department. A copy of report KA-1-M, which lists the equipment stored in Y-12 Stores, is filed by Mechanical Technology Engineering, Building 9201-3, Y-12 Plant.

1.3.2.3 Auxiliary Power System — R. B. Biggs

The design and installation of the Stage Alpha auxiliary power system²⁷ were completed. The installation design for the 7.5-kVA uninterruptible power supply (UPS) was not prepared. The UPS was purchased and stored in Building 9201-3.

1.3.2.4 Power Supply for Circulators — T. L. Hudson and E. M. Lees

All the factory witness tests required by Specification E-11590-RB-005-X-1, except the full-load test, were performed satisfactorily at Servo-Optics Systems, Inc. (SOS), Dallas, Texas, for the second and third units of the 250-kVA solid state VFPS²⁸ that provide power to the helium circulators.

The inadequacy of the installed electrical capacity at SOS to perform the full-load test made it necessary to conduct that test at the CFTL site in Building 9201-3, Y-12 Plant. The VFPS was connected to a 250-kVA, three-phase, resistive dummy load for the test. The site inspection and the full-load test for the second power supply produced by SOS were completed satisfactorily. Testing of the third supply produced by SOS was completed, and the check-out and full-load testing satisfactorily met all requirements.

The first power supply built by SOS, which was loaned to MTI to provide power for testing the circulators, was returned to ORNL. The supply was installed in the CFTL and during proof-test operation behaved as specified and reliably.

Each of the three VFPSs was connected to the appropriate helium circulator and supplied power during high-speed testing in air associated with the installation of the circulator rotary assemblies in their respective pressure vessels.

1.3.3 Instrumentation and Controls — P. G. Herndon

At the end of June 1980, the major measurement and control problems of the Stage 1 performance requirements had been solved, and the detailed design of that system was well advanced. In July a major redirection of the gas-cooled program required a revision of the CFTL design to a version identified as the Stage Alpha CFTL, which has reduced performance requirements.

Title II designs for the Stage Alpha CFTL instrumentation and control systems were completed. The systems are defined on the drawings listed in Appendix 3 and by the specifications listed in Appendix 4. The drawings and specifications are stored by the ORNL Instrumentation and Controls Division at File Point QD-4, Room 269, Building 9201-3, Y-12 Plant.

A scheme for digital control of the main loop HX1 was developed.

A letter report was issued summarizing steady state conditions corresponding to the tests outlined in the CFTL Test Specifications.

A series of calculations was made showing head-flow characteristics of the helium circulation system for the parallel, rather than the normal series, operation of the three helium circulators.

Procurement of four 102-mm (4-in.), schedule-80 control valves and actuators, which was initiated more than two years ago, was completed.

Performance tests on a modified commercial VSFM indicated adequate capability to cover the range of helium flow rates, and the VSFM was selected for use in the CFTL. The design, fabrication, and calibration of four VSFM meter runs, three 102 mm (4 in.) and one 152 mm (6 in.), were completed.

A versatile and sophisticated zone control system (not available commercially) to regulate power to CFTL test bundles was designed, fabricated, and tested satisfactorily for the unique bundle requirements.

Design, procurement, fabrication, and installation of the central control system for the Stage Alpha CFTL were completed. Fabrication, wiring, and installation of four main control board cabinets, five signal-conditioning cabinets, and five thermocouple patch panel cabinets were completed. Installation includes instrument components mounted in the loop area, cable trays, conduits, and associated interconnecting wires and cables.

The design, procurement, and installation of the Stage Alpha CFTL electrical control and protective interlock circuits were completed.

The DAS designed and built for the CFTL is completed and fully operational. In addition, utility programs have been written, which give the operator control over the system and provide loop status conditions on request. Extensive documentation is also provided to enable programmers to write new programs with minimal guidance from Instrumentation and Controls Division personnel.

Incomplete Title II design drawings for the Stage 1 CFTL instrument systems not required for the Stage Alpha CFTL, shown on the drawings listed in Appendix 5, are stored by the ORNL Instrumentation and Controls Division at File Point QD-4, Room 269, Building 9201-3, Y-12 Plant.

1.3.3.1 Dynamic Simulation and Control Analyses — S. J. Ball

A scheme for digital control of the main loop HX1 was developed. The simulation of HX1 used in the ORCULT code²⁹ was expanded to include the effects of variable inlet vane (VIV) and damper positions, blower speed, and buoyancy forces on cooling air flow. The effects of using the HX1 heaters (up to 75 kW) for the very-low-flow tests were also simulated.

Control algorithms were developed and checked out with the IBM Continuous System Modeling Program (CSMP) simulation of HX1. The control provides for automatic manipulation of the VIV, damper position, blower speed, and the heater power. Tests of the simulated HX1 showed that the circulator inlet temperature could be maintained within a few degrees for the most severe helium flow and temperature transients expected.

The control system algorithms for the DDC for HX1 were programmed in Fortran so that they can be transferred directly to the DDC.

A test program was developed for measuring HX1 coolant flow characteristics and cooling-heating capacities.

A letter report was issued summarizing steady state conditions corresponding to the tests outlined in the CFTL Test Specifications. The purpose of this work was to find the optimum initial circulator speeds and valve positions so that cooling air could be provided to cover the full range of flow variation required in each test. The steady state version of ORCULT, modified to include head versus flow data taken with the circulator prototype, was used to make the calculations. A series of calculations was also performed for parallel (rather than the normal series) arrangement of the three helium circulators. It was determined that, in order to double the test flow (with the parallel circulators), the allowable test section pressure drop should be reduced by approximately a factor of 10.

1.3.3.2 Helium Flow Control — P. G. Herndon

Steady state control of helium flow is achieved in Stage Alpha CFTL by manual adjustment of circulator speed. Because there are no valves in the Stage Alpha loop, the flow transient control³⁰⁻³¹ provided in previous designs is not practical. However, suitable valves are on hand and are

ready for installation should the need arise for transient flow control. The procurement³² of four 102-mm (4-in.) schedule-80 control valves, which was initiated approximately 2 1/2 years ago, was completed. The valve bodies were designed, fabricated, and tested to the requirements of Class 2 Valve Components of Section III of the *ASME Boiler and Pressure Vessel Code*. Procurement of three fast-acting hydraulic actuators and the associated high-pressure hydraulic supply was also completed. Each actuator is equipped with a high-pressure accumulator having sufficient volume to drive the valve to a predetermined fail-safe position on loss of either the control signal or the hydraulic pumping unit. The actuators, which required considerably less than 2 1/2 years to procure, are designed for the valves but are supplied by a different manufacturer for reasons reported previously.³²

1.3.3.3 Helium Flow Measurement — S. P. Baker, R. M. Ennis,* and P. G. Herndon

Performance tests were completed on a modified commercial VSFM (Fig. 1.11), with both helium and compressed air in the CFTL Vortex Shedding Flowmeter Test Facility,³³ located in the Y-12 Plant. The tests proved conclusively that the VSFM design as modified by ORNL would accurately measure to $\pm 1\%$ of reading all CFTL helium flows with Reynolds numbers of 10,000 and above specified for tests at pressures of 0.2, 3, and 9 MPa.³⁴ Usable output signals generated by flowrates at Reynolds numbers between 6000 and 10,000 indicated a high probability that the meter could also accurately measure helium flows with Reynolds numbers below 10,000 specified for tests at 0.2 MPa pressure. The modified VSFM was therefore selected for use in the CFTL.

The design, fabrication, and calibration of four VSFM meter runs, three 102 mm (4 in.) and one 152 mm (6 in.), were completed. The design (Fig. 1.12) incorporates the flowmeter components into the loop piping, eliminates the need for pipe flanges, and provides a very smooth upstream and downstream metering run. Weld-sealed dowel pins precisely align and

*TRW, Inc., Energy Systems Group, Oak Ridge, Tenn.

PHOTO 7510-80

Fig. 1.11. Photograph of wafer meter installed in short section of 10-cm-ID (4-in.) pipe.

firmly secure the bluff body to the pipe wall. Isolation valves in the sensor block permit the replacement of thermal sensing elements without losing the loop helium inventory to the atmosphere. The design also includes a comprehensive specification for performing calibration tests at a laboratory certified by the National Bureau of Standards.

The meter runs were fabricated by ORNL in accordance with the requirements of the *ASME Boiler and Pressure Vessel Code* for Section III, class 2, components. The design drawings and specifications for the CFTL VSFMs are listed in Table 1.3.

A survey of the capabilities of all known calibration facilities revealed that the Colorado Engineering Experiment Station (CEES) located near Denver, Colorado, was the only facility capable of providing the required calibration services. These include especially the calibration tests for very low flow rates at pressures of 3.0 and 9.0 MPa and the entire flow range at 0.2 MPa with helium at standard temperature. Its compressed air storage capability made it also possible to calibrate over the entire range of flows at pressures of 3.0 and 9.0 MPa with air at standard temperature.

Fig. 1.12. Design of the modified vortex shedding flowmeter for the CFTL.

Table 1.3. Core Flow Test Loop vortex shedding flowmeter drawings and specification

UCC-ND drawing	UCC-ND specification	Description
I2D-11590-Q-519		Modified Eastech vortex shedding flowmeter assembly
X2E-11590-068		Vortex shedding flowmeter FE-4, -7, -9, and -11 assembly
I2D-11590-Q-031		Vortex shedding flowmeter sensor and signal conditioner, wiring diagram
	IS-11590-QG-038	Specification for calibration of vortex shedding flowmeters for use in GCFR Core Flow Test Loop

The calibration of all four meter runs were performed at CEES with both air and helium over a range of flow rates greater than 200:1 and a density range of 45:1. Analysis of the calibration data yielded a nominal meter accuracy of $\pm 1\%$ of reading (2σ) over a 100:1 range of flow rates for a specific gas at a given density. An accuracy better than 1.8% of reading was measured over a 200:1 range of flow rates for both air and helium with a composite of densities.

This work is covered in two technical reports: the first³⁵ addresses the optimization of the meter design for the CFTL, and the second³⁶ describes the development, design, fabrication, and calibration of the VSFMs installed in the CFTL.

The design, fabrication, and calibration of a four-channel, frequency-to-voltage converter that converts the pulse train output from each VSFM to a voltage signal proportional to volumetric flow rate were also completed. Performance tests were conducted on a single-channel prototype. The results, given in Table 1.4, indicate that this converter will perform satisfactorily with the VSFMs without degrading their accuracies.

Table 1.4. Frequency-to-voltage
converter test results

Input range	0-500 Hz
Output range	0-10 V dc
Output voltage ripple	1.0 mV rms maximum
Nonlinearity	$\pm 0.1\%$ of reading
Repeatability	$\pm 0.01\%$ of range

1.3.3.4 Test Bundle Power Control — R. E. Harper

A versatile and sophisticated power control system³⁷⁻³⁹ (not available commercially) was designed, fabricated, and tested for the unique requirements of test bundle operation in the CFTL. The power control system is made up of one zone power control system (ZPCS) for each ZPS to the test bundle. The ZPCSs operate independently under the control of the CFTL computer system to generate the required power profiles across the test bundles and to perform bundle power transients to simulate the thermal effects of the neutron flux density in a gas-cooled breeder reactor. The power profile across a CFTL bundle can be continuously adjusted from uniform to an arbitrary skew including linear, exponential, and triangular. Power transients from 100 to 0% power are likewise totally adjustable with the ZPCS from as slow as 1 min to as fast as 200 ms. The shape of the transient is also adjustable and can include linear, exponential, and triangular power variations with time.

In addition to this versatility, the ZPCSs contain extensive diagnostic circuitry to monitor their proper operation as well as the proper functioning of the bundle power supply. These include the detection of internal timing errors, direct current in the secondary of the ZPS, excessive deviation from set point, and transformer overcurrents. On the detection of any error, all ZPCSs turn off the power to the bundle within 10 ms. Power cannot be restored until the error condition has been cleared.

The ZPCS operates by zero-phase firing the proper SCR pairs in an individual ZPS to control the average power delivered to resistive load represented by the fuel rod simulators (FRSs). The zero-phase firing minimizes the electromagnetic interference (emi) noise associated with other SCR firing schemes. The maximum power attainable with the CFTL system is 5 MVA utilizing 13 ZPCSs planned for the Stage 2 CFTL in which a single ZPCS may control as much as 500 kVA. Each ZPCS can control the average power to better than 1% of the maximum power setting in its zone.

Eight ZPCSs were fabricated and tested satisfactorily for the Stage 1 CFTL. Only two were installed in the Stage Alpha CFTL; the remaining six are stored in CFTL cage A, Building 9201-3, Y-12 Plant, for future use in the CFTL.

1.3.3.5 Central Control System — P. G. Herndon

The design, procurement, fabrication, and installation of the central control system Stage Alpha CFTL were completed. The system provides the measurements and manually operated controls necessary for limited but safe operation in steady state modes only. The Stage Alpha system is actually a portion of a more complex system⁴⁰⁻⁴¹ designed for the Stage 1 CFTL. The Stage 1 system employed three major devices, a fast-scan DAS, a DDC, and a programmable logic controller (PLC) to permit a wide range of operations in steady state and a variety of transient modes.

The DAS served the primarily passive function of collecting and recording data from both the loop and the test piece sensors. The DDC provided centralized coordinated control of the helium flow control valves, ZPSs, and heat exchangers during steady state and transient operations. The PLC is a relay logic emulator, which can provide the operating permissives and safety shutdown logic.

The general relationship between measurement sensors and final control elements connected through the DAS, DDC, and PLC in the Stage 1 design is presented in Fig. 1.13. In addition to the automated programmed control of CFTL operation implied in Fig. 1.13, manual controls were

Fig. 1.13. Relationship between measurement sensors and control elements.

provided to permit the operating engineer to perform steady state operations without depending on either the DAS or the DDC. The manual controls are retained in the Stage Alpha control system. The DAS is completely installed and is fully operational. Procurement and acceptance testing of the DDC computer, peripherals, software, and process input-output equipment were completed. The DDC is not a part of the Stage Alpha control system but is available for future requirements. The Stage Alpha control system is constructed so that the DAS and the DDC can be conveniently added as required.

At the end of June 1980 the major measurement and control problems associated with the Stage 1 performance requirements had been solved, and the detailed design of that system was well advanced. In July a major redirection of the gas-cooled program required a revision of the CFTL design to a version identified as the Stage Alpha CFTL having reduced

performance capabilities. Performance requirements are limited to those functions necessary to circulate helium at design temperatures and pressures under steady state conditions only.

The Stage Alpha instrumentation and controls are identified on the flow diagram in Fig. 1.14. The major measurement and control systems involve the helium circulators, the helium flow measurements, the test piece power supply and controller, and the heat-removal system. Flow is controlled by varying circulator rotor speed, which is controlled by manual adjustment of circulator motor supply frequency. Each circulator is provided with instrumentation to measure rotor speed, motor power, and bearing and winding temperatures. The film thicknesses for the three gas-lubricated bearings in an individual circulator are displayed graphically on a cathode ray tube.

Fig. 1.14. Stage Alpha instrumentation and controls.

Vortex shedding flowmeters (discussed in Sect. 1.3.3.3 of this report) measure loop flow rates. A single 500-kVA ac power supply and controller (the latter discussed in Sect. 1.3.3.4) provide test section power. Heat is removed from the system by air-cooled HX1. A 20:1 cooling air flow range is achieved by manual adjustment of damper position and blower speed. Helium temperature at the outlet of HX1 is held constant by automatic closed-loop control of the position of the blower VIVs. Pressure and temperature measurements are made at several strategic locations.

All of the above control functions are limited by a permissive and protective interlock system built around a PLC.

Fabrication, wiring, and installation of four main control board cabinets, five signal conditioning cabinets, and five thermocouple patch panel cabinets were completed. The CFTL control room, located adjacent to the loop area, is shown in Fig. 1.15. The installation includes instrument component, mounted in the loop area, cable trays and conduits, and associated interconnecting wires and cables.

1.3.3.6 Control and Protective Interlock Circuits — P. G. Herndon, A. H. Anderson, and W. R. DeVan*

The design, procurement, and installation of the Stage Alpha CFTL electrical control and protective interlock circuits were completed. The circuits consist generally of a system of electrical contacts interconnected in various logic arrangements to initiate or inhibit control actions in the loop systems and to alert the operator (by operating alarms or indicating lights) whenever abnormal conditions exist in the system. Control and/or alarm actions are initiated either automatically by process instrument switches or manually by hand-operated switches located on the control boards. The contacts of these switches are connected to the input terminals of a PLC. The output terminals of the PLC are connected to loop component control devices, such as motor starting contactors, circuit breakers, and solenoid valves. The PLC, which is a relay logic emulator,

*Oak Ridge Foster-Miller Associates, Inc., Oak Ridge, Tenn.

is programmed to interpret the state of the input contacts and to actuate its output contacts in accordance with the desired operating permissive and protective interlock logic functions. A program of instructions is simply a list of things to be done (what loop components are to be turned on and in what sequence) under certain conditions (according to what input signals are received).

The control logic developed for the Stage I CFTL was revised to meet the reduced requirements of the Stage Alpha design, which is defined by the block diagrams shown on Drawings 12D-11590-0610 and -Q611 listed in Sect. I of Appendix 3. The circuit configurations implementing the logic are shown on the drawings listed in Sect. III of Appendix 3.

1.3.3.7 Data Acquisition System — K. J. Cross

The DAS,⁴² designed and built for the CFTL, is completed and fully operational. It consists principally of the computer, system software, analog input subsystem, and various computer peripherals: disks, magnetic tape drives, terminals, and electrostatic printer-plotter. The major features of the DAS include:

1. Approximately 600 channels of analog inputs; each channel is individually programmable for 5 mV to 10 V full scale.
2. Analog instrument signals can be read and recorded on magnetic tape or disk at any aggregate rate of up to 10,000 readings per second.
3. Up to two high and/or low limits can be defined for each instrument; contact closures are activated when an out-of-limits condition is detected; built-in hysteresis eliminates false alarms from brief noise spikes; alarm checking is performed up to ten times per second.
4. The entire system is data-base driven, which allows any combination of a variety of instruments.

In addition, utility programs have been written, which give the operator control over the system and provide loop status conditions on request.

These utilities include

1. data base utility program, used to define which instruments are associated with which analog channels and to define the different types of instruments,

2. magnetic tape utility programs, including tape positioning operations, printouts from data tapes, tape catalog utility, tape duplication and modification utilities, and utilities to transfer data between the tapes and the disks,
3. scanning utility to initiate a scan sequence to record instrument readings on disk or tape or to display the current reading of a specific instrument,
4. calibration utility to perform a complete calibration on the analog system and to provide a printed summary for permanent records,
5. scan table utilities to define the list (scan table) of instruments to be read during a scan sequence, to modify a scan table, and to print scan tables,
6. alarm utilities to display and/or modify limits assigned to instruments and to notify the operator of out-of-limit conditions, and
7. operator's display utilities to provide the operators with real-time numeric displays of instruments and/or to print instrument readings periodically.

Extensive documentation is also provided to enable programmers to write new programs with minimal guidance from Instrumentation and Controls Division personnel.

To apply the DAS to the CFTL, the following steps are required:

1. define the instrument configuration by use of the data base utility,
2. generate engineering unit conversion algorithms for any instruments not currently defined (currently defined instruments include types K and S thermocouples and all linear instruments,
3. train operators to use the DAS, and
4. write any special programs desired, such as plotting, control algorithms, trend analysis, etc.

In summary, the CFTL DAS is an extremely powerful, flexible, general-purpose data acquisition and computing system. It is readily adaptable for virtually any foreseeable (CFTL) requirements.

The DAS was transported from the ORNL Instrumentation and Controls Division site to the CFTL site in the Y-12 Plant and connected to its dedicated power supply. At the end of this report period, the DAS diagnostics programs had been run satisfactorily to indicate readiness to perform in the CFTL programs.

1.4 TEST BUNDLE DESIGN AND DEVELOPMENT — H. C. Young and C. W. Collins

The design⁴³ of the 37-rod test bundle AG1, which was completed early in 1980, was reviewed by the bundle design review team, an entity independent of the CFTL project. The consensus of the team was that the design complies with the requirements; that the bundle can be built, installed, and operated as intended; and that all design problems of significance have been identified and addressed.

A technical memorandum⁴ describing the bundle and showing the location of all test bundle instrumentation was published. The design and procurement of thermocouples (TCs), TC materials, temperature and other sensors, and associated readouts were completed for the structurally related measurements that were to have been made during test bundle operation. Type K TCs were selected to make temperature measurements of bundle internals, of helium at bundle outlet, of bundle measurement sensors, and of the bundle hexagonal flow duct. The x-ray imaging technique was selected to measure the movement of bundle components during test operation. A system was designed to measure the pressure drop of helium flow for several distances through the test bundle. Specifications were prepared for the purchase of state-of-the-art microphones and accelerometers to characterize the acoustic behavior of the flowing helium and the vibrational characteristics of the bundle, respectively.

Fabrication of some test section parts being provided by General Atomic Company (GA) was near completion when the GCFR program was canceled. These parts were completed and delivered and are now stored at ORNL (Sect. 1.4.5).

The fabrication of roughened cladding needed to make fuel rod simulators (FRSs) for bundle AG1 was completed satisfactorily by GA after a sufficient quantity of unroughened cladding was qualified during extensive ultrasonic inspection conducted by and at ORNL.

Development efforts on the 8-mm-diam FRS for bundle AG1 were taken to logical stopping points in accordance with the closeout instructions for the GCFR program. Although the reliability performances of both the FRS and its internal TCs were improved, the unreliability of the center nickel electrode limited the FRS performance. Apparently minute amounts of free

boron form a boron-nickel (B-Ni) eutectic, which depresses the melting point of the electrode very slowly from 1450 to about 1080°C. Although most of the test program for bundle AG1 could be accomplished with the FRS, we believe the FRSs would fail before completion of the very severe test conditions that occur near the end of the test program. Development of suitable MgO insulation preforms to eliminate the B-Ni eutectic phenomenon was halted by the closeout before fruition could be achieved.

Development of suitable brazing techniques for attaching electrical conductors between the power supply leads and the FRS terminals for bundle AG1 was also taken to a logical stopping point and halted. An expensive jig-and-bundle mockup had already been fabricated before the closeout notice, and the very little additional work required to prove the brazing technique was completed satisfactorily.

Efforts to enhance the reliability of bulk material for small-diameter TCs were concluded satisfactorily.

1.4.1 Test Bundle Design — C. W. Collins

The detailed design⁴⁴ of 37-rod test bundle AG1 was completed and subjected satisfactorily to an independent formal design review. Design of a number of handling fixtures and jigs, required for fabricating and assembling the test bundle, were in the early conceptual stage when the GCFR was canceled. No formal design drawings of these fixtures were produced, and all design efforts were halted.

All test bundle drawings prepared by Union Carbide Corporation, Nuclear Division (UCC-ND) and test section drawings prepared by GA are listed in Appendix 1.

1.4.2 Structurally Related Measurements — S. P. Baker

The design and much of the procurement for the structurally related measurements to be made in test bundle AG1 were completed. Test bundle and test vessel measurements⁴⁵ (Fig. 1.16) include (1) internal temperatures of FRSs, (2) temperatures of other selected bundle components, (3) temperatures of the bundle exit gas, (4) bowing movement of individual

Fig. 1.16. Instrument application diagram for test bundle

Fig. 1.16. Instrument application diagram for test bundle AG1 and the test vessel.

Zang Power Supply (TK)		0005	
TEST VESSEL NO FLOW - NO-1		0003	
REFERENCE DRAWINGS		DWG NO	
DATE	BY	DATE	BY
12-2-68	113075		
DATE	BY	DATE	BY
DESIGNED BY P. G. HERMOND		CHECKED BY	
DATE	BY	DATE	BY
PROJECT TITLE		BLDG.	
GCFR - CORE FLOW TEST LOOP		2201-3	
<h2 style="text-align: center;">TEST VESSEL INSTRUMENT APPLICATION DIAGRAM</h2>			
<p style="text-align: center;">REPRESENTATION AND CONTROLS DIVISION OAK RIDGE NATIONAL LABORATORY</p> <p style="text-align: center;">KROCK CAMPUS CAMP</p>			
DATE	BY	DATE	BY
DATE	BY		

application diagram for test bundle AG1 and the test vessel.

FRSs and of FRS-grid-spacer assembly, (5) differential pressures along the duct, (6) duct vibrations, and (7) acoustics of flowing helium. Placement and methods of attaching these sensors in relation to the desired measured objectives are described extensively in a published document.⁴

Procurement of material for the FRS TCs was completed. The manufacturing methods developed to improve the reliability of these elements are described in Sect. 1.4.3.2 of this report.

Measurement of the temperature of bundle AGI components, such as thermal shroud, helium flow, duct, and the measurement sensors, and of the flowing helium past the grid spacers was specified in the design to be made with type K TCs of appropriate small diameter having ungrounded junctions and using MgO insulation and stainless steel sheaths.

A TC assembly was designed to measure the test bundle outlet gas temperature. A conceptual design for this assembly is shown in Fig. 1.17. The assembly, consisting of five type K, 0.159-cm (1/16-in.) stainless-steel-sheathed TCs with radiation shields mounted on a metal bar spanning the space between opposite faces of the hexagonal flow duct, is located at the exit of the duct. Fabrication and installation details are shown on Dwg. X2E-11590-220 (Appendix 1). To obtain a measurement response time of less than 2 s, a laser-welded side⁴⁶⁻⁴⁷ junction TC, developed by the ORNL Instrumentation and Controls Division, was specified.

We decided to measure the bowing of bundle AGI components during transient operation with x-ray imaging techniques. The efforts that undergrid the decision are documented.⁴⁸⁻⁴⁹

A system was designed to measure pressure losses at several points in the test bundle. Differential pressure measurement ranges were determined, and specifications were written for differential pressure sensors, which were not purchased.

Designs for the installation of acoustic microphones and accelerometers in bundle AGI were completed. Specifications IS-11590-QG-029 and -030, listed in Appendix 4 were written for the purchase of state-of-the-art commercial sensors. Table 1.5 presents a tabulation of the existing GA criteria and the ORNL recommended ranges and accuracies.

ORNL-DWG 81-1552 ETO

Fig. 1.17. Outlet gas thermocouple assembly for CFTL test bundle AG1.

These recommendations are based on the anticipated structural behavior of CFTL test bundles and the current capability of commercial sensor technology. Operating temperature limits of available sensors are 760°C for accelerometers and 540°C for acoustic microphones. This does not meet the current 1000°C requirement specified by GA, but a lower maximum temperature rating may be sufficient to provide useful data.

The microphones and accelerometers are located in two different areas of the bundle: at or near the inlet and at the outlet. Those sensors at the inlet (two microphones and two accelerometers) will not reach

Table 1.5. Test bundle structural sensor range and accuracy

Measurement	Sensor	Existing GA ^a		ORNL recommended	
		Range	Accuracy	Range	Accuracy
Vibration	Accelerometer	0-0.2 G ^b	±10% of reading	0-1 G	±2.5% of full scale
		0-10 Hz	±2% of reading	5-500 Hz	
Acoustic noise	Acoustic microphone	150 dB max SPL ^c	±2% of reading	112-152 dB SPL	±2% of full scale output
		10-10,000 Hz		10-8330 Hz	

^aGeneral Atomic Company.

^bG = gravity.

^c0 dB = 2×10^{-5} Pa SPL (sound pressure level).

temperatures above about 350°C and should function for the life of the bundle. The sensors located at the outlet (one microphone and two accelerometers) will reach temperatures approaching 1000°C and higher during the latter portions of the testing program for a bundle and will ultimately fail. After failure, structural data from the bundle outlet region will be inferred from the sensors located near the bundle inlet. Thermocouples 1.5 mm (1/16 in.) in diameter will be placed on all microphones and accelerometers to monitor and record their temperature.

Some concern exists about the performance of the specified accelerometers and acoustic microphones when subjected to the pressure and temperature transients that occur in the test bundle. The accelerometers are sealed in an Inconel housing and, according to vendor information, are not sensitive to pressure and temperature transients, but no test data are available to substantiate the claim.

Past experience with similar devices indicates strongly that the performance of the microphones will be adversely affected by both temperature and pressure transients. Also, the vendor calibrates the microphones at 104 Pa (15 psig) pressure only. Its expert opinion is that elevated gas pressures up to 21 MPa (3000 psi) will not cause large

changes in microphone performance, but it will not officially guarantee performance at pressures much higher than atmospheric and does not have the facilities necessary to calibrate them at higher pressures.

These questions can be resolved only by further investigation and development testing to advance the state of the art for high-temperature accelerometers and microphones. Funds were not available for such an effort. However, we believe that useful and reliable data can be obtained from available sensors operating under steady state pressure and temperature conditions.

1.4.3 Fuel Rod Simulator Development — R. W. McCulloch

This section delineates the progress in 1980 toward the development of a reliable, high-temperature, high-heat flux FRS for use in CFTL test bundles. Cladding of the FRS (Fig. 1.18) is to be made of material prototypic of GCFR fuel rod cladding and is to have the same dimensions, configuration, and thermal and heat transfer characteristics as the GCFR fuel rod cladding.

The reference FRS⁵⁰ is reentrant; that is, both power terminals enter at a single end. A copper tubular terminal joined to a tubular nickel lead is, in turn, joined to the near end of the variable-width heating element made of Kanthal A-1 alloy. The heating element is designed to provide a cosine heat-flux distribution that has a maximum-to-average heat-flux ratio of 1.21. The center terminal is made of a solid copper rod and is joined to a nickel lead, which, in turn, is joined through an adapter to the far end of the heating element to form the electric-current-carrying circuit in the FRS. Cold-pressed boron nitride (BN) preforms provide electrical insulation between (1) the cladding and the heating element with its associated tubular lead and terminal (outer annulus) and (2) the heating element and the center lead and terminal (inner annulus). The BN preforms are individually tamped and crushed during installation. They also provide thermal conduction between the heating element and the cladding. Six small-diameter type K TCs having 0.5-mm (0.020-in.) Inconel 600 sheaths and ungrounded junctions are

Fig. 1.18. Cross sectional drawing of 8-mm-diam fuel rod simulator for the CFTL.

installed inside the FRS cladding. The sheaths of the TCs run longitudinally along the inside surface and are located equidistantly around the perimeter of the FRS cross section.

The total length of one FRS is 2860 mm (112.6 in.), including a heating length of 1200 mm (47.24 in.).

The FRS is designed to operate at power levels up to a 43-kW maximum and to provide a heat flux of 1.7 MW/m^2 ($530,000 \text{ Btu h}^{-1} \text{ ft}^{-2}$) at a maximum cladding temperature of 1000°C (1832°F) and a matching maximum heating-element temperature at 43 kW of 1700°C (2372°F). Higher cladding temperatures are allowed at reduced values of rod power.

The operating conditions place stringent requirements on all materials used in the FRS. The heating element must operate at the maximum temperature without property degradation. The BN must maintain both high thermal conductivity and electrical resistivity at the maximum temperature; in addition, its properties must remain uniform both axially and circumferentially to provide accurate simulation of the cosine heat flux. The FRS must also maintain its integrity while enduring thermal transient tests.

The FRS development program staff at ORNL has performed materials, fabrication, inspection, testing, and failure analysis tasks to prepare procedures that are satisfactory for the production of adequate CFIL FRSs.

During 1980 two conductivity test cells and four rod prototypes were fabricated and tested. Table 1.6 summarizes these tests and (for the sake of continuity) also reports previous results for conductivity test cell GNK-L-28S and for rod prototype GNK-L-27P. Including these activities, a total of 26 rod prototypes and 9 conductivity cells have been produced and tested over a four-year period. The end result has been a demonstration that precise fabrication technology could be applied to upgrade existing FRS quality to meet heretofore unattainable performance requirements. Fuel rod simulators can be fabricated to operate for more than 1000 h at 1000°C and power levels as high as 200 W/cm^2 and for 50 h at 1200°C and 40 W/cm^2 .

The difficulties of a most complex FRS configuration, which included a central current return conductor, six internal 0.5-mm TCs, and a variable-width heating element, were surmounted. The ability to produce

Table 1.6. Results of tests of conductivity test cells and rod prototypes

Rod ^a	Heating-element material	Tabular lead materials	Central rod materials ^b	Instrumentation ^b	Test stand ^c	Remarks ^d
GNK-L-27P	Kanthal A-1 (variable width)	Nickel-copper	Nickel-copper	None	SBSL	Rod operated 70 h SS 10-34 kW at cladding temperature 700-925°C; failure was similar to that of 26P
GNK-L-28S	Kanthal A-1 (variable width)	Nickel	Type K TC	None		Test cell was fabricated to further evaluate effects of preform length and tamping energy on FRS transient properties; IR scans indicated preform length should be maintained at 10 mm or less
GNK-L-29P	Kanthal A-1 (ΔW)	Nickel-copper	Nickel-copper	None	HTS	First 8-mm rod; electric breakdown of inner BN region traced to scale on Kanthal A-1 material
GNK-L-30S	Kanthal A-1 (C-W)	Nickel-copper	Type K TC	None	WCTS	Used TS-1449 annular BN preforms
GNK-L-31S	Kanthal A-1 (C-W)	Nickel-copper	Type K TC	None	WCTS	Used PT-13 treated BN preforms made from TS-1449 powder

Table 1.6. (Continued)

Rod ^a	Heating-element material	Tabular lead materials	Central rod materials ^b	Instrumentation ^b	Test stand ^c	Remarks ^d
GNK-L-32P	Kanthal A-1 (ΔW)	Nickel-copper	Nickel-copper	6 each type K IJ, 304SS sheathed TCs	SRSL	Fabrication problems similar to 29P; used GA roughened cladding; rod endured 700 h of SS and transient tests and 8000 thermal cycles without TC failure; evidence of B-Ni reaction
GNK-L-33P	Kanthal A-1 (ΔW)	Nickel-copper	Nickel-copper	4 each type K IJ, 304SS sheathed TCs, 2 pt sheathed type S TCs	HTS	Fabrication OK; rod tested for 1472 h and 12,490 thermal cycles; two type S TCs failed; four type K TCs survived all operations until failure
GNK-L-34P	Kanthal A-1 (ΔW)	Nickel-copper	Nickel-copper	6 each type K IJ, Inconel sheathed TCs from GMI	SRSL	Fabrication OK; tested for 556 h and 5800 cycles in SRSL; SS and transient power was 29 kW and 0 to 29 kW, respectively; failure similar to 32P; differential thermal expansion on central Ni rod, weakened by B-Ni reaction, failed during thermal cycling

^aSerial number postscript S indicates conductivity cell and postscript P indicates FRS prototype.

^bIJ = insulated junction, TC = thermocouple, and GMI = Groth Mazur Industries.

^cSRSL = Single-rod sodium loops, HTS = helium test stand, and WCTS = water-cooled test stand.

^dSS = steady state, IR = infrared, and BN = boron nitride.

accurately the requisite chopped cosine heat flux distribution was demonstrated. A new, "nonswaged" FRS technology was created to preserve the roughening for enhancing heat transfer that is applied before FRS fabrication and to maintain the initial cold-work requirements for a completed FRS. This method made available for the first time a high-heat-flux-high-temperature FRS fabricated from cladding that is prototypic of the reactor it is intended to simulate.

Major materials joining, inspection, and terminal heat generation problems were met and solved. High-temperature braze joints and laser butt-welded connections with previously unattainable electrical and dimensional tolerances were developed. Thousands of stringent thermal cycles between 350 and 1000°C and much steady state operation at temperatures to 1200°C were logged.

Nevertheless, the GCFR FRS still has several shortcomings even after considerable development. The use of nickel material for the central current return conductor adversely affects FRS reliability. The conductor material was initially specified to be, and remains, nickel. No other material is available that matches better the combined requirements of high melting point, thermal expansion comparable to stainless steel, and low electrical resistivity at high temperatures. The nickel melting point (50°C lower than that of the Kanthal A-1 heating element) precludes higher operational performance, or, alternatively, reduces operational time at internal temperatures above 1000°C.

Additionally, a relatively slow B-Ni eutectic reaction was shown to occur at the higher temperatures. This reaction reduces the equivalent nickel melting point from 1450 to about 1000°C, which limits both the lifetime and the thermal cycling ability of the rods. This problem could be eliminated with the use of central MgO cold-pressed insulators. However, project closeout did not permit us to accomplish this goal.

Major problems with small-diameter TCs, 0.50-mm (20-mils) internal to the FRS were solved. Thermocouple failures were reduced from 100% in early rod prototypes containing four TCs to 0% for recent prototypes containing six TCs. Techniques to manufacture refined-grain-size TCs were developed to produce type K TCs having a maximum grain size of

ASTM 9 (17 μm) and 11 (9 μm), respectively, for Alumel and Chromel thermoelements (TEs) of 76- μm diameter (3-mils). The harmful effect of residual cold work on TC lifetime was discovered, and a method was devised to eliminate it. These TCs, when properly manufactured and assembled in accordance with the developed technique, were shown to survive the GCFR operational conditions imposed on them.

Results of development efforts with rod prototype GNK-L-27P, 29P, 32P, 33P, and 34P and conductivity test cells GNK-L-28S, 30S, and 31S and of fabrication efforts with small-diameter thermocouples are summarized.

1.4.3.1 Development of Nonswaged 8-mm Fuel Rod Simulator

Conductivity cells are fabricated and tested to obtain information about fabrication parameters and about the effective thermal conductivity of the crushed cold-pressed BN preforms in an FRS. Information was needed on the relationship of conductivity to the density of the BN preforms for the inner and outer annular insulation. Information was also needed about the effects of FRS power, cladding temperature, and the fabrication process for preforms made with new Union Carbide Corporation TS-1449 BN powder on 8-mm-diam rods. Test cells are a simple, effective means of obtaining useful information.

The conductivity cell configuration is similar to that of the CFTL FRS (Fig. 1.18) except that it has a heated length of 30.5 cm and that the center terminal (current return) is replaced with a 1.5-mm (60-mil) TC. The current return is provided by attaching the far end of the heating element to the cell cladding and grounding the cladding to complete the electrical circuit.

Conductivity test⁵⁰ cell GNK-L-28S, which was reported previously, was fabricated to evaluate the effects of BN preform length and tamping energy on the transient profile properties of 8-mm-diam rods. Correlation of tamping data with infrared scans indicated that the current values of tamping energy are sufficient but that the preform length should be limited to 10 mm or less.

A water-cooled test stand (WCTS), fabricated for previous test cells, was used to test conductivity test cells GNK-L-30S and -31S. Each test cell was mounted horizontally in the WCTS. Two or three TCs were attached

to the outer cladding surface in an intrinsic junction configuration. All junctions were located in the radial plane that contains the junction of the internal TC and were equidistant around the perimeter.

Figure 1.19 summarizes effective thermal conductivity k versus power for WCTS tests of these and several other conductivity cells. The data were repeatable to within $\pm 10\%$.

The variations in k from test cell to test cell were caused primarily by annular BN preform density. Test cell 30S, fabricated with TS-1449 powder, had the highest annular density [$\sim 90\%$ (TD)]. Test cell 31S contained highly oriented PT-13-treated TS-1449 powder of about 87% density. The density effect dominated the orientation effect. These data indicate that TS-1449 is an excellent powder for use in nonswaged FRSSs.

Fig. 1.19. Effective thermal conductivity as a function of power for several conductivity cells tested in the Core Flow Test Loop water-cooled test stand.

Rod prototype⁵⁰ GNK-L-27P, which was reported previously, was the first 8-mm-diam prototype fabricated. It contained no TCs and was fabricated with preforms that were cold-pressed locally. Several fabrication problems were encountered, primarily with tooling, as is normal in the major dimensional redesign of a rod. The same problems with low density of the inner BN preforms were again encountered in the nickel end-plug region, largely because of the increased rigidity of the Kanthal A-1 variable-width heating element. The heating element diameter had been increased from 4.24 to 4.75 mm, and the nickel rod diameter had been increased from 2.16 to 2.59 mm as part of the design change. These changes resulted in less internal thermal heating and increased strength of the central nickel rod and the heating element.

The rod was tested in the single-rod sodium loop (SRSL); the operation is summarized in Table 1.7. The rod failed at 35.3-kW power with the cladding temperature near 950°C. Failure analysis showed that the ground end of the nickel rod had been close to the melting point and that several cracks occurred along the nickel rod adjacent to the heated section. This analysis closely paralleled that for rod 26P, except that the nickel rod of 26P exhibited failure near the ground end only.

Table 1.7. Summary of operation testing of rod prototype GNK-L-27P

Rod power (kW)	Sodium outlet temperature (°C)	Time at conditions (h)
10.0	704	6.6
19.0	704	21.5
19.0	777	20.5
20.0	927	7.3
26.6	500	0.5
26.0	927	3.0
30.0	927	10.0
35.3	927	0.1

The fabrication procedure was further modified to correct the localized low-density region. A fixture was devised to eliminate virtually all movement of the heating element near the end plug area during inspection and welding.

The presence of a B-Ni eutectic in an FRS concerns us. Boron has very little solubility in nickel so that a eutectic phase can and does occur above 1080°C at levels of 208 ppm B in nickel. This boron must be present in the free form in the BN to be available. No reliable data have been found on dissociation of BN to form boron, but probably the BN disassociation rate will be very small at our operating temperatures. Both the dissociation and the eutectic phase formation depend on time. Although this fact may limit the useful life of the FRS at high temperature, similar tests at high temperature with BN contacting the central nickel rod did not show the formation of the B-Ni eutectic to be a problem. Because of the possible time-temperature limitation from B-Ni eutectic formation and because of the probable increase in operating capability, the use of MgO central preforms in place of BN was pursued.

Eagle-Picher Industries, Inc., (EPI) the BN preform fabricator, agreed to fabricate a small quantity of MgO preforms for our evaluation. On their receipt, a short test cell was fabricated to evaluate filling with these new preforms. Severe spalling occurred when the preforms were passed through the copper lead-in region. The copper rod was reduced in diameter by swaging from 4.02 to 3.78 mm (0.102 to 0.096 in.), but the spalling persisted. Spalling did not occur in the nickel terminals regions. Evidently the soft copper (resulting from the Ni-Cu braze employed to connect rod and tubular terminals) interacts with the hardened, relatively spherical MgO particles. Magnesium oxide, unlike BN, does not slide along the material surface but "digs" into it instead.

Discussions with the preform manufacturer as well as our own investigations indicated that MgO powder properties such as maximum particle size, particle size distribution, hardness, and particle shape contributed to these poor results. Magnesia crystallites are harder than are those of BN and are approximately spherical, whereas BN crystallites are flat, thin platelets, which tend to slide over each other.

These discouraging results made it clear that if cold-pressed MgO preforms were to be made usable for the CFIL FRS, a thorough analysis and optimization of the powder properties for fabricability was needed. We decided to retain BN preform for use in the FRSs for the first bundle and to continue the investigation into a potentially useful MgO preform, as practical.

Nonswaged rod prototype GNK-L-29P was uninstrumented and contained inner BN preforms fabricated by EPI from TS-1449 powder and outer BN preforms fabricated locally from the same powder. The TS-1449, a new, high-purity powder similar to HCM, was developed by Union Carbide Corporation, Parma, Ohio, in cooperation with ORNL.

Arcing and breakdown of the inner BN insulation was encountered, and investigation of the defect revealed a very thin (~ 0.0025 mm) "mill scale" on the surface of the Kanthal A-1 starting material used to fabricate the variable-width heating elements. Although the heating elements were subjected to routine quality assurance activity, the scale had not been previously detected. When the Kanthal sheet material was cut and wound into heating elements, regions of the scale became loose on the surface. When some of the heating elements were used subsequently to fabricate active component assemblies (ACA), pieces of the loose scale chipped off and were deposited within the inner annular BN. High-potential, electrical tests subsequently indicated that the insulation was contaminated.

Efforts to remove the scale were unsuccessful, so the heating elements were rejected. The Kanthal Corporation, supplier of the material, replaced the defective strip at no cost. Heating elements fabricated from the new material, as well as from Kanthal A-1 from another lot, were acceptable.

The short circuits in the rod prototype were partially cleared and the decision was made to test the unit in the helium test stand (HTS). Table 1.8 summarizes these tests.

The rod prototype operated normally for 120 h at about 700°C cladding temperature. The power was being adjusted for transient operation, and the rod had reached 900°C cladding temperature on a 12-s ramp at 12 kW when the heating element shorted to the nickel return rod through the

Table 1.8. Helium heat stand operational tests of rod prototype GNK-L-29P

Rod power (kW)	Maximum clad temperature (°C)	Transient ΔT (°C)	Number of cycles	Time of operation (h)
0.39	360	<i>a</i>		0.5
1.03	710	<i>a</i>		73.0
1.0	680	<i>a</i>		47.0
12.0	900	600	3	6 min

^aSteady state operation.

inner BN insulation. Postfailure examination showed that the short circuit occurred in the region that was contaminated with Kanthal scale during fabrication.

Rod prototypes GNK-L-32P and GNK-L-33P were successfully fabricated with the new Kanthal A-1 heating elements. Rod GNK-L-32P contained six type K, Inconel sheath TCs procured from Groth-Mazur Industries (GMI) for CFTL FRS: GNK-L-33P contained four GMI TCs and two type S (Pt versus Pt-Rh) TCs sheathed in platinum.

Table 1.9 summarizes operational tests in the SRSL on 32P. While the steady state operation was being completed with an existing supply, a prototype of the 500-kVA zone power supply for CFTL, was being installed adjacent to the SRSL. The rod prototype was then thermally cycled with the new power supply for more than 4 d continuously before failure of the rod occurred. The failure, caused by melting of the central nickel rod, occurred during weekend operation so that an accurate assessment of conditions leading to the failure was not possible. However, all the normally expected CFTL operational conditions were met or exceeded before failure, and more than 4 times the anticipated CFTL thermal transients were completed without a single rod TC failure.

Rod prototype GNK-L-33P was tested in the HTS. Table 1.10 summarizes its operation.

Table 1.9. Operational tests of rod prototype
GNK-L-32P in the single-rod sodium loop

Rod power (kW)	Loop temperature		Maximum cycling ΔT (°C)	Number of cycles	Operating time (h)
	Inlet (°C)	Outlet (°C)			
0	350	350			175
29.0	370	650			442
32.8 + 3.3	370	700	165	220	2.5
28.0 + 0	370	650	125	7892	90
Total					709.5

Table 1.10. Operational tests of rod proto-
type GNK-L-33P in the helium test stand

Rod power (kW)	Cladding temperature (°C)	Operation time (h)	Number of thermal cycles
0.3	370	50	
1.0	720	265	
1.2	700-720 ^a	914	
0-2.5	700-870 ^a	137.5	8,250
0-8.6	425-1000 ^b	106	4,240
Total		1,472.5	12,490

^aTemperature change at constant power
was because of cladding emissivity changes.

^bThermal cycling operations.

A total of 1472.5 h was logged, of which 1229 h was steady state, and most (914) was at about 700°C. The rod endured a total of 12,490 thermal cycles in 243.5 h of transient test operation. Over 4000 very severe (425–1000°C in 15 s) cycles were conducted before rod failure. All four type K (Chromel-Alumel) TCs remained operational throughout the entire test. This is additional verification that the lifetime of type K small-diameter TCs has been increased considerably. Both of the type S (Pt versus Pt-Rh) TCs failed early in the operation.

Rod failure was caused by a short between the heating element and the central rod located about 40 cm (15 in.) from the upper terminal. This placed the entire potential of 148 V across about 0.6 Ω , resulting in a heat flux of approximately twice the design rating of 200 W/cm² during the "on" position of the thermal cycle. As a result, internal rod temperatures were high enough to melt the heating element and nickel rod in a region about 25 cm (10 in.) long. Failure occurred when internal pressure blew a hole in the stainless sheath, ejecting molten nickel and Kanthal A-1 alloy and causing an open circuit.

Table 1.11 summarizes operational tests on rod prototype GNK-L-34P, the last CFTL prototype to be fabricated and tested.

This prototype contained six Inconel 600-sheathed, type K TCs, which had been fabricated for bundle AG1. All six TCs operated normally throughout 415 h of powered, steady state testing and 66 h of thermal

Table 1.11. Operational tests of rod prototype GNK-L-34P in the single-rod sodium loop

Rod power (kW)	Loop temperature		Maximum cycling ΔT (°C)	Number of cycles	Operating time (h)
	Inlet (°C)	Outlet (°C)			
0	350	350			75
28.6	350	600			415
28.6 + 0.3	350	655	125	5800	<u>66</u>
Total					556

transient testing, which included 5800 thermal cycles. The rod failed in a manner similar to that of 32P. Analysis indicated the presence of a low-melting B-Ni eutectic reaction. The reaction appeared to proceed quite slowly but weakened the nickel central rod and eventually caused failure. The reaction, when complete, reduces the equivalent nickel melting point from 1450 to about 1000°C, which limits both the lifetime and the thermal cycling ability of the rods. This problem could be eliminated by using central MgO cold-pressed insulators, as mentioned previously in the discussion of the failure of rod 27P.

All normal requirements of FRSs for GCFR test bundles were met. In addition, long-term transient operation was demonstrated. Completion of testing on this prototype ended fabrication and testing on CFTL FRSs. The task of obtaining a usable MgO central preform was not completed. Although operational requirements could be met with the FRS in its current design state, the increased thermal expansion of a central MgO preform would enhance operation by increasing annular radial thermal conductivity and eliminating the B-Ni reaction.

1.4.3.2 CFTL Fuel Rod Simulator Thermocouple Fabrication Development

Fabrication development⁵¹ in FY 1979 culminated in a process capable of producing small-diameter TCs having an ASTM 9 or smaller grain size. Subsequent attempts to produce long bulk material lengths (BMLs) revealed that the initial process was inadequate to produce a BML free of breaks in the internal TEs in lengths longer than 10 m. This section details the development necessary to provide BML lengths of 60 m and longer.

1.4.3.2.1 Recrystallization and Drawing Theory. The recrystallization of the TEs is a nucleation and growth phenomenon,⁵¹ the completion of which is dependent on annealing temperature, time, and cold work performed before annealing as well as on composition variations. A schematic of the effect of prior cold work and initial grain size before cold-working on the recrystallized grain size is shown in Fig. 1.20. The schematic suggests that a large amount of cold work is desired to refine grains by subsequent recrystallization; small amounts of cold work must be avoided unless the level can be reduced to near zero.

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Fig. 1.20. Recrystallized grain size versus cold work for α -brass as function of initial deformation. Source: P. G. Shewmon, *Transformations in Metals*, McGraw-Hill Book Co., N.Y., 1969, p. 96.

Because it is a nucleation and growth process, the amount of material transformed during recrystallization follows a sigmoidal ("S"-shaped) distribution with time.⁵² A process that takes 20 min to complete may be only 10% complete after 5 min and 90% complete after 15 min. Grain growth will continue after recrystallization is complete if the material remains at temperature.

The relationship between temperature and time of recrystallization is given by an Arrhenius-type equation found to hold for a number of metals:⁵³

$$1/t = A \exp(-Q_p/RT), \quad (1)$$

where

- t = time for a certain percent recrystallization,
- A = a constant,
- Q_p = activation energy for recrystallization,
- R = gas constant,
- T = absolute temperature.

From Eq. (1):

$$1/T = R/Q_p (\ln t + C) , \quad (2)$$

where C is a constant. This equation shows that, for a unit change in temperature, the time for a fixed amount of recrystallization changes logarithmically.

Figure 1.21 is a schematic of Eq. (2) for two materials with different activation energies. To a first approximation, material with a lower activation energy is characterized by the steeper slope and takes less time to recrystallize at a given temperature. Therefore, the material with the lower activation energy will have larger grain size. As temperature is reduced, the difference in recrystallization time increases. Thus, the difference in recrystallized structure is progressively decreased as temperature is increased and time is decreased.

If the grain size of two materials is to be minimized and they must be annealed at the same temperature (as is the case with the Chromel-Alumel TEs in a TC), the amount of recrystallization of the material with

Fig. 1.21. Schematic representation of Eq. (2) for two materials with different activation energies.

the higher activation energy (Chromel) determines the annealing time. Thus, the extent of recrystallization necessary for subsequent cold-working of that material without fracture during fabrication must be determined. This amount of recrystallization will determine the annealing time for the system and, therefore, the grain size of the material with the lowest activation energy. From Fig. 1.21, the difference in grain size will be smallest when the recrystallization time is shortest; this occurs at the highest temperature.

The drawing process was also examined in detail. The general equation for drawing from ref. 54 is

$$\sigma_d = 1/\eta \int \sigma d\epsilon, \quad (3)$$

where

- σ_d = draw stress,
- σ = material stress at ϵ ,
- η = process efficiency,
- ϵ = draw strain.

For materials that obey the strain-hardening power law,

$$\sigma = K\epsilon^n, \quad (4)$$

where K is a strength coefficient, and n is the strain hardening exponent. In this case, Eq. (3) becomes

$$\sigma_d = K\epsilon^{n+1}/\eta(n+1). \quad (5)$$

Now, Eq. (5) can be represented by

$$\sigma_d = \sigma_e \epsilon / \eta(n+1), \quad (6)$$

where σ_e is defined by Eq. (4) and

$$\epsilon = \ln(A_0/A_1) = \ln(d_0^2/d_1^2), \quad (7)$$

where A_0 and d_0 are the entering area and diameter, and A_1 and d_1 are the exiting area and diameter.

Figure 1.22 shows typical material stress and strain plots during steady state drawing as described by Eq. (6). The material stress σ increases in accordance with Eq. (4) and is σ_ϵ at the die exit. The material is strained to $\epsilon = \ln A_0/A_1$ at the die exit, and the draw stress σ_d acts on the reduced, strain-hardened material.

Figure 1.23 shows the drawing operation described by Eq. (6) for $\eta < 1$ and $\eta = 1$ as well as Eq. (4) for the material. The material is influenced by the draw die as it passes through but is again in pure tension, in a work-hardened state, as it exits. It is normally work hardened enough (more than $\epsilon_{\max \text{ pass}} \approx 0.3$ for a type K TC) so that it will neck and break if it yields. To prevent this σ_d must be less than σ_ϵ . Therefore, the drawing limit is reached when

$$\sigma_d = \sigma_\epsilon. \quad (8)$$

Fig. 1.22. The steady state drawing operation, as described by Eq. (6). Source: W. A. Backofen, *Deformation Processing*, Addison-Wesley Publishing Co., Inc., Reading, Mass., 1972, pp. 190-230.

Fig. 1.23. Flow curve ($K\epsilon^n$) for a wire that exhibits strain hardening as well as the work curve for ideal ($\sigma_\epsilon \epsilon / n + 1$) and typical [$1/\eta(\sigma_\epsilon \epsilon) / n + 1$] drawing process.

This is shown in Fig. 1.23 as the intersection between the σ_d and σ_ϵ curves. For this case Eq. (6) becomes

$$[\epsilon_{\max}]_{\text{draw}} = n(n + 1) . \quad (9)$$

For pulling in pure tension,

$$[\epsilon_{\max}]_{\text{pull}} = n . \quad (10)$$

Comparison of Eqs. (9) and (10) indicates that a maximum additional 100% elongation is possible with drawing as compared with pulling in pure tension. The amount achieved depends on η , the drawing efficiency.

Eq. (3) is also written in ref. 54 as

$$\sigma_d = [1 + C(\Delta - 1)](1 + \mu \cot \alpha) \sigma_\epsilon \epsilon / (n + 1) , \quad (11)$$

where

- C = A constant = 0.12 for wire,
- μ = coefficient of friction,
- α = die draw angle,
- Δ = a die design parameter $\approx \bar{d}/L$ (Fig. 1.22).

Comparing Eqs. (6) and (11) we can define η as the product of the redundant and frictional efficiencies

$$\eta = \eta_I \eta_f = (1/\phi)/(1/f) , \quad (12)$$

where the redundant work term is

$$\phi = 1 + C(\Delta - 1) , \quad (13)$$

and the frictional work term is

$$f = (1 + \mu \cot \alpha) . \quad (14)$$

From Eq. (11) it can be seen that the process efficiency depends on only Δ , μ , and α (C is a constant = 0.12 for wire drawing); Δ and α are die design parameters (Fig. 1.22), and μ is the lubricant coefficient of friction, which must be reduced as much as possible.

Although many drawing operations and commercial die designs⁵⁵ use a Δ of about 3, primarily to reduce the effects of friction, there are several disadvantages to Δ values this high:

1. Redundant work is increased [Eq. (13)], which lower efficiency [Eq. (11)].
2. Die wear is increased.
3. As Δ increases above 1, the strain becomes nonuniform and the material center experiences higher stresses than the outer surface.

High Δ drawing stresses the internal TC components more than the sheath, causing failure to occur in one or both TEs. The ensuing troubleshooting to find the TE break(s) is a time-consuming process.

The disadvantage of low Δ drawing is that friction becomes more important because low Δ implies a small die angle α , which yields a large value for $\cot \alpha$. For a large value of $\cot \alpha$, the frictional term in Eq. (14) increases sharply. However, if friction can be controlled, reduction of internal stresses on the TEs will allow increased drawing between anneals as well as decreased incidence in the breakage of TEs.

Based on this analysis, we concluded that a condition in which Δ is close to a value of 1 should approach the optimum for TC drawing, particularly if friction is low.

1.4.3.2.1 Process Development. Groth-Mazur, Inc., had previously fabricated small-diameter TCs by annealing for 6 min at 1000°C after introducing approximately 20% true strain. Figure 1.24 shows the microstructure that resulted from this process. The TE on the right of the figure is the Alumei alloy. The grain size of the Alumei alloy was extremely large (ASTM 6) and needed to be reduced to ASTM 7 or smaller to conform to ORNL specifications.

Fig. 1.24. Grain size of vendor-produced 0.51-mm-diam thermocouples before grain size refinement. Chromel (left) and Alumei average grain size is 23 and 47 μm (ASTM 8 and 6), respectively.

A new drawing and annealing schedule to permit this refinement was determined from the recrystallization and drawing literature, information on the TC components,⁵⁶⁻⁵⁷ and industry experience. The development consisted of three general tasks:

1. adjust annealing conditions to minimize grain growth of the Alumel TE while still obtaining full recrystallization of the Inconel sheath and Chromel TE;
2. define the drawing process in terms of Eq. (11); and
3. determine a new process to maximize the reduction between anneals by optimizing process parameters α , Δ , and μ and comparing draw and material stress σ_d and σ_c .

Optimum annealing conditions were determined by drawing annealed samples of Chromel and Alumel wire, and of assembled TCs, to 20 to 50% reduction [as defined in Eq. (7)], followed by annealing at several time-temperature conditions. Elongation to failure tests and metallographic and microhardness examination of annealed samples were also used. Optimum annealing conditions were found to be about 1025°C for 60 s for a 1-mm-diam TC. The annealing temperature was then held constant and the time varied to account for TC mass-per-unit-length changes with diameter. Annealing times ranged from 120 s at 2.7-mm diameter to 30 s at 0.5-mm diameter.

Task two consisted of evaluating the TC system to determine the applicability of Eq. (11), determining methods to measure σ_d and σ_c , and examining the existing process in terms of Eq. (11).

The application of Eq. (11) to this process depends on the assumptions that the materials (Chromel, Alumel, and Inconel) obey the strain hardening law given by Eq. (4), and that $C = 0.12$ for wire applies to this system. Stress-strain measurements were made on each of the components and on TC samples. Strain hardening behavior was verified; the strain hardening exponents were calculated and are given in Table 1.12.

The equivalence of behavior between wire and the small-diameter TC for the CFTL FRS appears to be valid after the electrical insulation has achieved maximum density, at which condition the insulation volume remains constant. The stress is then based only on the cross section of the metallic components, and the insulation transmits the compressive forces homogeneously from the sheath to TEs.

Table 1.12. Strain hardening exponent values for type K thermocouple components

Material	Strain hardening exponent n
Chromel	0.37
Alumel	0.30
Inconel	0.31
Type K thermocouple, MgO insulator	0.31

The draw stress $\sigma_d = F_d/A_1$ was measured with a standard spring balance placed between the draw bench puller jaws and the TC. The value of material stress σ_c was measured by Green's method,⁵⁸ wherein samples of drawn material are pulled in tension until failure. The stress to yield was then taken as σ_c .

Although little information was available on GMI's dies, we determined that they had used a die draw angle α of 12° and achieved area reductions of 20 to 25%. Drawing tests indicated a maximum reduction of 30 to 35%, in which σ_d exceeded σ_c , resulting in material failing. Efficiency η was calculated from Eq. (6) to be about 33%. This amount of reduction with the selected annealing schedule produced 0.5-mm-diam TCs having a maximum grain size of ASTM 7 to 7.5. However below about 1-mm TC diameter, it was not possible to obtain EMLs longer than a few meters because of TE breakage. We concluded that the combination of low efficiency and probable high Δ prevented further improvement with GMI's existing dies.

Task three, process parameter optimization, was initiated with the design of new dies in an effort to optimize draw stress and the draw die parameter Δ , which relates mean die diameter $\bar{d}$ and die length or thickness L . Wistreich⁵⁹ measured minima in the relationship of draw stress versus die angle based on this relationship. Figure 1.25 reproduces this σ , ϵ dependence for these minima. Wright⁵⁵ provides a table of Δ values as a function of α and ϵ . Figure 1.26 represents this in a manner consistent with Fig. 1.25 so that α and Δ can be determined and specified for the desired reduction ϵ .

Fig. 1.25. Optimized die angle versus drawing reduction.

Fig. 1.26. Die design parameter Δ range for various drawing reduction and die angle combinations.

New dies were designed and ordered on the basis of Figs. 1.25 and 1.26. No attempt was made to examine lubricants to optimize μ . For a reduction range of 35 to 45%, α was specified to be 16° and Δ less than 1.6. An attempt was made to minimize friction by limiting the die relief region to $0.15 L$ (Fig. 1.22).

The process was then optimized with the new dies by comparing σ_u and σ_e as before. Table 1.13 summarizes this process. Reductions of 40 to 45% were achieved. The efficiency was calculated from Eq. (6) to be as high as 45%, and the final maximum grain size was ASTM 8.5 to 9. Although BFL lengths up to 140 m were drawn without TC sheath breakage or TE opens occurring, consistent drawings of long lengths have not been demonstrated. Further development now in progress should permit us to draw long lengths.

Figure 1.27 shows the microstructure of the Chromel and Alumel TEs produced by this process.

Table 1.13. Draw-anneal schedule for CFTL thermocouples

Draw diameter (mm)	Reduction between anneals (%)	Anneal time at 1025°C (s)
2.71	~46.5	120
2.18	43.7	120
1.75	44.0	120
1.42	41.8	102
1.16	42.9	102
0.93	42.8	90
0.76	40.0	60
0.62	40.5	45
0.50	40.6	30

Fig. 1.27. Chromel (left) and Alumel average grain size is 9 and 17 μm (ASIM 11 and 9), respectively, after grain size refinement.

1.4.3.2.3 Conclusions. Premature failure of small-diameter TCs used in the prototypes of CFTL FRSs required an investigation into the causes of failure and the ways to improve lifetime. Failure was judged to be caused by grain boundary growth and growth of voids at the TE grain boundaries. Both of these phenomena result from the introduction of a small amount of cold work (prestrain) in the TC before installation into the FRS. These growth effects embrittled the TCs and caused open circuits when thermal expansion mismatch between the TCs and FRS cladding produced relatively small axial strains on the TE. Contributing factors were (1) oxidation of the chromium and aluminum in the TEs, causing further embrittlement as well as temperature measuring errors, and (2) large grains resulting in reduced strength of the TEs.

Significant improvements in lifetime were demonstrated simply by eliminating small amounts of cold work in the material by a recovery anneal before use. However, three characteristics were finally established as important to lifetime while also enhancing measurement accuracy:

1. minimization of the introduction of oxygen, moisture, and hydroxides during IC fabrication;
2. refinement of the TE grain size equal to or smaller than ASTM micrograin size 9; and
3. complete elimination of prestrain in TC materials before operation above their recrystallization temperature.

A fabrication process was developed in conjunction with GMI that resulted in a maximum ASTM micrograin size of 8.5 in TE samples. All three suggested improvements were incorporated into the specification for procurement of CFTL TCs.

Successful grain size refinement and production of 100-m and longer lengths of BML were accomplished with draw dies having a low value of Δ . A low value of Δ reduced the internal stresses imposed on TEs during drawing and decreased TE breakage sufficiently that sheath breakage became the dominant failure mode. Process optimization consisted of measuring and comparing the draw stress σ_d and the material failure stress σ_c to obtain maximum reduction and at the same time to avoid the breakage that occurs when σ_d is permitted to exceed σ_c . The process efficiency was improved from 33 to 45%.

Further grain size refinement and/or reduced process costs should be possible by optimizing the drawing process with respect to the lubricant.

1.4.4 Development in Support of Test Bundle Design — H. C. Young

A technique for joining the FRS cladding⁶⁰ to the tubesheet by gas tungsten arc (GTA) welding with a precision weld head was developed by the Metals and Ceramics Division (M&C). Prior to cancellation of test bundle AG1, plans were that M&C would lend a GTA programmable power supply and precision welding head to the CFTL project and would provide training for Y-12 craft welders to perform the joining. Thus, the actual cladding-to-tubesheet welding would be performed near the CFTL site.

While electron beam welding (EBW) was also applicable, it would have required transporting the large bundle and holding fixture back and forth across the continent to available EBW vacuum chambers. Such transport and associated handling can provide great opportunity for damage.

Initial practice brazing of the electrical power leads to the two concentric terminals on each FRS indicated that manual brazing methods were not feasible because good quality was not dependably reproducible. Early tests with the GTA precision weld head indicated feasibility, but further development was needed. As the design of bundle AG1 neared completion, details of the support configuration and all clearance dimensions for the heavy copper leads from each FRS electrical terminal were better defined. A full-scale mockup of about a 60° segment of the test bundle above the tubesheet was fabricated. A special drilled jig plate was fabricated for aligning the GTA welding head precisely to the electrical connectors. This mockup realistically simulated the most difficult space constrictions to be encountered by the craft workers during brazing the FRS electrical connectors in an actual bundle. Enough electrical connectors were brazed with the GTA precision weld head to demonstrate that the brazing technique was satisfactory.

1.4.4.1 Joining Fuel Rod Simulator Cladding to the Tubesheet — A. J. Moorhead

The FRSs for the GCFR fuel test bundles⁶¹ are closely packed on a triangular pitch of 11.2 mm (0.441 in.) in the tubesheet, which establishes the bundle configuration as shown in a plan layout in Fig. 1.28. The FRS cladding must be joined and sealed to the tubesheet, which also serves as a portion of the CFTL pressure boundary. The small pitch distance, the diameter and cladding thickness of the FRS, and the extended lengths of the two concentric electrical terminals on the FRS leave little room for the equipment needed to make the cladding-to-tubesheet joint and, in addition, introduced significant complexity into our development efforts.

It is possible to transport an entire LMFBR-THORS test bundle⁶² to the West Coast to make the cladding-to-tubesheet joint with EBW in an available vacuum facility. However, the greatly increased length and weight of the GCFR test bundle, the heavy weight of its transport and assembly fixture, the opportunities for damage during transcontinental transport, and the desire to increase direct control of the process indicated the need to develop an alternate to the EBW joining method.

Fig. 1.28. Plan layout of approximately one-sixth of a 91-rod bundle assembly (85 rods powered) of fuel rod simulators for the Core Flow Test Loop.

Consideration of the various geometric constraints on the weldment indicated that no available commercial GTA torch could do the job. We then set out to develop an electrode carrier for this particular application. The starting point was a commercial welding head (Fig. 1.29) that we used extensively in developing techniques for tube-to-tubesheet welding inside the confining bore of a 15.88-mm-OD (0.625-in.), 2.84-mm-wall (0.112-in.) tube. This welding head provides rotary movement of a tungsten electrode along a weld joint by use of a hollow copper electrode carrier, which also conducts an inert shielding gas to protect the weldment from contamination. The rotation speed of the welding tip and the welding current cycle are precisely controlled through a 200-A dc solid state programmable power supply.

On the basis of prior experience we selected a trepanned joint design (Fig. 1.30) for preliminary development. This design has several advantages: (1) the groove corrects the mass imbalance (and thus the differing heat requirements) between the large tubesheet and the thin wall of the

Fig. 1.29. Commercially made welding head modified for welding and brazing of fuel rod simulators.

simulator, (2) the resultant edge joint is readily weldable, and (3) cutting away the projecting weld bead for simulator removal and replacement without having to deepen the trepan is relatively easy. This type of weld is difficult to inspect volumetrically and has a built-in crevice at the root of the joint. However, as in the previous work,⁶² the surface of the tubesheet will be overlaid with type 308 stainless steel filler metal to minimize any hot-cracking tendencies in the weldments.

Our preliminary calculations on the size of a hollow electrode carrier that would clear both the central power leads wrapped with TCs and the adjacent simulators showed that even the diameter of the tungsten electrode required to carry adequate current was a factor in our design. We therefore made some welds with a manual GTA torch on two pieces of 0.51-mm (0.020-in.) stainless steel sheet clamped together in a vise to simulate the 1.02-mm (0.040-in.) edge joint. Welding currents of only 10 to 15 A were required. These low currents permitted the use of a 0.51-mm-diam (0.020-in.) tungsten electrode, and we designed our tip for that size.

We also calculated that the electrode had to be angled slightly toward the central axis to center the arc over the 7.47-mm-diam (0.294-in.) simulator cladding. We therefore designed and built our first

Fig. 1.30. Joint design used in developing techniques for attachment of fuel rod simulators to the tubesheet of a test bundle.

electrode carrier according to the design shown in Fig. 1.31 with holes in the tip to contain a 0.51-mm-diam (0.020-in.) tungsten electrode set at a 16° angle.

We subsequently made a series of welds on single-joint prototypes in which the space envelope of the copper leads wrapped with TCs and a potential cable connector were represented by a stainless steel shaft. The quality of these very early welds was excellent, as determined by visual examination for bead geometry, helium mass spectrometric leak detection, and metallographic examination.

Because of the high degree of success in these early welds, which were made to develop basic parameters, only one significant change has been made in the general design of the electrode carrier. We were not pleased with the degree of protection of the electrode from atmospheric contamination. Therefore, we modified the carrier by adding four radial holes connected to shallow longitudinal grooves on the outside of the tip,

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Fig. 1.31. Original design of tungsten electrode carrier for arc welding of simulators to the tubesheet.

as shown in Fig. 1.32. This allows inert gas to flow from the bore of the carrier out between the tip and the fused quartz gas cup and results in improved gas coverage of the weldment. To prevent aspiration of air from the closed end of the gas cup, we sealed this area with silicone rubber compound.

The next step in our efforts to develop an alternate to the EBW method for joining the FRS to a bundle tubesheet was to demonstrate that high-quality welds could be made consistently under the space limitations of an actual array of simulators. During the welding of the first of the seven-rod test assemblies (one is shown before welding in Fig. 1.33), we encountered a problem that has been the most difficult to solve in the entire welding study: the arcing from the bore of the copper electrode carrier to the TCs, which are stored during the welding process by wrapping them around the cylindrical terminals of the FRS. This is very significant because it results in the destruction of one or more of the sensors that will eventually be used to monitor the temperatures inside the FRS during test operation. Furthermore, these temperature measurements are critical to the successful test operation of the bundle.

We were aware of this potential problem from the beginning of this program and had therefore designed our electrode carrier to maximize the

Fig. 1.32. Final design of tungsten electrode carrier with addition of longitudinal grooves connected to radial hole: (high-lighted by arrow) for improved inert gas coverage. The part being welded was instrumented with thermocouples in the weld area to monitor the temperature of the spirally wrapped thermocouples in an actual fuel rod simulator.

distance between the carrier bore and the TCs. The inside diameter of the electrode carrier was machined to 7.24 mm (0.285 in.) so that the distance between the inside diameter of the carrier and the outside of the TCs wound on the electrical terminal [a diameter of about 5.3 mm (0.21 in.)] would be greater than the 0.51-mm (0.020-in.) arc length. With these dimensions the radial separation is 0.97 mm (0.038 in.), and we expected the arc to strike across the shorter distance to the weld joint. However, at this time arcing was to the TCs at the point where they exit from the top of the FRSs just before starting the spiral wrap around the larger terminal (as indicated by the arrow in Fig. 1.33). The spacing may have been less at that location (or we could attribute the behavior to the vagaries of the arc during high-frequency initiation).

Our solution to the arcing problem involved installing a very thin-wall quartz sleeve over the electrical terminals and the wrapped TCs at

Fig. 1.33. Seven-rod test piece being assembled for gas tungsten arc welding. The parts representing the fuel rod simulators are 9.52 mm (0.375 in.) in diameter. The arrow indicates where we had problems with arcing to the thermocouple.

the entrant end of the FRS (Fig. 1.34) to insulate them from arcing. The sleeve, which we made in our glass shop, is about 25 mm (1 in.) long and extends below the weld area and down into the open end of the FRS.

Although the quartz sleeves eliminated arcing in the weld area and along the length [25 mm (1 in.)] of the test terminals, the problem recurred when we began welding multirod assemblies with the bundle design terminal length of 114 mm (4.5 in.). We tried to use heat-shrinkable tubing over the portion of the terminal and TCs extending beyond the quartz sleeve, but arcing occurred where there was a slight gap at the intersection of the two insulators. The inside of the electrode carrier was coated with an insulating paint (Glyptal) and a polymer film, but we were unable to obtain a layer of adequate quality to prevent arcing during high-frequency initiation of the arc. The problem was finally resolved by

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Fig. 1.34. Quartz sleeve used to protect the thermocouples of a fuel rod simulator from arc damage during welding.

wrapping the extension terminal (from beneath the quartz sleeve out to the tip) with at least two layers of the very thin polytetrafluoroethylene (PTFE) tape used by plumbers as a pipe thread seal.

After these developmental activities, two seven-rod test assemblies were welded. One had 7.47-mm-diam (0.294-in.) simulated FRSs, and the other had an FRS diameter of 9.52 mm (0.375 in.) to evaluate a concept in which the end of the FRS would be flared in the weld joint area. These assemblies (which had type 316 stainless steel simulator cladding material and a type 308 welded layer on the tubesheet) were checked for leakage by helium mass spectrometry. The assemblies were then GTA-welded into test modules such as the one shown in Fig. 1.35. Testing consisted of thermally cycling 500 times from 370°C (698°F) down to 100°C (212°F) with an internal pressure of 11.7 MPa (1700 psi). Once during each thermal cycle the pressure was briefly dropped to 0.34 MPa (50 psi). No leakage was detected in either assembly (as determined by helium mass spectrometry) either before or after this extensive test series.

After completion of the thermal and pressure cycle tests, the assemblies were sectioned for metallographic examination. Photomicrographs (Fig. 1.36) indicate no discernable detrimental effects as a result of these tests.

As a result of this development effort, the GTA welding process was selected over the EBW process for making the FRS cladding-to-tubesheet joint. The welders at the CFTL site can be trained by personnel from the ORNL Metals and Ceramics Division to perform the work.

Fig. 1.35. Seven-rod test assembly [7.47-mm-diam (0.294-in.) simulators] after 500 thermal cycles between 370 and 100°C (698 and 212°F) with an internal pressure of 11.7 MPa (1700 psi). The simulators were machined from type 316 stainless steel bar, and the tubesheet was type 304L bar gas tungsten arc weld surfaced with type 308 filler metal before machining the joint area.

Fig. 1.36. Cross section of gas tungsten arc weldment in a seven-rod test assembly with 7.47-mm-diam (0.294-in.) type 316 stainless steel simulator and a type 304 stainless steel tubesheet, which was surfaced with type 308 filler metal to minimize hot-cracking tendencies. Etchant: 50 HCl, 10 HNO₃.

1.4.4.2 Electrical Connectors for Fuel Rod Simulators — A. J. Moorhead and H. C. Young

The task of joining the electrical supply leads to the terminals on the FRSs is complicated by the close-packed array of the FRSs in the GCPR test bundles and by the design in which two concentric terminals are located at one end of the FRS. The former limits seriously the working space, and the latter requires making two different in-line connections for each FRS. The need to consider the connections between the FRS internal TCs and the leads that complete the circuit to the data acquisition system lends further complexity to the task.

Several different techniques for making the connections were considered, including mechanical clamps and shape-memory alloy couplings. Some preliminary manual brazing with a GTA torch heating source was tried by the CFTL project. Although brazing appeared to be the best joining method, manual brazing could not provide the repeatability and the quality required.

The Metals and Ceramics Division continued work on the brazing technique considered to be most promising: automatic brazing with a GTA heating source and a special electrode carrier similar to the one developed for making the FRS cladding-to-tubesheet joint (Sect. 1.4.4.1). This technique permits making low-resistance connections with high-temperature capability at locations having limited access and to do so without problems of temperature control and heat-source positioning associated with manual torch brazing. Compared with the oxygen torch, the inert gas heating torch permits making the braze without the flux that is commonly used to protect the joint from atmospheric contamination. This eliminates both flux removal and consequential corrosion problems.

The electrode carrier designed especially for this application is shown in the center of Fig. 1.37 along with one of the shorter tips used for welding. Because the lengths of the terminals above the tubesheet had not been determined, we developed techniques to accommodate various lengths by using either long or short electrodes and gas cups, also shown in Fig. 1.37.

We considered and tested several different lead configurations. The design shown in Fig. 1.38 is currently the most favored. To use this geometry the foot (indicated by an arrow in Fig. 1.39) is first brazed to

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Fig. 1.37. Tungsten electrode carriers developed for welding (right) and brazing of electrical leads to terminals extending from fuel rod simulators (left). Also shown are three fused quartz gas cups to maintain inert gas in the joint area during heating.

a straight length of 5.18-mm-diam (0.204-in.) copper wire in a furnace. After bending to the proper radius (depending on the position of its FRS in the bundle), the subassembly is brazed to the tubular outer terminal of the FRS. The connection to the central terminal, a solid round rod, is also made by brazing with a special GTA heating source in which the electrode is held radially in the copper carrier. Brazed connectors of both types are shown in Fig. 1.39. Because of space limitations we were unable to design a foot of such size that the arc could be rotated in a circle around the tubular conductor. Instead, the arc is held stationary at the point indicated by the asterisk in Fig. 1.38, while the braze cycle is controlled by the programmable power supply.

We considered several different brazing filler metals as potential candidates for this application and have selected two. For the furnace braze of the foot to the end of the 5.18-mm-diam (0.204-in.) copper lead, which will connect to the outer terminal of the FRS, we have had good

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Fig. 1.38. Designs of electrical leads for the CFIL showing the one for the outer tubular terminal (right) and the one for the central rod terminal (left). The location of the stationary tungsten arc on the foot of the outer lead during brazing is indicated by an asterisk.

success with AWS-ASTM type BAu-4 wire (composition Au-18% Ni). This alloy, which flows well on copper, has a liquidus of 950°C (1742°F). We have also obtained good results with type BVAg-8b (an alloy having a composition of Ag-28% Cu-0.5% Ni) for the actual attachment of the foot and center lead to the respective FRS terminals. The 795°C (1463°F) liquidus of this alloy is sufficiently lower than the liquidus of the BAu-4 in the first braze that we have not experienced remelting problems when the

PHOTO 7652-80

Fig. 1.39. Electrical leads brazed to inner (above) and outer (below) fuel rod simulator terminations with a gas tungsten arc heat source and a brazing filler metal of Ag-28% Cu-0.5% Ni. The foot (arrow) of the lead for the outer termination is vacuum-furnace-brazed to the lead with Au-18% Ni filler metal.

second of these brazes is made. We chose the alloy with a slight amount of nickel rather than the Ag-28% Cu eutectic, which also flows well on copper, because the nickel improves wetting on oxide-bearing surfaces (such as on stainless steels). We thought that this alloy would therefore be more likely to flow on slightly oxidized copper parts resulting from incomplete inert gas coverage during heating.

To demonstrate that this brazing technique was applicable to multirod bundles as well as to a single rod, the mockup shown in Fig. 1.40 was constructed. The mockup simulates a 16-rod segment of a test bundle with provisions for attaching leads to six of the FRSSs. The space limitations provided by the other simulators in an actual bundle are represented by brass rods machined in the shape of the copper electrical conductors. The method of aligning and supporting the GTA automatic weld head is shown in Fig. 1.41.

PHOTO 5827-80

Fig. 1.40. Full-scale mockup of approximately 60° segment of CFTL bundle above the tubesheet. For demonstrating automatic brazing of electrical supply leads to fuel rod simulator terminals.

Two problems were encountered in brazing the leads to the FRS terminals in the full-scale mockup. First, we had instances in which the arc would wander from its intended impingement point on the foot of the lead to the tubular terminal. This resulted in a hole being melted in the 0.25-mm-thick (0.010-in.) wall of the tubular outer terminal of the FRS. This behavior was eliminated by inserting a short, thin-wall quartz sleeve around the end of the outer terminal that projected above the foot.

Fig. 1.41. Jig plate used for precisely aligning the automatic welding head gas tungsten arc for brazing electrical supply leads to fuel rod simulator terminals in full-scale mockup of approximately 60° segment of CFTL bundle. Region shown is above tubesheet.

The second problem was in providing adequate inert-gas shielding during brazing. If this is not done, an oxide layer tends to form on the copper components, and the brazing filler and the alloy will not flow, even at elevated temperatures. This problem was resolved by sealing the glass enclosure shown in Fig. 1.42 around the components as carefully as practical and filling the volume with argon to minimize the influx of air.

PHOTO 5829-80

Fig. 1.42. Copper leads in position for brazing to conductors from fuel rod simulators with gas tungsten arc heat source (arrow). The glass enclosure has been opened for clarity.

The GTA torch heat source provided good brazing of supply leads to FRS terminals for both single-rod and multirod configurations. The GTA torch was selected for this duty with the proviso that a 37-rod mockup of the GCFR bundle AG1 would be tested-brazed satisfactorily. The test brazing would be performed by Y-12 craft personnel after a period of training by ORNL Metals and Ceramics Division personnel.

1.4.5 Test Bundle Procurement — H. C. Young

The fabrication of some of the parts⁶³ for test bundle AG1 had been completed by GA when the GCFR program was halted in 1980. These parts, which were received from GA and will be held in storage in CFTL cage 8 in Building 9201-3, Y-12 Plant, through FY 1981 include: 1 lot of parts for hanger rods, 13 spacer grids, 15 load pads for the hexagonal flow duct,

and 64 acceptable, and 19 rejected, ribbed claddings for FRS. An extended delivery date into 1981 caused GA to cancel its order for the hexagonal flow duct.

We performed extensive ultrasonic examinations on, and evaluated, 94 smooth (unroughened or unribbed) claddings supplied by GA for use in fabricating FRSs for bundle AG1. Of the 94 claddings, 64 were accepted and 30 were rejected.

The original bar stock for the claddings, which was provided by Hanford Engineering Development Laboratory (HEDL), was gun-drilled by Clark and Wheeler Engineering of Cerritos, California, and then drawn by Palomar Precision Tubes, Inc., of El Cajon, California. The smooth claddings were subjected to ultrasonic inspection by TAC Technical Instrument Company (TAC/TIC) of Trenton, New Jersey. This inspection indicated a sufficient amount of "noise" to mask the identification of defects even larger than the criteria for rejection. It was at this juncture that ORNL offered to perform the additional ultrasonic examination and evaluation reported above.

A total of 83 claddings, including the 64 acceptable, were ribbed at Rosan, Inc., New Port Beach, California, by GA. The rejected claddings were utilized for development work at GA, for development of the GCFR FRS at ORNL, and for the pressure-drop and heat-transfer investigation made by KfK (Kernforschungszentrum, Karlsruhe, West Germany).

The engineer responsible for development of the GCFR FRS at ORNL witnessed both the ribbing and the quality control inspections of enough claddings to gain confidence in the Rosan product. General Atomic Company inspected all the ribbed claddings and subsequently shipped a total of 83 to ORNL, which included the 64 acceptable and 19 rejected claddings. The ribbed claddings are in storage in CFTL cage B in Building 9201-3, Y-12 Plant.

Small-diameter TCs for installation inside the FRS for bundle AG1 were ordered in January 1979. The lengths and quantities on order were changed several times to accommodate revisions to the bundle design based on changes made to the GCFR core design.

A drawing and annealing schedule for minimizing both the grain size of, and the cold work in the TEs was carried to a successful conclusion as a cooperative effort between ORNL and the TC manufacturer.

Since there is no specific need for the TCs as ordered, 1370 m (4500 ft) of EML was purchased from the CFTL project by the thermocouple procurement group in the Instrumentation and Controls Division for general use.

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2. GCFR SHIELDING AND PHYSICS

D. E. Bartine

2.1 INTRODUCTION

Activities performed in the Gas-Cooled Fast Reactor (GCFR) Shielding and Physics Program since December 31, 1979, have included completing the postanalysis of the Tower Shielding Facility (TSF) experiment to confirm the design of the GCFR radial blanket and shield; performing two TSF plenum shield experiments and their associated analyses (the Outer Radial Shield Heterogeneity Experiment and the Exit Shield Experiment); and preparing a report summarizing all the TSF experiments (and their analyses) performed during the five-year ORNL-GCFR shielding program. In addition, further analysis work was performed in support of the Conceptual Upflow Shielding Configuration III, and several reports on earlier work were published.

2.2 POSTANALYSIS OF RADIAL BLANKET AND SHIELD EXPERIMENT — D. T. Ingersoll

The integral experiment performed at the TSF to verify the radiation transport methods and nuclear data used for the design of the radial blanket and shield for the proposed 300-MW(e) GCFR and the postanalysis that had been completed to that date were described in the previous progress report.¹ Since that time the postanalysis has been completed, and final reports on both the experiment and the analysis have been issued.^{2,3} The experimental configurations consisted basically of rockups of the region of the GCFR Conceptual Shielding Configuration I extending from the inner surface of the thorium blanket, through the inner and outer radial shields, and into a portion of the prestressed concrete reactor vessel (PCRv). In the Conceptual Shielding Configuration I design the first row of the inner shield (to be replaced every three years) consists of boronated graphite clad with stainless steel, and the second row (to be replaced every six years) consists entirely of stainless steel. The permanent outer shield consists of graphite bound on each side by boronated graphite and clad with stainless steel.

With a modified spectrum of Tower Shielding Reactor II (TSR-II) neutrons used as the source, the first experimental configuration consisted of a mockup of one-half the first row of the ThO_2 blanket, the second consisted of a mockup of a full row of the blanket, the third consisted of two rows, etc. As sections were added, neutron and gamma-ray flux measurements were made beyond the configurations, and gamma-ray heating measurements were made within the configurations. The experiment also included alternative configurations in which a UO_2 blanket and/or different radial shields were used.

In the design of the Conceptual Shielding Configuration I shield, the uncertainties of most concern were those associated with the neutron cross sections used for the graphite, boronated graphite, and thorium regions. As a result, the analysis of the experiment was expanded to include detailed investigations of cross section effects. Although the GCFR program had been suspended as this work was nearing completion, most of the conclusions of the radial blanket and shield experiment (summarized in the next several paragraphs) are of generic value.

First, we found that the neutron transmission through ThO_2 could be predicted to within the same accuracy that the experimental transmission could be measured (5–20%). Also, neutron transmission through UO_2 was underpredicted, but not by more than 30%. Comparisons of calculated and measured neutron spectra beyond the two blanket materials showed fairly good agreement; however, the calculated spectrum for ThO_2 was slightly higher than was the measured spectrum. When ENDF/B-V cross sections for thorium were substituted for the ENDF/B-IV cross sections used throughout the analysis, the calculated spectrum moved closer to the measured spectrum, especially in the 0.1- to 3-MeV region.

The predicted gamma-ray heating rates for void regions distributed in the ThO_2 and UO_2 blankets agreed with the measured heating rates within the estimated uncertainties of 5 to 15%; however, the agreement for the ThO_2 blanket occurred only after the ENDF/B-V gamma-ray production cross sections for thorium were substituted into the calculation.

In contrast with the heating rates, the gamma-ray energy spectra at locations beyond the blankets were underpredicted, severely so for the ThO_2 blanket, with no significant improvements when ENDF/B-V cross sections

were used. The large underpredictions also occurred beyond the configurations that were extended with shield materials, and a subsequent investigation indicated that the experimental design was poor for gamma-ray spectral measurements outside the configuration. Specifically, a lithiated paraffin layer surrounding the configuration provided a channel for gamma rays that competed with the gamma rays emerging from the configuration proper.

The calculated neutron transmission through the inner and outer shields generally agreed with the measured transmission to within 15%. However, the attenuating characteristics of laminated shields that contained boron were dramatically affected by the spectral characteristics of the incident flux. In particular, the attenuation factors for the full radial shield (as determined from Bonner ball responses) were higher by factors of 3 to 6 when the incident neutrons had emerged from the ThO_2 blanket rather than from the spectrum modifier simulating the GCFR core spectrum. The shield was also 5 to 15% more effective with a preceding ThO_2 blanket than with a preceding UO_2 blanket.

In summary, the GCFR radial shield confirmation experiment and its analysis have shown that a capability exists for accurately predicting (1) the neutron transmission through thick UO_2 and ThO_2 blankets and laminated shields containing steel, graphite, and boronated graphite; (2) the gamma-ray heating rates within the configurations; and (3) the neutron spectra beyond the configurations. The experiment and analysis have also confirmed the necessity of using the proper source spectrum in an experiment. And, finally, they have shown that, if an experiment is to include gamma-ray spectral measurements outside the configuration, special additional design considerations will be necessary.

2.3 OUTER RADIAL SHIELD HETEROGENEITY EXPERIMENT — F. J. Muckenthaler, L. R. Williams, and M. B. Emmett

In the experiment discussed above, the outer radial shield in the Conceptual Shielding Configuration I design was mocked up with solid pieces of graphite to simplify the geometry of the thick region between the core and the PCRV. In the actual design, however, the outer radial shield will consist of several interwoven pieces of graphite separated by

voids and enclosed in stainless steel envelopes (Fig. 2.1). It was therefore desirable to (1) study the effects of neutron streaming through shield heterogeneities typical of those that might be present in the actual shield and (2) provide a benchmark against which the analytical methods used to design the shields could be tested. The experiment was performed in the summer of 1980, and the analysis was completed in June 1981.

The experimental configurations consisted of graphite pieces with and without carbon steel linings and arranged so that straight or stepped neutron streaming paths of variable width extended through them. In each case the configuration was preceded by a spectrum modifier consisting of 10 cm of iron, 2.54 cm of boral, and 10.2 cm of UO_2 , which preanalysis calculations had shown would convert the energy spectrum of the TS&II neutron beam to a spectrum typical of that incident on the GCFR radial shield. Sketches of the configurations are shown in Figs. 2.2 through 2.5.

Fig. 2.1. Cross section through GCFR midplane. (See stepped slits through outer radial shield.)

Fig. 2.2. Mockup of outer radial shield with single slit: Configuration I.

Fig. 2.3. Mockup of outer radial shield with iron-lined single slit: Configuration II.

**Fig. 2.5. Mockup of outer radial shield with single stepped site:
Configuration IV.**

The measurements beyond each configuration consisted of radial traverses in the horizontal midplane of the configuration with Bonner balls and the Hornyak button. Traverses with the Hornyak button and the 2-in. Bonner ball were made immediately behind the configurations, and traverses with all the detectors (these two plus the 5- and 10-in. Bonner balls) were made at a distance of 30.5 cm beyond the configurations.

Plots of Hornyak button and 2-in. Bonner ball responses obtained during horizontal traverses directly behind Configuration IV are shown in Figs. 2.6 and 2.7, respectively. Noting that, in general, the Hornyak button represents the fast-neutron flux and the 2-in. Bonner ball represents the low-energy flux, one sees that the presence of the slit, even with the offset, obviously enhances neutron streaming through the shield at all energies. The broadness of the peaks, especially for the wider slits, indicates considerable scattering off the right face of the exit slit. Also, the abrupt change in the slopes of the curves as the detectors move away from the slit to the north is indicative of the geometry of the mockup where the radial slit gives way to solid graphite. The fact that only a slight rise in the fast-neutron dose occurs opposite the entry slit indicates that what streaming exists in the entry slit is completely masked by the graphite wall.

As would be expected, the presence of a straight slit through the graphite (as in Configuration I) leads to a sharp increase in the transmission of high-energy neutrons at the slit location (by a factor of 2.8 for the 1.27-cm-wide slit) and to a lesser increase in the transmission of low-energy neutrons. When the straight slit is lined with iron (Configuration II), the high-energy transmission through the slit does not appear to be affected, the increases through a 1.27-cm-wide slit again being a factor of 2.8 over that for the no-slit case. But introducing parallel slits on each side of the primary slit (as in Configuration III) does affect the transmission through the primary slit; for the case of the 1.27-cm-wide primary slit, the transmission is higher by a factor of 5.5 over that in the no-slit case. In addition, the transmission through the side slits themselves (each 0.635 cm wide) is a factor of 3 higher than that for the no-slit case. Thus, the combination of slits appears to be an important design consideration.

Fig. 2.6. Radial traverses with Hornyak button directly behind Configurations IV.

Fig. 2.7. Radial traverses with 2-in. Bonner ball directly behind Configurations IV.

Analysis of the experiment was performed both with the DOT discrete ordinates code and with the MORSE Monte Carlo code. Typical results are presented in Tables 2.1 and 2.2 for the 2- and 5-in. Bonner ball responses. (The 5-in. Bonner ball responses represent the total neutron flux.) The DOT results and the measurements agree within 20%, with some notable exceptions. In particular, the calculations yield significantly higher results for the iron-lined straight slit (Configuration II). In general, the MORSE results and the measured results are in poor agreement, but curtailment of the GCFR program will not permit a detailed investigation of the reasons why.

Details of this experiment have been reported in a topical report,⁴ and both the experiment and the analysis are described in a report that reviews all the TSF-GCFR experiments.⁵

Table 2.1. Comparison of DOT-calculated and measured Bonner ball responses 30.5 cm beyond various TSF configurations mocking up heterogeneities in GCFR radial shield

Detector distance from slit centerline (cm)	Detector response, counts/s·W					
	2-in. Bonner ball			5-in. Bonner ball		
	Calc.	Meas.	Calc./Meas.	Calc.	Meas.	Calc./Meas.
<i>Configuration I.E, single slit</i>						
0.0	65.0	62.7	1.04	1499	1530	0.89
2.5	68.0	62.3	1.09	1600	1530	1.05
5.0	30.0	62.9	1.27	2000	1430	1.40
<i>Configuration II.C, single slit with iron liners</i>						
0.0	43.0	40.2	1.07	1065	836	1.27
2.5	45.0	39.2	1.15	1090	831	1.31
5.0	46.4	39.2	1.18	1290	790	1.63
<i>Configuration III.B, three slits with iron liners</i>						
0.0	47.0	40.3	1.17	1000	881	1.14
2.0	45.0	40.3	1.12			
3.0				980	856	1.14
5.0	45.0	39.7	1.13			
<i>Configuration IV.C, single offset slit</i>						
0.0	65.0	61.1	1.06	1167	1090	1.07
2.5	69.2	62.3	1.11	1283	1110	1.16
5.0	75.0	63.4	1.18	1467	1160	1.26

Table 2.2. Comparison of MORSE-calculated and measured Bonner ball responses 30.5 cm beyond various TSF configurations mocking up heterogeneities in GCFR radial shield

Detector distance from slit centerline (cm)	Detector response, counts/s·W					
	2-in. Bonner ball			5-in. Bonner ball		
	Calc.	Meas.	Calc./Meas.	Calc.	Meas.	Calc./Meas.
<i>Configuration I.E, single slit</i>						
0.0	64.2	62.7	1.02	1988	1580	1.26
2.5	65.2	62.3	1.05	2012	1530	1.32
5.0	65.9	62.9	1.05	1752	1430	1.23
<i>Configuration II.C, single slit with iron liners</i>						
0.0	9.74	40.2	0.242	878	836	1.05
2.0		39.2		732	831	0.88
5.0	5.61	39.2	0.114	506	790	0.64
<i>Configuration III.B, three slits with iron liners</i>						
0.0	21.0	40.3	0.52	669	881	0.76
2.0	17.3	40.3	0.43			
3.0				425	856	0.50
5.0	15.6	39.7	0.39			
<i>Configuration IV.C, single offset slit</i>						
0.0	90.7	61.1	1.48	1199	1090	1.10
2.5	89.2	62.3	1.43	1208	1110	1.09
5.0	89.9	63.4	1.42	1203	1160	1.04

2.4 EXIT SHIELD EXPERIMENT — F. J. Muckenthaler, D. T. Ingersoll, and S. N. Cramer

The sixth and final experiment in the five-year TSF-GCFR integral shield testing program was performed in the summer of 1980. The experiment simulated that portion of the GCFR plenum shield identified as the "exit shield," so called because it would provide a helium coolant exit path from the core while providing protection for the components in the plenum above the core. The exit shield was designed as an integral part of the reactor core, and, in fact, comprised the upper section of each fuel element. The shield components in each element consisted of two cone-shaped sections of B_4C , which were interfaced at their bases and centered on the fuel element axis (Fig. 2.8).

Fig. 2.8. Schematic of exit shield subassembly.

As in earlier experiments, this one was designed both to test the effectiveness of the shield design and to provide data against which the design methods could be checked (through analysis of the experiment). The first experimental configuration (Fig. 2.9) consisted of a fueled region mocking up seven GCFR fuel subassemblies, followed by seven exit shield subassemblies. The subassemblies of the two regions were fabricated to the same dimensions so that they would appear as continuous subassemblies separated by coolant flow paths (and neutron streaming paths).

In subsequent configurations the center fuel and shield subassemblies were removed and replaced with a control rod subassembly, the configurations differing in the position of a control rod mockup within the subassembly. In addition, B_4C shielding was sometimes used in the control rod subassembly housing and at other times, was not used. The control rod itself consisted of a 15.9-cm-diam B_4C -filled iron cylinder attached to a

Fig. 2.9. Tower Shielding Facility experimental configuration simulating GCFR fuel and exit shield.

control rod follower of similar composition but with a smaller diameter that decreased gradually to the end. Both the control rod and the control rod follower were fabricated in sections so that they could be used in different lengths to simulate various control rod positions without protruding from the end of the configuration. A sketch of the configuration with a half-inserted control rod is shown in Fig. 2.10. (In the configuration simulating a fully inserted control rod, the thick control rod section would be assumed to be inserted deeper into the core so that the thinner control rod follower would fill most of the experimental configuration.)

During the experiment neutron flux measurements were made beyond each configuration with Bonner balls and the Hornyak button. In addition, neutron spectral measurements were made beyond a few of the configurations.

Because the decision to discontinue the GCFR program had already been made by the time the analysis for this experiment was begun, the analysis

Fig. 2.10. Tower Shielding Facility experimental configuration simulating GCFR fuel and exit shield with half-inserted control rod.

was limited to three of the measured configurations: one that consisted of the fueled region only, one that included the full exit shield (seven subassemblies), and one in which the half-inserted control rod was simulated. All three configurations were analyzed with the DOT discrete ordinates code; the second configuration was also analyzed with the MORSE Monte Carlo code.

Comparisons of the measured and DOT-calculated Hornyak button and Bonner ball responses for the configuration containing the half-inserted control rod are shown in Figs. 2.11 and 2.12, where the sketch at the bottom of each figure represents part of the central control rod subassembly and an adjacent exit shield subassembly. In this case, no B_4C shielding was included in the subassembly housing.

The peaks that occur in the curves for the calculated responses at the exit shield axis result from modeling limitations (difficulties in modeling the interfaced cones as cylindrical annuli); the slight

Fig. 2.11. Comparison of measured and DOT-calculated Hornyak button responses 1.9 cm behind TSF exit shield configuration with half-inserted control rod. (Calculations normalized to measurements at centerline because of normalization problem with Hornyak button response function.)

displacements of the peaks at the edges of the subassemblies also result from modeling limitations. Overall, however, agreement between the measurements and the calculations is good.

Based on these results, we concluded that the exit shield configurations could be calculated, and the remainder of the experiment was interpreted by analogy. The overall conclusions of the experiment were that the GCFR exit shield would be highly effective in protecting the components in the upper plenum region and that the shield would not be compromised by control rod penetrations. In fact, a comparison of the measured neutron fluxes emerging from an exit shield with and without a mockup of a control rod subassembly in the center of the shield shows that, when B_4C shielding was included in the control rod subassembly housing, the flux directly behind the control rod subassembly was lower than that directly behind an exit shield subassembly in the same location for most positions of a control rod mockup within the subassembly. Furthermore, the neutron fluxes emerging from the adjacent exit shields were also reduced.

Fig. 2.12. Comparison of measured and DOT-calculated Bonner ball responses 39.8 cm beyond TSF exit shield configuration with half-inserted control rod. (a) Two-in. Bonner ball. (b) Five-in. Bonner ball.

Detailed descriptions of the measurements and calculations for this experiment have been published.^{6,7}

2.5 DESIGN SUPPORT ANALYSIS FOR GCFR SHIELDING — C. O. Slater,
S. N. Cramer, M. B. Emmett, D. A. Reed, E. T. Tomlinson, and
L. R. Williams

The previous GCFR progress report¹ described the analysis of the shielding design for the preliminary upflow GCFR (Conceptual Shielding Configuration II). This work has since been completed and documented.⁸ Also mentioned in the earlier report was the initiation of the analysis of the Conceptual Upflow Shielding Configuration III. This design was an extensive redesign of Conceptual Shielding Configuration II; in particular, the upper and lower plenum shields were designed so that helium would flow through them rather than through the large gaps formed by offsetting the radial and plenum shields.

Localized Monte Carlo and discrete ordinates calculations were performed on preliminary flow-through shield designs to determine their shielding effectiveness before final design selection. Following the plenum shield design selection, both global and localized discrete ordinates calculations were performed for the plenum shield designs. The global calculations, which treated the plenum shields as concentric rings of homogeneous material, indicated large margins between the liner and PCRV design constraints and the correspondingly calculated radiation levels. On the other hand, the localized calculation for the lower plenum shield showed the thermal neutron fluence in the PCRV liner to be only about a factor of 2.0 below its design constraint and the dose to the tendon lubricant to be only about a factor of 3.0 below its design constraint.

Detailed results of the analysis, together with a discussion of several items that should be considered for their effect on radiation levels in the shielded regions, have been published.⁹ Each of the several items discussed could have a potentially major impact on the shielding design, particularly in those areas having a small margin between the calculated radiation level and the design constraint.

2.6 RECENT PUBLICATIONS

Since the last progress report, two additional documents have been published, which describe work reported in earlier progress reports. One describes a preliminary evaluation of various alternative fuel cycles for the GCFR,¹⁰ and the other presents the analysis of the ThO₂ and thorium-metal axial blanket experiments performed at the Swiss PROTEUS critical facility.¹¹

In addition to the above, a report has been prepared that summarizes all the TSF-GCFR integral shielding test experiments (and their analyses) performed during the five-year ORNL-GCFR program.⁵

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3. GCFR PRESSURE VESSEL AND CLOSURE STUDIES

D. J. Naus, J. R. Dougan, and G. C. Robinson

3.1 INTRODUCTION

Under sponsorship of the U.S. Department of Energy (DOE), we have conducted design verification and support studies of the prestressed concrete reactor vessel (PCRv) for a 300-MW(e) Gas-Cooled Fast Reactor (GCFR) demonstration power plant. These studies were planned and conducted in close cooperation with the General Atomic Company (GA), which has the overall design and development responsibility.

The three principal activities of the ORNL program were analyses and tests of (1) 1:20- to 1:15-scale closure plug models, (2) 1:4-scale closure plug models, and (3) a 1:10-scale model of the complete PCRv. The first of these activities had the primary objective of determining the margin of safety and the structural response caused by overload. In addition, although limited by the relatively small scale, experimental data in the elastic regime were obtained for validation of design analyses. The second of these activities was to provide detailed confirmation of design methods employed by the designer by using a different computer code from the designer and by obtaining precise experimental strains and displacements at critical locations. The third activity was to obtain the margin of safety and the structural response caused by overload for the complete PCRv. Because the GCFR program has been recently terminated, only the first of the principal activities was completed. Activities during this last reporting period were related to a close-out of the program. During this period the third in a series of small-scale closure plug models was tested.

3.2 BACKGROUND

Three closure plug model tests were conducted: two 1:15-scale steam generator cavity closure plugs and a 1:20-scale central core cavity closure plug. The first steam generator cavity closure model,¹ which represented the original design, was subjected to pressure in excess of

7.5 times the design value without experiencing detectable cracking of the concrete or failure of the plug, although yielding of the metallic components was recorded by strain gages. A second steam generator cavity closure model was then fabricated, in which the thickness of the plug and the amount of steel reinforcement were significantly reduced.² The model was subjected to a pressure of 9.9 times the design value before failing by abrupt punching shear. The third model in the test series was a 1:20-scale model of the central core cavity closure plug. Results of the third model test are summarized below. Details on the test have been published.³

3.3 THE 1:20-SCALE CENTRAL CORE CAVITY CLOSURE PLUG MODEL

The vertical cross section view of the PCRV for the 300-MW(e) GCFR shown in Fig. 3.1 indicates the relative size, location, and principal features of the central core cavity closure. The design maximum cavity pressure is 10.08 MPa. Concrete in the closure plug is confined on the side and bottom surfaces by a relatively thin steel liner. A ring forging is attached to the top of the side liner, the function of which is to transfer the resulting pressure loads from the plug to the adjacent axial prestressing tendons of the PCRV. This transfer is accomplished by a series of circumferentially spaced two-force members called "toggles," which are inclined at an angle of 25° from the vertical and induce radial compression loading into the ring forging at the top of the side liner wall. Thus, together with the lateral pressure of the coolant, they produce a circumferential prestress on the plug, which remains directly proportional to the pressure loading induced by the reactor coolant.

3.3.1 Model Description

Figure 3.2 presents plan and cross-section views on the 1:20-scale central core cavity closure model. All physical features of the prototype have been linearly scaled by a factor of 20 except the tubes, for which the scale factor was 19.3 (required to procure tubing to national standards). The model also departed from the prototype in that a vertical reactor support in lieu of toggles was used for load restraint because GA, at the time of the test, was considering modifying the design of the plug

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Fig. 3.1. Vertical cross section of PCRV for the 300-MW(e) GCFR demonstration power plant.

Fig. 3.2. Plant and cross section views of 1:20-scale central core cavity plug model.

support to that of a vertical reactor support scheme. (The main effect of the deviation in the support scheme was to provide conservative results because prestressing forces proportional to the pressure would not be applied to the plug.)

Steel materials for the prototype liner and gusset structures were designated by GA as either ASTM A 508, class 2, forging ASTM A 537, class 2, plate materials. In the model the outer liner was simulated by heat-treated ASTM A 106, grade C, pipe, with the remainder of the liner and gusset structure simulated with ASTM A 533, grade B, class 1, material. Reinforcing steel, to conform to the requirements of ASTM A 615, grade 60, reinforcing bar, was simulated by extruding, heat treating, and deforming (scaled prototype bar deformations) low-alloy 2 1/4 Cr-1 Mo stock wire. Control rod and penetration tubes were to conform to ASTM A 333, grade 6, but analysis results predicted that tubes fabricated to scale from this material would fail prematurely. Therefore, instead of using an increased tube wall thickness to prevent premature failure, a high-strength, age hardenable alloy, Inconel 718, was used. Ends of the tubes extending above the concrete were sealed by end-caps attached to the tubes by brazing in a vacuum furnace.

The prototype concrete was simulated by a microconcrete (mortar) mixture developed in the laboratory to have a minimum compressive strength of 55.2 MPa and modulus of elasticity of 31.0 GPa (at the time of the test these values were 73.7 MPa and 36.2 GPa, respectively). The mixture utilized a crushed limestone aggregate screened to pass a No. 8 standard sieve and be retained on a No. 50 sieve. Type II portland cement was used. A water-reducing agent was added to the mix water to increase the fluidity of the concrete mixture for placement between the closely spaced penetration tubes. Figure 3.3 presents the model after casting the concrete.

Fig. 3.3. Central core cavity closure plug model after fabrication.

3.3.2 Instrumentation and Test Facility

Instrumentation applied to the model was primarily intended to assist GA in understanding the strain distribution in two particularly sensitive zones: the central midheight penetration tube ligament zone and the zone immediately underneath the gusset structure. (Placement of gages in three zones, because of limited space and lack of availability of commercial devices, required a development effort. Results of this effort have been published.³) In addition, strain and displacement gages were placed in locations similar to those of the first two models tested to permit comparisons of behavior. A total of 46 gages were used to monitor the model behavior: 17 surface foil resistance, 21 embedded, 3 beam transducer, 3 eddy-current, and 2 capacitance gages. All gage output was read and automatically recorded by a data acquisition system.

Figure 3.4 presents the test facility, which was also used for the two previous 1:15-scale model tests. The facility consists basically of

Fig. 3.4. Closure plug model test facility.

an isolated test pit, a pressurization system capable of providing pressurization to 276 MPa, and a vessel test fixture. The test fixture, designed to permit pressure testing to 138 MPa, contained penetrations in the bottom of the vessel to permit pressurization and to provide entry of up to 24 (three-wire) channels of instrumentation. Figure 3.5 is a top view of the model inserted into the test fixture with eddy-current displacement gages and instrumentation leads attached. A threaded bushing assembly was used to secure the model in the test fixture, and sealing was accomplished by elastometric O-ring seals.

Fig. 3.5. Test fixture for closure plug model tests.

3.3.3 Model Testing

The model was scheduled to be tested by initially applying 10 loading cycles between approximately 1 MPa and the maximum cavity pressure of 10.08 MPa, followed by an 11th pressurization cycle to failure. However, on the 11th cycle, pressurization had to be interrupted at 32.08 MPa because of excessive leakage of a fitting on the pressurization line to the test fixture. The leak was repaired and pressurization resumed (cycle 12) until, at 41.3 MPa, excessive leaking of a seal at an instrumentation penetration in the test fixture developed and the test had to be interrupted. The seal was repaired and pressurization resumed (cycle 13) until failure of an end-cap braze joint occurred at 48.3 MPa and the test was interrupted. Instead of repairing only the defective end-cap and risking failure of another end-cap, we decided to reinforce all end-caps by epoxy-cementing cup-shaped plugs into the penetration tubes, with the plugs sealed against the end-cap and the cup end oriented toward the bottom. The length of the plugs was designed so that the stiffness of the tubes at the level of the upper concrete surface was not significantly affected. After curing of the epoxy, pressurization resumed (cycle 14) until failure of an intensifier seal occurred at 58.4 MPa. The intensifier was repaired and pressurization resumed (cycle 15) until, at a pressure of 79.3 MPa, an end-cap partially failed, relieving the pressure. The test was then terminated because, even if the leaking cap could be repaired, no practical means was available to ensure avoiding further end-cap failures.

3.3.4 Model Analysis

An inelastic analysis was conducted to provide an estimate of the ultimate strength of the closure plug and to determine the potential mode of failure. The finite-element code ADINA⁴ was used to conduct the analysis. Figure 3.6 presents the mesh layout. Two-dimensional axisymmetric elements were used to represent the geometry of the structure. Because the penetration array in the plug was asymmetric, reduced stiffness axisymmetric elements with smeared material properties were used in areas affected, that is, steel liners of penetrations, portions of bottom

Fig. 3.6. Mesh layout for analysis of central core cavity closure model.

liner, and concrete adjacent to the penetrations. The modified stiffness was accomplished by a procedure that reduced the element volume over which stresses were integrated.⁵ This procedure was also applied to the gussets and to the concrete between them because neither material was continuous in this area. Steel elements used to model bearing plates attached to the bottom of the gusset received no stiffness reductions because the size of the gap between adjacent plates in the model was negligible. The array of reinforcement in the closure plug was not modeled. Pressure loadings in the penetrations were neglected because an acceptable procedure for modeling the loadings could not be identified and because we felt that, by neglecting triaxial effects in the concrete ligaments between penetrations, the results obtained would be conservative. A bilinear kinematic hardening material model contained in ADINA was used to represent the stress-strain response of the elastic-plastic steel elements. A

constitutive model based on the endochronic theory⁶ was used for the concrete. Boundary conditions for the model were obtained by fixing the top three nodes of the liner against vertical motion, with the nodes farthest from the centerline of the closure plug having an additional restraint against horizontal motion.

In the analysis the model was subjected to a monotonic load by increasing pressure in 6.89-MPa increments from zero load to 48.26 MPa. Loading was continued in 1.38-MPa increments until a final value of 57.92 MPa was reached. During loading, minor tensile cracks formed along the entire top surface of the concrete at 13.79 MPa. At 34.47 MPa, yielding of the steel liner began in the thinner portion of the liner just below the thickened section. On continued loading to 49.6 MPa, approximately one-half the thickened portion of the liner had yielded, and concrete cracking had spread to mid-depth in the reduced stiffness area and to the bottom of the gussets. Complete yielding of the liner (except for a small portion from gusset midheight to bottom) and extensive concrete cracking occurred by the time a pressure of 57.92 MPa was reached. At this point the analysis terminated, apparently caused by the large displacements incurred from yielding of the liner rather than by structural failure.

3.3.5 Conclusions

Although the model did not fail, test results indicate that it has a significant overload capacity; that is, the model was loaded to 7.9 times the maximum cavity pressure without showing visible signs of distress. Analytical results indicate that available concrete constitutive models provide conservative results. Improved constitutive relationships are required for concrete material systems in order to improve the accuracy of the analysis methods.

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5. U. Gat and P. R. Kasten, *Gas-Cooled Fast Reactor Program Annu. Prog. Rep. Dec. 31, 1978*, ORNL-5560, August 1979.
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GAS-COOLED REACTOR PROGRAMS

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APPENDIXES

Appendix 1

DESIGN DRAWINGS AND SPECIFICATIONS FOR CFTL MECHANICAL SYSTEMS

The documents are grouped in lists in accordance with the CFTL Work Breakdown Structures (WBS) 2, 3, 4, and 5. These are, respectively, the heat removal system, the helium system, the test vessel, and the building facilities. All mechanical components and systems are treated except the gaseous impurities injection system and the x-ray manipulator. The drawings prepared by Mechanical Technology Inc. and Buehler Nuclear Product Company for the helium circulators are listed. The "x" notation in the right-hand column indicates that the drawing was used for the construction of the Stage Alpha CFTL.

The ORNL drawings for the GCFR CFTL test bundle AG1 and the associated drawings prepared by the General Atomic Company (GA) are listed, as are some drawings prepared by GA for additional proposed test bundles.

All the drawings and specifications are on file in the Mechanical Technology Engineering Department, Room 325, Building 9201-3. Those for WBS-5, Building Facilities, are stored at Y-12 Reproduction Department, Building 9739. Both buildings are located in the Y-12 Plant, Oak Ridge, Tennessee.

<u>Document No.</u>	<u>Rev.</u>	<u>Title</u>	<u>Check if Fabricated for Stage Alpha</u>
<u>WBS-2 HEAT REMOVAL SYSTEM DRAWINGS:</u>			
X2E-11590-015	0	Process Flow Sheet	X
X2E-11590-020	1	HX-1 Heat Exchanger Assembly	X
X2E-11590-021	4	HX-1 Heat Exchanger Subassembly	X
X2E-11590-022	2	HX-1 Exch. Tube to Header Weldment	X
X2E-11590-023	3	HX-1 Heat Exch. Tube to Header Weldment	X
X2E-11590-024	1	HX-1 Heat Exch. Weldment and Details	X
X2E-11590-025	0	HX-1 Heat Exch. Weldments	X
X2E-11590-026	1	HX-1 Exch. Transition Weldment	X
X2E-11590-027	1	HX-1 Heat Exch. Upper Transition Weldment	X
X2E-11590-028	1	HX-1 Support Stand Weldment	X
X2E-11590-030	0	HX-2 Heat Exchanger Assembly	
X2E-11590-031	0	HX-2 Heat Exch. Subassembly	
X2E-11590-032	0	HX-2 Heat Exch. Tube to Header Weldment	
X2E-11590-033	0	HX-2 Heat Exch. Tube to Header Weldment	
X2E-11590-034	0	HX-2 Exch. Weldment and Details	
X2E-11590-035	0	HX-2 Heat Exch. Transition Weldments	
X2E-11590-036	0	HX-2 Heat Exch. Transition Weldments	
X2E-11590-037	0	HX-2 Support Stand Weldment	
X2E-11590-040	0	HX-1 Cooling Air System	X
X2E-11590-050	1	HX-2 Cooling Air System	X
<u>Specifications</u>			
ES-XED-11590-001		4.4MW Helium-to-Air Heat Exch. (HX-1)	X
ES-XED-11590-002		0.4MW Helium-to-Air Heat Exch. (HX-2)	

**WBS-3 Helium System
Drawings:**

X2E-11590-060	0	Primary Piping Assembly, Plan View	
X2E-11590-061	0	Primary Piping Assembly, Elev. & Sections	
X2E-11590-062	1	Primary Piping Subassemblies, Det., Sht. 1	X
X2E-11590-063	1	Primary Piping Subassemblies, Det., Sht. 2	X
X2E-11590-064	0	Primary Piping - Pipe Hangers	
X2E-11590-065	0	Primary Piping - Support Beams	
X2E-11590-066	0	Primary Piping - Loop Checkout Vessel	
X2E-11590-067	2	Primary Piping - Flow Monitor Details	X
X2E-11590-068	7	Vortex Shedding Flow Meters	X
X2E-11590-069	3	Primary Piping Installation, Stage Alpha	X
X2E-11590-070	2	Helium Filter - Assembly	X
X2E-11590-071	1	Helium Filter - Details	Y
X2E-11590-072	0	Primary Piping - Support Beams, Stage Alpha	X
X2E-11590-073	1	Primary Piping - Pipe Hangers, Stage Alpha	X
X2E-11590-074	0	Helium Circulator Service Crane Support Frm.	X
X2D-11590-075	0	Helium Circulator Base Mounting Plates	X
X2E-11590-076	0	Helium Circulator Cooling Water System	
X2E-11590-077	0	Valve Actuator Hydraulic System	
X2E-11590-078	0	Hydraulic System Cooling Line	
X2D-11590-079	0	Helium Circulator Beam Sling	X
X2E-11590-080	0	Evacuation System, Assembly & Details	X
X2E-11590-081	3	Helium Vent System, Assembly & Details	X
X2E-11590-082	0	Blowdown Rupture Disk	
X2E-11590-083	0	Helium Circ. Motor & Cooling Ves. Assembly Fix.	X
X2E-11590-084	0	Helium Circ. Assembly Cart	X

Specifications:

ES-XED-11590-003	Fabrication of Helium Circ.	
	Pressure Vessel	X
ES-XED-11590-005	Helium Filter Pressure Vessel	X
ES-XED-11590-006	Helium Piping System	X
ES-XED-11590-007	Helium Purification System	X
M-11590-RB-001-S-5	Helium Circulators	X

NOTE: The following drawings of the helium circulator pressure vessel were originated by Buehler Nuclear Products.

X2E-11590-125	2	Pressure Vessel Assembly	X
X2E-11590-126	0	Pressure Vessel Inlet Head & Shell Assembly	X
X2D-11590-128	0	Pressure Vessel Head Detail	X
X2D-11590-129	0	Pressure Vessel Outlet Nozzle Detail	X
X2E-11590-131	0	Pressure Vessel Inlet Nozzle	X
X2E-11590-132	0	Pressure Vessel C Ring Detail	X
X2E-11590-133	3	Pressure Vessel Closure Head Assembly	X
X2E-11590-134	0	Pressure Vessel Shell Outlet Nozzle Assembly	X
X2D-11590-135	0	Pressure Vessel Head to Nozzle Assembly	X
X2C-11590-137	1	Pressure Vessel Stub Bolt	X
X2C-11590-138	1	Pressure Vessel Hex Nut	X
X2D-11590-139	0	Pressure Vessel Seal Register Ring	X
X2E-11590-140	0	Pressure Vessel Flange Detail	X
X2E-11590-141	1	Pressure Vessel Shell to Flange Assembly	X
X2E-11590-142	0	Pressure Vessel Shell to Flange Assembly	X
X2E-11590-143	1	Cooling Vessel Assembly	X
X2E-11590-144	0	Cooling Vessel Assembly	X
X2E-11590-145	0	Cooling Vessel Assembly	X
X2D-11590-146	0	Cooling Vessel Water Tube	X
X2D-11590-147	0	Cooling Vessel Housing Forging Detail	X
X2D-11590-148	0	Cooling Vessel Sleeve Forging Detail	X
X2D-11590-149	2	Support Ring	X
X2D-11590-150	0	Support Ring	X
X2D-11590-151	0	Cooling Water Pass-Thru Design	X
X2C-11590-152	0	Cooling Water Flange	X

NOTE: The following drawings of the helium circulators were prepared by Mechanical Technology, Inc.

<u>Document No.</u>	<u>Rev.</u>	<u>Title</u>	<u>Checked if Fabricated for Stage Alpha</u>
316B18	A	Impeller Spinner	X
316B19	A	Seal Ring	X
316B22	-	Tie Rod - Impeller	X
316B25	A	Pivot-Tilting Pad Bearing	X
316B35	A	Probe, Capacitance (Thrust Bear.)	X
316B36	A	Probe, Capacitance (Journal Bear.)	X
316B38	B	Reed Equalizing Valve	X
316B40	-	Tie Rod	X
316B64	A	Insulator - Power Lead	X
316B65	-	Insulator - Instrumentation	X
316B67	-	Bracket - Probe Mounting	X
316B68	-	Bracket - Speed Pickup	X
316B69	-	Pin	X
316B71	-	Pin - Impeller Drive	X
316B73	-	Seal Ring	X
316B74	B	Cable Assembly - Bearing Probe	X
316B80	-	Space Block	X
316B81	-	Tie Bar	X
316B87	-	Wedge	X
316B88	-	Slot Tube	X
316B90	A	Gasket (Reed Valve)	X
316B91	-	Stator Coil	X
316B92	-	Orifice	X
316B95	-	Shim	X
316B98	-	Pivot	X
316B111	-	Spacer	X
316B125	-	Shaft Support	X
316B126	-	Shaft	X
316B127	-	Shim	X
316B141	-	Drive Nut	X
316B142	-	Drive Screw	X
316B144	A	Spacer, Cap. Probe Bracket	X
316B155	B	Strain Relief Pass Thru	X
316C21	A	Inlet Adapter, Impeller	X
316C31	F	Baffle Assembly	X
316C32	B	Gimbal Ring	X
316C37	-	Valve Plate	X
316C39	B	Backup Plate-Equalizing Valve	X
316C48	C	Seal Ring	X
316C57	-	Flexure-Bearing Pad	X
316C60	B	Shim Diffuser Backplate	X
316C61	A	Seal Ring - Compressor Inlet	X
316C70	-	Shim Fan Housing	X
316C78	-	Flow Equalizer	X
316C82	-	End Ring	X

316C83	-	Lamination	X
316C84	-	Space Block Assembly	X
316C97	-	Spacer Block	X
316C106	-	Cooling Jacket Support	X
316C107	-	Cooling Plenum	X
316C108	-	Exhaust Plenum	X
316C114	-	Duct Union	X
316C117	-	Flange - Cooling Water	X
316C128	-	Clamp Ring	X
316C131	-	Baffle Assembly	X
316C133	-	Bracket	X
316C138	-	Angle Bracket	X
316C139	-	Thrust Block	X
316C140	-	Drive Nut Support	X
316C145	-	Nameplate	X
316C146	-	Warning Plate	X
200C03	-	Shop Run Tolerances and Practices	X
316D13	D	Cooling Fan	X
316D14	C	Diffuser	X
316D20	E	End Ring	X
316D24	D	Bearing Set-Tilting Pad	X
316D29	F	Thrust Bearing	X
316D33	B	Shaft Assembly	X
316D34 (Sheet 1)	A	Support Ring	X
316D34 (Sheet 2)	A	Support Ring	X
316D41	A	Shaft End-Cooling Fan	X
316D42	A	Journal - Compressor Fan	X
316D43	C	Journal - Compressor End	X
316D46	-	Base, Compressor Test	X
316D49	-	Heat Shield	X
316D50	-	Insulator - Thermal	X
316D52	-	Heat Shield	X
316D53	-	Insulator	X
316D54	-	Heat Shield	X
316D59	A	Baffle	X
316D63	A	Thrust Bearing-Rotor Assembly	X
316D66	A	Cover	X
316D72	C	Back Plate - Seal Assembly	X
316D85	-	End Ring	X
316D143	-	Base Compressor	X
316E16	D	Impeller Assembly	X
316E17 (Sheet 1)	H	Motor Housing Cooling Vessel	X
316E17 (Sheet 2)	F	Motor Housing Cooling Vessel	X
316E17 (Sheet 3)	F	Motor Housing Cooling Vessel	X
316E30	B	Retainer Fan End Bearing	X
316E44	C	Shaft	X
316E45	A	Circulator Base	X
316E51 (Sheet 1)	A	Back Plate	X
316E51 (Sheet 2)	A	Back Plate	X
316E55 (Sheet 1)	B	Support Ring	X
316E55 (Sheet 2)	-	Support Ring	X

316E56	C	(Proprietary) Rotor Assembly	X
316E58	B	Retainer Compressor End Bearing	X
316E86	B	(Proprietary) Motor Stator Assembly)	X
316E89	B	Cooling Vessel - Stator Assembly	X
316E96	C	Housing	X
316E100	C	Test Loop Instrumentation Schematic	X
316E105 (Sheet 1)	F	Compressor Test Loop	X
316E105 (Sheet 2)	E	Compressor Test Loop	X
316E112	-	Housing	X
316E123	D	Support Bracket	X
316E124	B	Rail Support	X
316E132	-	Rotor Assembly Fixture	X
316E137	-	Cable Support	X
316E153	-	Cable Cover	X
316J03 (Sheet 1)	H	Helium Circulator Assembly	X
316J03 (Sheet 2)	D	Helium Circulator Assembly	X
316J03 (Sheet 3)	C	Helium Circulator Assembly	X
316J15 (Sheet 1)	M	Pressure Vessel Assembly	X
316J15 (Sheet 2)	L	Pressure Vessel Assembly	X
316J122	B	Fixture Circulator Assembly	X
316B152	-	Terminal Block Contact	X
316D156	A	Terminal Block Modification	X
316D151	A	Terminal Block Bracket	X
316D154	-	Pressure Vessel Closure Head Modification	X
316D155	B	Diffuser Vaneless	X
316B157	A	Cable Assembly Ext. Probe	X

WBS-4 Test Vessel**Drawings:**

X2E-11590-100	1	Test Vessel Shell Weldment
X2E-11590-101	1	Test Vessel Shell Details, Sht. 1
X2E-11590-102	1	Test Vessel Shell Details, Sht. 2
X2E-11590-105	1	Test Vessel Outlet Plenum Liner Assembly
X2E-11590-110	0	Test Vessel Assembly, Inlet
X2E-11590-111	0	Test Vessel Assembly, Outlet
X2E-11590-112	0	Test Vessel Transporter Weldment and Details
X2E-11590-113	0	Transporter and Test Vessel Assembly
E-SK-BHD-5249	-	CPTL Test Vessel with Test Bundle

Specification:

ES-XED-11590-004	-	Test Vessel
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WBS-5 Building Facilities**Engineering Mechanics**

P2E96901	0	Inst. Air Heater & Circ. Cool Water	X
P2E96902	0	Circ. Cool. Water & Drain, HVAC Cool Water	X
P2E96903	0	Helium Supply System	X
P2E96904	0	HVAC Steam, Condensate, & Cool Water Piping	X
P2E97544	0	HVAC Steam, Condensate, & Cool Water Piping	X
P2E97545	0	Process Water Drain	X
P2E97546	0	Process Water Installation	X
P2E97547	0	Floor Penetrations, 1st Floor	X
P2E97548	0	Helium Supply System	X
P2E97622	0	Process Water Drain	X
P2E97623	0	Process Water Installation	X
P2EE33948SK	0	Piping Demolition, 1st Floor	X
P2E99831	0	Instrument Air Inst. 1st Floor	X
P2E33799SK	0	Piping Demolition	X
P2E33800SK	0	Piping Demolition	X

Engineering Mechanics - Fire Protection

P2E97606	A	CFTL Control Room Fire Protection	X
D2E14908	C	Sprinkler Installation	X
YE13005	D	Sprinkler Piping Plan - 2nd Floor	X
YE13001	D	Sprinkler Piping Plan - 1st Floor	X
YE13009	D	Sprinkler Piping Plan - 2nd Floor	X

Civil and Architectural

S2E96991	A	Penthouse Plan and Sections	X
S2E96992	A	Penthouse Sections and Details	X
S2E96993	A	Helium Supply Trailer Pad	X
S2E96994	A	Filter House No. 1 Plan & Details	X
S2E96995	A	Filter House No. 1 Elev. & Sections	X
S2E96996	A	Filter House No. 1 Elev. & Sections	X
S2E96997	A	Filter House No. 2 Plan & Details	X
S2E96998	A	2nd Floor Control Room & Demo. Plan	X
S2E96999	A	2nd Floor Exp. Cooling Duct Pen. & Supports	X
S2E97000	A	2nd Floor Control Room	X
S2E97001	A	2nd Floor Control Room	X
S2E97002	A	Roof Plan and Sections	X
S2E97003	A	2nd Floor Cont. Room - H&V Platform	X

S2E97004	A	2nd Floor Reinf. Plan & 1st Floor Partitions	X
S2E97005	A	Penetrations at Elev. 926' 0" Plan and Det.	X
S2E97006	A	Plan at Air Tunnel No. 2 & Fan Room Mod.	X
S2E97007	A	1st Floor Elec. Equipment Platform	X
S2E97008	A	Penetrations at Elev. 962' 0" Sections and Det.	X

Environmental Control

H2E98201	A	Control Room A/C System	X
H2E98206	O	HVAC Basement Plan	X
H2E98207	O	HVAC First Floor Plan	X
H2E98208	O	HVAC Air Tunnel Plan and Elev.	X
H2E98209	O	HVAC Elevations	X
H2E98210	O	HVAC Elevations	X
H2E98211	O	HVAC First Floor Plan and Elev.	X
H2E98212	O	HVAC Mezzanine Plan and Elev.	X
H2E98216	A	HVAC Elevations	X
E-EC-87710	B	Transformer Vault Ventilation	X
H2E33885SK		HVAC Demolition Plan	X
H2E33951SK		Fan Room Demolition	X
H2E33804SK		CFTL Demolition	X
H2E33805SK		CFTL Demolition	X
H2E33806SK		CFTL Demolition	X
FR7066	B	Bldg. 9201-3 Ventilation (Sht. 1)	X
FR7301	B	Bldg. 9201-3 Ventilation (Sht. 2)	X

Test Bundle

X2E-11590-115	O	Brazing Fixture Assembly	X
X2E-11590-116	O	Brazing Fixture Details	X
X2E-11590-200	O	Bundle AGI Assembly	
X2E-11590-201	O	Test Section Subassembly	
X2E-11590-202	O	Disconnect Panel & Lead Subassembly	
X2E-11590-203	O	Inner Flange Subassembly	
X2E-11590-204	O	Inlet Plenum & Duct Subassembly	
X2E-11590-205	O	FRS/Tube Sheet Subassembly	
X2E-11590-206	O	Skelton Assembly	
X2E-11590-207	O	Disconnect Panel Frame Assembly	
X2E-11590-208	O	FRS Terminal Cooling System Subassembly	
X2E-11590-209	O	FRS Terminal Cooling Systems Details	
X2E-11590-210	O	Hex Duct & Instrumentation Subassembly	

X2E-11590-211	0	FRS/Tube Sheet Subassembly Sections
X2E-11590-212	0	Transition Duct Subassembly
X2E-11590-214	0	FRS Details
X2E-11590-215	0	FRS Details
X2E-11590-216	0	FRS Active Component Assembly
X2E-11590-220	0	TE Rake and Plug Subassembly
X2E-11590-221	0	Rake and Plug Details
X2E-11590-222	0	Rake and Plug Details
X2E-11590-232	0	Tube Sheet
X2E-11590-233	0	Tube Sheet Sections
X2E-11590-234	0	Hex Duct Modification
X2E-11590-235	0	Outer Baffle Weldment
X2E-11590-236	0	Bundle Seal Plate
X2E-11590-237	0	Inst. Feed Thru & Flow Baffle Details
X2E-11590-238	0	Hanger Rod Modification and Details
X2E-11590-239	0	Gas TE Locations & Attachments
X2E-11590-240	0	Misc. Details
X2E-11590-241	0	Tube Sheet Adapter and Duct Extension
X2E-11590-243	0	Hanger Rod Assemblies
X2E-11590-244	0	Misc. Details
X2E-11590-245	0	Conax Seal Details
X2E-11590-246	0	TE Disconnect Support Bracket Weldment
X2E-11590-247	0	Disconnect Panel-Elev. View Z, D, H
X2E-11590-248	0	Disconnect Panel Plan View
X2E-11590-249	0	Disconnect Panel Section View
X2E-11590-250	0	Disconnect Panel Elev. View M, R, V
X2E-11590-251	0	Disconnect Panel Details
X2E-11590-252	0	Power Lead Support & Details
X2E-11590-253	0	Power Lead Subassembly
X2E-11590-254	0	Thermocouple Routing & Protection
X2E-11590-260	0	Restraint Subassembly
X2E-11590-261	0	Restraint Subassembly & Details
X2E-11590-262	0	Thermal Shroud Subassembly (Inlet)
X2E-11590-263	0	Thermal Shroud Subassembly Weldment & Details
X2E-11590-264	0	Thermal Shroud Subassembly (Middle)
X2E-11590-265	0	Thermal Shroud Subassembly (Outlet) & Details
X2E-11590-266	0	Restraint Support Subassemblies
X2E-11590-267	0	Restraint Support Details
X2E-11590-270	0	Fuel Rod Simulator - Type A
X2E-11590-271	0	Fuel Rod Simulator - Type B
X2E-11590-272	0	Fuel Rod Simulator - Type C
X2E-11590-273	0	Fuel Rod Simulator - Type D
X2E-11590-274	0	Fuel Rod Simulator - Type E
X2E-11590-275	0	Fuel Rod Simulator - Type F

X2E-11590-276	0	Fuel Rod Simulator - Type G
X2E-11590-277	0	Fuel Rod Simulator - Type H
X2E-11590-278	0	Fuel Rod Simulator - Type I
X2E-11590-279	0	Fuel Rod Simulator - Type J
X2E-11590-280	0	Fuel Rod Simulator - Type K
X2E-11590-281	0	Fuel Rod Simulator - Type L
X2E-11590-282	0	Fuel Rod Simulator - Type M
X2E-11590-283	0	Fuel Rod Simulator - Type N
X2E-11590-284	0	Fuel Rod Simulator - Type O
X2E-11590-285	0	Fuel Rod Simulator - Type P
X2E-11590-286	0	Fuel Rod Simulator - Type Q
X2E-11590-287	0	Fuel Rod Simulator - Type R
X2E-11590-288	0	Fuel Rod Simulator - Type S
X2E-11590-289	0	Fuel Rod Simulator - Type T

NOTE: The following drawings of the CFTL AGI Test Section were prepared by General Atomic

024794	B	37-Rod Fuel Bundle Test Assembly
024795	C	Bundle Skelton
024796	C	Spacer Grid
024797	B	Hanger Rod
024799	E	Fuel Rod Simulator Cladding
024800	D	Roughened Spacer Tube
024801	B	Smooth Spacer Tube
024802	B	Duct
024838	C	Hanger Rod Assembly
024839	B	Hanger Rod Assembly
025028	C	Load Pad
025029	B	Hex Duct Assembly
025081	C	Nut
023976	A	Rod Simulator Numbering System for Test Bundles

NOTE: The following drawings of proposed future test sections were prepared by General Atomic.

7170000066	B	Bundle Skelton (61 Rod Test Bundle)
7170000067	B	Bundle Skelton (91 Rod Test Bundle)
7170000069	B	Hex Duct Subassembly (61 Rod Test Bundle)
7170000070	B	Hex Duct Subassembly (91 Rod Test Bundle)
7170000071	B	Spacer Grid-Type A (61 Rod Test Bundle)
7170000072	B	Spacer Grid-Type A (91 Rod Test Bundle)

7170000073	B	Inlet Flange (61 Rod Test Bundle)
7170000074	B	Inlet Flange (91 Rod Test Bundle)
7170000075	B	Hex Duct (61 Rod Test Bundle)
7170000076	B	Hex Duct (91 Rod Test Bundle)
7170000077	B	61 Rod Fuel Bundle Test Assembly
7170000078	B	91 Rod Fuel Bundle Test Assembly
7170000085	C	Roughening of Prototype CFTL Fuel Rod Simul.
7170000086	C	Roughening of Prototype LMFR Fuel Rod Simul.
7170000090	A	61 Rod Blanket Bundle Test Assembly
7170000091	B	Hex Duct Subassembly (Blanket Test Bundle)
7170000092	B	Rod Simulator (Blanket Test Bundle)
7170000093	B	Inlet Flange (Blanket Test Bundle)
7170000094	B	Hex Duct (Blanket Test Bundle)
7170000095	B	Tubing (Blanket Rod Simulator)
7170000096	B	End Plug (Blanket Rod Simulator)
7170000100	A	90 Rod Control Bundle Assembly
7170000101	A	Hex Duct Subassembly (Control Rod Test Bundle)
7170000102	A	Bundle Skeleton (90 Rod Control Assembly)
7170000103	A	Guide Duct
7170000104	A	Spacer Grid (90 Rod Control Assembly)
7170000105	A	Spacer Tube Type D
7170000106	A	Spacer Tube Type E
7170000107	A	Spacer Tube Type F
7170000108	A	Inlet Flange (90 Rod Control Assembly)
7170000109	A	Hex Duct (90 Rod Control Assembly)

Appendix 2

DRAWINGS, SPECIFICATIONS, AND DATA SHEETS FOR THE CFTL
ELECTRICAL EQUIPMENT, SYSTEMS, AND CABINETS

Information listed in this Appendix includes the:

- A. Zone power supply drawings made by UCCND, Robicon Corp., and General Electric Company.
- B. Cabinets and patch panel drawings for test bundle power.
- C. Schematic drawings of test bundle zones.
- D. Equipment layout, switchgear, auxiliary power, conduit, cable tray, and cabinets.
- E. Drawings prepared by Y-12 Electric Engineering and Y-12 Instrument Engineering.
- F. Specifications and data sheets.
- G. Drawings and material lists prepared by Servo Optics Systems of Dallas for the variable frequency power supply to the helium circulators.

The drawings noted as being partially complete in the remarks in the Status column pertain to the power supply for the discontinued GCFR test bundles and will not be completed in the foreseeable future. The incomplete drawings are stored by Mechanical Technology Engineering at Building 9201-3 in the Y-12 Plant separately from the completed drawings. The item E drawings are stored at the Y-12 Engineering Division office in the Y-12 Plant.

A. Zone power supply drawings by UCCND, Robicon Corp., and General Electric Co.

Drawing no.	Document title	Status
E2E-11590-0731	Zone Pwr. Supply 'A'-SH.#1, Schem. Diag.	Drawing are 80% complete. Revisions need to be made and some corrections also.
E2E-11590-0732	Zone Pwr. Supply 'A'-SH.#2, Schem. Diag.	
E2E-11590-0733	Zone Pwr. Supply 'B'-SH.#1, Schem. Diag.	
E2E-11590-0734	Zone Pwr. Supply 'B'-SH.#2, Schem. Diag.	
E2E-11590-0735	Zone Pwr. Supply 'C'-SH.#1, Schem. Diag.	
E2E-11590-0736	Zone Pwr. Supply 'C'-SH.#2, Schem. Diag.	
E2E-11590-0737	Zone Pwr. Supply 'D'-SH.#1, Schem. Diag.	
E2E-11590-0738	Zone Pwr. Supply 'D'-SH.#2, Schem. Diag.	
E2E-11590-0739	Zone Pwr. Supply 'E'-SH.#1, Schem. Diag.	
E2E-11590-0740	Zone Pwr. Supply 'E'-SH.#2, Schem. Diag.	
E2E-11590-0741	Zone Pwr. Supply 'F'-SH.#1, Schem. Diag.	
E2E-11590-0742	Zone Pwr. Supply 'F'-SH.#2, Schem. Diag.	
E2E-11590-0743	Zone Pwr. Supply 'G'-SH.#1, Schem. Diag.	
E2E-11590-0744	Zone Pwr. Supply 'G'-SH.#2, Schem. Diag.	
E2E-11590-0745	Zone Pwr. Supply 'H'-SH.#1, Schem. Diag.	
E2E-11590-0746	Zone Pwr. Supply 'H'-SH.#2, Schem. Diag.	
E2E-11590-0747	Zone Pwr. Supply 'J'-SH.#1, Schem. Diag.	
E2E-11590-0748	Zone Pwr. Supply 'J'-SH.#2, Schem. Diag.	
E2E-11590-0749	Zone Pwr. Supply 'K'-SH.#1, Schem. Diag.	
E2E-11590-0750	Zone Pwr. Supply 'K'-SH.#2, Schem. Diag.	
E2E-11590-0751	Zone Pwr. Supply 'L'-SH.#1, Schem. Diag.	
E2E-11590-0752	Zone Pwr. Supply 'L'-SH.#2, Schem. Diag.	
E2E-11590-0753	Zone Pwr. Supply 'M'-SH.#1, Schem. Diag.	
E2E-11590-0754	Zone Pwr. Supply 'M'-SH.#2, Schem. Diag.	
E2E-11590-0755	Zone Pwr. Supply 'N'-SH.#1, Schem. Diag.	
E2E-11590-0756	Zone Pwr. Supply 'N'-SH.#2, Schem. Diag.	
E2E-11590-0692	Ind. Volt. Reg. and 500 KVA Pwr. Sup. Elem. Diagram	Issued CFC
E2E-11590-0693	Balance Resistor Permissives and Cont. Elem.	98% complete
E2E-11590-0694	Alarms, Fans, and Misc. Control Elem. Diagram	98% complete
E2E-11590-0695	SCRAM Control Elem. Diagram	98% complete
E2E-11590-0696	FRS Elect. Protection Diagram	98% complete
E2E-11590-0697	FRS Interlock and Remote Alarm PCB Layout	98% complete
E2E-11590-0698	CFTL - AC System Block Diagram	98% complete
E2E-11590-0699	Ind. Volt. Reg Relay and Cont. Cab. Details	Issued CFC

Master Document List

Drawing no.	Rev.	Document title
<u>500 kVa zone power supply</u>		
361775		Gate drive board comp. assembly
373981		Schematic gate drive board P/N 361775
361774		Overcurrent detector
375080		Schematic overcurrent detector bd. P/N 36177
462940		Power supply and logic ckt. comp. assembly
474487		Power supply and logic board schematic
361776		Suppressor board
474483 sheet 1	A	Schematic PN 400943 sheet 1
474483 sheet 2		Schematic PN 400943 sheet 2
474483 sheet 3		Schematic PN 400943 sheet 3
474483 sheet 4		Schematic PN 400943 sheet 4
474483 sheet 5		Schematic PN 400943 sheet 5
474483 sheet 6		Schematic PN 400943 sheet 6
474483 sheet 7		Schematic PN 400943 sheet 7
474483 sheet 8		Schematic PN 400943 sheet 8
400943 sheet 1		1 ϕ water cooled tap changing system
400943 sheet 2		1 ϕ water cooled tap changing system
400943 sheet 3		1 ϕ water cooled tap changing system
400943 sheet 4		1 ϕ water cooled tap changing system
400943 sheet 5		1 ϕ water cooled tap changing system
400943 sheet 6		1 ϕ water cooled tap changing system
400943 sheet 7		1 ϕ water cooled tap changing system
400943 sheet 8		1 ϕ water cooled tap changing system
400943 sheet 9		1 ϕ water cooled tap changing system
400943 sheet 10		1 ϕ water cooled tap changing system
Manufacturer: Robicon Corp.		
<u>500 kVa induction voltage regulator</u>		
3908C786 sheet 1		Diagrams of connections sheet 1
3908C786 sheet 2		Diagrams of connections sheet 2
3908C786 sheet 3		Diagrams of connections sheet 3
3908C786 sheet 4		Diagrams of connections sheet 4
Manufacturer: General Electric		

B. Cabinets and patch panel for test bundle power

Drawing no.	Document title	Status
E2E-11590-0650	Patch Panel Assy.	Issued CFC Partially
E2E-11590-0651	Patch Panel Fabrication Details	Issued CFC fabricated
E2E-11590-0652	Patch Panel Layout - item 2 and 4	Issued CFC but not
E2E-11590-0653	Patch Panel Layout - item 3	Issued CFC installed
E2E-11590-0654	Patch Panel Photometal Nameplate	Issued CFC
E2E-11590-0655	Patch Panel Wiring Diagram	Issued CFC
E2E-11590-0657	Circuit Breaker and Fuse Cabinet Assy.	Issued CFC
E2E-11590-0658	Circuit Breaker and Fuse Cabinet Fab. Details	Issued CFC
E2E-11590-0660	Current Transformer Cab. Assy.	Issued CFC Partially
E2E-11590-0661	C.T. Cab. Wiring Details	Issued CFC fabricated
E2E-11590-0662	C.T. Cab. Fabrication Details	Issued CFC but not
E2E-11590-0664	Crowbar SCR Cab. Assy.	Issued CFC installed
E2E-11590-0665	Crowbar SCR Cab. Wiring Details	Issued CFC
E2E-11590-0667	Test Cabinet Assy.	95% complete - need
E2E-11590-0668	Test Cabinet Fab. Details	to finalize decision to use P.T. or resistive network for power measurement
E2E-11590-0669	Crowbar Pulse X'fmr. Cab. Assy.	Issued CFC Partially
E2E-11590-0670	Crowbar Pulse X'fmr. Drawer Assy.	Issued CFC fabricated
E2E-11590-0671	Crowbar Pulse X'fmr. Drawer Fab.	Issued CFC but not
E2E-11590-0672	Crowbar Pulse X'fmr. P.C. Board Assy.	Issued CFC installed
E2E-11590-0674	WATT Transducer Cab. Assy.	95% - same comment
E2E-11590-0675	WATT Transducer Cab. Details	as for - 0667
E2E-11590-0676	WATT Transducer Cab. Wiring Dia.	
E2E-11590-0682	Crowbar Pulse X'fmr. and Detector Cab. Layout	50% complete
E2E-11590-0685	Crowbar Detector Cab. Wiring Details	10% complete
E2E-11590-0701	Dummy Load Watt X'der. and P.T. Cab. Assy.	95% - same comment
E2E-11590-0702	Dummy Load Watt X'der. and P.T. Cab. Details	as - 0667
E2E-11590-0703	Dummy Load Watt X'der. and P.T. Cab. Wiring Details	

C. Schematic Drawings of Test Bundle Zones

Drawing no.	Document title	Status
E2E-11590-0758	Fuel Rod Simulators-Section 'P', SH.#1, Schem. Diag.	Drawing are 80% complete. Sepias need to be made and some correc- tions also.
E2E-11590-0759	Fuel Rod Simulators-Section 'P', SH.#2, Schem. Diag.	
E2E-11590-0760	Fuel Rod Simulators-Section 'R', SH.#1, Schem. Diag.	
E2E-11590-0761	Fuel Rod Simulators-Section 'R', SH.#2, Schem. Diag.	
E2E-11590-0762	Fuel Rod Simulators-Section 'S', SH.#1, Schem. Diag.	
E2E-11590-0763	Fuel Rod Simulators-Section 'S', SH.#2, Schem. Diag.	
E2E-11590-0764	Fuel Rod Simulators-Section 'T', SH.#1, Schem. Diag.	
E2E-11590-0765	Fuel Rod Simulators-Section 'T', SH.#2, Schem. Diag.	
E2E-11590-0766	Fuel Rod Simulators-Section 'U', SH.#1, Schem. Diag.	
E2E-11590-0767	Fuel Rod Simulators-Section 'U', SH.#2, Schem. Diag.	
E2E-11590-0768	Fuel Rod Simulators-Section 'V', SH.#1, Schem. Diag.	
E2E-11590-0769	Fuel Rod Simulators-Section 'V', SH.#2, Schem. Diag.	
E2E-11590-0770	Fuel Rod Simulators-Section 'W', SH.#1	Schem. Diag.
E2E-11590-0771	Fuel Rod Simulators-Section 'W', SH.#2	Schem. Diag.
E2E-11590-0772	Fuel Rod Simulators-Section 'X', SH.#1	Schem. Diag.
E2E-11590-0773	Fuel Rod Simulators-Section 'X', SH.#2	Schem. Diag.

D. Equipment layout, switchgear, auxiliary power, conduit, cable tray, and cabinets

Drawing no.	Document title	Status	
E2E-11590-0677	Equip. Layout Sections, Gnd. Fl. Col. K-N/11-14	98% complete	
E2E-11590-0680	Equip. Layout, East Side, Gnd. Fl.	100% complete	
E2E-11590-0681	Equip. Layout, West Side, Gnd. Fl.	98% complete	
E2E-11590-0686	CFTL-One Line Diagram	98% complete	
E2E-11590-0688	Switchgear 7EA Control Elementary Diag.	Issued CFC	
E2E-11590-0689	Switchgear 7EB Control Elementary Diag.	98% complete	
E2E-11590-0690	Switchgear 7EC and 7ED Cont. Elem. Diag.	Issued CFC	
E2E-11590-0705	MCC 7EC-1 One Line Diagram	95% complete	
E2E-11590-0706	MCC 7EC-1 Interconnection Diagram	95% complete	
E2E-11590-0707	MCC 7EC-1 Misc. Diagrams	95% complete	
E2E-11590-0708	HX-1 HTR. Misc. Diagrams	95% complete	
E2E-11590-0713	Cable Tray Layout - Gnd. Fl. - East Side	Issued CFC	
E2E-11590-0714	Cable Tray Layout - Gnd Fl. - West Side	Issued CFC	
E2E-11590-0716	Cable Tray Layout Sections - Gnd. Fl. - East Side	Issued CFC	No construction performed
E2E-11590-0717	Cable Tray Layout Sections - Gnd. Fl. - West Side	Issued CFC	
E2E-11590-0718	Cable Tray Layout Sections - Gnd. Fl. - East Side Platform	Issued CFC	
E2E-11590-0719	Cable Tray Bill of Materials	Issued CFC	
E2E-11590-0724	Conduit Plan - Gnd. Fl., West Side	Issued CFC	
E2E-11590-0726	Conduit Plan - Gnd. Fl., East Side	Issued CFC	
E2E-11590-0774	Elec. Sys. Cab. ES-1 thru ES-6 Layout	98% complete	
E2E-11590-1699	Ind. Reg. Relay and Cont. Cab. Details	Issued CFC*	
E2E-11590-1775	Elec. Sys. Cab. ES-1 Layout and Fab. Detail,	Issued CFC*	
E2E-11590-1776	Elec. Sys. Cab. ES-1 Wiring Diagram	Issued CFC*	
E2E-11590-1777	Elec. Sys. Cab. ES-2 Layout and Fab. Detail	Issued CFC*	
E2E-11590-1778	Elec. Sys. Cab. ES-2 Wiring Diagram	Issued CFC*	
E2E-11590-1790	CFTL/Alpha Interconnect. Diagram - SH. 1	Issued CFC*	
E2E-11590-1791	CFTL/Alpha Interconnect. Diagram - SH. 2	Issued CFC*	
E2E-11590-1800	Conduit Schedule - SH. 1	Issued CFC*	
E2E-11590-1801	Conduit Schedule - SH. 2	Issued CFC*	
E2E-11590-1810	Cable Schedule - SH. 1	Issued CFC*	
E2E-11590-1811	Cable Schedule - SH. 2	Issued CFC*	
E2E-11590-1680	Equip. Layout - Gnd. Fl. - East Side	Issued CFC*	
E2E-11590-1681	Equip. Layout - Gnd. Fl. - West Side	Issued CFC*	
E2E-11590-1686	CFTL-Stage ALPHA One-line Diagram	Issued CFC	
E2E-11590-1706	Interconnection Diagram Sh. 3	Issued CFC*	
E2E-11590-1707	Aux. Pwr. One-line Diagram	Issued CFC*	
E2E-11590-1718	Control Room Conduit Plan	Issued CFC*	
E2E-11590-1724	Conduit Plan - Gnd. Fl. - West Side	Issued CFC*	
E2E-11590-1726	Conduit Plan - Gnd. Fl. - East Side	Issued CFC*	
E2E-11590-1727	Control Room - Conduit Plan	Issued CFC*	

*Issued for stage Alpha

All drawings stored with XEE in Bldg. 9201-3

**E. Drawings and specifications prepared by Y-12 Electrical Engineering
and Y-12 Instrument Engineering**

The following drawings were prepared by Y-12 Electrical Engineering
for CFTL Facility Construction and are stored with Y-12 Engineering.

E5f-13504, Rev. S

FR7218, Rev. D

E2E-33784SK - Demolition

E2E-33785SK - Demolition

E2E-98841

E2E-98849

E2E-98850

RR7212, Rev. K

E2E-99961

E2E-33982SK - Demolition

FR7889, Rev. F

E2E-33959SK - Demolition

EE-56684, Rev. C

E2E-33967SK - Demolition

FR7186, Rev. H

E2E-98860

E5f-18191, Rev. L

E5f-19193, Rev. C

E5f-18192, Rev. P

E5f-18881, Rev. K

E2E-91235, Rev. A

E2E-99860

E2E-98849, Rev. A

E2E-98850, Rev. A

E2E-99730

E2E-99947

E2E-99958

E5f-13198, Rev. T

E5f-13209, Rev. G

E5f-13503, Rev. C

The following drawings were prepared by Y-12 Instrument Engineering for CFIL and are stored at Y-12 Engineering (these drawings issued CFC).

12D-55667 GCFR-CFIL Universal Current Detector-Schematic

12D-55668 GCFR-CFIL Universal Current Detector-Photometal Panel Detail

12D-55669 GCFR-CFIL Universal Current Detector P.C. Board Assembly

12D-55670 GCFR-CFIL Universal Current Detector Module Cage Assembly

12E-97913 GCFR-CFIL Universal Current Detector P.C. Board Layout

BM-YIE-8800A-1 GCFR-CFIL Universal Current Detector

The following specifications were prepared by Y-12 Electrical Engineering and are stored with Y-12 Engineering.

ES-YEE-11590-11 480 Volt Unit Substation 7EA and β EB

ES-YEE-11590-12 480 Volt Unit Substation 7EC

ES-YEE-11590-13 480 Volt Unit Substation 7ED

ES-YEE-11590-14 13.8 KV Switchgear

F. Specifications and data sheets

The following specifications and data sheets were completed and are stored by the Experimental Electrical Engineering Department in Building 9201-3.

XEE-11590-001 - 480 volt Motor Control Center

XEE-11590-002 - SCR Power Controller

ES-XEE-11590-15 - 7.5 kVA Uninterruptible Power Supply (UPS)

ES-XEE-11590-12-2 - Variable ac Power Supply (500 kVA, Special Tap Transformer)

ES-XEE-11590-13 - Electrical Load Bank (Dummy Load)

ES-XEE-11590-14 - Water Cooled Resistor Assembly (Balance Resistor)

E-11590-RB-005-X-1 - Variable Frequency Power Supply for the CFTL Helium Circulators

ES-XEE-11590-11-1 - Induction Voltage Regulator

G. Drawings and material lists prepared by Servo Optics Systems of Dallas for the variable frequency power supply to the helium circulators

CFIL VFPS #3 (SOS#1)

<u>Drawing no.</u>	<u>Size</u>	<u>Rev</u>	<u>Title</u>	<u>Source</u>
1720-000-AS	D	A	Schematic diagram: frequency control card w/datel oscillator	Servo
1804-000-AD	D	A	+25, +9, -20 4k Hz power supply bd.	Task
1804-000-AS	C	A	Schematic +25, +9, -20 4k Hz power supply board	Task
1979-000-AD	D	C	Voltage current regulator card ass'y	Task
1979-000-AS	D	B	Schematic voltage current regulator-card ass'y	Task
2507-000-AS	B	B	Schematic gate drive ass'y (2 card)	Task
3544-000-AD	D	C	Logic module ass'y	Task
3544-000-AS	D	C	Schematic logic module	Servo
3661-000-AD	D	D	Monitor card ass'y	Task
3661-000-AS	C	D	Schematic diagram monitor card	Task
4005-000-AD	D	C	Inverter module ass'y series 'D' inverter	Servo
4005-000-AS	C	C	Schematic inverter module series 'D'	Task
4006-000-AD	D	B	Bridge module ass'y series 'D' inverter	Servo
4006-000-AS	B	C	Schematic bridge module	Task
4018-000-AD	C	A	Precharge X'FMR module ass'y	Task
4023-000-AD	C	B	Feedback module ass'y	Task
4067-000-AD	C	A	Power supply ass'y logic module	Servo
4067-000-AS	C	B	Schematic diagram power supply, logic module	Servo
4092-000-AD	B		PCB ass'y detail current limit iso.	Servo
4092-000-AS	C	B	Schematic diagram current limit iso. PCB ass'y	Servo
4121-010-AD	B	A	ISO feedback PCB ass'y	Servo
4121-010-AS	D	A	Schematic diagram ISO feedback PCB	Servo
4128-000-AD	D	C	PCB ass'y options - R1035	Servo
4128-000-AS	D	C	Schematic diagram option PCB - R-035	Servo
R035-001-OD	C	A	System outline detail, 250 kVA inverter	Servo
R035-002-ID	D	A	Interconnection diagram	Servo
R035-100-AD	D	A	Assembly detail series 'DV' inverter	Servo
R035-100-AS	D	C	Schematic diagram inverter assembly	Servo
R035-200-AS	D	C	Schematic diagram inverter assembly unit	Servo
R1035-200-AD	D	B	Assembly detail, unit B inverter	Servo
R035-1CA-AD	B	A	Custom panel assembly unit 'A'	Servo

R035-1CA-AS	C	B	Schematic diagram, custom panel unit 'A'	Servo
R035-1CC-AD	B	A	PCB modification, control card	Servo
R035-1FM-AS	B	B	Schematic diagram feedback module	Servo
R035-1LN-AD	B	A	PCB modification, monitor PCB ass'y (PCA)	Servo
R035-1PT-AS	C	B	Schematic diagram precharge module	Task
R035-2CA-AD	B	A	Custom panel ass'y unit 'B'	Servo
R035-2CA-AS	C	B	Schematic diagram, custom PNL unit 'B'	Servo
R035-ONI-AS	C		Inter connect diag. remote metering	Servo
0780-000-AD	C	B	Optical coupled gate drive bd. ass'y	Servo
0780-000-AS	C	B	Schematic diagram: optical coupled gate drive card ass'y	Servo
0783-000-AS	B		Schematic (3 card) gate drive ass'y	Task
1050-000-AD	D	A	Control card ass'y	Servo
1050-000-AS	D	A	Schematic: control card ass'y	Servo
1050-000-AD	D	B	Start/stop card ass'y	Task
1054-000-AS	D	A	Schematic: start/stop card ass'y	Servo
1210-000-AD	C	B	Gate drive supply card ass'y	Servo
1210-010-AS	C	C	Schematic diagram: gate drive supply mod. ass'y	Servo
1716-000-AD	C	1	Oscillator coil circuit ass'y-DATEL VFV-10 k	Servo
1716-060-AS	C		Schematic diagram oscillator coil circuit DATEL VFV-10 k	Servo
1720-000-AD	D	D	Frequency control card ass'y with DATEL oscillator 3	Servo

Material list	Size	Rev	Title	Source
R035-100-ML	A	C	Sht. 1 customer inverter ass'y unit 'A' Sht. 2 Sht. 3	Servo
R035-200-ML	A	B	Sht. 1 customer inverter ass'y with 'B' Sht. 2 Sht. 3	Servo
R035-1CA-ML	A	A	Sht. 1 customer panel ass'y unit 'A'	Servo
R035-1CC-ML	A	A	Sht. 1 modification: control PCB ass'y	(PCI) Servo
R035-1CF-ML	A	A	Sht. 1 DC bus capacitor bank ass'y Sht. 2	Servo
R035-1CP-ML	A	A	Sht. 1 controls plate ass'y	Servo
R035-1CR-ML	A	A	Sht. 1 modification: logic module	Servo
R035-1LM-ML	A	A	Sht. 1 modification: monitor PCB ass'y	Servo
R035-1MA-ML	A	A	Sht. 1 modification ass'y Sht. 2	Servo
R035-2CA-ML	A	A	Sht. 1 custom panel ass'y unit 'B'	Servo
R035-2CP-ML	A	A	Sht. 1 controls plate	Servo
R035-2MA-ML	A	A	Sht. 1 modification ass'y	Servo
0780-000-ML	A	B	Sht. 1 gate drive board	Servo
0780-000-ML	A	B	Sht. 2	Servo
0783-000-ML	A		Sht. 1 gate drive - 3 cards	Servo
1050-000-ML	A	A	Sht. 1 control card assembly Sht. 2 Sht. 3	Task
1054-000-ML	A	B	Sht. 1 start/stop card w/accel/decel and pause Sht. 2 Sht. 3 Sht. 4	Task
1210-010-ML	A	A	Sht. 1 4 kHz PCB ass'y Sht. 2	Servo
1716-000-ML	A	B	Sht. 1 oscillator coil circuit sht. 2	Task
1720-000-ML	A	E	Sht. 1 freq. control card w/DATTEL osc. Sht. 2 Sht. 3 Sht. 4	Task
1804-000-ML	A		Sht. 1 +24, +9, -20 4 kHz power supply board Sht. 2	Task
1979-000-ML	A	B	Sht. 1 V.I. card ass'y Sht. 2 Sht. 3	Task
2507-000-ML	A		Sht. 1 gate drive - 2 cards	Servo
3544-000-ML	A	E	Sht. 1 logic module, variable bus Sht. 2	Servo

3661-000-ML	A	D	Sht. 1 monitor card ass'y	Task
			Sht. 2	
			Sht. 3	
4005-000-ML	A	C	Sht. 1 inverter module ass'y series 'D'	Servo
			Sht. 2	
			Sht. 3	
4006-000-ML	A	C	Sht. 1 bridge module series 'D'	Task
			Sht. 2	
			Sht. 3	
			Sht. 4	
4018-000-ML	A	B	Sht. 1 precharge module series 'D'	Servo
			Sht. 2	
			Sht. 3	
4023-000-ML	A	B	Sht. 1 feedback module series 'D'	Task
			Sht. 2	
4036-000-ML	A	D	Sht. 1 standard inverter ass'y series	Servo
			'DV'	
			Sht. 2	
			Sht. 3	
			Sht. 4	
			Sht. 5	
			Sht. 6	
4067-000-ML	A	B	Sht. 1 power supply ass'y logic module	Servo
			Sht. 2	
			Sht. 3	
4092-000-ML	A	C	Sht. 1 current limit iso. PCB ass'y	Servo
			Sht. 2	
4121-010-ML	A	F	Sht. 1 feedback module 3 channel iso.	Servo
			Sht. 2	
			Sht. 3	
			Sht. 4	
4128-000-AS	A	C	Sht. 1 option PCB ass'y (R035)	Servo
			Sht. 2	
			Sht. 3	
			Sht. 4	
			Sht. 5	

CPIL VFP2 1 and 2 (R05 2 and 3)

R035-002-ID	A	Interconnection diagram, UCC
R690-301-AD	A	Freq. control PC ass'y w/DATF, osc. (Sh. 2 of 2)
R690-301-AD	A	Freq. control PC ass'y w/DATF, osc. (Sh. 1 of 2)
4005-000-AS	C	Inverter module schematic series D
R690-0PT-AS	A	Schematic diagram - option PCB
R690-0PT-AD	A	PCB ass'y options
R1690-100-AD	A	Cabinet layout, Unit A inverter
R1690-200-AD	A	Cabinet layout, Unit B inverter
R690-100-AS	A	Schematic diagram, inverter ass'y, series DV, Unit A
R690-200-AS	A	Schematic diagram, inverter ass'y, series DV, Unit B
R690-306-AD	A	Start/stop card ass'y
R690-306-AS	A	Start/stop card ass'y schematic
R1690-304-AD	A	Control PC board ass'y
R1690-304-AS	A	Control PC board ass'y schematic
R690-305-AD	A	V/I regulator card ass'y
R690-305-AS	A	V/I regulator card ass'y schematic
R690-303-AD	A	Monitor card ass'y
R690-303-AS	A	Monitor card schematic
R690-301-AS	A	Freq. control card w/DATF, osc, schematic
4006-000-AD	C	Bridge module ass'y, Series B inverter
4005-000-AD	C	Inverter module ass'y, Series D inverter
3544-000-AS	C	Logic module, schematic
4092-000-AS	D	Current limit isolation, PCB ass'y, schematic
4006-000-AS	D	Bridge module Series D, schematic
0780-000-AS	B	Optical coupled gate drive card ass'y
4018-000-AS	E	Precharge module - schematic
1210-000-AS	B	Gate drive supply module ass'y schematic
4067-000-AS	B	Power supply logic module, schematic
1804-000-AS	A	Power supply board, +25, +9, -20, 4 kHz schematic
1169-010-AS	C	Six-stop Hertz meter PCB ass'y, schematic
1169-010-AD	D	Six-stop Hertz meter PCB ass'y, schematic
R035-1FT-AS	C	Precharge module schematic
R035-20A-AS	B	Custom panel, Unit B schematic
R690-10A-AS	A	Custom panel, Unit A schematic
R035-10A-AS	B	Custom panel, Unit A schematic
4023-000-AS	C	Feedback module, schematic
R035-1FM-AS	B	Feedback module, schematic
0783-000-AS	A	Gate drive ass'y (3-card) schematic
2507-000-AS	C	Gate drive ass'y (2-card) schematic
R035-0MI-AS	-	Interconnection, remote metering
1057-000-AS	B	Voltmeter ass'y
AD		
1064-000-AS	A	Ammeter ass'y
AD		

I. GENERAL SYSTEM

<u>Dwg. No.</u>	<u>Title</u>
I2D-11590-Q600	Instrument Application Tabulation
I2D-11590-Q601	Instrument Application Diagram, Sheet 1
I2D-11590-Q602	Instrument Application Diagram, Sheet 2
I2D-11590-Q603	Instrument Application Diagram, Sheet 3
I2D-11590-Q604	Instrument Power Distribution, Sheet 1
I2D-11590-Q605	Instrument Power Distribution, Sheet 2
I2D-11590-Q607	Instrument Piping Schematic
I2D-11590-Q608	Instrument Air Supply Schematic
I2D-11590-Q610	Control Circuits Block Diagram, Sheet 1
I2D-11590-Q611	Control Circuits Block Diagram, Sheet 2
I2D-11590-Q613	Circulator No. 1 Control Circuits Engineering Elementary Diagram
I2D-11590-Q614	Circulator No. 2 Control Circuits Engineering Elementary Diagram
I2D-11590-Q615	Circulator No. 3 Control Circuits Engineering Elementary Diagram
I2D-11590-Q616	Process Instrument Switch Tabulation

II. LAYOUT DRAWINGS

I2D-11590-Q100	Control Room Layout, Plan View
I2D-11590-Q747	Main Control Board Cabinet Arrangement Drawing
I2D-11590-Q855	Auxiliary Control Board Cabinet Arrangement Drawing
I2D-11590-Q151	Thermocouple Signal Conditioning Cabinet Front Panel Layout

III. CONTROL SYSTEM

I2D-11590-Q617	Control Circuit Engineering Elementary Diagram, Sheet 1
I2D-11590-Q618	Control Circuit Engineering Elementary Diagram, Sheet 2
I2D-11590-Q619	Control Circuit Engineering Elementary Diagram, Sheet 3

All of these materials are stored by the ORNL Instrumentation and Controls Division at File Point QD-4 which is located in Room 269, Building 9201-3, Y-12 Plant.

<u>Dwg. No.</u>	<u>Title</u>
I2D-11590-Q520	Control Circuit Engineering Elementary Diagram, Sheet 4
I2D-11590-Q621	Control Circuit Engineering Elementary Diagram, Sheet 5
I2D-11590-Q622	Control Circuit Engineering Elementary Diagram, Sheet 6
I2D-11590-Q623	Control Circuit Engineering Elementary Diagram, Sheet 7
I2D-11590-Q624	Control Circuit Engineering Elementary Diagram, Sheet 8
I2D-11590-Q625	Control Circuit Engineering Elementary Diagram, Sheet 9
I2D-11590-Q626	Control Circuit Engineering Elementary Diagram, Sheet 10
I2D-11590-Q900	Control Circuit Maintenance Elementary Diagram, Sheet 1
I2D-11590-Q901	Control Circuit Maintenance Elementary Diagram, Sheet 2
I2D-11590-Q902	Control Circuit Maintenance Elementary Diagram, Sheet 3
I2D-11590-Q903	Control Circuit Maintenance Elementary Diagram, Sheet 4
I2D-11590-Q904	Control Circuit Maintenance Elementary Diagram, Sheet 5
I2D-11590-Q905	Control Circuit Maintenance Elementary Diagram, Sheet 6
I2D-11590-Q906	Control Circuit Maintenance Elementary Diagram, Sheet 7
I2D-11590-Q907	Control Circuit Maintenance Elementary Diagram, Sheet 8
I2D-11590-Q908	Control Circuit Maintenance Elementary Diagram, Sheet 9
I2D-11590-Q909	Control Circuit Maintenance Elementary Diagram, Sheet 10
I2D-11590-Q910	PLC Logic Diagram, Sheet 1
I2D-11590-Q911	PLC Logic Diagram, Sheet 2
I2D-11590-Q912	PLC Logic Diagram, Sheet 3
I2D-11590-Q913	PLC Logic Diagram, Sheet 4
I2D-11590-Q914	PLC Logic Diagram, Sheet 5
I2D-11590-Q915	PLC Logic Diagram, Sheet 6
I2D-11590-Q916	PLC Logic Diagram, Sheet 7

IV. INSTRUMENT SIGNAL CIRCUITS

<u>Dwg. No.</u>	<u>Title</u>
I2D-11590-Q633	Loop #103B, HX1 Helium Outlet Temperature
I2D-11590-Q634	Loop #106, HX1 Inlet Air Temperature
I2D-11590-Q635	Loop #107, HX1 Outlet Air Temperature
I2D-11590-Q637	Loop #111A, HX1 Helium Inlet Temperature
I2D-11590-Q651	Loop #1, Helium Flow Control Valve
I2D-11590-Q652	Loop #2, Helium Flow Control Valve
I2D-11590-Q653	Loop #4, Helium Flow Measurement
I2D-11590-Q654	Loop #6, Helium Temperature
I2D-11590-Q655	Loop #12, Circulator No. 3 Helium Discharge Temperature
I2D-11590-Q656	Loop #13, Circulator No. 2 Helium Discharge Temperature
I2D-11590-Q657	Loop #14, Circulator No. 1 Helium Discharge Temperature
I2D-11590-Q658	Loop #15, Circulator No. 1 Helium Intake Temperature
I2D-11590-Q659	Loop #17, Helium Filter Differential Pressure
I2D-11590-Q660	Loop #30, Circulator No. 1 Input Power Measurement
I2D-11590-Q661	Loop #31, Circulator No. 2 Input Power Measurement
I2D-11590-Q662	Loop #32, Circulator No. 3 Input Power Measurement
I2D-11590-Q663	Loop #101, HX1 Air Outlet Damper Control
I2D-11590-Q665	Loop #108, HX1 Fan Inlet Vane Control
I2D-11590-Q666	Loop #300, Test Piece Power Measurement
I2D-11590-Q676	Loop #5, Circulator No. 3 Helium Discharge Pressure
I2D-11590-Q677	Loop #11, Helium Flow Measurement
I2D-11590-Q678	Loop #16, Circulator No. 1 Intake Pressure
I2D-11590-Q679	Loop #103A, HX1 Helium Outlet Temperature
I2D-11590-Q680	Loop #104, Fan Speed Control
I2D-11590-Q681	Loop #111B, HX1 Helium Inlet Temperature
I2D-11590-Q682	Induction Regulator A Control Schematic
I2D-11590-Q683	Induction Regulator B Control Schematic
I2D-11590-Q684	Loop #27, #28, and #29, Circulator Speed Control
I2D-11590-Q689	Circulator Temperature Measurement Circuits
I2D-11590-Q690	Loop #24, Circulator No. 1 Speed Measurement

<u>Dwg. No.</u>	<u>Title</u>
I2D-11590-Q691	Loop #25, Circulator No. 2 Speed Measurement
I2D-11590-Q692	Loop #26, Circulator No. 3 Speed Measurement
I2D-11590-Q693	Circulator Bearing Monitor Circuits, Sheet 1
I2D-11590-Q694	Circulator Bearing Monitor Circuits, Sheet 2
I2D-11590-Q695	Loop #46, Circulator Differential Pressure
I2D-11590-Q712	Zone Power Control Station Power Supply Schematic
I2D-11590-Q759	Zone A Power Control Schematic, Sheet 1
I2D-11590-Q760	Zone A Power Control Schematic, Sheet 2
I2D-11590-Q761	Zone B Power Control Schematic, Sheet 1
I2D-11590-Q762	Zone B Power Control Schematic, Sheet 2

V. FABRICATION DRAWINGS

A. Main Control Boards

I2D-11590-Q701	Main Control Board MB1, Assembly Drawing
I2D-11590-Q702	Main Control Board MB2 Assembly Drawing
I2D-11590-Q703	Main Control Board MB3 Assembly Drawing
I2D-11590-Q704	Main Control Board MB4 Assembly Drawing
I2D-11590-Q714	Annunciator Window Location and Lettering
I2D-11590-Q715	Annunciator Pushbutton Panel Assembly
I2D-11590-Q716	Pressure Indication Panel Assembly
I2D-11590-Q717	Pushbutton and Meter Panel Assembly
I2D-11590-Q718	Heat Exchanger No. 1 Control Panel Assembly
I2D-11590-Q719	Flow and Power Indication Panel Assembly
I2D-11590-Q720	Zone Power Supply Control Station, Panel Assembly
I2D-11590-Q721	Control Valve Control Panel Assembly
I2D-11590-Q722	Robicon Interface Board, Assembly Drawing
I2D-11590-Q723	Robicon Interface Board, Details
I2D-11590-Q728	MB1 and MB3 Panel Cutouts
I2D-11590-Q729	MB1 and MB3 Panel Assemblies
I2D-11590-Q746	Switch Legend Chart
I2D-11590-Q758	Induction Regulator Pushbutton Panel Assembly
I2D-11590-Q803	Induction Regulator Speed Control Panel Assembly
I2D-11590-Q809	FRS Power Control Station Power Supply Assembly
I2D-11590-Q810	FRS Power Control Station Power Supply Panel Cutouts

B. Auxiliary Control Boards

<u>Dwg. No.</u>	<u>Title</u>
I2D-11590-Q812	PLC and Power Supply Panel Assembly
I2D-11590-Q820	Communications Power Supply Panel Assembly
I2D-11590-Q850	Auxiliary Control Board AB1 Assembly Drawing
I2D-11590-Q851	Auxiliary Control Board AB2 Assembly Drawing
I2D-11590-Q852	Auxiliary Control Board AB3 Assembly Drawing
I2D-11590-Q853	Auxiliary Control Board AB4 Assembly Drawing
I2D-11590-Q854	Auxiliary Control Board AB5 Assembly Drawing
I2D-11590-Q862	Alarm Panel Assembly
I2D-11590-Q867	Power Supply Panel Cutout
I2D-11590-Q868	Power Supply Panel Assembly

C. Thermocouple Signal Conditioning Cabinets

I2D-11590-Q152	Thermocouple Signal Conditioning Cabinets SC1 through SC3, Assembly Drawing
I2D-11590-Q153	Thermocouple Signal Conditioning Cabinet SC4, Assembly Drawing
I2D-11590-Q154	Thermocouple Signal Conditioning Cabinet SC5, Assembly Drawing
I2D-11590-Q155	Thermocouple Signal Conditioning Cabinet SC5, Subassembly and Details
I2D-11590-Q156	Thermocouple Signal Conditioning Cabinets SC1 through SC5, Mechanical Details
I2D-11590-Q157	Thermocouple Signal Conditioning Cabinet SC1, Cabling Diagram
I2D-11590-Q153	Thermocouple Signal Conditioning Cabinet SC2, Cabling Diagram
I2D-11590-Q159	Thermocouple Signal Conditioning Cabinet SC3, Cabling Diagram
I2D-11590-Q160	Thermocouple Signal Conditioning Cabinet SC4, Cabling Diagram
I2D-11590-Q161	Thermocouple Signal Conditioning Cabinet SC5, Cabling Diagram
I2D-11590-Q162	Thermocouple Signal Conditioning Cabinets, Misc. Connector Wiring Details
I2D-11590-Q163	Thermocouple Signal Conditioning Cabinets, Misc. Wiring Details
I2D-11590-Q164	Thermocouple Signal Conditioning Cabinet SC1, Interconnection Tabulation
I2D-11590-Q165	Thermocouple Signal Conditioning Cabinet SC2, Interconnection Tabulation

<u>Dwg. No.</u>	<u>Title</u>
I2D-11590-Q166	Thermocouple Signal Conditioning Cabinet SC3, Interconnection Tabulation
I2D-11590-Q167	Thermocouple Signal Conditioning Cabinet SC4, Interconnection Tabulation

D. Instrument Racks

I2D-11590-Q857	Helium Fill Station Assembly Drawing
I2D-11590-Q858	Valve Mounting Bracket Details
I2D-11590-Q860	Valve Mounting Bracket Details
I2D-11590-Q880	Circulator Instrument Rack Assembly Drawing
I2D-11590-Q886	Circulator Instrument Rack Piping Details
I2D-11590-Q890	HX1 Instrument Rack Assembly Drawing

E. Cable Trays, Conduit, Junction Boxes, and Piping

I2D-11590-Q101	Control Room and Loop Area Cable Tray Layout, Sheet 1
I2D-11590-Q102	Control Room and Loop Area Cable Tray Layout, Sheet 2
I2D-11590-Q103	Control Room and Loop Area Cable Tray Details
I2D-11590-Q111	Control Room and Loop Area Conduit, Junction Box, and Piping Layout, Sheet 1
I2D-11590-Q112	Control Room and Loop Area Conduit, Junction Box, and Piping layout, Sheet 2
I2D-11590-Q113	Circulator Junction Box Installation and Details, Sheet 1
I2D-11590-Q114	Circulator Junction Box Installation and Details, Sheet 2
I2D-11590-Q115	Penthouse and Circulator Conduit and Piping Routing
I2D-11590-Q031	Vortex Shedding Flowmeter Sensor and Signal Conditioner Wiring Diagram
I2D-11590-Q032	Loop Temperature Sensor - RTD Installation Details, Sheet 1 of 2
I2D-11590-Q033	Loop Temperature Sensor - TC Installation Details, Sheet 2 of 2

VI. WIRING DIAGRAMS

A. Panel Wiring

I2D-11590-Q713	Zone Power Control Station Power Supply Wiring Diag.
I2D-11590-Q763	Main Control Board MBI Front Panel Wiring Diagram

<u>Dwg. No.</u>	<u>Title</u>
I2D-11590-Q764	Main Control Board MB1 Rear Panel Wiring Diagram
I2D-11590-Q765	Main Control Board MB2 Panel Wiring Diagram
I2D-11590-Q766	Main Control Board MB2 Rear Wiring Diagram
I2D-11590-Q767	Main Control Board MB3 Panel Wiring Diagram
I2D-11590-Q769	Main Control Board MB4 Panel Wiring Diagram
I2D-11590-Q778	Auxiliary Control Board AB1 Front Wiring Diagram, Sheet 1
I2D-11590-Q779	Auxiliary Control Board AB1 Front Wiring Diagram, Sheet 2
I2D-11590-Q780	Auxiliary Control Board AB1 Rear Wiring Diagram
I2D-11590-Q781	Auxiliary Control Board AB2 Front Wiring Diagram
I2D-11590-Q782	Auxiliary Control Board AB3 Wiring Diagram, Sheet 1
I2D-11590-Q783	Auxiliary Control Board AB3 Wiring Diagram, Sheet 2
I2D-11590-Q784	Auxiliary Control Board AB4 Wiring Diagram
I2D-11590-Q787	Auxiliary Control Board AB5 Rear Wiring Diagram
I2D-11590-Q790	Cable Tabulation
I2D-11590-Q792	Signal Conditioning Cabinet SC3 Connection Tabulation
I2D-11590-Q869	Power Supply Panel Wiring Diagram
B. Interconnection Wiring	
I2D-11590-Q770	Main Control Boards MB1 and MB2 Interconnection Diagram
I2D-11590-Q771	Main Control Boards MB3 and MB4 Interconnection Diagram
I2D-11590-Q772	Auxiliary Control Boards AB1 and AB2 Interconnection Diagram
I2D-11590-Q773	Auxiliary Control Boards AB3 Interconnection Diagram
I2D-11590-Q774	Auxiliary Control Boards AB4 and AB5 Interconnection Diagram
I2D-11590-Q775	Instrument Rack Interconnection Diagram
I2D-11590-Q776	Circulator and Signal Cond. Cabinet SC3, Interconnection Diagram
I2D-11590-Q777	Field Instruments Interconnection Diagram

VII. SPECIAL INSTRUMENTS

<u>Dwg. No.</u>	<u>Title</u>
A. VSFM Frequency-to-DC Converter	
Q5825-1	Vortex Shedding Flowmeter F/V Converter
Q5825-2	Vortex Shedding Flowmeter F/V Converter
B. Zone Power Supply Controller	
Q5788-1	Isolation Amplifier - Schematic
Q5788-2	Isolation Amplifier - Rear View Interconnection Diagram
Q5788-3	NRC Isolation Amplifier Etched Wiring Board
Q5489-21	System Overview
Q5489-22	Analog Signal Conditioner Circuit Diagram
Q5489-24	Strobeless 4 Bit Analog to Digital Converter Circuit Diagram
Q5489-26	High Accuracy Converter Circuit and Block Diagram
Q5489-33	Timing and Control Signals Circuit Diagram
Q5489-38	Analog Error Monitoring Board Circuit Diagram
Q5489-40	Error Latching Board Circuit Diagram
Q5489-42	Four Mode Multiplexer Circuit Diagram
Q5489-44	Litronix Opoisolator Interface
Q5489-50	Mother Board Connectors Interconnecting Layout
Q5489-52	Robicon to ZPCS Interface Circuit Diagrams
Q5489-54	Robicon to ZPCS Interface Circuit Diagrams
C. Circulator Speed Monitor	
Q2922-45A	Circulator Speed Monitor, Schematic Diagram
Q2922-45B	Circulator Speed Monitor, Printed Circuit Board Layout

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Appendix 4

CPTL INSTRUMENT SPECIFICATION TABULATION

<u>Spec. No.</u>	<u>Title</u>
IS-11590-QG-001	Helium Control Valves*
IS-11590-QG-002	Gas Chromatograph*
IS-11590-QG-003	Trace Moisture Analyzer
IS-11590-QG-004	CAMAC Crate & Crate Controller*
IS-11590-QG-005	CAMAC Module, Thermocouple Input*
IS-11590-QG-006	CAMAC Module, Analog Input*
IS-11590-QG-007	CAMAC Module, Contact Input*
IS-11590-QG-008	CAMAC Module, Contact Input*
IS-11590-QG-009	CAMAC Module, Triac Output*
IS-11590-QG-010	CAMAC, Isolated Binary Output*
IS-11590-QG-011	CAMAC, Watchdog Timer*
IS-11590-QG-012	CAMAC, Dataway Display*
IS-11590-QG-013	CAMAC, 4-20 ma Driver*
IS-11590-QG-014	Reference Box, Uniform Temperature
IS-11590-QG-015	Oscilloscope, Dual Beam
IS-11590-QG-016	Gauge, Pressure, Digital
IS-11590-QG-017	Gauge, Pressure, Digital*
IS-11590-QG-018	
IS-11590-QG-019	Helium Control Valves (Bellows Sealed)*
IS-11590-QG-020	Helium Control Valves (Packed Seal)*
IS-11590-QG-021	
IS-11590-QG-022	Controller, Manual Ratio*
IS-11590-QG-023	
IS-11590-QG-024	
IS-11590-QG-025	
IS-11590-QG-026	Hydraulic Valve Actuator & Power Supply*
IS-11590-QG-027	Flowmeter, Air Velocity Measurement*
IS-11590-QG-028	Vortex Shedding Flowmeter Elements

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*For CFTL Stage One. All others for CFTL Stage Alpha.

<u>Spec. No.</u>	<u>Title</u>
IS-11590-QG-029	Acoustic Noise Measuring System*
IS-11590-QG-030	Vibration Measuring System*
IS-11590-QG-031	Multichannel Temperature Monitor, 0-1200°C*
IS-11590-QG-032	Multichannel Temperature Monitor, 0-500°C
IS-11590-QG-033	
IS-11590-QG-034	
IS-11590-QG-035	
IS-11590-QG-036	Reference Box, Ice Point*
IS-11590-QG-037	
IS-11590-QG-038	Calibration of VSPM Flowmeters
IS-11590-QG-039	
IS-11590-QG-040	
IS-11590-QG-041	
IS-11590-QG-042	
IS-11590-QG-043	
IS-11590-QG-044	Temperature Sensor, RTD, Platinum Resis.
IS-11590-QG-045	Temperature Transmitter, RTD, Line Powered
IS-11590-QG-046	Valve, Hand, 3/8"
IS-11590-QG-047	Recorder, 4-pen, Strip Chart
IS-11590-QG-048	
IS-11590-QG-049	
IS-11590-QG-050	
IS-11590-QG-051	
IS-11590-QG-052	
IS-11590-QG-053	
IS-11590-QG-054	
IS-11590-QG-055	
IS-11590-QG-056	
IS-11590-QG-057	
IS-11590-QG-058	
IS-11590-QG-059	

*For CFTL Stage One. All others for CFTL Stage Alpha.

<u>Spec. No.</u>	<u>Title</u>
IS-11590-QG-060	
IS-11590-QG-061	
IS-11590-QG-062	
IS-11590-QG-063	
IS-11590-QG-064	
IS-11590-QG-065	Counter, Digital Panel
IS-11590-QG-066	Voltmeter, Digital Panel
IS-11590-QG-067	
IS-11590-QG-068	
IS-11590-QG-069	Power Supply, 5 VDC, 1A
IS-11590-QG-070	Power Supply, <u>+15</u> VDC, 7A
IS-11590-QG-071	Power Supply, 10 VDC, 12A
IS-11590-QG-072	Power Supply, 48 VDC, 2.6A
IS-11590-QG-073	Switch, Thumbwheel, Binary Code d
IS-11590-QG-074	Annunciator
IS-11590-QG-075	
IS-11590-QG-076	
IS-11590-QG-077	
IS-11590-QG-078	
IS-11590-QG-079	
IS-11590-QG-080	Enclosure, Signal Transmitter & Alarm
IS-11590-QG-081	Switch, Voltage
IS-11590-QG-082	Switch, Millivolt*
IS-11590-QG-083	Transmitter, Millivolt*
IS-11590-QG-084	Transmitter, AC Voltage
IS-11590-QG-085	Transmitter, Track and Hold*
IS-11590-QG-086	Oxygen Monitor
IS-11590-QG-087	Controller, Auto/Manual with Remote/Local Setpoint
IS-11590-QG-088	
IS-11590-QG-089	Recorder, Multipoint

*For CPTL Stage One. All others for CPTL Stage Alpha.

<u>Spec. No.</u>	<u>Title</u>
IS-11590-QG-090	Switch, Pressure
IS-11590-QG-091	
IS-11590-QG-092	Switch, Voltage
IS-11590-QG-093	Switch, Voltage
IS-11590-QG-094	Cabinet, Instrument
IS-11590-QG-095	Cabinet, Instrument
IS-11590-QG-096	Process Monitor, Digital
IS-11590-QG-097	PLC System
IS-11590-QG-098	Power Supply, 12 VDC
IS-11590-QG-099	Switch, Pushbutton
IS-11590-QG-100	
IS-11590-QG-101	
IS-11590-QG-102	Controller, Manual
IS-11590-QG-103	
IS-11590-QG-104	Transmitter, Differential Pressure
IS-11590-QG-105	
IS-11590-QG-106	
IS-11590-QG-107	Converter, Current to Pneumatic
IS-11590-QG-108	Recorder, 2-Pen Strip Chart
IS-11590-QG-109	Switch, Thumbwheel, BCD Coded
IS-11590-QG-110	Potentiometer, Ten Turn
IS-11590-QG-111	Potentiometer, 3 Gang Ten Turn
IS-11590-QG-112	Power Supply, 24V, 15A
IS-11590-QG-113	Flow Orifice Assembly, Integral
IS-11590-QG-114	Transmitter, Differential Pressure, Pneumatic
IS-11590-QG-115	Gauge, Receiver
IS-11590-QG-116	Gauge, Pressure
IS-11590-QG-117	Valve, Hand, Bellows Seal
IS-11590-QG-118	Valve, Hand, Severe Service, Cv = 0.24
IS-11590-QG-119	Valve, Hand, Severe Service, Cv = 1.9
IS-11590-QG-120	
IS-11590-QG-121	Regulator, Pressure Reducing, Non-Relieving
IS-11590-QG-122	Valve, Pressure Relief
IS-11590-QG-123	

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Appendix 5

**INSTRUMENTATION AND CONTROLS TABULATION OF INCOMPLETE
DRAWINGS FOR STAGE 1 CFTL**

<u>Drawing No.</u>	<u>Title</u>
I2D-11590-Q001	Test Vessel I.A.D.
I2D-11590-Q002	Circulator & HX-2, I.A.D.
I2D-11590-Q003	Test Vessel He Flow & HX-1 I.A.D.
I2D-11590-Q004	He Fill Cleanup & Impurities System I.A.D.
I2D-11590-Q005	Zone Power Supply (Typ.) I.A.D.
I2D-11590-Q006	Circulator & HX-2 T.E. Diagram
I2D-11590-Q010	Instrumentation Application Tabulation
I2D-11590-Q011	Signals One Line Diagram Circ. Speed & Pwr.
I2D-11590-Q012	Signals One Line Diagram Valve Control (Typ. FCV-1, 2, & 3)
I2D-11590-Q013	Signals One Line Diagram Flow Measurement
I2D-11590-Q014	Signals One Line Diagram Circ. Bearing Monitor
I2D-11590-Q015	Signals One Line Diagram Ht. Exchanger Cont. Sh. 1
I2D-11590-Q016	Signals One Line Diagram Ht. Exch. Cont. Sh. 2
I2D-11590-Q017	Signals One Line Diagram Zone Pwr. Cont. (Typ. 13 zones)
I2D-11590-Q035	Main Control Boards Grounding
I2D-11590-Q041	EIC External Voltages & Signals Conn. Cards P1A & P2A Conn. Diag.
I2D-11590-Q042	EIC External Voltages & Signals Conn. Cards P1B & P2B Conn. Diag.
I2D-11590-Q043	EIC External Voltages & Sig. Conn. Cards P1C & P2C Conn. Diag.
I2D-11590-Q044	EIC External Voltages & Sig. Conn. Cards P1D & P2D Conn. Diag.
I2D-11590-Q045	EIC External Voltages & Sig. Conn. Cards P1E & P2E Conn. Diag.
I2D-11590-Q046	EIC External Voltages & Sig. Conn. Cards P1F & P2F Conn. Diag.

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<u>Drawing No.</u>	<u>Title</u>
I2D-11590-Q047	EIC External Voltages & Sig. Conn. Cards P1G & P2G Conn. Diag.
I2D-11590-Q048	EIC External Voltages & Sig. Conn. Cards P1H & P2H Conn. Diag.
I2D-11590-Q049	EIC External Voltages & Sig. Conn. Cards P1J & P2J Conn. Diag.
I2D-11590-Q050	EIC External Voltages & Sig. Conn. Cards P1K & P2K Conn. Diag.
I2D-11590-Q051	EIC External Voltages & Sig. Conn. Cards P1L & P2L Conn. Diag.
I2D-11590-Q052	EIC External Voltages & Sig. Conn. Cards P1M & P2M Conn. Diag.
I2D-11590-Q053	EIC External Voltages & Sig. Conn. Cards P1N & P2N Conn. Diag.
I2D-11590-Q054	EIC External Voltages & Sig. Conn. Cards P1SP & P2SP Conn. Diag.
I2D-11590-Q055	Robicon Pwr. Supply Conn. J1A & J2A Conn. Diag.
I2D-11590-Q056	Robicon Pwr. Supply Conn. J1B & J2B Conn. Diag.
I2D-11590-Q057	Robicon Pwr. Supply Conn. J1C & J2C Conn. Diag.
I2D-11590-Q058	Robicon Pwr. Supply Conn. J1D & J2D Conn. Diag.
I2D-11590-Q059	Robicon Pwr. Supply Conn. J1E & J2E Conn. Diag.
I2D-11590-Q060	Robicon Pwr. Supply Conn. J1F & J2F Conn. Diag.
I2D-11590-Q061	Robicon Pwr. Supply Conn. J1G & J2G Conn. Diag.
I2D-11590-Q062	Robicon Pwr. Supply Conn. J1H & J2H Conn. Diag.
I2D-11590-Q063	Robicon Pwr. Supply Conn. J1J & J2J Conn. Diag.
I2D-11590-Q064	Robicon Pwr. Supply Conn. J1K & J2K Conn. Diag.
I2D-11590-Q065	Robicon Pwr. Supply Conn. J1L & J2L Conn. Diag.
I2D-11590-Q066	Robicon Pwr. Supply Conn. J1M & J2M Conn. Diag.
I2D-11590-Q067	Robicon Pwr. Supply Conn. J1N & J2N Conn. Diag.
I2D-11590-Q068	Robicon Pwr. Supply Conn. J1SP & J2SP Conn. Diag.
I2D-11590-Q070	Circulator Power Supply Simplified Diagram
I2D-11590-Q071	Control Circuits E.E.D., Sheet 1
I2D-11590-Q072	Control Circuits E.E.D., Sheet 2
I2D-11590-Q073	Control Circuits E.E.D., Sheet 3

<u>Drawing No.</u>	<u>Title</u>
I2D-11590-Q074	Control Circuits E.E.D., Sheet 4
I2D-11590-Q075	Control Circuits E.E.D., Sheet 5
I2D-11590-Q076	Control Circuits E.E.D., Sheet 6
I2D-11590-Q077	Control Circuits E.E.D., Sheet 7
I2D-11590-Q079	Control Circuits E.E.D., Sheet 9
I2D-11590-Q080	Control Circuits E.E.D., Sheet 10
I2D-11590-Q081	Control Circuits E.E.D., Sheet 11
I2D-11590-Q082	Control Circuits Block Diagram, Sh. 1
I2D-11590-Q083	Control Circuits Block Diagram, Sh. 2
I2D-11590-Q084	Control Circuits Block Diagram, Sh. 3
I2D-11590-Q089	Main Board Cab. Mech. Details, Sh. 1
I2D-11590-Q090	Main Board Cab. Mech. Details, Sh. 2
I2D-11590-Q091	Annunciator Circuits M.E.D., Sh. 1
I2D-11590-Q092	Annunciator Circuits M.E.D., Sh. 2
I2D-11590-Q093	Annunciator Circuits M.E.D., Sh. 3
I2D-11590-Q094	Main Control Board #10 Front Wiring Inter-connection Diagram
I2D-11590-Q095	Main Control Board #10 Rear Wiring Inter-connection Diagram
I2D-11590-Q096	Main Control Board #11 Front Wiring Inter-connection Diagram
I2D-11590-Q097	Main Control Board #11 Rear Wiring Inter-connection Diagram
I2D-11590-Q098	Main Control Board #12 Front Wiring Inter-connection Diagram
I2D-11590-Q099	Main Control Board #12 Rear Wiring Inter-connection Diagram
I2D-11590-Q105	Main Control Board Cab. MB1 thru MB4 Front Elevation
I2D-11590-Q106	Main Control Board Cabs. MB5 thru MB9 Front Elevation
I2D-11590-Q107	Main Control Board Cabs. MB10 thru MB12 Front Elevation
I2D-11590-Q108	Main Board Cabinets Physical Assy. Sh. 1
I2D-11590-Q109	Main Board Cabinets Physical Assy. Sh. 2
I2D-11590-Q124	Cab. MB-3 Assy. & Parts List

<u>Drawing No.</u>	<u>Title</u>
I2D-11590-Q128	Main Control Board #4 Panel Cutouts
I2D-11590-Q130	Main Control Boards 10, 11, & 12 Cabinet Assy. & Parts List
I2D-11590-Q131	Main Control Boards 10, 11 & 12 Panel Cutouts
I2D-11590-Q132	Main Control Board #10 Wiring
I2D-11590-Q133	Main Control Board 10, 11 & 12 Cab. Assy. & Parts List, Sh. 2
I2D-11590-Q134	Main Control Board #11 Rear Wiring
I2D-11590-Q135	Main Control Board #12 Rear Wiring
I2D-11590-Q169	Zone Power Supply MCB-10 Cab. Assy.
I2D-11590-Q170	Zone Power Supply Control Panel & Assy.
I2D-11590-Q171	Main Control Board 10, 11, & 12 Panel Cutouts
I2D-11590-Q172	Wiring Diag. Zone Power Supply Control Panel A & B
I2D-11590-Q173	Wiring Diagram Zone Power Supply Control Panel C & D
I2D-11590-Q174	Wiring Diagram Zone Power Supply Control Panel E & F
I2D-11590-Q175	Wiring Diagram Zone Power Supply Control Panel G & H
I2D-11590-Q176	Wiring Diagram Zone Power Supply Control Panel J & K
I2D-11590-Q177	Wiring Diagram Zone Power Supply Control Panel L & M
I2D-11590-Q178	Wiring Diagram Zone Power Supply Control Panel N & SP
I2D-11590-Q179	M.C.B 10EIC Remote/Loc Relay, Pnl. Det. Assy.
I2D-11590-Q181	MCB 11 Cab. Assy.
I2D-11590-Q182	MCB 11 Panel
I2D-11590-Q184	MCB 12 Cabinet
I2D-11590-Q185	Robicon Interface Power Housing Assy. & Parts List
I2D-11590-Q186	Robicon Interface Power Panel Cutout & Cover Detail
I2D-11590-Q188	Zone A Power Supply Control Schematic
I2D-11590-Q189	Zone B Power Supply Control Schematic
I2D-11590-Q190	Zone C Power Supply Control Schematic

<u>Drawing No.</u>	<u>Title</u>
I2D-11590-Q191	Zone D Power Supply Control Schematic
I2D-11590-Q192	Zone E Power Supply Control Schematic
I2D-11590-Q193	Zone F Power Supply Control Schematic
I2D-11590-Q194	Zone G Power Supply Control Schematic
I2D-11590-Q195	Zone H Power Supply Control Schematic
I2D-11590-Q196	Zone J Power Supply Control Schematic
I2D-11590-Q197	Zone K Power Supply Control Schematic
I2D-11590-Q198	Zone L Power Supply Control Schematic
I2D-11590-Q199	Zone M Power Supply Control Schematic
I2D-11590-Q200	Zone N Power Supply Control Schematic
I2D-11590-Q201	Zone SP Power Supply Control Schematic
I2D-11590-Q202	Zone A Power Supply Conn. Schematic
I2D-11590-Q203	Zone B Power Supply Conn. Schematic
I2D-11590-Q204	Zone C Power Supply Conn. Schematic
I2D-11590-Q205	Zone D Power Supply Conn. Schematic
I2D-11590-Q206	Zone E Power Supply Conn. Schematic
I2D-11590-Q207	Zone F Power Supply Conn. Schematic
I2D-11590-Q208	Zone G Power Supply Conn. Schematic
I2D-11590-Q209	Zone H Power Supply Conn. Schematic
I2D-11590-Q210	Zone J Power Supply Conn. Schematic
I2D-11590-Q211	Zone K Power Supply Conn. Schematic
I2D-11590-Q212	Zone L Power Supply Conn. Schematic
I2D-11590-Q213	Zone M Power Supply Conn. Schematic
I2D-11590-Q214	Zone N Power Supply Conn. Schematic
I2D-11590-Q215	Zone SP Power Supply Conn. Schematic
I2D-11590-Q216	EIC Zone P.S. & Monitor Cutout Dwg.
I2D-11590-Q217	EIC - Zone P.S. & Monitor Assy & Parts List
I2D-11590-Q218	EIC - Zone P.S. Monitor Wiring Diagram
I2D-11590-Q219	Zone Control Power Supply Schematic
I2D-11590-Q220	Cabinet AB-1 Panel Cutout, Assy. & P/L
I2D-11590-Q221	Cab. AB-1 Assy & Parts List
I2D-11590-Q223	Cab. AB-1 Front Wiring Diagram
I2D-11590-Q224	Cabinet AB-1 Rear Wiring Diagram

<u>Drawing No.</u>	<u>Title</u>
I2D-11590-Q225	Cab. AB-1 Cabling Diagram
I2D-11590-Q246	Cab. AB-5 Assy. & Parts List
I2D-11590-Q247	Cab. AB-5 Wiring Diagram
I2D-11590-Q248	Cab. AB-5 Panel Cutout, Assy. & Parts List
I2D-11590-Q249	Cab. AB-5 Cabling Diagram
I2D-11590-Q256	Cab. AB-5 48V P.S. Assy. & Parts List
I2D-11590-Q257	Cab. AB-5 Cutout Drawing
I2D-11590-Q258	Cab. AB-5 48V P.S. Wiring Diagram
I2D-11590-Q285	Zone A Induction Reg. Control Schematic
I2D-11590-Q286	Zone B Induction Reg. Control Schematic
I2D-11590-Q287	Zone C Induction Reg. Control Schematic
I2D-11590-Q288	Zone D Induction Reg. Control Schematic
I2D-11590-Q289	Zone E Induction Reg. Control Schematic
I2D-11590-Q290	Zone F Induction Reg. Control Schematic
I2D-11590-Q291	Zone G Induction Reg. Control Schematic
I2D-11590-Q292	Zone H Induction Reg. Control Schematic
I2D-11590-Q293	Zone J Induction Reg. Control Schematic
I2D-11590-Q294	Zone K Induction Reg. Control Schematic
I2D-11590-Q295	Zone L Induction Reg. Control Schematic
I2D-11590-Q296	Zone M Induction Reg. Control Schematic
I2D-11590-Q297	Zone N Induction Reg. Control Schematic
I2D-11590-Q298	Zone SP Induction Reg. Control Schematic