PC-000539
Rev. 0

PRE-CONCEPTUAL DESIGN OF A HIGH TEMPERATURE TEACHING AND TEST REACTOR (HT^{3}R)

TECHNICAL AND DESIGN PLAN

by
PROJECT STAFF

GENERAL ATOMICS
UNIVERSITY OF TEXAS OF THE PERMIAN BASIN
PARKHILL, SMITH & COOPER, INC.

Prepared for
The Regents of the University of Texas System
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☐ SEE LIST OF EFFECTIVE PAGES

☐ GA PROPRIETARY INFORMATION

☒ NO GA PROPRIETARY INFORMATION

LIST OF ACRONYMS

ACHE	air-cooled heat exchanger
ACRS	Advisory Committee for Reactor Safeguards
BOP	balance of plant
CD	conceptual design
CP	construction permit
CPHE	compact plate heat exchanger
d.c.	direct current
DBE	design basis event
EMCPS	electric motor control and power subsystem
EMCS	energy management and control system
ET	energy transfer
FD	final design
FHS	fuel handling system
FLA	facility level analysis
FSV	Fort St. Vrain
GA	General Atomics
GNEP	Global Nuclear Energy Partnership
HEPA	high efficiency particulate air
HEU	high-enriched uranium
HSS	helium services system
HT^{3}R	High-Temperature Teaching and Test Reactor
HTGR	high temperature gas-cooled reactor
HTMP	high temperature materials and processes
HTR-10	High Temperature Reactor (China)
HTTR	High Temperature Test Reactor (Japan)
HVAC	heating, ventilation and air-conditioning
HXV	heat exchanger vessel
I/O	inlet/outlet
ISI	in-service inspection
L/D	length-to-diameter
LBP	lumped burnable poison
LEU	low-enriched uranium
LLM	long lead material
MHR	modular helium reactor
MIT	Massachusetts Institute of Technology
MLSV	main loop shutoff valve

NCA	neutron control assemblies
NCNR	National Institute of Standards and Technology's Center for Neutron Research
NGNP	next generation nuclear plant
NRC	Nuclear Regulatory Commission
NS	non-safety
OPDD	overall plant design description
PB-1	Peach Bottom I
PCD	pre-conceptual design
PCDIS	plant control, data, and instrumentation system
PCHE	printed circuit heat exchanger
PD	preliminary design
PDRD	Plant Design Requirements Document
PHC	primary helium circulator
PHX	primary heat exchanger
PHXV	primary heat exchanger vessel
PRS	pressure relief subsystem
PS	primary system
PyC	pyrocarbon
R&D	research and development
RCCS	reactor cavity cooling system
RCPS	reactor control and protection system
RCPS	Reactor Control and Protection System
RPS	reactor protection system
RS	reactor system
RV	reactor vessel
SAR	Safety Analysis Report
SCS	shutdown cooling system
SCWS	shutdown cooling water system
SHX	secondary heat exchanger
SRD	source range detector
SSC	system, structure and component
STHE	shell and tube heat exchanger
UTPB	University of Texas of the Permian Basin
VS	vessel system
WBS	work breakdown structure

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1. EXECUTIVE SUMMARY

1.1. PCD OBJECTIVE

The University of Texas of the Permian Basin (UTPB), in partnership with General Atomics (GA), The University of Texas System, and with the participation of local city and county governments as well as with the collaboration of several academic, industrial, and government laboratories, has proposed to design, license, construct and operate a High-Temperature Teaching and Test Reactor (HT^3R) as a multifaceted energy research facility. The proposed location for this facility is near the UTPB campus in Andrews County, Texas and is projected to be operational by year 2012. The first step is the development of a pre-conceptual design (PCD) for the HT^3R facility.

The objective of the HT^3R PCD is to develop an initial design for the facility and its major components that satisfy top level requirements for the facility. A further objective is the preparation of definitive cost and schedule estimates for design, licensing, and construction of the facility.

The Technical and Design Plan provides a summary of the PCD work on the HT^3R design, including a description of the overall facility, and the individual components of the facility and their design requirements. Engineering cost and schedule estimates are presented along with cost and schedule estimates for construction of the facility.

1.2. HT^3R MISSION

The mission of the HT^3R facility is research and testing that supports the education and training of the next generation of nuclear scientists and engineers, as well as performance of research and development (R&D) on materials and processes for the economic production of electricity, hydrogen, synthetic hydrocarbon fuels, and desalinated water. To support this R&D mission the HT^3R facility includes a radiation laboratory, a high temperature materials and process laboratory, and an energy transfer laboratory.

The HT^3R will be the cornerstone for a new UTPB R&D "Center of Excellence" that will investigate new frontiers in the applications of high-temperature materials and processes, plus nuclear science and engineering R&D. The HT^3R will be a high temperature, gas-cooled reactor (HTGR) with passively safe design features. These types of HTGRs have become known as modular helium reactors (MHRs), and have been selected by the U.S. Department of Energy as the U.S. Generation IV design concept for the next generation nuclear plant (NGNP). Outlet temperatures of 850°C to > 950°C will lead to a variety of applications with the potential for significantly higher thermal efficiencies. Generation IV reactors are advanced reactors that are designed to provide a significant improvement over existing power reactors with regard to safety, economics, proliferation-resistant fuel cycles, and flexibility of applications.

The proposed design of the HT^3R and its associated facilities are synergistic with the proposed NGNP authorized by U.S. Congress for deployment at the Idaho National Laboratory, as well as the Global Nuclear Energy Partnership (GNEP) that has been proposed by the President of the United States. The planned physical and operating characteristics of the HT^{3}R are very similar to the proposed commercial scale MHR plants. With these characteristics, the HT^{3}R can significantly benefit the NGNP development by reducing key identified risks.

1.3. PCD DESCRIPTION

1.3.1. Overall Facility

The HT^{3}R facility will be located within a rectangular perimeter fence on a 363 acre site in Andrews County, Texas, near the campus of the UTPB campus. The reactor and associated facility buildings will be located within a central area separated from the perimeter fence by a 1350 × 1350 ft buffer zone. This central area is shown in Fig. 1-1

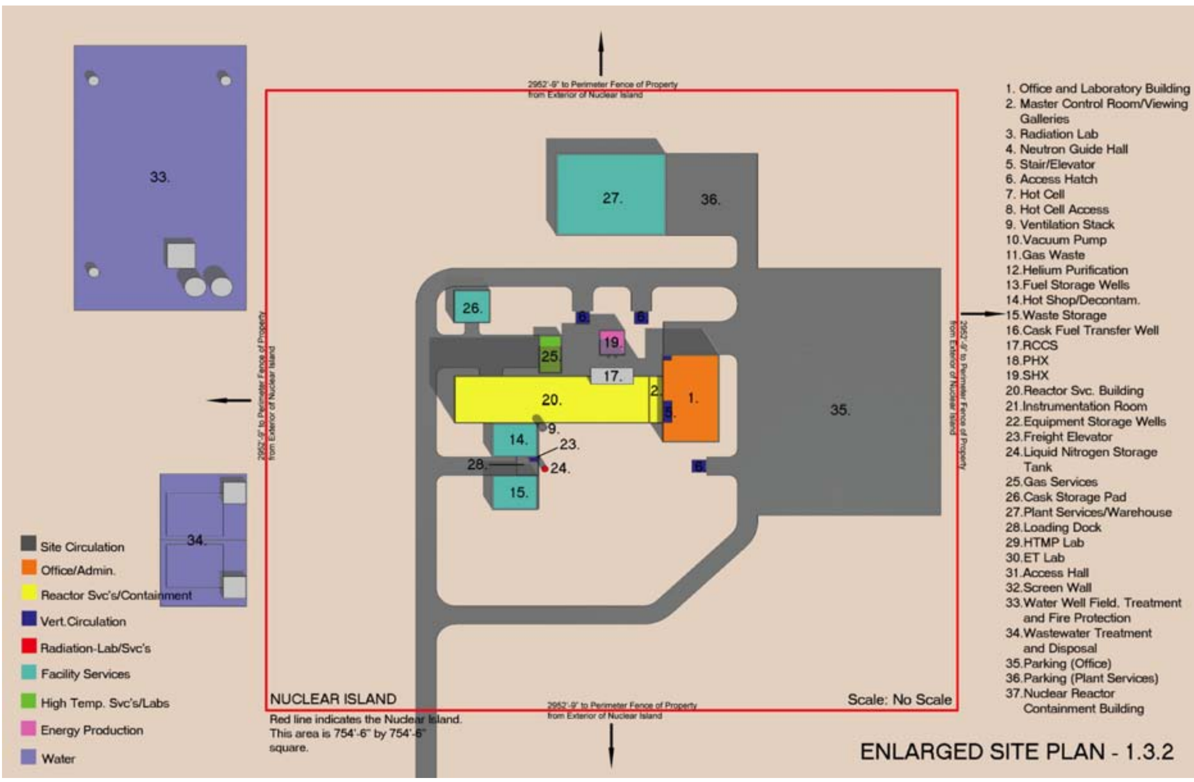

Fig. 1-1: HT^{3}R central site plan.

The facility buildings shown in Fig. 1-1 include the reactor containment and service buildings, the radiation laboratory, the high temperature laboratories, the energy production facility, the support facilities and the offices and administration building. A three-dimensional view of this central complex, including identification of the buildings, is shown in Fig. 1-2.

The HT^{3}R primary system, including the underground location of the reactor, is shown in more detail in Fig. 1-3.

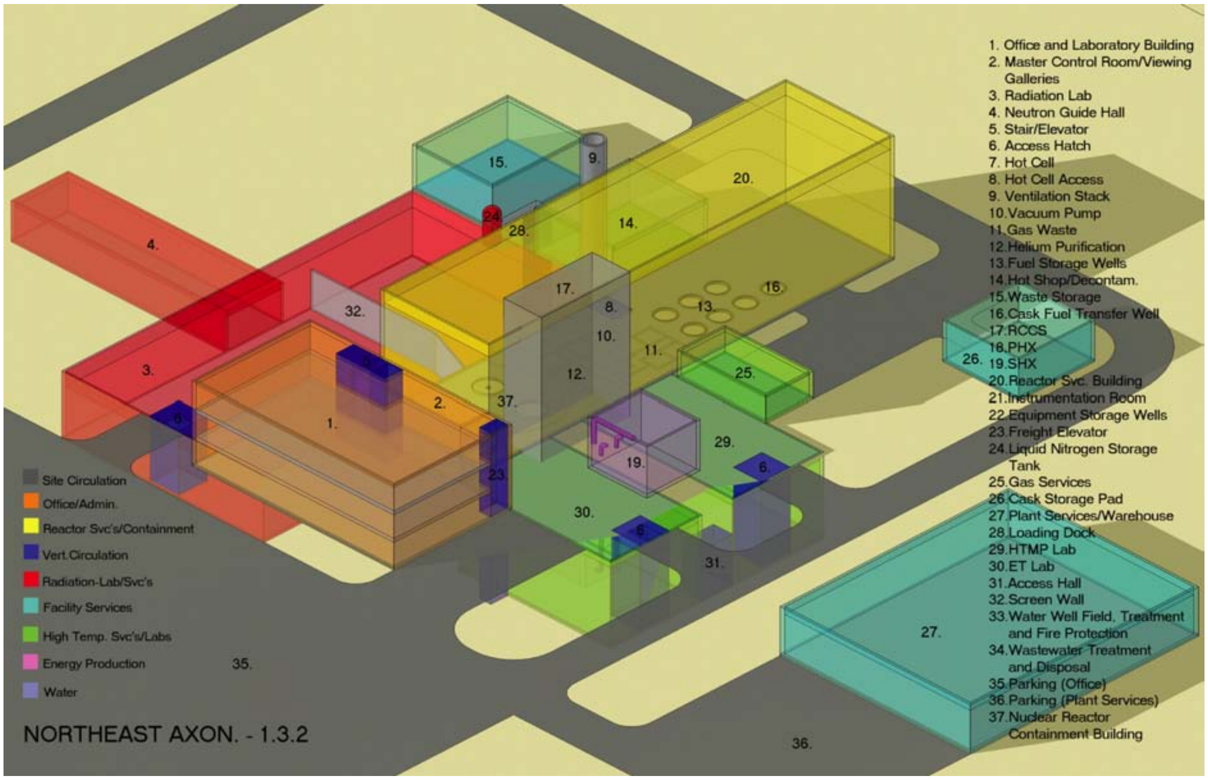

Fig. 1-2. HT^{3}R facility nuclear Island layout.

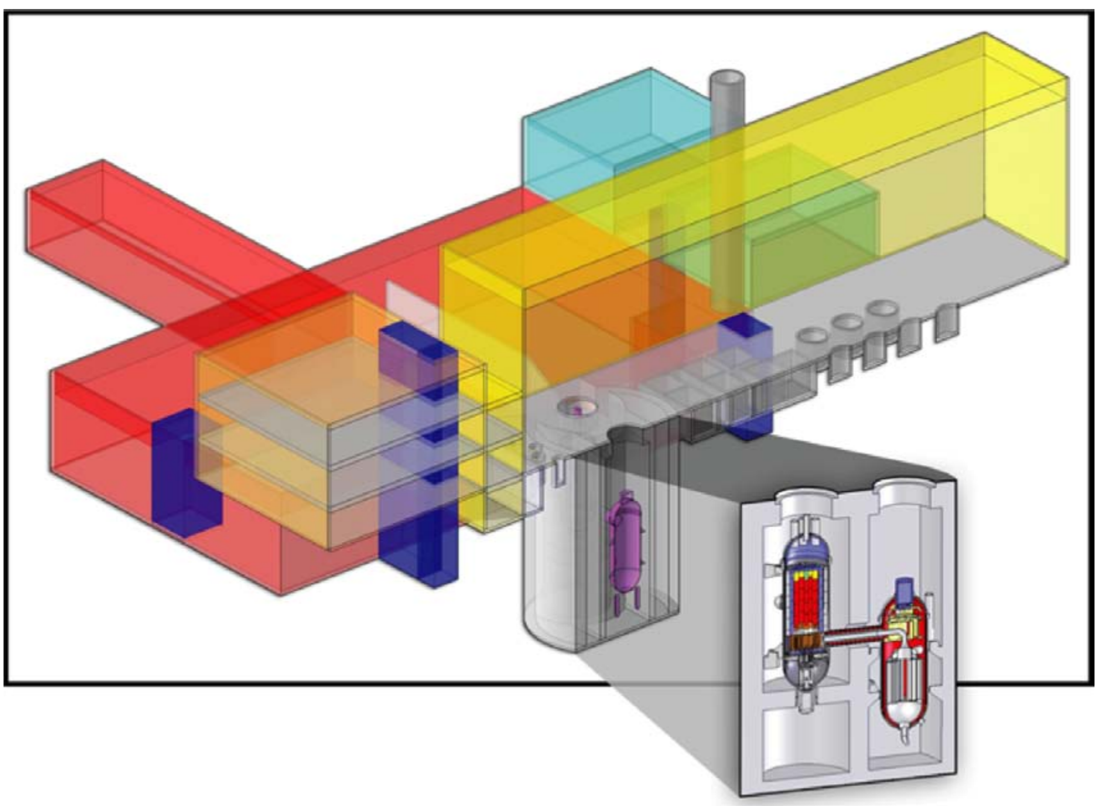

Fig. 1-3. HT^{3}R primary system located in nuclear island.

1.3.2. Reactor and Heat Transport Systems

The HT^{3}R is planned to be a 25 MW(t) Generation-IV type reactor and would be capable of generating 10 MW(e) with a suitable power conversion system. A schematic of the HT^{3}R high temperature process flow system is shown in Fig. 1-4. This figure shows the basic interconnections between the primary reactor system, the secondary heat exchanger system, and the heat rejection system along with the research, testing, and development laboratories.

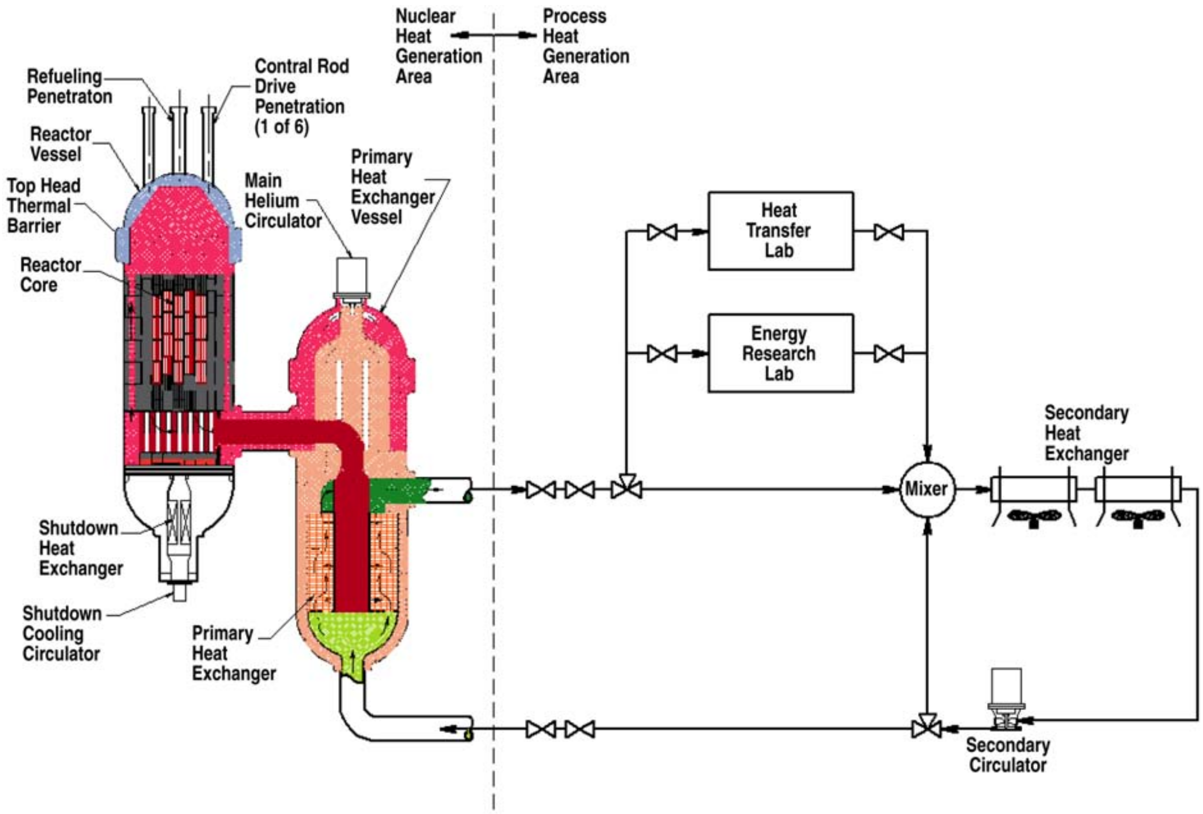

Fig. 1-4. HT^{3}R primary, secondary and heat transport systems layout.

The primary system consists of the reactor and the primary heat exchanger. Heat generated by nuclear fission in the reactor is transferred by the primary coolant to the primary heat exchanger where the heat is transferred to the secondary coolant. The secondary coolant transfers the heat to the process heat and energy conversion laboratories or to the secondary heat exchangers for rejection into the atmosphere.

The reactor uses the same coolant (helium), moderator (graphite) and fuel (coated particle) as the reactor selected for the NGNP. The HT^{3}R will be designed with the same passive safety characteristics as the NGNP and will operate at temperatures representative of that design. Key characteristics of the HT^{3}R include:

1. **Passive Safety.** The reactor does not require active safety systems to ensure public and worker safety. Under accident conditions, reactor decay heat is removed by means of natural heat transfer mechanisms and will maintain reactor fuel

temperatures well below damage limits and ensure nuclear safety. A core meltdown is not physically possible.

2. **High Temperature Capability.** The reactor is capable of producing process-heat temperatures up to 950°C. This high-temperature capability translates into a high-energy conversion efficiency for a variety of energy outputs including electricity, hydrogen production, and synthetic fuel production.

3. **Flexible Fuel Cycles.** The reactor can operate efficiently and economically with several different fuel cycles. HTGR designs have been developed utilizing low-enriched uranium (LEU) fuels, high-enriched uranium (HEU) fuels, mixed uranium/thorium fuels, and surplus weapons-grade plutonium fuels. The thermal neutron spectrum of the HTGR, combined with robust, ceramic-coated particle fuel, allow for very high burnup in a single pass through the reactor. More recently, an MHR design has been developed to deeply burn plutonium and other transuranic actinides that can be recovered from light-water reactor spent fuel. The flexible fuel cycle capability of the MHR, combined with its flexible energy output capability, result in a design concept that is very well suited for a wide variety of energy-growth scenarios.

The HT[3]R reactor core design consists of 19 columns of prismatic graphite fuel blocks stacked 4 rows high. A cross sectional view of the reactor core is shown in Fig. 1-5. The fuel is LEU (10% U^{235}) and is encapsulated in extremely robust, ceramic-coated *"TRISO"* particles. The prismatic block core is supported by graphite structural components that moderate and reflect neutrons. The graphite materials also act as a large, efficient heat sink. Initially, the helium coolant outlet temperature will be limited to 850°C, but it is planned to operate at temperatures up to 950°C. The maximum operating fuel temperature is less than 1250°C, and the primary system pressure is 3 MPa (435 psi). One of the most significant features of the HT[3]R is that it is inherently safe, which means that even if the coolant system fails, the residual heat from the reactor can be safely dissipated to the environment without the need for an active cooling system. A core "meltdown", therefore, is not a credible event with this graphite reactor.

The complete reactor assembly is housed in a steel pressure vessel that is connected to the primary heat exchanger vessel by a cross vessel. As shown in Fig. 1-3, the entire primary system is located below grade in a hardened concrete structure. The primary coolant circulator is mounted on top of the heat exchanger vessel. Refueling penetrations are located in the reactor vessel top head, and the core shut down cooling system is located in the bottom of the reactor vessel.

The primary heat exchanger, located in the primary heat exchanger pressure vessel within the reactor cavity, transfers the reactor energy from the primary helium coolant to the secondary system coolant, nitrogen. From there the nitrogen coolant can be directed to the heat transfer laboratory and/or the energy research laboratory as required by the experimental programs, before flowing to the secondary heat exchanger through a mixer. The secondary system circulator and isolation valves are also shown in Fig. 1-4.

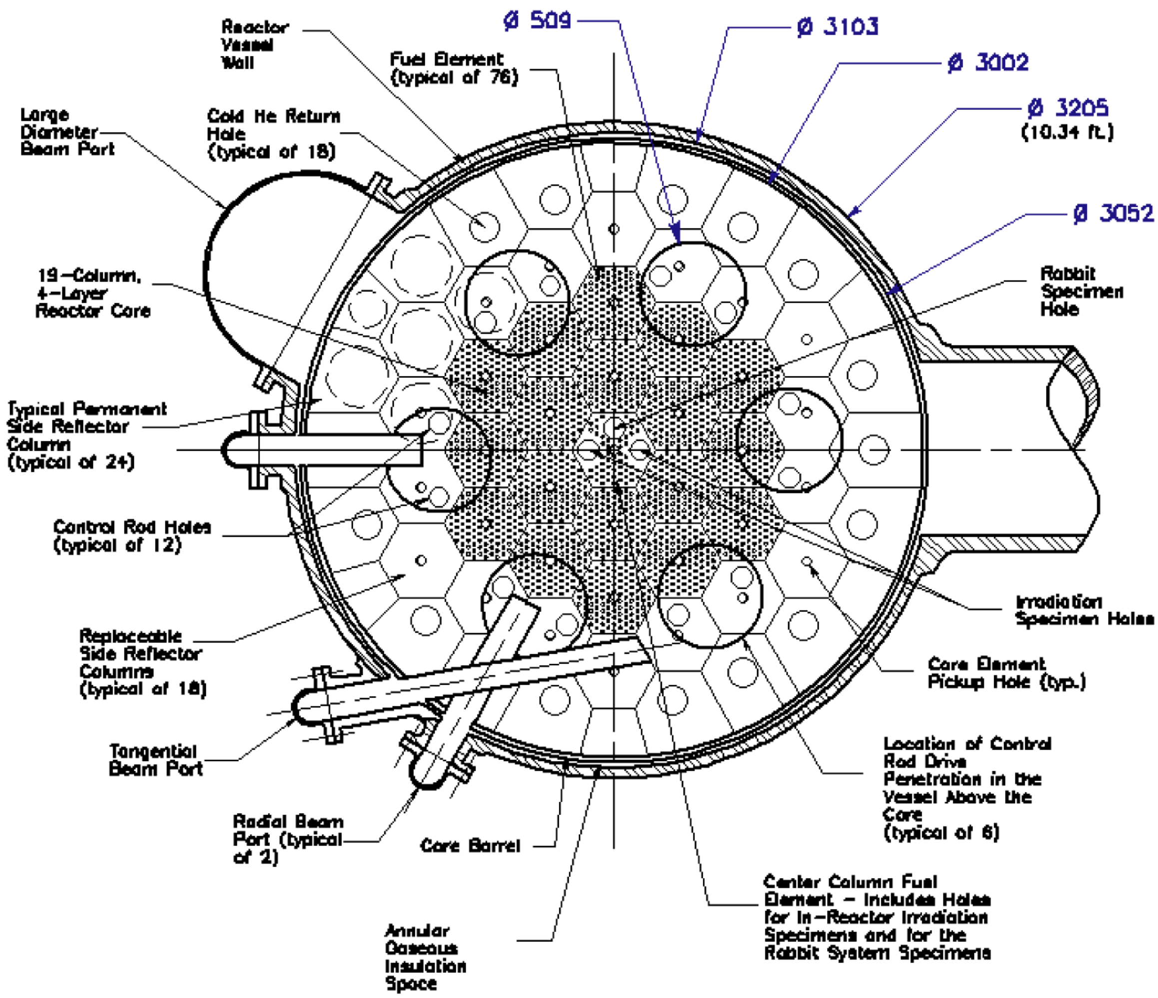

Fig. 1-5. Cross section through reactor core at center plane.

1.3.3. Research Laboratories

In addition to the primary reactor system and heat transfer system, the HT^3R facility will have three other key research, development, and testing components. These are:

1.3.3.1. Radiation Laboratory. This laboratory will have the potential for multiple, high flux, horizontal beam ports and remote sample transport systems for materials and basic science research, plus in-core irradiation and hot-cell facilities for testing of advanced nuclear fuel cycles. The high flux neutron beams and in-core irradiation facilities will result in a truly multipurpose research facility which can accommodate a wide range of applications. These include state-of-the-art neutron beam experiments, advanced nuclear fuel cycle and material irradiation test programs plus production of radioisotopes. A hot cell equipped with remote handling capabilities will be located adjacent to the radiation laboratory, and allow detailed examination of samples from in-core fuel and other material test programs. The hot cell will be accessible from the reactor service building floor.

1.3.3.2. High-Temperature Materials and Process Laboratory. This laboratory will provide for the development of new, advanced, economical, high-temperature processes such as the production of hydrogen, synthetic hydrocarbon fuels, and water desalinization using the reactor's high temperature heat capabilities. Utilization of nuclear heat at temperatures of 850°C up to 950°C will lead to new industrial materials and processes. These new processes can be tested to support the deployment of the hydrogen economy as well as synthetic liquid hydrocarbon fuels or "synfuel" production. These new materials will help this country make the transition from a transportation system that runs on petroleum hydrocarbons – to one that runs on synthetic hydrocarbons – to one that runs on hydrogen fuel cells. This high temperature capability will also be used to develop and test new high temperature metals and ceramics. Among the processes that will be investigated on a pilot scale include hydrogen production by both "water-splitting" and electrolysis, plus synthetic hydrocarbon production and seawater (or brine) desalinization for production of potable water.

1.3.3.3. Energy Transfer Laboratory. This laboratory will enhance the development and testing of improved methods of electricity production by serving as a test bed for the development of new high-efficiency methods, such as the Brayton cycle, plus the development of equipment that utilizes high-temperature gas turbines similar to those found in jet aircraft engines.

1.4. ENGINEERING AND LICENSING COST AND SCHEDULE ESTIMATES

An overview of the schedule estimated for performing the engineering of the HT^{3}R facility is provided in Fig. 1-6. The engineering activities are planned to be conducted in the sequential phases of conceptual design (CD), preliminary design (PD) and final design (FD). As shown in Fig. 1-6, the engineering can be completed over an estimated period of 39 months beginning in project year 1. At the completion of each design phase, the estimated costs for each of the follow-on phases are intended to be updated as required for authorization of the next engineering phase.

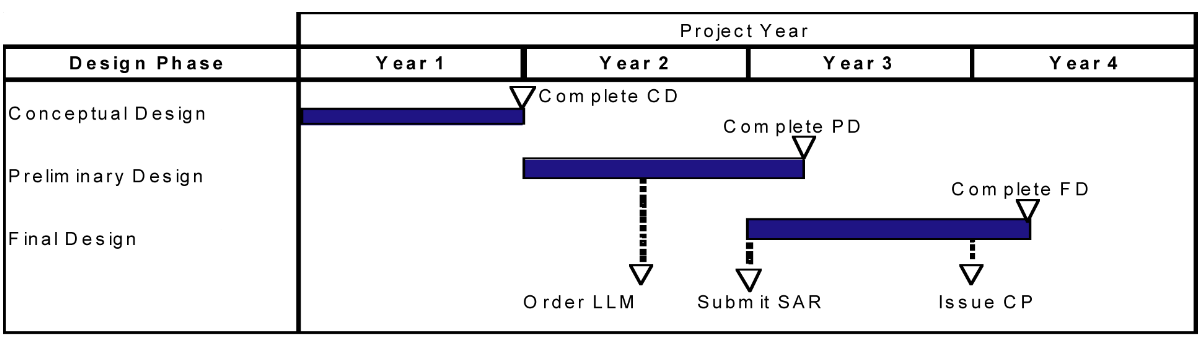

Fig. 1-6. Summary HT^{3}R engineering schedule.

Key milestones during the engineering phases include completion of CD, PD, and FD, plus the release of long lead material (LLM) orders. Key licensing related milestones include submittal of the Safety Analysis Report (SAR) and issuance of a construction permit (CP). These milestones are also shown in Fig. 1-6.

Table 1-1 summarizes the engineering cost estimates for each of the design phases. The costs in Table 1-1 are itemized for each of the Work Breakdown Structure (WBS) Level 2 elements given in Appendix A. The total estimated cost for CD is ~$14 M, the total estimated cost for PD is ~$21 M and the total estimated cost for FD is ~$39 M for a total estimated cost of ~$74 M, without a contingency allowance. The time phasing for the funding for these activities would occur based on the schedule shown in Fig. 1-6.

Table 1-1
Summary of HT^{3}R Engineering Cost Estimates ($K)

WBS Element	Title	Conceptual Design	Preliminay Design	Final Design	Totals
1.1	Primary System	6,104	8,896	13,199	28,198
1.2	Secondary System	2,455	2,196	2,204	6,855
1.3	Facilities Buildings and Structures	1,552	3,122	14,023	18,697
1.4	Facility Systems	274	551	2,475	3,299
1.5	Facility Level	3,582	5,984	7,150	16,716
	Totals	13,966	20,750	39,050	73,766

1.5. ENGINEERING AND CONSTRUCTION COST AND SCHEDULE ESTIMATES

An overview of the schedule estimated for engineering and constructing the HT^{3}R facility is shown in Fig. 1-7.

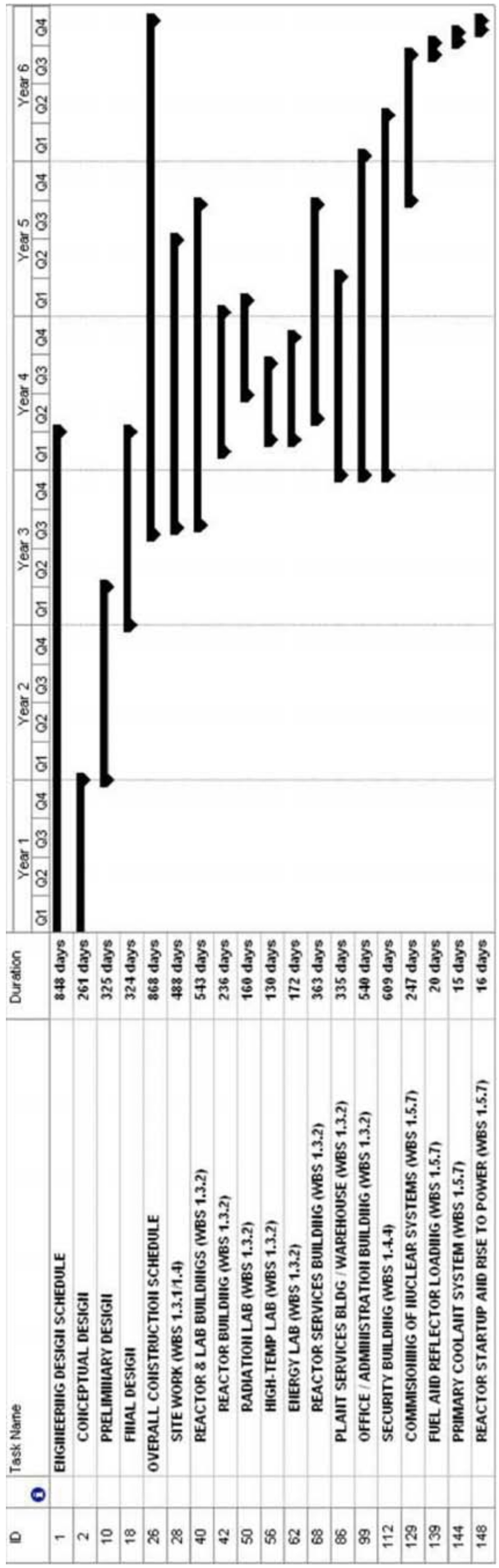

Fig. 1-7. Integrated HT3R engineering and construction schedule estimate.

A summary of the total engineering and construction costs is provided in Table 1-2 at WBS Level 2. Table 1-2 includes a 20% bottom line contingency on both the engineering and construction cost estimates

Table 1-2
Summary of Total Engineering and Construction Cost Estimates

		Engineering	Construction	Totals
1.1	Primary System	$28,200	$109,711	$137,911
1.2	Secondary System	$6,855	$6,590	$13,445
1.3	Buildings and Structures	$18,696	$133,840	$152,536
1.4	Plant Systems	$3,300	$12,801	$16,101
1.5	Facility Level	$16,716	$118,934	$135,650
	TOTALS	$73,767	$381,876	$455,643
	Contingency @ 20%	$14,753	$76,375	$91,129
	TOTALS	$88,520	$458,251	$546,772

2. INTRODUCTION

This technical and design plan presents a pre-conceptual design (PCD) of a High Temperature Teaching and Test Reactor (HT^3R) for the University of Texas of the Permian Basin (UTPB). The HT^3R PCD and this plan has been prepared in accordance with the Teaming Agreement [2-1]. The HT^3R PCD is based on High Temperature Gas-cooled Reactor (HTGR) technology that features helium gas coolant, graphite moderator and coated particle fuel. In the following introductory sections, an introduction is first provided to HTGR technology. The design approach that was used to develop the PCD is described followed by a summary of this plan.

2.1. BACKGROUND

The HTGR technology employed by the HT^3R design evolved from early air-cooled and CO_2-cooled reactors. The use of helium as a coolant in lieu of air or CO_2 in combination with a graphite moderator offers enhanced neutronic and thermal efficiencies. This combination also makes possible production of high temperature nuclear heat and, hence, the name — high temperature gas-cooled reactor.

To-date, seven HTGR plants have been built and operated (Table 2-1). The first was the 20 MW(t) Dragon test reactor in the United Kingdom. Dragon was followed by construction of two relatively low power plants, the 115 MW(t) Peach Bottom I (PB-1) in the U.S. and the 49 MW(t) AVR in Germany. PB-1 and AVR demonstrated electricity generation from HTGR nuclear heat using the Rankine (steam) cycle. These two plants were followed by the construction of two mid-size steam cycle plants, the 842 MW(t) Fort St. Vrain (FSV) plant in the U.S. and the 750 MW(t) THTR plant in Germany. In addition to demonstrating the use of helium coolant (with outlet temperatures as high as 950°C) and graphite moderator, these early plants also demonstrated the effectiveness of coated particle fuel, a fuel form that employs ceramic coatings for containment of fission products at high temperature which is a key feature of HTGRs.

More recently, two additional HTGR test reactors were constructed and are successfully operating, the 30 MW(t) High Temperature Test Reactor (HTTR) in Japan and the 10 MW(t) High Temperature Reactor (HTR-10) in China. These reactors have design outlet temperatures of 950°C and 900°C, respectively.

The U.S. modular HTGR concept began in 1984 when the U.S. Congress challenged the U.S. HTGR industry to investigate the potential for using HTGR technology to develop a “simpler, safer” nuclear power plant design. The goal was to develop a passively safe HTGR plant that was also economically competitive. Like most nuclear power plants up to that time, HTGR plants were designed with reactor core length-to-diameter (L/D) ratios of about 1 for good neutron economy. Detailed evaluations showed that low power density HTGR cores with L/D ratios of 2, 3, or more were effective for passively rejecting decay heat. In long, slender, low power density HTGR cores, it was found that decay heat could be passively transferred by natural means (conduction, convection and thermal radiation) to a steel reactor vessel wall and then thermally radiated (passively) from the reactor vessel wall to surrounding reactor cavity walls for conduction to a naturally circulating cooling system or to the ground itself.

Table 2-1
HTGR Plants Constructed and Operated

Feature	Dragon	Peach Bottom	AVR	Fort St. Vrain	THTR	HTTR	HTR-10
Location	UK	USA	Germany	USA	Germany	Japan	China
Power [MW(t)/MW(e)]	20/ –	115/40	46/15	842/330	750/300	30/ –	10/ –
Fuel Elements	Cylindrical	Cylindrical	Spherical	Hexagonal	Spherical	Hexagonal	Spherical
He Temp (In/Out°C)	350/750	377/750	270/950	400/775	270/750	395/950	300/900
He Press (Bar)	20	22.5	11	48	40	40	20
Pwr Density (MW/m^3)	14	8.3	2.3	6.3	6	2.5	2
Fuel Coating	TRISO[a]	BISO[b]	BISO[b]	TRISO[a]	BISO[b]	TRISO[a]	TRISO[a]
Fuel Kernel	Carbide	Carbide	Oxide	Carbide	Oxide	Oxide	Oxide
Fuel Enrichment	LEU[c]/ HEU[d]	HEU[d]	HEU[d]	HEU[d]	HEU[d]	LEU[c]	LEU[c]
Reactor Vessel	Steel	Steel	Steel	PCRV[e]	PCRV[e]	Steel	Steel
Operation Years	1965–1975	1967–1974	1968–1988	1979–1989	1985–1989	1998 –	1998 –

[a]TRISO refers to a fuel coating system that uses three types of coatings, low density pyrolytic carbon, high density pyrolytic carbon and silicon carbide.

[b]BISO refers to a fuel coating system that uses two types of coatings, low density pyrolytic carbon and high density pyrolytic carbon.

[c]LEU = low enriched uranium (<20% U^{235}).

[d]HEU = high enriched uranium (>20% U^{235}).

[e]PCRV = prestressed concrete reactor vessel.

Today, modular HTGRs, also known as modular helium reactors (MHRs), are being developed by a number of organizations throughout the world as part of the global effort to further develop nuclear power. Nuclear power will help satisfy future energy requirements with less reliance on fossil fuels and reduced emissions of greenhouse gases.

Growing international interest in the MHR concept is the direct result of the following MHR design features:

1. **Passive Safety**. The MHR does not require active safety systems to ensure public and worker safety. Reactor decay heat is removed by means of natural heat transfer mechanisms to maintain reactor fuel temperatures low for assurance of nuclear safety.
2. **High Temperature Capability**. The MHR is capable of producing process-heat temperatures of 950°C and higher. This high-temperature capability translates into a high-energy conversion efficiency for a variety of energy outputs, including electricity, hydrogen production, and synthetic fuel production.
3. **Competitive Economics**. The high-energy conversion efficiency of the MHR, combined with the elimination of active safety systems, results in a design that is more economically competitive than other non-passively safe reactor concepts.

4. **Flexible Fuel Cycles**. The MHR can operate efficiently and economically with several different fuel cycles. MHR designs have been developed utilizing low-enriched uranium (LEU) fuels, high-enriched uranium (HEU) fuels, mixed uranium/thorium fuels, and surplus weapons-grade plutonium fuels. The thermal neutron spectrum of the MHR, combined with robust, ceramic-coated particle fuel, allow for very high burnup in a single pass through the reactor. More recently, an MHR design has been developed to deeply burn plutonium and other transuranic actinides recovered from light-water reactor spent fuel. The flexible fuel cycle capability of the MHR, combined with its flexible energy output capability, result in a design concept that is very well suited for a wide variety of energy-growth scenarios.

The MHR is one of the advanced reactor concepts within the internationally supported Generation IV program. Due to excellent design features and design maturity, the MHR was selected by the U.S. Department of Energy as the U.S. Generation IV design concept for the next generation nuclear plant (NGNP). Other countries which include Russia, Japan, South Korea, China, South Africa, and France are also developing this technology. As a result, large-scale deployment of MHR technology is a realistic element of future energy-growth scenarios.

Technology development programs are now being performed in preparation for the design and construction of full-scale MHR demonstration plants. Following completion of full-scale demonstration, wide scale commercial deployment of the technology is projected throughout the world. The design, licensing, construction, and operation of a large number of MHR plants will require research in the performance of materials and components under MHR conditions. Widespread MHR technology will also require educating thousands of engineers, scientists, and technicians.

To satisfy these research and educational requirements, the UTPB perceived the need for, and utility of, a small-scale MHR system having physical and operating characteristics similar to the commercial MHR plants planned for deployment. Their perceptions have lead to the decision to prepare a PCD of the HT^3R described in this technical and design plan. A PCD of the HT^3R has been developed to provide:

- A platform for education of technical staff and development of the technology that will be required for the design, development, operation, and regulation of commercial MHR plants.
- A test bed for testing advanced fuels, materials, components and systems for enhancing performance of commercial MHR plants.
- A system for acquisition of actual performance data on like-type systems and equipment for accurate risk predictions to support the design and licensing of commercial MHR plants.
- A vehicle for fostering cooperation between industry and the university.

2.2. DESIGN APPROACH

The first step in development of the design approach for the HT^3R PCD was the identification of a general overall arrangement concept to define systems to be designed. A block diagram of the general arrangement concept selected for the HT^{3}R PCD is as shown by the schematic in Fig. 2-1.

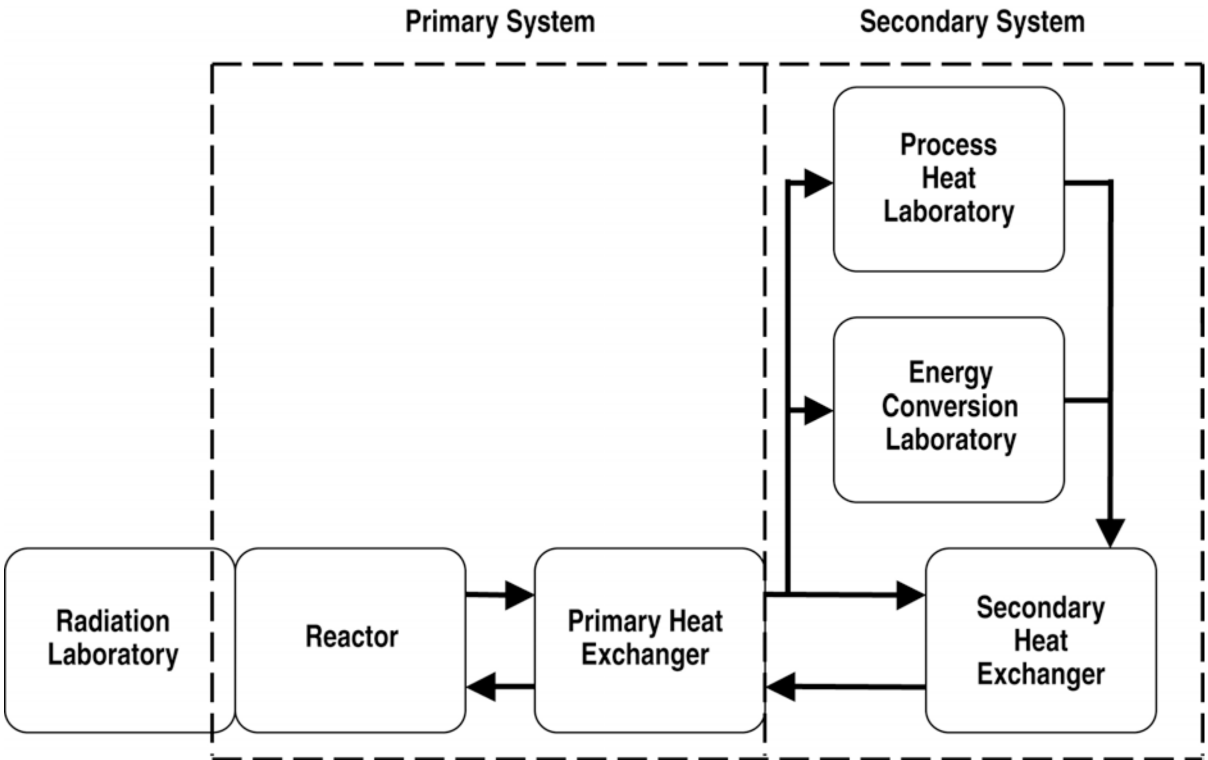

Fig. 2-1. HT^{3}R general arrangement concept selected for PCD.

The second step in establishing the design approach for the HT^{3}R PCD was development of a work breakdown structure (WBS). The HT^{3}R PCD WBS developed is contained in Appendix A. The Level 1 WBS elements are as shown in Table 2-2. The focus of the PCD effort was on WBS element number 1, the HT^{3}R facility included development of the buildings and structures required for the laboratories, WBS elements 2, 3 and 4.

Table 2-2
Top Level HT^{3}R PCD WBS Elements

WBS Element	Title
1	High Temperature Teaching and Testing Reactor Facility
2	Radiation Laboratory
3	High Temperature Materials and Process Laboratory
4	Advanced Energy Conversion Laboratory

Responsibility for the PCD work scope was divided between General Atomics (GA) and the UTPB as noted by the color coding in Appendix A. UTPB, in turn, subcontracted major portions of their work scope as follows:

- PCD WBS elements 1.2 and 1.1.3, the secondary system and primary heat exchanger, was subcontracted to the University of Texas at Austin and O'Donnell Consulting Engineers, Inc.
- PCD WBS elements 1.3 and 1.4, buildings and structures and balance of plant systems was subcontracted to Parkhill, Smith & Cooper, Inc. a Texas A-E.

GA was responsible for the PCD of the primary system (with the exception of the primary heat exchanger). GA's approach for development of the primary system was to base the PCD on MHR design. The design information was developed by GA based on the initial conceptualization of the MHR model in the mid-1980s. This approach was supplemented by adopting a key design principle that the PCD should be based on the use of proven technology to the maximum practical extent. Significant portions of the technology used in the HT^3R PCD were proven in the FSV HTGR.

2.3. SCOPE

The overall scope of the PCD effort was to develop an initial design for the HT^3R in sufficient detail to permit development of initial costs and schedules for engineering the HT^3R equipment, systems, and structures composing the facility. Technical descriptions of the HT^3R PCD are provided as follows:

- A description of the PCD developed for the overall facility is presented in Section 3.
- Technical descriptions of the primary system and subsidiary systems developed for the PCD are presented in Section 4.
- Technical descriptions of the secondary system and subsidiary systems developed for the PCD are presented in Section 5.
- Technical descriptions of the balance of plant (i.e., the facility buildings and structures, the plant systems, and the research laboratories) developed for the PCD are presented in Section 6.
- The costs and schedules for engineering the PCD HT^3R equipment, systems, and facility are presented in Section 7.
- The costs and schedules for constructing the HT^3R facility, based on the PCD design and associated assumptions, are presented in Section 8.
- An integrated schedule for engineering and construction of the facility is presented in Section 8.

REFERENCES FOR SECTION 2

[2-1] Teaming Agreement dated February 2006.

3. OVERALL FACILITY DESCRIPTION

3.1. FACILITY PLOT PLAN

3.1.1. Overall Site Arrangement

The HT^3R Energy Research Facility complex will be arranged on a secured site covering an area of approximately 800 acres contained with a perimeter fence as shown in the plot plan, Fig. 3-1. Access to the site will be through a security checkpoint located integral to the security building at the perimeter fence line.

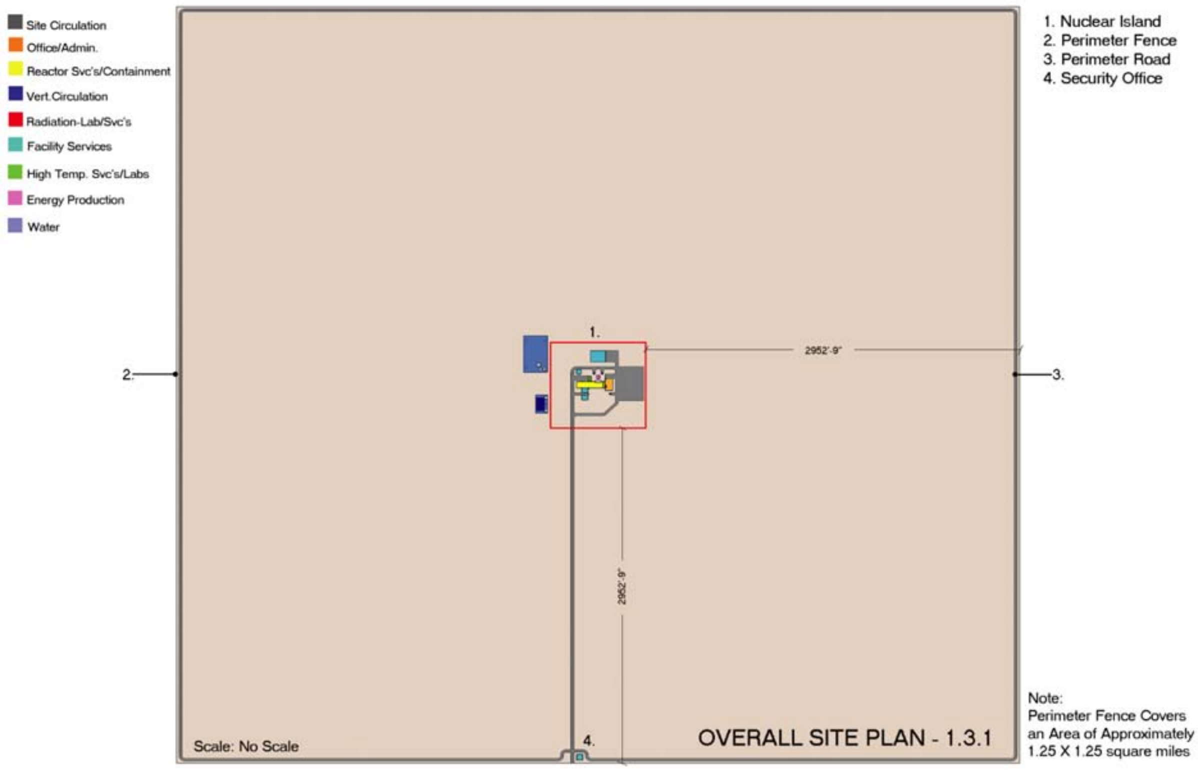

Fig. 3-1. HT^3R facility plot plan.

Transportation in and around the complex will be accommodated by concrete paved roads with curbing capable of supporting the anticipated truck traffic and freight loads. Paved asphalt parking areas will be provided for personnel vehicles.

The nuclear island, consisting of various buildings, will be located at the center of the complex. The entire nuclear island will be secured by an additional perimeter security barrier.

3.1.2. Major Buildings and Structures

The HT^3R Energy Research Facility will consist of the following types of building structures as shown on Fig. 3-2:

- Reactor building and service buildings

- Office building
- Nuclear island service and storage
- Laboratories
- Plant services and storage
- Services: water storage sanitary treatment, parking, and roadways

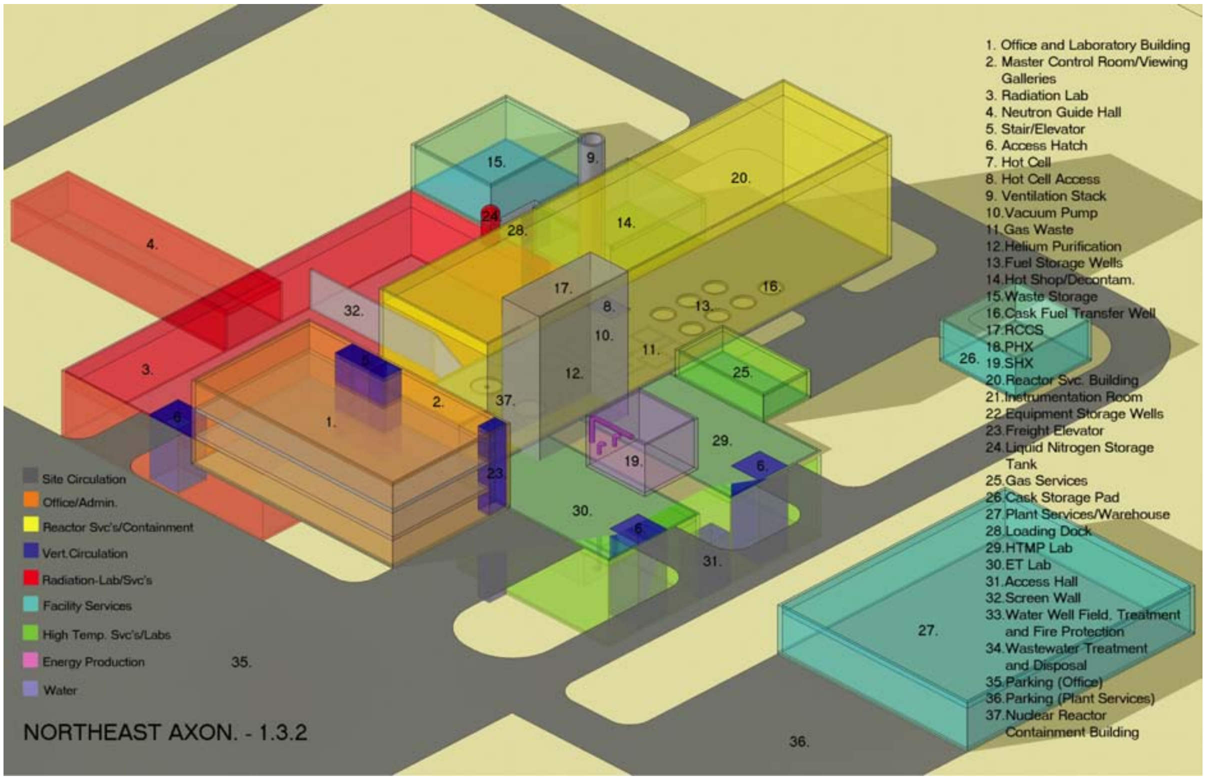

Fig. 3-2. HT^{3}R facility nuclear island.

The services areas, including a retention pond, sanitary treatment, parking, roadways, and water supply systems are located on the site. The office building, reactor and service buildings, laboratories, nuclear island services, and storage are located within the nuclear island.

The main components of the HT^{3}R Energy Research Facility include (1) a high-temperature helium-cooled teaching and test reactor, (2) a Brayton cycle laboratory [energy transfer (ET) laboratory], (3) a high-temperature process and materials (HTMP) laboratory, and (4) radiation laboratories. In addition to these facilities, there will be several buildings and structures as required to provide various support and auxiliary services.

The HT^{3}R Energy Research Facility will have a single access point. This access point will be constructed in conjunction with the security building, a perimeter road throughout boundaries of the entire site, the nuclear island, support areas and plant services/ warehouse building. The nuclear island will consist of the reactor containment building, the reactor service building, an office building, several laboratories and other support service structures within the interior perimeter road. Surrounding the nuclear island, within the project site area, will be a retention pond, water storage, sanitary treatment area, a plant service/warehouse building, and parking areas.

3.2. MAJOR FACILITY COMPONENTS

3.2.1. Primary System

The HT^3R primary system consists of the following systems and components:

- Reactor System (RS). The reactor system includes the reactor core, the reactor internal structures, and the neutron control subsystems.
- Vessel System (VS). The vessel system consists of the reactor pressure vessel, the heat exchanger pressure vessel, the cross vessel (that interconnects the reactor pressure vessel with the heat exchanger vessel), a vessel support subsystem, and a pressure relief subsystem.
- Primary Heat Exchanger (PHX). A high effectiveness exchanger that transfers heat from the primary helium coolant to the secondary system coolant.
- Primary Helium Circulator (PHC). The primary helium circulator system consists of an electric motor/compressor rotor, a compressor stator/diffuser, heat exchangers for cooling the motor and associated structural, electric power, bearings and instrumentation support subsystems.
- Shutdown Cooling System (SCS). The SCS provides the capability for cooling the reactor during shutdown conditions in the event the primary cooling system (PHX and circulator) are not available. The SCS consists of a shutdown heat exchanger, a shutdown circulator, a shutdown cooling water system and associated control systems.
- Fuel Handling System (FHS). The FHS consists of a fresh fuel handling and storage system, a reactor refueling system, a spent fuel storage system, plus handling systems for other associated reactor equipment such as the neutron control assemblies.
- Helium Services System (HSS). The HSS consists of a helium purification system, a helium transfer and storage system, and a liquid nitrogen system that supports of the purification system.
- Reactor Cavity Cooling System (RCCS). The RCCS surrounds the reactor vessel and provides the capability for passive rejection of reactor decay heat in the event that neither the primary cooling system nor the SCS was available for decay heat removal.
- Reactor Control and Protection System (RCPS). The RCPS includes all of the instrumentation and controls required to operate, monitor and ensure safe operation of the reactor.

3.2.1.1. System Functions and Requirements. The primary system functions are:

- Contain the primary coolant.
- Provide flow paths for directing the primary coolant through the reactor, the heat exchangers and the coolant circulators.
- Provide the means for maintaining the primary coolant chemistry.
- Provide the means for managing the primary coolant inventory.

- Provide a means for cooling the reactor core during shutdown periods when the primary cooling system (PHX and circulator) is unavailable.
- Provide for rejection of reactor decay heat to the RCCS without causing any of the primary system components to become overheated.
- Provide for refueling the reactor core.

3.2.1.1. System Definition and Arrangement. The major components of the HT^{3}R primary system are located below grade within a reinforced concrete containment structure as shown in Fig. 3-3. The key features of the primary system are two similarly sized vertical steel vessels, a reactor vessel and a PHX vessel, arranged in a side-by-side configuration and connected by a short coaxial cross vessel. The reactor vessel, PHX vessel, and the cross vessel are the major components of the vessel system.

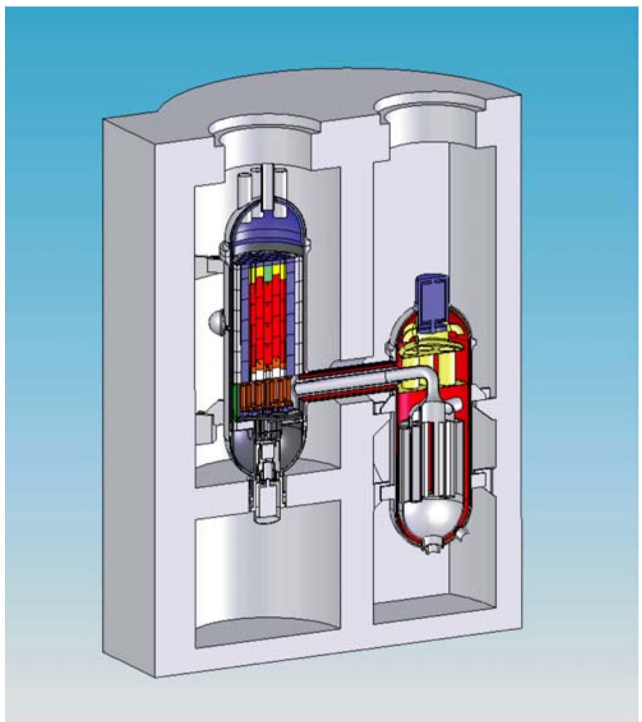

Fig. 3-3. HT^{3}R primary system general arrangement.

The reactor vessel, which is un-insulated on its outside surface, contains the RS. The RS consists of the reactor core, reflector, core support structure, and neutron control system components. The reactor is graphite-moderated and helium-cooled, and uses prismatic fuel elements in the form of hexagonal blocks. The active core is centrally located within top, bottom and side graphite reflector elements. Gravity assisted control rod drive mechanisms installed in penetrations on the reactor top head are used to operate the control rods that move in channels located in the replaceable reflector elements.

The SCS is installed in the bottom head of the reactor vessel. The SCS removes reactor decay heat when the reactor is shutdown for maintenance or refueling and when the primary cooling system (the PHC and PHX) is unavailable. The SCS consists of a motor-driven circulator coupled with a compact heat exchanger mounted below the reactor core at the bottom of the reactor vessel. The shutdown heat exchanger is water-cooled. The SCS is not designated as safety related. The SCS provides cooling to ensure investment protection of primary system components and to facilitate maintenance of the PHX and PHC.

The PHC system is mounted vertically in the top head of the heat exchanger vessel. This vessel contains the PHX system that consists of gas-to-gas heat transfer elements to transfer heat generated in the reactor to a secondary system. The heat will be used in the secondary system for the study of high temperature process heat applications and/or will be rejected to the atmosphere.

The simplified flow diagram shown in Fig. 1-4 illustrates how reactor heat is transferred during normal operation. Within the vessel system, helium coolant flows from the helium circulator to the reactor vessel through the outer annular region of the co-axial cross vessel, and then through the metallic core support structure. The coolant flows from the metallic core support structure up through multiple cylindrical flow in the permanent side reflector and empties into an inlet plenum at the top of the reactor core. The coolant then flows down through the reactor core to absorb heat and exits into the reactor lower plenum from which the flow passes through the hot duct (the central region of the co-axial cross vessel) to the gas-to-gas heat exchanger and back to the inlet of the helium circulator. Cold leg secondary gas enters the heat exchanger vessel at the bottom, flows through the gas-to-gas heat transfer elements and exits at the upper side of the vessel.

Key primary system parameters are listed in Table 3-1 and a heat balance is contained in Table 3-2. Table 3-3 presents pressure losses as the helium passes through the primary system. These pressure losses are overcome by the pressure rise through the PHC.

Table 3-1
HT^3R Primary System Design Parameters

Design Parameter	Value at Full Power
Primary Heat Exchanger	
Inlet helium flow rate, kg/s	13.3
Inlet helium temperature, °C	852
Inlet helium pressure, MPa	3.000
Outlet helium temperature, °C	490.3
Helium pressure drop, kPa	28.3
Primary Helium Circulator	
Circulator flow rate, kg/s	13.3
Inlet helium temperature, °C	490.3
Inlet helium pressure, MPa	2.972
Helium temperature rise, °C	6.2
Helium pressure rise, kPa	49.3

Table 3-2
Overall Plant Heat Balance At Full Power

NSSS Heat Balance	MW(t)
Heat generated by core	25.00
Heat added by circulator	0.43
Total heat to helium	25.43
Loss to RCCS	0.38
Net heat to PHX	25.05

Table 3-3
Primary System Pressure Drops at Full Power

Component	Pressure drop, kPa (psi)	
Core inlet to outlet	11.38	(1.65)
Core outlet plenum	0.04	(0.01)
Hot duct inlet to outlet	0.63	(0.09)
Primary heat exchanger inlet to outlet	28.27	(4.10)
Cold duct inlet to outlet	1.12	(0.16)
Core support floor plenum	3.01	(0.44)
Cold return pipes to core inlet	4.89	(0.71)
Total Primary System Pressure Loss	49.34	(7.16)

3.2.2. Secondary System

The HT^{3}R secondary system will make available the heated secondary nitrogen working fluid for use in two laboratories (HTMP laboratory and ET laboratory). Energy not used in the secondary system [up to 25 MW(t)] is exhausted to the local atmosphere. This entails several separate functions working together to adequately mate the cooling needs of the reactor core to the high-temperature process heat needs of the laboratories.

The functions of the secondary system are:

- Safely contain the nitrogen working fluid at temperatures up to 950°C.
- Deliver none, some, or all of the hot nitrogen to the HTMP and ET laboratories in a controlled manner for use in experiments.
- Deliver any heat not used by the two laboratories to the secondary heat exchanger.
- Circulate nitrogen in the loop at a rate appropriate for adequately cooling the reactor core and driving experiments in the laboratories.
- Discharge excess heat from the nitrogen coolant to the atmosphere via the secondary heat exchanger.

These functions set requirements for the various components of the system that drive its design. The overarching challenge facing the development of the HT^{3}R facility is identical to one of the primary driving forces for its creation: high temperatures. The secondary system's design goal is to discharge up to 25 MW(t) of core process heat contained in the working fluid at temperatures of up to 950°C.

Requirements that have been set for the secondary system are:

- High-temperature piping capable of handling nitrogen gas temperatures up to 950°C.
- A circulator capable of moving the nitrogen in the secondary loop at a velocity sufficient to provide 25 MW(t) of cooling to the reactor's primary system.
- A system to discharge up to 25 MW(t) heat to the atmosphere through a gas-to-gas heat exchanger.
- Control valves capable of protecting the systems from local depressurization coupled with flow of the working fluid operating at ~3 MPa pressure and high temperatures.
- A plant layout maximizing the delivery of high temperature nitrogen to the laboratories while minimizing the cost of exotic piping.

Several layouts of the secondary system have been considered to gain an accurate estimate of the cost and schedule of construction for the secondary system. One proposed design is depicted in Fig. 3-4. The preferred configurations all minimize the length of hot-leg piping, as these pipes will require the most expensive high-temperature alloys in their construction. The heat-exchange system for the final “heat dump” was chosen to be air-air for several reasons. One of the most obvious reasons is the reactor’s planned location in West Texas where water is scarce. Cooling towers are efficient, but also commonly blamed for heat pollution of water sources where aquatic life may require cool water. Further, construction of similarly sized facilities may occur in remote locations with an unreliable, chemically undesirable or inadequate water supply. The HT^3R facility will demonstrate that such a plant can operate in the absence of a significant water source while minimizing the environmental impact.

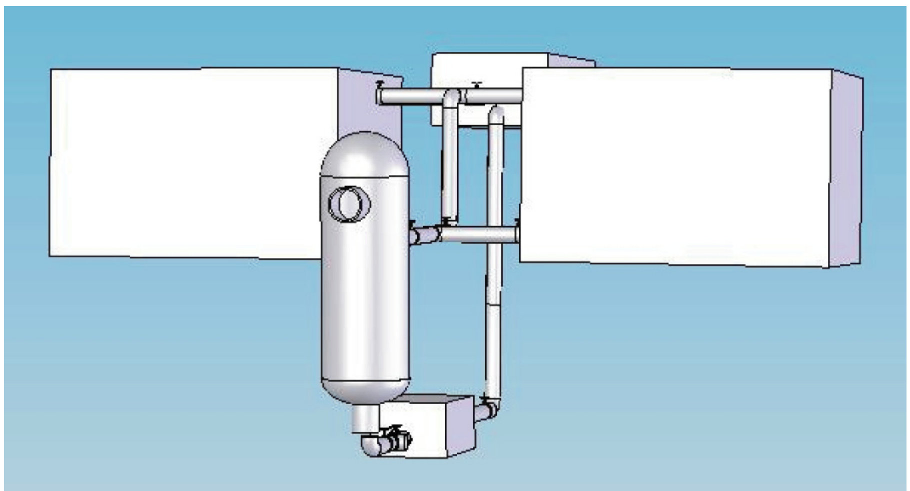

Fig. 3-4. Layout of the secondary piping, labs, circulator, and heat exchanger.

The circulator for the secondary system balances the pressure losses that occur while circulating the nitrogen through the piping, valves, laboratories, and secondary heat exchanger. Any serious depressurization in the laboratories will be compensated within the laboratories themselves to avoid interference with the pressure in the remaining secondary loop. This allows the circulator, for purposes of pre-conceptual design, to be based on the design of the primary circulator instead of a design capable of compensating for unpredictable pressure drops in future experiments. Experiments in the ET laboratory, in particular, may involve large pressure drops but will generate significant power on their own for recompression.

3.2.3. Research Laboratories

At the stage of pre-conceptual design, it would be premature to design specific experiments to be performed in the laboratories. Changes in technology and future experimental work during the construction of the facility will further guide initial concepts into the deeper details of experimental setup and design of the facility. To maximize the research value of the HT^3R, however, extensive laboratory space has been included to maximize the flexibility and capability of the potential research to be performed. Existing laboratories and experimental facilities, such as the National Institute of Standards and Technology’s Center for Neutron Research (NCNR) and the High Temperature Test Reactor (HTTR) in Japan, were extensively investigated to determine the space requirements and physical arrangements for the three separate laboratories that will make maximum use of the reactor's two main research products: heat and radiation.

3.2.3.1. Radiation Laboratory. The radiation laboratory at the HT^{3}R facility is located directly adjacent to the reactor containment structure but as close as reasonably possible to the core. The floor level of the laboratory is located approximately 5 ft below the center plane of the reactor core. These two considerations are necessary to make use of radiation beams from ports placed at the center plane of the radiation field emanating from the reactor core.

From an investigation of current neutron research activities around the world, the primary requirement for flexibility in cutting-edge neutron research is clear: space. Longer flight paths allow for better-controlled beams of neutrons and better resolution in scattering experiments. Consequently, the radiation laboratory is designed to be quite large as seen in Fig. 3-5. To extend the research power of the facility and make it comparable to state-of-the-art facilities such as NCNR, a guide hall (also shown in orange) in the radiation laboratory allows the flight path available for neutron experiments to be a full 80 m. A bridge crane will allow the facility to handle heavy scientific equipment such as large magnets necessary to carry out cutting-edge research in the radiation laboratory.

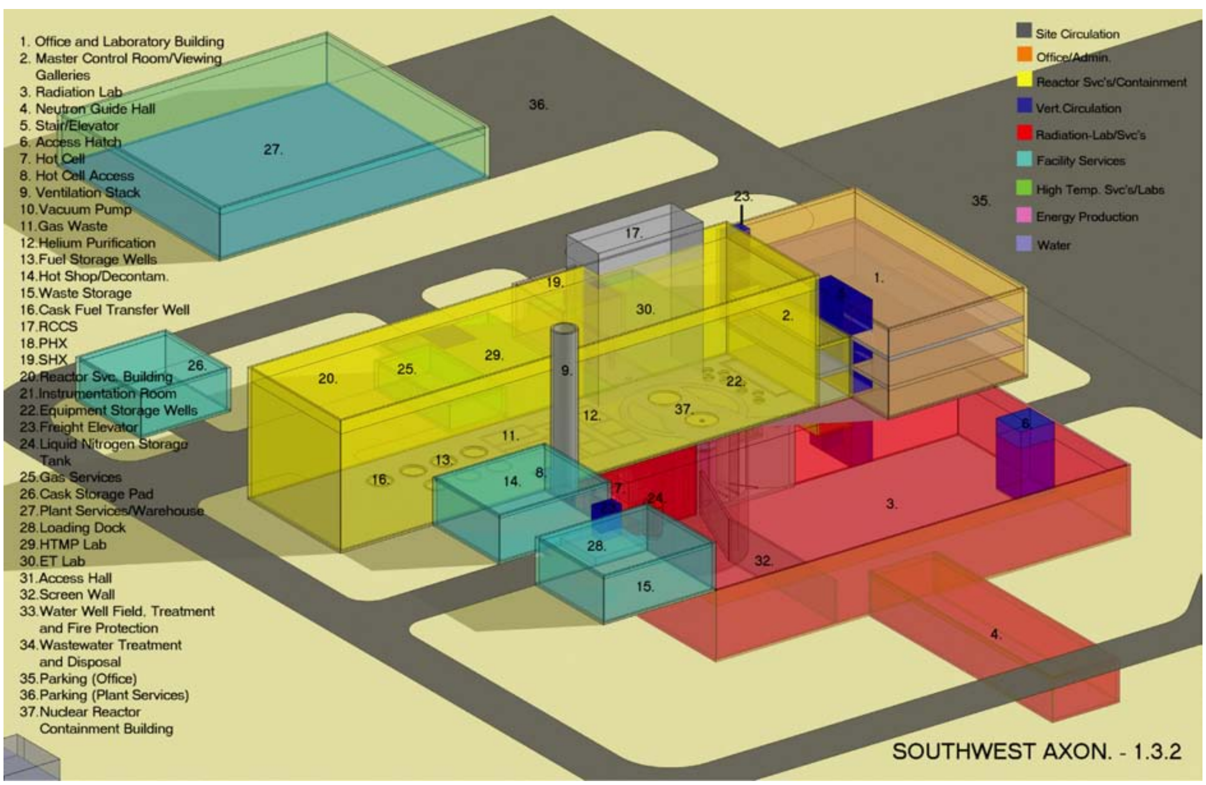

Fig. 3-5. The HT^{3}R facility showing the radiation laboratory (orange, near bottom of figure).

The wide space available in the laboratory facilitates the setup of separate shielded beam-lines to provide neutrons and gamma rays to several different experiments running in parallel. The reactor vessel and shielding at this research facility are being subjected to special design considerations that will allow the facility to be capable of research which is currently not possible anywhere else in the world. The unique features include a 36 in. beam port to allow large neutron and gamma currents to be extracted into a special high-radiation area of the radiation laboratory, cordoned off with a wall of large, moveable shielding blocks. The possibility of such a large beam of core radiation has already generated interest in both the high energy particle physics and fundamental physics communities. Such a facility has the potential to extend previous measurements of controversial physical phenomena (such as the Lobachev experiment) and extend previous searches for revolutionary particle physics processes such as neutron-antineutron oscillations. Attention is also being paid to the use of high fluxes of gamma rays that will facilitate research programs currently possible at only a few facilities in the world.

3.2.3.2. Hot Cell Research Area. Decades of research at other facilities has shown the continuing research utility of directly irradiating samples in the reactor core. The HT^{3}R facility has been designed with multiple laboratory spaces for analyzing irradiated samples passed in and out of the core. Some of these sample analysis and preparation areas will be located in the adjacent office building, where an array of low-level samples may be investigated and worked with directly. Highly radioactive samples, however, must be handled remotely to prevent personnel radiation exposure. Space in the radiation laboratory has been allocated for an array of hot cells for handling such samples. Small radioactive samples will be delivered to this space through rabbit tubes directly accessing the core.

The hot cell space also has direct vertical access from the reactor service building's floor for delivery of full fuel blocks by the fuel handling machine. This will facilitate remote inspection and maintenance of the fuel handling machine within the hot cell. Heavy telemanipulators and cranes in the hot cells will also allow for the manipulation of full test fuel blocks, which will be highly radioactive upon exit from the reactor core and weigh up to 450 lb.

Hot cell research will be one of the focal points of research at the HT^{3}R. Analysis of fuel burning in the radiation environment of an high temperature gas-cooled reactor (HTGR) has the potential to unlock valuable information regarding alternative fuel cycles. One of the primary problems with nuclear power, and one most on the minds of the public, is the issue of nuclear waste. Research on fuel cycles may not only unlock new fuels for use in nuclear reactors, but has the potential to provide methods for beneficially using as fuel what is now considered waste.

Another problem with nuclear power that has become especially pressing due to events in energy deficient developing countries is the issue of non-proliferation. New and potentially proliferation-resistant reactor fuels such as those using thorium have received some attention as possible solutions to this problem. The core of the HT^{3}R is specifically designed with the capability to perform long-term irradiation of samples, a capability which in North America exists only at Massachusetts Institute of Technology (MIT). Long-term irradiation of alternative fuels, analyzed in the hot cell facility, will provide direct evidence of their byproducts and allow a possible technological solution to future political standoffs with developing countries which desire nuclear power. These fuels (e.g., thorium, a fuel more abundant than uranium) typically require fissile material to breed nuclear fuel. Extensive research at HT^{3}R is planned to optimize the reduction of the weaponizable byproducts and waste in a full-scale fuel block test situation in an HTGR. This testing is also a mandatory step that must be taken before any of these new fuel designs can be licensed for use in a U.S. facility. The HT^{3}R facility will also be important in providing the long-term irradiation of materials to simulate a high-temperature, high-radiation environment resembling outer space. The inclusion of such capability in a new reactor is important as private industry enters into a new "space race" for space tourism that would allow testing to assure reliability of reusable spacecraft.

3.2.3.3. Energy Transfer (ET) Laboratory. Approximately two-thirds of the energy generated at most power plants in operation today is simply wasted due to the physics of the thermodynamic cycle involved in conversion of heat to electrical energy. At temperatures where standard power plants operate to produce steam, energy losses are fundamentally unavoidable. However, one of the most basic physical principles of heat engines is their efficiency increases at higher temperatures. Further, at higher temperatures, and using a working fluid that does not "lock away" energy as it undergoes a phase transition (as with water vaporizing), different thermal cycles offer much higher efficiencies. One such cycle is the Brayton cycle. Using design temperatures projected in the HT^3R facility, energy conversion efficiencies as high as 55% may be possible. Of course this efficiency may be increased further by using techniques such as "combined cycles," "bottoming," and "topping." Demonstrating such efficiency increases in the laboratory would strongly encourage investment in high-temperature technology.

Research into these advanced thermal cycles and ET techniques will take place in the ET laboratory (Fig. 3-6). The laboratory floor is located approximately 6 ft below the mid-plane of the PHXV, immediately adjacent to the PHXV thus minimizing piping requirements into the laboratory. The ET laboratory space consists of an open bay with floor space of 50 × 100 ft and approximately four stories high to allow for the layout of turbines, generators and compressors. This space will allow for experimentation with idealized energy recovery and conversion techniques with a continuous stream of hot fluid containing 25 MW(t) of energy. This will be the only university research facility in the world, outside of China and Japan, with these unique capabilities.

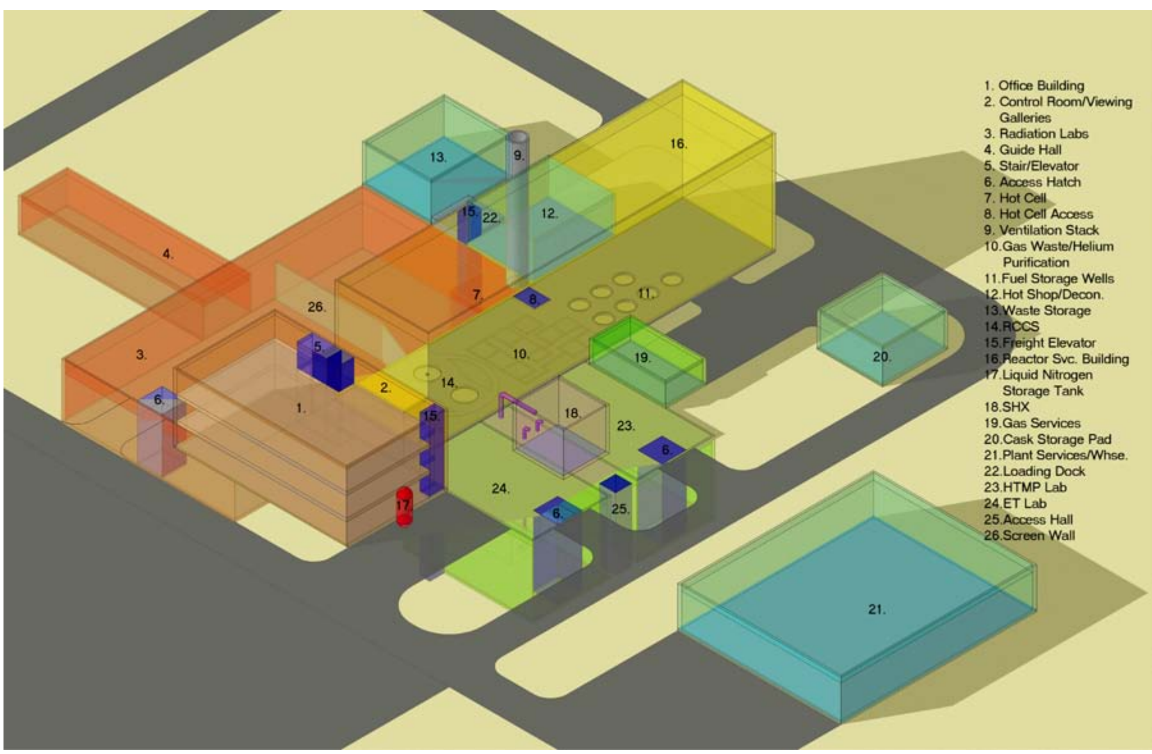

Fig. 3-6. The HT^3R facility, showing the ET and HTMP labs (green, beneath purple SHX).

3.2.3.4. High Temperature Materials and Processes Laboratory. Research in the HTMP laboratory will focus on the development of new high temperature materials and processes. This includes the production of synthetic fuels (hydrogen and synthetic hydrocarbons) from high temperature processes as well as other processes that can benefit from relatively low temperature increases such as the desalinization of water. The first type of research fills an obvious purpose in supporting the design and construction of future HTGRs, which depend critically on high temperature materials in their design.

Synthetic fuels and water desalinization are critical to looming environmental and economic problems in the U.S. and the world. In 2006, the United States spent more than one quarter of a trillion dollars on imported oil. This represents an enormous hole in our economic bucket, as well as causing critical environmental crises from the continued combustion of massive quantities of hydrocarbons. Conversion to a hydrogen economy is often touted as a solution, and hydrogen production research in the HTMP lab has the potential to answer the question, “but where will you get the hydrogen?” High temperatures not only make turbines more efficient, but they also make electrolysis and other conventional chemical reactions more efficient and economical (if the heat is available in large quantities, and especially if it is generated as a by-product to another industrial process). As an example, heat itself can be used to energize chemical cycles for the direct production of hydrogen from water without electrolysis.

Further, synthetic fuels which were used by the German military over 60 years ago can be recreated by utilizing a high temperature heat source. This will provide a domestic source of synthetic fuels. Potentially this could replace the currently used fossil hydrocarbon fuels to shorten the transition to a true hydrogen economy. Research into the creation of clean synthetic fuels could result in the production of synthetic fuels from a power reactor when full electrical power is not required. This could lead to financial incentive amongst industries to construct commercial models of these high temperature gas reactors.

Water may be desalinated in many ways, but all of these methods (such as reverse osmosis) are far more efficient at higher temperatures. In fact, waste heat from nuclear reactors and other power plants may provide a significant source of fresh water. The depletion of aquifers is a world-wide problem affecting every nation. As the human population expands, this problem will only increase. Research in the HTMP laboratory into the efficient creation of fresh water from waste heat could have a real economic and environmental impact on the entire planet.

The HTMP laboratory is located immediately adjacent to the ET laboratory. These two laboratory spaces are symmetrically located with respect to the PHX from which the hot nitrogen is obtained as the working fluid in the secondary system. The remote chance of leakage in a future hydrogen production experiment makes this a safety consideration. This ET laboratory space is anticipated to be filled in a modular way, expanding upward as space is needed on successive metal platforms in the style of the HTTR facility’s hydrogen production research laboratory in Japan (Fig. 3-7). This type of facility can be constructed quickly and cheaply and divided into individual modules with individual temperature control units and experimental goals. This type of structure maximizes versatility and control in the research space. The variety of research planned for this facility can be accommodated by the utility of such a large and flexible laboratory space.

Fig. 3-7. Modular design of process heat experimental laboratory space.

4. PRIMARY SYSTEM TECHNICAL DESCRIPTION

This section provides a technical description of each of the systems and components that make up the primary system (PS) listed in Section 3.2.1.

4.1. REACTOR SYSTEM

A cross section view the HT^{3}R reactor is shown in Fig. 4-1, and an elevation view is shown in Fig. 4-2. The reactor system consists of the following:

- Reactor core consisting of an array of hexagonal-shaped graphite fuel elements in a cylindrical arrangement. These elements contain *"TRISO"* fuel particles.
- Single ring of identically sized, solid graphite, replaceable reflector elements surrounding the reactor core.
- Reflector elements contain six pairs of control rods evenly spaced about the core axial centerline.
- Graphite reflector elements both above and below the core.
- Region of permanent graphite elements surrounding the replaceable radial reflector elements. All elements are located within a metallic barrel.
- Coolant passages in both the core and permanent elements.
- Graphite core support posts on a graphite support block with provision for mixing coolant gas exiting from the core.
- Metallic core support floor structure.
- Hot duct to channel the core outlet coolant gas to the heat removal system.

The PS functions are described in Section 4.1.1, and an overall system description is given in Section 4.1.2. Details of the reactor core, internals and hot duct, and neutron control system are given in Sections 4.1.3, 4.1.4, and 4.1.5, respectively.

4.1.1. System Functions

Reactor System (WBS 1.1.1)

The functions of the Reactor System are:

- Produce heat energy in a controlled and predictable manner and transfer heat from the reactor core to the primary coolant helium.
- Maintain reactor core in a safe shutdown condition when not operating.
- Shield reactor vessel (RV) from both excessive heat and nuclear radiation during routine operation.
- Control power generation of the reactor using moveable control rods.
- Provide a flow path for movement of the primary coolant from reactor inlet to reactor core inlet.
- Provide a flow path for movement of hot primary coolant from outlet of reactor core to inlet of hot duct.

- Provide an interface with fuel handling equipment to accomplish remote removal, installation, and inspection of fuel and reflector elements and other reactor internal equipment items during routine refueling and reactor internal maintenance.
- Transfer decay heat from reactor core to RV under pressurized and depressurized conditions.

Reactor Core (WBS 1.1.1.1)

The functions of the reactor core are:

- Generate heat by controlled fission process and transfer heat to primary coolant.
- Generate heat at full power for a defined cycle-length between scheduled refuelings.
- Contain fissionable material and fission products produced during reactor operation.
- Moderate fission neutrons through use of graphite as a structural material while minimizing neutron loss by use of graphite reflector surrounding the core.
- Control radiation from the core and control neutron fluence to RV walls while providing a flow path for coolant returning to the core.
- Provide for easy replacement of reflector elements located both above, below, and adjacent to fueled region of core.

Core Support Structures (WBS 1.1.1.2)

The functions of the core support structures are:

- Support core assembly within the reactor pressure vessel, maintain core geometry, channel helium coolant into and out of the core, and prevent the hot primary coolant helium exiting the core from contacting the vessel walls.
- Thoroughly mix hot helium coolant exiting the core to eliminate hot streaks and channel the coolant into the hot duct.
- Limit neutron fluence into the lower RV area.

Neutron Control System (WBS 1.1.1.3)

The functions of the Neutron Control System area:

- Control reactivity of reactor core during startup, shutdown, and core power shaping, and compensate for reactivity depletion.
- Ensure reactor core can be maintained in a safe shutdown condition for an indefinite period of time, with adequate reactivity margin, under all normal and accident conditions.
- Control neutron population during normal operating conditions and ensuring desired core thermal power level.
- Utilize a neutron source of sufficient intensity to ensure safe and predictable reactor startup under controlled conditions at all times.
- Provide a means by which neutron flux levels within the reactor core can be measured and primary functions of power level control and safe shutdown.

4.1.2. Overall System Description

The HT^3R core consists of an array of hexagonal-shaped fuel element blocks in a cylindrical arrangement surrounded by a single ring of identically sized, solid graphite, replaceable reflector elements containing 12 control rods. Surrounding this region, is a set of permanent reflector elements. All elements are located within a core barrel. The core is designed to operate at 25 MW(t) with a power density of 3.68 W/cm^3. The core is arranged in a cylindrical geometry consisting of 19 fuel element columns stacked 4 blocks high. The permanent reflector elements are individually shaped to mate accurately with the inner hexagonal reflector elements and with the core barrel that separates the core elements from the RV wall. Certain of these reflector elements contain channels for the returning core inlet gas, plus borated steel pins to reduce neutron dose to the RV. A horizontal cross-section of the core and RV through the core center plane is shown in Fig. 4-1.

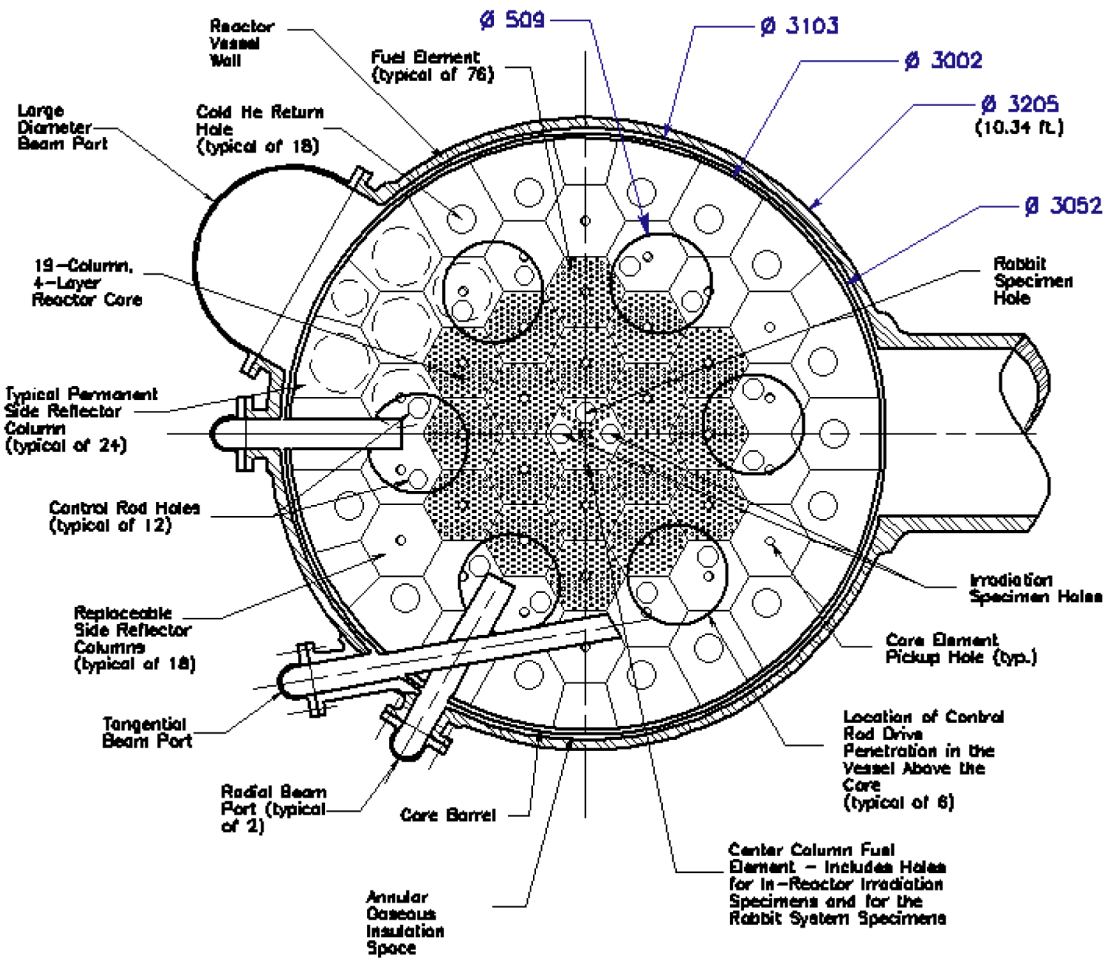

Fig. 4-1. Cross section through reactor core at center plane.

An elevation view through the vertical centerline of the RV is shown in Fig. 4-2. The location of the primary coolant inlet flow channels in the permanent side reflector is also shown in the figure.

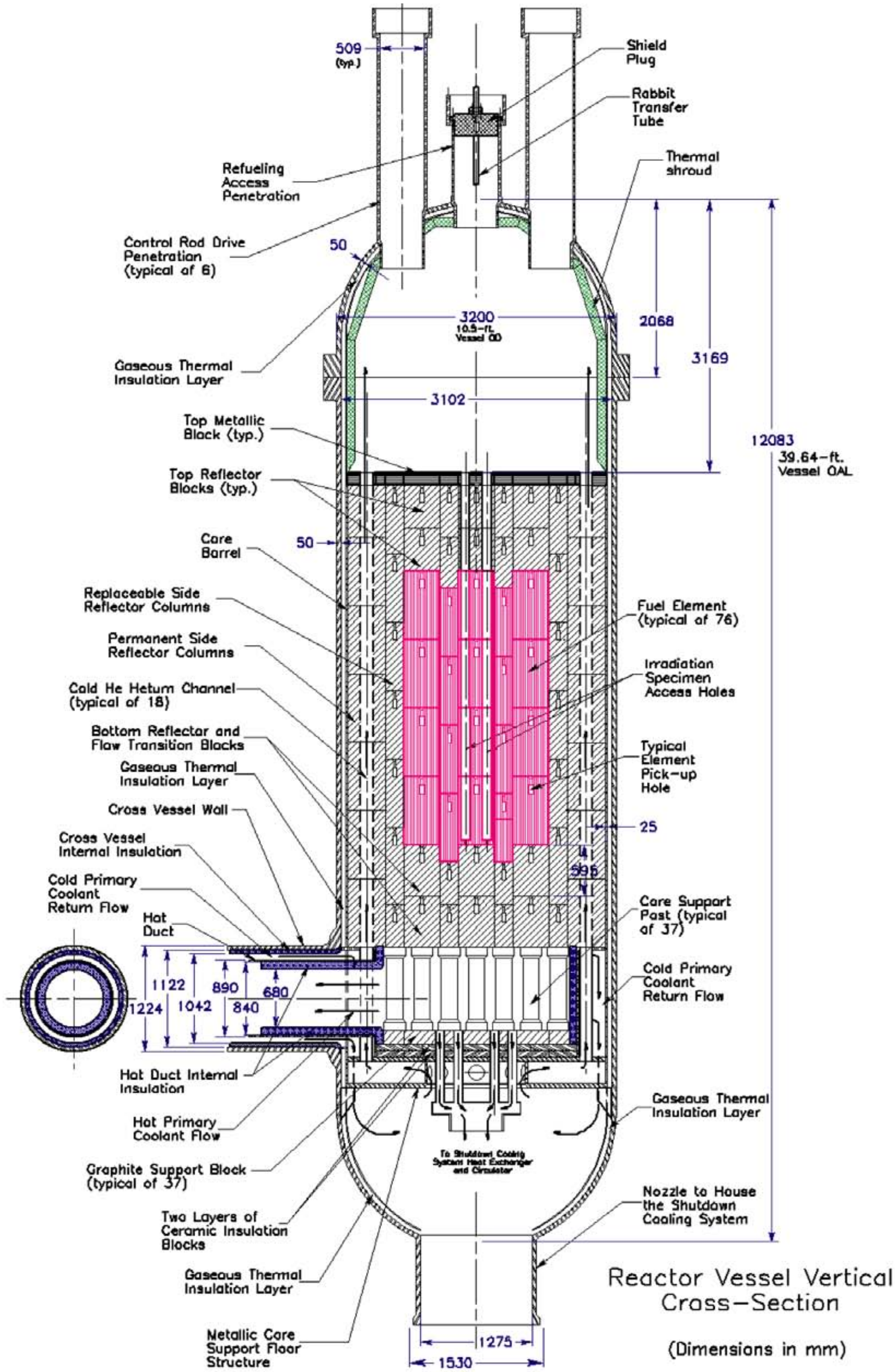

Fig. 4-2. Reactor core and pressure vessel elevation view.

The columns of fuel and reflector elements are axially supported by graphite posts located in the core outlet plenum. The graphite core support posts and the bottom plenum are collectively designed to allow mixing of the outlet coolant gas before it flows through the hot duct in the cross vessel to the primary heat exchanger (PHX). Below the core support posts is a layer of ceramic insulation that provides thermal insulation for the metallic core support floor. Axially, above and below the fueled core elements, are replaceable axial reflector elements with borated steel pin regions at the very top and bottom of these reflectors. The middle ring of core fuel elements is slightly offset axially from the inner and outer elements to provide additional resistance to any lateral forces during seismic events.

4.1.3. Reactor Core

The reactor consists of two types of hexagonal fuel elements — a standard fuel element, and an irradiation specimen fuel element. The standard fuel element, shown in Fig. 4-3, contains continuous pattern of fuel and coolant holes in a triangular array, except for the central handling hole, which is surrounded by slightly smaller coolant holes.

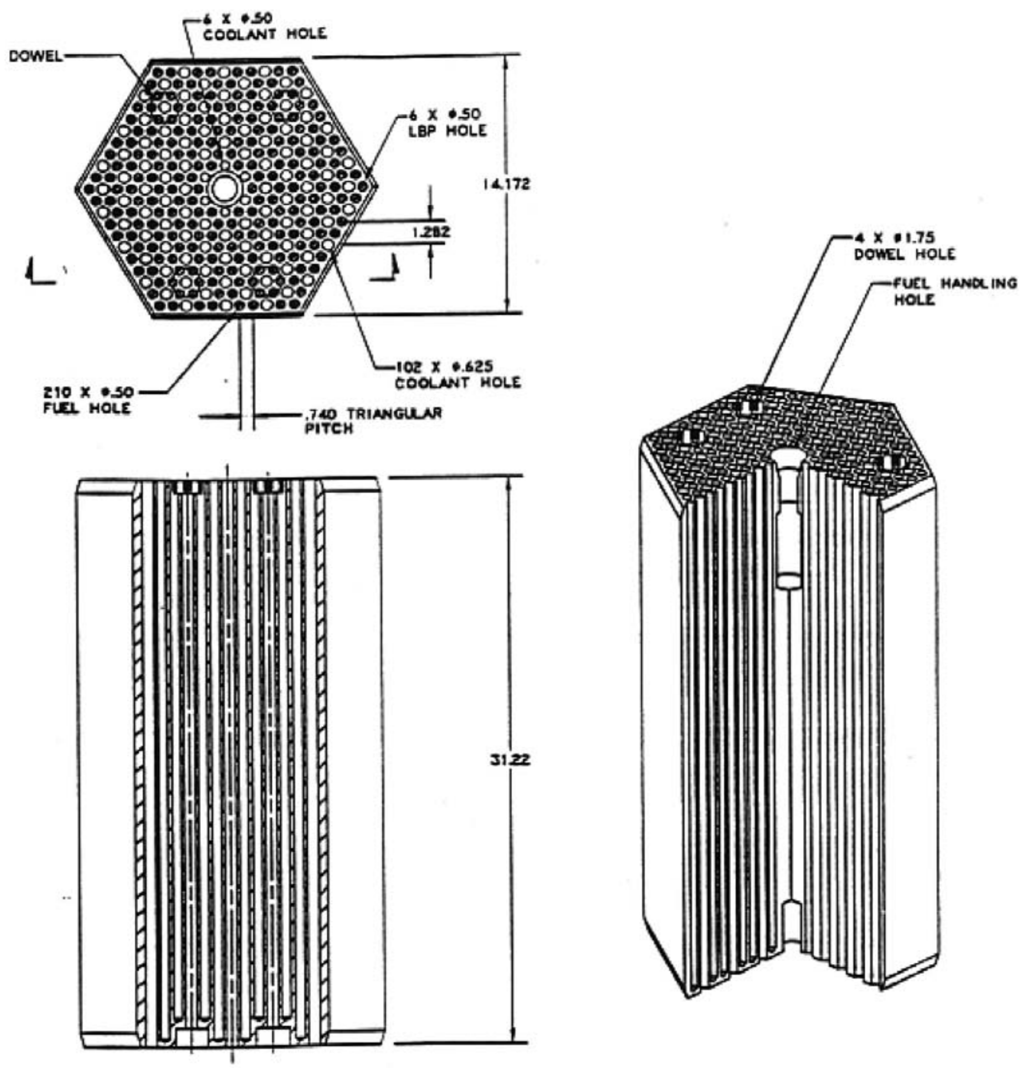

Fig. 4-3. Standard fuel element design.

Currently, the design assumes that all six of the fuel holes at the corners of the fuel elements will be occupied with lumped burnable poison (LBP) compacts. The handling hole is used to lift the element during loading or unloading from the core. Dowel pins extend above the top surface of each element. Each element also has a matching pattern of dowel holes on the bottom surface. Thus, when one element is placed on top of another element, the dowels fit into the dowel holes on the bottom surface of the element above it. This assures that proper vertical alignment is maintained in a column of elements, and that the coolant holes line up precisely between the individual elements in the column. The irradiation specimen fuel element, shown in Fig. 4-4, contains experiment locations, including a single hole for a rabbit tube and two holes for long-term irradiation. The rabbit tube is described in Section 4.1.4. The irradiation holes have centering tabs held in place in the fuel element at the top with a retaining ring threaded and glued in a fashion similar to the fuel elements dowels.

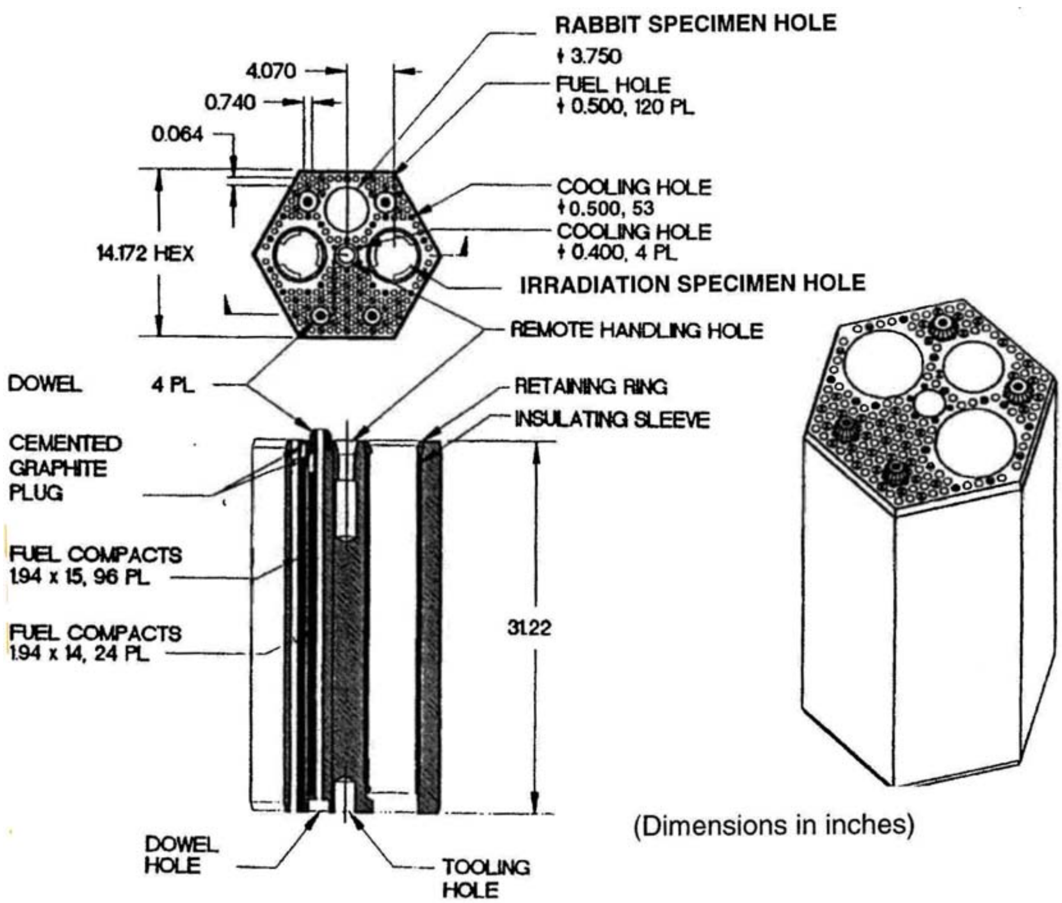

Fig. 4-4. Specimen fuel element design.

The HT^{3}R fuel is based on the use of TRISO-coated particles. As depicted in Fig. 4-5, the coated particle design consists of a fuel kernel surrounded by a buffer (porous) layer of graphite, followed by two pyrocarbon (PyC) layers with a silicon carbide layer between the PyC layers. The buffer layer allows for limited kernel migration and provides retention of fission gases. The silicon carbide layer ensures the structural integrity of the particle and also helps retain metallic fission products. The TRISO particles are dispersed in a graphite matrix to form fuel rods (compacts) which are inserted into vertical fuel channels drilled into the fuel element.

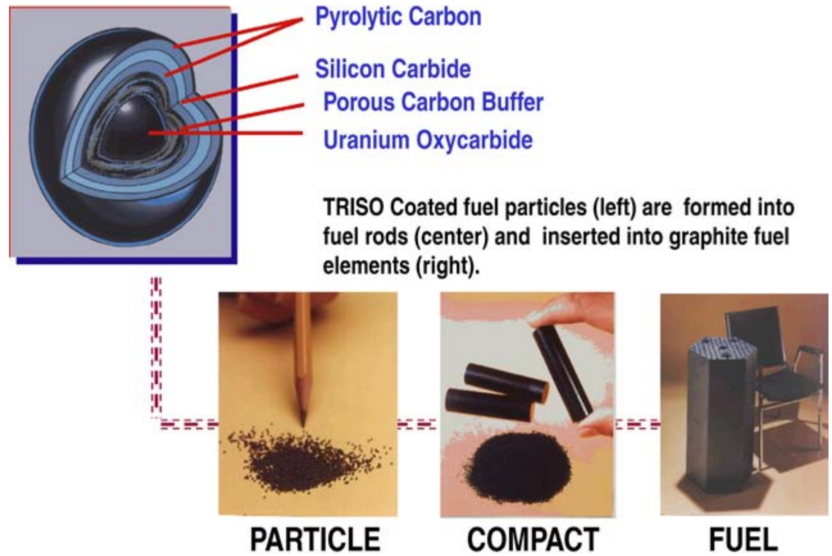

Fig. 4-5. Standard fuel element and its components.

The core replaceable reflector elements have a size, shape, and handling hole identical to a fuel element, except that some of the axial reflector elements are half or three-quarter height. The replaceable reflector elements contain no cooling holes. However, 12 of these elements contain a control rod channel as shown in Fig. 4-6. The control rod channel has a diameter of 10.16 cm (4.0 in.) terminating in the bottom fuel block at an elevation just below the active core. The control rod channel is centered on the flat nearest the active core and is 9.756 cm (3.841 in.) from the center of the reflector element.

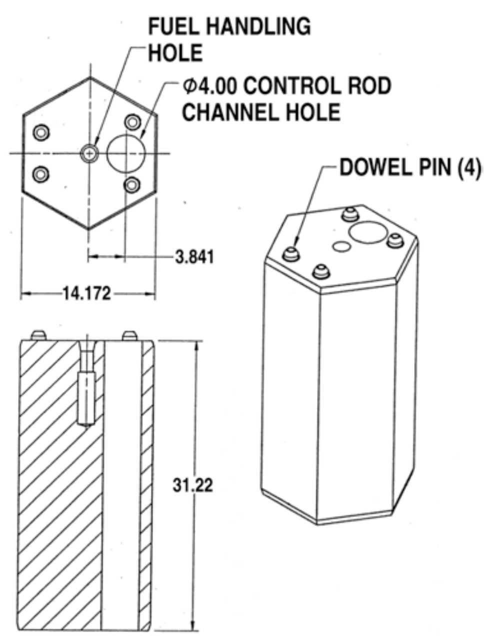

Fig. 4-6. Replaceable reflector element with control rod hole (dimensions in inches).

Core reactivity is controlled by a combination of moveable poison, LBP, and an inherent negative temperature coefficient. The moveable poison consists of 12 boronated control rods located in the replaceable reflector immediately adjacent to the reactor core. The LBP is inserted as compacts within fuel elements and consists of B_4C granules dispersed with graphite shim particles within a graphite matrix. The amount of poison in the LBP compacts is determined by reactivity control and power peaking requirements and may vary radially, axially, and with each core reload.

4.1.4. Reactor Internals and Hot Duct

The reactor core support structures and the other vessel internals are shown as an elevation view in Fig. 4-2. The graphite core support structure is located below the core and lower reflector in the lower hot gas outlet plenum which connects to the outlet hot duct located in the cross vessel. The other vessel internals consist of the metallic core support structure, core barrel lateral restraint and permanent side reflector. The metallic core support is mounted on a ring integral with the RV.

The core graphite support structure serves as a support for both the core and the permanent side reflector columns. The graphite support structure includes the bottom reflector and flow transition blocks, the primary flow transition blocks, plus the core support posts and ceramic insulation. The core support posts are made of graphite columns with hexahedral prism structures at the bottom where they are supported by the ceramic insulation layer. The bottom reflectors below the fuel columns contain flow transition passages to aid in thermal mixing of the core outlet helium flow before the flow discharges into the reactor outlet plenum.

The cross vessel contains two flow passages: an outer annular flow passage to channel the coolant gas from the primary helium circulator (PHC) back to the core; and an inner flow passage, identified as the hot duct, to channel the hot core outlet coolant into the PHX. The hot duct is thermally insulated on the inside surface, is attached to the core barrel at one end, and to the PHX inlet at the other end. The hot duct includes a bellows to accommodate thermal expansion, plus seals to prevent bypass flow.

Stability and alignment of the reactor core components, shielding for the RV, as well as core inlet flow channels, are provided by the permanent side reflector. This reflector consists of graphite blocks stacked to form a cylinder around the core as shown in Fig. 4-1. These permanent side reflector blocks are shaped to mesh with the hexagonal replaceable reflectors on the inner side and with the core barrel and lateral restraint on their outer side. Radial restraint is provided to the core, through the permanent side reflector, and by the core lateral restraints located between the core barrel and the RV wall. The permanent side reflectors contain vertical coolant channels (Fig. 4-2) to transfer the reactor inlet helium into the reactor upper plenum where the coolant mixes before passing down through the core. Radial space is provided between the core barrel and the RV (Fig. 4-2). This annular space provides an insulating function that serves to keep the vessel walls at an acceptable operating temperature.

To fulfill its research reactor functions, the HT^{3}R will be equipped with a rabbit tube for insertion, irradiation, and removal of small samples. Three beam ports (two horizontal and one tangential) will be added for the performance of neutron and gamma irradiation experiments using a flux spectrum typical of a graphite moderated reactor. The location of the rabbit system and beam ports are shown in Figs. 4-1 and 4-7. The rabbit tube is a closed double-walled tube capable of withstanding temperatures and gas pressures in the core. The tube is inserted through the central fuel handling penetration and reaches into the middle of the core in the central column. The tube can be inserted through the fuel handling hole drilled through the top block and, if necessary, extended as a blind hole into the second layer. The rabbit transfer tube is contained within a long, small diameter penetration that is inserted through, and sealed to, the refueling penetration shield plug that is bolted and sealed to the refueling penetration. The rabbit transfer penetration is a closed tube whose lower end is situated just above the core centerplane. The refueling shield plug and the rabbit transfer penetration assembly form a part of the primary coolant pressure boundary.

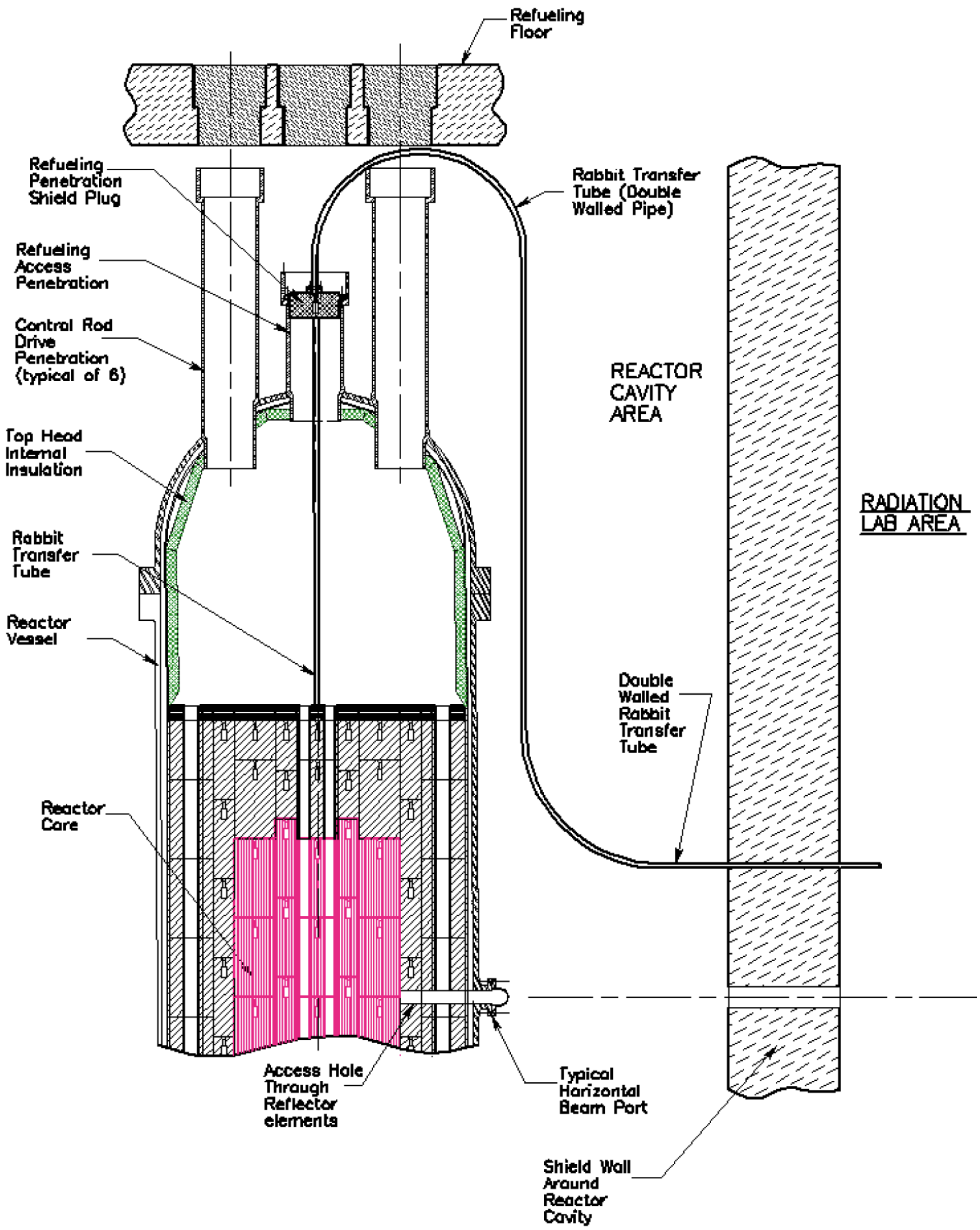

Fig. 4-7. Elevation view showing rabbit tube and neutron beam port layout.

The neutron beam ports require special holes through the permanent and replaceable graphite reflectors between the reactor and the core barrel. Flanged penetrations closed by outward-facing hemispherical caps are provided in the RV at the beam port locations (Figs. 4-1 and 4-7). The beam port penetrations and associated seals are part of the primary coolant pressure boundary. The flange will contain inner and outer high-temperature steel alloy window frames that are replaceable if long-term radiation dose limits are exceeded.

4.1.5. Neutron Control

The neutron control system consists of control rods, control rod drives, neutron source, source range detector (SRD) assembly, and ex-vessel neutron detector assemblies. In-core flux mapping units may be added at a later stage in the design process.

Two control rods, with their individual drive motors, are grouped together to form a neutron control assembly (NCA). This NCA is contained within one of the circular vessel penetrations (Fig. 4-1). There are 6 of these assemblies, for a total of 12 individual control rods. The control rod drive consists of a motor-driven cable support system, an upper structural frame, gamma shielding, neutron shielding, a thermal barrier, plus control rod guide tubes and seals. A typical layout for these components is provided in Fig. 4-8.

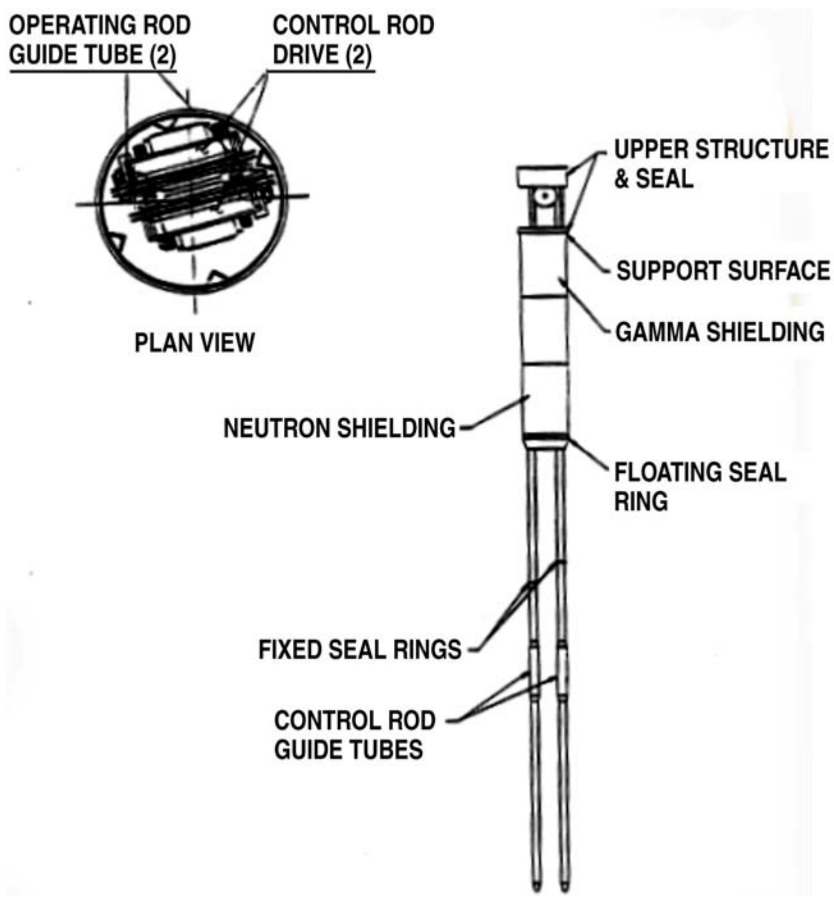

Fig. 4-8. Overall view of NCA.

The top part of the NCA houses the control drive. Each control rod is lowered and raised on a flexible high-nickel alloy cable taken up on the cable storage drum. These components are mounted on a metal frame attached to the upper support structure by means of a pivoting support shaft. Monitoring devices are included in the mechanism to detect a broken control rod or support cable.

The upper structural frame of the NCA consists of vertical corrosion-resistant structural angles, welded to a top lifting ring and a lower horizontal plate, to transfer the weight of the assembly to the RV penetration that contains the assembly. The gamma shielding is a corrosion-resistant plug that protects personnel from the gamma radiation emanating from the core and the activated control rods whenever they are withdrawn into the upper housing. The neutron shielding consists of boronated graphite elements that prevent activation of the upper portion of the vessel. The control rod guide tubes extend from the gamma shielding downward through the top head of the vessel to the metallic blocks at the top of the core and provide a clear passage for the control rods to enter the reflector blocks. The control rod design is shown in Fig. 4-9. The rods consist of a set of hollow boron-carbide compacts in alloy 800H tubes with a central support and guide tube. Guide ribs are also provided on the outside of the rod to ensure correct insertion into the core.

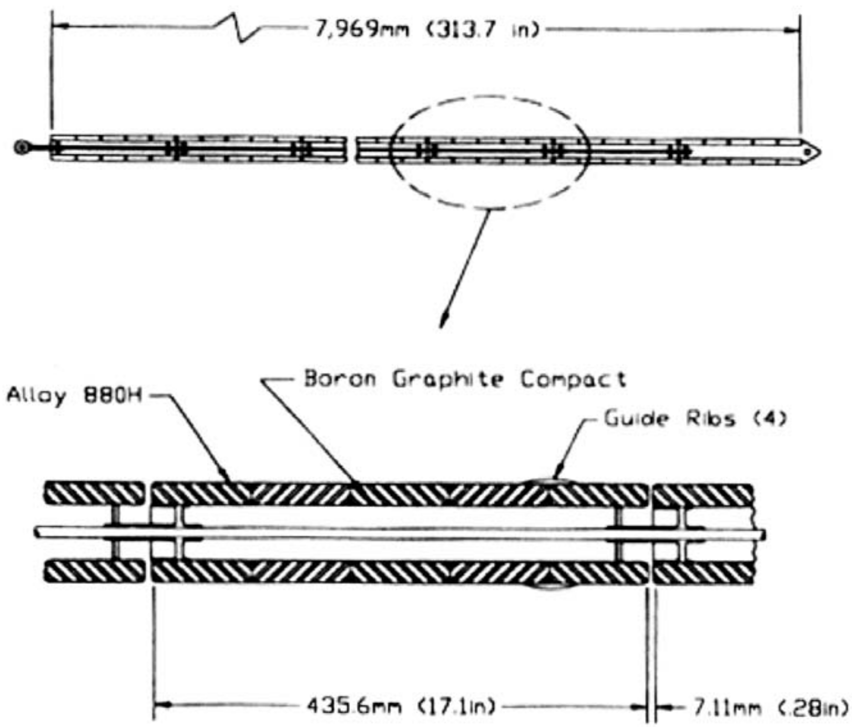

Fig. 4-9. Control rod design.

Nuclear instrumentation on the HT^{3}R consists of SRDs and ex-vessel neutron detectors. During power operation, neutron flux is monitored by the ex-vessel detectors. For startup and shutdown periods, neutron flux is monitored by the SRDs. The ex-vessel detectors consist of fission chamber thermal neutron detectors mounted in four symmetrically oriented vertical wells located outside the RV, directly behind the reactor cavity cooling system (RCCS) panels. The signals from these detectors are supplied to the automatic control and protection systems that operate the control rod drives, such that the neutron flux levels within the core are always maintained at appropriate levels.

SRDs are necessary during startup and shutdown periods. These detectors must be sufficiently sensitive to detect the very low neutron flux levels at the ex-vessel detector locations. SRDs consist of fission chambers with appropriate cabling, support structures, and reentrant penetrations. The SRDs will be located either beside the lower part of the reactor core and inserted from the bottom of the RV or as moveable detectors in radial beam tubes.

4.2. VESSEL SYSTEM

An isometric view of the HT^{3}R vessel system (VS) is shown in Fig. 4-10. The HT^{3}R VS consists of the following:

- A RV that includes the control rod drive housings and the penetrations, closures, and appurtenances required for the systems and components that interface with the RV.
- A primary heat exchanger vessel (PHXV) that includes the penetrations, closures, and appurtenances required for the systems and components that interface with the PHXV.
- A cross vessel that interconnects the reactor and PHXVs.
- A vessel support subsystem.
- A pressure relief subsystem (PRS).

Design descriptions for these components and/or subsystems are provided in subsections that follow. The schedule and cost for performing the engineering of the VS are provided in Section 7.2 and the cost and schedule for fabricating and installing the VS into the HT3R facility are provided in Section 8.1.

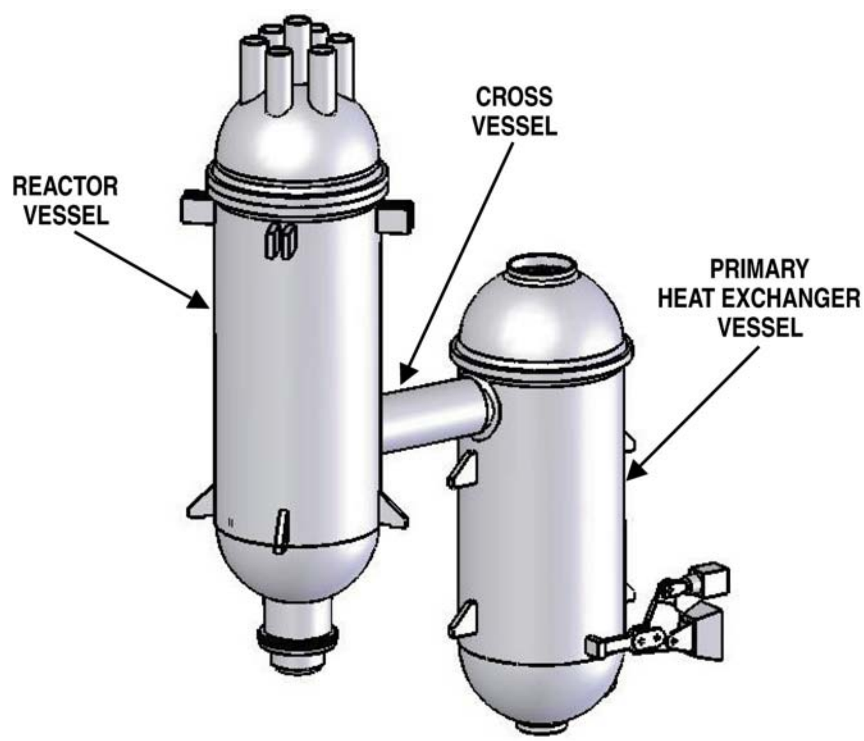

Fig. 4-10. Isometric drawing of VS.

4.2.1. System Functions and Requirements

The primary functions and requirements established for the HT^3R VS pre-conceptual design (PCD) are as follows:

- Contain the primary coolant inventory.
- Maintain primary coolant pressure boundary integrity.
- Provide support for the Reactor System, PHX, Primary Circulator and the shutdown cooling system (SCS).
- Maintain the geometry of the reactor core with respect to the RV.
- Maintain the alignment of the RV with respect to the RCCS.
- Maintain the geometry of core and movable poisons to control heat generation.
- Limit air ingress and consequent core oxidation to control chemical attack of core.

4.2.2. Overall System Description

A cross sectional layout of the HT^3R VS PCD is shown in Fig. 4-11. The VS is configured to accommodate the following items: (1) the reactor system, (2) the primary coolant (helium) circulator, (3) the PHX, and (4) the shutdown cooling circulator and heat exchanger. The primary components of the VS pressure boundary are the RV, the PHXV and the cross vessel that interconnects the RV and heat exchanger vessel (HXV). The RV contains items (1) and (4) and the HXV contains items (2) and (3). Each vessel configuration contains a large bolted flange joint for servicing and replacement of items (1)–(4).

The RV is un-insulated on the outside surfaces and is configured in relationship to the RCCS surrounding the RV. This ensures that core decay heat can be passively rejected by radiation heat transfer from the RV outside surfaces to the RCCS in the event both the main cooling loop and the SCS are inoperable. With this system, core decay heat can be rejected without exceeding either fuel or vessel temperature limits.

4.2.3. Reactor Vessel

The RV is a welded, steel pressure vessel consisting of a cylindrical shell closed at the bottom with a hemispherical lower head and a bolted hemispherical top head. A flange for bolting the SCS heat exchanger and circulator housing is located in the lower head. Housings for NCAs, refueling access, rabbit tubes, and instrumentation are attached to the upper head. Nozzles for beam ports are provided in the vessel cylindrical section at approximately the reactor core mid-plane.

The length and diameter of the RV were selected to accommodate the physical size of the reactor system with space allowances above the core for refueling equipment and below the core support structure for the SCS.

The materials selected in the PCD for the RV are SA-508 Class 3 steel forgings and SA-533 Grade B Class 1 steel plates. These materials have been successfully used for many of the light water reactor nuclear power reactors. The RV is not thermally insulated on the exterior surfaces to enable thermal radiation of the core decay heat from the outside surfaces of the RV to the RCCS.

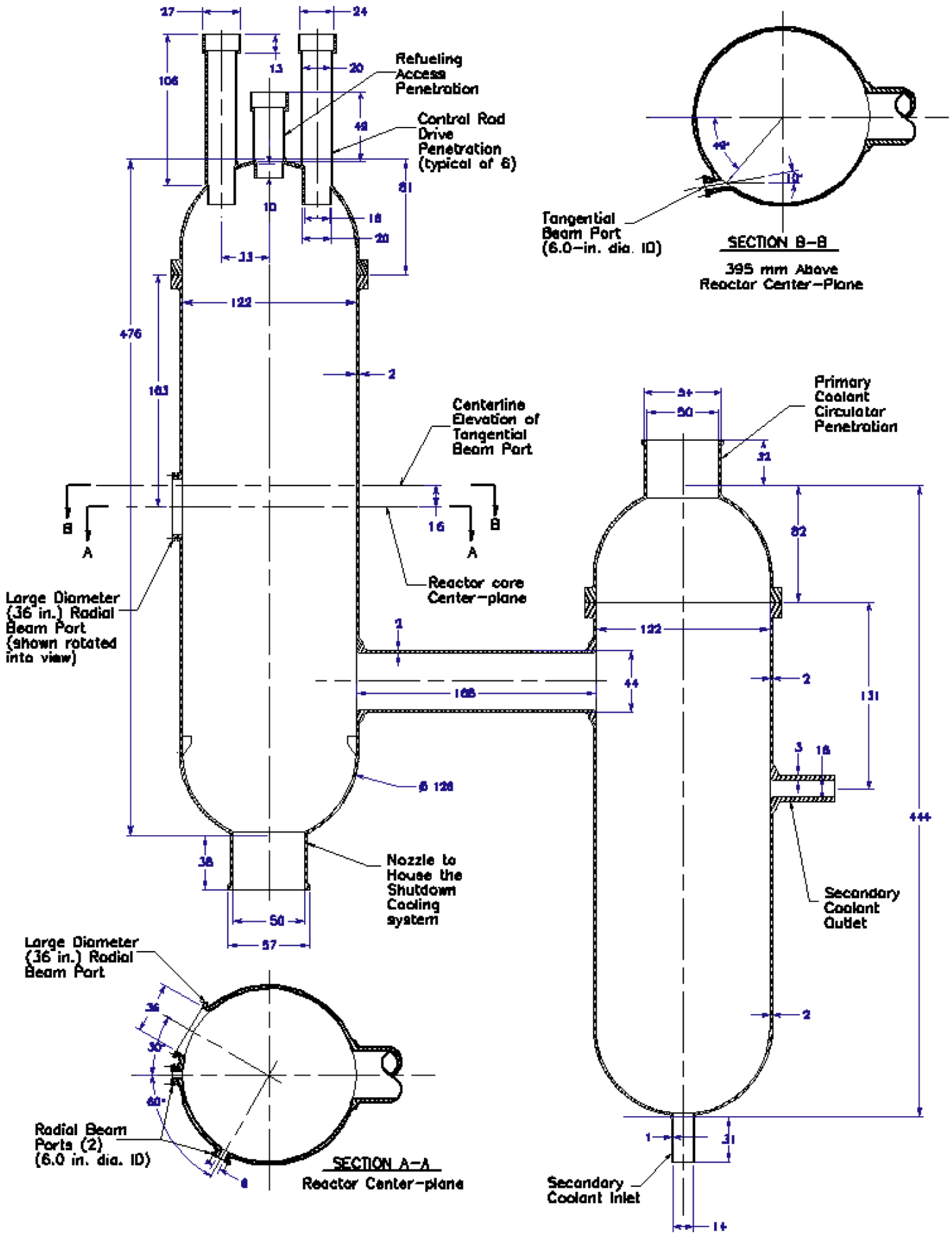

Fig. 4-11. VS cross section.

The pressure and temperature design conditions selected for PCD of the RV are:

- Design pressure: 3.1 MPa (450 psi)
- Design temperature: 371°C (700°F)

The basis for the selected RV design temperature is that this temperature is the maximum allowable by Section III of the ASME B&PV Code for the selected material.

Temperature distribution analyses indicate that the RV wall adjacent the to core can be maintained below 371°C when the reactor inlet temperature is ≤491°C by (1) configuring the flow path for the core inlet helium to flow upward into the inlet plenum above the core through coolant channels in the permanent graphite reflector, and (2) maintaining a gap of stagnant helium between the reactor core barrel and the RV inside diameter.

If the reactor inlet helium is raised to temperatures higher than 491°C, as may be the case for a core outlet temperatures of >850°C (the reference PCD core outlet temperature), a combination of a radiation shield and a flow of cooler helium in the gap between the core barrel and vessel may be needed. These approaches require investigation and more detailed analyses during follow-on engineering phases.

In regions not adjacent to the reactor core, where there is no need for a passive decay heat transfer path (i.e., in the upper and lower head areas), the RV is planned to be internally insulated on its inside surfaces with Kaowool blankets held in place by cover plates and/or shells.

4.2.4. Primary Heat Exchanger Vessel

The configuration of the PHXV is similar to that of the RV. The HXV consists of a cylindrical shell section closed at the bottom with a hemispherical lower head and a bolted hemispherical top head to provide to enable removal of the HXV internals. A nozzle is located in the bottom head for connection with the secondary system inlet coolant piping. A nozzle connecting the secondary coolant outlet piping is located in the cylindrical shell section of the HXV. A flange for bolting the primary coolant circulator housing is located in the top head.

The same pressure and temperature design conditions used for the RV also apply to the HXV. The HXV has essentially the same diametrical size as the RV, thus allowing the vessel wall thickness for the HXV to be the same as that selected for the RV.

As in the case of the RV, the materials selected for the HXV PCD are SA-508, Class 3 steel forgings and SA-533 Grade B, Class 1, steel plate. The HXV is designed to be insulated on all of its internal surfaces by means of Kaowool blankets held in place by cover plates and/or shells.

4.2.5. Cross Vessel

The cross vessel is a horizontally oriented cylindrical pressure vessel. The PCD design is based on fabrication of the cross vessel from a single piece forging of SA-508 Class 3 material. The cross vessel design connects to the RV and the PHXV by means of full penetration weld joints at the cross vessel ends. The single piece forging increases the structural reliability and decreases the in-service inspection (ISI) requirements.

As in the case of the HXV, the cross vessel is insulated on all of its inside surfaces by means of Kaowool blankets held in place by means of cover plates and/or shells.

4.2.6. Vessel Support Arrangement

A schematic of the vessel support subsystem is shown in Fig. 4-12.

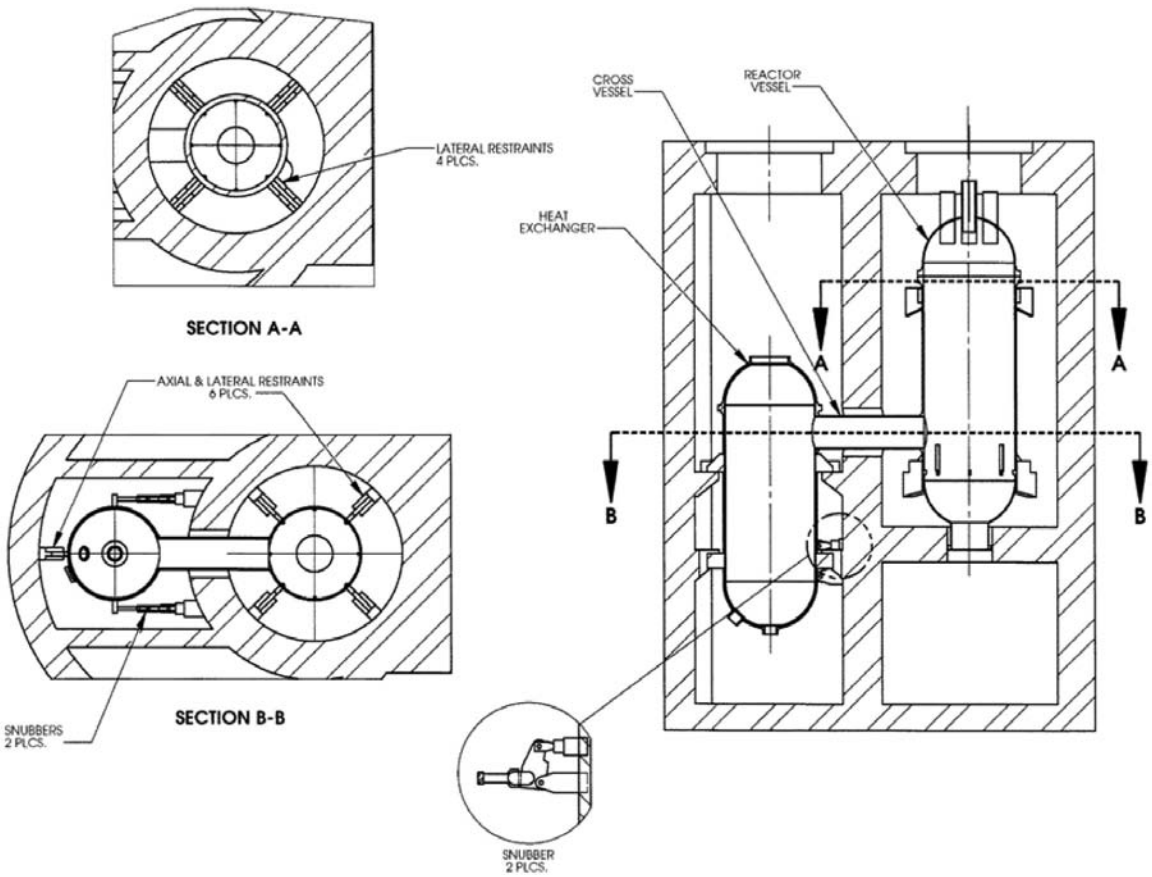

Fig. 4-12. Schematic of vessel support subsystem.

The RV supports include:

- Four (4) sliding bearing assemblies that mate with four integral RV lower support lugs located just below the cross vessel. These bearing assemblies are oriented at an angle of 45 deg relative to the cross vessel axis. The integral support lugs interface with expansion plate assemblies that, in turn, mate with the building structure. The RV sliding bearing and expansion plate assemblies accommodate the radial thermal growth of the RV during normal and abnormal plant operating conditions, while also providing vertical and horizontal support to the RV.
- Four (4) upper lateral support keys, each oriented at an angle of 45 deg relative to the cross vessel axis. These keys interface with expansion plate assemblies that, in turn, mate with the reactor building structure. The RV upper lateral supports and expansion plate assemblies accommodate axial and radial thermal growth of the RV during normal and abnormal operating conditions, while also providing horizontal support for the RV.

The HXV supports include:

- Two (2) sliding bearing assemblies that mate with two (2) integral HXV upper support lugs located just below the cross vessel. The support lugs interface with expansion plate assemblies that, in turn, mate with the building structure. The HXV sliding bearing and expansion plate assemblies accommodate the HXV radial thermal growth, plus the thermal expansion of the VS relative to the centerline of the RV during normal and abnormal operating conditions. These bearings and plates also provide for HXV vertical support and horizontal support perpendicular to the cross vessel axis.

- Two (2) lower lateral support keys are oriented parallel to the axis of the cross vessel and interface with expansion plate assemblies that, in turn, mate with the building structure. The HXV lower lateral support lugs accommodate the axial thermal growth of the HXV during both normal and abnormal operating conditions, while also providing horizontal support for the HXV perpendicular to the cross vessel axis.
- Two (2) snubber assemblies attached to integral HXV lugs at the lower portion of the HXV. These snubber assemblies accommodate both vertical thermal expansion and translational motion of the HXV (sliding in the direction of the axis of the cross vessel), while also providing horizontal support parallel to the cross vessel axis during seismic events.

The cross vessel is supported solely through the weld joint connections to the reactor and PHXVs.

4.2.7. Pressure Relief Subsystem

The PRS provides overpressure protection for the primary coolant pressure boundary. A flow diagram of the PRS PCD is provided in Fig. 4-13.

This subsystem consists of two redundant, full capacity pressure relief trains connected to the PHXV. Each train includes a self-actuated pilot operated relief valve and a rupture disk located downstream of the relief valve. The PRS discharges to the cavity volume surrounding the VS.

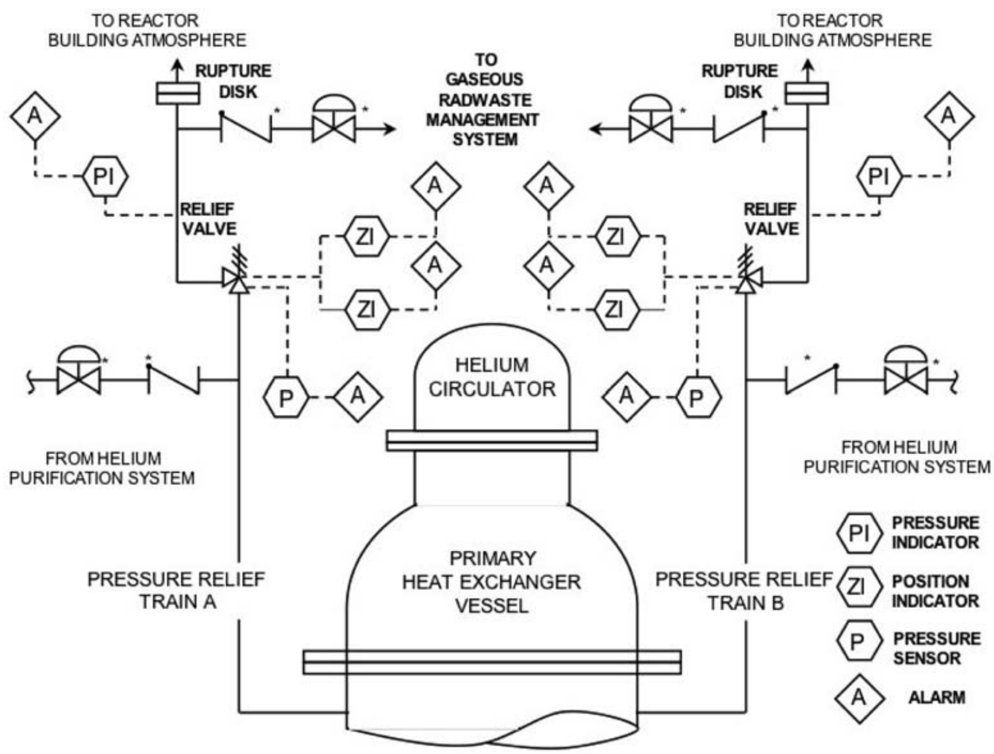

Fig. 4-13. PRS flow diagram.

4.3. PRIMARY HEAT EXCHANGER

The PHX consists of a high-effectiveness heat exchanger for transfer of heat in the primary coolant to the secondary system coolant.

4.3.1. Primary Heat Exchanger Functions and Requirements

The PHX functions are:

- Transfer heat from primary helium coolant loop to secondary nitrogen coolant loop.
- Bring temperature of secondary coolant to a maximum value for use in experiments requiring high temperatures.
- Prevent loss of primary coolant in the event of secondary coolant loss.

The PHX requirements are:

- PHX shall be capable of transferring 25 MW(t) from primary helium coolant to secondary system nitrogen coolant.
- PHX shall have a thermal transfer efficiency of 95%.
- PHX shall be designed to operate with sustained helium inlet temperatures up to 950°C and nitrogen inlet temperatures up to 450°C.
- Design of PHX shall accommodate temperature transients from reactor core.
- Design of PHX shall accommodate pressure transients in secondary coolant.
- PHX shall fit within the PHXV.
- PHX shall be sized to fulfill functions and requirements allowing for 10% compromised coolant capability.

4.3.2. Primary Heat Exchanger Design Description

The thermal energy from the reactor will be transferred in the PHX from the primary helium coolant loop to a secondary coolant loop containing a nitrogen working fluid. The hot nitrogen will pass into the laboratories for experimentation or be sent directly into the secondary heat exchanger (SHX). The PHX must be capable of removing the full 25 MW(t) produced by the reactor core at full power to control the core inlet temperature. The PHX must also transfer heat at maximum efficiency to the secondary coolant to achieve usable temperatures in the high temperature materials and processes (HTMP) and energy transfer (ET) laboratories.

As shown in Fig. 4-14, the PHX was designed to be located at the bottom of the HXV. Primary helium coolant at temperatures up to 950°C flows into the center of the PHX from the top. From there, the primary coolant flows radially through the heat exchanger elements, reducing temperature to 450°C, and flowing into the primary circulator to be returned to the reactor core. Secondary nitrogen coolant enters the PHX at the bottom of the HXV, absorbing the heat from the primary coolant and exiting through the side of the HXV. The secondary coolant then enters the secondary loop piping system for use in the laboratories or through the SHX for discharge of heat to the atmosphere.

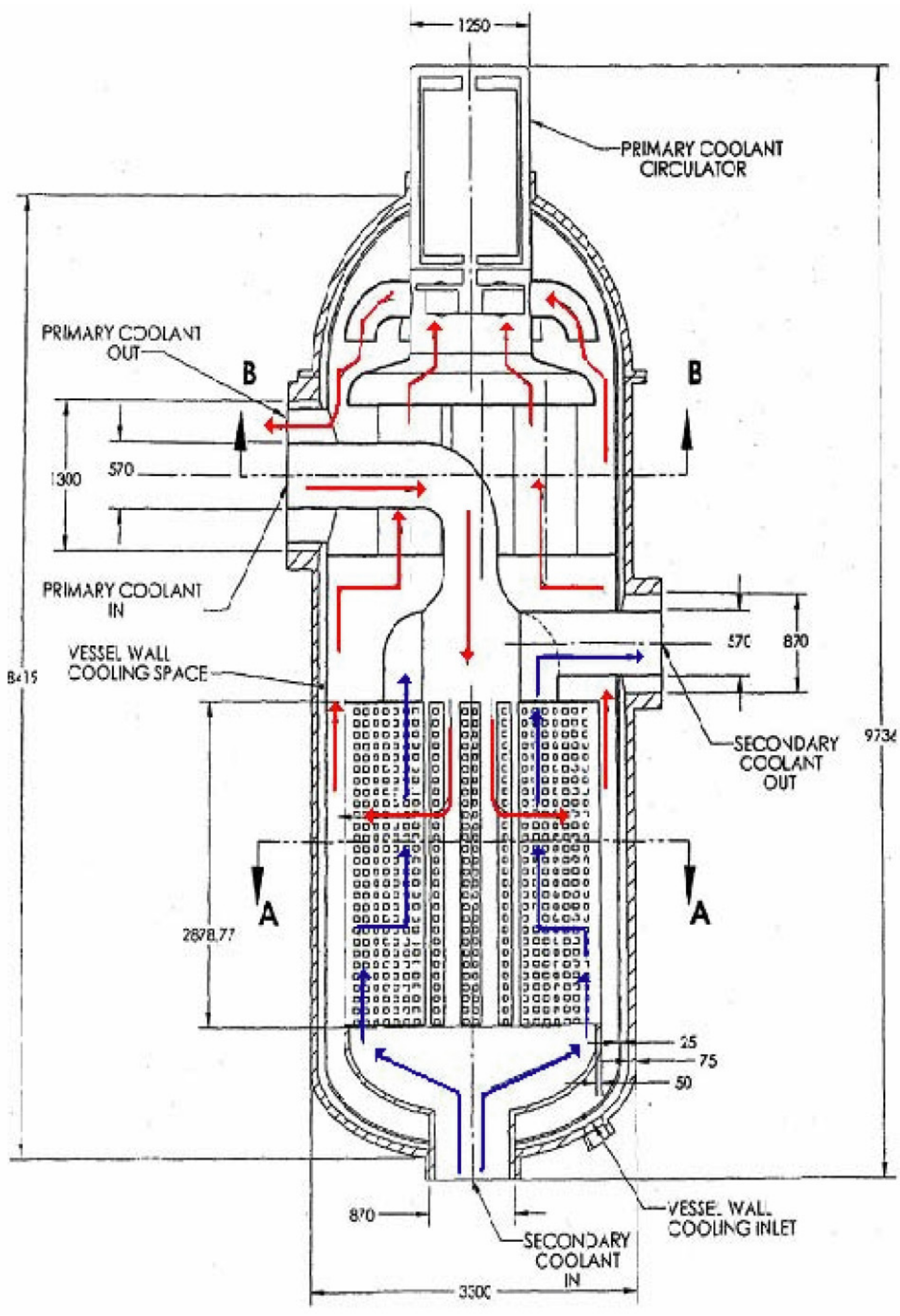

Fig. 4-14. PHX inside pressure vessel. Helium coolant flow (red) and nitrogen coolant flow (blue).

The primary function of the PHX is to achieve an effective exchange of energy between the primary and secondary coolants while keeping the coolant loops isolated from one another. A review of available heat exchanger designs by the University of Texas at Austin considered size, overall cost, and performance issues associated with shell and tube heat exchanger (STHE), printed circuit heat exchanger (PCHE), and compact plate heat exchanger (CPHE) types of commercial heat exchangers. This study resulted in the selection of a PCHE as the heat exchanger of choice in the PHX. The characteristics of the PCHE outperform other types of heat exchangers for this application, especially in terms of size.

The PHX is required to operate with a primary coolant inlet temperature of 950°C and intermittent temperature spikes. During normal operation, the PHX will operate at a pressure of at least 3 MPa on the primary and secondary sides, with the operating pressure of the secondary side slightly greater than the operating pressure of the primary side. This pressure difference will ensure that gas will flow from the secondary to the primary side if a leak occurs within the PHX. Similar pressures in the two loops have been selected to minimize pressure stresses within the PHX. The design must also allow for transients in the unlikely event of loss of coolant in one of the coolant loops. The last PHX requirement involves the heat exchanger margin which allows for fouling by unforeseen contaminants in either coolant loop.

4.3.3. Printed Circuit Heat Exchanger Design

PCHE are a type of heat exchanger developed by Heatric LTD. The design involves chemically etching fluid channels into flat metal plates. Each individual plate is approximately 5 mm high with each channel etched 2 mm in depth. The channels themselves can be straight or wavy. The layouts of the plates are dependent upon the type of heat transfer desired. In the simplest case, both the primary plate and secondary plate are etched longitudinally, but the secondary plate is etched with two 90 deg bends at each end to allow proper placement of primary and secondary flow ports to prevent overlap. Figure 4-15 shows the design of the plates.

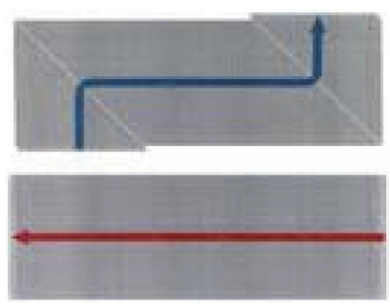

Fig. 4-15. PCHE plate layout.

Primary coolant flow is indicated by the straight red arrow, and secondary coolant flow is indicated by the angled blue arrow.

Once placed on top of each other, the plates are diffusion bonded by pressing the plates together at a temperature below the melting point of the metal. This “solid-state joining” causes grain growth between the plates allowing the joints to closely simulate the strength of the parent metal. The finished PCHE becomes one block with internal channels for the coolants to pass through.

The unique process and design of the PCHE allows a more compact heat exchanger than either the STHE or the CPHE. A PCHE also allows higher pressures (up to 600 bars), larger temperature ranges (from cryogenic temperatures up to 1000°C or higher), and reach higher effectiveness percentages up to 98%. A distinctive design feature of the PCHE is the geometry of the channels that are etched into each plate. In straight channels, the coolant flows can become fully developed leading to low heat transfer values. Wavy channels allow higher heat transfers due to higher Reynolds numbers. At low Reynolds numbers (~200), there is no distinction between straight and wavy channels, but once the Reynolds number reaches a transition phase to turbulent flow (~1200–4000), the coolant creates vortices and eddies that result in higher heat transfer. Figure 4-16 shows flow through a wavy channel, depicting the eddies and vortices created.

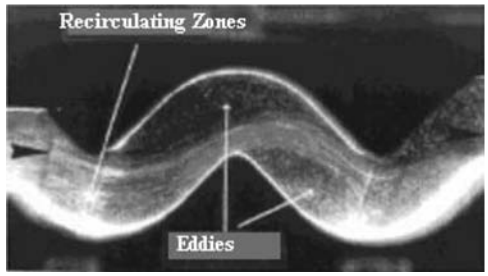

Fig. 4-16. Fluid flow in a PCHE.

Pressure loss is one disadvantage of the PCHE which occurs at higher Reynolds numbers. When the Reynolds number reaches 4000 or higher, the flow becomes very turbulent causing higher pressure losses than would occur in straight channels. A balance of the Reynolds number and heat transfer rate must be determined to obtain a minimal pressure drop. The price of the PCHE is also a disadvantage of the unit, but other technologies requiring a larger pressure vessel would have vastly greater associated costs.

A design arrangement for the PHX was developed in SolidWorks based on eight PCHE stacks (modules). A top view of the PHX within the HXV, showing the PCHE modules and the associated coolant flows, is shown in Fig. 4-17. The inner pipe contains the helium from the reactor and the outer pipe contains the helium that is returned to the reactor. The heat exchanger modules are radially aligned around the vessel centerline and situated in the bottom half of the pressure vessel (Fig. 4-14).

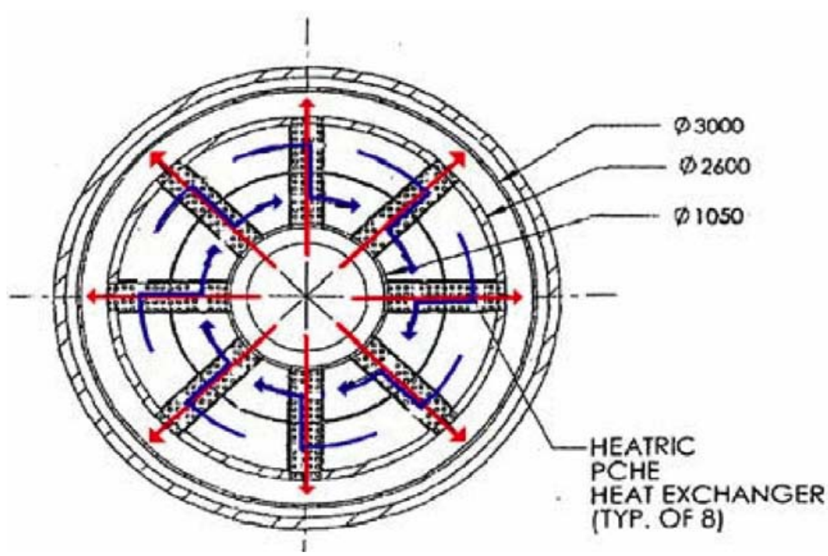

Fig. 4-17. Top view of the PHX. Helium flow is shown in red, nitrogen in blue.

4.3.4. Heat Exchanger Performance

To transfer 25 MW(t) requires 1100 m^2 heat transfer surface area. The PCHE key advantage is the large number of small channels which allow for a large surface area in a low-volume heat exchanger. Diffusion-bonded exchangers can withstand pressures exceeding 62 MPa and temperatures up to 815°C when constructed from stainless steel. Even greater limits can be achieved by using either Incoloy 800H or Inconel 617 as the fabrication material. Heatric LTD indicated that the PCHE is typically 20% the size and weight of STHX.

The performance of the PHX (Fig. 4-17) has been optimized by iterating the mass flow rates, channel geometries, and total number of channels in the thermal model. This adjustment should satisfy the effectiveness requirement of 95%. The physical model of the PHX is based on the ideal number of passages and required surface area extracted from the thermal model. A sensitivity analysis reveals the thermodynamic performance is a function of the secondary mass flow rate. Data points from the iterative model have been recorded from 49–55 kg/s. This range is chosen by raising the secondary mass flow rate above 55 kg/s causing the heat exchanger effectiveness to fall below 95%. As the secondary mass flow rate is lowered below 49 kg/s, the required surface becomes greater than the actual surface area, and the overall heat transfer falls below 25 MW(t). The heat transfer and the effectiveness are tracked over the specified mass flow range (Figs. 4-18 and 4-19).

Pressure loss through the heat exchanger was calculated to maximize operational efficiency. The pressure loss through the heat exchanger was determined by analyzing three regions of interest: exchanger core, inlet and outlet manifold ports, and elevation differences. These losses are shown in Table 4-1.

The PHX creates a 1.4% loss on the helium side and a 1.9% on the nitrogen side. The difference in these calculations is due to the corresponding mass flow rates. For the pressure drop analysis, the helium and nitrogen mass flow rates were approximated at 13.3 and 50 kg/s. With the initial coolant pressures of 3.026 and 3.137 MPa for helium and nitrogen on the inlet side, flow through the exchanger creates pressures of 2.985 and 3.026 MPa at the outlet. The nominal performance parameters for the reference PHX are provided in Table 4-2.

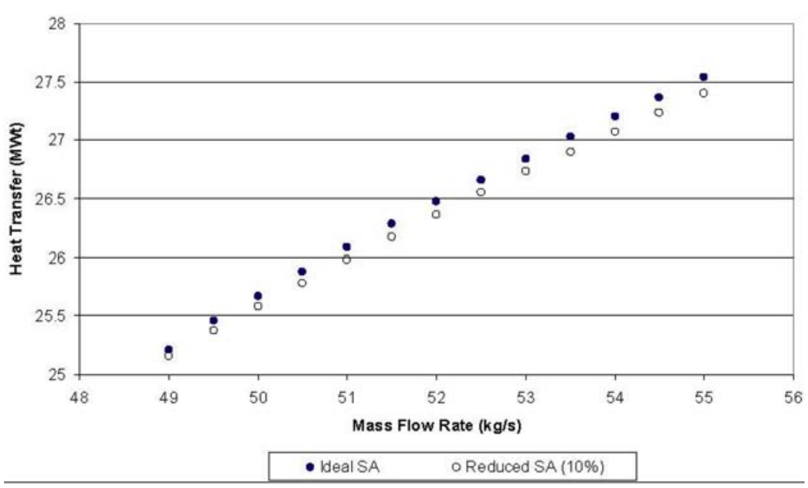

Fig. 4-18. Heat transfer versus secondary mass flow rate.

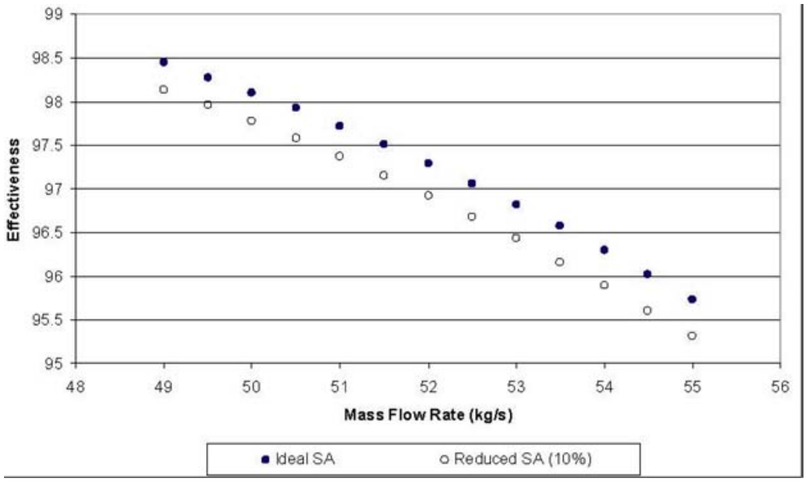

Fig. 4-19. Effectiveness versus secondary mass flow rate.

Table 4-1
Eight Module Heat Exchanger Pressure Losses

Coolant	Pressure Loss				
	Core	Port	Elevation	Total	Percentage
Units	kPa	kPa	kPa	kPa	%
Helium	16.6	24.7	0.46	41.8	1.3
Nitrogen	18.2	40.4	0.39	59	1.9

Table 4-2
Ideal Parameters and Results of HX Analysis

Summary of Ideal Parameters and Results of HX Analysis			
Inlet Temperature		**HX Performance**	
Primary	905°C	Primary outlet temperature	521.5°C
Secondary	450°C	Secondary outlet temperature	892.7°C
		Heat transfer	26.47 MW(t)
Mass Flow Rates		Effectiveness	97.3%
Primary	13.3 kg/s		
Secondary	52 kg/s	**Module Dimensions**	
		Length	0.845 m
Geometrical Parameters		Width	0.199 m
Diameter of channels	2 mm	Height	2.4 m
Length of Channels	0.845 m		
Channels/layer	50		
Layers (per coolant)	600		
Modules	8		
Actual SA	1104.1 m^2		
Required SA	577.8 m^2		

The HT3R reactor has, as an objective, an output a temperature of 950°C to the PHX. The PCHE and all pipes that are in contact with the hot primary coolant are recommended to be composed of Inconel 617 or some other alloy that can withstand temperatures up to 1000°C. Fouling within the channels of the PHX is minimized due to closed primary and secondary loops. In the event that fouling does occur on either side, the PHX is oversized with a 10% margin. In the extreme case where over 10% of the channels are plugged, thus preventing transfer of up to 25 MW(t), the PHX will need to be taken offline to unfoul the channels. However, this case is unlikely and additional research is recommended.

The PHX proposed by the analysis at UT Austin is a PCHE design that creates a solid block once all of the plates have been diffusion bonded together. The channels of each plate are separated by 1.75 mm of alloy while each plate is separated by approximately 1 mm of the same material, thus preventing the fluids from combining. There exists a small possibility that a hole could develop between the plates allowing the primary helium coolant to mix with the secondary nitrogen coolant. If this occurs, the pressure difference between the primary channels at a lower pressure of 3.026 MPa, compared to the secondary channels at 3.137 MPa, will result in the secondary coolant leaking into the primary coolant. It would be unfavorable for the primary coolant to leak into the secondary system because the because the primary coolant may contain trace fission byproducts from the core, which would require expensive decontamination of the secondary loop. In the event of a leak, trace helium from the primary loop would diffuse into the secondary system, allowing for easy detection of the leak itself with standard helium detection equipment.

4.4. PRIMARY HELIUM CIRCULATOR

The general arrangement of the HT3R PHC is given in Fig. 4-20. The HT3R PHC consists of the following:

- Variable speed electric motor.
- Axial flow impeller and diffuser.
- Main loop shutoff valve (MLSV).
- Electric motor control and power subsystem (EMCPS).
- Magnetic bearing control and power subsystem.
- Labyrinth seal.
- Internal circulator cooler.
- Barrier plate and motor outer sleeve.

Design descriptions for these components and/or subsystems are provided in the following sections. The schedule and cost for performing engineering of the PHC are provided in Section 7.2. The cost and schedule for fabricating and installing the PHC into the HT3R facility are provided in Section 8.1.

4.4.1. System Functions

The primary functions established for the HT3R PHC PCD are as follows:

- Provide pressure rise necessary for forced circulation of helium coolant throughout the PS (i.e., through the reactor and PHX) for all modes of plant operation including: (1) steady state operation, (2) part-load operation, (3) startup and shutdown, (4) transient conditions, and (5) upset conditions.

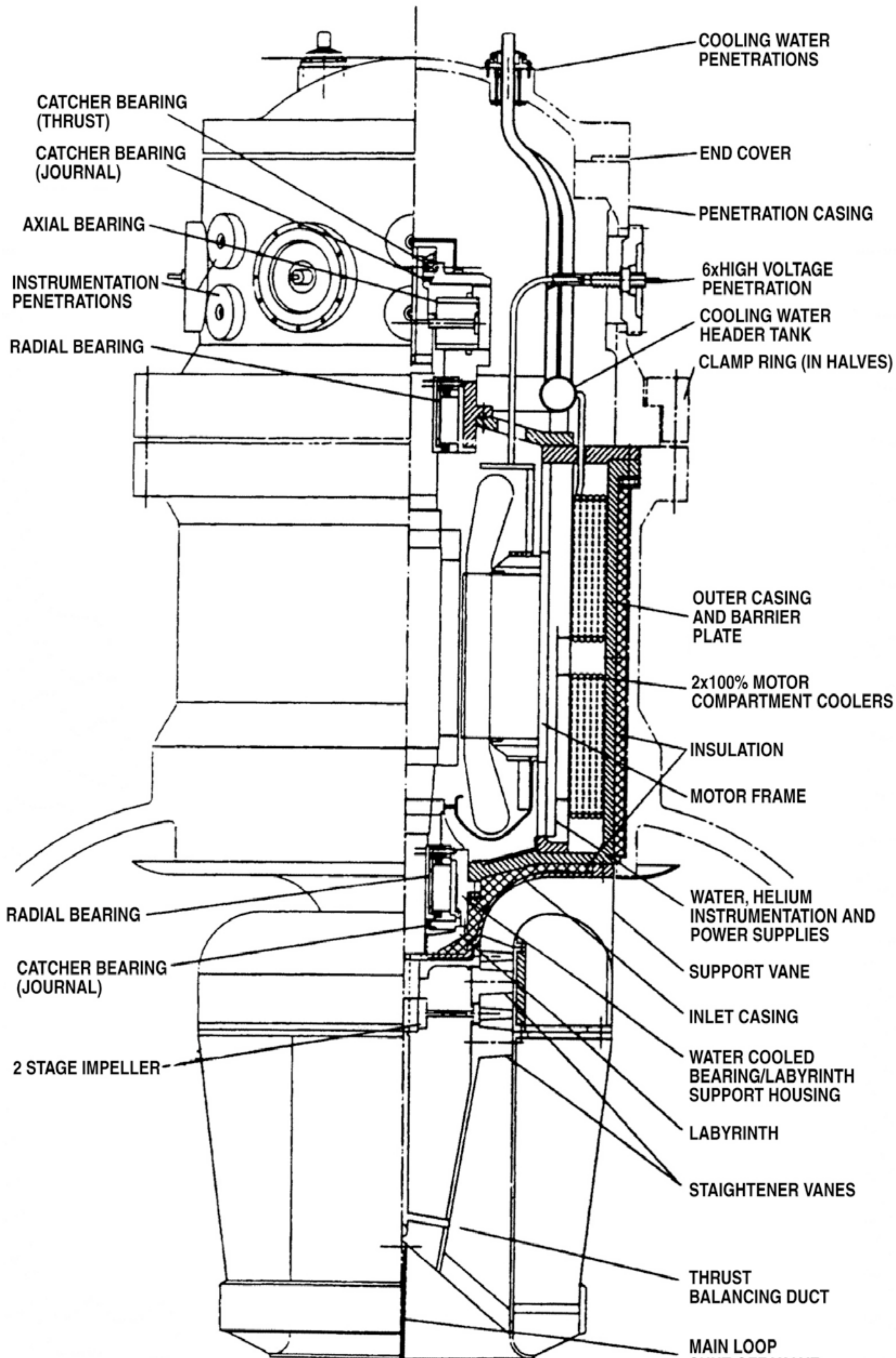

Fig. 4-20. PHC arrangement.

- Control coolant mass flow through PS for all modes of plant operation.
- Provide a means for isolating reactor system from PHX when the circulator is not operational to prevent bypass of either natural circulation flow or shutdown cooling circulator flow of hot gas from the reactor to the PHX.

4.4.2. Overall System Description

The general arrangement of the HT3R PHC is given in Fig. 4-20. The PHC is mounted vertically at the top of the HXV closure head and is part of the pressure boundary for the primary coolant. Helium flow rate can be adjusted by varying motor speed. The axial flow impeller is mounted to the bottom of the motor shaft. The cold return helium enters the circulator inlet, flows downwards through the impeller and the MLSV, and is discharged into the circulator outlet plenums of the HXV. The helium collected in the HXV's outlet plenums is then returned to the RV via the cross vessel. The MLSV assembly shuts off primary coolant flow through the PHC when the SCS circulator is operating.

Detailed analyses to establish the optimum impeller geometry must be undertaken using proven aerodynamic design methodology. The major parameters to be considered in the rotating group analysis include: (1) impeller size and weight, (2) bearing span (dictated by electric motor rotor length), (3) impeller overhang dimension (controlled by the labyrinth seal block, if required), and (4) motor heat removal capability. Based on the PCD of the PS, the minimum necessary pressure head to overcome the pressure losses throughout the PS during steady state conditions is 49.34 kPa (7.16 psid). Using a conservative value of 80% for the efficiency of the PHC, an initial estimated power requirement for the PHC motor is 430 kW.

4.4.3. Electric Motor, Power Supply and Cooling

The main circulator is driven by an induction motor. Based on past experience for larger circulators, the circulator PCD designers selected a six-phase two-pole variable speed induction motor driven by two frequency converters. The PHC conceptual design phase will examine whether a three-phase induction motor would be a better selection. The circulator speed can be varied from its nominal value as required to adjust helium flow during transient or part load conditions.

Motor speed is controlled using a solid-state variable frequency power supply, which is part of the EMCPS. The EMCPS is comprised of a frequency converter and control modules. The EMCPS shall provide means of stopping the rotor from maximum speed to rest within 10 s, using either motor regenerative braking or d.c. electrical braking.

The length and diameter of the RV have been selected to accommodate the physical size of the reactor system with space allowances above the core for refueling equipment and below the core support structure for the SCS.

Cooling water is provided to heat exchanger units within the motor cavity and to the labyrinth seal mounting block. The cooling subsystem provides adequate cooling of the electric motor and magnetic bearings. Shaft-mounted fans on the motor/compressor shaft circulate the helium coolant through the motor cooling passages for heat rejection. Two independent 100% motor cooling heat exchangers are installed in the motor cavity to remove heat generated by the motor and heat transferring into the motor cavity from circulating primary coolant. The bottom radial bearing and labyrinth seal are mounted off a water-cooled block attached to the barrier plate. The water passages in the mounting block are internally drilled with welded water connections that can be checked. The bearing will be cooled by conduction to the mounting block and/or forced gas circulation. The mounting block also acts as a cooler for the labyrinth purge gas.

4.4.4. Axial Flow Impeller and Diffuser

The axial flow impeller (Fig. 4-20) is a two-stage impeller with flow straighteners before, between, and after the rotor stages. A single stage impeller with pre-rotators and straighteners is another possible configuration which will be examined in the conceptual design phase.

4.4.5. Main Loop Shutoff Valve

The flow-activated MLSV is located in the lowest portion of the circulator outlet duct. The valve design is based on two lightweight flaps of semi-elliptical shape supported at their upstream edge and with a central divider. The MLSV is equipped with position sensor instrumentation plus a jet-assisted position override mechanism to allow for remote-manual closure.

4.4.6. Magnetic Bearing and Labyrinth Seal

The vertical shaft is supported by one magnetic thrust bearing and magnetic journal bearings at the upper and lower ends of the shaft. The PHC PCD design is based on non-redundant bearings and on redundant control electronics. Each bearing could have a spare, nonactive sensor installed. The redundant electronics should incorporate an automatic transfer circuit. Manual transfer would also be an option.

A labyrinth seal is required to separate the primary coolant helium from the motor cavity environment. The shaft labyrinth seal will be buffered with purified helium at pressure sufficient to prevent ingress of primary coolant helium into the motor cavity at all times. The shaft labyrinth seal is located directly above the under-hung impeller and is mounted off the bottom of a water-cooled mounting block.

4.5. SHUTDOWN COOLING SYSTEM

The HT^3R SCS consists of a shutdown heat exchanger, shutdown circulator, shutoff valve, shutdown cooling control system, and shutdown cooling water system (SCWS).

4.5.1. System Functions and Requirements

The SCS functions are as follows:

- Provide reactor cooling during shutdown conditions in the event that the primary cooling system is not available for heat removal.
- Perform a transient reactor cooldown function with either pressurized pure helium or in a depressurized mode with a mixture of air and helium.
- Maintain the integrity of the primary coolant pressure boundary.
- Provide controls for maintaining proper operation of the SCS for all possible operating conditions including pressurized and depressurized shutdown and standby operation when the reactor is being cooled by the primary coolant system.

- Reject reactor decay heat to the atmosphere for all modes of operation including pressurized and depressurized shutdown, as well as standby operation when the reactor is being cooled by the primary coolant system.

4.5.2. Overall System Description

The SCS provides reactor cooling when the main cooling system (PHX and primary circulator) is not operational. The SCS consists of a shutdown circulator, shutoff valve, shutdown heat exchanger, shutdown cooling control system, and SCWS. Service equipment is also included as part of the SCS for shutdown circulator and shutdown heat exchanger.

The SCS consists of a single loop with the shutdown heat exchanger in series with the shutdown circulator and shutdown loop shutoff valve assembly, all of which are located at the bottom of the RV as shown schematically in Fig. 4-21. Hot helium from the core outlet plenum flows downward through multiple parallel openings (pipes) in the center of the core support structure and into the shutdown heat exchanger. Once cooled, the helium continues downward through the shutdown loop shutoff valve to the shutdown circulator where it is compressed and discharged into the RV bottom head cavity. The cool helium then flows through internal passages in the core support structure and up the coolant channels in the permanent side reflector blocks, discharging into the core inlet plenum. The loop is completed as the helium flows down through the reactor core, exiting into the core outlet plenum. Helium back-flow through the heat transfer vessel is minimized by a main loop shut off valve in the PHC assembly. Heat is rejected from the shutdown cooling water to the atmosphere through an air-cooled heat exchanger.

During a pressurized conduction cooldown event, the shutdown cooling water loop is sized to cool the reactor following an SCS startup. The peak heat load is 1.7 MW(t). The shutdown circulator and the shutdown heat exchanger are also sized to remove 0.7 MW(t) during depressurized maintenance conditions 24 h after reactor shutdown.

For high reliability, the SCS can be powered by either normal or standby electrical power. Table 4-3 provides the design parameters for the SCS components.

The SCS has two operating modes depending on the condition of the reactor:

1. Standby Mode. During normal reactor operation, a small amount of cold leg helium leaks through the closed loop shutoff valve and flows in a direction opposite to the normal flow path through the shutdown circulator and associated shutdown heat exchanger tubes. In this mode, the shutdown circulator is not operating. However, during the standby mode, the SCWS, by design, supplies a small amount of water flow to the shutdown heat exchanger to prevent thermal shock when the SCS switches to the cooldown mode. Since this water flow removes a small amount of heat from the primary coolant, the flow rate must be set as low as possible without resulting in either of the following adverse conditions: (a) development of a boiling condition in the exchanger, or (b) the onset of static instability due to the hydrostatic head in the exchanger tubes.
2. Cooldown Modes. When shutdown is necessary for the main loop cooling function and reactor, the SCS provides cooling of the reactor core with a flow rate sufficient to prevent the development of reverse flow through the reactor core. The VS can be either pressurized or depressurized. During each of these cooldown modes, the water flow through the shutdown heat exchanger must be high enough to provide an adequate subcooling margin.

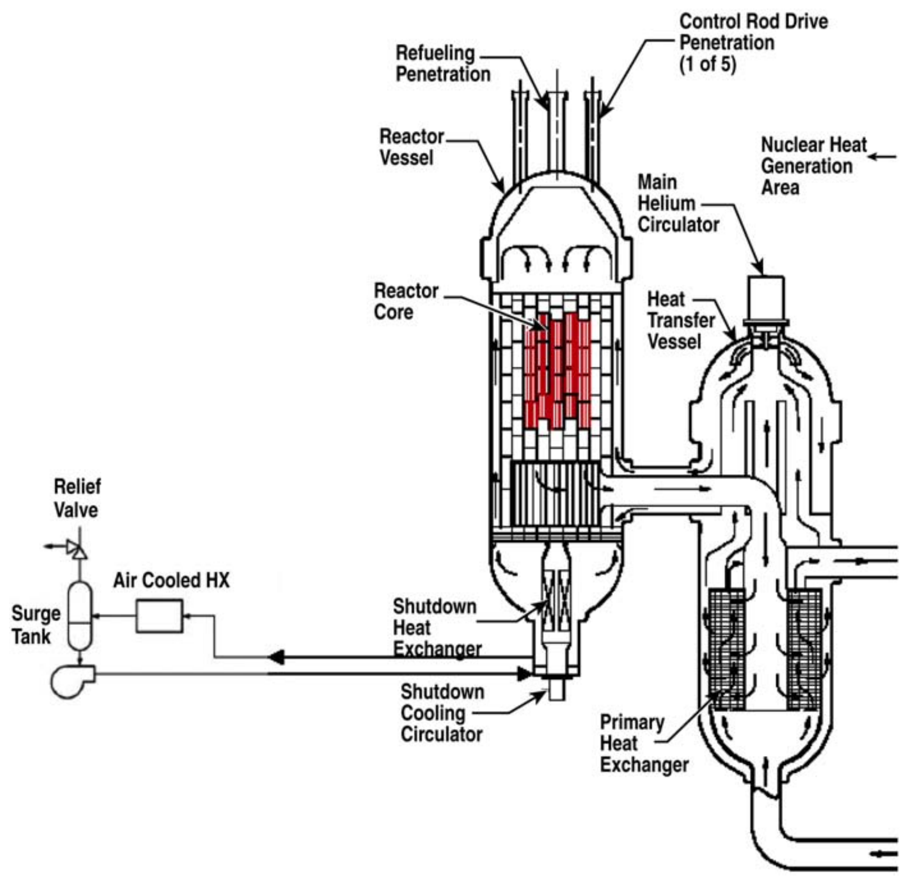

Fig. 4-21. SCS general arrangement.

Table 4-3
Shutdown Cooling System Design Parameters

	Depressurized	Pressurized
Shutdown Heat Exchanger		
Heat duty MW(t)	0.64	1.7
Helium inlet temperature °C (°F)	950 (1742)	850 (1562)
Helium outlet temperature °C (°F)	295 (563)	490 (914)
Helium flow kg/s (lb/h)	0.19 (1483)	0.9 (7207)
Water flow kg/s (lb/h)	2.77 (2.2×10^4)	2.77 (2.2×10^4)
Water inlet temperature °C (°F)	50 (122)	50 (122)
Water outlet temperature °C (°F)	105 (221)	197 (386)
Water pressure MPa (psia)	4.9 (711)	4.9 (711)
Shutdown Circulator		
Motor power kW (hp)	5.0 (6.7)	0.65 (0.9)
Speed (rpm)	TBD	TBD
Exit pressure kPa (psia)	102.8 (14.9)	3000 (435)
Inlet temperature °C (°F)	295 (563)	490 (914)
Helium pressure rise kPa (psid)	1.38 (0.2)	0.9 (0.13)
Helium flow kg/s (lb/h)	0.19 (1483)	0.9 (7207)

Transfer from the standby mode to the cooldown mode, or from the cooldown mode to the standby mode, is a manual operation that is performed only after the operator has verified acceptable reactor and primary coolant conditions and can safely accommodate the transfer.

4.5.3. Shutdown Heat Exchanger

The shutdown heat exchanger is located below the core support floor shield on the bottom centerline of the RV. The general configuration is shown in Fig. 4-22. The shutdown heat exchanger is a vertically oriented, helical coil shell-and-tube, cross-counterflow heat exchanger fabricated from 2-1/4 Cr-1 Mo steel. In the standby mode, the exchanger operates in a cross-parallel flow regime (reverse primary flow). The helical tube bundle has an estimated surface area of 4.7 m^2 (50.1 ft^2) and weighs about 68.3 kg (150.5 lb). Key parameters for the shutdown heat exchanger are given in Table 4-3.

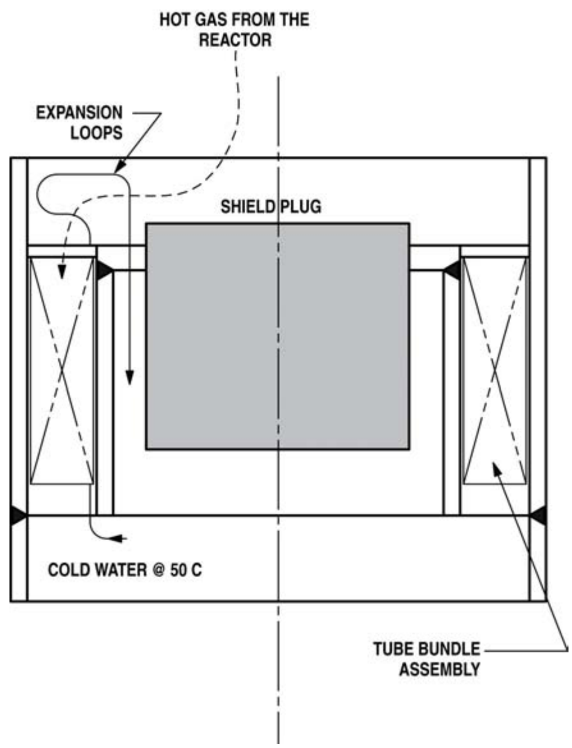

Fig. 4-22. Shutdown heat exchanger.

Water inlet and outlet flows pass through tubesheets located in the lower region of the heat exchanger. The tubes are attached to the inlet tubesheet, routed under circulator conduits to the helical bundle, spiraled upward through the bundle to an expansion loop at the top, and routed back down and attached to the outlet tubesheet. Thus, the tubes are continuous from tubesheet to tubesheet and are accessible from both ends for inspection and tube plugging.

For normal SCS operation, helium enters the shutdown heat exchanger tube bundle through a series of pipes from the core outlet plenum and flows downward over the cross-counterflow helical tubes and through the shutoff valve. After passing through the circulator, the flow returns to the lower RV cavity via the annulus formed between the heat exchanger shroud and RV wall. During the standby operational mode, the heat exchanger flow is reversed. Thus helium leaks from the lower RV cavity, through the circulator and the "closed" shutoff valve, then passes upward through the tube bundle before returning to the core outlet plenum.

During normal reactor operation, when the primary coolant is being cooled by the PHX, the SCS is operating in the standby mode. Under this condition, the SCWS is operating at a pressure less than that of the primary coolant. Thus, any leaks in the heat exchanger tubes result in a flow of primary coolant helium into the SCWS. However, when the SCS is operating in the normal cooling mode, the water pressure in the shutdown cooling heat exchanger must be increased to prevent boiling in the heat exchanger tubes. Under these conditions, the water pressure in the heat exchanger will be greater than that of the primary coolant, and any leaks would result in water leaking into the primary coolant (helium). In the unlikely event of significant water leakage into the PS, the SCS can be isolated to avoid any detrimental effects.

4.5.4. Shutdown Circulator

The shutdown circulator is a vertically oriented, radial-flow compressor driven by an electric motor. The integral motor/compressor rotor is supported on magnetic bearings. Figure 4-23 illustrates the circulator assembly installed in the RV. The key parameters for the shutdown circulator were presented in Table 4-3.

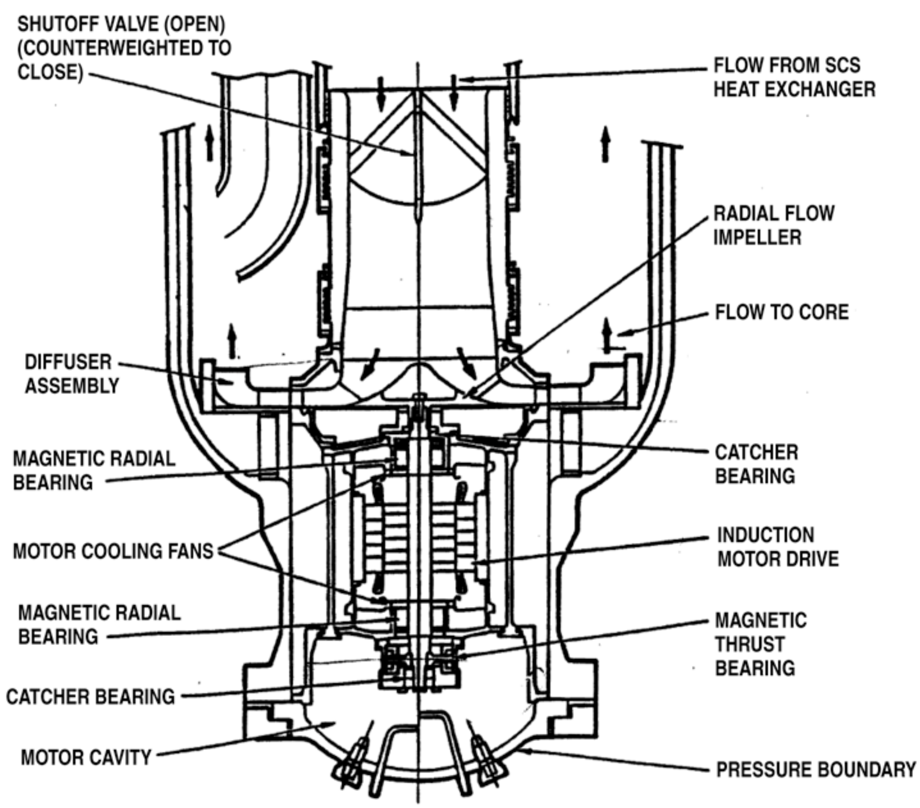

Fig. 4-23. Shutdown circulator and shutoff valve.

A shutoff valve is installed in the vertical inlet ducting above the shutdown circulator. When the SCS loop is operating in the standby mode, a small amount of primary coolant leakage flow occurs in an upward direction through the closed valve. When the SCS is operating in a cooldown mode, the loop flow is downward through the open shutoff valve. The shutoff valve is similar in concept to the main loop shutdown valves proven in the Fort St. Vrain (FSV) reactor.

4.5.5. Shutdown Cooling Water System

The SCS is designed to be both redundant to, and diverse from, the primary coolant system. Therefore, a dedicated cooling water loop has been included in the SCS design to provide coolant flow to the shutdown cooling heat exchanger. A process flow diagram of the SCWS is shown in Fig. 4-24. The shutdown cooling water loop consists of one 100% capacity jockey pump (for standby mode water flow), one 100% capacity cooldown pump, a pressurizer tank, one makeup water storage tank, and one 100% capacity air-cooled heat exchanger equipped with two 100% capacity fan banks.

In the SCS standby mode, the SCWS operates continuously removing heat from the helium leaking through the shutdown heat exchanger. In the reactor cooldown mode, the SCS maintains the primary coolant temperature at levels compatible with the desired in-vessel maintenance activities. The maximum shutdown cooling water heat load occurs when the SCS is started up following a pressurized conduction cooldown event. The heat load during this cooldown mode is ~2.0 MW(t).

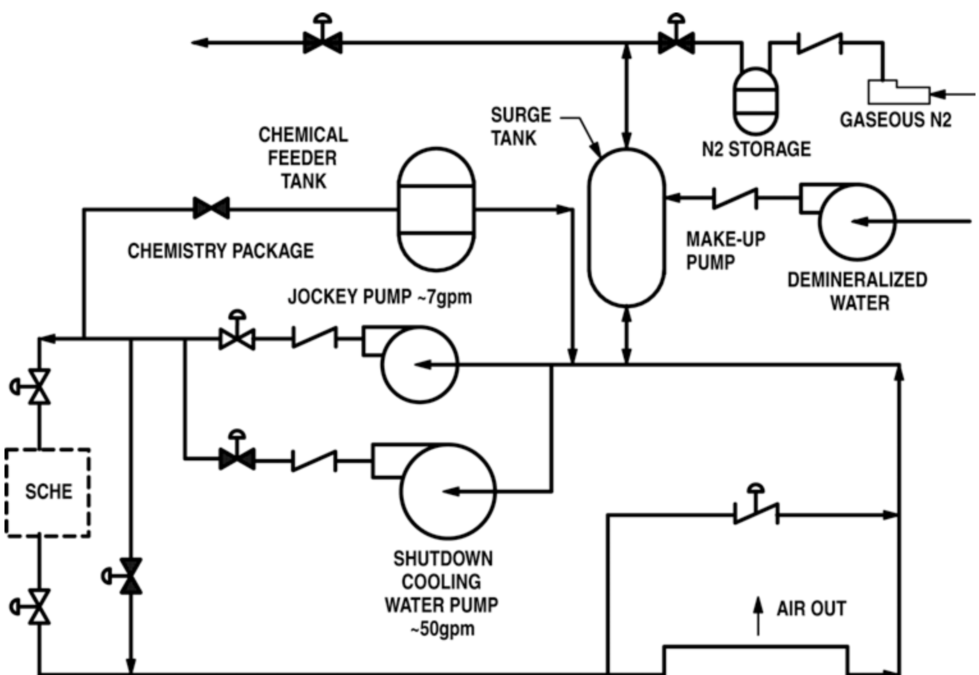

Fig. 4-24. SCWS flow diagram.

4.5.6. Shutdown Cooling Control System

The shutdown cooling control system provides controls for maintaining the proper water and primary coolant flows though the shutdown cooling heat exchanger. This system also provides controls for maintaining conditions on the cooling water side. The major control functions for the SCS are:

- Startup or shutdown operations by coordinating the activation of the SCS shutoff valve and circulator power supply.
- Shutdown heat exchanger cooling water exit temperature by adjusting the shutdown circulator speed set point (helium flow).
- Shutdown circulator speed by adjusting the output frequency and voltage of the circulator motor power supply.
- Switching between the standby mode water pump and the cooldown mode water pump.

Other SCS controllers include those required to maintain level and pressure in the water cooling system surge tank, shutdown cooling water pressure control, and maintenance of the circulator speed set point by adjusting motor frequency.

The control system also includes several SCS protection features such as loop isolation upon shutdown, heat exchanger leak detection, shutdown circulator overspeed protection, low water flow protection, loss of net positive suction head protection on the system water pumps, and shutdown heat exchanger high temperature protection.

During the cooldown mode of operation, the control system maintains both helium and water-side conditions. During the standby mode, the shutdown circulator is shutdown and the control system maintains only the water-side conditions.

4.6. FUEL HANDLING SYSTEM

4.6.1. System Functions and Requirements

The primary functions and requirements established for the HT^{3}R fuel handling system (FHS) PC are as follows:

- Refuel the reactor, perform other fuel and reflector element handling operations at the facility, receive and store fresh fuel elements, handle and store irradiated core elements, and prepare spent fuel elements for shipment.
- Limit radionuclide release from the fuel handling and storage equipment and provide personnel protection from radiation exposure.
- Provide for removal and replacement of NCAs in the RV, and provide storage of these assemblies when not installed in the vessel.
- Provide a means by which inspections and certain internal maintenance procedures can be performed within the RV.
- The fuel handling machine shall contain an integral cooling system and shall be hermetically sealed.
- The fuel handling equipment shall be designed for complete, automatic, programmed operation.

4.6.2. Overall System Description

The FHS accommodates receipt, inspection, and storage of fresh fuel elements. These elements are stored temporarily in fuel storage wells, in a specific sequential order as necessary to assure their placement in the reactor at designated locations.

A typical refueling involves the removal and replacement of fuel and reflector elements in the reactor core. Refueling is performed using the fuel handling machine operating through the central refueling penetration located on the RV centerline. None of the NCAs are required to be removed from the reactor to perform a typical refueling procedure. Fuel handling machine operations are carried out from a dedicated control room located on the refueling floor.

The fuel handling machine is designed to operate on a fully automatic basis during any particular element movement sequence. The internal mechanisms within the fuel handling machine are designed to reach all of the replaceable elements in the reactor — both fuel and reflector. Figure 4-25 shows a typical fuel handling operation.

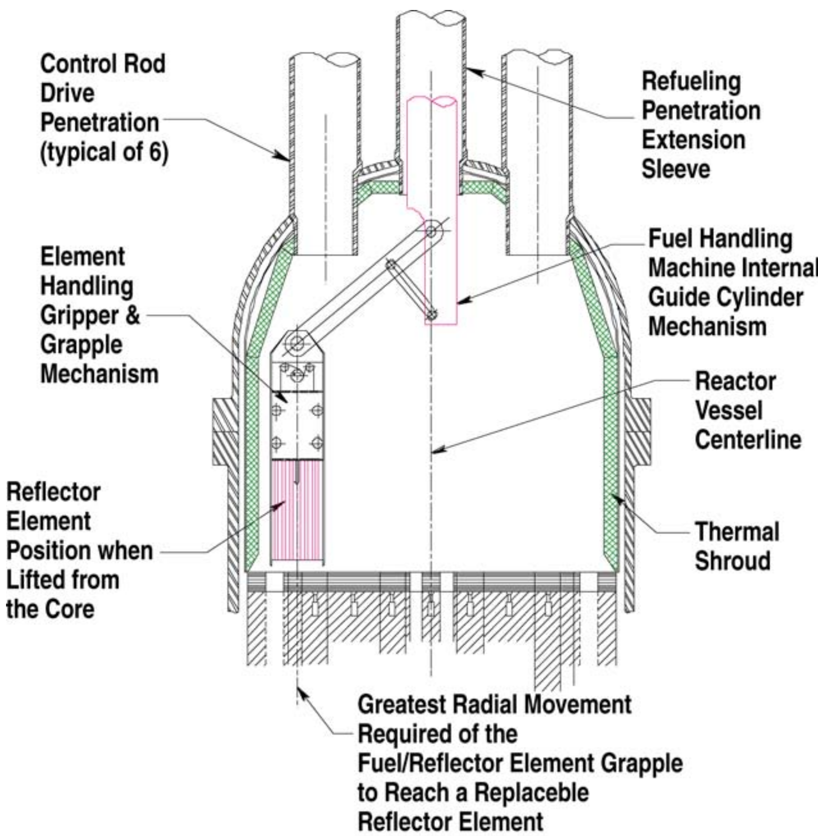

Fig. 4-25. Fuel handling machine element grapple positioned in the RV.

The fuel handling machine contains sufficient shielding to protect personnel from radiation exposure due to the spent fuel elements contained in the machine. The machine design includes an internal cooling system.

The pick-up head and grapple mechanism in the fuel handling machine can be changed in the facility hot cell to allow this mechanism to also remove and replace NCAs in the reactor.

The fuel handling machine is designed to withstand seismic forces. Stabilizing connections between the machine and the building floor, or other appropriate structures, are required to provide the necessary seismic support.

The internal volume of the fuel handling machine is completely sealed such that no helium contained therein can leak out, nor can the local atmospheric air leak in. A large gate valve equipped with seals is installed at the base of the machine. A similar gate valve assembly is installed over the top of the refueling penetration at the reactor (or at a fuel or equipment storage well).

A dedicated vacuum system provides for control of the machine internal atmosphere, plus the small interspace volume between the two gate valves when the machine is installed on the reactor or over a storage well. The vacuum system also provides for evacuation of the fuel storage wells and equipment storage wells. Clean helium is used to backfill the machine, gate valve interspaces, fuel storage wells, and equipment storage wells.

The spent fuel removed from the reactor is placed in hermetically sealed, helium-filled storage wells where the decay heat generated by these elements can be removed on a continuous basis by a dedicated cooling system.

From time to time, a NCA will have to be removed from its vessel penetration and replaced with a spare unit. This operation is performed using the fuel handling machine, suitably outfitted with the equipment handling grapple mechanism.

The fuel handling machine can also be configured to perform routine inspections within the RV, carry out internal maintenance of hardware items in the vessel, and insert and remove test articles at various points within the core or the RV.

4.6.3. Fresh Fuel Handling and Storage

Fresh fuel is received at the reactor facility in sealed containers. The contained fuel assemblies are prepared (cleaned, inspected, identified, logged, measured, weighed, photographed, etc.) and placed into fuel storage wells in a specific order that will support the required sequence for placement of these elements into the reactor core.

After all of the assigned fuel (and reflector) elements required by the refueling have been placed in the well, a large isolation gate valve is installed over the top of the well. The well is then evacuated and back-filled with helium. The fresh fuel elements are now ready for pickup by the fuel handling machine for transfer to the reactor core.

4.6.4. Refueling System

Before actual in-core refueling begins, the reactor is shutdown with all control rods inserted, where they remain for the duration of the refueling procedure. The VS is depressurized to slightly above atmospheric pressure, and the reactor SCS is placed in service to control the primary coolant temperature. Preparations are then made to remove the refueling penetration shield plug from the penetration (Fig. 4-26).

The refueling penetration concrete shield plug is removed from the refueling floor and a refueling penetration extension sleeve is manually installed in the penetration and bolted tightly to form a seal between them. The reactor refueling isolation valve is installed over the refueling sleeve, anchored to the building floor, and bolted securely to create a tight seal. The air in the volume space between the valve gate and the shield plug in the refueling penetration is purged with helium to eliminate the air from this volume.

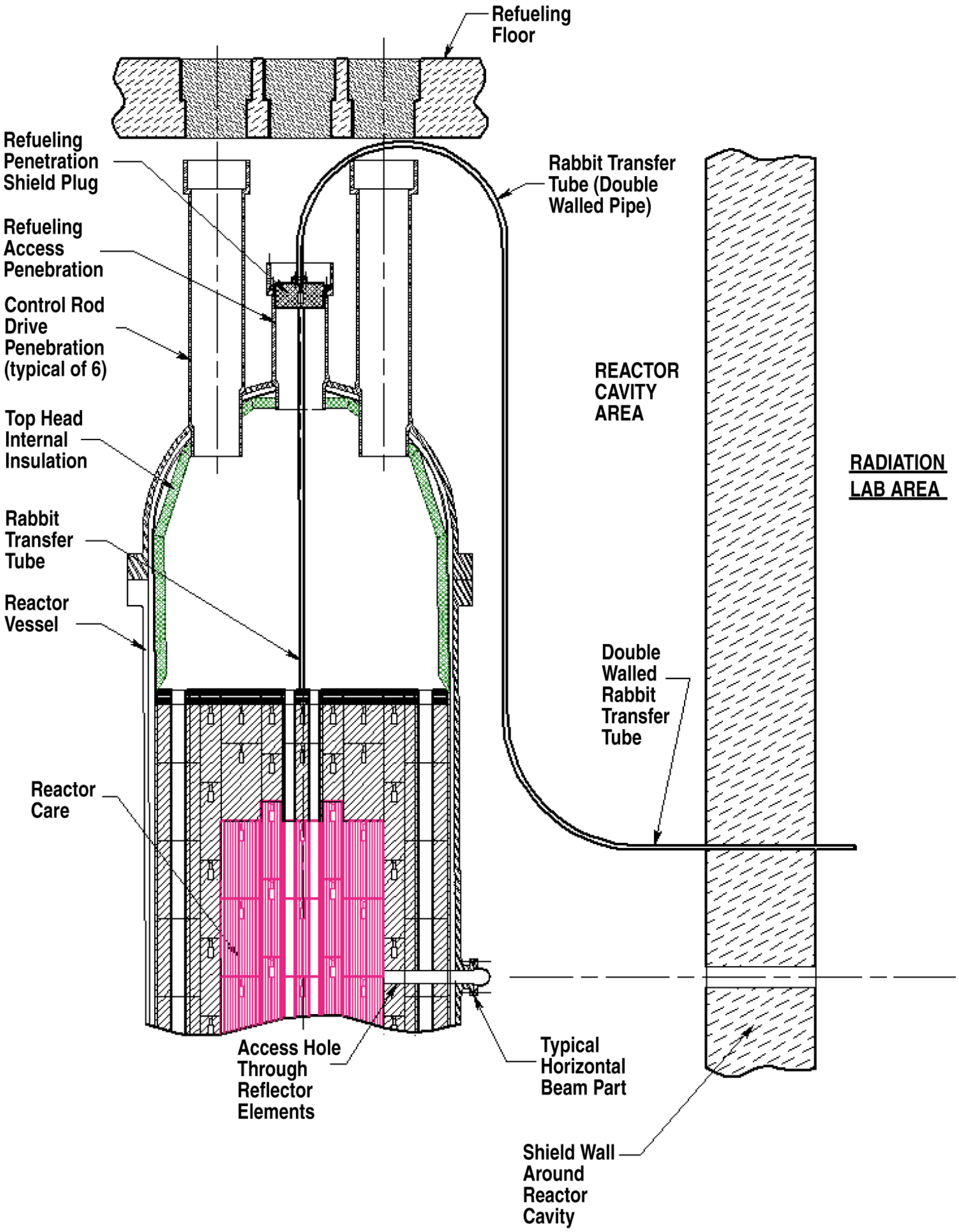

Fig. 4-26. Refueling penetration preparations.

The fuel handling machine, outfitted with the equipment handling grapple assembly, is positioned over the refueling penetration gate valve and mechanically anchored to the building. After evacuating and backfilling the small interspace between the valves with helium, the gates are opened and the shield plug in the refueling penetration is lifted into the machine. The isolation gate valves are closed, the interspace between them is evacuated and backfilled with air, and the machine is disconnected from the vessel and moved to an equipment storage well. The refueling penetration shield plug is then placed in storage.

The fuel handling machine internal grapple mechanism is changed over to the fuel handling function. The machine is then moved to a fuel storage well to pick up the first group of fresh fuel elements. These elements are placed in the machine in a specific sequence as required to support a prescribed one-by-one replacement of the fuel elements removed from the reactor core.

The reactor is refueled on a column-by-column basis, which means that the four elements comprising a given fuel column in the core will be removed, one element at a time, and placed in one of the empty storage columns in the fuel handling machine — one element on top of the other. Specific fresh fuel elements in the fuel handling machine are then sequentially installed in the core to replace those removed, also one at time.

Figure 4-27 shows a typical arrangement of fuel elements in the fuel handling machine, with each group of elements stacked four deep. The machine is capable of transporting 16 fresh fuel elements to the reactor. The 16 spent fuel elements which were removed from the four columns are returned to a fuel storage well.

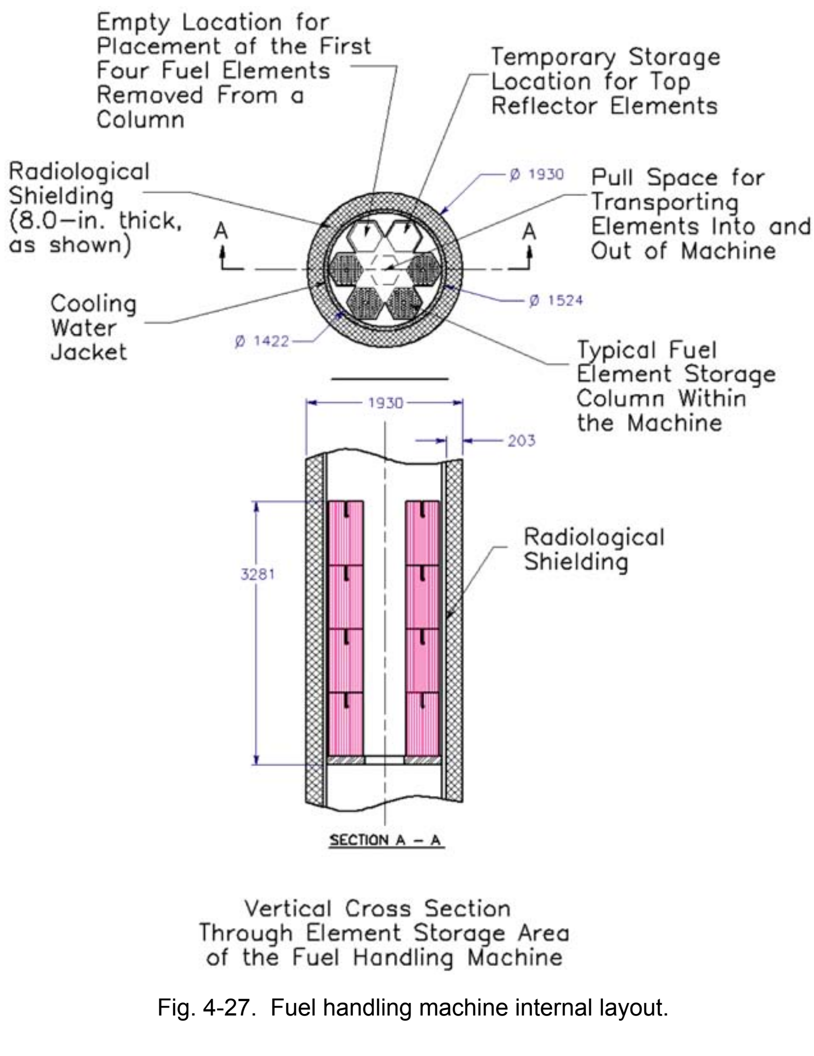

Fig. 4-27. Fuel handling machine internal layout.

After all spent fuel elements in the machine have been off-loaded into a fuel storage well, the machine is moved to another well containing fresh fuel elements. The prescribed fuel (and/or reflector) elements are loaded into the machine in the exact order they will be needed to support the refueling sequence when they are installed in the core. The machine returns to the core, and the next set of four columns is refueled. This process continues until refueling has been completed.

Following a procedure that is the reverse of that used to initiate the refueling program, the refueling penetration shield plug is replaced and bolted securely to the penetration to obtain a helium leak-tight seal. Leak testing of the shield plug installation is performed, the penetration extension sleeve is removed, and the refueling floor biological concrete shield plug is reinstalled.

4.6.5. Spent Fuel Storage System

The spent fuel storage system consists of a series of wells located in the refueling floor of the reactor service building. Each well is closed and sealed by a shield plug and a cover plate flush with the floor (Fig. 4-28). These wells are designed to contain 42 spent fuel elements in a helium atmosphere. Each well is equipped with a cooling capability to absorb decay heat from the stored elements. This cooling system operates continuously once the fuel storage wells contain spent fuel, although short interruptions can be tolerated. Figure 4-28 indicates a series of cooling tubes. However, a double-wall system could be designed or the wells could be simply supported from a steel framework and permitted to cool via natural convection. These options will be reviewed during conceptual design.

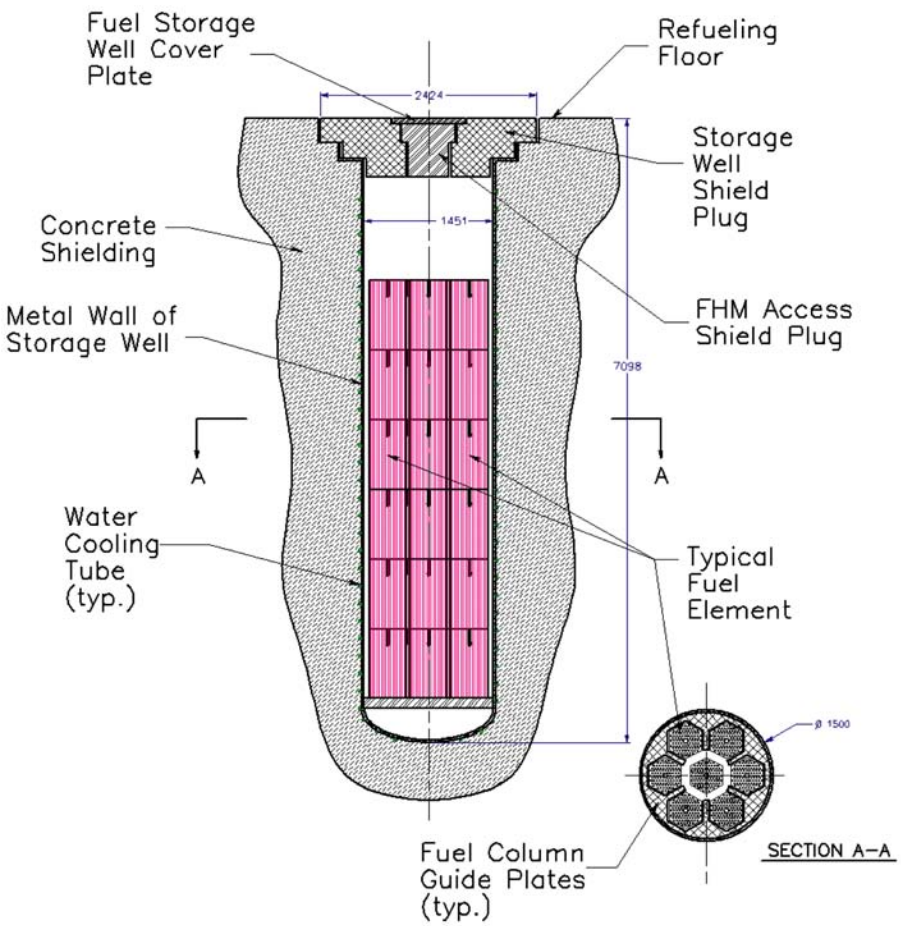

Fig. 4-28. Typical fuel storage well arrangement – capacity = 42 elements.

4.6.6. Neutron Control Assembly Handling

From time to time, a NCA will be removed from its vessel penetration and replaced with a spare unit. This operation is performed using the fuel handling machine, outfitted with the equipment handling grapple head mechanism. The initial procedures necessary to remove a NCA are essentially the same as those performed during the opening steps of a refueling. The reactor is shut down, all control rods are inserted, and the VS is depressurized. Following approved procedures, the two control rods in the assembly to be removed are withdrawn to their normal, “full-out” position. The rods, along with their guide tubes, are then withdrawn further into the upper housing of the assembly and mechanically locked to prevent any downward movement. [The reactor core is designed to remain subcritical at all times with one pair of control rods (out of six pairs) removed.]

The NCA is unbolted from the penetration, electrical leads, instrumentation leads, and service lines are disconnected, and the pickup adapter is installed in the upper housing of the assembly. A reactor isolation gate valve is installed at the penetration and the volume space between the valve and the top of the assembly is purged of all air. The fuel handling machine is positioned over the valve and anchored to the building. The small interspace between the isolation gate valve and the gate valve at the bottom of the machine is evacuated and backfilled with helium and both valves are opened. The grapple is lowered and connected to the NCA. The assembly is then lifted into the machine. Load cells are carefully monitored during the lift to monitor for any unexpected resistance to movement. After removal, the isolation gate valves are closed, and the small interspace between them is evacuated and backfilled with air.

The fuel handling machine is relocated to an equipment storage well for deposition of the assembly. A replacement assembly is similarly grappled, lifted from its storage well, and transferred back to the reactor. The assembly is installed, and the fuel handling machine bottom valve is closed. After the volume space between the top of the assembly and the closed fuel handling machine bottom valve is purged with air, the fuel handling machine is removed. The NCA is then torqued to the penetration and the installation is leak checked. The isolation gate valve is removed, and the reactor is prepared for resumption of operation by completing the service connections at the assembly, and lowering the control rods and guide tubes into their normal operating positions.

4.7. HELIUM SERVICES SYSTEM

4.7.1. System Functions and Requirements

The primary functions and requirements established for the HT^3R helium services system are as follows:

- Transfer helium between storage system and primary coolant system to support VS pressurization and depressurization. Maintain a high pressure supply of helium for makeup and other uses within the facility.
- Utilize a helium purification subsystem to process primary coolant helium to remove chemical and radioactive impurities. Supply purified helium purge needs.
- Regenerate low temperature adsorbers and packed-bed dessicant adsorbers in the helium purification trains. Regenerate packed-bed dessicant adsorber in the regeneration section of the helium purification subsystem.

- Supply liquid nitrogen for cooling of low temperature adsorbers in the helium purification subsystem. Provide a source of gaseous nitrogen for the analytical instruments and various other routine bulk nitrogen needs around the facility.
- The high-pressure helium storage volume supply an amount of helium equal to 10% of plant inventory per year to compensate for routine plant consumption. Provide make up for minor system losses due to leakage from helium bearing systems throughout the facility.
- The helium purification subsystem shall remove the following chemical impurities: Br, I, H_2O, CO, CO_2, H_2, (including tritium) N_2, O_2, H_2S, Kr, Xe, CH_4, other hydrocarbons, and certain metallic elements and filterable particulates.
- A regeneration section will remove impurities from adsorber beds when saturated. Impurities removed from train components shall be discharged to radioactive liquid and gas waste systems.
- The liquid nitrogen subsystem shall supply either liquid or gaseous nitrogen to the users depending upon specific need.
- Redundant liquid nitrogen refrigeration components (tanks, pumps, recondensers, etc.) shall be provided to support both continuous operation and on-line maintenance of liquid nitrogen subsystem equipment.

4.7.2. Overall System Description

The helium services system provides purification of the primary coolant helium, storage of both high and low pressure sources of helium, and periodic transfer of the primary coolant inventory between the VS and the helium storage tanks. The system also provides a source of liquid nitrogen for use in low temperature adsorbers of the helium purification subsystem.

A helium purification subsystem provides for continuous removal of impurities contained in the primary coolant inventory. A separate regeneration section within the purification subsystem transfers the concentrated impurities from the purification subsystem to the radioactive liquid and gas waste systems.

The helium transfer and storage subsystem transfers the helium inventory in the VS to a nearby high-pressure helium storage facility using a process of pressure equalization plus operation of one or more compressors. The helium inventory is transferred back to the VS in a similar manner. A small volume within the helium storage and transfer subsystem is set aside to provide a dedicated source of high pressure helium for use within the facility. Makeup helium from outside sources is received at the site and off-loaded directly into the VS or into the available storage volume.

The liquid nitrogen subsystem provides support for the cryogenic adsorption process in low temperature adsorbers in the purification subsystem. The liquid nitrogen subsystem includes a storage tank, transfer piping, transfer pump (if required), and one or more recondenser machines to reject the heat absorbed by the liquid nitrogen transfer process.

4.7.3. Helium Purification Subsystem

This subsystem removes circulating impurities from the primary coolant and transfers those impurities to the radioactive liquid and gas waste systems of the facility. A separate regeneration section removes the impurities that accumulate in the purification subsystem adsorbers.

The helium purification subsystem consists of two separate, independent, but identical trains. A typical arrangement of components is shown in Fig. 4-29. Accumulated impurities adsorbed in the trains require these components to be located in shielded vaults to eliminate personnel radiation exposure.

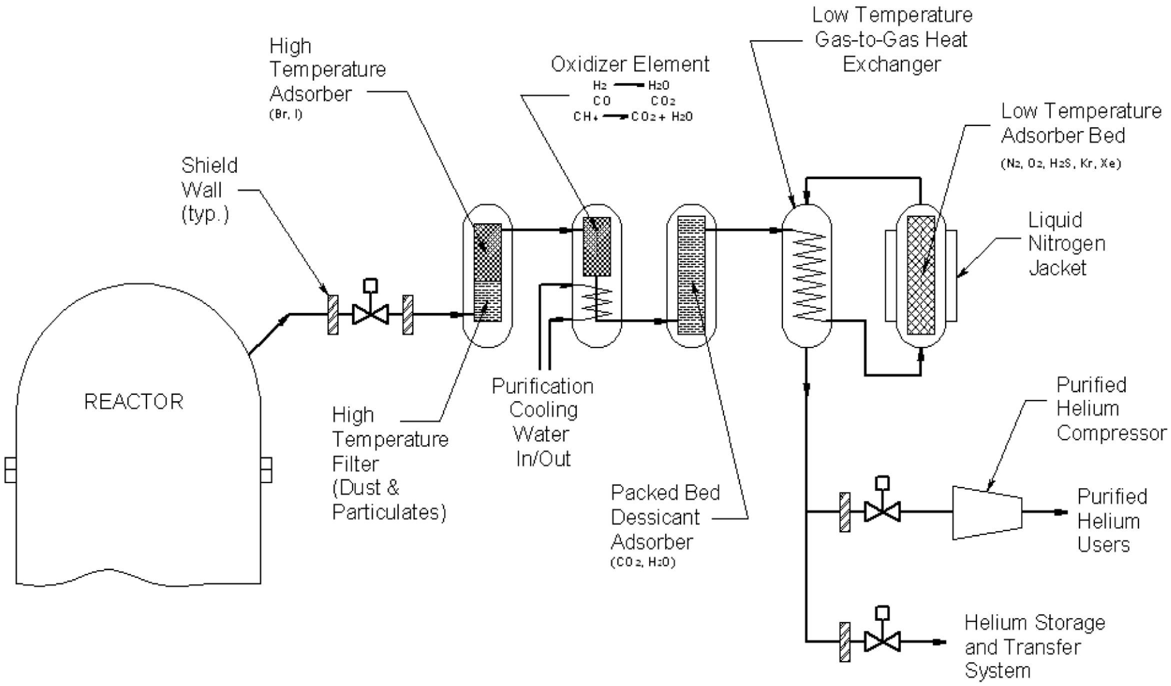

Fig. 4-29. Helium purification subsystem schematic diagram.

To accommodate the need for subsystem maintenance and regeneration of both low temperature adsorbers and the packed-bed dessicant adsorbers, two identical trains of components are provided. One of these trains is always on-line, while the other is either being regenerated or is otherwise maintained in a standby status ready for immediate use. Each of these trains is designed to support the elevated initial mass transfer flow rate necessary to complete a vessel depressurization within a 24-h period.

The helium purification process involves routing a small flow of primary coolant into the high temperature filter-adsorber at the front end of the purification train. This unit removes iodine, bromine, and metallic impurities, plus filterable particulates such as graphite dust. The flow then passes through an oxidizer unit. Here, hydrogen is converted into water, carbon monoxide is converted into carbon dioxide, and methane is converted into both water and carbon dioxide.

Flow then passes through a heat exchanger to lower the process temperature to about 20°C. The flow then passes into a packed-bed dessicant adsorber where carbon dioxide and moisture (to some extent) are removed.

The flow then enters the inlet side of a low temperature gas-to-gas heat exchanger where the helium temperature is reduced to cryogenic levels by exchanging heat with the helium flow leaving the low temperature adsorber. From the low temperature heat exchanger, the flow passes through the low temperature adsorber where all gaseous impurities are removed. The helium effluent from the adsorber is directed back through the low temperature heat exchanger where the purified helium temperature is increased to

~20°C. The helium effluent is now purified, but requires the use of a small compressor to provide sufficient head for distribution to the users. System flow not required by users is returned to the primary coolant system.

When the adsorber elements in a purification train become saturated with impurities, the train must be taken off-line for regeneration, and the clean standby train placed in service. Figure 4-30 shows the general layout and equipment arrangement for the regeneration section. The heavy line represents the flow path for normal regeneration operation.

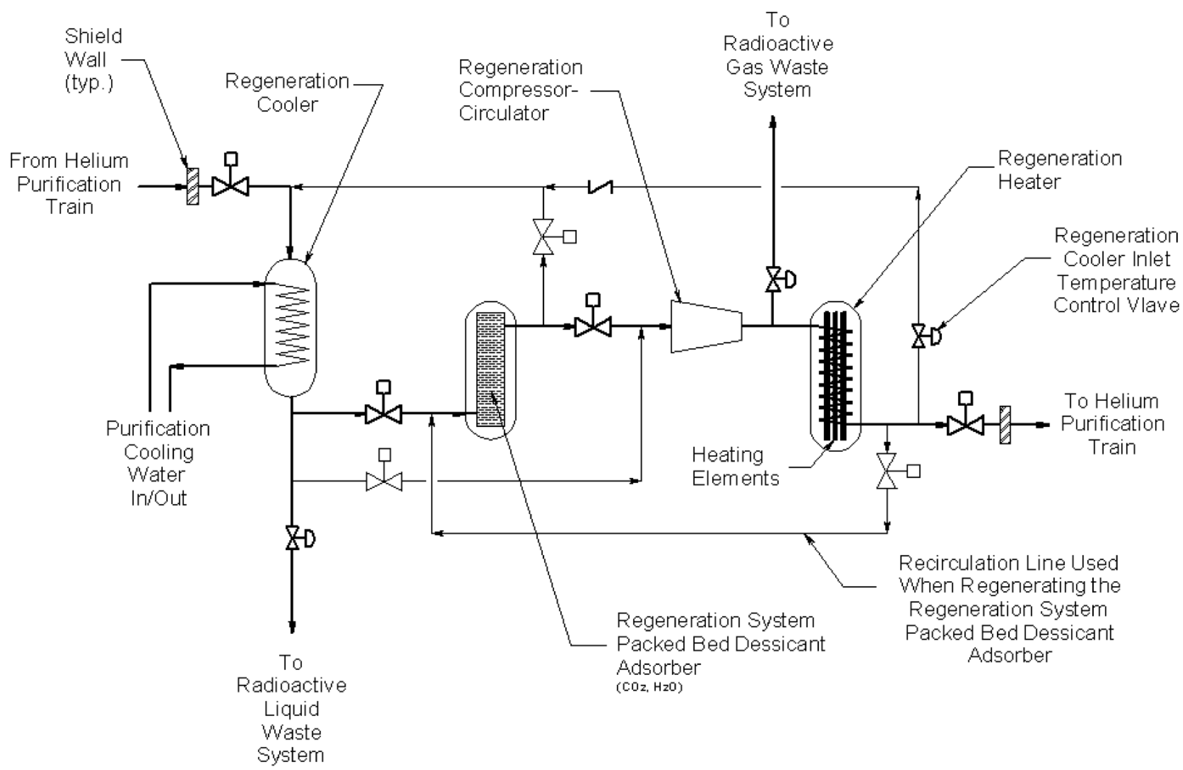

Fig. 4-30. Helium purification subsystem regeneration section schematic diagram.

Typical regeneration process begins by terminating the flow of liquid nitrogen to the off-line low temperature adsorber. A purge flow of hot, dry helium is then passed through the packed-bed dessicant adsorber in the off-line purification train. Flow continues until the discharge temperature reaches about 350°C. The regeneration flow temperature is then reduced to about 50°C to cool the adsorber bed to near 50°C.

The regeneration flow is directed to the low temperature adsorber, with the temperature programmed slowly upward from the initial 50°C. Flow continues until the adsorber temperature reaches about 150°C. At this temperature, almost all gaseous impurities will have been desorbed and transferred to the radioactive gas waste system. The regeneration flow temperature is reduced to around 50°C, and the adsorber bed is cooled down. Following cool-down, liquid nitrogen is again introduced to re-establish normal operating conditions. The freshly regenerated train is then held in standby mode to await further use.

The regeneration flow is driven by a small dedicated compressor-circulator. As noted in Fig. 4-30, discharge from this circulator is passed through a heater unit to obtain the desired regeneration temperatures. Regeneration flow returning from the purification train passes through a heat exchanger, then through a packed-bed dessicant dryer where remaining moisture contained in the flow is eliminated. Flow then passes to the compressor-circulator inlet for recirculation through the subsystem. When regenerating the low temperature adsorber, gases driven from the cryogenic bed will increase the regeneration section pressure. These desorbed gases are vented to the radioactive gas waste system using a pressure controller to maintain the normal operating pressure of the regeneration section. The initial flow returning to the regeneration section from the low temperature adsorber is extremely cold. To prevent freezing of the cooling water in the heat exchanger, a temperature control valve feeds a small amount of regeneration section discharge flow back into the incoming regeneration flow just upstream of the heat exchanger to prevent water freezing in the exchanger. When the train components have completed regeneration, the regeneration section packed-bed dessicant adsorber is itself regenerated in a similar manner. The flow path for this operation is noted in Fig. 4-30.

4.7.4. Helium Transfer and Storage Subsystem

The helium transfer and storage subsystem provides for movement of primary coolant helium between the VS and nearby helium storage tanks. This subsystem also provides a source of high-pressure helium for miscellaneous uses within the facility. Makeup helium received at the facility from outside sources can either be stored in this subsystem or transferred directly into the VS. One or more compressors are provided to assist with helium transfer between the various storage tanks and the VS. Figure 4-31 shows a diagram of the helium transfer and storage subsystem arrangement.

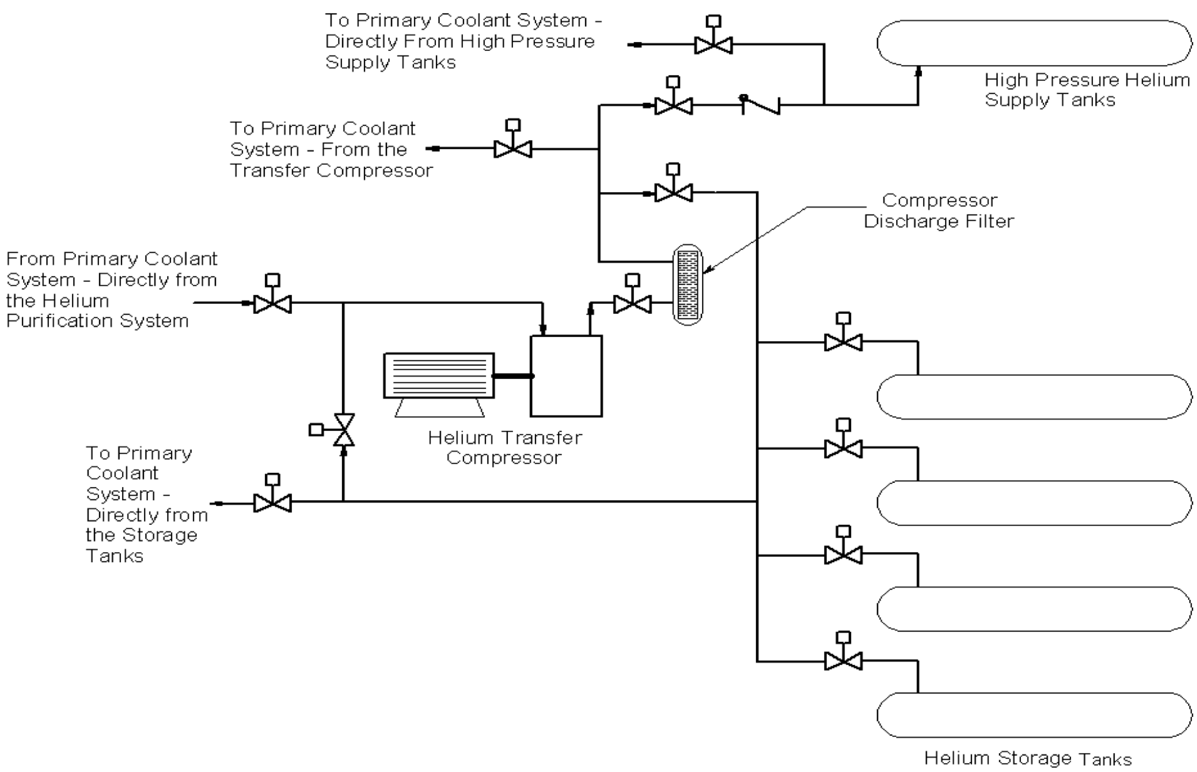

Fig. 4-31. Helium transfer and storage subsystem schematic diagram.

The helium transfer compressor is sized, from a volumetric flow standpoint, to allow completion of a VS depressurization within a 24-h period. When helium is transferred between storage and the VS, in either direction, the overall helium inventory is allowed to equilibrate in pressure between the two locations. Transfer is then completed using the helium transfer compressor. All helium removed from the VS must first pass through the helium purification subsystem.

4.7.5 Liquid Nitrogen Subsystem

The liquid nitrogen subsystem is shown schematically in Fig. 4-32. Liquid nitrogen is supplied to low temperature adsorbers via vacuum-jacketed (or equivalently insulated) transfer piping. The liquid nitrogen subsystem provides a flow rate sufficient to service both low temperature adsorbers on a continuous basis. Higher flow rates of liquid nitrogen are required during the initial stages of a VS depressurization when the primary coolant helium flowing through the purification train(s) is increased by a factor of approximately four.

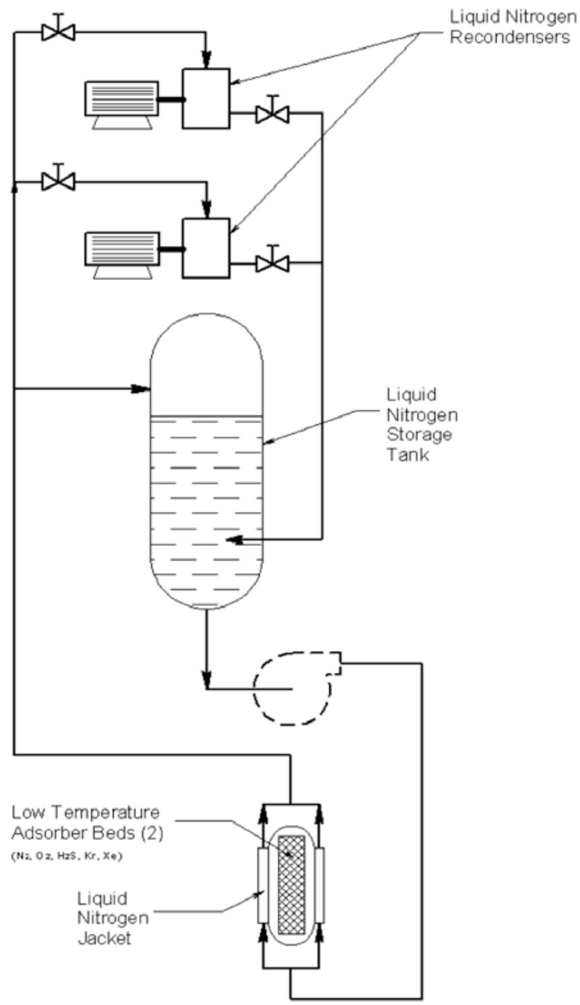

Fig. 4-32. Liquid nitrogen subsystem schematic diagram.

A recondenser machine (or machines) is used to draw upon the gaseous volume in the liquid nitrogen storage tank to condense the gaseous nitrogen back to a liquid thus rejecting any heat energy absorbed by the process flow. Liquid nitrogen produced by the recondenser(s) drains directly back to the storage tank via gravity flow.

Makeup liquid nitrogen can be supplied from an external source such as a tank truck or an auxiliary storage tank. Further, if necessary, the liquid nitrogen subsystem can be operated as a once-through system by continuously supplying liquid from an external source and venting the gaseous nitrogen effluent to the atmosphere. This situation could exist if the recondensers were not available.

4.8. REACTOR CAVITY COOLING SYSTEM

The natural draft air cooling concept of the HT^{3}R RCCS is shown schematically in Fig. 4-33. The HT^{3}R RCCS consists of the following:

- Two inlet/outlet (I/O) structures for ingress and egress of atmospheric air.
- A set of cooling panels that surround the RV within the reactor cavity.
- Main loop shutoff valve (MLSV).
- A set of concentric hot and cold ducts for transporting air between the cooling panels and the inlet outlet structures.

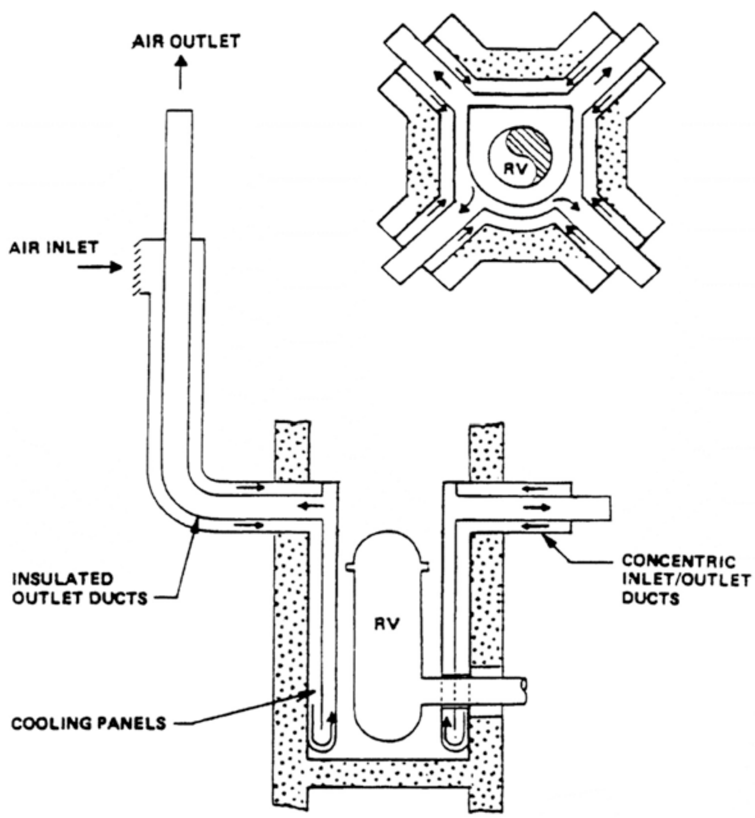

Fig. 4-33. Passive, air-cooled RCCS concept.

Design descriptions and performance of these components and structures are provided in the following subsections. The schedule and cost for performing engineering of RCCS are provided in Section 7.2. Cost and schedule for fabricating and installing RCCS into the HT^{3}R facility are provided in Section 8.1.

4.8.1. System Functions

The primary functions established for the HT^{3}R RCCS PCD are as follows:

- Protect the concrete structure of the reactor building that surrounds the RV from overheating during all modes of reactor operation.
- Provide an alternate means of transferring the reactor decay heat to the outside atmosphere when neither the PS nor the SCS is available.
- Provide for isolation of the local reactor cavity atmosphere from the outside atmosphere.

4.8.2. Overall System Description

During periods of normal reactor shutdown, decay heat is removed either through the PHX and secondary cooling system or through the SCS. However, in the event that these heat removal paths are not available, then decay heat is removed by conduction through the graphite reflector and by radiation and natural convection from the uninsulated RV. The RCCS absorbs the heat transferred from the RV to the cooling panel placed around the RV. The RCCS removes heat from the RV walls and the local reactor cavity by natural circulation of outside air through the cooling panel. A schematic airflow configuration of the RCCS is shown in Fig. 4-34.

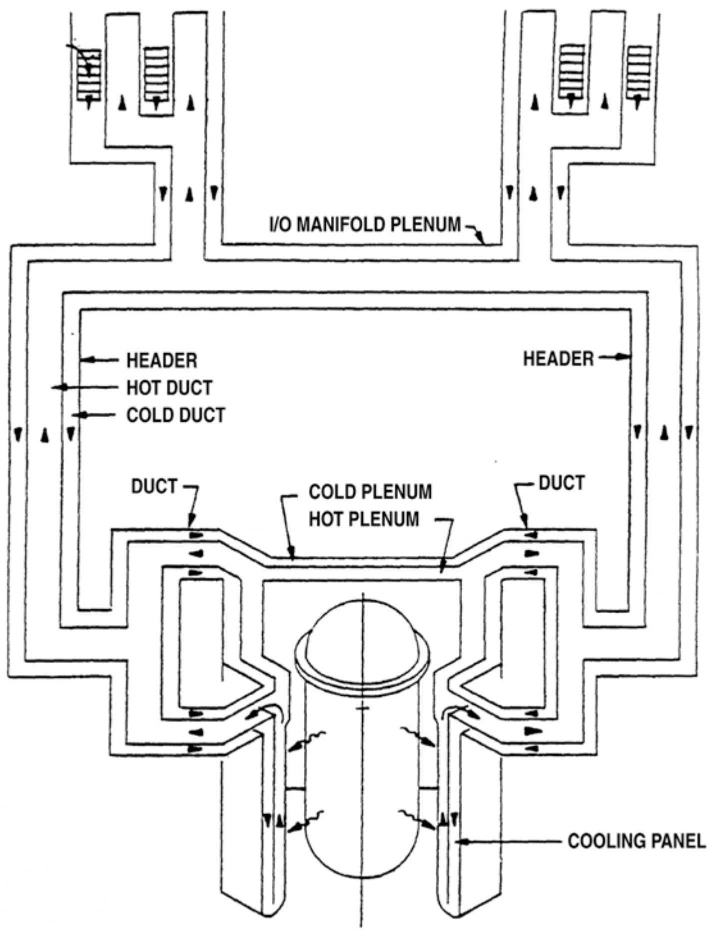

Fig. 4-34. Schematic RCCS airflow configuration.

The RCCS has no valves or any other active components. The surfaces of the cooling panel serve to separate the outside atmosphere from the reactor cavity atmosphere. This separation minimizes the site boundary dose due to the possible release of activated air in the cavity. The RCCS contains multiple I/O ports and interconnected parallel flow paths to ensure continued cooling in the event that any single duct or opening becomes blocked.

The I/O structures are located above grade, immediately adjacent to the reactor building. These I/O structures connect to a series of concentric cold/hot ducts. These ducts are routed within the reactor building structure and connect to the RCCS cooling panel. This cooling panel, which consists of cold downcomers and hot risers, is located within the reactor cavity and surrounds the RV.

The inlet openings of the I/O structures supply cold atmospheric air to the system, and the outlet openings facilitate the exhaust of hot air back to the atmosphere. The hot air carries heat from the reactor cavity. The concentric cold/hot ducts transport cold and hot air between the I/O structures and the cooling panel. The outer duct transports cold air from the I/O structure to the cooling panel while the inner duct transports hot air from the cooling panel to the I/O structure.

The cold air, upon entering the cooling panel, flows downward by gravity to the bottom of the reactor cavity via the cold downcomer section of the cooling panel. The air then moves upward in the riser section that faces the RV and begins to collect the heat radiated and convected from the RV. The buoyancy imparted to the air due to the heat input causes the air to rise toward the top of the reactor cavity through the riser section of the cooling panel. As the air moves upward, it collects more heat over the length of the RV, as well as over its full circumference. The heated air then exits the cooling panel and the reactor cavity, flows through the hot duct, enters the hot side of the I/O structure, and finally exhausts to the atmosphere.

The RCCS air I/O structure concept as shown in Fig. 4-35 consists of two inlet and two outlet chambers. Airflow direction is shown by arrows in the Fig. 4-35. Each inlet and outlet chamber consists of a secondary chimney and a quiescent chamber. Section B-B of Fig. 4-35 shows the configuration of an inlet chamber in which air primarily enters through the inlet screens on the side of the structure. Section A-A of Fig. 4-35 shows the configuration of an outlet chamber. In this case, air exhausts through the top of the secondary chimney. As shown in Fig. 4-35, the secondary chimney and the quiescent chamber are identical for both the inlet and outlet configurations. The purpose of this feature of the RCCS I/O structure is two-fold. The first is to make the inlets and outlets insensitive in wind conditions. Secondly, the diversity and redundancy of the configuration make certain that the inlets and outlets are insensitive to partial blockage of the side screen or the top of the chimney due to wind-borne objects or icing in winter months.

The most adverse wind condition is a wind with a strong vertical or horizontal velocity component. The wind loses its strong velocity component in the quiescent chamber. In addition, this configuration causes both the inlet and outlet to be equally affected by adverse wind conditions thus creating no net effect on RCCS performance.

As mentioned earlier, the cold/hot ductwork connects the I/O structure and the cooling panel, and transports cold and hot air between them. The cold duct is formed as a rectangular concrete structure inside the reactor building. The duct is routed with a number of bends and long runs. These bends and long runs, together with the concrete wall of the duct, limit neutron streaming from the reactor cavity, and provide shielding to allow personnel access to the adjacent areas. The hot duct is also rectangular, but is made of carbon steel. The hot duct is routed concentrically inside the cold duct. The hot duct is covered with 3 in. of rigid insulation to reduce regenerative heating of the cold inlet air. This configuration has a couple of benefits. First, the concrete forming the cold duct is always in contact with the atmospheric air, thus eliminating the need to cool the concrete around the hot duct as would otherwise be the case if the hot duct were routed external to the cold duct. Secondly, the concentric configuration saves valuable space in the reactor building.

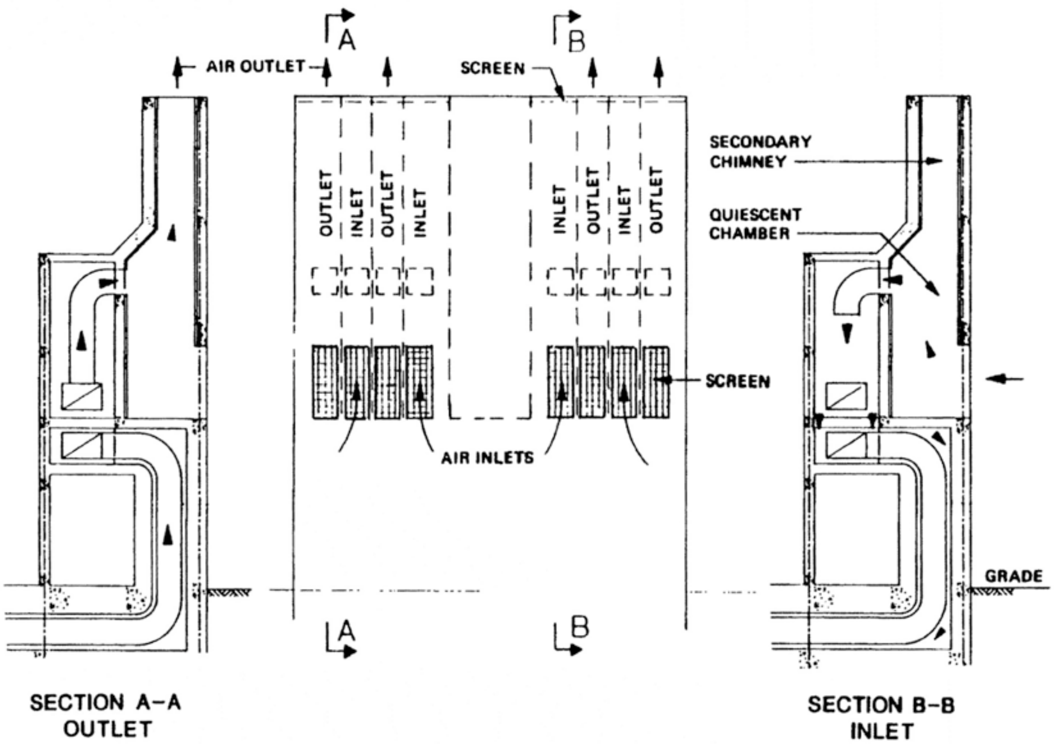

Fig. 4-35. RCCS air I/O structure.

Four cold/hot ducts, grouped into two pairs, connect to the cooling panel at four locations. Each pair combines to form a header which leads up to and connects with one of the two identical I/O structures. This header also cross-connects both of the I/O structures and is referred to as an I/O manifold plenum. This arrangement forms two symmetrical halves of ductwork, each connecting to one I/O structure and one-half of the cooling panels. The overall configuration has several advantages. The cross-connected header between the two I/O structures ensures an adequate air supply even if one of the I/O structures becomes completely unavailable due to some unforeseen reason. Furthermore, if one-half of the ductwork connecting the cooling panel to the I/O structures becomes unavailable, the remaining half of the ductwork is capable of meeting the airflow requirements. Another feature of this arrangement is that the I/O manifold plenum equalizes any pressure disturbance that might be transmitted through the inlets.

An elevation view of the RCCS panel configuration inside the reactor cavity is shown in Fig. 4-36. A plan view of the configuration is shown in Fig. 4-37. As shown in these figures, the RCCS panel follows the internal contour of the reactor cavity and surrounds the RV over its full circumference and length. The RCCS panel will have penetrations to allow passage of neutron beam tubes from the reactor. The cold side of the RCCS panel is directly in contact with the concrete wall of the reactor cavity thus protecting the concrete from RV heat. The cold side of the RCCS panel consists of four parts: upper cold plenum, downcomer, bottom cold plenum, and drain arrangement. The upper cold plenum receives cold air from the ductwork at four different locations. This plenum distributes the incoming cold air over the full circumference and directs the airflow into the downcomers. This plenum also protects the concrete portion of the reactor cavity ceiling from RV heat while also serving as a quiescent/damping chamber, thus further attenuating the effects of any atmospheric disturbances in the incoming cold air.

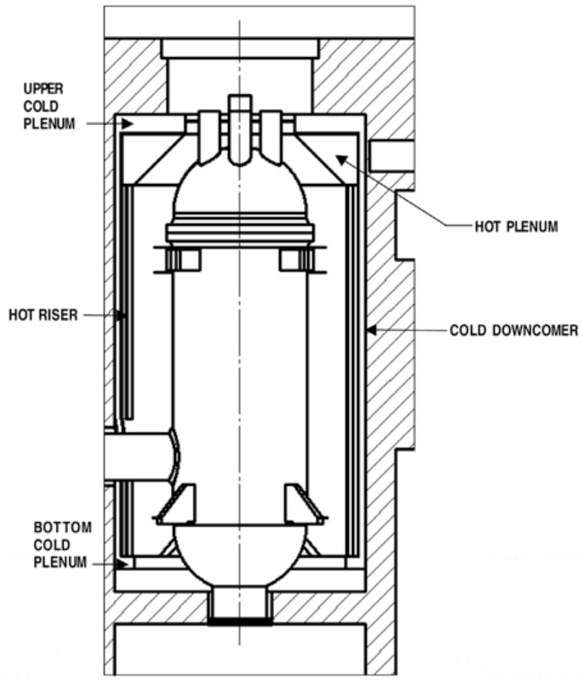

Fig. 4-36. RCCS panel configuration – elevation view.

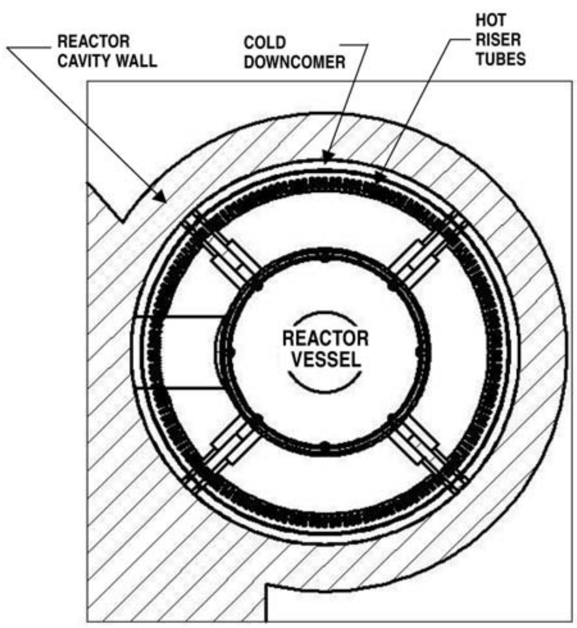

Fig. 4-37. RCCS panel configuration – plan view.

The downcomer part of the cooling panel provides a guided vertical flow path for the cold air to travel to the bottom of the panel. The downcomer is formed by two parallel vertical steel plates held 6 in. apart by vertical steel channel. The outer plate is anchored to the reactor cavity wall, and the inner plate is bolted to the channels placed at approximately 2 ft intervals along the wall of the cavity. These vertical channels also guide the airflow within the downcomer.

A reflective surface/insulation is provided as part of the downcomer. This surface is attached to the inner plate facing the RV. The insulation also serves to reflect the RV heat back into the cavity, while simultaneously protecting the cold incoming air from being prematurely heated in its downward journey.

The bottom cold plenum, located at the bottom end of the downcomer, is essentially a box-shaped continuous ring header around the RV along the cavity wall. The cold plenum permits a change in airflow direction with minimal flow resistance, while also facilitating the proper distribution of airflow to the riser part of the cooling panel. Any atmospheric disturbances and mal-distribution effects are suppressed in the bottom plenum.

The hot side of the RCCS cooling panel consists of the riser and the hot plenum. The riser consists of 167 vertical rectangular structural steel tubes arranged around the RV as shown in Fig. 4-37. A 3-ft space between the RV and the hot riser tubes allows for ISI. These tubes are omitted where they might interfere with the RV lateral restraints. The tubes rise from the bottom cold plenum and connect to the hot plenum located at the top of the reactor cavity. The tubes are vertically supported by the bottom cold plenum and are laterally supported from the downcomer by lateral support plates.

Each tube is a standard structural steel tube of rectangular cross section having external dimensions 2 × 6 in. with a 0.1875-in. wall thickness. These tubes are arranged with a 2-in. gap between adjacent tubes. The gap between the tubes allows fractions of thermal radiation from the RV to reach the reflective surface. The reflected radiation then heats up the back side of the riser tubes, thus more fully utilizing the full tube surface area and enhancing heat transfer.

The hot plenum is arranged around the top head of the RV. This plenum receives hot air from the riser tubes and distributes it to the hot duct at four locations. The hot plenum is completely supported by the riser tubes and is relatively free to expand. Tandem bellow expansion joints are provided between the hot duct and the hot plenum to accommodate thermal expansion of the riser and hot plenum assembly. The entire RCCS cooling panel assembly is a very stable and rigid structure designed for all required thermal, seismic, and pressure loadings.

4.8.3. System Performance Characteristics

The following sections describe the different modes of operation and performance of the RCCS during both normal and abnormal conditions.

4.8.3.1. Normal Steady-State Performance. The RCCS is not required to remove decay heat during normal operation. However, since the system is passive, and due to the difference in the RV temperature and the outside temperature, the system removes a small amount of heat during normal operation, as well as some decay heat during a normal reactor shutdown.

During normal operation, the reactor primary helium cold leg temperature is maintained nearly constant at 491°C. Normal forced circulation of primary coolant helium results in a nearly uniform RV temperature. Outside air temperature, and therefore, RCCS inlet temperature is assumed to vary over a range of –25°C to 45°C. These conditions lead to varying levels of parasitic heat loss to the RCCS cooling panel. The performance of the RCCS under nominal conditions is summarized in Table 4-4.

Table 4-4
RCCS Steady-State Performance

Parameter	100% Power
Reactor Vessel	
Heat loss to RCCS, kW	380
Inside wall temperature, °C	348
Outside wall temperature, °C	339
Cooling Panel	
Maximum temperature, °C	131
Air inlet temperature, °C	27
Air outlet temperature, °C	89
Airflow, kg/s	6.0
Maximum airflow velocity, m/s	4.8
Structure	
Concrete surface temperature, °C	27

Shutdown for maintenance or refueling requires that the reactor be depressurized and the primary helium cold leg temperature be maintained between 32°C and 116°C. At these low temperatures, the decay heat removal through the RCCS is minimal.

4.8.3.2. Transient Performance. During events when neither the PHC nor the SCS are available, decay heat removal must be by the RCCS alone. If the reactor remains pressurized, decay heat is removed by conduction through the vessel wall to the RCCS. This event is called a pressurized conduction cooldown.

A depressurized conduction cooldown is when a primary coolant leak develops simultaneously with a loss of forced circulation cooling. The depressurized conduction cooldown results in higher peak core and vessel temperatures than the pressurized conduction cooldown. RCCS heat removal is a function of both vessel temperature and ambient air temperature. For depressurized conduction cooldown event, there is very little convective heat transfer from the core. Decay heat is removed primarily by conduction horizontally through the graphite reflector to the RV sidewall. Preliminary results show that during this event, the core and vessel temperatures are not much higher than those predicted during normal steady-state operation. Results from a two-dimensional heat transfer analysis are presented in Table 4-5.

Table 4-5
RCCS Transient Performance

Parameter	Depressurized Conduction Cooldown	
	Unirradiated	Irradiated
Reactor Vessel		
Heat loss to RCCS, kW	490	480
Inside wall temperature, °C	364	350
Outside wall temperature, °C	354	341
Cooling Panel		
Maximum temperature, °C	131	131
Air inlet temperature, °C	27	27
Air outlet temperature, °C	101	100
Airflow, kg/s	6.4	6.4
Maximum airflow velocity, m/s	5.3	5.3
Structure		
Concrete surface temperature, °C	27	27

4.9. REACTOR CONTROL AND PROTECTION SYSTEM (RCPS)

The RCPS includes a specific reactor protection system (RPS) that supports and enhances inherent HT^{3}R safety features. The RPS includes safety-related and non-safety (NS) functions, which are developed under the engineering design areas listed below:

- Safety-related electric supply systems.
- RPS instrumentation and data processing systems.
- Decision logic processors.
- End-action hardware to perform safety-related and non-safety actions.
- RPS operator consoles, displays, and documentation to provide real-time information, warnings, alarms, and operator input.
- Equipment, documentation, and facilities for on-line maintenance and verification.

Additionally, the RCPS includes a specific plant control, data, and instrumentation system (PCDIS) for normal control and instrumentation functions. The PCDIS combines the control and protection functions into a single, plant control architecture. The design areas related to the PCDIS are as follows:

- Instrumentation and Data System. Includes instrumentation lists, ranges, locations, etc., for plant instrumentation specifications.
- Plant Control Specifications. Includes documentation, algorithms, control logic, software specifications, hardware specifications and control architecture specifications for implementation of the computer-based control functions.
- Control Installation Specifications. Includes control room console layouts, distributed control processor layouts, and various support facility specifications.

4.9.1 RCPS Functions and Requirements

The function of the RPS is to detect abnormal events and provide corrective action. The various reactor protection functions fall into one of the following broad categories of detection and correction:

- Detection of an abnormal increase in neutron flux.
- Primary coolant release into the reactor building.
- Interruption of the normal heat rejection process, or detection of conditions that require interruption of the normal heat rejection process.
- Detection of conditions that indicate a VS primary coolant leak, or a condition that could eventually exceed the VS operating limits.
- External conditions, such as “loss of off-site power,” that may require “safe-shutdown” actions.

The design requires combined action of the RPS and PCDIS to maintain normal cooling (or to initiate SCS cooling if normal cooling cannot be maintained) during a response to any of the above events. The combined RPS/PCDIS protective actions maintain normal cooling whenever possible. In addition to providing the normal control and backup cooling functions for reactor startup, shutdown and steady-state power operation, the following requirements apply to the PCDIS design:

- The PCDIS shall quickly restore and operate the reactor and secondary systems following an abnormal shutdown event.
- The PCDIS shall incorporate a redundant design strategy. A specific reliability requirement shall be developed in the follow-on engineering phase.
- The RPS/PCDIS shall provide real-time information, available on all operator interfaces, regarding action taken and status of plant processes.

Specific additional requirements apply to the combined RPS/PCDIS design:

- The design shall include documentation and analysis that includes transient analysis, simulated real-time operations, and event descriptions to support the control and safety design strategy.
- The design shall utilize equipment, logic functions, displays, and documentation to minimize the frequency of reliance on the inherent HT^3R safety features that protect the general public against fission product release from the reactor core.
- The RPS design shall avoid unnecessary designation of functions as “safety-related,” but shall adhere to a consistent design approach for all RPS safety-related and non-safety functions (except as required for qualification of “safety-related” equipment).
- Processing and decision making equipment shall rely on use of digital computer technology for protection and control equipment to implement algorithms for processing of instrumentation data, issuance of commands to end-action hardware, and provide information to the plant operators.
- The RPS design shall incorporate 2-out-of-4 or similar logic to provide redundant decision/action pathways that are the least susceptible to “spurious tripping” by reverting to 2 out of 3 logic during on-line maintenance or in the event of equipment failure.

- The RPS shall provide real-time data to the PCDIS for information, control and PCDIS backup of RPS actions.
- Functions specifically incorporated in the RPS shall be independent of the PCDIS.
- The RPS shall be capable of performing its functions before, during, and for an adequate time after being subjected to a design basis event (DBE). DBEs for the RPS design shall be developed in the follow-on engineering phase.
- All structures, systems, and components designated "safety-related" shall come under a Quality Assurance Program that complies with the requirements of Title 10 Code of Federal Regulations, Part 50 (10CFR50), Appendix B.

4.9.2. Overall System Description

4.9.2.1. Reactor Protection System. The RPS electric power, for both safety-related and non-safety components, is provided by a Class 1E electrical system for a 2-out-of-4 protection logic design. The RPS instrumentation provides sensor inputs to each of the four separate channels used in the 2-out-of-4 logic. The RPS logic processors compare trip requests from all four channels to determine if two or more "like trips" have been requested by separate RPS DECISION LOGIC processors. When this is confirmed by RPS COINCIDENCE LOGIC processors, RPS end-action hardware associated with the RPS function performs the action required.

The RPS also provides real-time status, warning, and alarm information to the RPS operator consoles and displays. Additionally, the RPS transfers information regarding events-in-progress to the plant control processors to allow continuation of normal cooling processes.

Table 4-6 lists end-action hardware needed for RPS protection actions as determined by the decision logic. This hardware is contained in other systems. Table 4-6 identifies the systems that provide the end-action function, end-action method, and safety designation of each end-action.

4.9.2.2. Plant Control, Data, and Instrumentation System. Instrumentation for HT^{3}R plant control and protection is distributed throughout the reactor plant systems and the balance of plant (BOP) components. Specific reactor instrumentation (nuclear, flow and temperature measurements) important to operation and safety requires assessment of thermal and mechanical restrictions as part of the design process. In particular, nuclear instrumentation will require a survey of available suppliers and the capabilities of various neutron detectors. The neutron detection equipment will consist of the following:

- SRD assemblies (2 each)
- Source range monitoring channels (2 each)
- Power range detectors (4 each)
- Intermediate and power range monitoring channels (4 each)

Data processing requirements will be developed in the follow-on engineering phase and will be included as part of the computing hardware specification.

Table 4-6
Reactor Protection System (RPS) End-Action Hardware

End-Action	RPS Trip or Action Name	End-Action Method	Safety Related	Responsible System
1	Control rod trip	De-energize control rod holding coils	Yes	Reactor system
2	Reactor building isolation	Close reactor building isolation valves	Yes	Reactor building
3	SCS startup	Shutdown main circulator and start SCS	No	SCS
4	Primary heat exchanger vessel isolation and pressure balance	Close vessel system Isolation valves. Start pressure balance system	No	Secondary system
5	Hss charging isolation	Close HSS charge line isolation valves	No	HSS
6	SCHE isolation and drain	Close SCHE Isolation valves. Open SCHE drain	No	SCS
7	Process heat isolation and bypass	Open or override bypass shut-off. Isolate process heat (TBD)	No	Secondary system
8	Power conversion isolation and bypass	Open or override bypass shut-off. Isolate power conversion (TBD)	No	Secondary system

HT^3R plant control design relies on an iterative process of control system selection, detailed control and plant-model development, followed by control algorithm design and revision to the final design implementation form.

Real-time simulator verification and documentation is provided as part of the RPS/PCDIS design. Documentation describing analytical modeling, control algorithm design, and the man-machine interface features, to be incorporated in the control design, result from the above effort.

4.9.3 Plant Control Architecture

The RPS features of the RPS/PCDIS require separation of RPS displays and networks included in the PCDIS architecture. The following additional considerations are incorporated in the PCDIS architecture:

- Designation of a Reactor Protection System Data and Command Center. RPS command pathways are implemented on separate, independent networks ("safety information networks") which reach the control room RPS displays and RPS controls independently of the PCDIS.
- PCDIS Provision of Backup Cooling. Data from the RPS networks and command data from the operator interface are available to the "plant control network." This allows immediate automatic activation of the normal cooldown process in response to RPS intervention in the normal control process.
- Operator Visibility. Data is passed back to the operators through the "plant information network" to allow operator visibility to all plant operations.

The plant architecture design features support a central control room for all plant operations. Control room features include and are characterized by:

- Modern digital display interfaces.
- A "command view" arrangement of all consoles, displays, lighting, viewing areas, etc., to achieve maximum overview, minimize necessary staffing, optimize test operations, and create "university type visibility" for all reactor and test operations. Previous HTGR studies also support these selections.

Figure 4-38 illustrates considerations important to the HT^{3}R PCDIS design. Separate safety information networks and operator control interfaces for safety-related actions are provided. Safety information necessary for normal PCDIS follow-up safety actions and appraise the operators of other safety information (warnings, alarms, equipment conditions, etc.) is fed back to the control networks and plant information networks separately. Lower level networks, distributed through the plant, perform information and control data gathering and issue end-action commands through digital-to-analog hardware.

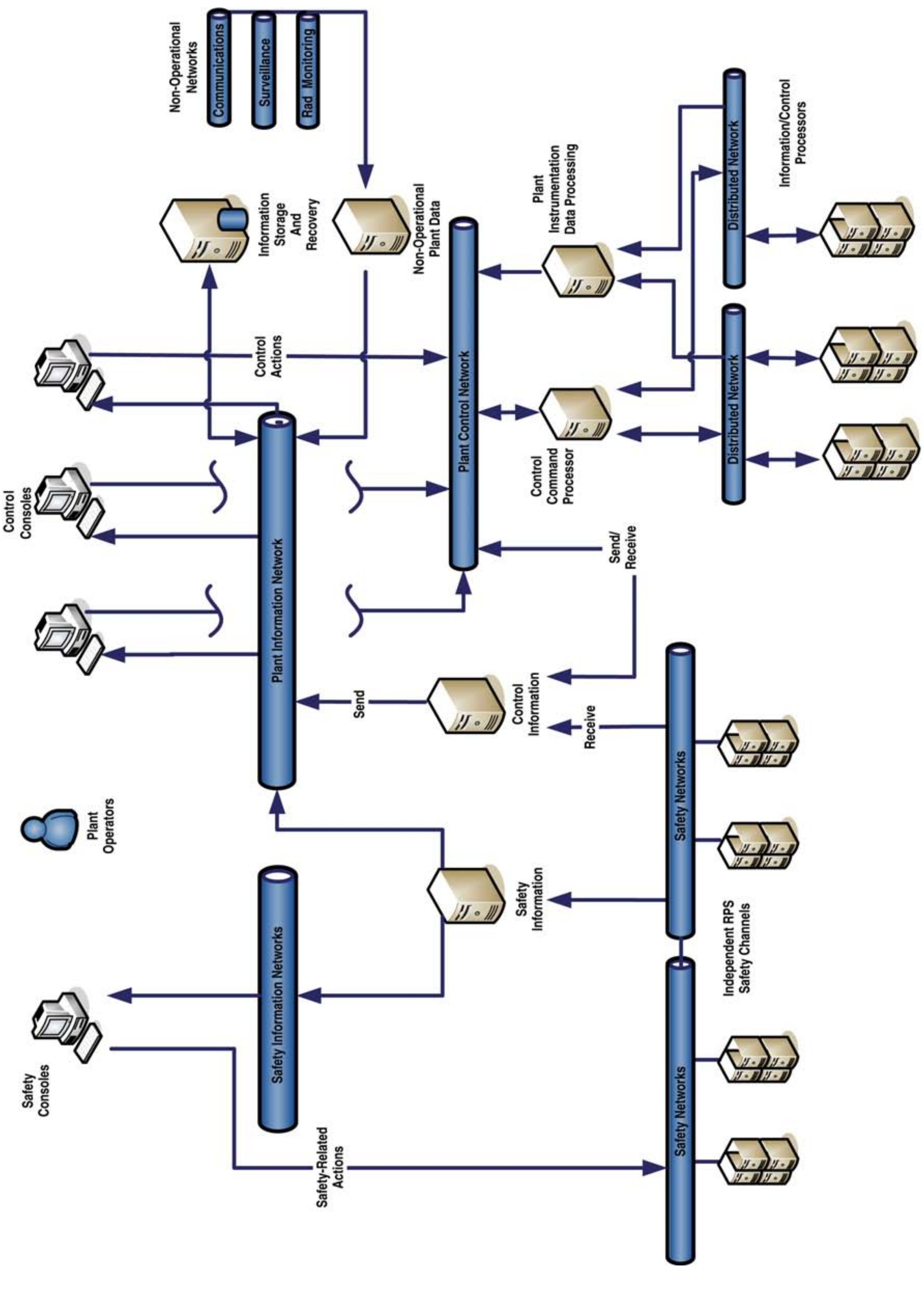

Fig. 4-38. Overview of plant control architecture.

5. SECONDARY SYSTEM TECHNICAL DESCRIPTION

5.1. SECONDARY SYSTEM HEAT EXCHANGER

5.1.1. Functions and Requirements

The purpose of the secondary heat exchanger (SHX) is:

- Reject waste heat from the HT^3R reactor received via the secondary heat transfer fluid (nitrogen) from the primary heat exchanger (PHX).

The SHX requirements are:

- Capable of dissipating the full 25 MW(t) generated by the reactor.
- Designed to operate with an inlet pressure of 3.1 MPa and high temperatures generated by the PHX.
- Cooling capability must be maintained by the SHX during all anticipated operational and design-basis events conditions.
- Design shall not make use of depleted water resources located in West Texas.
- Design of the SHX must comply with environmental regulations for heat dissipation.

5.1.2. Secondary System Heat Exchanger Design Description

Pre-conceptual design (PCD) level parameters such as the composition of secondary gas, inlet and outlet temperatures have been determined by the design of the primary systems and experimental goals of the facility. The SHX must be able to exhaust 25 MW(t) generated when the reactor is running at full power, even when the energy transfer (ET) and high-temperature process and material (HTMP) labs are not in use. A specification sheet shown in Table 5-1 was created to aid the design process

The constraints of the project include fluid, thermal, material, geometrical, environmental, and service life constraints. The geometric and service life constraints are common design requirements for heat exchangers and other power plant components. The environmental constraint pertains to the thermal exhaust of the heat exchanger. It is undesirable to have an exhaust temperature that would be harmful to the local ecosystem. Regulations that limit exhaust temperature do not appear to exist. In response, methods for reducing exhaust temperature have been devised, should the temperature need to be lowered. However, it should be noted that large modern power plants that generate >1000 MW(t) presently exhaust ~ 650 MW(t) if operating at 35% efficiency. Our maximum total exhaust heat will just be a fraction of this.

The air-cooled heat exchanger (ACHE) is currently the most promising technology for meeting the requirements of the SHX. The ACHE is constructed differently than the typical shell and tube heat exchanger. The major difference is that, for the ACHE, the shell flow is replaced by a fan-driven air duct. Since the ACHE is specifically designed to use air as its coolant fluid, it performs well under the given requirements and constraints.

Table 5-1
Specification Sheet for the SHX

D/W(a)	Functional Requirements/Constraints
	Functional Requirements
D	Dissipate all thermal energy produced in reactor [up to 25MW(t)]
	Constraints
	Fluid
D	Flow distribution uncertainty of at least 10%
D	Operate at a pressure of at least 3.1 MPa on gas side
W	Pressure drop (nitrogen-side) <60 kPa
W	Pressure drop (air-side) <30 kPa
W	Fluid velocity < 30 m/s
	Thermal
D	Operate with secondary system inlet temp of at least 950°C
D	Reduce temp of N_2 mixture by at least 400°C
D	Secondary side heat transfer correlation uncertainty >20%
D	SHX gas outlet must not exceed 450°C
	Material
D	Material conductivity uncertainty of at least 10%
	Geometry
D	Increased HX surface area to compensate for plugging (10%)
D	Tube diameter (TEMA) range: .25"<d<2"
	Environmental
W	Air exhaust from exchanger < 450°C
	Quality
D	Life expectancy of at least 20 years
W	Life expectancy of at least 30 years

(a)DW corresponds to demand/wish.

A schematic of the ACHE is shown in Fig. 5-1.

The ACHE is composed of a bundle of finned tubes connected to rectangular box headers at both ends. The front headers are welded boxes that divide the flow between the pipe and the tube bundle. The rear headers redirect the flow from one tube pass to another. The heat transfer is driven by convection between the tube bundle and ambient air. This process is enhanced by fans to increase the mass flow rate of the air.

The fans can be placed above or below the tube bundle. These systems are called induced draft and forced draft, respectively. The forced and induced draft configurations are shown in Figs. 5-2 and 5-3.

The forced draft setup is the best for our operating conditions. Forced draft fans are placed below the pipes, not in the hot stream of exhaust air, which in the case of this heat exchanger could be extremely hot. If the fans are placed in the hot stream of air, thermal stresses can cause problems. In addition, forced draft systems are easier to manufacture and maintain. The induced draft system main advantage is that it prevents warm air recirculation. Warm air recirculation occurs when fans draw in exhausted hot air.

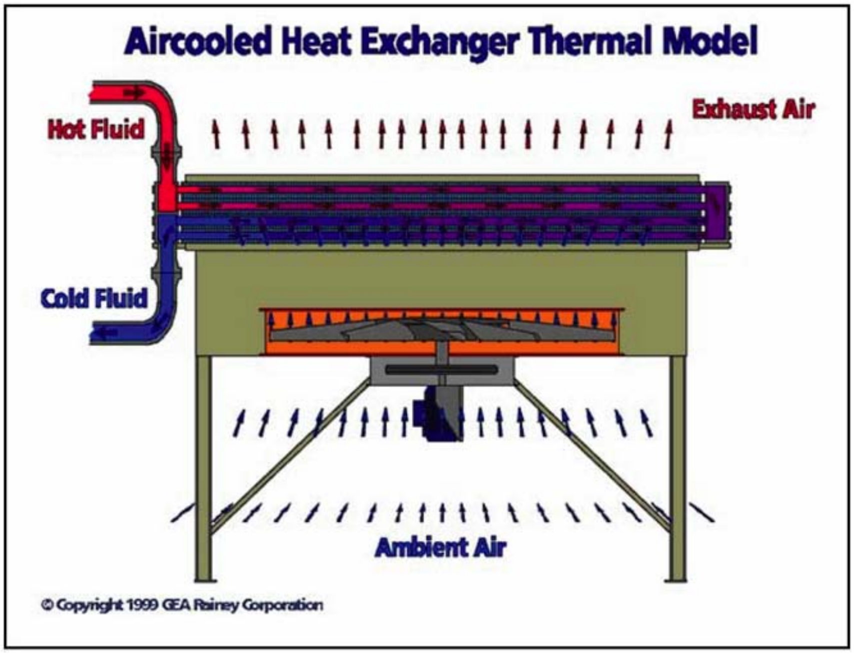

Fig. 5-1. Side view of air flow in the ACHE.

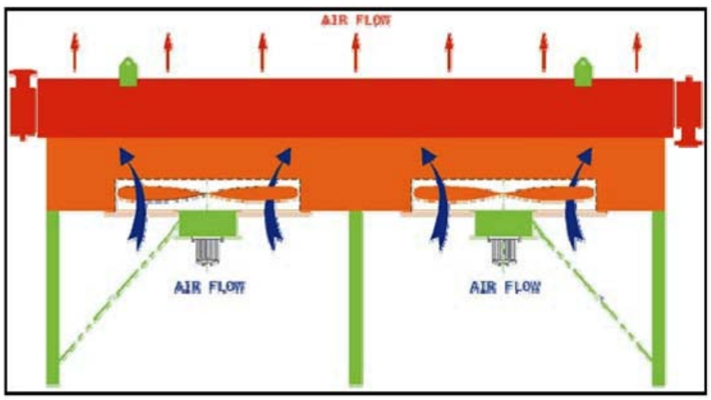

Fig. 5-2. Forced draft ACHE fan configuration.

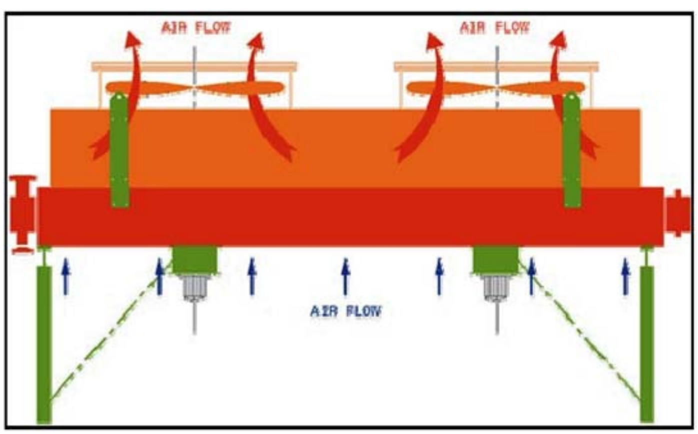

Fig. 5-3. Induced draft ACHE fan configuration.

Ecodyne MRM provided a basic quote and schematic for a two-unit ACHE to be coupled with a recuperator. Ecodyne MRM quoted a system price of $506,800. The quoted ACHE is designed to cool a 43 kg/s flow of the secondary coolant fluid from 450°C to 50°C by rejecting 22 MW(t). The unit contains two coolers, with two 30 kW fans per cooler. Each cooler utilizes 411 tubes made from 304SS. Ecodyne MRM and other vendors were unwilling to provide a product quote that would satisfy the high temperature requirements for a heat exchanger with an inlet of 950°C. A design for a high temperature heat exchanger would be different from the standard products provided by vendors. Normally, fins are embedded on the tubes to aid in the heat transfer. The temperatures for our application are too high to permit the use of standard materials used to construct the fins, so bare tubes of a high temperature alloy must be used.

For purposes of initial PCD construction and operating costs, an ACHE was designed that could satisfy the high temperatures and pressures required of the SHX. An initial overall heat transfer coefficient was assumed to solve for an initial area. The geometrical features of the exchanger were then set and a new overall heat transfer coefficient was calculated. The resulting exchanger design concept is a two-bay unit similar to the Ecodyne design. A connecting section of pipe guides the flow from the outlet of one bay into the inlet of the second bay. This two-bay design is meant to keep the exchanger from being too long, which would lead to tube manufacturing problems.

The design, similar to the Ecodyne design, includes a few modifications to accommodate higher temperatures. First, the tubes would be made of a high-temperature alloy instead of stainless steel used by Ecodyne. Also, the Ecodyne tubes include embedded aluminum fins which would not be suitable for the high temperature design. Therefore, bare tubes are used, which require an increase in tube length or number to account for the extra heat transfer surface area required.

The resultant high-temperature ACHE has the properties shown in Table 5-2. This design uses 410 Inconel tubes per bay for a total of 820 tubes. This initial design of SHX will reduce the hot gas temperature from 850°C to 437°C and will raise the temperature of air passing over the tubes from 50°C to 352°C. Four fans will blow air over the tube bundle at a speed of about 20 m/s.

Table 5-2
High-Temperature ACHE Properties

	Fluid Properties		**Exchanger Geometry per Bay**	
	Tube Side	**Air Side**	Number of tubes	410
Inlet temp (°C)	850	50	Tube outer diameter (mm)	19.05
Outlet temp (°C)	437	352	Tube inner diameter (mm)	12.7
Mass flow (kg/s)	55	80	Tube length (m)	12.5
Pressure (kPa)	3100	101.5		

The pressure drop through the tubes was calculated using the same method as with the shell and tube. The air-side pressure drop is a function of mass velocity of air, density of air at the inlet and outlet, tube layout, friction factor, and free flow area. The calculated pressure drop through the tubes is 47 kPa and 2.13 kPa over the tube bundle. The power required by the secondary circulator to overcome the pressure drop is 226 kW in the tube bundle and 228 kW for the air flowing over the tube bundle. This design yields an overall heat transfer coefficient of 126 W/m-k.

The recommended ACHE system is standard in industrial practices, but the temperatures and pressures are not. As a refinement to the initial high-temperature design using temperatures up to 950°C, the use of a mixer in the secondary coolant loop has been considered. To lower the nitrogen gas to 650°C, a mixer would be used to mix cooled nitrogen leaving the SHX with hot nitrogen leaving the PHX or laboratories. The mixer could consist of a pressure vessel composed of a metal that can withstand the temperature and pressure requirements. Alternatively, a simple pipe junction could be used instead of a dedicated mixer. Further analysis must be performed to determine which method is preferable for a high pressure and temperature environment.

The mixer would require a new section of pipe to divert a portion of the outflow from the SHX back into the inlet stream. The mixer would input hot nitrogen gas either directly from the PHX, the output of the high temperature labs, or a combination of the two. A schematic of the proposed layout is shown in Fig. 5-4.

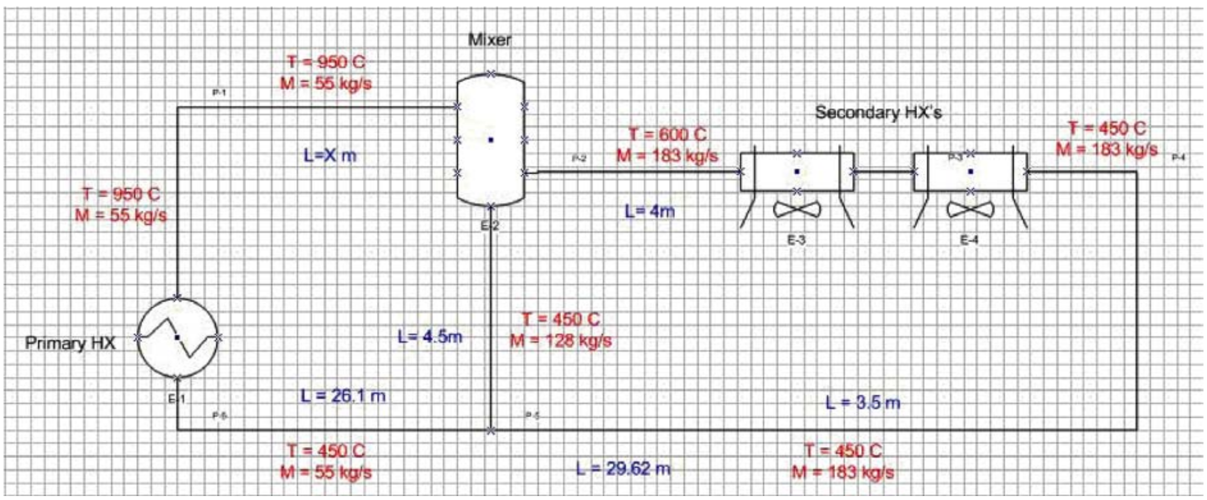

Fig. 5-4. Schematic of the secondary system with a mixer.

A Matlab code was constructed to determine flow rates through each section of pipe in the secondary loop based on specified temperatures. The input to the code is the desired temperature at the entrance of the SHX, which corresponds to different alloy specifications. The program then performs mass and energy balances on the system and then iterates on the corresponding enthalpy values. The enthalpy values converge with a small difference, resulting in equal temperatures. The mass flow rate corresponding to these temperatures can then be found from an energy balance.

Assuming an inlet temperature of 650°C, a flow rate of 137.5 kg/s would be passed through the SHX. It was determined that 82.5 kg/s of nitrogen would be directed out of this flow into the mixer, with the remaining 55 kg/s flowing to the PHX. Table 5-3 lists the different mass flow rate values.

The design from Ecodyne MRM can still be used for the SHX with few modifications in specifications or cost. Table 5-3 lists the details of the ACHE. Tube material would need to be changed from 304SS. An inlet temperature of 650°C would allow Grade 91 steel to be used as the tube material. This would significantly reduce the cost of using an expensive high-temperature alloy such as Inconel 617. The tubing cost was determined from the volume of material required to achieve appropriate heat transfer surface area. A surface area of 1,153,047.3 in.^{2} is required to reject 25 MW(t) from the nitrogen gas, resulting in a volume of 619.5 in.^{3} of material. The inner diameter of each tube is 2.59 in. The cost of using Grade 91 steel as the tube material is $2286. The overall heat transfer coefficient uranium has a value of 128.25 W/m^2-K.

Table 5-3
Mass Flow Rates with
ACHE Inlet Temp of 650°C

ACHE inlet temp (°C)	650
mdot1 (kg/s)	55
mdot2 (kg/s)	137.5
mdot3 (kg/s)	137.5
mdot4 (kg/s)	82.5
mdot5 (kg/s)	55

A Matlab script was created to observe the dependence of the outlet temperature for fluid to mass flow rate. The heat load and inlet temperature of fluid is specified as 25 MW(t) and 850°C and 52°C for the gas and air side, respectively. The outlet temperatures are solved for the range of mass flow rates. A graph of this relation can be seen in Fig. 5-5.

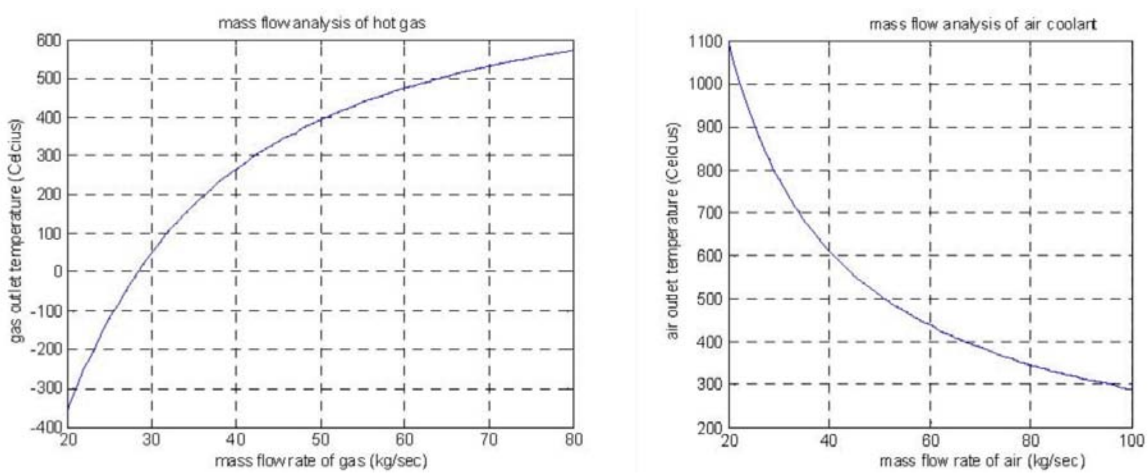

Fig. 5-5. Nitrogen and air outlet temperatures as functions of their mass flow rates.

The parameters of the reactor core and PHX indicate that the SHX needs to reduce the temperature of the secondary to 450°C. The SHX must also accommodate a PHX output gas mass flow rate of 55 kg/s. This flow rate is believed to be high enough to run the turbine in the ET lab. For the air side, it is desirable to reduce the outlet temperature of the exhausted air as much as possible. A mass flow rate of 80 kg/s was chosen which corresponds to an exhaust temperature of 352°C. Several vendors were contacted and it was determined that this flow rate, while relatively high, is possible at the expense of increased power consumption in the fans.

A Solid Works model of the selected design representing the new design was created based on engineering drawings from Ecodyne. This model is shown in Fig. 5-6 and specified dimensions are in meters.

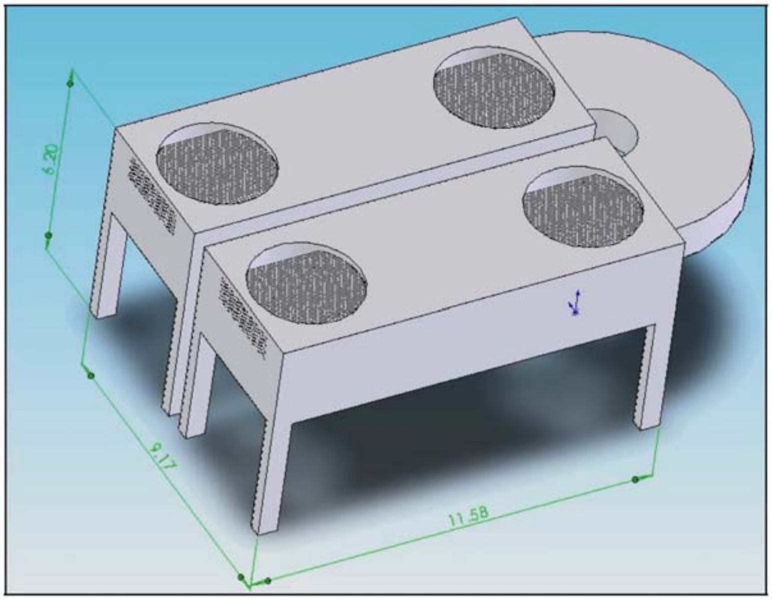

Fig. 5-6. Solidworks drawing of the ACHE.

Dust particles present in the ambient air pose a problem for heat exchangers. As debris builds up, fouling resistance increases, reducing the amount of heat transfer from the nitrogen to the air. Cleaning the outside of the tubes routinely for four shell and tube units would be time consuming, but as Fig. 5-6 shows, the ACHE design is fairly open and should facilitate cleaning.

5.2. SECONDARY SYSTEM CIRCULATOR

The cost and design requirements of the secondary system circulator at the stage of PCD will be estimated based on the cost of the primary circulator. These two components of the reactor systems have essentially the same function. Both circulate a 450°C gaseous working fluid. Both must make up for pressure drop in the PHX. The primary circulator compensates for pressure drop through the reactor core while the secondary circulator compensates for pressure drop in the SHX. A mixer in the secondary system is under consideration as part of a later design for the HT^3R. Since the secondary circulator will perform a function similar in nature to the primary circulator, any changes in the secondary circulator design will have to accommodate the mixer. A higher powered secondary circulator or parallel circulators to accommodate the higher mass flow rates needed for a mixer are possible. The complete design need not be repeated at this stage, merely adjusted later to accommodate the mixer.

5.3. ISOLATION VALVES

5.3.1 Isolation Valve Functions and Requirements

The function of the isolation valve are:

- Prevent unwanted coolant flow during shutdown.
- Restrict the rate of coolant flow to useable levels.
- Isolate the reactor systems for safety.

- Direct coolant in a controllable manner.
- Prevent damage to systems due to unwanted backflow.

A requirement set for the isolation valves is:

- A fast response time to prevent the flow of gas from the secondary system to the primary system through the PHX. A change in pressure in the secondary system will indicates it is necessary. The isolation valves shall function at temperatures up to 1000°C.

5.3.2. Isolation Valve Design Description

The operation temperature of the plant layout ranges from 460°C to 950°C. Inconel 617 and 9Cr-1Mo-V are valve materials that operate in this temperature range and conform to ASME boiler and pressure vessel, process piping, and power piping codes. Valves meeting these codes must be installed as shown in Figs. 5-7 and 5-8 to control the flow of coolant in the secondary system. To maximize the flexibility and utility of the facility, it is necessary to direct the flow of hot secondary coolant to areas where it is needed and away from all other areas.

The types of valves selected for use in the plant are important. The valves must control the flow of the working fluid for personnel safety in laboratory areas and prevent backflow. Components such as the circulator may fail due to backflow. From contacting the various valve vendors, it has been determined that there are two main types of valves: stop valves and check valves. Stop valves can shut or partially shut off flow of fluid. There are four types of stop valves: globe, gate, butterfly, and ball. Traditionally, gate valves are not suitable for throttling due to valve design because fluid hitting a partially open gate can cause excessive damage. For the same reason, neither butterfly valves nor ball valves can be used for throttling. Globe-type valves are the remaining option. Though globe valves are the most commonly used, they have a high pressure loss due to the two changes in direction of fluid flow. B & E Stainless Valve Co. has an alternative design called the Stargate-O-Port. The Stargate-O-Port valve, also called a slide-gate or through-port, has a well-guided blade that passes through both ends of the valve body allowing straight flow direction. Due to the versatility of this valve, it is the valve of choice for the HT^3R facility. An example of this type of valve is shown in Figs. 5-9 and 5-10.

To comply with the engineering codes at these temperatures and pressures, the valves in the piping of secondary systems will have the following parameters. Dimensions of hot-leg valve selection: 12-in. inner diameter, 18-in. outer diameter. Weight of one hot-leg valve: 6972 lb. Number of valves needed in the hot leg: 8. Dimensions of one cold-leg valve: 12 in. inner diameter, 14 in. outer diameter. Weight of one cold-leg valve: 4777 lb. Number of valves needed in the cold leg: 4. Hot leg valves are estimated to cost a total of $853,816 and cold leg valves $47,922, based on current valve costs adjusted to reflect the material costs of Inconel 617 (hot leg) and 9Cr-1Mo-V (cold leg).

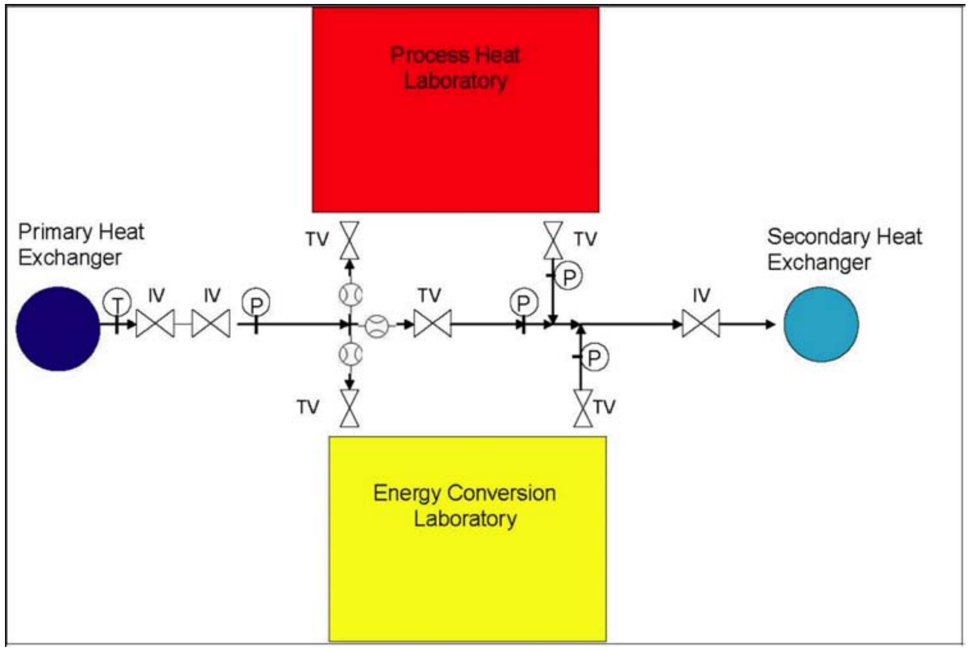

Fig. 5-7. Two-dimensional representation of hot leg piping layout showing placement of valves in the system.

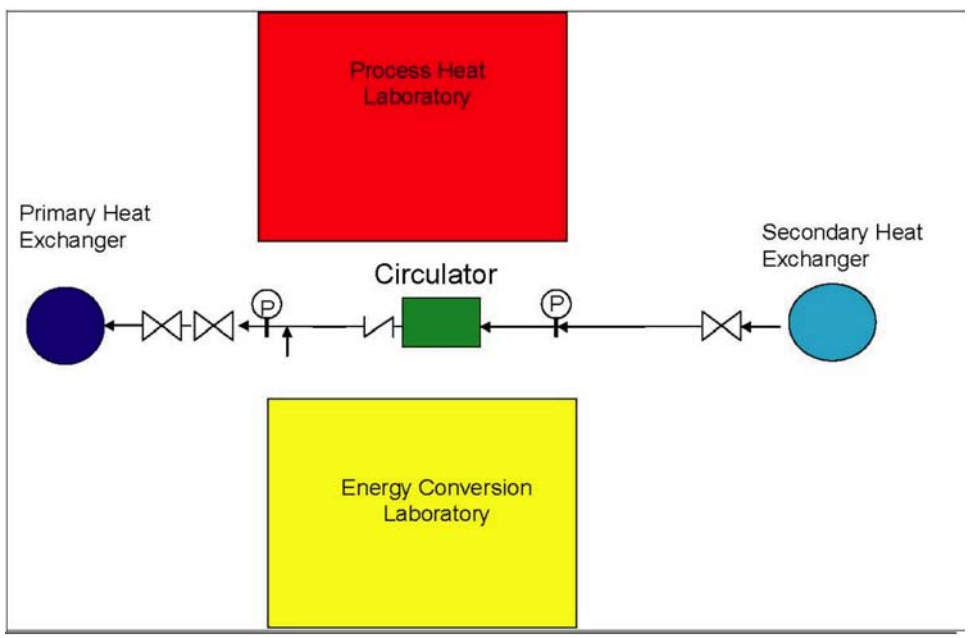

Fig. 5-8. Two-dimensional layout of the cold leg showing valve placement.

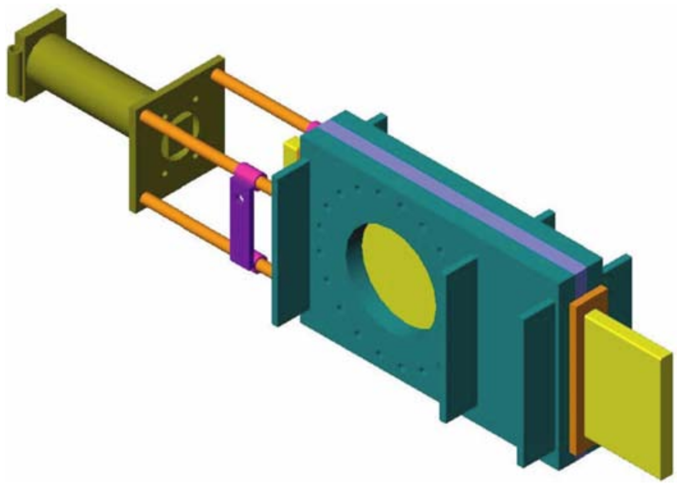

Fig. 5-9. 14 in. Stargate O-Port 900 class valve with hydraulic actuator.

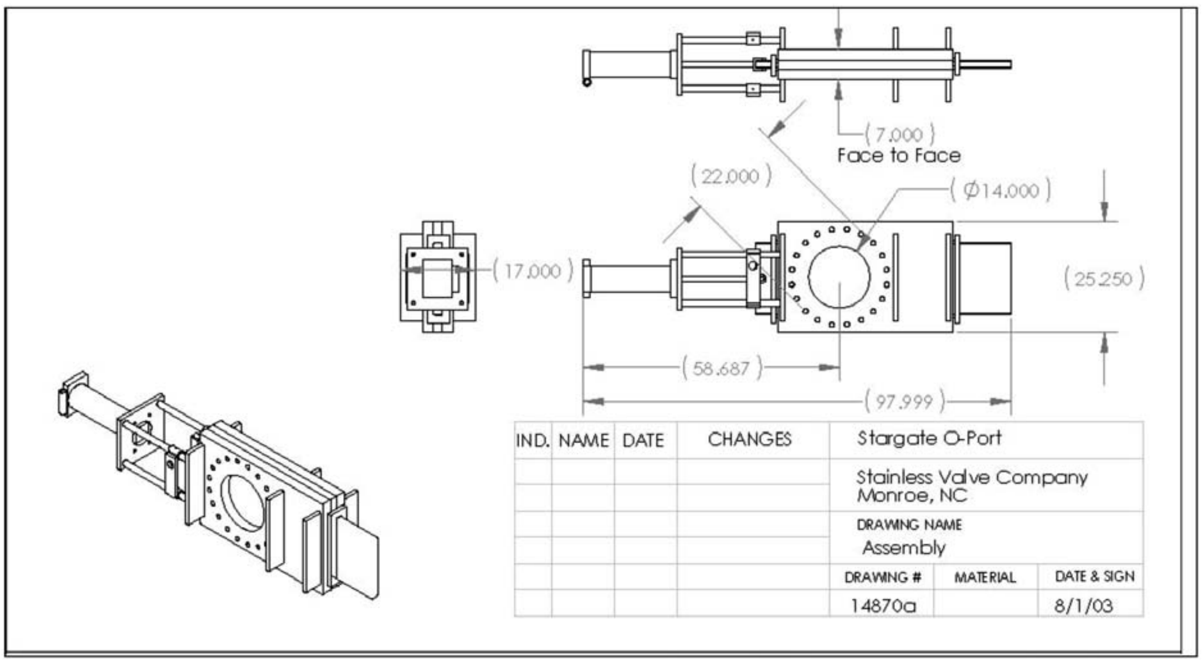

Fig. 5-10. Engineering schematic of valve shown in Fig. 9.

6. BALANCE OF FACILITY TECHNICAL DESCRIPTION

6.1. FUNCTIONS AND REQUIREMENTS

The requirements of the buildings and structures are to provide a functional and independent facility for the training of both engineers and scientists in the utilization of new energy technologies by performing research, testing, and development of alternative sources of energy. Research of radiation, materials properties, and generation of electricity will be conducted through the operation of a high temperature gas-cooled reactor and performance of associated experiments.

The buildings and support facilities provide a location to house and conduct experiments, office accommodations, and essential support services as required for a complete and operable facility. All facilities and structures shall be designed based on the applicable codes and standards that govern. All structures and systems shall provide a safe, operable, and functional facility that will support operation of the reactor.

6.2. GENERAL ARRANGEMENT OF BUILDINGS AND STRUCTURES

The buildings and structures will be contained in the nuclear island as described in Section 3.1 Overall Site Arrangement. The primary buildings within the nuclear island include the reactor building, and reactor services building, office building, radiation laboratory, energy transfer (ET) laboratory, and high temperature material processing (HTMP) laboratory.

The radiation laboratory, reactor containment building and both the ET and HTMP laboratories will be located below grade level. The reactor services building will be located at grade level. The reactor containment building is located below the floor of the reactor services building. The office building will be located adjacent to the reactor services building and allows for personnel access to adjacent spaces.

The other support facilities for warehouse operations and plant services are also located within the nuclear island.

6.3. REACTOR CONTAINMENT BUILDING

The reactor containment building consists of a concrete structure and support system for the reactor primary system (Fig. 3-3). This structure is located below grade and below the floor of the reactor services building with the top of the building flush with the reactor services building floor. The concrete structure around the vessel will be approximately 2 m thick for shielding.

Concrete additives will be provided for optimization of the shielding properties. Vessel supports will be designed to provide for thermal movement as required, and seismic and consideration of resistance to impact effects will be included.

6.4. REACTOR SERVICES BUILDING

As noted above the reactor services building will be constructed at grade level above the reactor building. The reactor services building will be constructed of cast-in-place concrete. The total building will be approximately 15,500 ft^2, with total building height above grade approximately 63 ft, and a roof system constructed of steel joist and metal decking. The floor of the building will support reactor refueling and other reactor service operations as well as providing for below-floor fuel and equipment storage cubicles. Containment for controlled personnel circulation will be provided between the reactor services building and the radiation laboratory. Personnel circulation will be provided between the ET and HTMP laboratories.

Freight elevators and personnel stairwells will be provided for circulation between the reactor services building and the laboratories.

An overhead crane/rail system will be provided in the reactor service building to allow for movement of the fuel handling equipment and other heavy equipment items throughout the floor area.

6.5. OFFICE BUILDING

The planned office building is three stories high. Construction for this building will consist of a reinforced cast-in-place concrete framing system with concrete floor slabs and roof deck. The exterior of the building will be constructed using a pre-cast concrete plank wall system supported by a reinforced cast-in-place concrete framing system. Exterior windows and doors will be blast resistant. The roofing will consist of a modified bitumen roofing system adhered to tapered rigid insulation. There will be minimal architectural aesthetic detailing associated with the exterior of the building.

The interior of the building will consist of concrete masonry shaft walls at the stair and elevator shafts as necessary. All other interior partition walls will be drywall construction. Interior floor finishes will consist of vinyl tile finish in the corridors, lobby, break room, computer rooms, service rooms, and storage rooms. Carpeting will be located in the offices and conference rooms. Restrooms will receive a ceramic tile floor finish. Stairways will receive a textured rubber tread and riser floor finish. The lab will receive a chemical-resistant floor finish. All walls will receive a painted gypsum wallboard finish with the exception of the restrooms, which will receive a ceramic tile wall finish. In addition, the interior walls of the stairwells will receive a painted concrete masonry unit finish. All ceilings will consist of suspended acoustical lay-in ceilings. Most lighting will be 2×4 fluorescent type light fixtures set in lay-in ceiling grids. The heating, air-conditioning and ventilation system will be a ducted system. The building will be completely wired for all electrical services and will include a cable tray system located above the ceiling for all communication and data requirements. The building will have a complete fire detection system, a complete fire alarm system, and a complete fire suppression system throughout.

6.6. RADIATION LABORATORY

The radiation laboratory will be located below grade adjacent to the reactor containment building. The radiation laboratory will include structural provisions to maximize clear span to allow for maximum flexibility and future use of experiments. The guide hall will be constructed underground as an extension of the radiation laboratory as required for the performance of experiments. Vertical access through elevators and stairwells will be included for controlled personnel circulation and emergency egress.

This building will be constructed of cast-in-place concrete walls. Sub-grade structure will be designed for support of anticipated loading on the roof. Provisions will be included to support movement of equipment and material throughout the laboratory space with overhead crane/rails or floor-mounted rails as required.

Heating, ventilation and air-conditioning (HVAC) systems will be designed for cooling requirements based on the anticipated loads. All ventilation systems will be processed through appropriate filtering prior to discharge.

Electrical power for experiments and general use will be provided. Stand-by emergency power will also be provided where required.

6.7. OTHER LABORATORIES

In addition to the radiation laboratory, the ET and HTMP laboratories will be located below grade adjacent to the reactor building opposite the radiation laboratories. The lab building will be constructed of cast-in-place concrete walls. Sub-floor structures will be designed for support of anticipated loading on the roof structure.

High-temperature relief ventilation will be provided for the laboratories. Excess heating from the secondary loop piping will be provided with independent chilled water cooling systems.

Power and lighting will be provided for the laboratories, as required, to support the expected experiments. Isolated power will be provided for specialized instrumentation.

6.8. OTHER BUILDINGS AND STRUCTURES

Other facilities on the complex will be constructed for support of ancillary systems. These facilities will include plant services warehouse facilities, radiation waste storage, a loading dock, and necessary ventilation stacks.

The construction material for the plant services building will be cast-in-place concrete for durability and protection of the facility electrical standby power and water treatment components that service the overall complex.

The security building will be located at the entrance point in the outer perimeter fence and will be of standard masonry construction.

6.9. PLANT SYSTEMS

6.9.1. Plant Control Data and Instrumentation System

In addition to the control and safety systems associated with the nuclear processes, the facility will be provided with a control and instrumentation system to establish and maintain control of the various facility functions. The control system will be integrated for building and process operations.

The control room design will provide for a controlled environment within a centralized location for control and monitoring of facility safety-related systems, environmental controls, redundant power systems, fire protection, and security operations.

The physical location and arrangement of the control room will be designed to maximize the efficiency and ease of the operator interface to monitor and control plant operations. Cable supporting and hardware components will be located to facilitate this arrangement.

6.9.2. Plant Electrical Systems

The electrical system will provide for delivery of power from the local utility service company to support the various electrical loads throughout the complex. The primary electrical systems will be distributed underground throughout the complex for service to pad-mounted electrical transformers and switch gear. The primary system will be configured for 100% redundancy in the event of a failure.

Standby electric power will be provided through independent diesel generators to maintain continuous power for critical systems in the event of loss of normal power from the utility.

Direct current (d.c.) electrical distribution will be provided and distributed throughout the facility to provide power for all d.c. motors and controls.

6.9.3. Radwaste and Decontamination System

6.9.3.1. Radioactive Gas Waste. All gaseous effluents generated within the facility are controlled and monitored. Gas waste streams known to contain low levels of activity can be discharged directly to the facility ventilation exhaust system. Effluents containing activity levels above the maximum allowable for ventilation system discharge are routed to a gas waste vacuum tank. This tank is maintained at some vacuum level (e.g., 300 mm Hg) by one of two gas waste compressors. The on-line compressor discharges into one of two gas waste storage and monitor tanks. When the on-line tank reaches a set pressure, it is isolated, and the gas waste compressor discharge is re-routed to the second tank.

The contents of the isolated tank are analyzed to determine the rate the contained gases can be released to local atmosphere. The correct rate is set into a flow controller, and the tank contents are permitted to vent into the building ventilation exhaust system discharge. Venting continues steadily until the storage and monitor tank pressure have been reduced to slightly above atmospheric pressure (e.g., 300 kPa). The tank is then placed on standby.

6.9.3.2. Radioactive Liquid Waste. All potentially contaminated liquids generated within the facility are either drained by gravity or are pumped into one of two radioactive liquid waste tanks. The on-line tank is permitted to fill over time as required. When full, the tank is isolated and the standby tank is placed on line. The contents of the full tank are analyzed to determine the contents, after which the liquid can be pumped to a nearby holding pond. When empty, the tank is placed on standby.

6.9.3.3. Solid Waste Disposal. Radioactively contaminated waste materials and small equipment items are compacted to minimize volume. The compacted waste is then packaged for shipment to an outside disposal organization or otherwise stored on site for later disposal. Routine solid waste include such items as contaminated rags, shoe covers, coveralls, hair covers, small instruments and tools, etc.

Spent fuel and reflector blocks, and rejected or discarded activated control rod sections for example, are handled remotely using specialized equipment. These items are placed in sealed, shielded containers that can be stored on site under controlled conditions. The facility hot cell can be used to package this type of waste. Spent fuel elements require accountability due to the radiation levels and specific nature of their contents.

6.9.3.4. Decontamination System. Equipment and materials containing surface contamination can be cleaned manually using rags, solvents, or other simple techniques. Liquids generated by these operations are transferred to the R/A liquid waste system, and the rags, tools, and other solid waste items generated by these activities can be processed as solid waste. The actual decontamination work is performed under controlled conditions using the decontamination — hot shop facility located at the refueling floor of the adjacent reactor service building.

If the level of contamination is significant, or strongly adheres to the material surface, more powerful cleaning techniques are required. These include pressure washing, steam cleaning, heavy duty cleaning fluids, or other such procedures. This type of work is performed under controlled conditions in the decontamination — hot shop where the cleaning fluids can be collected and inadvertent release to other nearby clean areas is prevented.

6.9.4. Plant Service Systems

The plant services systems consist of HVAC system, water systems, air systems, and fire protection systems for the complex. System sizing for the chilled water plant will be based on the expected internal loads for occupants to accommodate the heat gains generated from the experiments as well as large heat gains from the reactor cavity and associated piping in the secondary loop. It is expected that the cooling plant will consist of air-cooled condensing units that will provide cooling water to central air-handlers through a closed loop system. All systems will include 100% redundancy.

The experiments conducted in the radiation laboratory will be provided with air-conditioning and ventilation that will be independent of other parts of the building and will include high efficiency particulate air (HEPA) filters. All monitoring and control of the mechanical systems will be accomplished through an energy management and control system (EMCS).

All buildings in the complex will be protected with a fire suppression system. Water storage and working pressure will be provided by two 300,000 gallon elevated storage tanks. Locations that require protection without the use of wet pipe sprinklers will be provided with alternate dry chemical solution. All fire protection features will be integrated with the overall fire alarm and reporting system serving the complex.

7. ENGINEERING COST AND SCHEDULE

7.1. ENGINEERING COSTS

The HT^{3}R engineering activities are to be conducted in the sequential phases of conceptual design (CD), preliminary design (PD) and final design (FD). The primary objective of the CD phase is to prepare a reference design for each system, structure and component (SSC); the primary objective of the PD phase is to prepare a detail design for each of the SSCs; and the primary objective of the FD phase is to prepare the detail requirements (drawings, specifications, and design reports) required for manufacture of the SSCs.

The estimated cost to perform the engineering for each design phase (CD, PD and FD) are provided in Table 7-1 at the 3-digit work breakdown schedule (WBS) level.

PCD SSCs descriptions at the 3-digit level Table 7-1 are provided in Sections 4, 5 and 6 for the Primary System (WBS 1.1), Secondary System (WBS 1.2), Facilities Buildings and Structures (WBS 1.3), and Facility Systems (WBS 1.4), respectively. Summary descriptions of the HT^{3}R Facility Level (WBS 1.5) engineering activities at the 3-digit WBS level as shown in Table 7-1 are as follows:

WBS 1.5.1 – Requirements Management and Planning

In this WBS element, the requirements that the HT^{3}R facility will be designed to satisfy will be identified and maintained. At the onset of CD, a Plant Design Requirements Document (PDRD) will be developed and periodically updated, as required, during the course of the balance of the design phases.

WBS 1.5-2 – Facility Level Reports

Facility level documentation, other than the PDRP, will be accomplished in this WBS element. Documentation will include preparation of design reports such as an overall plant design description (OPDD) document which summarizes the overall plant design. An OPDD would be prepared at the conclusion of the CD phase and updated at the completion of the PD and FD phases. This technical and design plan was prepared under this WBS element concluding the PCD phase.

WBS 1.5-3 – Safety and Licensing

The activities necessary for obtaining the required construction and operation licenses for the HT^{3}R from the U.S. Nuclear Regulatory Commission (NRC) will be performed under this WBS element. The licensee, University of Texas of the Permian Basin (UTPB), is primarily responsibile for safety and submission of documents supporting the license application. The major documents required by the NRC for a test reactor license are a Safety Analysis Report (SAR), technical specifications, security plan, emergency plan, operator qualification plan, and environmental assessment report. During CD, the primary effort will be to establish requirements and guidelines for the preparation of licensing documents and incorporating safety into the design process. During PD, safety and licensing activities will include preparing drafts of the SAR, technical specifications, security plan, environmental assessment report, and draft emergency plan. During the first part of FD, the licensing documents would be submitted to the NRC for review. The NRC review would then run concurrently with the remainder of the FD. During this time, the focus of safety and licensing will be on responses to NRC inquiries, meetings with the NRC and the Advisory Committee for Reactor Safeguards (ACRS), and public meetings.

Table 7.1-1
HT^3R Engineering Cost Estimate Summary
(Cost in $K)

WBS Element		Title	Conceptual Design	Preliminay Design	Final Design	Totals
1.1		**Primary System**	**6,104**	**8,896**	**13,199**	**28,198**
	1.1.0	Primary System	280	752	832	1,864
	1.1.1	Reactor System	1,400	1,816	5,016	8,232
	1.1.2	Vessel System	600	900	901	2,401
	1.1.3	Primary Heat Exchanger	450	450	1,301	2,201
	1.1.4	Primary Helium Circulator	568	992	848	2,408
	1.1.5	Shutdown Cooling System	520	380	520	1,420
	1.1.6	Fuel Handling System	472	881	856	2,209
	1.1.7	Helium Services System	350	605	604	1,558
	1.1.8	Reactor Cavity Cooling System	440	672	928	2,040
	1.1.9	Reactor Control and Protection System	1,024	1,448	1,394	3,866
1.2		**Secondary System**	**2,455**	**2,196**	**2,204**	**6,855**
	1.2.1	Piping & Equipment	2,171	1,700	1,780	5,651
	1.2.2	Secondary Coolant Circulator	284	496	424	1,204
1.3		**Facilities Buildings and Structures**	**1,552**	**3,122**	**14,023**	**18,697**
	1.3.1	Plot Plan	251	505	2,268	3,024
	1.3.2	Reactor Building	434	872	3,918	5,224
	1.3.3	Operations Center	342	689	3,093	4,124
	1.3.4	Other Buildings and Structures	525	1,056	4,743	6,324
1.4		**Facility Systems**	**274**	**551**	**2,475**	**3,299**
	1.4.1	BOP Control Data and Instr Systems	46	92	412	550
	1.4.2	Plant Electrical System	46	92	412	550
	1.4.3	Radwaste and Decontamination System	46	92	412	550
	1.4.4	Plant Service Systems	137	276	1237	1,650
1.5		**Facility Level**	**3,582**	**5,984**	**7,150**	**16,716**
	1.5.1	Requirements Management & Planning	580	850	600	2,030
	1.5.2	Facility Level Reports	240	300	300	840
	1.5.3	Safety and Licensing	910	2,100	2,100	5,110
	1.5.4	Facility Level Analysis	582	848	600	2,030
	1.5.5	Project Management	1,270	1,886	3,550	6,706
		Totals	**13,966**	**20,750**	**39,050**	**73,766**

WBS 1.5.4 – System Level Analysis

This facility level analysis (FLA) WBS element is to assure the design can be operated to satisfy the required range of operating parameters as specified in the PDRD. During CD, a preliminary operating envelope will be prepared based on achievable power level, temperature, pressure, heat rejection capacity, etc., and compared operating envelope objectives in the PDRD. Recommendations will be made for CD design modifications needed to meet all objectives. Recommendations will also be developed for analytical tools to analyze plant level steady-state and transient performance.

During PD, facility level steady-state and transient analysis models will be developed and used to establish steady-state operating points to refine the operating envelope and facility level transient analyses performed to characterize transient performance and support safety and licensing activities.

During FD, the FLA steady-state model will be updated to define the FD operating envelope and off-design transient predictions will be prepared. Results will be coordinated with safety and licensing activities in support of the SAR.

WBS 1.5.5 – Project Management

Project management entails all of the activities necessary for planning, implementing, performing, coordinating and reporting the engineering activities conducted during CD, PD and FD.

7.2. ENGINEERING SCHEDULE

An overview of the schedule to perform the engineering of the HT^3R is provided in Fig. 7-1. Figure 7-1 shows the sequential phases CD, PD, and FD. Key schedule milestones during the engineering phase include completion of CD, PD, FD, long lead material (LLM) order, submittal of the SAR and issuance of the construction permit (CP) by the NRC following SAR review.

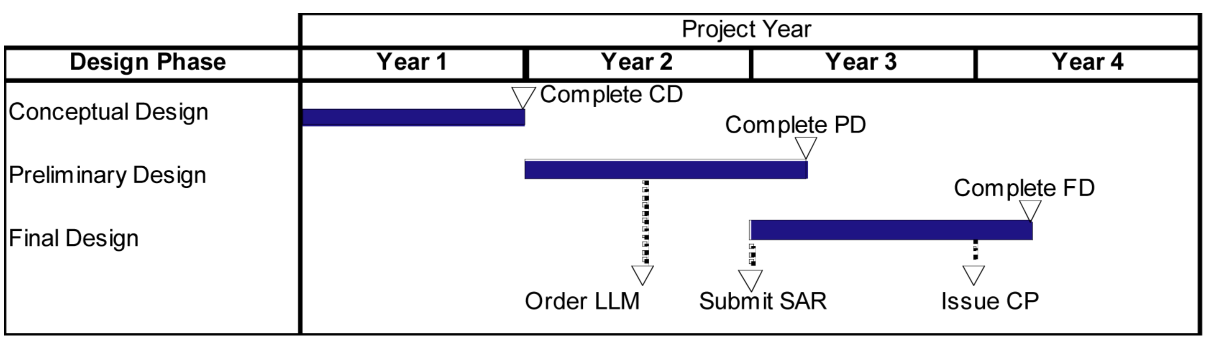

Fig. 7-1. Summary HT^3R engineering schedule.

8. FACILITY CONSTRUCTION COST AND SCHEDULE

8.1. FACILITY CONSTRUCTION COST

The estimated cost to construct the HT^3R facility based on the pre-conceptual design (PCD) are given in Table 8-1 at the 3-digit work breakdown schedule (WBS) level. The total estimated cost to construct the facility is estimated to be $381,876K without contingency. A contingency allowance of 20% is estimated to cover unknowns based on the level of PCD detail. The total estimated construction cost with a 20% contingency is $458,252K.

Table 8-1 includes a breakdown of the estimated cost at the 3-digit WBS level in terms of equipment, material, and labor. The material and labor cost for equipment items cover the equipment shipping and installation costs. The estimated construction cost at the estimated level of detail and the assumptions used to develop the construction cost estimate are provided in Appendix B.

8.2. FACILITY CONSTRUCTION SCHEDULE

A summary of the schedule estimated for construction of the HT^3R facility is shown in Fig. 8-1. The estimated time for construction of the facility, from start of site work to completion of facility commissioning, totals 40 months. It is further estimated that the site work could start in the third quarter of Year 3 and completed in the fourth quarter of Year 6. A more complete breakdown of the construction schedule is provided in Appendix C.

8.3. COMMISSIONING COST AND SCHEDULE

8.3.1. Introduction

When major facility construction is complete, the next phase will be transition from a construction program to operational status. As these systems, or portions thereof, are completed, the construction program requires that certain “construction (or commissioning) tests” be completed. This includes items such as leak testing of lines, pumps, tanks, and other equipment items, pressure testing (to meet code), motor operations (correct rotation), valve functions, and various tests to ensure that all equipment operates as expected. Control from the assigned switches and other automatic inputs will also be tested. Systems that require filling with water, air, or other media are filled and verified to assure normal plant operations. Construction testing of basic plant support systems, such as fire protection, sanitary systems (toilets, etc.), building heating and ventilation systems, plant lighting, potable water, electrical distribution, compressed air, etc., are normally completed before plant operating personnel occupy the buildings. Of particular importance are data and information technology systems that must be completed and tested to support the overall commissioning program.

When construction testing has been sufficiently completed to allow function of operating staff, the major plant systems and equipment are turned over to staff for routine operation or pre-operational testing for those systems that directly support reactor operation such as helium circulator, neutron control assemblies, shutdown cooling system, etc. A certain level of construction personnel is retained to support the pre-operational test program, make repairs to equipment, and generally wrap up the final details of plant construction as may be required based on results observed. All documentation must be brought current and maintained for future reference to satisfy commitments made to regulatory agencies responsible for approving the completed facility.

Table 8-1
HT^{3}R Facility Construction Cost ($K)

1.1	PRIMARY SYSTEM		EQUIPMENT	UNIT LABOR	MATERIALS/ SHIPPING	TOTALS
	1.1.1	Reactor System	$9,622	$205	$75	$9,902
	1.1.2	Vessel System	$35,675	$650	$385	$36,710
	1.1.3	Primary Heat Exchanger	$11,100	$100	$75	$11,275
	1.1.4	Primary Helium Circulator	$13,400	$75	$50	$13,525
	1.1.5	Shutdown Cooling System	$3,311	$100	$80	$3,491
	1.1.6	Fuel Handling System	$25,209	$160	$65	$25,434
	1.1.7	Helium Service System	$915	$23	$15	$953
	1.1.8	Reactor Cavity Cooling System	$1,490	$120	$40	$1,650
	1.1.9	Reactor Protection System	$6,686	$75	$11	$6,772
	TOTAL PRIMARY SYSTEM		**$107,408**	**$1,508**	**$796**	**$109,712**
1.2	**SECONDARY SYSTEM**					
	1.2	Heat Rejection System	$6,400	$140	$50	$6,590
	TOTAL SECONDARY SYSTEM		**$6,400**	**$140**	**$50**	**$6,590**
1.3	**BUILDINGS AND STRUCTURES**					
	1.3.1	Plot Plan	$18	$6,398	$5,559	$11,975
	1.3.2	Nuclear Island	$4,391	$3,632	$99,049	$107,073
	1.3.3	Security Building	$18	$1,255	$13,520	$14,792
	TOTAL BUILDINGS AND STRUCTURES		**$4,427**	**$11,285**	**$118,128**	**$133,840**
1.4	**PLANT SYSTEMS**					
	1.4.1	BoP Control Data and Instru Systems	$0	$0	$250	$250
	1.4.2	Plant Electrical System	$0	$2,443	$3,378	$5,821
	1.4.3	Radwaste and Decontamination System	$0	$75	$125	$200
	1.4.4	Plant Service Systems	$0	$3,366	$3,164	$6,530
	TOTAL PLANT SYSTEMS		**$0**	**$5,885**	**$6,917**	**$12,801**
TOTAL DIRECT CONSTRUCTION COSTS			**$118,234**	**$18,818**	**$125,891**	**$262,943**
1.5.6	**CONSTRUCTION SERVICES**					
		GC General Conditions			20%	$52,589
		Bond			1.50%	$3,944
		GC Profit			8%	$21,035
		QA/QC			5%	$13,147
		Engineering Support During Construction				$24,261
	TOTAL CONSTRUCTION SERVICES					**$114,977**
1.5.7	**COMMISSIONING**					**$3,957**
TOTAL INDIRECT CONSTRUCTION COSTS						**$118,933**
TOTAL FACILITY BASE CONSTRUCTION COST						**$381,876**
		CONTINGENCY			20%	**$76,375**
GRAND TOTAL						**$458,252**

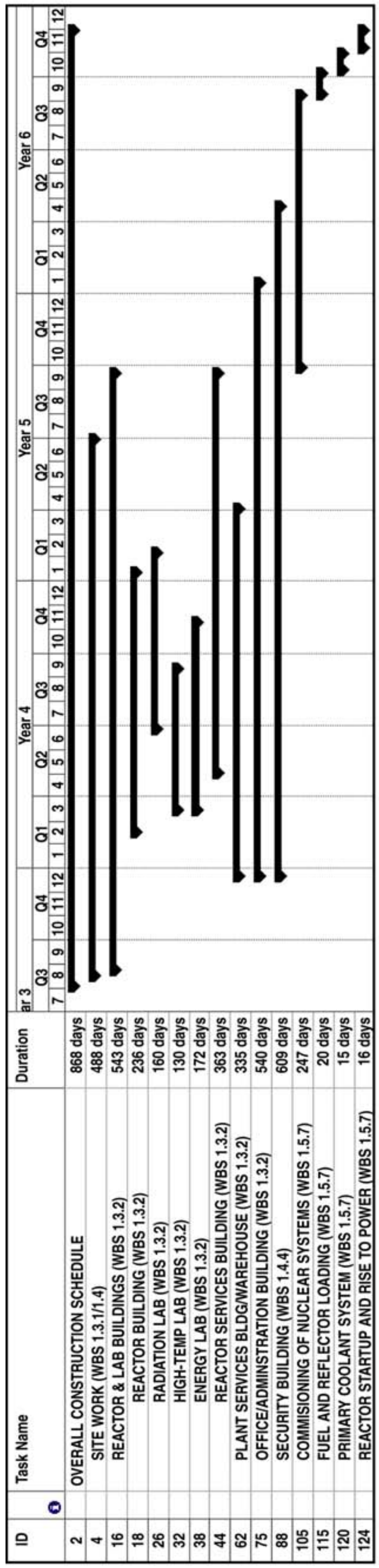

Fig. 8-1. Summary level HT_3R estimated construction schedule.

Commissioning of conventional plant systems occurs as systems are completed in the normal course of plant construction. Testing and commissioning of systems that are directly related to reactor operations can begin as soon as the equipment is ready. The reactor commissioning program normally overlaps the completion of plant construction and will require considerable coordination between operating staff and the construction organization to minimize time required to make this transition.

Pre-operational test procedures must be prepared for the systems to be tested during this phase of plant startup and commissioning. These procedures must be approved prior to start of testing, personnel must be assigned testing responsibilities, and the sequence of testing must be carefully arranged and scheduled to minimize time required for performance.

8.3.2. Pre-Operational Testing

Each major reactor-related system must be carefully tested and documented before the nuclear reactor can be taken critical for the first time. Pre-operational testing includes basic operation of the primary helium circulator and all support systems, operation of the shutdown cooling circulator and all support systems, and all functions required of the neutron control assemblies. All nuclear instrumentation must be thoroughly tested and cleared for normal operation.

All of the automatic control functions for each of the conventional plant systems are verified during the commissioning program. For nuclear and reactor-related systems, control functions are verified during the pre-operational testing program. During testing, all instrument set points that initiate a response within these systems are verified by allowing the process variables to become the initiating events rather than forcing the control functions to occur via temporary or simulated inputs.

The fuel can be loaded into the reactor vessel before initial flow testing of the primary system using helium as the operating fluid. Fuel loading requires that all nuclear instrumentation and safety systems be fully operational before loading commences. Early fuel loading will minimize the duration of the commissioning program since fuel loading can be done in parallel with other pre-operational testing. Installation of fuel will also allow a complete analysis of the fuel handling equipment and procedures. The presence of a full reactor core will provide realistic flow paths and resistances resulting in more accurate assessments of the overall primary system performance when helium circulation begins. The hot-functional test of the primary system can be carried out using compression heat from the primary helium circulator. Additional heat input to the primary system can be obtained by heating the secondary coolant and allowing the primary heat exchanger to transfer that heat into the primary coolant system. The heat input required from the secondary system would be only that necessary for compensation of heat losses in the primary system. No nuclear heat should be required to support the hot functional testing program.

8.3.3 Reactor Startup and Overall Plant Commissioning

When all plant systems necessary to support reactor operation have been thoroughly tested and turned over to operating personnel, reactor startup will commence. All pre-requisites for initial reactor startup must be completed, approved, and authorized by plant management. Approved overall plant operating procedures must be used for all aspects of these initial operations, with step-wise authorizations and formal approvals obtained at major points of development. Outstanding discrepancies must be resolved to the satisfaction of plant management. This may require additional work by the remaining construction organization. Otherwise, such activities can be performed by the assigned plant operations and maintenance personnel. Again, all work must be accompanied by fully approved procedures and documentation.

The secondary coolant system must be operational before reactor startup can begin. The initial approach to first reactor criticality is performed carefully, using approved procedures to assure that all parameters meet expectations and that all prerequisites for increasing reactor power level have been satisfied. Once reactor heat is generated, the plant secondary systems can be brought on-line, and further plant testing can be undertaken to ensure that ultimate plant heat sink is performing within specifications.

Upon completion of commissioning and startup testing, and all prescribed tests have been completed with results accepted and approved, the facility can be turned over to the customer for normal operation.

8.3.4. Cost and Schedule

The estimated cost of the commissioning program is included in Table 8-1. The estimated schedule for the commissioning program is included in Fig. 8-1.

9. INTEGRATED ENGINEERING AND CONSTRUCTION COST AND SCHEDULE

9.1. INTEGRATED ENGINEERING AND CONSTRUCTION COST

The combined estimated engineering and construction costs are given in Table 9-1. The combined costs, including a 20% contingency on both engineering and construction cost estimates, total $546,721.

9.2. INTEGRATED ENGINEERING AND CONSTRUCTION SCHEDULE

An integrated schedule that combines the estimated engineering and construction schedules is provided in Fig. 9-1. The total span time for the engineering and construction activities is estimated to be 71 months.

Table 9-1
Integrated HT^3R Engineering and Construction Cost Estimate

		Engineering	Construction	Totals
1.1	Primary System	$28,200	$109,711	$137,911
1.2	Secondary System	$6,855	$6,590	$13,445
1.3	Buildings and Structures	$18,696	$133,840	$152,536
1.4	Plant Systems	$3,300	$12,801	$16,101
1.5	Facility Level	$16,716	$118,934	$135,650
	TOTALS	$73,767	$381,876	$455,643
	Contingency @ 20%	$14,753	$76,375	$91,129
	TOTALS	$88,520	$458,251	$546,772

ID		Task Name	Duration
1		ENGINEERING DESIGN SCHEDULE	848 days
2		CONCEPTUAL DESIGN	261 days
10		PRELIMINARY DESIGN	325 days
18		FINAL DESIGN	324 days
26		OVERALL CONSTRUCTION SCHEDULE	868 days
28		SITE WORK (WBS 1.3.1/1.4)	488 days
40		REACTOR & LAB BUILDINGS (WBS 1.3.2)	543 days
42		REACTOR BUILDING (WBS 1.3.2)	236 days
50		RADIATION LAB (WBS 1.3.2)	160 days
56		HIGH-TEMP LAB (WBS 1.3.2)	130 days
62		ENERGY LAB (WBS 1.3.2)	172 days
68		REACTOR SERVICE BUILDING (WBS 1.3.2)	363 days
86		PLANT SERVICES BLDG/WAREHOUSE (WBS 1.3.2)	335 days
99		OFFICE/ADMINISTRATION BUILDING (WBS 1.3.2)	540 days
112		SECURITY BUILDING (WBS 1.4.4)	609 days
129		COMMISIONING OF NUCLEAR SYSTEMS (WBS 1.5.7)	247 days
139		FUEL AND REFLECTOR LOADING (WBS 1.5.7)	20 days
144		PRIMARY COOLANT SYSTEM (WBS 1.5.7)	15 days
148		REACTOR STARTUP AND RISE TO POWER (WBS 1.5.7)	16 days

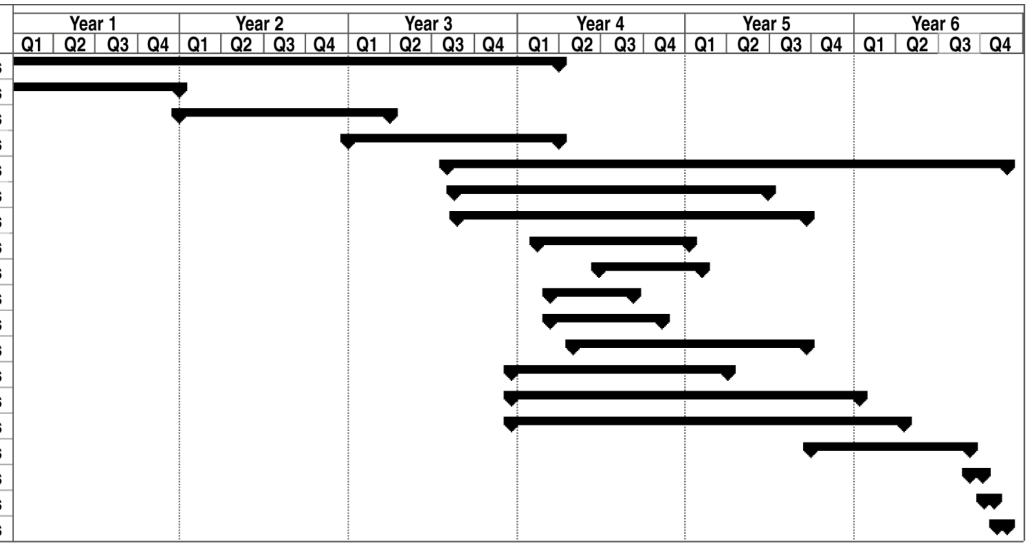

Fig. 9-1. Integrated engineering and construction schedule.

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Parts of the equipment costing and layout of the secondary system were used as a Summer Design Project for Undergraduate Students of the Mechanical Engineering Department and Nuclear Engineering Teaching Laboratory of the University of Texas at Austin.

APPENDIX A
WORK BREAKDOWN STRUCTURE (WBS)

WBS Element	Function & Requirements	Design Description	Engineering Cost & Schdule Estimate	Construction Cost & Schdule Estimate	Summary Report
1.1 Primary System	GA	GA			GA
1.1.1 React or System	GA	GA	GA	GA	GA
1.1.1.1 React or Core	GA	GA	GA	GA	
1.1.1.2 Core Support Structures	GA	GA	GA	GA	
1.1.1.3 Neutron Control Systems	GA	GA	GA	GA	
1.1.2 Vessel System	GA	GA	GA	GA	GA
1.1.2.1 React or Vessel	GA	GA	GA	GA	
1.1.2.2 Heat Exchanger Vessel	GA	GA	GA	GA	
1.1.2.3 Cross Vessel	GA	GA	GA	GA	
1.1.2.4 Vessel Support System	GA	GA	GA	GA	
1.1.2.5 Vessel Pressure Relief Subsystem			GA	GA	
1.1.3 Primary Heat Exchanger	GA	GA /UT	GA /UT	GA /UT	GA /UT
1.1.4 Primary Helium Circulator	GA	GA /UT	GA	GA	GA
1.1.5 Shutdown Cooling System	GA	GA	GA	GA	GA
1.1.5.1 Shutdown Heat Exchanger	GA	GA	GA	GA	
1.1.5.2 Shutdown Circulator	GA	GA	GA	GA	
1.1.5.3 Shutdown Cooling Water System	GA	GA	GA	GA	
1.1.5.4 Shutdown Cooling Control System			GA	GA	
1.1.6 Fuel Handling System	GA				GA
1.1.6.1 Fresh Fuel Handling and Storage System	GA	GA /AE	GA /AE	GA /AE	
1.1.6.2 Refueling System	GA	GA	GA	GA	
1.1.6.3 Spent Fuel Storage System	GA	GA	UT /AE	AE	
1.1.6.4 Neutron Control Assembly Handling System	GA	GA	GA	GA	
1.1.7 Helium Services System	GA				GA
1.1.7.1 Helium Purification System	GA	GA	GA	GA	
1.1.7.2 Helium Transfer and Storage System	GA	GA	GA	GA	
1.1.7.3 Liquid Nitrogen System	GA	GA	GA	GA	
1.1.8 React or Cavity Cooling System	GA	GA	GA	GA	GA
1.1.9 React or Control & Protection System	GA	GA	GA	GA	GA
1.2 Secondary System (Heat Rejection System)	UT	UT	UT	UT	UT
1.2.1 Secondary System Heat Exchanger	UT	UT	UT	UT	
1.2.2 Secondary System Circulator	UT	UT	UT	UT	
1.3 Buildings and Structures	UT				AE
1.3.1 Plot Plan	UT	UT /AE			
1.3.2 Nuclear Island	GA	UT /AE	AE	AE	
1.3.3 Security Building	UT	UT /AE	AE	AE	
1.4 Plant Systems	UT				AE
1.4.1 Plant Control Data and Instrumentation System	UT	UT /AE	AE	AE	
1.4.2 Plant Electrical System	UT				
1.4.3 Radwaste and Decontamination System	UT	UT /AE	AE	AE	
1.4.4 Plant Service Systems	UT				
1.5 HT3R Facility Level					GA /UT
1.5.1 Requirements Management & Planning			GA /UT	GA /UT	
1.5.2 Facility Level Reports			GA /UT	GA /UT	
1.5.3 Safety and Licensing			GA /UT	GA /UT	
1.5.4 Facility Level Analysis			GA /UT	GA /UT	
1.5.5 Project Management			GA /UT	GA /UT	
1.5.6 Construction Services			GA /UT/AE	GA /UT/AE	
1.5.7 Commissioning			GA /UT/AE	GA /UT/AE	

APPENDIX B
HT^3R CONSTRUCTION COST ESTIMATE
DETAIL LEVEL

Cost Estimate Basis and Assumptions
Pre-Conceptual Cost Estimate for the Reactor Plant Equipment
High Temperature Teaching and Test Reactor (HTTTR)
Planned for the University of Texas of the Permian Basin
Dated 12/9/2006

Cost Estimate Assumptions; from General Atomics

1) The cost estimate for the Reactor Plant Equipment represents a single module First of a Kind (FOAK) plant for the UTPB site
2) Costs are presented in present day January 2006$
3) The cost estimate represents a plant with a Pre-Conceptual Design status
4) The Construction site was assumed to be the Permian Basin in Texas
5) The Reactor Plant Equipment unit costs were developed using current cost data from High Temperature Gas Cooled Reactor Plant studies
6) The Reactor Plant Equipment costs include Manufacturers First of a Kind charges, shipping costs and installation costs
7) Costs assume World Market Prices and competitive bidding
8) Shipping costs assume that components will be shipped from various vendor locations using overland modes
9) The cost estimate is presented without a contingency.
10) Due to the Pre-Conceptual nature of the design and related cost estimate a contingency of 25% is suggested to be included within the total plant cost table to provide a 50-50 probability
11) The cost estimate is for the Reactor Plant Equipment in General Atomics scope of responsibility and Account 1.2 Secondary Heat Rejection System, and 1.4.3 Radwaste and Decontamination System
12) The Fuel Handling System 1.1.6 utilizes a modified Fuel Handling Machine to complete its functions and the functions of the Fuel Transfer Machine which is now not required for the HTTTR Program

Assumptions for the indirect cost for engineering and services assumptions

1) The scope of supply for the Primary System assumes that the Equipment is supplied from various vendors but that a single source willprovide assistance in the procurement, receiving inspection, acceptance testing and verification of performance, of subsystems and components,as well as installation, pretest, startup and operational acceptance testing.

2) The Indirect Costs are provided on the task and system level and involve assistance provided during the procurement, construction, installation, preoperational and start-up testing and acceptance phases of the project.

3) The assistance is based on the scope of supply designated to the responsibility of General Atomics.

4) Assistance will be preformed by both Home Office and Field Office personnel when required.

5) Costs are based on a composite crew rate of $200 per man hour (January 2006 $)

6) The cost estimate is based on the information provided for the Conceptual Design Phase and will be updated as the design progresses.

7) A contingency of 20 % is recommended to be added to the estimate to provide for the state of design maturity.

Cost Estimate Assumptions from Parkhill, Smith & Cooper, Inc.

1) The genesis of all material used in the construction of the project will be documented and cataloged to provide a complete record of the origin, manufacturing, shipping, storage, installation, and certification of all components.
2) Water, natural gas and electrical utilities are available within reasonable distances of the proposed construction site of the project
3) The soil conditions and geotechnical information is assumed to be similar to other locations in the geographical area.
4) Mechanical and ventilation loads for comfort cooling for occupants are based on approximations of the square footages of the buildings as noted in the report.
5) Mechanical cooling and ventilation of the process and laboratory equipment and processes is based on assumptions of the loads and work to be performed.
6) Electrical loads for the buildings and processes are based on the assumed loads in the buildings and the work to be performed.
7) The costs for the standby power systems are based on sizing for continued operation of only the critical safety controls as noted.
8) Climatic conditions are based on those for Andrews County, Texas
9) All costs are based on fiscal year 2006 construction costs.
10) General Conditions incorporates cost incured by the general contractor (GC) for typical construction overhead such as job shack, supervisor salary, port-a-johns, equipment from the GC, office overhead, etc.
11) QA/QC inludes the cost for the contractor to manage the required paperwork for pedigree

COST ESTIMATE SUMMARY

High Temperature Teaching and Test Reactor
University of Texas of the Permian Basin
Pre-Conceptual Design Study

PSC Job Number: 05.9871.06
Pricing Year 2006
Date Prepared 12/12/2006

1.1	**PRIMARY SYSTEM**				
	1.1.1 Reactor System		$ 9,901,800		
	1.1.2 Vessel System		$ 36,710,000		
	1.1.3 Primary Heat Exchanger		$ 11,275,000		
	1.1.4 Primary Helium Circulator		$ 13,525,000		
	1.1.5 Shutdown Cooling System		$ 3,491,000		
	1.1.6 Fuel Handling System		$ 25,433,574		
	1.1.7 Helium Service System		$ 953,000		
	1.1.8 Reactor Cavity Cooling System		$ 1,650,000		
	1.1.9 Reactor Protection System		$ 6,772,282		
	TOTAL PRIMARY SYSTEM				**$ 109,711,656**
1.2	**SECONDARY SYSTEM**				
	1.2 Heat Rejection System		$ 6,590,000		
	TOTAL SECONDARY SYSTEM				**$ 6,590,000**
1.3	**BUILDINGS AND STRUCTURES**				
	1.3.1 Plot Plan		$ 11,974,960		
	1.3.2 Nuclear Island		$ 107,072,550		
	1.3.3 Security Building		$ 14,792,460		
	TOTAL BUILDINGS AND STRUCTURES				**$ 133,839,970**
1.4	**PLANT SYSTEMS**				
	1.4.1 Balance of Plant Control Data and Instrumentation Systems		$ 250,000		
	1.4.2 Plant Electrical System		$ 5,821,400		
	1.4.3 Radwaste and Decontamination System		$ 200,000		
	1.4.4 Plant Service Systems		$ 6,530,000		
	TOTAL PLANT SYSTEMS				**$ 12,801,400**
SUB TOTAL					**$ 262,943,026**
		GC General Conditions		20%	$ 52,588,605
		Bond		1.50%	$ 3,944,145
		GC Profit		8%	$ 21,035,442
		QA/QC		5%	$ 13,147,151
		Engineering Support During Construction			$24,261,466
1.5.6	**CONSTRUCTION SERVICES**				**$ 114,976,810**
1.5.7	**COMMISSIONING FOR NON-NUCLEAR**				**$ 3,956,583**
		CONTENGENCY		20%	**$ 76,375,284**
GRAND TOTAL					**$ 458,251,703**

CONSTRUCTION COST ESTIMATE
DETAIL LEVEL

ACCT	ACCOUNT DESCRIPTION	QUANTITY	UNIT	EQUIPMENT	UNIT LABOR	SHIPPING	TOTAL
1.1.1	REACTOR SYSTEM						
1.1.1.1	REACTOR CORE (w/o Fuel)						
	Reflector Elements	1	lot	$506,900	$ 95,000	$ 45,000	$ 646,900
	Plenum Elements	1	lot	$444,900			$ 444,900
	Neutron Source	1	lot	$89,000			$ 89,000
	Permanent Side reflectors	1	lot	$1,286,100			$ 1,286,100
	Graphite Core Support Structure	1	lot	$432,000			$ 432,000
	SUBTOTAL 1.1.1.1			**$2,758,900**	**$95,000**	**$45,000**	**$2,898,900**
1.1.1.2	CORE SUPPORT STRUCTURES						
	Core Lateral Restraint Assy.(Core Barrel)	1	lot	$ 4,937,800	$ 80,000	$ 25,000	$ 5,042,800
	Metallic Core Support Structure	1	lot	$ 804,100			$ 804,100
	Upper Plenum Thermal Structure	1	lot	$ 339,000			$ 339,000
	Reactor Internals Installation	1	lot	$ 230,000			$ 230,000
	SUBTOTAL 1.1.1.2			**$ 6,310,900**	**$ 80,000**	**$ 25,000**	**$ 6,415,900**
1.1.1.3	NEUTRON CONTROL SYSTEMS						
	Neutron Control Assembly (Inner)	1	lot	$ 330,000	$ 30,000	$ 5,000	$ 365,000
	In-Core Flux Mapping Assembly	1	lot	$ 32,000			$ 32,000
	Ex-Vessel Detector Assembly	1	lot	$ 85,000			$ 85,000
	Start-up Detector Assembly	1	lot	$ 70,000			$ 70,000
	Rod Control Cabinet	1	lot	$ 17,000			$ 17,000
	Reactor Power Trip Control Cabinet	1	lot	$ 18,000			$ 18,000
	SUBTOTAL 1.1.1.3			**$ 552,000**	**$ 30,000**	**$ 5,000**	**$ 587,000**
	Reactor System Total 1.1.1			**$ 9,621,800**	**$ 205,000**	**$ 75,000**	**$ 9,901,800**
1.1.2	VESSEL SYSTEM						
1.1.2.1	REACTOR VESSEL						
	Vessel Top Head	1	lot	$ 2,850,000	$ 210,000	$ 150,000	$ 3,210,000
	Refueling Access Nozzles	1	lot	$ 400,000			$ 400,000
	Expmt Penetrations (Rabbit Transfer Tube)	1	lot	$ 130,000			$ 130,000

	Penetration Shield Plug	1	lot	$ 115,000			$ 115,000
	Control Rod Drive Nozzles	1	lot	$ 2,625,000			$ 2,625,000
	Vessel Body	1	lot	$ 6,650,000			$ 6,650,000
	Cross Duct Nozzle	1	lot	$ 380,000			$ 380,000
	Horizontal Beam Port Nozzle	1	lot	$ 110,000			$ 110,000
	Bottom Head	1	lot	$ 2,590,000			$ 2,590,000
	Lower Nozzle (Shutdown Cooling Circulator)	1	lot	$ 145,000			$ 145,000
	Vessel Internals Support Flanges	1	lot	$ 95,000			$ 95,000
	Reactor Seal Service Equipment	1	lot	$ 230,000			$ 230,000
	Barge Transport of Major Equipment to Site	1	lot	$ 700,000			$ 700,000
	Overland Transport of Major Equip. to Site	1	lot	$ 350,000			$ 350,000
	SUBTOTAL 1.1.2.1			**$ 17,370,000**	**$ 210,000**	**$ 150,000**	**$ 17,730,000**
1.1.2.2	HEAT EXCHANGER VESSEL						
	Vessel Top Head	1	lot	$ 3,350,000	$ 200,000	$ 150,000	$ 3,700,000
	Pressure relief	1	lot	$ 1,330,000			$ 1,330,000
	Main Helium Circulator Nozzle	1	lot	$ 145,000			$ 145,000
	Vessel Body	1	lot	$ 6,650,000			$ 6,650,000
	Cross Duct Nozzle	1	lot	$ 380,000			$ 380,000
	Mid Vessel Nozzle (Process Heat Input)	1	lot	$ 70,000			$ 70,000
	Bottom Head	1	lot	$ 2,840,000			$ 2,840,000
	Lower Nozzle (Process Heat Return)	1	lot	$ 70,000			$ 70,000
	Vessel Internals Support Flanges	1	lot	$ 120,000			$ 120,000
	Barge Transport of Major Equipment to Site	1	lot	$ 700,000			$ 700,000
	Overland Transport of Major Equip. to Site	1	lot	$ 350,000			$ 350,000
	SUBTOTAL 1.1.2.2			**$ 16,005,000**	**$ 200,000**	**$ 150,000**	**$ 16,355,000**
1.1.2.3	CROSS VESSEL						
	Cross Vessel Wall	1	lot	$ 720,000	$ 160,000	$ 45,000	$ 925,000
	Hot Duct Insulation	1	lot	$ 60,000			$ 60,000
	Cold Duct	1	lot	$ 320,000			$ 320,000
	Cold Duct Insulation	1	lot	$ 70,000			$ 70,000
	SUBTOTAL 1.1.2.3			**$ 1,170,000**	**$ 160,000**	**$ 45,000**	**$ 1,375,000**
1.1.2.4	VESSEL SUPPORT SYSTEM						
	Reactor vessel supports	1	lot	$ 320,000	$ 80,000	$ 40,000	$ 440,000
	Reactor vessel and supports install	1	lot	$ 30,000			$ 30,000
	Heat Exchanger vessel supports	1	lot	$ 720,000			$ 720,000
	Heat Exchanger vessel and supports install	1	lot	$ 60,000			$ 60,000
	SUBTOTAL 1.1.2.4			**$ 1,130,000**	**$ 80,000**	**$ 40,000**	**$ 1,250,000**

	Vessel System Total 1.1.2			**$ 35,675,000**	**$ 650,000**	**$ 385,000**	**$ 36,710,000**
1.1.3	PRIMARY HEAT EXCHANGER						
	Primary Heat Exchanger	1	lot	$ 9,000,000	$ 100,000	$ 75,000	$ 9,175,000
	Primary Heat Exchanger supports	1	lot	$ 500,000			$ 500,000
	Primary Heat Exchanger Internals	1	lot	$ 1,600,000			$ 1,600,000
	SUBTOTAL 1.1.3			**$ 11,100,000**	**$ 100,000**	**$ 75,000**	**$ 11,275,000**
1.1.4	PRIMARY HELIUM CIRULATOR						
	Primary Helium Circulator	1	lot	$ 9,000,000	$ 75,000	$ 50,000	$ 9,125,000
	Main Loop Shut Off Valve	1	lot	$ 1,800,000			$ 1,800,000
	Startup and shutdown system	1	lot	$ 1,700,000			$ 1,700,000
	BOP control and instrumentation system	1	lot	$ 700,000			$ 700,000
	Heat Exchanger system components install	1	lot	$ 200,000			$ 200,000
	SUBTOTAL 1.1.4			**$ 13,400,000**	**$ 75,000**	**$ 50,000**	**$ 13,525,000**
1.1.5	SHUTDOWN COOLING SYSTEM						
1.1.5.1	SHUTDOWN HEAT EXCHANGER						
	Shutdown Heat Exchanger	1	lot	$ 705,000	$ 40,000	$ 35,000	$ 780,000
	Shutdown Heat Exchanger Maint. & ISI Equip.	1	lot	$ 226,000			$ 226,000
	SUBTOTAL 1.1.5.1			**$ 931,000**	**$ 40,000**	**$ 35,000**	**$ 1,006,000**
1.1.5.2	SHUTDOWN CIRCULATOR						
	Shutdown Circulator Machine Assembly	1	lot	$ 900,000	$ 40,000	$ 30,000	$ 970,000
	Shutdown Circulator Ducting & Shutoff valve	1	lot	$ 132,000			$ 132,000
	Shutdown Circulator Service Module	1	lot	$ 69,000			$ 69,000
	Shutdown Circulator Service Equipment	1	lot	$ 104,000			$ 104,000
	Shutdown Circulator Storage Wells	1	lot	$ 58,000			$ 58,000
	Shutdown Cooling Sys Control Cabinet	1	lot	$ 20,000			$ 20,000
	SCS Circ Power Supply Motor Contactor	1	lot	$ 54,000			$ 54,000
	SCS Power Supply Isolation Transformer	1	lot	$ 75,000			$ 75,000
	SCS Power Supply Commutated Inverter	1	lot	$ 70,000			$ 70,000
	Control Boards and Consoles	1	lot	$ 10,000			$ 10,000
	Instrument Enclosures and Racks	1	lot	$ 12,000			$ 12,000
	Instrumentation/Hardware/Software	1	lot	$ 11,000			$ 11,000
	SUBTOTAL 1.1.5.2			**$ 1,515,000**	**$ 40,000**	**$ 30,000**	**$ 1,585,000**

1.1.5.3	SHUTDOWN COOLING WATER SYSTEM						
	Shutdown Cool Water Pump	1	lot	$ 105,000	$ 20,000	$ 15,000	$ 140,000
	Shutdown Cool Water Jockey Pump	1	lot	$ 42,000			$ 42,000
	Shutdown Cooling Water Chemistry Package	1	lot	$ 62,000			$ 62,000
	Shutdown Cool Water Chemical Feeder Tank	1	lot	$ 42,000			$ 42,000
	Shutdown Cooling Water Surge Tank	1	lot	$ 62,000			$ 62,000
	Shutdown Cooling Water Make-up Pump	1	lot	$ 42,000			$ 42,000
	Shutdown Cool Water Ext Heat Exchanger	1	lot	$ 172,000			$ 172,000
	Shutdown Cool Water Nitrogen Storage Tank	1	lot	$ 42,000			$ 42,000
	Shutdown Cooling Water Gas Supply System	1	lot	$ 82,000			$ 82,000
	Shutdown Cool Water System Piping & Valves	1	lot	$ 122,000			$ 122,000
	S.C. W.S. Instrumentation/Hardware/Software	1	lot	$ 92,000			$ 92,000
	SUBTOTAL 1.1.5.3			**$ 865,000**	**$ 20,000**	**$ 15,000**	**$ 900,000**
	Shutdown Cooling System Total 1.1.5			$ 3,311,000	$ 100,000	$ 80,000	$ 3,491,000
1.1.6	FUEL HANDLING SYSTEM						
1.1.6.1	FRESH FUEL HANDLING AND STORAGE SYSTEM						
	Fuel Isolation Valve	1	lot	$ 1,259,775	$ 45,000	$ 30,000	$ 1,334,775
	New Fuel Storage Racks(FSIF)	1	lot	$ 375,136			$ 375,136
	New Fuel Handling Equipment	1	lot	$ 672,291			$ 672,291
	Temporary Fuel Container Storage Racks	1	lot	$ 338,696			$ 338,696
	Reactor Module Fuel Storage Pool	1	lot	$ 2,274,315			$ 2,274,315
	Control Module	1	lot	$ 295,112			$ 295,112
	SUBTOTAL 1.1.6.1			**$ 5,215,325**	**$ 45,000**	**$ 30,000**	**$ 5,290,325**
1.1.6.2	REFUELING SYSTEM						
1.1.6.2.1	REFUELING SYSTEM						
	Refueling Machine	1	lot	$ 10,234,749	$ 55,000	$ 5,000	$ 10,294,749
	Fuel Handling Support Structure	1	lot	$ 387,409			$ 387,409
	Fuel Handling Positioner	1	lot	$ 1,883,292			$ 1,883,292
	Refueling Accessories	1	lot	$ 324,913			$ 324,913
	Fuel Handling Control Station	1	lot	$ 2,799,134			$ 2,799,134
	Remote Manipulator (Hot Cell)	1	lot	$ 1,300,000			$ 1,300,000
	Instrumentation/Hardware/Software	1	lot	$ 533,779			$ 533,779
	SUBTOTAL 1.1.6.1			**$ 17,463,276**	**$ 55,000**	**$ 5,000**	**$ 17,523,276**

1.1.6.2.2	REFUELING HANDLING EQUIPMENT						
	Reflector Packaging Equipment	1	lot	$ 266,421	$ 60,000	$ 30,000	$ 356,421
	Shipping Port Closure	1	lot	$ 135,963			$ 135,963
	Container Sealing Equipment	1	lot	$ 382,384			$ 382,384
	Shipping Cask Transporter Assembly	1	lot	$ 628,805			$ 628,805
	Floor Valve	1	lot	$ 121,648			$ 121,648
	Fuel Sealing and Inspection Facility(FSIF)	1	lot				$ -
	Hoist and Grapple assembly(FSIF)	1	lot	$ 135,963			$ 135,963
	Shipping Cask Closure Service Equipmen	1	lot	$ 164,954			$ 164,954
	Reflector Storage Racks(FSIF)	1	lot	$ 336,146			$ 336,146
	Container Storage Racks(FSIF)	1	lot	$ 357,689			$ 357,689
	SUBTOTAL 1.1.6.2			**$ 2,529,973**	**$ 60,000**	**$ 30,000**	**$ 2,619,973**
	Fuel Handling System Total 1.1.6			**$ 25,208,574**	**$ 160,000**	**$ 65,000**	**$ 25,433,574**
1.1.7	HELIUM SERVICES SYSTEM						
1.1.7.1	HELIUM PURIFICATION SYSTEM						
	High Temperature Filter/Adsorber Module	1	lot	$ 36,000	$ 8,000	$ 5,000	$ 49,000
	Oxidizer-Cooler Module	1	lot	$ 53,000			$ 53,000
	Dryer Module	1	lot	$ 33,000			$ 33,000
	Low Temperature Adsorber Module	1	lot	$ 63,000			$ 63,000
	Regeneration Oxidizer Module	1	lot	$ 42,000			$ 42,000
	Regeneration Module	1	lot	$ 44,000			$ 44,000
	Purified Helium Compressor Module	1	lot	$ 69,000			$ 69,000
	High Temperature Filter Module	1	lot	$ 67,000			$ 67,000
	Helium Purification System Control Cabinet	1	lot	$ 31,000			$ 31,000
	Instrumentation Enclosures and Racks	1	lot	$ 23,000			$ 23,000
	Instrumentation/Hardware/Software	1	lot	$ 18,000			$ 18,000
	SUBTOTAL 1.1.7.1			**$ 479,000**	**$ 8,000**	**$ 5,000**	**$ 492,000**
1.1.7.2	HELIUM TRANSFER AND STORAGE SYSTEM						
	Electric Motor Driven Compressors	1	lot	$ 82,000	$ 8,000	$ 6,000	$ 96,000
	Low Pressure Storage Tanks	1	lot	$ 23,000			$ 23,000
	High Pressure Storage Tanks	1	lot	$ 36,000			$ 36,000
	Pipe, Hangers and Supports	1	lot	$ 13,000			$ 13,000
	Instrumentation and Controls	1	lot	$ 6,000			$ 6,000
	SUBTOTAL 1.1.7.2			**$ 160,000**	**$ 8,000**	**$ 6,000**	**$ 174,000**
1.1.7.3	LIQUID NITROGEN SYSTEM						
	Nitrogen Recon denser Unit	1	lot	$ 120,000	$ 7,000	$ 4,000	$ 131,000
	Pipe, Hangers and Supports	1	lot	$ 150,000			$ 150,000

	Instrumentation and Controls	1	lot	$ 6,000			$ 6,000
	SUBTOTAL 1.1.7.3			**$ 276,000**	**$ 7,000**	**$ 4,000**	**$ 287,000**
	Helium Service System Total 1.1.7			**$ 915,000**	**$ 23,000**	**$ 15,000**	**$ 953,000**
1.1.8	REACTOR CAVITY COOLING SYSTEM						
	Inlet Structure	1	lot	$ 315,000	$ 120,000	$ 40,000	$ 475,000
	Outlet Structure	1	lot	$ 275,000			$ 275,000
	Cavity Cooling Panels	1	lot	$ 290,000			$ 290,000
	Hot and Cold Ducts	1	lot	$ 475,000			$ 475,000
	Thermal Insulation	1	lot	$ 135,000			$ 135,000
	SUBTOTAL 1.1.8			**$ 1,490,000**	**$ 120,000**	**$ 40,000**	**$ 1,650,000**
1.1.9	REACTOR PROTECTION SYSTEM						
1.1.9.1	PRIMARY SYSTEM PROTECTION						
	Reactor Protection Cabinet	1	LOT	$ 127,776	$ 20,000	$ 2,000	$ 149,776
	Reactor Protect Remote Instrument Module	1	LOT	$ 737,847			$ 737,847
	Instrumentation/Hardware/Software	1	LOT	$ 197,150			$ 197,150
	SUBTOTAL 1.1.9.1			**$ 1,062,773**	**$ 20,000**	**$ 2,000**	**$ 1,084,773**
1.1.9.2	INVESTMENT PROTECTION SYSTEM						
	Investment Protection Module	1	LOT	$ 439,280	$ 25,000	$ 2,000	$ 466,280
	Investment Protection Satellite Module	1	LOT	$ 226,223			$ 226,223
	Hygrometer Module Assembly	1	LOT	$ 152,552			$ 152,552
	Compressor Module	1	LOT	$ 45,486			$ 45,486
	Accumulator Tank	1	LOT	$ 32,696			$ 32,696
	Non Module Equipment	1	LOT	$ 41,022			$ 41,022
	Special Nuclear Area Instrumentation	1	LOT	$ 111,856			$ 111,856
	Special Nuclear Area Module	1	LOT	$ 76,624			$ 76,624
	Instrumentation/Hardware/Software	1	LOT	$ 65,802			$ 65,802
	SUBTOTAL 1.1.9.2			**$ 1,191,541**	**$ 25,000**	**$ 2,000**	**$ 1,218,541**
1.1.9.3	PLANT CONTROL SYSTEM						
	Plant Radiation Monitors	1	LOT	$ 666,400	$ 15,000	$ 3,000	$ 684,400
	Plant Meteorological Monitoring Equipment	1	LOT	$ 512,300			$ 512,300
	Plant Seismic Monitoring Equipment	1	LOT	$ 396,725			$ 396,725
	Plant Analytical Instrumentation	1	LOT	$ 153,509			$ 153,509
	SUBTOTAL 1.1.9.3			**$ 1,728,934**	**$ 15,000**	**$ 3,000**	**$ 1,746,934**

1.1.9.4	PRIMARY SYSTEM ANALYTICAL INSTR.						
	Instr. Depressurization Rack	1	LOT	$ 279,926	$ 15,000	$ 4,000	$ 298,926
	Instr. & Control Cabinet	1	LOT	$ 366,149			$ 366,149
	Tritium Monitor	1	LOT	$ 589,594			$ 589,594
	Control Analyzer	1	LOT	$ 459,260			$ 459,260
	Gas Chromatograph	1	LOT	$ 386,986			$ 386,986
	Radiation Monitors	1	LOT	$ 308,687			$ 308,687
	Moisture Monitors	1	LOT	$ 212,446			$ 212,446
	Instrumentation I & C Cabinet	1	LOT	$ 99,986			$ 99,986
	SUBTOTAL 1.1.9.4			**$ 2,703,034**	**$ 15,000**	**$ 4,000**	**$ 2,722,034**
	Reactor Protection System Total 1.1.9			**$ 6,686,282**	**$ 75,000**	**$ 11,000**	**$ 6,772,282**
1.2.1	SECONDARY SYSTEM HEAT EXCHANGER						
1.2.1	Secondary Sys HX	1	lot	$ 2,200,000	$ 140,000	$ 50,000	$ 2,390,000
1.2.2	Secondary Sys Circulator	1	lot	$ 3,000,000			$ 3,000,000
1.2.3	System Piping	1	lot	$ 1,200,000			$ 1,200,000
	SUBTOTAL 1.2.1			**$ 6,400,000**	**$ 140,000**	**$ 50,000**	**$ 6,590,000**
1.3.1	PLOT PLAN						
	Site and Road Lighting	75	EA		$ 4,000	$ 2,000	$ 450,000
	Perimeter Site Fence	26,400	LF		$ 25	$ 25	$ 1,320,000
	Nuclear Island Security Fence	5,280	LF		$ 25	$ 75	$ 528,000
	Gas Distribution	1	LS		$ 250,000	$ 500,000	$ 750,000
	Passive Security Measures	1	ls		$ 1,500	$ 3,000	$ 4,500
	Roads and Paving	1	LS		$ 1,500,000	$ 1,500,000	$ 3,000,000
	Water and Sanitary Systems	1	LS		$ 2,600,000	$ 1,500,000	$ 4,100,000
	Fire Pump	4	EA		$ 75,000	$ 150,000	$ 900,000
	Retention Pond	1	LS		$ 250,000	$ 250,000	$ 500,000
	Miscellaneous	1	LOT	$ 17,710	$ 404,750		$ 422,460
	SUBTOTAL 1.3.1			**$ 17,710**	**$ 5,085,300**	**$ 3,905,100**	**$ 11,974,960**
ACCT	ACCOUNT DESCRIPTION	QUANTITY	UNIT	EQUIPMENT	UNIT LABOR	UNIT MATERIAL	TOTAL
1.3.2	NUCLEAR ISLAND						
1.3.2.1	REACTOR CONTAINMENT BUILDING						
	Excavation and backfill including blasting	14,000	C.Y.			$ 172	$ 2,408,000
	Slab-concrete incl. Reinforcing and forms	2,400	C.Y.			$ 600	$ 1,440,000
	Walls and roof-concrete	7,500	C.Y.			$ 2,000	$ 15,000,000
	Specialty Building Components	9,000	SF			$ 500	$ 4,500,000

	lifting and handling equipment		LOT	$ 2,500,000			$ 2,500,000
	Crane girders and rails		LOT	$ 1,500,000			$ 1,500,000
	Miscellaneous		LOT	$ 345,640	$ 360	$ 994,780	$ 1,340,780
	SUBTOTAL 1.3.2.1			**$ 4,345,640**	**$ 360**	**$ 998,052**	**$ 28,688,780**
1.3.2.2	REACTOR SERVICE BUILDING	160 ft by 160 ft by 75 ft high					
	Excavation and backfill including blasting	13,000	C.Y.			$ 172	$ 2,236,000
	Slab-concrete incl. Reinforcing and forms	1,500	C.Y.			$ 600	$ 900,000
	Walls and roof-concrete	2,000	C.Y.			$ 2,000	$ 4,000,000
	Specialty Building Components	17,000	SF			$ 500	$ 8,500,000
	Electrical (Lig, Pow, Com) - Refueling Building	15,550	SF		$ 10	$ 20	$ 466,500
	Ventilation Stack	1	LS		$ 125,000	$ 125,000	$ 250,000
	HVAC & Plumbing	15,550	SF		$ 20	$ 30	$ 777,500
	Electrical (Lig, Pow, Com) - Hot shop	2,000	SF		$ 20	$ 30	$ 100,000
	HVAC & Plumbing - Hot Shop	2,000	SF		$ 20	$ 30	$ 100,000
	Miscellaneous	1	LOT	$ 2,680	$ 2,080	$ 8,300	$ 13,060
	SUBTOTAL 1.3.2.2			**$ 2,680**	**$ 127,150**	**$ 136,682**	**$ 17,343,060**
1.3.2.4	OTHER STRUCTURES						
	Excavation and backfill	4,000	C.Y.			$ 75	$ 300,000
	Slab-concrete incl. Reinforcing and forms	1,300	C.Y.			$ 600	$ 780,000
	Walls and roof-concrete	1,100	C.Y.			$ 2,000	$ 2,200,000
	Specialty Building Components	13,000	SF			$ 200	$ 2,600,000
	Site Communication Service	52,800	LF		$ 5	$ 5	$ 528,000
	Lightning Protection System	80,000	SF		$ 2	$ 3	$ 400,000
	SUBTOTAL 1.3.2.4			**$ -**	**$ 7**	**$ 2,883**	**$ 6,808,000**
1.3.2.5	RADIATION LABORATORY BUILDING						
	Excavation and backfill including blasting	25,000	C.Y.			$ 172	$ 4,300,000
	Slab-concrete incl. Reinforcing and forms	1,700	C.Y.			$ 600	$ 1,020,000
	Walls and roof-concrete	2,800	C.Y.			$ 2,000	$ 5,600,000
	Specialty Building Components	20,000	SF			$ 500	$ 10,000,000
	Electrical (Lig, Prow, Com) - Radiation Lab	17,220	SF		$ 10	$ 20	$ 516,600
	HVAC & Plumbing - Radiation Lab	17,220	SF		$ 20	$ 30	$ 861,000
	Miscellaneous		LOT	$ 17,710	$ 404,750		$ 422,460
	SUBTOTAL 1.3.2.5			**$ 17,710**	**$ 404,780**	**$ 3,322**	**$ 22,720,060**
1.3.2.6	OTHER LABORATORIES						
	Excavation and backfill including blasting	18,000	C.Y.			$ 172	$ 3,096,000
	Slab-concrete incl. Reinforcing and forms	1,400	C.Y.			$ 600	$ 840,000
	Walls and roof-concrete	5,000	C.Y.			$ 2,000	$ 10,000,000
	Specialty Building Components	10,000	SF			$ 500	$ 5,000,000
	HVAC & Plumbing - ET Lab	5,000	SF		$ 30	$ 40	$ 350,000
	HVAC & Plumbing - HTMP Lab	5,000	SF		$ 30	$ 40	$ 350,000
	Electrical (Lig, Pow, Com) - ET Lab	5,000	SF		$ 10	$ 20	$ 150,000

	Electrical (Lig, Pow, Com) - HTMP Lab	5,000	SF		$ 10	$ 20	$ 150,000
	Miscellaneous		LOT	$ 17,710	$ 404,750		$ 422,460
	SUBTOTAL 1.3.2.6			**$ 17,710**	**$ 404,830**	**$ 3,392**	**$ 20,358,460**
1.3.2.7	OFFICE AND LABORATORY BUILDING						
	Excavation and backfill	2,500	C.Y.			$ 75	$ 187,500
	Slab-concrete incl. Reinforcing and forms	4,500	C.Y.			$ 600	$ 2,700,000
	Walls and roof-concrete	900	C.Y.			$ 2,000	$ 1,800,000
	Specialty Building Components	25,000	SF			$ 200	$ 5,000,000
	Signage	1	LOT			$ 10,000	$ 10,000
	Miscellaneous	1	LOT	$ 7,480	$ 72,210		$ 79,690
	SUBTOTAL 1.3.2.7			**$ 7,480**	**$ 72,210**	**$ 12,875**	**$ 9,777,190**
1.3.2.7.1	OFFICE AND LAB SPACE						
	Electrical (Lig, Pow, Com)	18,500	SF		$ 8	$ 12	$ 370,000
	HVAC & Plumbing	18,500	SF		$ 30	$ 20	$ 925,000
	SUBTOTAL 1.3.2.7.1			**$ -**	**$ 38**	**$ 32**	**$ 1,295,000**
1.3.2.7.2	CONTROL ROOM						
	Electrical (Lig, Pow, Com)	1,000	SF		$ 8	$ 12	$ 20,000
	HVAC & Plumbing	1,000	SF		$ 20	$ 30	$ 50,000
	SUBTOTAL 1.3.2.7.2			**$ -**	**$ 28**	**$ 42**	**$ 70,000**
1.3.2.7.3	VIEWING ROOM						
	Electrical (Lig, Pow, Com)	300	SF		$ 8	$ 12	$ 6,000
	HVAC & Plumbing	300	SF		$ 8	$ 12	$ 6,000
	SUBTOTAL 1.3.2.7.2			**$ -**	**$ 16**	**$ 24**	**$ 12,000**
	Nuclear Island Total 1.3.2.			**$ 4,391,220**	**$ 1,009,419**	**$ 1,157,304**	**$ 107,072,550**
1.3.3	SECURITY BUILDING						
	Excavation and backfill	10,000	C.Y.			$ 75	$ 750,000
	Slab-concrete incl. Reinforcing and forms	2,000	C.Y.			$ 600	$ 1,200,000
	Walls and roof-concrete	4,500	C.Y.			$ 2,000	$ 9,000,000
	Specialty Building Components	8,400	SF			$ 150	$ 1,260,000
	Electrical (Lig, Pow, Com) - Security Building	2,500	SF		$ 8	$ 12	$ 50,000
	HVAC & Plumbing	2,500	SF		$ 20	$ 30	$ 125,000
	Electrical (Lig, Pow, Com) - Plant Services	8,000	SF		$ 10	$ 20	$ 240,000
	HVAC & Plumbing	8,000	SF		$ 60	$ 80	$ 1,120,000

	Electrical (Lig, Pow, Com) - Security Building	2,500	SF		$ 8	$ 12	$ 50,000
	HVAC & Plumbing - Security Building	2,500	SF		$ 20	$ 30	$ 125,000
	Security Camera System	1	LS		$ 100,000	$ 200,000	$ 300,000
	Electric/Com Utilities - Security Building	1	LS		$ 50,000	$ 100,000	$ 150,000
	Miscellaneous		LOT	$ 17,710	$ 404,750		$ 422,460
	SUBTOTAL 1.3.3			**$ 17,710**	**$ 554,876**	**$ 303,009**	**$ 14,792,460**
1.4.1	BALANCE OF PLANT CONTROL DATA AND INSTRUMENTATION SYSTEMS						
	Balance of Plant Controls (non-nuclear)	1	LOT			$ 250,000	$ 250,000
	SUBTOTAL 1.4.1			**$ -**	**$ -**	**$ 250,000**	**$ 250,000**
1.4.2	PLANT ELECTRICAL SYSTEM						
1.4.2.1	AC ELECTRICAL SYSTEM						
	Primary electrical service to site	52,800	LF		$ 15	$ 15	$ 1,584,000
	Primary Substation with Transformers	1	LS		$ 700,000	$ 1,300,000	$ 2,000,000
	Site Underground Duct-Bank System Power/Com	5,280	LF		$ 40	$ 40	$ 422,400
	Stand-by Power System 500KW with UPS	1	LS		$ 450,000	$ 650,000	$ 1,100,000
	Miscellaneous	1	LS		$ 100,000	$ 100,000	$ 200,000
	SUBTOTAL 1.4.2.1				**$ 1,250,055**	**$ 2,050,055**	**$ 5,306,400**
1.4.2.2	DC ELECTRICAL SYSTEM						
	Inverters	1	ls		$ 75,000	$ 100,000	$ 175,000
	DC Distribution 225KVA	1	LS		$ 100,000	$ 200,000	$ 300,000
	Miscellaneous	1	LS		$ 15,000	$ 25,000	$ 40,000
	SUBTOTAL 1.4.2.2				**$ 190,000**	**$ 325,000**	**$ 515,000**
	Plant Electrical Total 1.4.2				**$ 1,440,055**	**$ 2,375,055**	**$ 5,821,400**
1.4.3	RADWASTE AND DECONTAMINATION SYSTEM						
	Electrical (Lig, Pow, Com) - RAD Waste	2,500	SF		$ 10	$ 20	$ 75,000
	HVAC & Plumbing - Rad Waste	2,500	SF		$ 20	$ 30	$ 125,000
	Liquid Radwaste System	1	lot	$ 45,000	$ 40,000	$ 15,000	
	Solid Radwaste System	1	lot	$ 35,000			
	Gaseous Radwaste System	1	lot	$ 45,000			
	SUBTOTAL 1.4.3			**$ 125,000**	**$ 40,030**	**$ 15,050**	**$ 200,000**
1.4.4	PLANT SERVICES SYSTEM						
1.4.4.1	HVAC SYSTEM NON-OCCUPANT						
	HVAC -	17,220	SF		$ 30	$ 40	$ 1,205,400
	Miscellaneous	1	LS		$ 50,000	$ 50,000	$ 100,000

	SUBTOTAL 1.4.4.1			**$ -**	**$ 50,000**	**$ 50,000**	**$ 1,305,400**
1.4.4.2	AIR SYSTEM NON-OCCUPANT						
	AIR	17,220	SF		$ 40	$ 40	$ 1,377,600
	Unspecified Specialty Air Systems	1	lot			$ 25,000	$ 25,000
	SUBTOTAL 1.4.4.2			**$ -**	**$ -**	**$ 25,000**	**$ 1,402,600**
1.4.4.3	WATER SYSTEM NON-OCCUPANT						
	WATER SYSTEM	17,220	SF		$ 50	$ 50	$ 1,722,000
							$ -
	SUBTOTAL 1.4.4.3			**$ -**	**$ -**	**$ -**	**$ 1,722,000**
1.4.4.4	FIRE PROTECTION SYSTEM						
	Fire Suppression System	80,000	SF		$ 15	$ 10	$ 2,000,000
	Miscellaneous	1	LS		$ 50,000	$ 50,000	$ 100,000
	SUBTOTAL 1.4.4.4			**$ -**	**$ 50,000**	**$ 50,000**	**$ 2,100,000**
	Plant Services Total 1.4.4				**$ 100,000**	**$ 125,000**	**$ 6,530,000**

PRIMARY SYSTEM ENGINEERING SERVICES DURING CONSTRUCTION

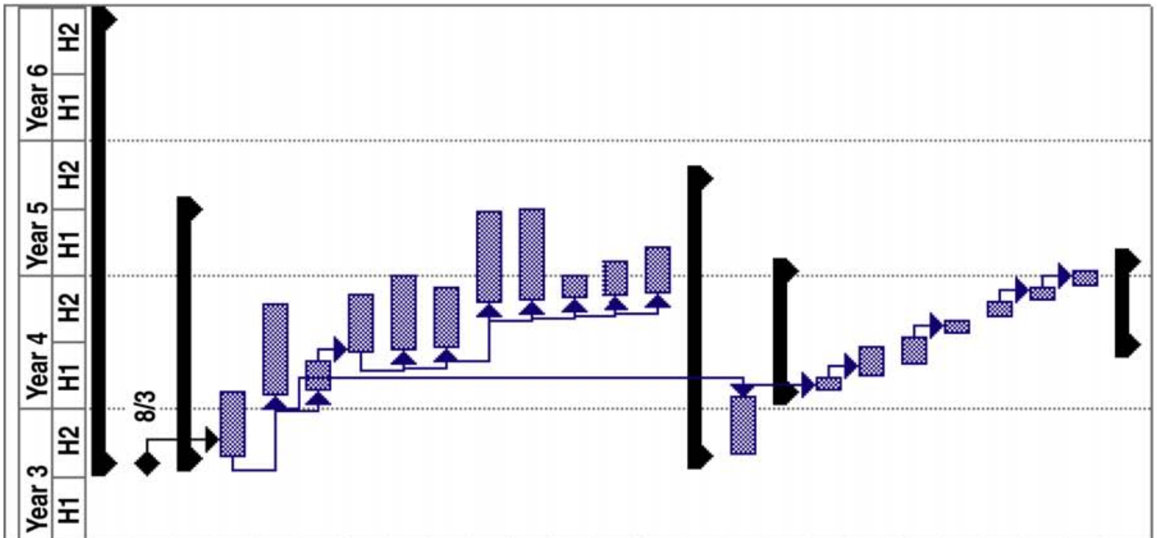
		ManPower	Duration-Weeks	ManWeeks	Cost
1.1	PRIMARY SYSTEM				
1.1.1	REACTOR SYSTEM	3	245	195	$1,560,000
1.1.1.1	Reactor Core	1	95	95	$760,000
1.1.1.2	Core Support Structures	1	50	50	$400,000
1.1.1.3	Neutron Control Systems	1	100	50	$400,000
1.1.1.3.1	Primary Neutron Control System	0.5	50	25	$200,000
1.1.1.3.2	Reserve Shutdown System	0.5	50	25	$200,000
1.1.2	VESSEL SYSTEM	3	380	285	$2,280,000
1.1.2.1	Reactor Vessel	1	95	95	$760,000
1.1.2.2	Heat Exchanger Vessel	1	95	95	$760,000
1.1.2.3	Cross Vessel	0.5	95	47.5	$380,000
1.1.2.4	Vessel Support System	0.5	95	47.5	$380,000
1.1.3	PRIMARY HEAT EXCHANGER	1	95	95	$760,000
1.1.4	PRIMARY HELIUM CIRCULATOR	1	85	85	$680,000
1.1.5	Shutdown Cooling System	3	190	190	$1,520,000
1.1.5.1	Shutdown Heat Exchanger	1	70	70	$560,000
1.1.5.2	Shutdown Circulator	1	60	60	$480,000
1.1.5.3	Shutdown Cooling Water System	1	60	60	$480,000
1.1.6	FUEL HANDLING SYSTEM	3.5	395	275	$2,200,000
1.1.6.1	Fresh Fuel Handling and Storage System	1	75	75	$600,000
1.1.6.2	Refueling System	1	260	170	$1,360,000

1.1.6.2.1	Refueling Machine	1	80	80	$640,000
1.1.6.2.2	Transfer Cask	0.5	80	40	$320,000
1.1.6.2.3	Refueling Handling Equipment	0.5	100	50	$400,000
1.1.6.3	Spent Fuel Storage Sustem	1.5	60	30	$240,000
1.1.6.3.1	Interim Storage Facility	0.5	20	10	$80,000
1.1.6.3.2	Interim Storage Facility Cooling System	0.5	20	10	$80,000
1.1.6.3.3	Long term Storage System	0.5	20	10	$80,000
1.1.7	HELIUM SERVICES SYSTEM	3	100	100	$800,000
1.1.7.1	Helium Purification System	1	40	40	$320,000
1.1.7.2	Helium Transfer and Storage System	1	30	30	$240,000
1.1.7.3	Liquid Nitrogen System	1	30	30	$240,000
1.1.8	REACTOR CAVITY COOLING SYSTEM	1	20	20	$160,000
1.1.9	REACTOR PROTECTION SYSTEM	1	85	85	$680,000
1.2	SECONDARY SYS. (HEAT REJ.SYS.)	2	110	110	$880,000
1.2.1	Secondary Sys HX	1	50	50	$400,000
1.2.2	Secondary Sys Circulator	1	60	60	$480,000
1.1	PRIMARY SYS. ENGR. & SERVICES TOTAL		1,595	1,440	$11,520,000

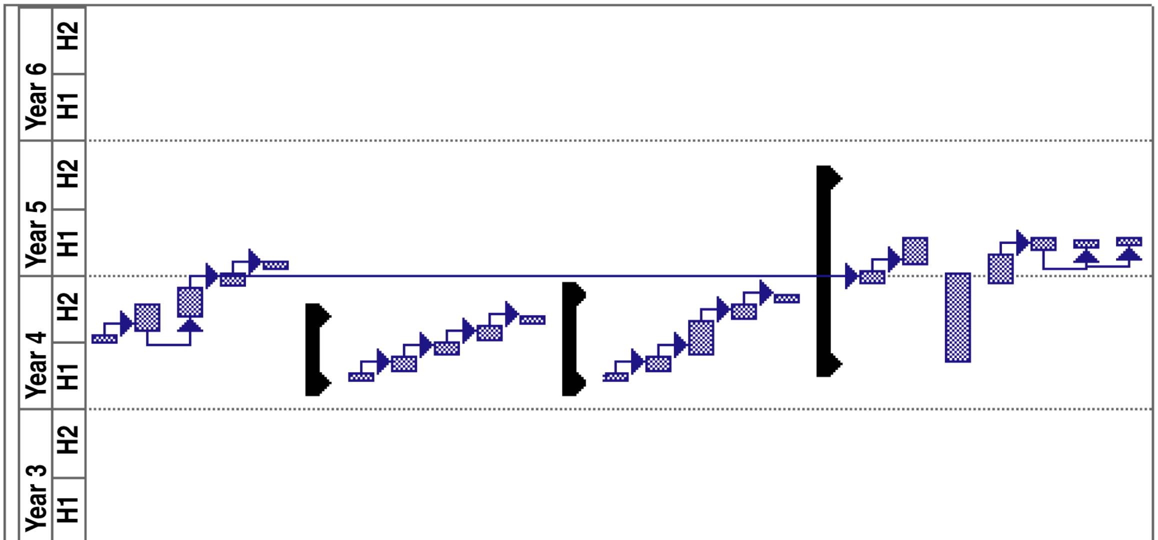
OTHER CONSTRUCTION SUPPORT SERVICES		
Bidding	$	1,592,683
Construction	$	9,556,100
Commissioning	$	1,592,683

APPENDIX C
HT^3R FACILITY ESTIMATED CONSTRUCTION SCHEDULE
DETAIL ESTIMATE LEVEL

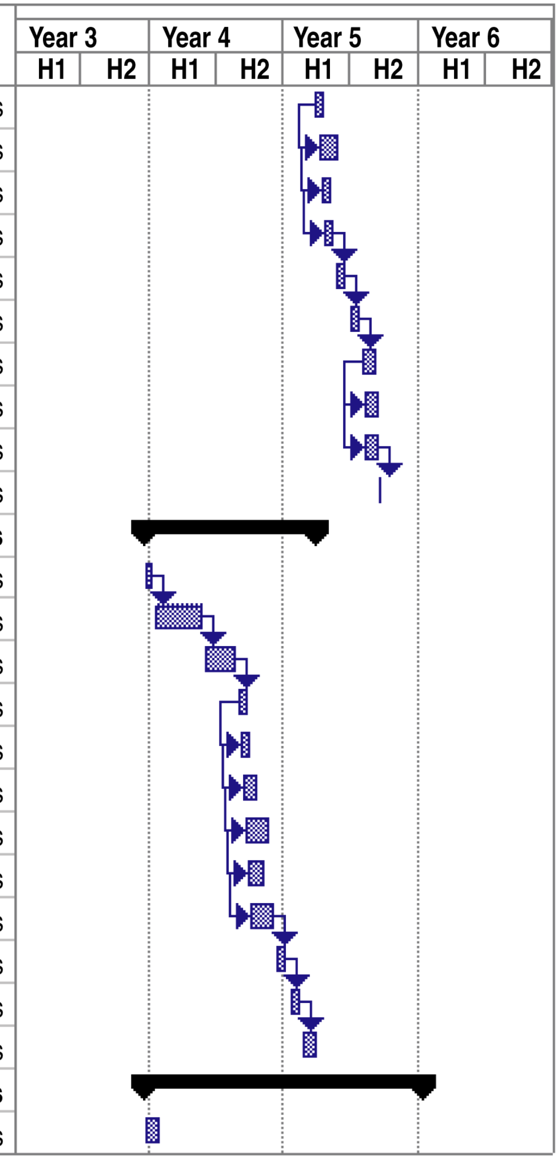
ID	Task Name	Duration
2	**OVERALL CONSTRUCTION SCHEDULE**	**868 days**
3	Start Construction	0 days
4	**SITE WORK (WBS 1.3.1/1.4)**	**488 days**
5	Site Clearing and Demolition	134 days
6	Coordination / Siting of Sub-Station	180 days
7	Extension / Routing of Gas Supply	60 days
8	Develop Water Supply / Storage	120 days
9	Water Treatment Facilities	150 days
10	Water Storage Facilities	120 days
11	Electrical Primary Distribution / Sub	180 days
12	Roadways	180 days
13	Cask Storage / Gas Pads	45 days
14	Perimeter Fencing	70 days
15	Retention Pond	90 days
16	**REACTOR & LAB BUILDINGS (WBS 1.3.2)**	**543 days**
17	Excavation	120 days
18	**REACTOR BUILDING (WBS 1.3.2)**	**236 days**
19	Foundation	30 days
20	Cast-in-place Forms	60 days
21	Cast-in-place Concrete	60 days
22	Set Ractor Vessel	30 days
23	Set HX Vessel	30 days
24	Alignment / Crossduct Installation	30 days
25	Complete Secondary System Piping Connections	30 days
26	**RADIATION LAB (WBS 1.3.2)**	**160 days**



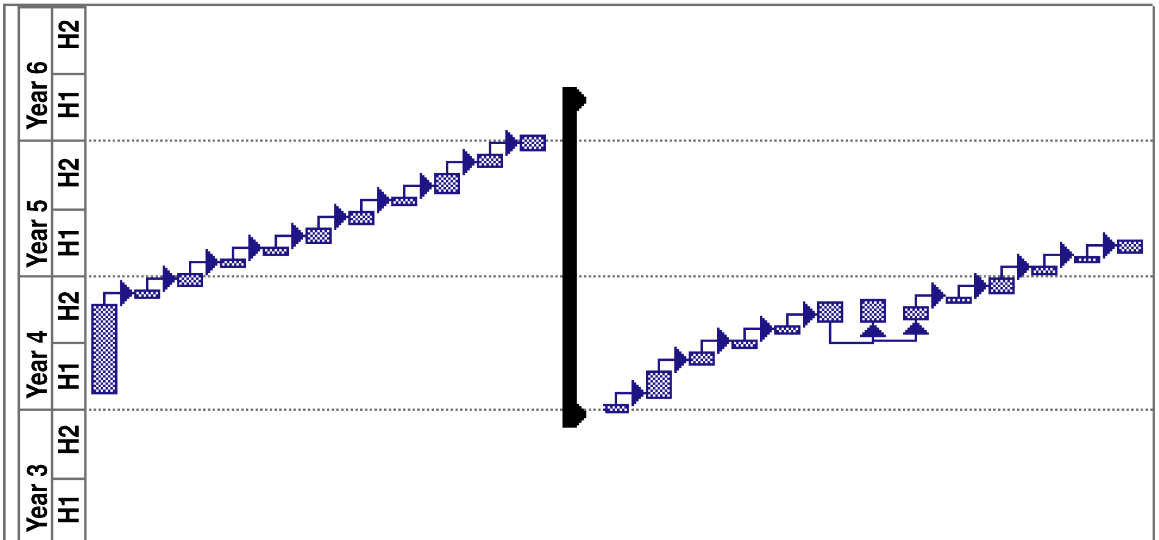
ID	Task Name	Duration
27	Foundation	20 days
28	Cast-In-Place Forms	60 days
29	Cast-In-Place Concrete	60 days
30	Shielding	30 days
31	Loop Piping	20 days
32	**HIGH-TEMP LAB (WBS 1.3.2)**	**130 days**
33	Foundation	20 days
34	Cast-In-Place Forms	30 days
35	Cast-In-Place Concrete	30 days
36	Shielding	30 days
37	Loop Piping	20 days
38	**ENERGY LAB (WBS 1.3.2)**	**172 days**
39	Foundation	20 days
40	Cast-In-Place Forms	30 days
41	Cast-In-Place Concrete	72 days
42	Shielding	30 days
43	Loop Piping	20 days
44	**REACTOR SERVICES BUILDING (WBS 1.3.2)**	**363 days**
45	Foundation	30 days
46	Cast-In-Place Forms	60 days
47	Cast-In-Place Concrete	180 days
48	Form / Pour Bldg Floor & Sub-Floor System	60 days
49	Underfloor Plumbing	30 days
50	Electrical Rough-In	20 days
51	Fire Protection Systems	20 days



ID		Task Name	Duration
52		Interior Framing	20 days
53		Special Structures	42 days
54		HVAC System Rough-In	20 days
55		Lighting and Ductwork	20 days
56		Finishes	20 days
57		Trim Out	20 days
58		Commissioning	30 days
59		Radioactive Gas and Liquid Waste Systems	30 days
60		Helium Services Systems	30 days
61		Receive initial Helium charge at site	3 days
62		**PLANT SERVICES BLDG / WAREHOUSE (WBS 1.3.2)**	**335 days**
63		Foundation Layout	15 days
64		Structure	90 days
65		Cast-In-Place Construction	60 days
66		Underfloor Plumbing	20 days
67		Electrical Rough-In	20 days
68		Interior Framing	30 days
69		Special Structures	45 days
70		Ceilings	30 days
71		HVAC / Lights	45 days
72		Finishes	20 days
73		Trim Out	20 days
74		Commissioning	30 days
75		**OFFICE / ADMINISTRATION BUILDING (WBS 1.3.2)**	**540 days**
76		Foundation Layout	30 days



ID	Task Name	Duration
77	Structure	180 days
78	Cast-In-Place Construction	20 days
79	Underfloor Plumbing	30 days
80	Electrical Rough-In	20 days
81	Interior Framing	20 days
82	Special Structures	30 days
83	Ceilings	30 days
84	HVAC / Lights	20 days
85	Finishes	45 days
86	Trim Out	30 days
87	Commissioning	30 days
88	**SECURITY BUILDING (WBS 1.4.4)**	**609 days**
89	Foundation Layout	20 days
90	Structure	60 days
91	Underfloor Plumbing	30 days
92	Electrical Rough-In	20 days
93	Interior Framing	20 days
94	Central Fire Alarm System	45 days
95	Central Security System	45 days
96	Access Control System	30 days
97	Ceilings	15 days
98	HVAC / Lights	30 days
99	Finishes	20 days
100	Trim Out	10 days
101	Commissioning	30 days



ID	Task Name	Duration
102	Site Hardening Obsacles	90 days
103	Site Grading and Curbs	90 days
104	Hardscapes and Landscaping	75 days
105	**COMMISIONING OF NUCLEAR SYSTEMS (WBS 1.5.7)**	**247 days**
106	Vessel System and Internal Structures	7 days
107	Neutron Control Assemblies-Functional Checks	14 days
108	Nuclear instrumentation and Control Systems	20 days
109	Radiation Monitoring Systems	30 days
110	Reactor Analytical Instrumentation Systems	30 days
111	Primary Helium Circulator and Auxillaries	30 days
112	Secondary Coolant and System Commissioning and Startup	30 days
113	Shutdown Cooling Water System	7 days
114	Shutdown Cooling Circulator and Auxillaries	14 days
115	**FUEL AND REFLECTOR LOADING (WBS 1.5.7)**	**20 days**
116	Reactor Reflector Element Installation	7 days
117	Install Neutron Control Assembilies into Reactor	2 days
118	Load Fuel into Reactor	3 days
119	Close and Pressure Check Vessel System	4 days
120	**PRIMARY COOLANT SYSTEM (WBS 1.5.7)**	**15 days**
121	Evacuate and Backfill Primary System with Helium	3 days
122	Hot Flow Testing-Primary System	10 days
123	Evaluation-RCCS Performance	2 days
124	**REACTOR STARTUP AND RISE TO POWER (WBS 1.5.7)**	**16 days**
125	Initial Reactor Criticality	2 days
126	Step-by-Step Approach to Full Power	14 days