SNS 100000000-BL0005-R00

Spallation Neutron Source Project Completion Report

A U.S. Department of Energy Multilaboratory Project

SPALLATION NEUTRON SOURCE

Argonne National Laboratory • Brookhaven National Laboratory • Thomas Jefferson National Accelerator Facility • Lawrence Berkeley National Laboratory • Los Alamos National Laboratory • Oak Ridge National Laboratory

SNS

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June 2006

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SPALLATION NEUTRON SOURCE
PROJECT COMPLETION REPORT

OAK RIDGE NATIONAL LABORATORY

June 2006

Prepared for the
U.S. Department of Energy
Office of Science

UT-BATTELLE, LLC
managing
Spallation Neutron Source activities at
Argonne National Laboratory
Thomas Jefferson National Accelerator Facility
Los Alamos National Laboratory
Brookhaven National Laboratory
Lawrence Berkeley National Laboratory
Oak Ridge National Laboratory
under contract DE-AC05-00OR22725
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SPALLATION NEUTRON SOURCE COMPLETION REPORT

June 2006

Thomas

Submitted by Thomas E. Mason
ORNL Associate Laboratory Director for the
Spallation Neutron Source

6/16/06

Date

Approved by Lester K. Price
DOE Federal Project Director for the
Spallation Neutron Source

6/16/06

Date

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ACRONYMS

ACL	acceptance criteria listing
AE-CM	architect/engineer-construction manager
ALARA	as low as reasonably achievable
ANL	Argonne National Laboratory
ANS	Advanced Neutron Source
APP	advanced procurement plan
ARR	accelerator readiness review
ASD	Accelerator Systems Division
ASME	American Society of Mechanical Engineers
B&PV	Boiler and Pressure Vessel (Code)
BCM	beam current monitor
BESAC	Basic Energy Sciences Advisory Committee
BLM	beam loss monitor
BNL	Brookhaven National Laboratory
BPM	beam position monitor
CCL	coupled cavity linac
CCR	Central Control Room
CD	critical decision
CDR	conceptual design report
CEC	credited engineering control
CHL	central helium liquefier
CHL	cryogenic helium liquefier
CLO	Central Laboratory and Office Building
CMS	cryogenic moderator system
COW	console on wheels
CRL	Central Research Laboratories
CTF	cryogenic test facility
CUB	Central Utility Building
DI	deionized
DOE	U.S. Department of Energy
DOE-SC	DOE Office of Science
DOE-ORO	DOE Oak Ridge Operations
DTL	drift-tube Linac
DVTM	design validation training module
EA	enterprise architecture
EAC	estimate at completion
EDIA	engineering, design, inspection, and administration
EIS	environmental impact statement
EPICS	Experimental Physics and Industrial Control System
ES&H	environment, safety, and health,
ESH&Q	environment, safety, health, and quality
FES	front-end systems
FHA	Fire Hazards Analysis
FOIST	full integrated system testing
FODO	focus defocus
FSAD	final safety assessment document
HDPE	high-density polyethylene
HEBT	high-energy beam transport
HEPA	high-efficiency particulate air
HOG	hot off-gas

HR	human resources
HUR	hydrogen utility room
HVAC	heating, ventilation, and air-conditioning
HVCM	high-voltage converter modulator
I/O	input/output
ICS	Integrated Control System
IOC	input/output controller
IST	integrated systems test
IPPS	Instrument Personnel Protection System
IRP	inner reflector plug
JLab	Thomas Jefferson National Accelerator Facility
LANL	Los Alamos National Laboratory
LBNL	Lawrence Berkeley National Laboratory
LEBT	low-energy beam transport
linac	linear accelerator
LLLW	low-level liquid waste
MEBT	medium-energy beam transport
MOTS	Mercury Off-Gas Treatment System
MPFL	maximum possible fire loss
MPS	Machine Protection System
NAD	network attached device
NAS	National Academy of Sciences
NFPA	National Fire Protection Association
NPDES	National Pollutant Discharge Elimination System
ODH	oxygen deficient hazard
OEP	operations execution plan
OPI	operator interface
ORNL	Oak Ridge National Laboratory
ORP	outer reflector plug
PBW	proton beam window
PCE	primary confinement exhaust
PCES	primary confinement exhaust system
PEP	project execution plan
PLC	programmable logic controller
PPS	Personnel Protection System
QA	quality assurance
R&D	research and development
RF	radio frequency
RFQ	radio-frequency quadrupole
RIBS	ring injection beam stop
RID	ring injection dump
RSB	Ring Service Building
RTBT	ring-to-tunnel beam transport
RTD	resistance temperature detector
RTDL	real-time data link
SAD	safety assessment document
SANS	small-angle neutron scattering
SBMS	Standards-Based Management System
SCE	secondary confinement exhaust
SCL	superconducting linac
SCR	silicon-controlled rectifier
SNS	Spallation Neutron Source
SRD	system requirements document

SRF	superconducting frequency
SSC	structure, systems, and components
SSI	soil-structure-interaction
TCP/IP	transfer control protocol/internet protocol
TEC	total estimated cost
TOF	time of flight
TPC	total project cost
TPS	Target Protection System
TVA	Tennessee Valley Authority
USI	unreviewed safety issues
VCT	vinyl composition tile
VSD	variable-speed drive
WBS	work breakdown structure
WSS	work smart standards
WWS	window work station
XFD	Experimental Facilities Division

EXECUTIVE SUMMARY

The goal of the Spallation Neutron Source (SNS) project was to design, construct, and commission into operation an accelerator-based, pulsed neutron research facility for studies of the structure and dynamics of materials that is substantially better than any other facility in the world. Key requirements, captured in the Level-0 baseline, were to complete a facility capable of ≥1 MW at a total project cost of $1,411.7M by the end of June 2006. This goal has been not only achieved but exceeded. The SNS construction project was completed in May 2006 at an estimate at completion (EAC) of $1,405.2, meeting all of its performance milestones with a scope that exceeds what was originally envisaged at the time the project was approved.

Established to serve the mission needs of the U.S. Department of Energy (DOE) and the scientific community, the mission need (then Critical Decision 1) for the SNS project was approved in August 1996. In December 1997, Critical Decision 2, establish performance baseline, was approved, and a Project Execution Plan was developed to establish overall project requirements and responsibilities of the participants. The Final Environmental Impact Statement was signed in June 1999. Critical Decision 3, start construction, was approved in November 1999, and formal groundbreaking took place in December 1999.

The following conditions have been met, allowing the project to formally conclude. This completion milestone is Critical Decision 4 (CD-4):

- All facilities and technical hardware are in place, and system test results confirm the design capability of 1.4 MW proton beam power on target operation, exceeding the ≥1 MW requirement.
- Analyses that define the operating safety envelope required to control facility hazards are complete, and authorization for initial operation has been granted.
- Integrated performance tests have demonstrated proton beam delivery to an operating target and the neutron conversion efficiency of the target system.
- An initial complement of five state-of-the-art instruments (three installed and two with all components ordered) has been provided.
- Provision has been made for a future, cost-effective upgrade of SNS to significantly higher power.
- Qualified operating staff and operating procedures consistent with initial operation are in place.

The highest priority for management during a project is safety, and SNS had an outstanding construction safety record. At its height, the construction force for SNS exceeded 600 craft persons on site. During the 2000 to 2006 period, more than 4 million construction hours were worked without a lost workday incident. This record exceeds both government and industry standards and reflects the strong commitment and teamwork of both management and labor to achieve a safe workplace.

One of the most important elements of the SNS project was the unprecedented partnership among six DOE national laboratories. This collaboration was undertaken to bring the best expertise and experience to this challenging, one-of-a-kind endeavor. Argonne, Brookhaven, Lawrence Berkeley, Los Alamos, and Jefferson labs joined Oak Ridge National Laboratory (ORNL) in the design and construction of SNS. In general, the partner labs were responsible for subsystem R&D, design, procurement and delivery. ORNL was responsible for installation, subsystem testing and commissioning. Argonne led the design of the initial suite of scattering instruments, working with a team of collocated ORNL staff. Brookhaven was responsible for the accumulator ring and proton beam transport. Lawrence Berkeley designed and built the front-end systems. Los Alamos was responsible for the physics design and normal-conducting portions of the linear accelerator and all of the linac radio-frequency systems. Jefferson Lab was responsible for the superconducting linac and associated cryogenic systems. ORNL was responsible for target systems, conventional facilities construction, systems integration, and overall project management, including risk and contingency management. ORNL will also operate the SNS as an Office of Science User Facility.

Although the technical aspects of the project were complicated and demanding, all systems were successfully brought together to culminate in a complete, functioning facility. In addition, the conventional facilities were consistently on schedule to support equipment installation and commissioning. Several technical firsts were achieved, most notably the world's first superconducting proton accelerator, which greatly increases the efficiency of the accelerator, and the first liquid mercury target, which circulates 20 tons of mercury. Moreover, establishment of the first five initial instruments will bring novel capabilities to the scientific community and provide the basis for further instrument development, which will continue throughout the operating life of the facility.

In addition to the actual project accomplishments, some important lessons were learned:

- A clear mission need and program support are imperative.
- Safety requires the unrelenting attention and commitment of management and labor.
- Early establishment of effective project leadership is critical to establish the right vision and attract a qualified staff.
- Project leadership must have the authority to make decisions.
- Competent, independent, regular assessment and advice is imperative.
- Appropriate project management tools and processes are necessary but must be applied with judgment to effectively manage project performance.
- Innovative human resources tools are key for successful recruiting and retention of staff.
- Planning for commissioning and operations should take place early.
- Multilaboratory partnerships, with clear responsibilities and centralized budget authority, can be successfully used for new big-scale projects

Looking towards the future, an Operations Execution Plan has been prepared that satisfies the requirement for an SNS operational plan, as well as the strategy for key elements of the Office of Science 20-Year Facilities Plan and the ORNL agenda. The plan also establishes the foundation for SNS operations for the initial planning cycle (CD-4 through FY 2010) and serves as the primary management document for all SNS activities. Additional SNS plans and policies and procedures for science programs; future upgrades; instrument development; risk management; environment, safety, health, and quality; resource management; performance assessment and reporting, etc., are based on this document.

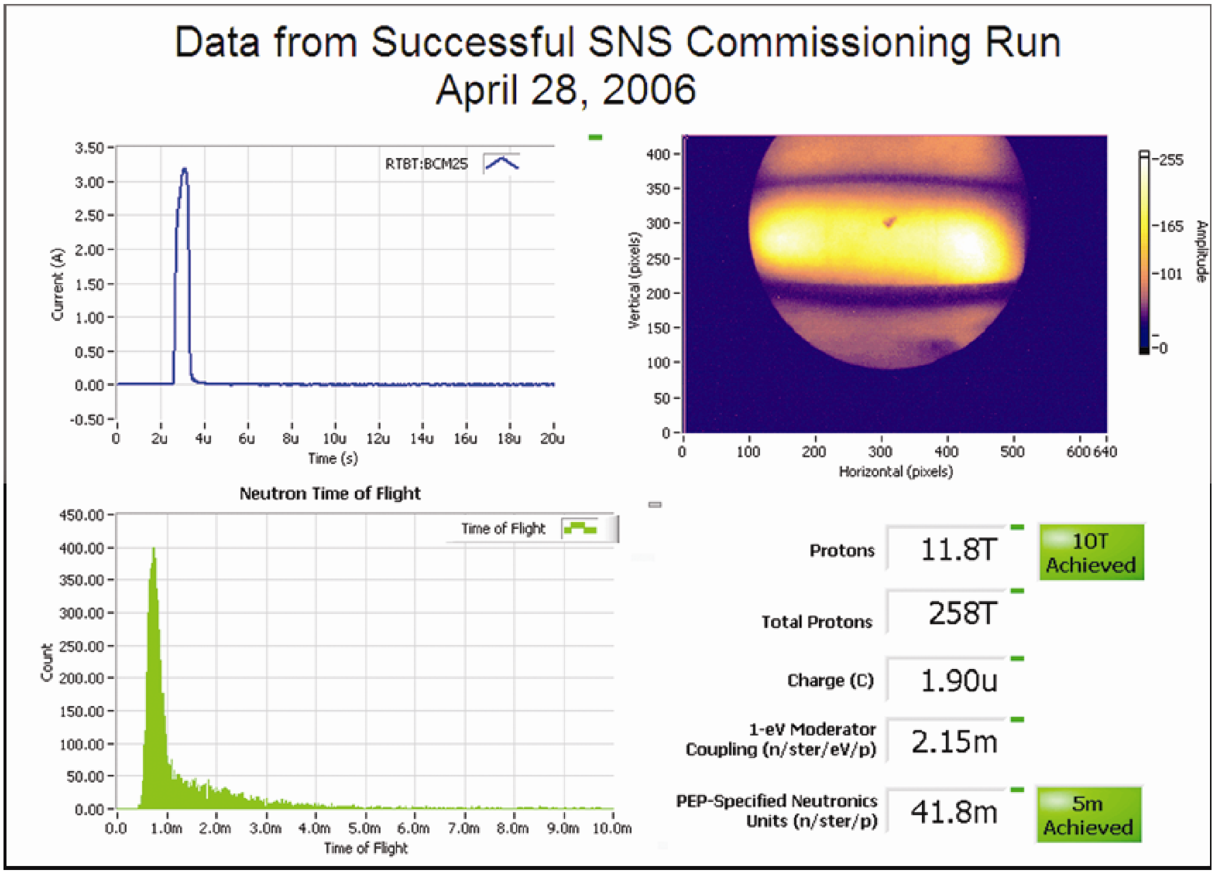
To conclude, the SNS project has been a unique venture into scientific and technological frontiers. The project began with technically challenging requirements and a novel multilaboratory management approach. The accomplishments of the project are due, unquestionably, to the hard-working, diverse, and dedicated staff who have devoted themselves to the success of this project over the last ten years. Completion of the SNS construction project and advancement into operations was a goal shared by everyone, evidenced by the jubilation on April 28, 2006, when SNS delivered its first neutrons. The most definitive documentation of completion of the project is the facility itself. This document is intended to serve as a summary.

SNS will provide unparalleled scientific capabilities for basic research in many different fields. The facility is designed to ensure high reliability and availability for users, and its state-of-the-art instruments and support facilities are designed to maximize the scientific output of the facility. The DOE mission need and the scientific community's need for an accelerator-based, pulsed neutron research facility that is substantially better than any other facility in the world has been met.

1. INTRODUCTION

The goal of the Spallation Neutron Source (SNS) project was to design, construct, and commission into operation an accelerator-based, pulsed neutron research facility for studies of the structure and dynamics of materials that is substantially better than any other facility in the world. Key requirements, captured in the Level-0 baseline, were to complete a facility capable of ≥1 MW at a total project cost of $1,411.7M by the end of June 2006. This goal has been not only achieved but exceeded. The SNS construction project was completed in May 2006 at an estimate at completion (EAC) of $1,405.2M, meeting all of its performance milestones with a scope that exceeds what was originally envisaged at the time the project was approved (see Fig. 1-1).

The purpose of this report is to document project completion presented by the Oak Ridge National Laboratory (ORNL) Associate Lab Director for SNS and acceptance of that completion by the DOE Federal Project Director. Included is information on the project scope and history; technical deliverables, cost performance, and schedule performance; accelerator and target systems; instruments; control systems; conventional facilities; accelerator readiness; environment, safety, and health (ES&H); project management; operations planning; and key lessons learned.



Data from Successful SNS Commissioning Run
April 28, 2006

Protons: 11.8T — 10T Achieved

Total Protons: 258T

Charge (C): 1.90u

1-eV Moderator Coupling (n/ster/eV/p): 2.15m

PEP-Specified Neutronics Units (n/ster/p): 41.8m — 5m Achieved

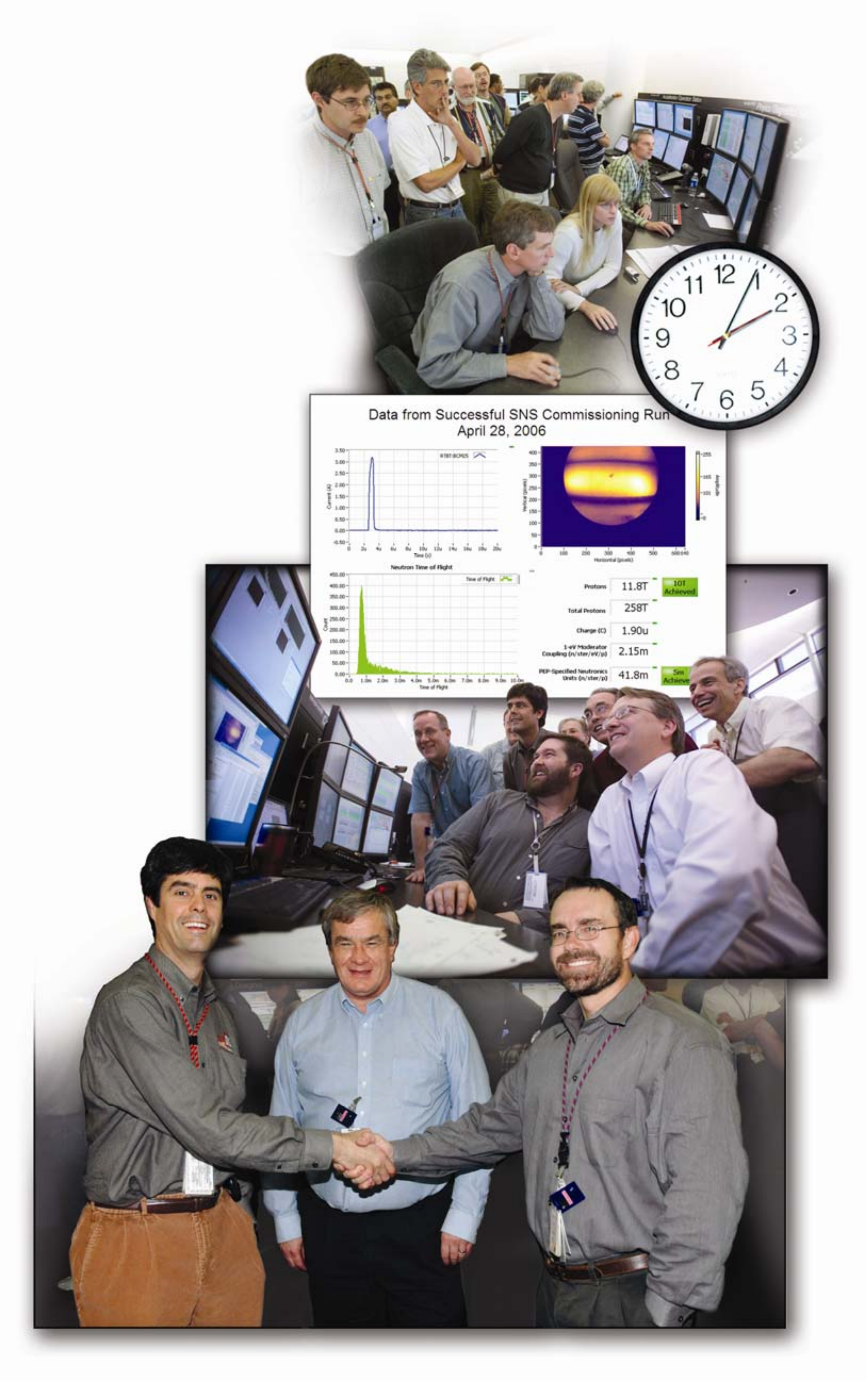
Fig. 1-1. Data from the successful SNS commissioning run on April 28, 2006.

On the afternoon of April 28, 2006, all of the many years of hard work and commitment paid off with the production of the first SNS neutrons. That day was without a doubt the most exciting one in the history of the project.

After a frustrating morning of technical problems, it looked as if the planned generation of neutrons was not going to happen that day. Faces in the Central Control Room (CCR) were anxious and showed signs of disappointment. In the end, however, all difficulties were resolved, and at 2:04 p.m., the accelerated proton beam hit the mark. A phosphor screen attached to the front of the mercury target flashed, showing clearly that the proton beam was on target. Simultaneously, instruments in the Target Building recorded the first burst of neutrons, the target view screen showing the detection of neutrons. Another, somewhat surprising, achievement came 90 minutes after the initial beam on target. The official commissioning goal of a pulse of 10^{13} protons on target was reached, a feat that was expected to take several weeks to achieve.

Some of the photos taken in the CCR that day are shown in Fig. 1-2. Later that afternoon, staff gathered in the lobby of the Central Laboratory and Office Building (CLO) for a celebration of the day's success. Both SNS Project Director Thom Mason and ORNL Laboratory Director Jeff Wadsworth addressed the crowd and praised the dedicated efforts of the many individuals who contributed to the success of the project (Fig. 1-3).

The formal signing of the Critical Decision 4 papers—documenting completion of the project—were signed by Clay Sell, Deputy Secretary of Energy in Washington, D.C., on June 5, 2006. Photos of the event are shown in Figs. 1-4 and 1-5.



Data from Successful SNS Commissioning Run
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Protons 11.8T
Total Protons 258T
Charge (C) 1.90u
1-eV Moderator Coupling (n/ster/eV/p) 2.15m
PEP-Specified Neutronics Units (n/ster/p) 41.8m

Fig. 1-2. SNS staff celebrate beam on target: April 28, 2006.

Fig. 1-3. Celebration in the lobby of the Central Laboratory and Office Building.

Fig. 1-4. Top: Clay Sell, Deputy Secretary of Energy, and Pat Dehmer, Director, Office of Basic Energy Sciences, Office of Science, signing the formal documentation confirming the successful completion of the SNS project.

Fig. 1-5. Dignitaries at the signing of Critical Decision 4—completion of the SNS project. From left to right: Jim Decker, Principal Deputy Director, Office of Science; Dan Lehman, Director, Office of Project Assessment, Office of Science; Les Price, Federal Project Director, Spallation Neutron Source, DOE-ORO; Clay Sell, Deputy Secretary of Energy; Pat Dehmer, Director, Office of Basic Energy Sciences, Office of Science; Jeff Hoy, SNS Program Manager, Office of Basic Energy Sciences, Office of Science; Ray Orbach, Under Secretary for Science, U.S. Department of Energy; George Malosh, Acting Chief Operating Officer, Office of Science.

2. PROJECT PURPOSE AND SCOPE

The SNS facility will provide important scientific capabilities for basic research in many fields, including materials science, life sciences, chemistry, solid state and nuclear physics, earth and environmental sciences, and engineering sciences. A beam of negatively charged hydrogen ions (H^-) is generated and accelerated to an energy of one billion electron volts (1 GeV) using a linear accelerator (linac). The H^- beam is transported to a proton accumulator ring, where it is injected after stripping away of the electrons, leaving the desired protons. In the ring, the protons are bunched into short (under 1 μs) pulses of 60 per second. Finally, the proton beam is directed onto a liquid mercury target, where pulses of neutrons are created through spallation reactions of the protons with the mercury nuclei. Inside the Target Building, the emerging neutrons are slowed, or moderated, and channeled through beam lines to experimental stations. These stations contain state-of-the-art instruments designed to maximize the scientific output of the facility. SNS is designed to ensure high reliability and availability for the user programs and includes the necessary support facilities to ensure excellent scientific productivity. Figure 2-1 shows a pictorial view of the facility.

Fig. 2-1. Spallation Neutron Source site with facility overlay.

SNS is a DOE major system project that was carried out as a partnership among six DOE national laboratories and that was led by the SNS Project Office in Oak Ridge, Tennessee. The national laboratories in the SNS partnership were Oak Ridge (ORNL), Argonne (ANL), Brookhaven (BNL), Lawrence Berkeley (LBNL), Los Alamos (LANL), and Thomas Jefferson National Accelerator Facility (JLab). This partnership approach was used to efficiently take advantage of each laboratory's specific technical expertise and to provide the best possible facility to the neutron research community. As indicated in Fig. 2-2, and defined in the *Spallation Neutron Source Project Execution Plan* (PEP), each laboratory was responsible for a specific scope of work. A commercial architect/engineer-construction manager (AE-CM) team (Knight-Jacobs Joint Venture) handled design and construction management of the conventional facilities under a task order contract.

SNS has developed in-house expertise capable of bringing the SNS complex through commissioning and into routine operation. Project planning ensured continued partner lab support through the end of commissioning each segment of the accelerator, which allowed a smooth transition to routine operation by the SNS in-house staff. SNS has been integrated into ORNL, and the SNS project director is also an ORNL associate laboratory director.

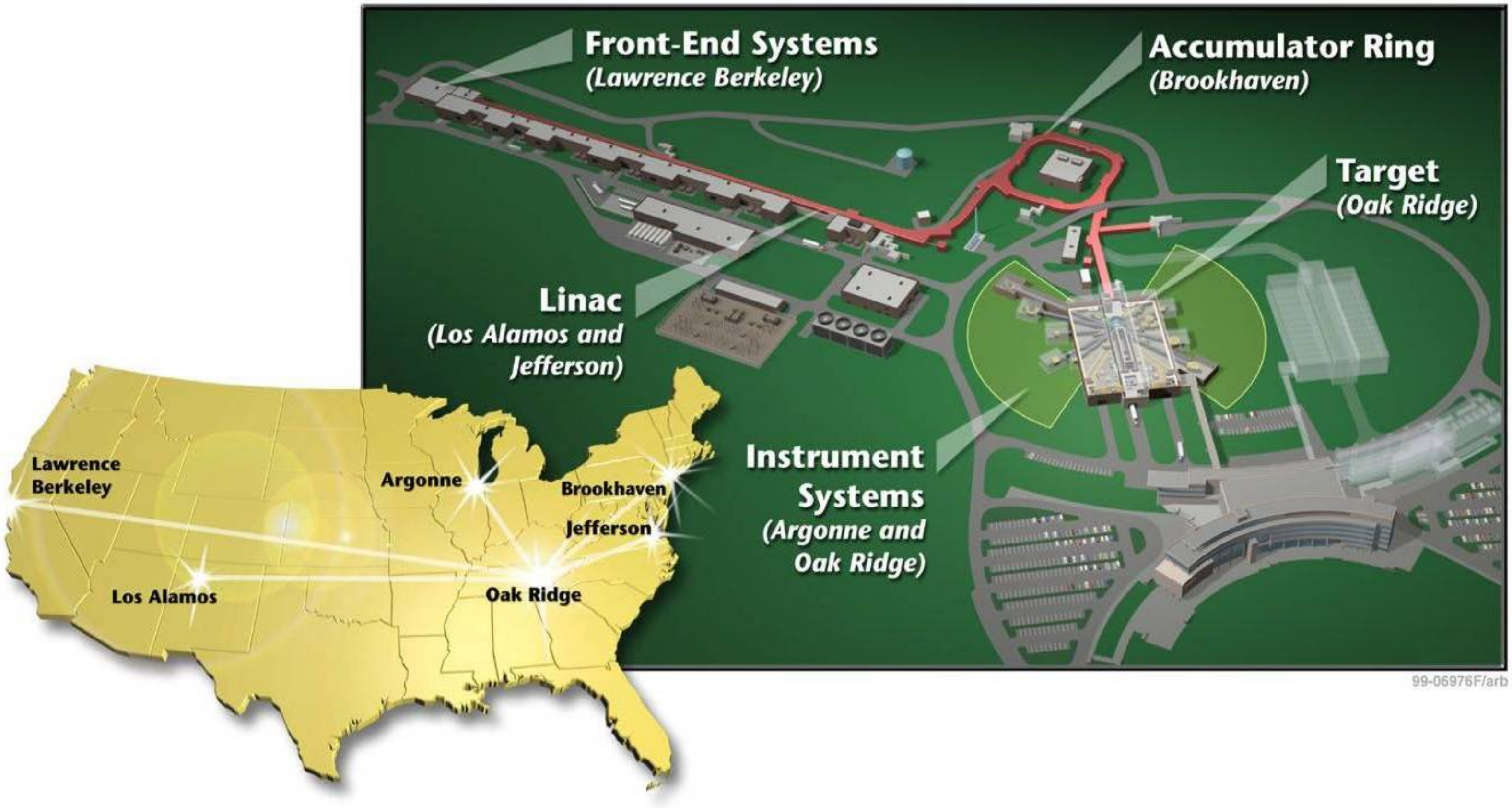


Fig. 2-2. Schematic view of the SNS facility showing the responsibilities of the partner laboratories.

3. PROJECT HISTORY

Public law 95-91, dated August 7, 1977, assigned responsibility to DOE for ensuring a coordinated and effective administration of the federal energy policy and programs. In turn, the DOE Office of Science is charged with maintaining the nation's competitiveness in scientific areas, including the conduct of long-term programs oriented to high-risk research and development (R&D) with potentially high payoffs, which the private sector cannot reasonably be expected to undertake. One aspect of this mission is the design, construction, and operation of major national facilities for research. Public law 102-486, "Energy Policy Act of 1992," under Sect. 220-3, "Supporting Research and Technical Analysis (a) Basic Energy Sciences (2) User Facilities states that "The Secretary shall carry out planning, construction and operation of user facilities to provide special scientific and research capabilities, including technical expertise and support as appropriate, to serve the research needs of the nation's universities, industry, private laboratories, federal laboratories, and others." This mission includes the development and application of neutron-based research. Neutrons are a unique and increasingly essential tool in broad areas of the physical, chemical, and biological sciences, as well as in new materials development. Facilities required to adequately support neutron research are, by nature, large and capital intensive, but they provide vital resources to large numbers (thousands per year) of individual research programs.

A new facility was needed to satisfy U.S. research requirements and to regain world-class status for the United States. The disparity between U.S. and European neutron sources has been recognized by every national panel that has reviewed the status of neutron sources and science in the United States. In 1977, the National Research Council of the National Academy of Sciences (NAS) published "Neutron Research on Condensed Matter," which recommended a high-flux, pulsed spallation source. In 1984, the NAS reviewed the needs for major facilities and in the report *Major Facilities for Materials Research and Related Disciplines* (Seitz-Eastman Committee) recommended (1) construction of a new high-flux, steady-state neutron source and (2) development of a plan leading to a high-intensity pulsed neutron facility. Recommendations of the Seitz-Eastman Committee were reaffirmed in 1993 by a Basic Energy Sciences Advisory Committee (BESAC) Panel on Neutron Sources for America's Future, the Kohn Committee. Following cancellation of the proposed Advanced Neutron Source (ANS) reactor project, BESAC convened another panel in 1996 to reevaluate the need for neutron facilities in the United States, and this panel strongly recommended that a 1- MW pulsed spallation source that could be upgraded be given the highest construction priority. In response, SNS was conceived, and the secretary of energy approved Critical Decision (CD) 1, "Approval of Mission Need," and CD-2, "Approval of Level 0 Project Baseline," for SNS in August 1996 and December 1997, respectively. The SNS PEP, which defines the requirements for the SNS project and governed how the project was managed, was initially approved by the secretary of energy in December 1997. The Level 0 cost and schedule baselines in the current PEP include a TPC of $1411.7M and a seven-year design/construction schedule, with facility commissioning occurring in FY 2006.

Table 3-1 shows key dates, and Appendix A provides a more detailed chronology of the key events during the project.

Table 3-1. Key project dates

October 1995	Conceptual design and R&D started
August 1996	Mission need approved (CD-1)
December 1997	Level 0 Project baseline approved (CD-2)
October 1998	Line item project started
June 1999	Environmental Impact Statement Record of Decision
July 1999	SC Review-Validation of Level 1 Cost/Schedule Baseline
November 1999	Start construction approved (CD-3)
December 1999	Groundbreaking
May 2000	Superconducting linac change approved
December 2002	First beam accelerated in front-end system
June 2003	TVA substation dedicated
November 2003	1mA beam accelerated through DTL tank 1
March 2004	Begin instrument installation – placed backscattering tank
June 2004	Project staff moves into Central Laboratory and Office Building
August 2004	Beam through warm linac (DTL & CCL)
August 2005	SNS operates world's first high-power, high-energy superconducting linac
January 2006	SNS demonstrates successful "accumulator ring" operation to increase beam intensity
January 2006	Successful 72-hour mercury loop flow test
April 2006	First beam on target integrated performance test accomplished
May 2006	Project work completed (CD-4)

Other important project dates are listed in Appendix A.

4. TECHNICAL, COST, AND SCHEDULE OBJECTIVES

SNS has achieved the objectives that were defined before project initiation by the BESAC subpanel in the Russell Panel report. These objectives follow:

- The SNS will provide a short-pulsed spallation source in the >1-MW power range dedicated to neutron scattering with sufficient design flexibility such that it can be operated at a significantly higher power at a later stage.
- SNS will provide a carefully selected initial set of instruments to maximize early scientific impact.
- The SNS linear accelerator design was chosen so as not to exclude direct injection of long pulses into a viable spallation target.
- The SNS was designed and built with the capability of additional targets, as required, with multiplexing to accommodate an expanding experimental instrument suite.

Additionally, the project has achieved the technical, cost, and schedule requirements set forth in the PEP. Table 4-1 contains a summary of the PEP requirements for the SNS project and the conditions that satisfy those requirements. Construction was initiated in the December of 1999. Commissioning goals were achieved in April 2006. A project summary schedule is shown in Fig. 4-1.

The capability to support the project completion goal of 1×10^{13} protons per pulse has been consistently met through all commissioning runs. In general, much higher intensities were actually delivered. The greater than 1-MW beam power capability of the SNS facility has been achieved and demonstrated with all major technical equipment, although not with beam which is not possible due to the beam dump power capabilities. Moreover, all subsystems have been designed, constructed and installed, sufficient to ultimately support the specified 1.4-MW operation. Many of the technical subsystems can support more than 2-MW operation, which goes beyond the present project. Three research instruments are installed and tested, which will support initial experiments. Components of two other instruments have been procured and partially installed (as per the PEP). Trained staff and systems documentation are in place.

The final projected cost for the project is $1,405.2M against a TPC of $1,411.7M. A tabulation of the EAC by work breakdown structure (WBS) is provided in Appendix B. Appendix C shows the allocations of budget to the project participants. Appendix D shows the project's EAC in terms of engineering, design, inspection, and administration (EDIA). Appendix E provides a history of the cost baseline. Table 4-2 shows the level 0 baseline history. The funding profile is shown in Fig. 4-2.

Table 4-1(a). Project Execution Plan baseline (Acquisition Executive)

Technical

Baseline	Status
Accelerator-based neutron scattering facility providing ≥1 MW proton beam power on target.	All facilities and equipment in place required to operate the SNS at >1 MW proton beam on target.

Schedule

Baseline	Status
1. CD-1 Mission Need 8/96 (A) 2. CD-2 Baseline Approval 12/97 (A) 3. EIS Record of Decision 6/99 (A) 4. CD-4 Acceptance/Completion 5/06 (A)	Completion Criteria Satisfied May 2006

Cost

Baseline	Status
Total Project Cost: $1,411.7M	Estimate at completion (EAC): $1405.2

Table 4-1(b). Project Execution Plan baseline (Program Office)

Technical

Baseline	Status
Five Instruments: Backscattering Spectrometer	Installed and ready for experiment measurements.
Magnetism Reflectometer	Installed and ready for experiment measurements.
Liquids Reflectometer	Installed and ready for experiment measurements.
Small Angle Scattering	Partial installation with all components ordered.
Powder Diffractometer	Partial installation with all components ordered.
1×10^{13} protons per pulse	1.75×10^{13} proton pulse delivered to the target
5×10^{-3} neutrons per steradian solid angle per incident proton measured viewing a moderator face.	42×10^{-3} neutrons per steradian solid angle per incident proton measured at beam line 7 moderator face.

Schedule

Baseline (WBS)	Status
1A-1. Start Line Item Project 10/98 (A)	Complete
1A-2. EIS Record of Decision 6/99 (A)	Complete
1A-3. CD-3 Construction Approval 11/99 (A)	Complete
1A-4. Start Target Commissioning (first beam) 4/06 (A)	Complete
1A-5. Submit the Project Completion Report 6/06 (A)	Complete
1B-1. Award AE/CM contract 11/98 (A)	Complete
1B-2. PSAR Submitted to DOE 12/99 (A)	Complete
1B-3. Linac Design Complete 4/02 (A)	Complete
1B-4. Linac Tunnel Beneficial Occupancy 12/02 (A)	Complete
1B-5. Ring Tunnel Beneficial Occupancy 6/03 (A)	Complete
1B-6. Front-End Beam Available to Linac 12/02 (A)	Complete
1B-7. Target Design Complete 6/03 (A)	Complete

Table 4-1(b). Project Execution Plan baseline (Program Office)

Technical	
Baseline	**Status**
1B-8. Instrument Systems Design Complete 10/04 (A)	Complete
1B-9. Linac Beam Available to Ring 8/05 (A)	Complete
1B-10. Ring Beam Available to Target 2/06 (A)	Complete

Table 4-1(c). Project Execution Plan baseline (DOE Project Office)

Technical	
Baseline	**Status**
Preliminary and Final Safety Documents	SNS Accelerator Safety Envelope Rev 4 Approved 4/06
Quality Assurance Plan	SNS QA Plan Rev 3 Approved 3/04
Facility Documentation (As-Built Drawings, and Operating and Maintenance Manuals)	Drawings and manuals recorded in “ProjectWise” database.
Trained and Qualified Operating Staff	Approximately 450 fully trained and qualified staff in place
Schedule	
Baseline (WBS)	**Status**
1.2 Project Support Issue PSAD for Info. 9/00 (A)	Complete
Submit PSAR 12/99 (A)	Complete
Issue FSAD for front end & Linac 8/02 (A)	Complete
Issue FSAD for Proton Systems 6/05 (A)	Complete
Issue FSAD for Neutron Systems 8/05 (A)	Complete
1.3 Front End Design Complete 5/01 (A)	Complete
Begin Equipment Installation 6/02 (A)	Complete
1.4 Linac Systems Initiate Prototype Cryomodule Testing 4/02 (A)	Complete

Table 4-1(c). Project Execution Plan baseline (DOE Project Office)

Technical **Baseline**	**Status**
Begin Equipment Installation 4/03 (A)	Complete
1.5 Ring Systems Design Complete 8/03 (A)	Complete
Begin Equipment Installation 8/03 (A)	Complete
1.6 Target Systems Begin Equipment Installation 4/03 (A)	Complete
1.7 Instruments Begin Equipment Installation 3/04 (A)	Complete
Complete Acceptance Test 5/06 (A)	Complete
1.8 Conventional Facilities Begin Site Preparation 3/00 (A)	Complete
Front End Beneficial Occupancy 10/02 (A)	Complete
Target Beneficial Occupancy 4/05 (A)	Complete
Conventional Facility Construction Complete 3/06 (A)	Complete
1.9 Controls Design Complete 9/02 (A)	Complete
Start Controls Installation 6/02 (A)	Complete
Integrated Controls Subproject Test Complete 3/06 (A)	Complete

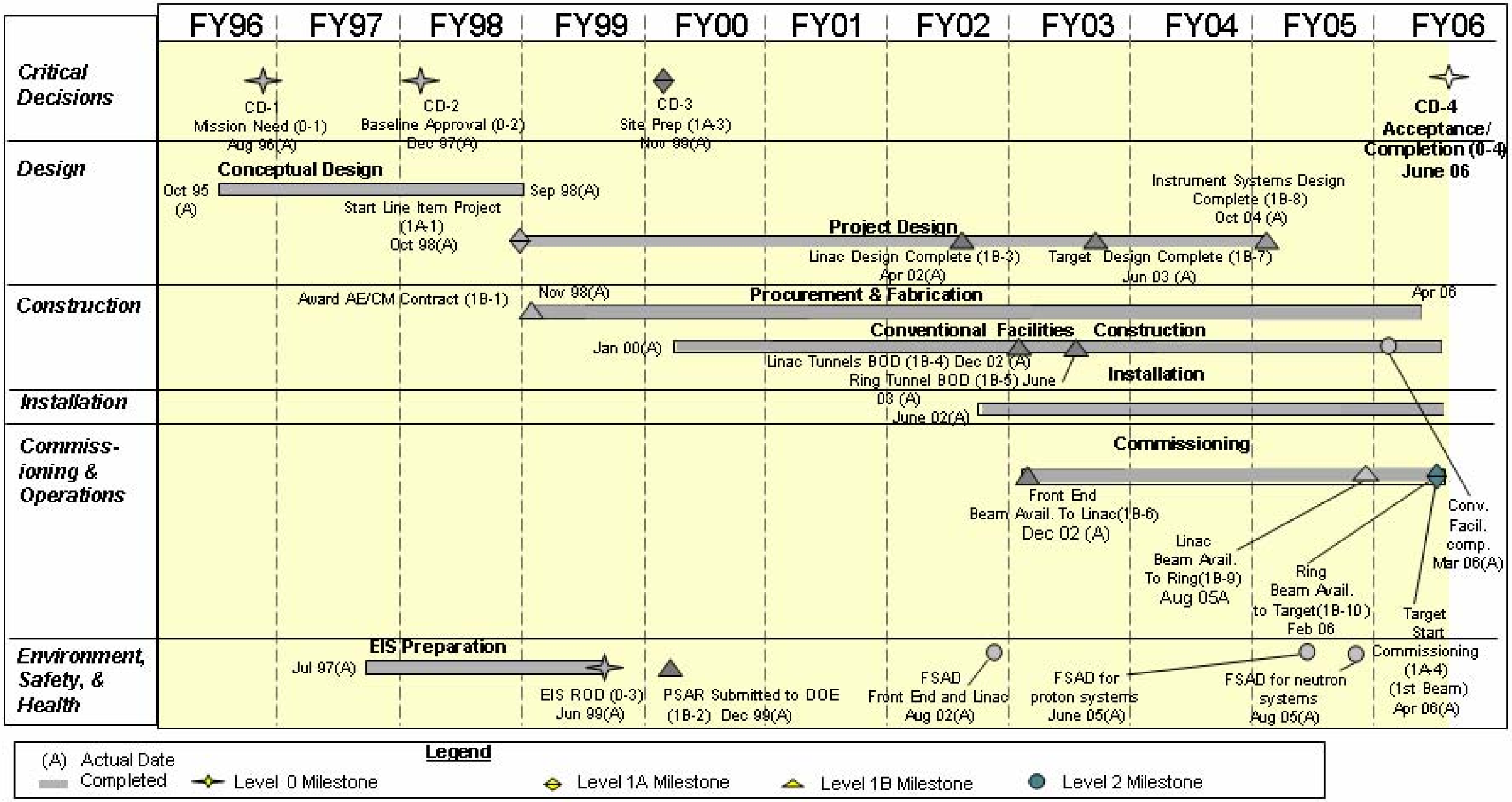


Fig. 4-1. SNS project summary schedule.

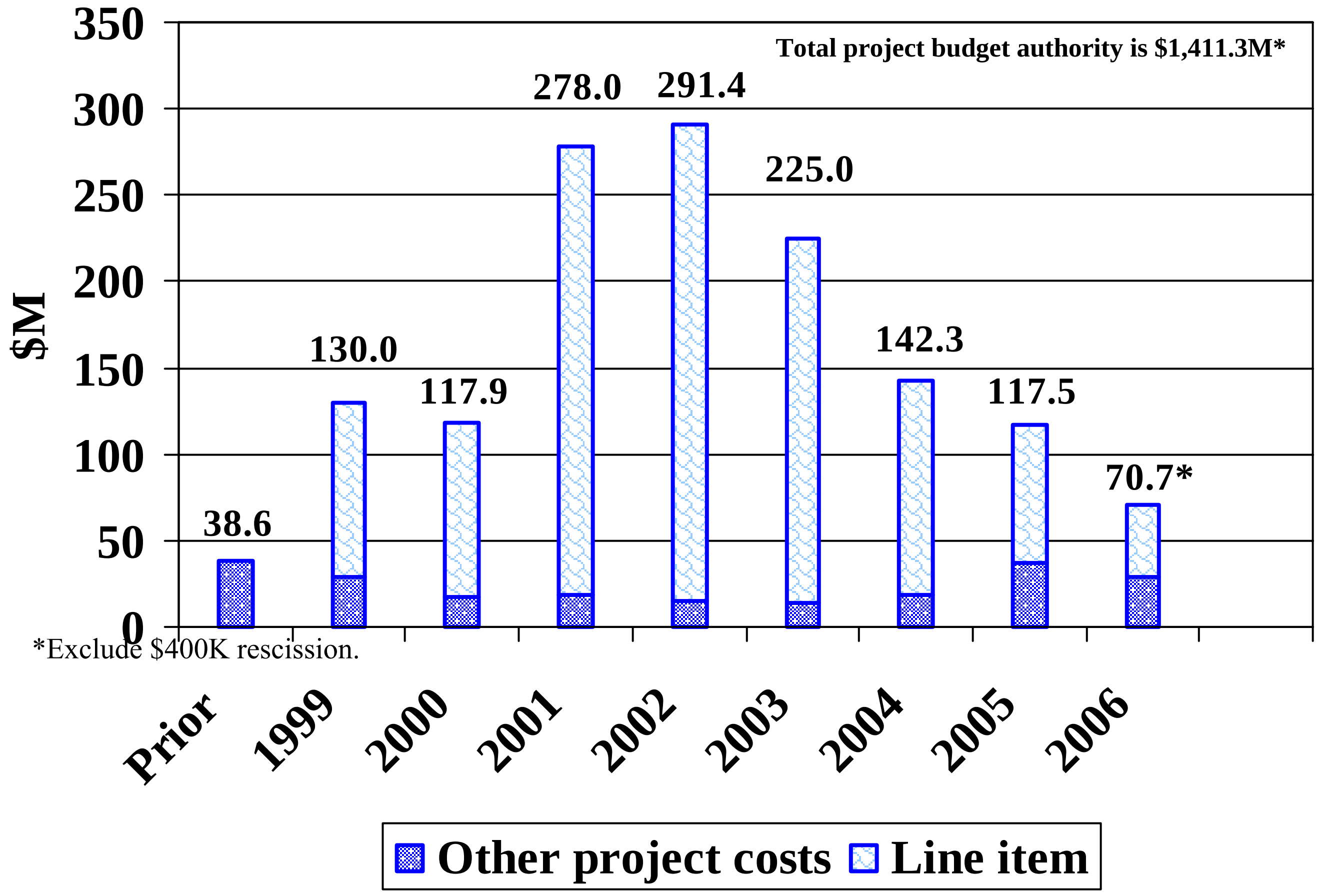


Fig. 4-2. SNS funding profile by fiscal year.

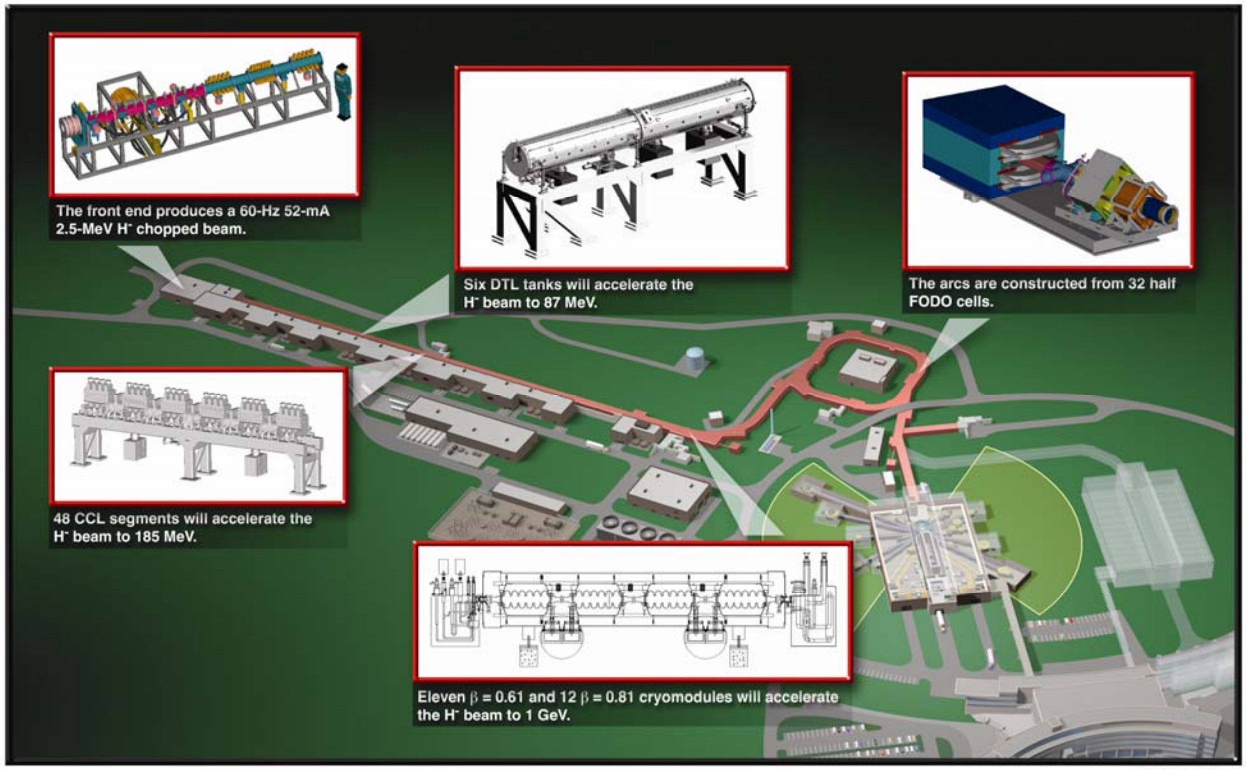
Table 4-2. SNS level 0 baseline history

	Technical scope	Total Project Cost ($M)	Project Completion Date
Dec. 1997 - Original Baseline (CD-2)	Facility capable of ≥1 MW beam on target	1,332.8	9/05
Oct 1998 – impact of FY1999 funding reduction	No change	1,360.0	12/05
Dec 1999 – impact of FY2000 funding reduction & out year profile	No change	1,440.0	6/06
April 2000 – elimination of Tennessee tax	No change	1,411.7	6/06
May 2006 – final (CD-4)	1.4 MW facility capability	1,405.2	5/06

5. PROJECT DESCRIPTION

5.1 ACCELERATOR SYSTEMS

The SNS accelerator systems provide the driving beam power for the SNS target. An illustration of the accelerator systems technical equipment is shown in Fig. 5.1-1.



06-G00792/arm

Fig. 5.1-1. Illustration of accelerator systems technical equipment.

Beam Physics Introduction to the Accelerator Systems. The SNS accelerator system consists of two basic subsystems. The first subsystem is the linac, which generates a stream of negative H- ions and accelerates them to an energy of 1 GeV (equivalent to applying a voltage of one thousand million volts. The linac is ~300 m long. By the time the ion beam reaches the end of the linac, it has reached 90% of the speed of light. Although the ion current accelerated in the linac is relatively small, each pulse is 250,000 m long and is injected into the proton accumulator ring. It is sliced into 1000 smaller pulses, which are stacked on top of each other. The ring circumference is ~250 m, and after a full accumulation cycle the intensity of the pulse is increased 1,000 times, shrinking the pulse length to a little less than 1 µs before being extracted and sent to the target. During normal operation, 60 pulses per second are generated.

In Fig. 5.1-2, the layout of the accelerator and the basic cycle is explained in a more detail. The linac is divided into six subsystems: the ion source, radio-frequency quadrupole (RFQ), drift-tube linac (dtl), coupled-cavity linac (CCL), and two superconducting linac sections consisting of medium- and high-beta cryomodules. Although the journey of the H^- ions starts out in the ion source as a pulsed dc beam, the RFQ accelerates and bunches the beam at its operating frequency of 402.5 MHz. From there on, different types of accelerating structures are used to subsequently increase the kinetic energy of the ions through a series of gaps that have a voltage across them. The voltage is generated by radio-frequency (RF) waves coming from RF power sources, which are fed into the structures.

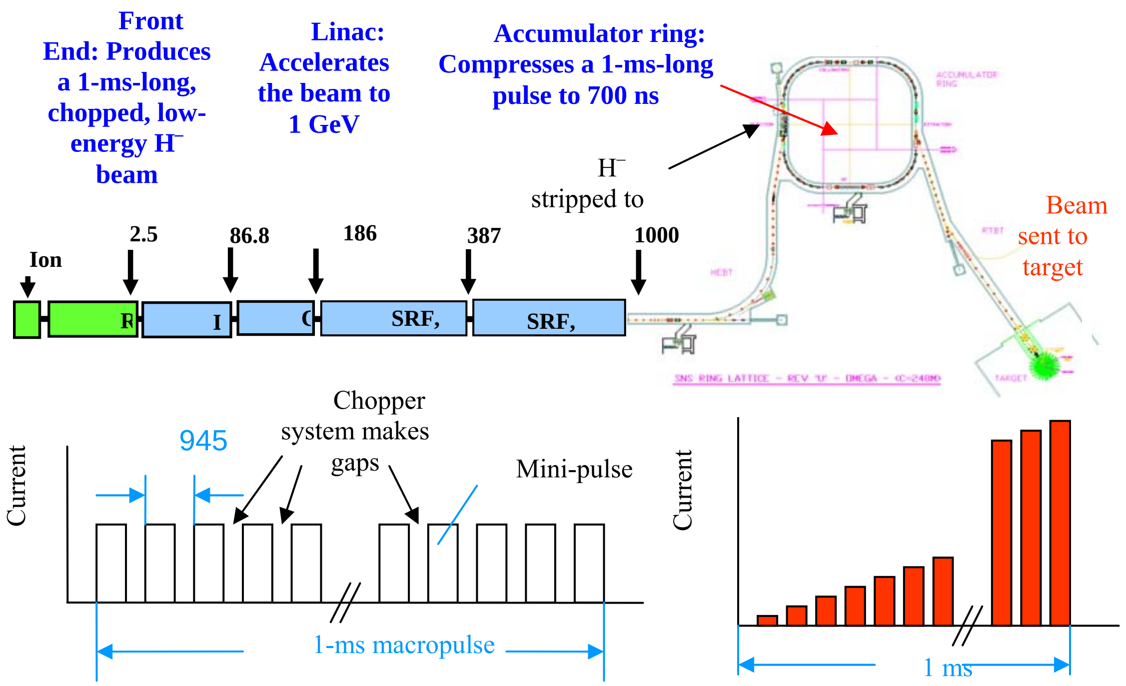


Fig. 5.1-2. Basic layout of accelerator systems. The linac is divided into several subsystems. The proton accumulator ring follows the linac. The bottom graphs depict the current pulse in the linac, consisting of a series of equally spaced mini-pulses with a 402.5-MHz structure. For the ring, the current increases as more and more mini-pulses are stacked on top of each other.

The functionality of the accelerator subsystem is described in more detail subsequently, together with the beam operation of these systems.

Accelerator Systems Design. The baseline parameters that guided the overall design are shown in Table 5.1-1.

Table 5.1-1. Baseline parameters for the SNS accelerator, guiding the overall design

Baseline parameters for the SNS accelerator		
Kinetic energy	GeV	1.0
Beam power on target	MW	1.4
Average current on target	mA	1.4
Linac beam macropulse duty factor	%	6
Average macropulse H^- current	mA	26
Peak linac current	mA	38
Linac average beam current	mA	1.6
SRF cryomodule number		11 + 12
SRF cavity number		33 + 48
Peak gradient medium beta	MV/m	27.5
Peak gradient high beta	MV/m	35
Ring accumulation turns		1060
Ring current at end of accumulation	A	27.08
Ring bunch intensity	10^{14}	1.6
Ring space-charge tune spread	ΔQ	0.15
Pulse length on target	ns	695

The accelerator design, construction, installation, and commissioning was done within the Accelerator Systems Division (ASD) at ORNL in collaboration with four national laboratories that were responsible for the different subsystems of the complex. LBNL was responsible for the front-end systems (FES), including the ion source development and the RFQ, as well as the medium-energy beam transport (MEBT) system up to an energy of 2.5 MeV. LANL was responsible for the design and construction of the normal conducting linacs—the DTL up to 86.8 MeV, the CCL up to 185.6 MeV, all RF systems, some of the diagnostics, and linac beam dynamics. JLab designed, procured, and built the cryogenic plant and the superconducting cavities within the cryomodules, which supply the bulk of the acceleration up to 1 GeV. BNL was responsible for the ring, as well as the beam transport lines connecting the linac to the ring and the ring to the target. BNL designed and built almost all ring components and the majority of the ring diagnostics. Finally, ASD performed the integration, installation, and commissioning of all accelerator systems, as well as some of the technical scope in various areas, such as cryodistribution line assembly and installation, diagnostics development and integration, low-level RF development and integration, and radiation shielding for all accelerators.

Beginning in 2002, with installation of the FES and their delivery from LBNL, these subsystems were brought online with the goal of demonstrating their full capability, as long as reasonably achievable, but to at least guarantee the capability to support the project completion requirement of delivering more than 1×10^{13} protons per pulse to the target. In the case of SNS, reasonably achievable is defined as the capability to contain the beam power that would be delivered by the different subsystems into beam dumps that are either designed into the facility or that could be temporarily installed and used without violating as-low-as-reasonably-achievable (ALARA) considerations for later occupancy of the tunnel enclosures.

Following the integrated project schedule (IPS), the subsystems had to be certified by an independent readiness review process [Accelerator Readiness Review (ARR)] that would declare the system's completion and all safety systems, as well as procedures, in place. After signoff approval by the DOE project manager, the systems were commissioned. The results from these subsystem tests are described and documented in the following paragraphs.

Commissioning the Accelerator Subsystems with Beam. The SNS accelerator system consists of a 1-GeV linear accelerator and beam compressor ring. As of April 2006, the FES, DTL, all four CCL structures, superconducting linac, ring, and the associated support infrastructure were commissioned and have achieved, and in most cases exceeded, the project completion specifications, as far as can be tested, both with and without beam, under the existing safety envelope. Successful completion of the ARR in April 2006 gives SNS permission to operate at a power level of 100 kW. A final high-beam-power ARR is expected to take place in April 2007. A successful review will allow operation at the full beam power of the current baseline design of 1.4 MW. This schedule is consistent with the power rampup assumption that was described in an earlier white paper (SNS 102000000-TR0004-R00, *The Spallation Neutron Source: Operational Aspects And Reliability In The Transition From Commissioning To Fully Committed User Operatio*n). By April 2007, there will be sufficient operational experience to permit high-power operation with acceptable losses and associated activation of components. In addition, any improvements or modifications in hardware needed to support high-reliability operations needed for the user program will have been implemented. Although beam power capability of 1 MW or more existed in April 2006, assessment of initial risk, ALARA considerations, learning curves, and the need to develop an understanding of machine performance at moderate power levels before proceeding to full power make a measured approach to full power (as outlined in the white paper) prudent.

During all commissioning runs (apart from the FES and DTL1 run), beam power capability could not be fully exploited because an appropriate beam dump was not available. In fact, the liquid mercury target is the only target that will be able to absorb the full-beam-power capabilities of the system. Nevertheless, the capability to operate well beyond CD-4 commissioning levels of 1×10^{13} protons per pulse has been demonstrated, as shown in Table 5.1-2, where an overview of the different commissioning runs is given. The second requirement, demonstrating that all equipment is installed to support 1-MW operation, has been consistently accomplished with beam. For example, to date all hardware has been tested to that level, as far as one can technically assess. Test results have been presented to technical and DOE advisory committees and were discussed on a regular basis to better define the acceptance criteria.

Table 5.1-2. Subsequent beam commissioning runs in which the project completion requirements for these subsystems were demonstrated and/or exceeded

Subsequent beam commissioning runs for the accelerator subsystems					
Title of the run	Date for ARR permission to operate	Energy (MeV)		Intensity (H^-/pulse)	
		Design	Achieved	Design	Achieved
FES	10/29/2002	2.5	2.5	1.6×10^{14}	1.0×10^{14}
FES + DTL1	08/26/2003	7.5	7.5	1.6×10^{14}	1.3×10^{14}
FES—DTL3	04/08/2004	23	23	1.6×10^{14}	1.0×10^{13}
FES—CCL3	09/07/2004	157	157	1.6×10^{14}	1.0×10^{13}
FES—HEBT	07/25/2005	1000	950	1.6×10^{14}	8.0×10^{13}
FES—Ring extraction	01/05/2006	1000	932–950	1.5×10^{14}	1.3×10^{13}
FES—Target	03/15/2006	1000	860	1.4×10^{14}	2.5×10^{13}

Major Subsystems of the Accelerator. The following sections contain short descriptions of the major subsystems. Each of these systems consists of a significant part of the SNS infrastructure. It is important to appreciate that the SNS infrastructure and many of the technical subsystems were conceived, designed, and constructed from the beginning to be upgradeable to higher beam power. Buildings, tunnels, accelerator and target layouts, and various other components were constructed to allow for higher beam power and, as much as possible, have already been implemented within the limitations of the current SNS project budget and schedule constraints.

5.1.1 Front-End Systems (LBNL) and DTL1 (LANL)

The FES generates the H^- ions in a volume source, where a glow discharge attaches the loosely bound second electron to the hydrogen atom. The ions are extracted with a positive voltage of 65 kV and are then directly injected into the RFQ, where they are bunched and accelerated to 2.5 MeV. Figure 5.1-3 shows the basic layout of the SNS ion source.

After acceleration, the 1-ms-long bunch train is “chopped” into ~1000 pieces, each ~700 ns long. These systems are shown in Fig. 5.1-4 and largely represent the deliverable from LBNL. The ion source was originally set up and tested at LBNL and then tested again at the SNS site. During this run the FES demonstrated currents above 50 mA in short pulses, which is well above specification. It also demonstrated a full 1-ms-long beam pulse with almost design intensity.

In the next run, the FES were tested in combination with the first DTL. From experience and from calculation it was well known that this was a major step to be able to match the beam into the linac. It was planned to test this thoroughly with a special beam dump and beam diagnostics section built to absorb the full-duty cycle beam (12-kW beam power @7.5 MeV) and to fully characterize the beam in its longitudinal and transverse dimensions. A picture of the FES and DTL1 is shown in Fig. 5.1-5.

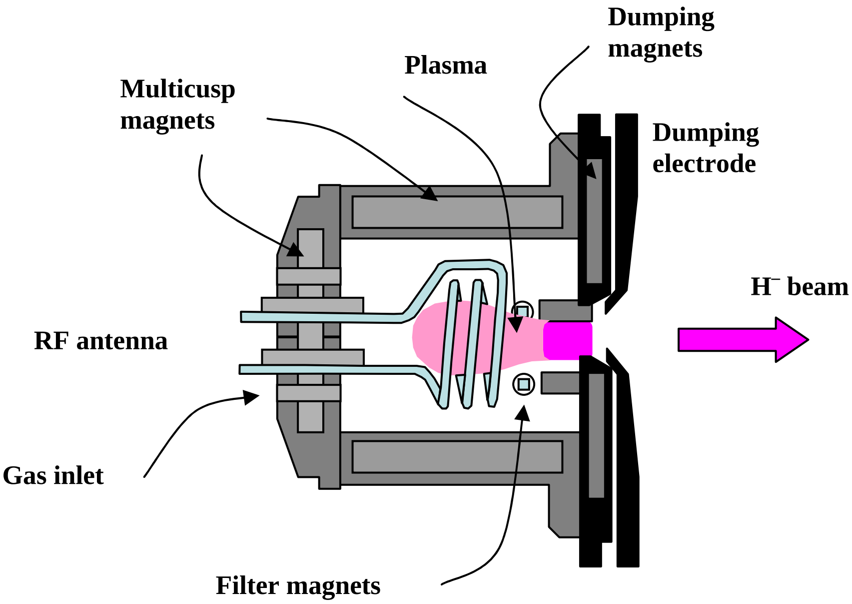


Fig. 5.1-3. SNS ion source geometry.

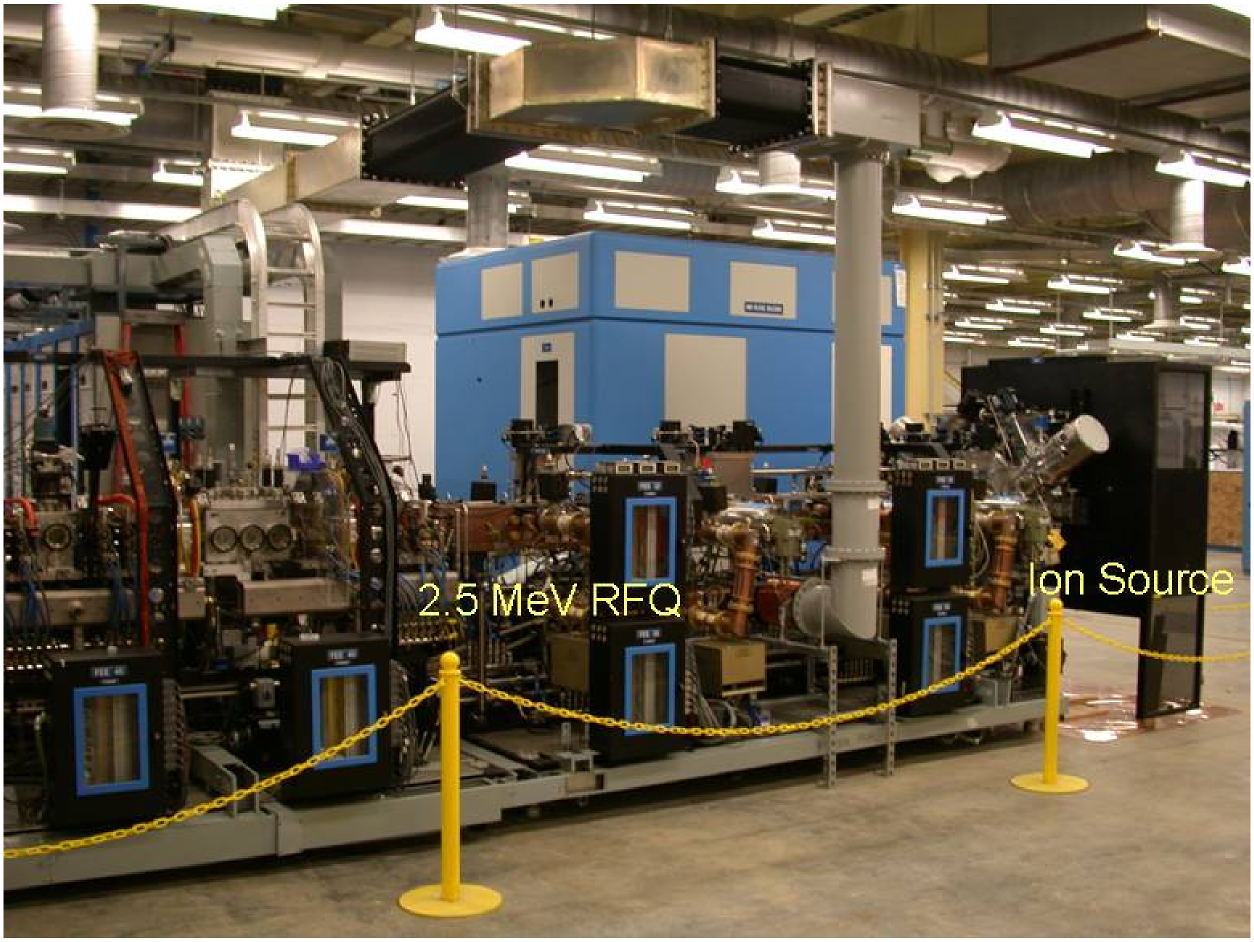


Fig. 5.1-4. From right to left: ion source, RFQ, and MEBT. This was largely the deliverable from LBNL.

Fig. 5.1-5. Attached to the FES is the first DTL tank with a diagnostics section and a 12-kW beam dump attached. This was used to fully characterize the beam.

During this commissioning run a beam power capability was tested up to 7.5 kW operating at 60 Hz and ~20-mA average current, ~60% of the SNS design intensity, which is approximately a factor of 7 above the project completion requirement. A typical beam pulse is shown in Fig. 5.1-6.

5.1.2 Linac Systems (LANL)

5.1.2.1 Normal conducting linac

The normal conducting linac consists of six DTL tanks and four CCL structures. While the DTLs and the RFQ are driven by 402.5-MHz RF systems, the beam transitions into a 805-MHz structure entering the CCL. The associated RF systems in the klystron gallery are shown in Fig. 5.1-7.

The accelerating structure are shown in Fig. 5.1-8. Six DTL tanks bring the linac energy up to 86.8 MeV, with the CCLs accelerating further on to 185.6 MeV. Installation of this part of the linac was accompanied by two commissioning runs, in which the first three DTLs were operated, and in a second run, the beam was accelerated through CCL3. In both cases temporary beam stops were installed in the tunnel, which allowed full single-pulse intensity but not full repetition rate at the same time, therefore limiting the beam power that could be tested.

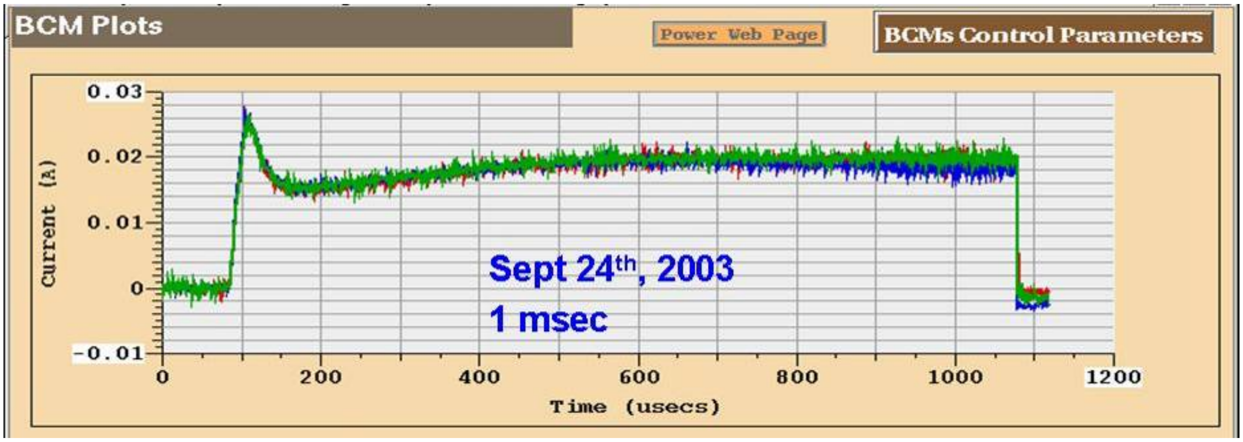


Fig. 5.1-6. A typical beam pulse during the commissioning run shows a current of ~20 mA and a design pulse length of 1 ms.

Fig. 5.1-7 The first part of the klystron gallery accommodates the 402.5-MHz klystrons and the associated support systems (left), followed by four 805-MHz klystrons driving the CCL (right).

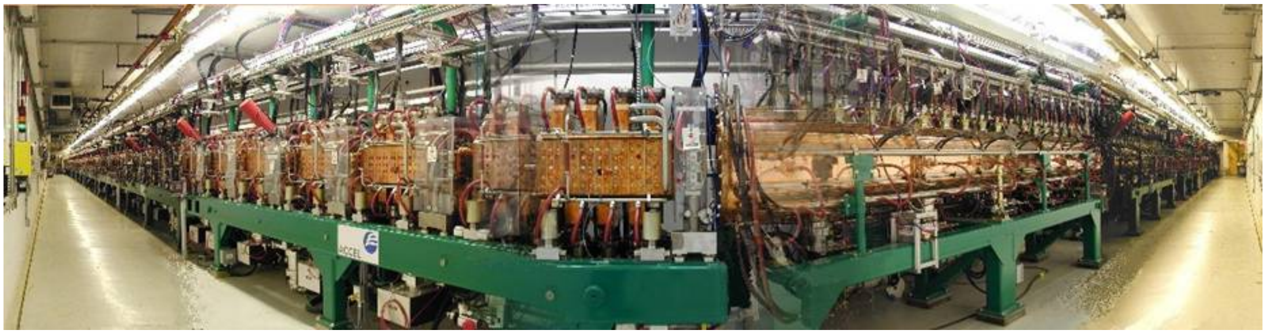


Fig. 5.1-8. The normal conducting linac from right to left in beam direction shows the six DTL tanks in place, followed by the CCL structure. This photo was taken with a frog eye camera, making the beam line appear curved.

To characterize the beam quality, permanently installed diagnostics within these RF structures were used. In both cases beam quality and peak intensity met specification and project completion requirements. A typical beam pulse used during commissioning is shown in Fig. 5.1-9. The exact energy measurements and the characterization of the beam quality can be found in Tables 5.1-3 and 5.1-4.

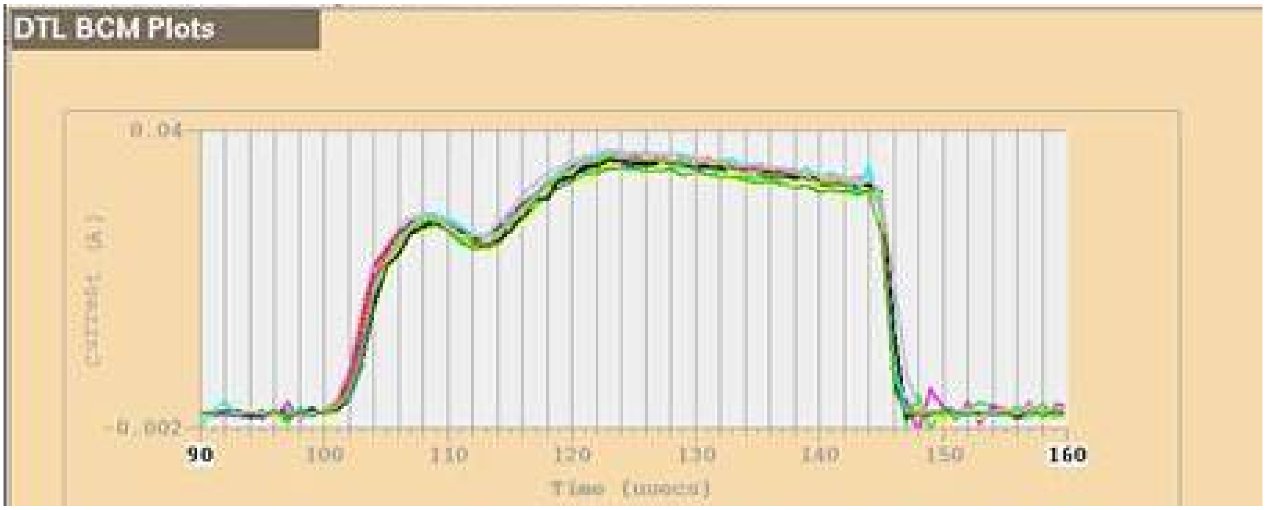


Fig. 5.1-9. Typical beam pulse used for normal-conducting linac commissioning. A peak current of close to 40 mA can be seen with a pulse length of ~50 *μ*s.

Table 5.1-3. Energy measurement of the beam after the different accelerating structure (**agreement with the design is excellent.)**

Energy characterization during linac commissioning

Module	**Design (MeV)**	**Measured (MeV)**	**Deviation (%)**
DTL6	86.83	87.48 ± 0.03	0.75
CCL1	107.16	107.36 ± 0.12	0.19
CCL2	131.14	131.53 ± 0.14	0.40
CCL3	157.21	158.08 ± 0.40	0.55

Table 5.1-4. A comparison of measured vs design values for the various commissioning runs in the normal-conducting linac

Beam parameter comparison for the different Linac commissioning runs

Parameter	Design	Achieved	Units
MEBT transverse output emittance at 38 mA	0.3	0.29 (H), 0.26 (V)	π mm-mrad (rms,norm)
DTL1 transverse output emittance at 38 mA	0.3	0.40 (H), 0.31 (V) ±0.10 (systematic err)	π mm-mrad (rms,norm)
DTL6 transverse output emittance at 38 mA	0.33	0.32 (H), 0.39 (V)	π mm-mrad (rms,norm)
Peak current	38	> 38	mA
Average current	1.6	1.05 (DTL1 run) 0.002 (CCL run)	mA
H^-/pulse	1.6×10^{14}	1.3×10^{14} (DTL run) 1.0×10^{13} (CCL run)	Ions/pulse
Pulse length/rep-rate/duty factor	1.0/60/6.0	1.0/60/3.8 (DTL1 run) .050/1/.005 (CCL run)	ms/Hz/%
MEBT bunch length	18.5	18	degrees rms
CCL1 bunch length	2.8	3.5	degrees rms

Finally, it is worth mentioning that apart from the ion source, the normal-conducting linac can support a beam power substantially higher than 1 MW. All RF systems have significant overhead designed into the hardware, resulting in no upgrade requirements in this area for any power upgrade other than for the anode driving power supplies [high-voltage converter modulator (HVCM)]. This subsection, including the RF systems for the superconducting linac, comprises the LANL deliverables.

5.1.2.2 Superconducting linac (JLab)

The decision to use a superconducting linac at SNS was made relatively late into the construction project at the end of 2000. Since recent progress toward highly reliable and high gradient cavities over previous years had been extraordinary, the potential pay off for SNS would be substantial. Higher gradients would reduce the required tunnel length, provide larger longitudinal acceptance, and reduce halo growth. The excellent vacuum reduced beam gas scattering and therefore residual radiation. Gradient independent RF power consumption allows larger flexibility during operation. All of the prospects came to fruition. In spite of the little time that was available for R&D, the design gradients of the superconducting cavities, while conservatively chosen, today support generally 20% higher accelerating gradients than originally designed, providing substantial overhead for both energy and reliability purposes. In addition, the linac tunnel geometry was laid out from the beginning to accommodate an additional 300 MeV, providing space for nine more cryomodules. The full 1.3-GeV cryogenic distribution system is already installed.

5.1.2.3 Cryogenic support systems

The flow diagram of the cryogenic plant is shown in Fig. 5.1-9. The warm gas is compressed through “warm” compressors and then expanded through a series of Joule Thompson valves in the 4.5-K cold box, bringing the temperature of the helium to liquefaction level. A transfer line transports the gas into the tunnel, and while the 2-K cold box reduces the pressure in the return line to 40 mbar, expansion through another Joule Thompson valve in each cryomodule into the reduced pressure of the return line lowers the liquid helium temperature to 2 K in each of the cavity vessels. Figure 5.1-10 shows the layout of the actual building with geometric arrangement of the subsystems in the building. Toward the right side of the building, the cryogenic test facility will be used to repair, maintain, disassemble, and reassemble cryomodules. Although the facility itself is not part of the project scope, the space is foreseen, and rudimentary build out has started already using project contingency.

The distribution system in the tunnel is shown in Fig. 5.1-11. The cryogenic plant that supports the operation of the superconducting linac at 2 K consists of three major subassemblies that are all installed in a separate building, the Cryogenic Helium Liquefier (CHL) Building. Three streets with major compressor engines, shown in Fig. 5.1-12, feed into a 4.5-K cold box (Fig. 5.1-13) and from there through a 80-ft-long transfer line across the street into the tunnel transfer line shown in Fig. 5.-1-11. At the return, the 2-K cold box shown in Fig. 5.1-14 pumps the transfer line down to 40 mbar, which allows generation of 2-K superfluid helium in the cryomodules. As shown in these pictures, a massive installation is required to be able to support the operation of a superconducting linac. The cryoplant was fully commissioned in November 2004 and since then has supported commissioning and operation of the superconducting linac. Today the cryoplant operates mainly unmanned from the CCR. Previous experience in other national laboratories, as well as other countries, showed that a commissioning time of 1 to 2 years was to be expected, while the plant at SNS largely came online without major operational issues and maintains a very high reliability.

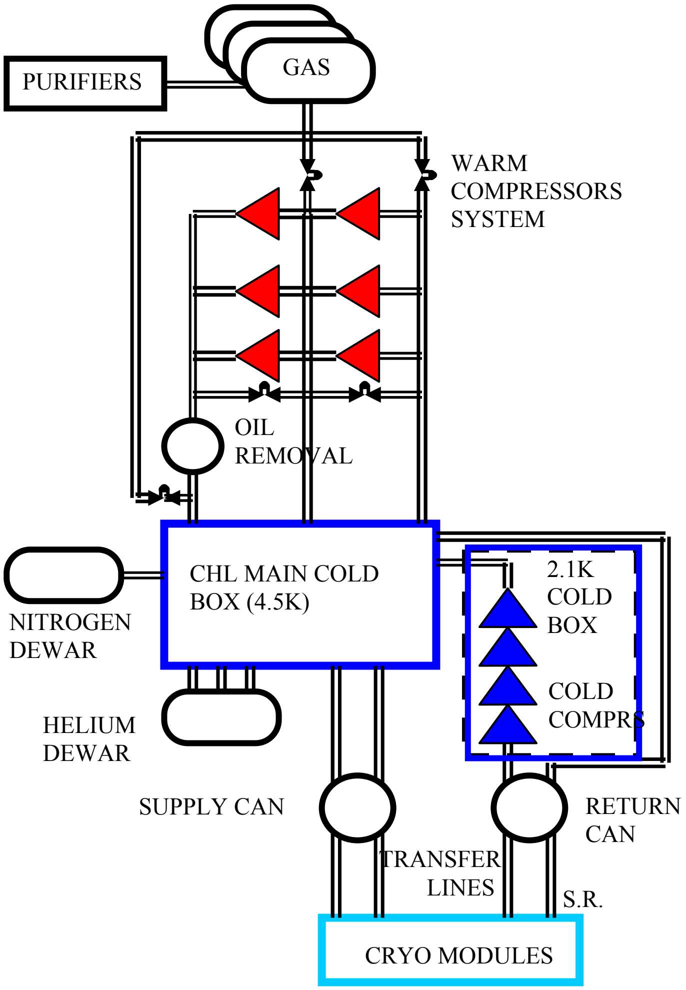


Fig. 5.1-10. Gas flow diagram showing the conceptual layout of the cryogenic plant. The helium refrigerator system has a cooling capacity of 2400 W at 2.1 K and 8300-W shield load capacity at 38/50 K.

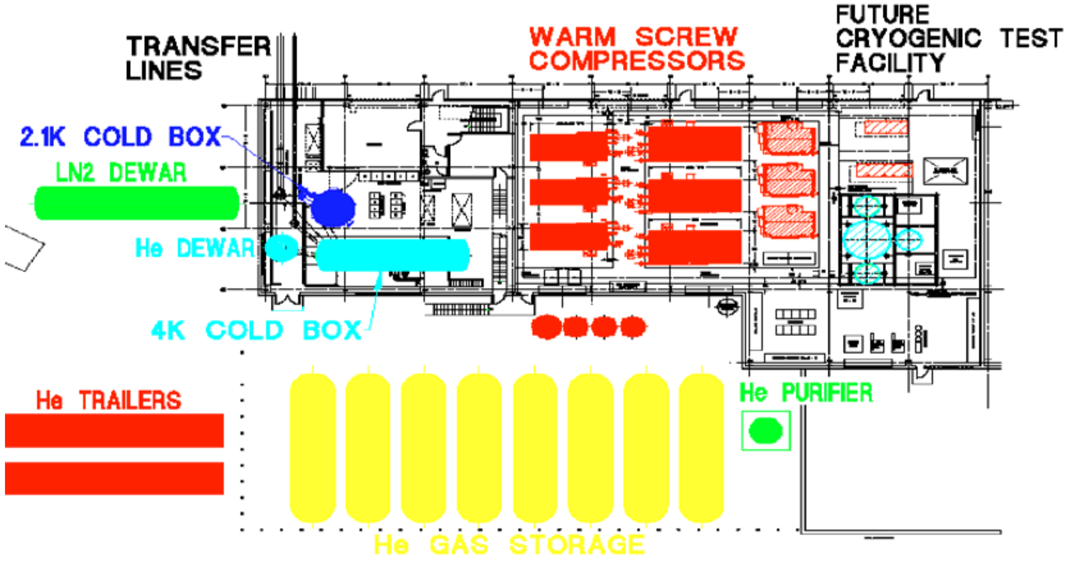


Fig. 5.1.11. General layout of the cryogenic plant showing the warm compressor streets on the left and the 4.5-K and 2.0-K box to the right. Storage tanks are indicated in the upper part.

Fig. 5.1-12. Cryogenic transfer line in the linac tunnel all the way to the end of the additional nine cryomodules that are foreseen for a future power upgrade.

Fig. 5.1-13. Warm compressor installation in the CHL Building feeding into the 4.5-K cold box.

Fig. 5.1-14. The 4.5-K cold box (left) and associated controls (right) in the CHL Building feeding the liquid helium into the transfer line.

Fig. 5.1-15. Massive 2-K cold box in the CHL Building pumping down the transfer line to 40 mbar, allowing the generation of 2-K superfluid helium in the cryomodules.

5.1.3 Superconducting Linac

A photograph of the superconducting linac, with its eleven medium-beta cryomodules and twelve high-beta cryomodules, is shown in Fig. 5.1-16. Figure 5.1-17 shows the niobium cavities within the cryomodules. At the very end of the linac tunnel, the beam line is built out to replace beam pipes, with cryomodules as part of a power upgrade program. In general, this figure shows the deliverables of JLab.

The RF systems that feed to cavities are upstairs in the klystron gallery. Because a “one klystron per cavity” geometry was chosen early on, a total of 81 klystrons had to be installed in the gallery, with an unprecedented density of these tubes. Today, SNS is the second largest klystron installation in the world (Fig 5.1-18).

During commissioning of the superconducting linac, not all cavities from the total available of 81 could be operated. Typically 75 are in operation and generate a total beam energy of 930–950 MeV. At the end of the linac, a permanently installed beam dump was used to dispose the high-power, high-energy beam, which is nevertheless limited to an average beam power of 7.5 kW but can accept the full beam pulse intensity. In Fig. 5.1-19 a pulse with a total of 8×10^{13}, about half the design value and eight times the project completion requirement, was generated, accelerated through the linac, and delivered to the beam dump. In addition, the beam quality was verified again at the entrance and the exit of the superconducting linac, and with a normalized horizontal/vertical emittance at the entrance of 0.27 and 0.35 π*mm*mrad, is smaller than the design of 0.41. A similar result was shown at the entrance to the linac beam dump after accelerating the beam to its final energy with 0.26 and 0.27 π*mm*mrad vs 0.41.

Fig. 5.1-16. View of the superconducting linac with a total of 23 cryomodules installed. The transfer line shown in Fig. 5.1-12 is behind the modules.

Fig. 5.1-17. Niobium cavity for the superconducting accelerator.

Fig. 5.1-18. Snapshot of the klystron gallery with some of the 81 klystrons feeding the superconducting linac.

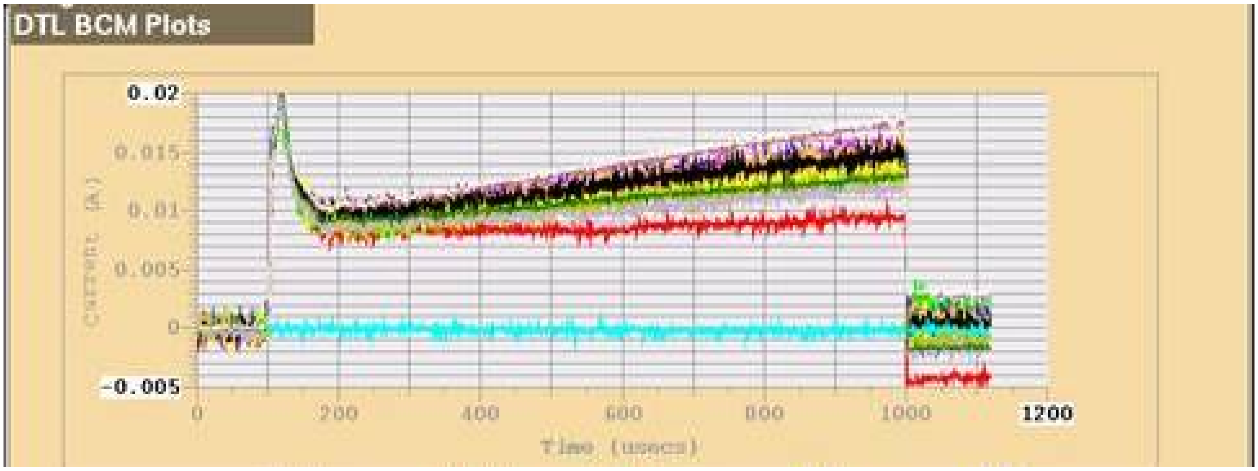
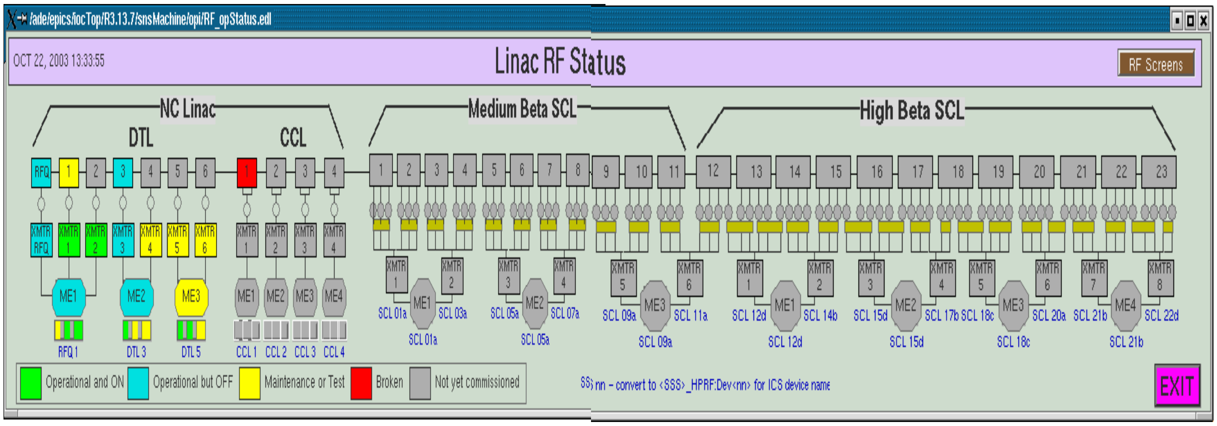


Fig. 5.1-19. The graph shows an overlay of several beam current monitors along the linac delivering a total of 8 × 10^{13} H^- to the linac beam dump.

5.1.3.1 RF system overview

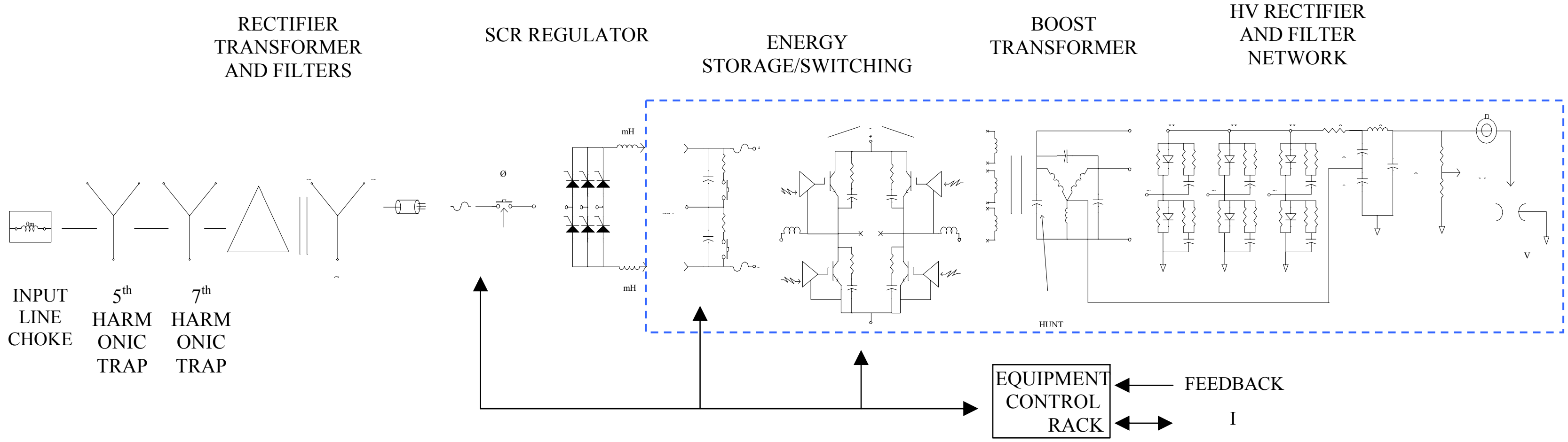
The RF system installed in the klystron gallery provides the RF power for the linac and transfers ac power from the grid to beam power on target. A conceptual layout of the RF system is shown in Fig. 5.1-20, where from the bottom to the top of the picture the power distribution is presented. Electrical power coming from electrical substations enter the building at 13.2 kV and is rectified in the silicon-controlled rectifier (SCR) controller. It further on feeds into the HVCM, which generates the specific dc voltage required by the klystrons (compare Fig. 5.1-21). Seven HVCM are required for the normal-conducting linac and another seven for the superconducting part.

Once RF power is available, phase and amplitude are controlled through transmitters. They also manage safe operation of the klystron, as well as any beam- or hardware-related interlock. Photos of the klystrons used at SNS are shown in Figs. 5.1-7 and 5.1-18 in their final configuration in the klystron gallery.



SSS nn – convert to <SSS>_HPRF:Dev<nn> for ICS device name

Fig. 5.1-20. Schematics of the RF systems throughout the linac. HVCMs (called MEs), klystrons, and the associated RF structures are displayed.




RECTIFIER TRANSFORMER AND FILTERS

SCR REGULATOR

HIGH-VOLTAGE CONVERTER/MODULATOR

EQUIPMENT CONTROL RACK

Fig. 5.1-21. AC power is fed from a 13.2-kV transformer to an SCR regulator, rectifying the current before feeding it to the converter modulator, which modulates and transforms the voltages to the specific level required by the klystron—typically between 65–130 kV.

5.1.4 Accumulator Ring (BNL)

The ring was designed, constructed, and built by or under supervision of BNL and industry. The ring circumference is one thousandth of the linac pulse length, which means that the circulating ion current increases one thousand fault going up to 26 A as the pulse is injected into the ring—a remarkable number by itself. Before the beam is injected into the ring, longitudinal and transverse halo particles, meaning particles that are off the design orbit or the design energy, are collimated from the core. This is done mainly in the High-Energy Beam Transport (HEBT), which is a 150-m-long beam line going from the end of the linac to the ring injection point. Parts of the beam line like the bending magnets (used for energy collimation) and the straight section following the linac used for transverse halo collimation are shown in Fig. 5.1-22 (also compare Fig. 5.1-23).

Based on experience with high-intensity storage rings at the LANL proton storage ring, Brookhaven, and many other places, it was clear that the ring design had to be conservative not only to be able to easily support the baseline parameters but also to provide margins for upgrades. In addition, only such a design would minimize beam loss throughout the accumulator ring, therefore minimizing residual radiation and allowing hands-on maintenance.

Although the project baseline parameters were developed in detail, the original ring design was aimed for 2-MW operation at 1.0 GeV, well beyond today's 1.4-MW baseline, and during the course of the project this design was retained with the difference being treated as extra margin. In addition, since the energy upgrade of the linac to 1.3 GeV was foreseen from the beginning, the basic geometry of the beam transport lines and the ring were chosen to support 1.3-GeV operation. In fact, almost all magnets and their power supplies that have been installed can support 1.3 GeV today. RF systems and injection kickers have been designed to support 1.3-GeV operation, and only a few modifications and upgrades will be necessary to operate the ring at 1.3 GeV. Although beam power scales with energy, potential beam instability thresholds scale inversely and studies show that at 1.3 GeV the ring as installed can support 3-MW beam power and maybe more.

Fig. 5.1-22. Tunnel enclosure of the HEBT arc (left) and the beam transport from the linac to the arc (right). The beam is transported into the injection straight section of the ring.

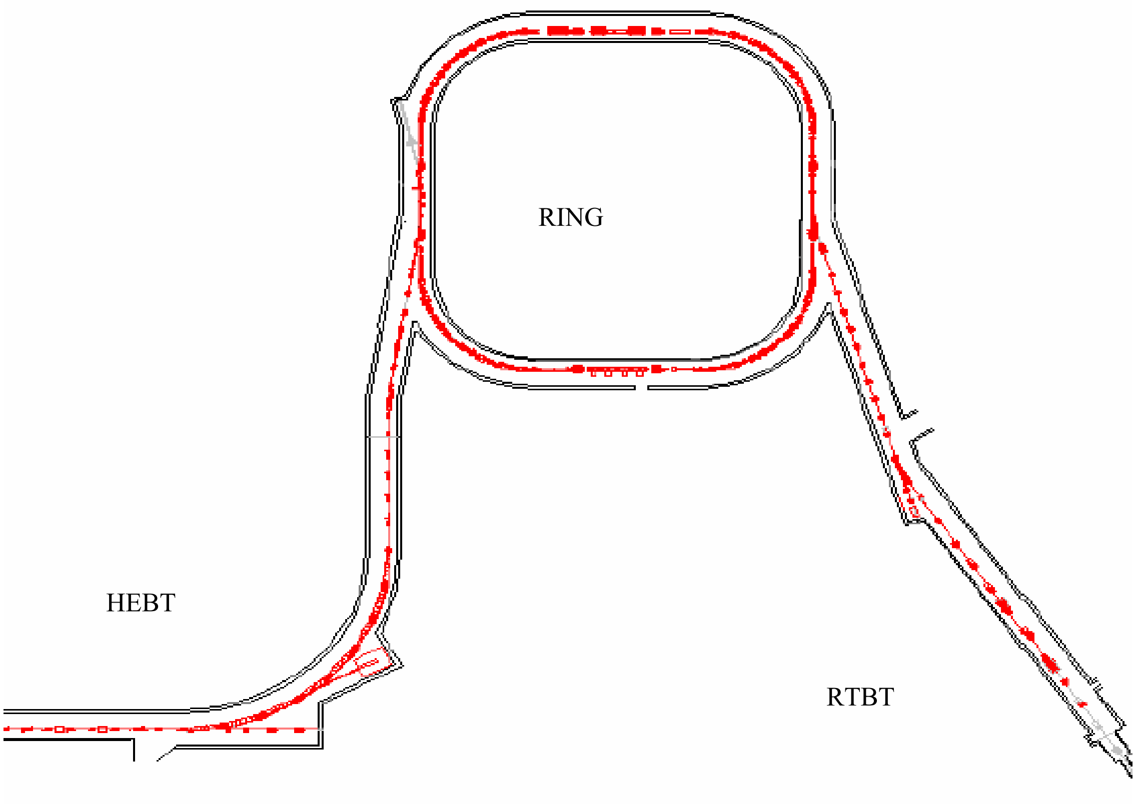


Fig. 5.1-23. General layout of the HEBT, ring-to-target beam transport (RTBT), and ring.

During the design and construction of the ring, great care was taken to ensure that all the latest knowledge on prevention and/or control of beam instabilities was taken into account. Often several systems or techniques were integrated into the design, while typically one would be sufficient. Additional systems were incorporated, while computer simulations showed they would likely not be necessary (feedback systems, extra diagnostics, larger aperture, coating of vacuum chambers, extra collimation etc.). In the ring, this very conservative approach was taken because beam power will ultimately be limited by the losses that appear during the accumulation cycle. Having a vast number of countermeasures available to minimize these losses allows for fast integration and rampup of the beam power during the first few years—for safe and reliable user operation at maximum performance—and for fast access to the equipment and hands-on maintenance if repair is required.

The ring itself consists of four straight sections and four arcs. Each straight section has a specific function beginning with the 9:00 o'clock position for injection and then in clockwise direction collimation, extraction, and RF. In the injection area, the H^- ion beam passes through a thin carbon or diamond foil, about one micrometer thick, where the two electrons are stripped off and the incoming H^- beam is merged in phase space with the circulating proton beam. This is a technique called charge exchange injection, which virtually allows particles to populate the same phase space without violating phase space conservation. A principal picture of the process is shown in Fig. 5.1-24, where H^- beam, the H^0 beam (only one electron stripped), and the unstripped beam is shown.

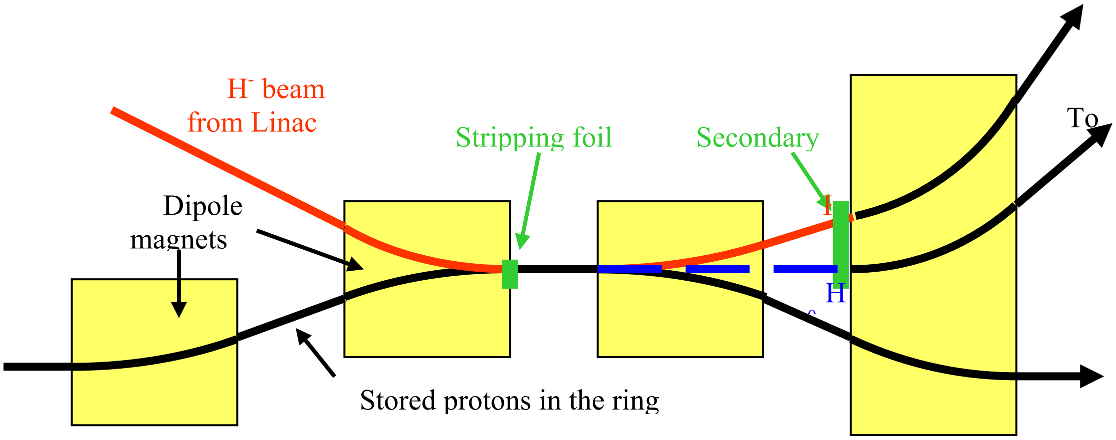


Fig. 5.1-24. Conceptual layout of the injection area. The circulating beam in the ring (bottom black line) is shown together with the incoming H– beam for the linac (red line). At the stripping point they both match up, and, after stripping, circulate in the ring. An unstripped and partially stripped beam is shown as well.

The series of photos in Figs. 5.1-25, 5.1-26, and 5.1-27 show views of the straight sections starting at the 9:00 o'clock position with injection, collimation, extraction, and the RF at 6:00 o'clock. A photo of the RTBT beam line leading into the Target Building is also shown.

All support systems are distributed aboveground in several buildings. The Ring Service Building (RSB) has the majority of the power supplies, the diagnostics installation, the water support systems, and the electrical distribution.

During ring commissioning all systems were brought online. Because they were thoroughly tested, commissioning proceeded very quickly. After only three days, charge exchange injection, accumulation, and extraction were demonstrated. Approximately two weeks later the project completion requirement was met. Figure 5.1-28 shows a pulse extracted to the extraction beam dump with a peak current of more than 3 A over ~700 ns. This converts into 1.3×10^{13} protons. Again, since the extraction beam dump can handle the design peak intensity but is limited to 7-kW average beam power, high-power testing is not possible.

Towards the end of the commissioning run, a bunched beam intensity as high as 5.5×10^{13} protons per pulse was achieved, which corresponds to a circulating peak current of more than 15 A. A coasting beam intensity of 1.0×10^{14} has been accumulated as well, which is significantly more than one-half of the design value and likely close to the world record for this type of accelerator. Initial studies of beam instabilities confirmed calculations that show instability thresholds beyond the present baseline design values.

5.1.5 RTBT Target Commissioning

During the target commissioning run, the remaining task was to turn on the last bend dipole in the RTBT beam line and send the beam straight into the target. The last four focusing magnets that provide the proper beam spot are very close to the target itself. Backstreaming neutrons from the target provide a significant radiation load (~1500 rem/h at 1.4-MW beam power) during operation. The design of these magnets is therefore quite different and encompasses radiation hard coils. The actual conductor is surrounded by a mineral insulation layer, which itself is contained by a copper tube. While providing a bad packing factor for wiring of the magnet, the insulation is 100% radiation resistant and should never have to be replaced in spite of the adverse conditions. Figure 5.1-29 shows one of the four magnets during initial delivery and a sketch of the vault for these radiation hard magnets.

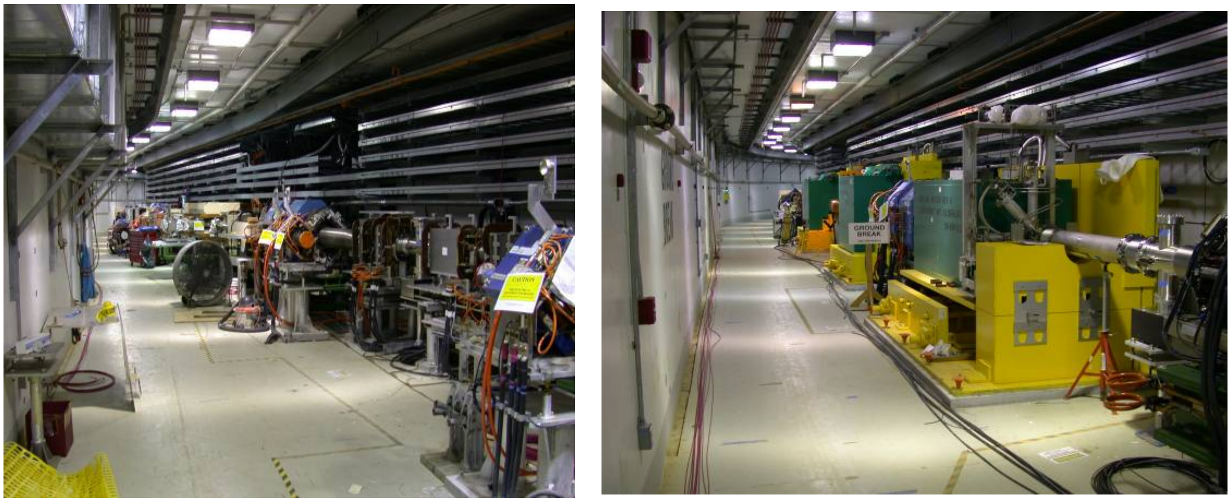


Fig. 5.1-25. View of the 9:00 and 12:00 o'clock positions of the ring. The left photo shows the junction between the HEBT and ring (injection), and the right shows the large collimators, half covered in yellow.

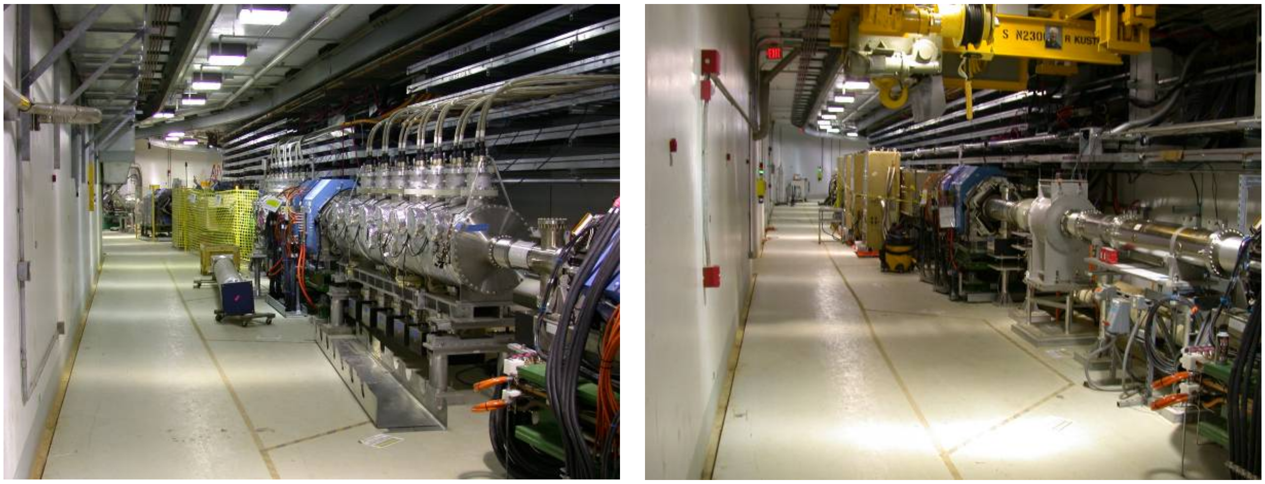


Fig. 5.1-26. View into the ring at the 3:00 and 6:00 o'clock positions. The left photo displays the two large extraction kicker tanks. The right photo shows the high-power RF systems (golden boxes) directly connected in the tunnel.

Fig. 5.1-27. Straight view into the RTBT tunnel toward the Target Building.

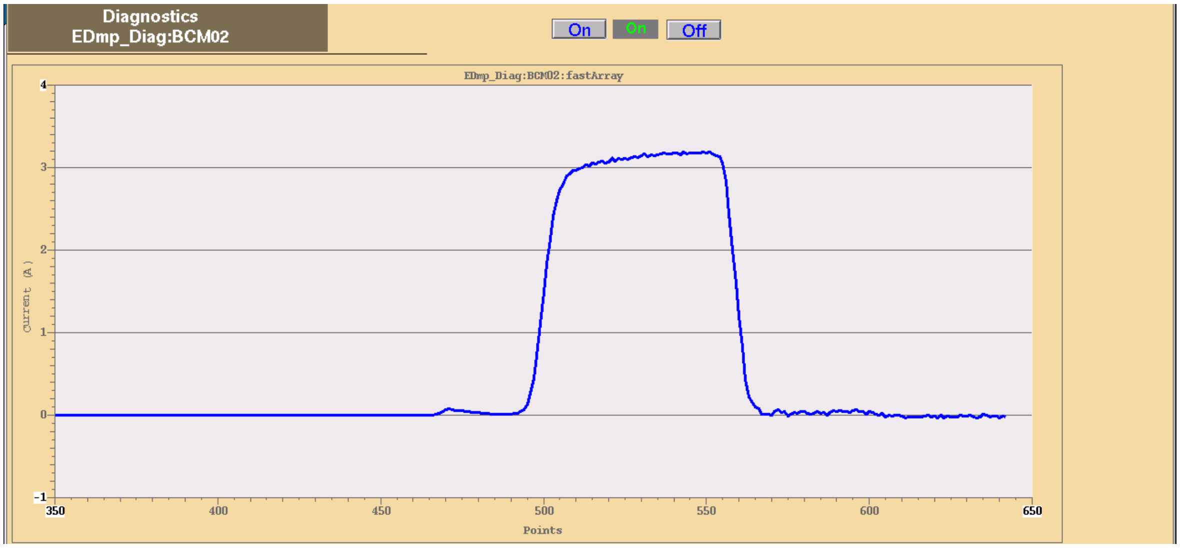


Fig. 5.1-28. Current pulse of an extracted proton beam measured in the extraction beam line towards the tuning beam dump. The current was integrated in the ring over ~200 revolutions and converts into 1 × 10^{13} protons.

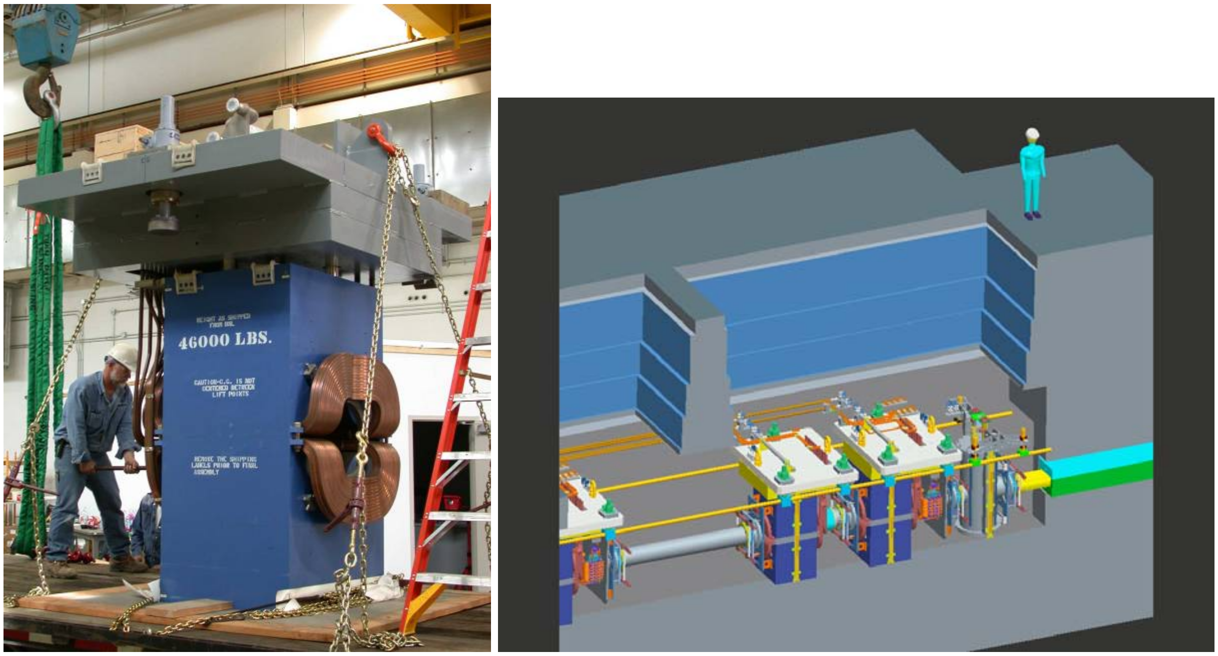


Fig. 5.1-29. One of the quadrupoles with its special radiation hard coils (left). On the right are shown the vault and the location of these magnets, together with the beam line leading to the target (to the right). On April 28, 2006, the first protons struck the target going down this beam line. Very quickly the intensity was raised to more than 1.0 × 10^{13} protons per pulse, which fulfilled the beam intensity requirement, as laid out it in the PEP. The beam size was qualified, and beam operation continued, since then transitioning directly into operation mode.

5.1.6 Beam Instrumentation and Diagnostics

The beam power that SNS will provide is approximately a factor of 10 higher than any other facility in the world. To be able to ramp up to this beam power and to control it, a whole new suite of instrumentation and diagnostics was necessary on top of the standard set that is required to operate an accelerator. Especially with respect to beam loss control and instrumentation, SNS had to foresee an order of magnitude higher resolution and precise control to ensure that hands-on maintenance would be possible and that beam spills would be detected immediately. Figure 5.1-30 gives an overview of the number of diagnostics tools that are made available for SNS during operation.

Even during construction of SNS, much of the diagnostics were further developed, and, for example, in the linac a completely new transverse beam size monitor system was developed and implemented with a baseline change in 2002. A laser-based system replaced the more standard carbon wire system, offering a list of advantages. For example, it can be used without interrupting user operation, no residual material from broken wires threatening performance of neighboring superconducting cavities, and an order of magnitude better resolution. This system clearly benefits SNS and pioneers future high beam power facilities. A picture of the laser beam line installed in the tunnel is shown in Fig. 5.1-31.

Even more standard hardware like beam position monitors (BPMs), beam current monitors (BCMs), and beam loss monitors (BLMs) were further developed and specifically adapted to SNS requirements. In many cases, features were added to these systems that have not been used before to the level of integration implemented at SNS. Time-of-flight measurement, used to energy tune the linac, is one example. The extraordinary dynamic range for the BCMs in the ring (10 mA–50 A) is another one. All of these systems were integrated and used during the commissioning runs so far. For the vacuum systems that are already installed in the ring, the electronic outfit for halo monitors, ionization profile monitors, quadrupoles moment monitors, and feedback pickups and kickers are planned.

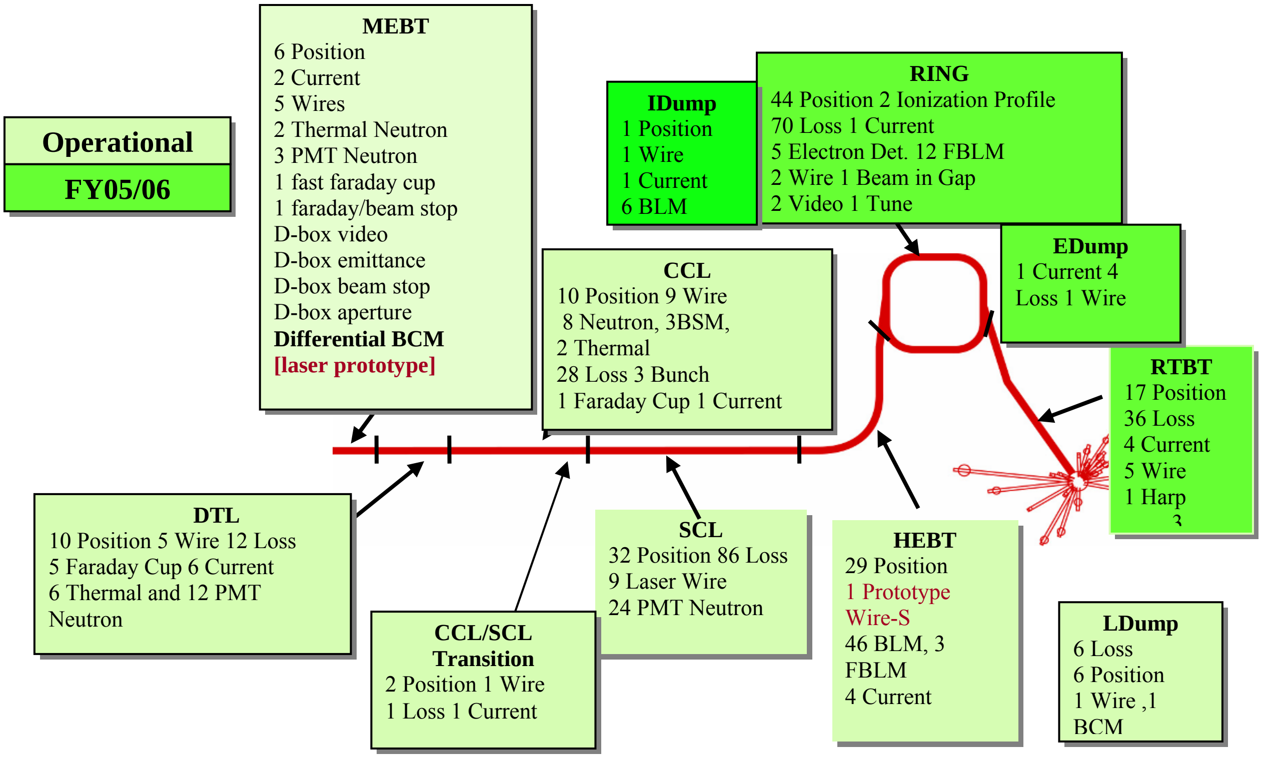


Fig. 5.1-30. Conceptual layout of SNS lists the available diagnostics and instrumentation. In addition, a whole set of more sophisticated tools is under development and is already foreseen in the ring, with vacuum chambers designed and installed to house them.

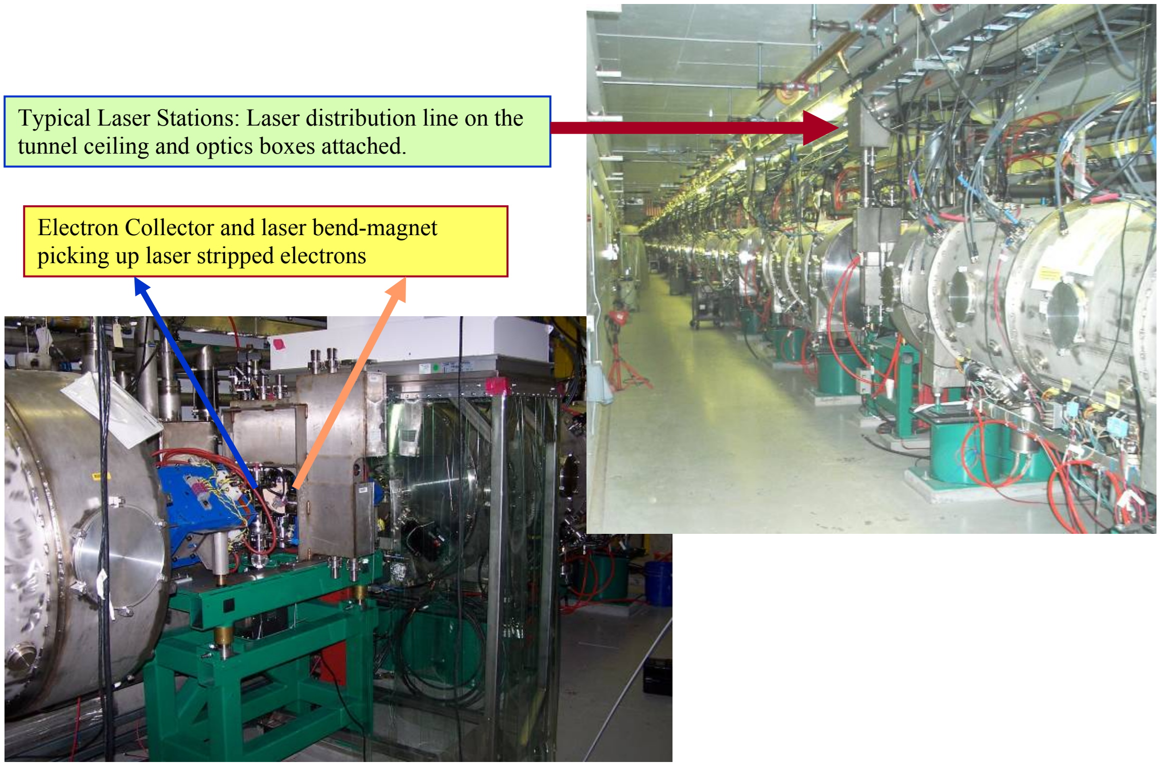


Fig. 5.1-31. Integration of the laser distribution in the linac tunnel, as well as the actual measurement stations within the beam line.

5.1.7 Summary

In summary, this assessment shows that the capability to support the project completion goal of 1×10^{13} protons per pulse has been consistently met through all commissioning runs. In general, much higher intensities were actually delivered. The ARR process guaranteed that all documentation and control processes, policies, procedures, and training are in place to support that operation. The greater than 1-MW technical beam power operation of the SNS facility has been achieved at this time and demonstrated with all major technical equipment, although not with beam, which is not possible because of the beam dump power capabilities. Moreover, all subsystems have been designed, constructed, and installed sufficient enough to ultimately support the specified 1.4-MW operation. Many of the technical subsystems can support more than 2-MW operation, which goes beyond the present project requirement and directly facilitates the proposed Beam Power Upgrade Project for SNS.

5.2 TARGET SYSTEMS (ORNL)

5.2.1 Target and Mercury Process Systems

5.2.1.1 System description

The SNS target assembly comprises a target module mounted on a target carriage that moves on, and is propelled by, the carriage transport system. The target module is subjected to both irradiation and cavitation erosion and, therefore, must be replaced periodically.

As illustrated by Figs. 5.2-1 through 5.2-5, the target module is an assembly of stainless steel vessels that mounts to a weldment at the end of the mercury loop piping assembly. It is held in place with eight bolts. Part of the module is a flange with a diameter of ~25 in. that incorporates an inflatable metal seal comprising two concentric stainless steel contact surfaces separated by an actively pumped cavity that separates the core vessel and target service bay volumes. The location of the target module is shown at the end of the target plug in Fig. 5.2-6. The term target "plug" refers to the assembly that combines the target module, lengths of mercury loop piping, carriage, and shielding.

In front of the inflatable seal flange, the module consists of two concentric vessels: an inner vessel for containing the target mercury and an outer vessel for containing mercury that could leak from the inner vessel. These vessels are of welded fabrication. The forward-most section of both vessels receives nuclear heating load from the incident proton beam, as well as the neutrons that are produced by proton beam interactions with the mercury. These sections, or beam windows, are constructed with double walls with well-defined coolant flow conditions in the gaps between the walls. The walls of the inner vessel, referred to as the "mercury vessel," are cooled by flowing mercury, while the outer vessel is cooled by water, resulting in its designation as the "water cooled shroud." The mercury used to cool the beam windows of the mercury vessel is supplied separately from that in the bulk portion of the target. This window flow reunites with the bulk flow at a point inside the module for the return to the cooling loop. The proportion of window flow to bulk flow is determined by a fixed orifice selected to yield window flow in the desired range.

The module section to the rear of the inflatable seal flange is a block of stainless steel with machined internal passages that direct the flowing mercury into the respective passages in the forward mercury vessel. Concentric knife edges are machined into the lower surface of the rear sections for sealing mercury passages with soft iron gaskets. A seal plate with knife edges on both the top and lower surfaces provides both a leak-tight joint between the mercury flow channels on the module and those on a mating manifold at the end of the piping on the carriage and the ability to replace the sealing surface on the permanent carriage piping.

The water lines on the module, as well as the nitrogen, helium, and vacuum lines needed to operate the seals, are connected to the respective utility lines on the carriage by demountable jumpers. Other jumpers connect the carriage to points on the target module used for venting the mercury lines during filling and for interfacing to instrumentation installed on the target module.

The mercury vessel and water-cooled shroud provide redundant barriers against the leakage of mercury into the core vessel. The mercury vessel and water-cooled shroud are separated by a helium-filled interstitial region. Two instruments are provided to detect leakage into the interstitial space. The first employs a heated resistance temperature detector (RTD) concept to detect the presence of liquid and is able to discriminate between water and mercury. The second monitoring instrument is an electrical conductivity probe that detects when mercury is between the contacts.

The target module is designed for periodic remote replacement. Before replacement of the target module, mercury is drained to the storage tank, piping connections are removed in the target service bay, and the target carriage locking mechanism is released. The target plug (i.e., the whole target carriage, including the target module) can then be driven from the operational position back into the target service bay, where the replacement can begin using specially designed remote manipulator equipment.

The carriage is mounted on wheels that move along precisely aligned rails to allow the target to be installed and removed. Once in position, the target carriage is firmly locked to prevent movement. The carriage assembly includes passive shielding surrounding the piping connecting the target module to the process systems. Figure 5.2-7 shows the target plug, target carriage, and mercury process system.

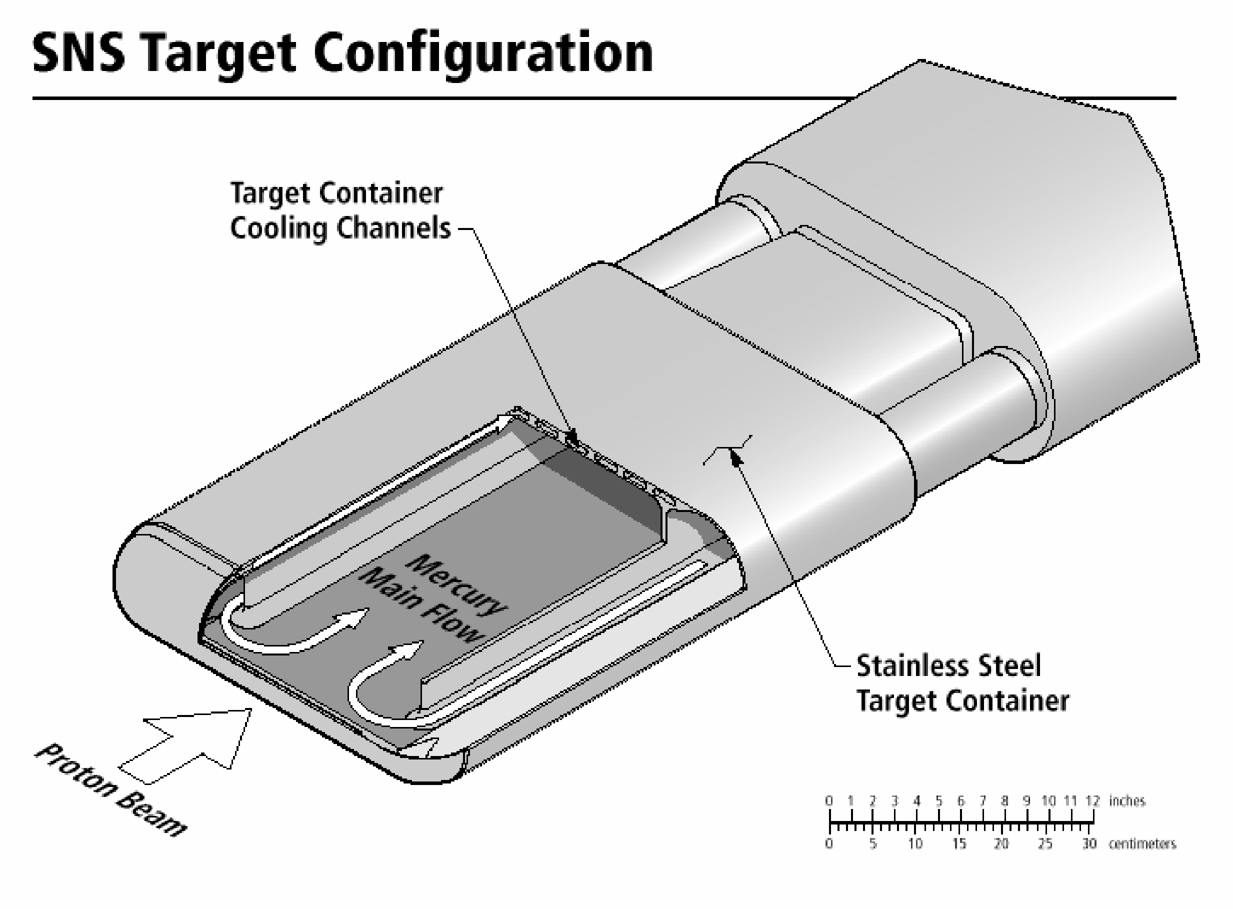


Fig. 5.2-1. Target module illustration showing internal mercury flow paths.

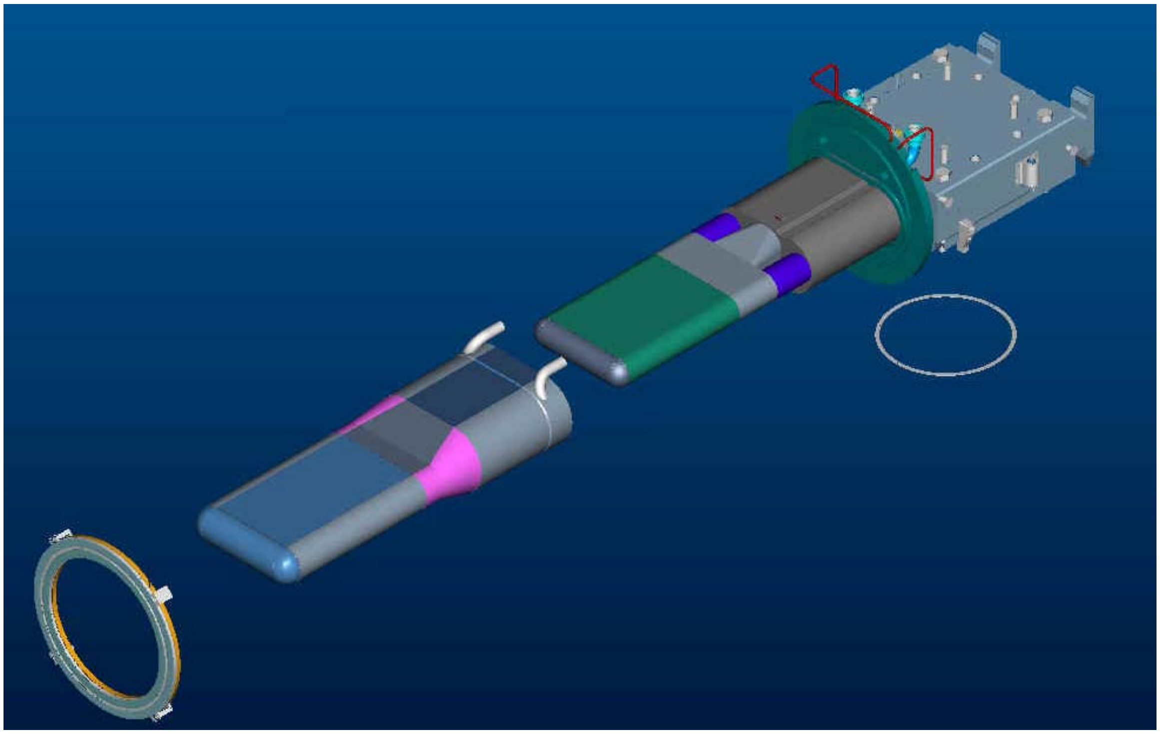
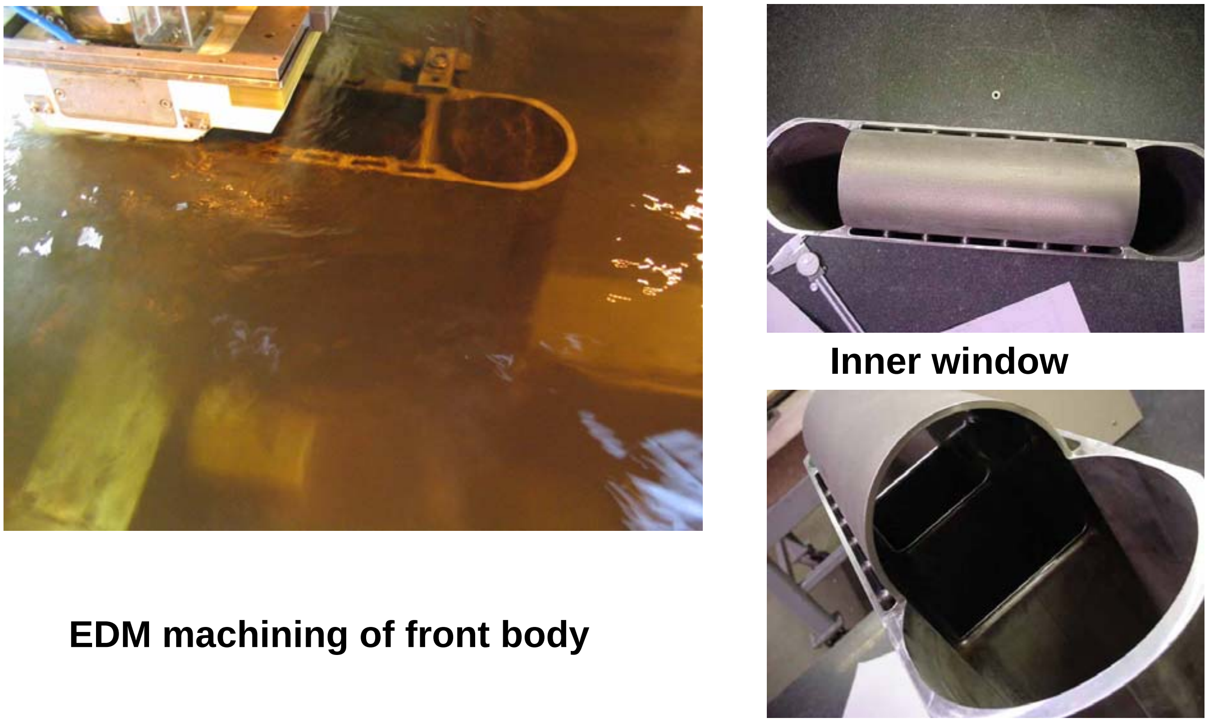


Fig. 5.2-2. Exploded view of target module.

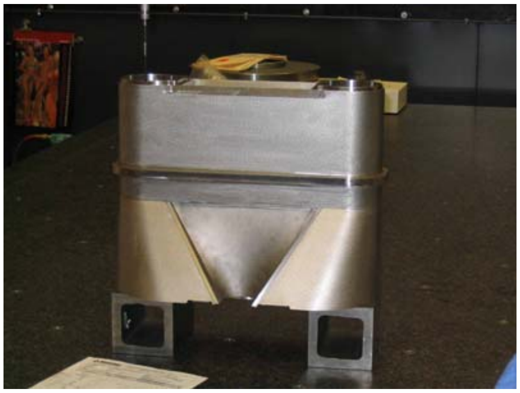


Inner window

EDM machining of front body

Fig. 5.2-3. Fabrication of target module front body.

Transition



Rear body with mounting block

Figure 5.2-4. Fabrication of target module transition and rear body sections.

Fig. 5.2-5 .Target module mercury vessel and water shroud before welding.

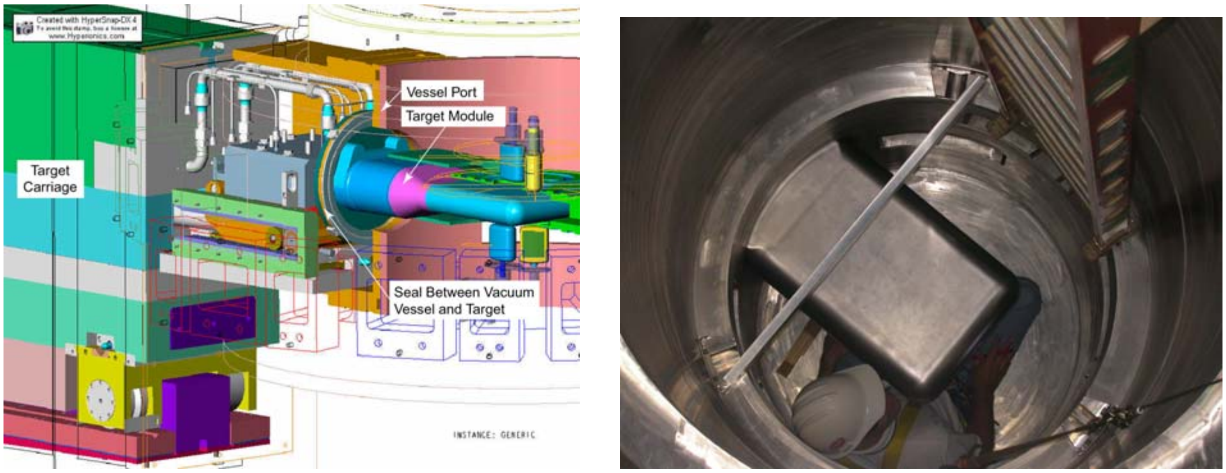


Fig. 5.2-6. Target module interface with core vessel.

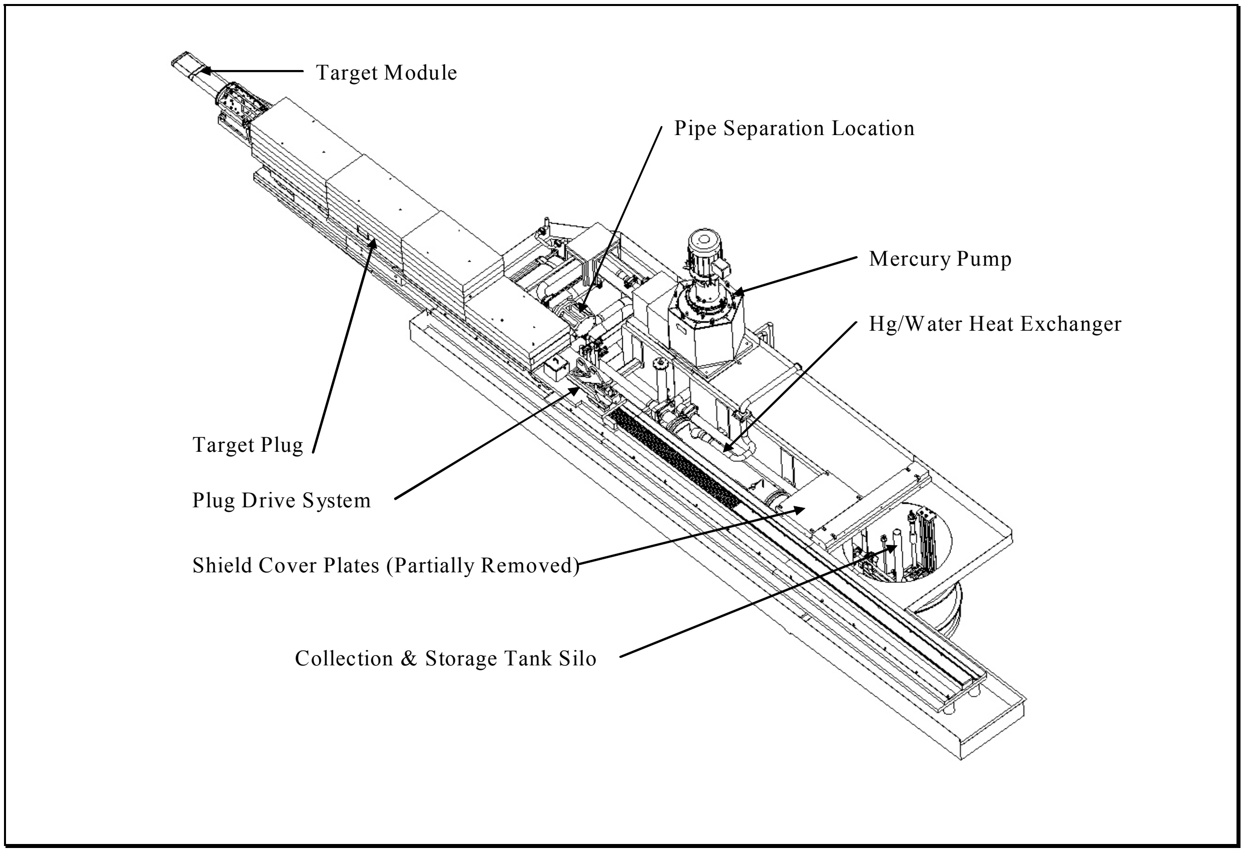


Fig. 5.2-7. Components of the mercury target system.

A system of mechanical levers (Figs. 5.2-6 through 5.2-9) driven by pressurized water actuators is used to drive the carriage between its withdrawn position in the target service bay and its operational position inserted into the target tunnel. The water pressure utilized is within the range of a standard industrial hazard. The quantity of water in the actuator system would not challenge the storage capability within the target service bay if a line failure occurred. Figures 5.2-10 through 5.2-14 show installation of the carriage assembly, heat exchanger, and valve.

The mercury process loop contains a total of ~1.4 m^3 (~19,000 kg) of mercury circulating at a rate of ~325 kg/s. The pressure of the mercury as it flows through the target module region is ~0.3 MPa. Interaction with the proton beam raises its bulk temperature from a nominal 60°C at the inlet to a predicted ~90°C at the outlet during normal operation at the maximum 2-MW beam power.

The western approximately half of the target service bay contains the components required to process, circulate, and cool the mercury, as well as the cooling water in the shroud surrounding the target, as shown in Figs. 5.2-7 and 5.2-15. The mercury loop includes the piping, valves, main circulating pump, and mercury-to-water heat exchanger, along with storage tank, and control and monitoring sensors necessary for operation. Since the mercury will be radioactive, the system is located in the target service bay and will be operated and maintained remotely. Components expected to require changeout are connected by remotely operated flanged connections. As detailed subsequently, the stainless steel liner of the process bay is designed to allow spilled mercury to gravity drain to the collection basin. A double-wall heat exchanger configuration is used to present an extra barrier between the flowing mercury and its coolant water in the heat exchanger.

Mercury storage tank and collection basin. As shown in Figs. 5.2-7, 5.2-16, and 5.2-21, both the storage tank and the collection basin are located in a compact arrangement in a cylindrical silo surrounded by concrete. The enclosed storage tank is suspended above the collection basin, at an elevation below any part of the mercury loop. This allows gravity drainage from the loop to the storage tank. The mercury loop is drained to the storage tank periodically for replacement of the target module. After the loop is reassembled and leak tested, helium pressure is increased in the storage tank gas space to refill the loop. The elevated helium pressure on top of the mercury during the loop filling operation forces the mercury into the pipe that connects the loop with the storage tank. During operation, ~1.4 m^3 of the mercury inventory is in the loop and ~0.2 m^3 in the storage tank. After loop drainage, the entire inventory (~1.6 m^3) is held in the storage tank.

The collection basin is constructed as a double-wall stainless steel vessel open at the top and is installed to be structurally independent from the surrounding concrete pit. The depth of the basin was determined so that the entire mercury inventory could be contained in the volume between it and the storage tank. Spilled fluids reach the collection tank through the open annulus between the storage tank and the silo wall.

The storage tank is a cylindrical vessel with dished heads. A circular passage connects the heads along the axial centerline. In addition to providing a duct for air cooling of the storage tank, this passage can be used to access the collection basin for removal of contained liquids. A small depression is provided in the collection basin directly below the passage to facilitate the ability to remove liquid contents from the basin.

The wall of the upper part of the silo is covered by a stainless steel liner connected at the top to the floor liner and at the bottom to the collection basin. A continuous stainless steel path is thus formed for the flow of all spilled mercury toward the collection basin. Thermal analysis has shown that under the worst-case spill conditions the mercury temperature in the collection basin remains in an acceptable range without active cooling.

Mercury spill drainage design features and function. The target service bay (i.e., the west approximately half of the target service bay that contains the mercury loop) is designed to allow mercury spillage to drain to the collection basin by gravity. The key to this design is the 1° nominal slope specified for the stainless steel floor liner underneath mercury loop components.

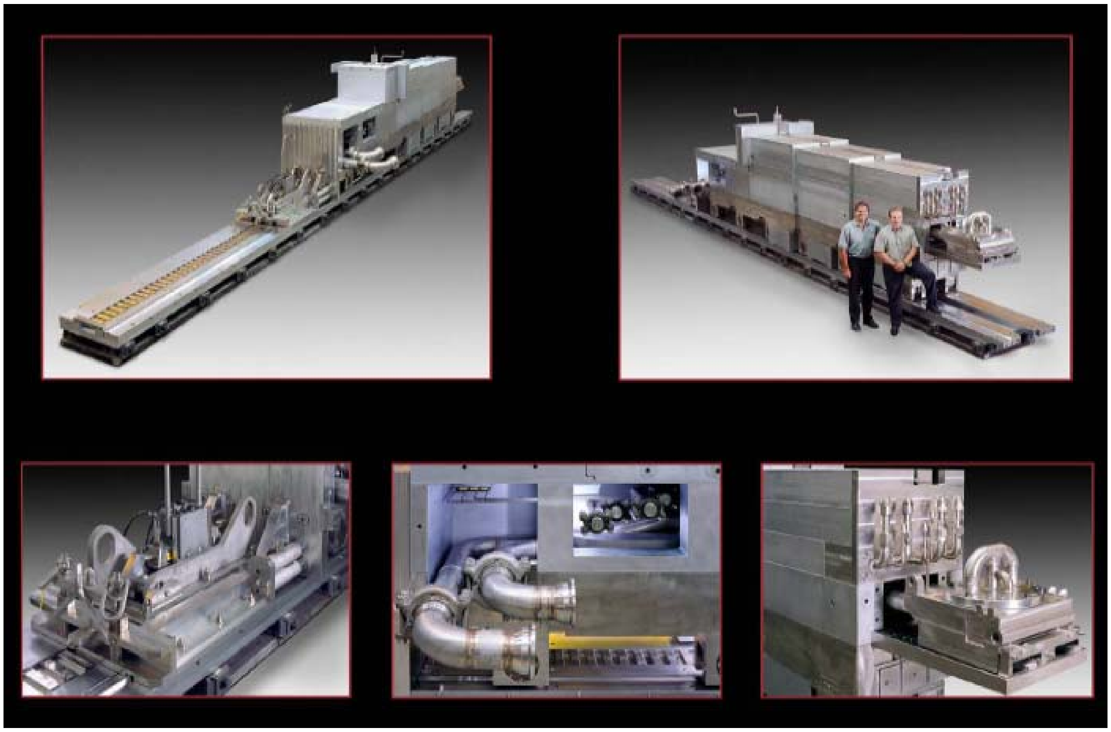


Fig. 5.2-8. Target plug and rail system at Major Tool & Machine (August 2004).

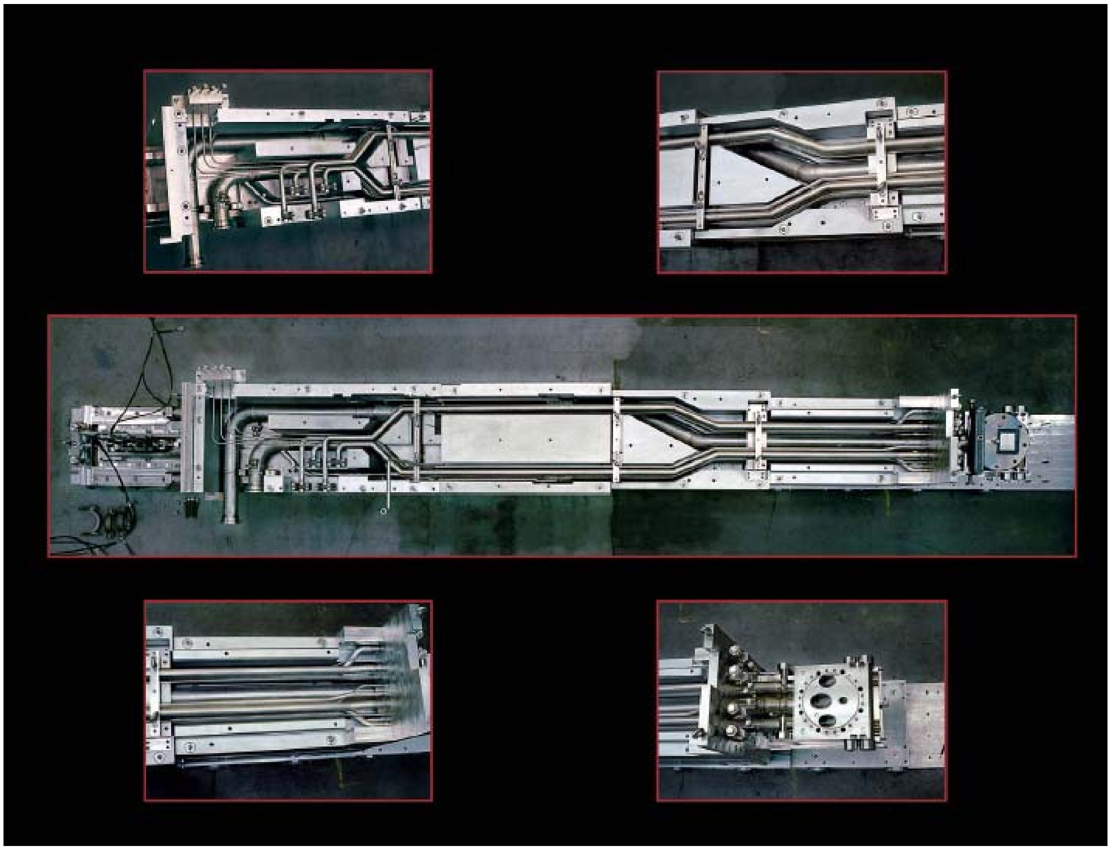
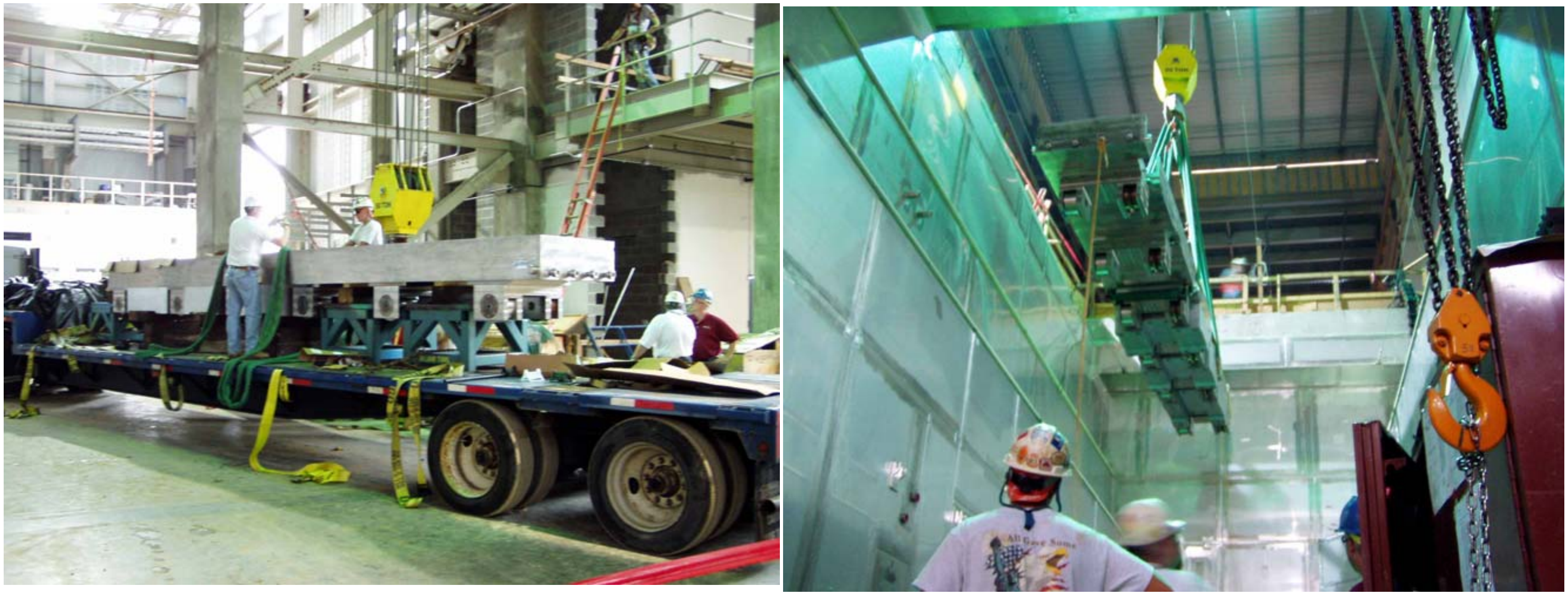


Figure 5.2-9. Target carriage piping.

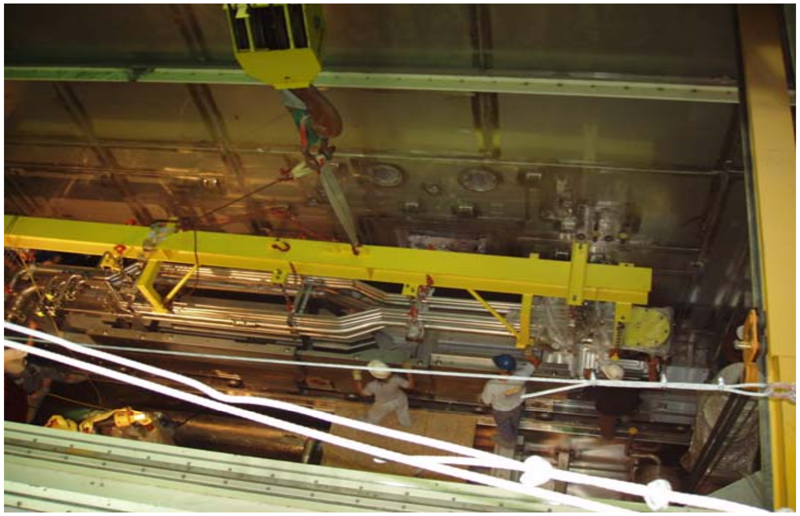


Arrival on truck

Being lowered into service bay

Fig. 5.2.-10. Installation of target carriage base.

Delivery of the mercury and utility piping assembly. The fixture is designed to allow manufacture of replacement piping.



Installation of the piping assembly on the carriage base.

Fig. 5.2-11. Installation of carriage piping.

External view of pump

Pump removed from vessel

Fig. 5.2-12. Mercury pump.

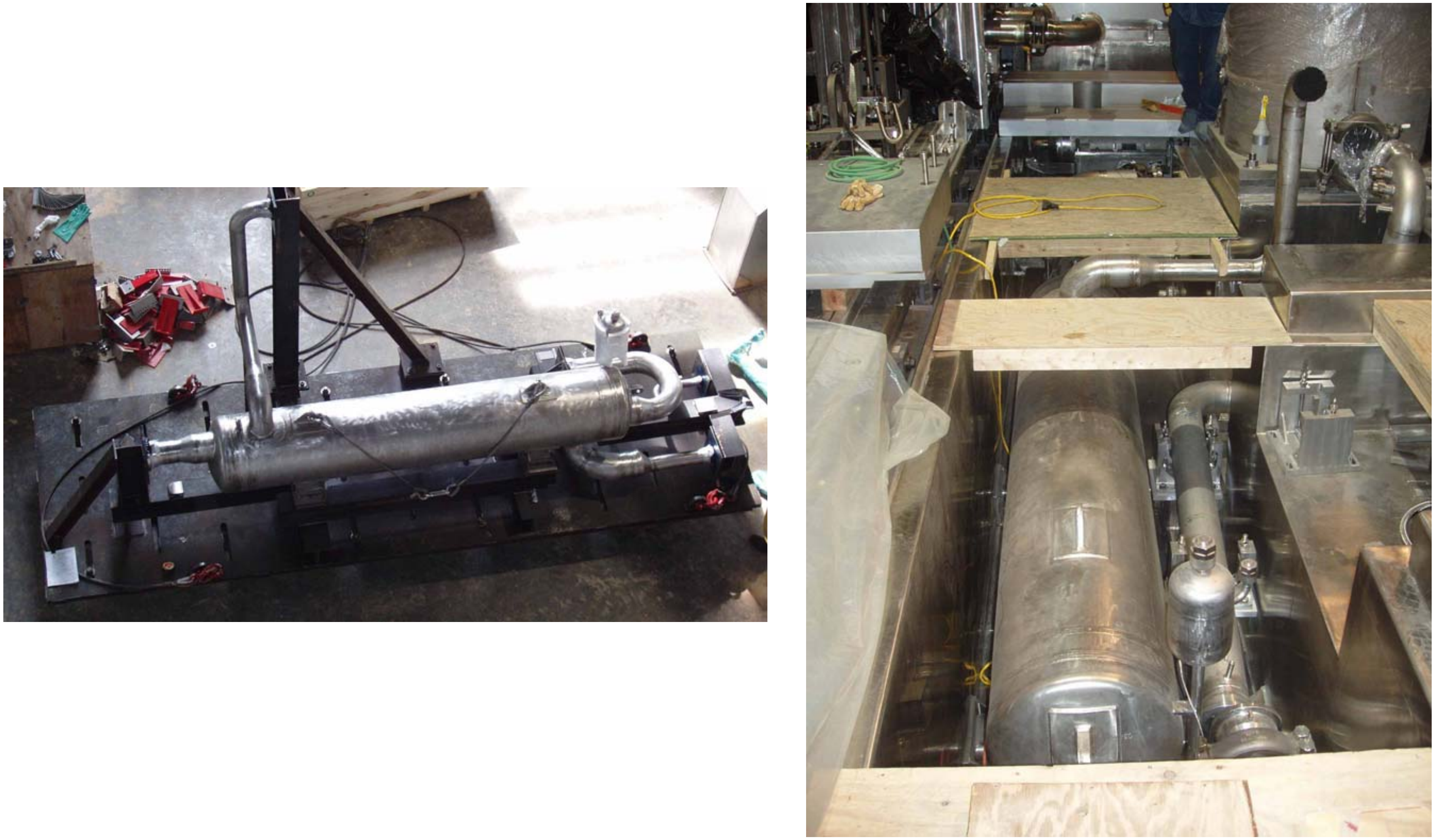
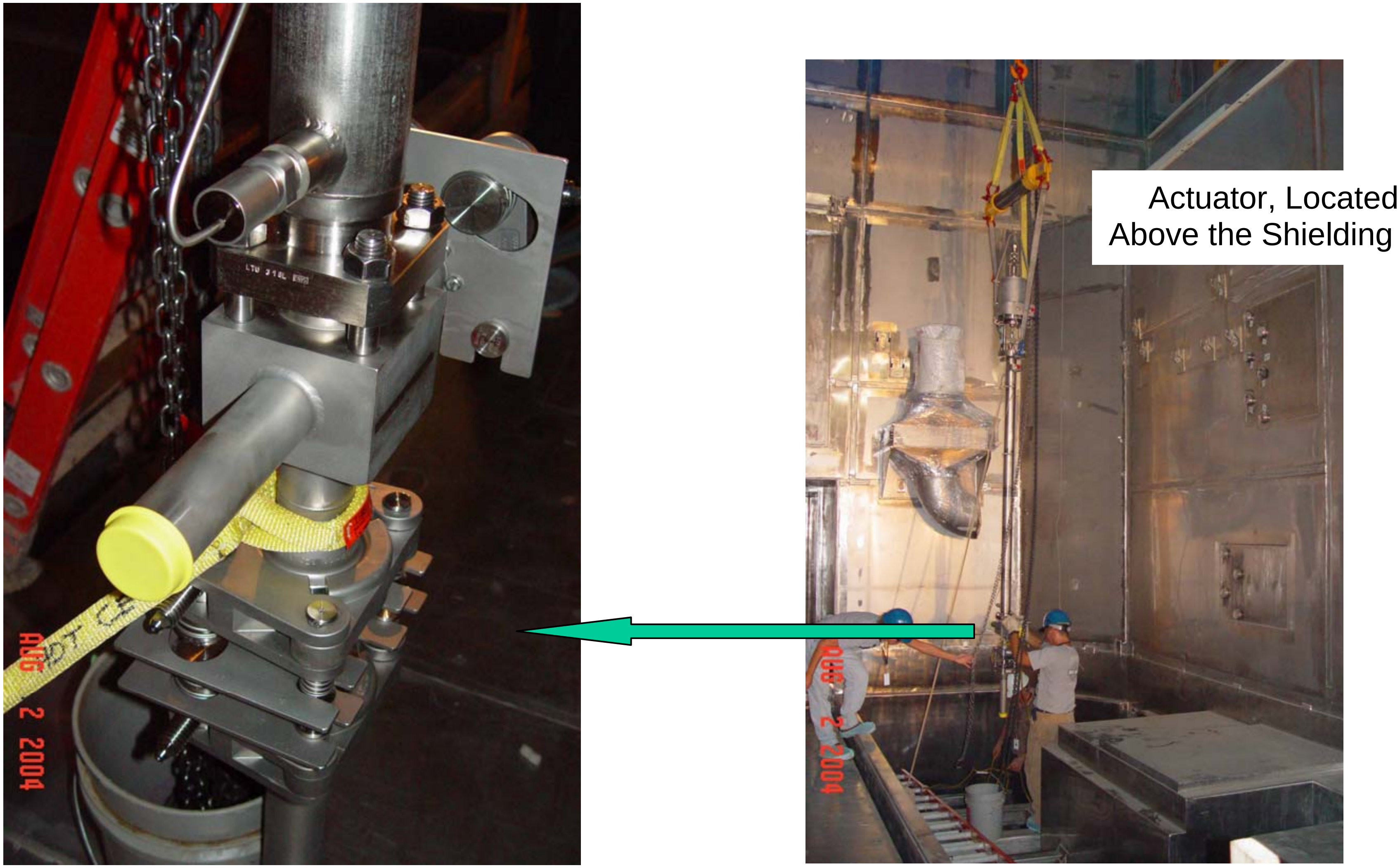


Fig. 5.2-13. Mercury double wall heat exchanger on tooling and installed in target service bay.



20-in. (50-mm) right-angle valve with remote flanges

Installation of the valve

Fig. 5.2-14. Mercury transfer valve.

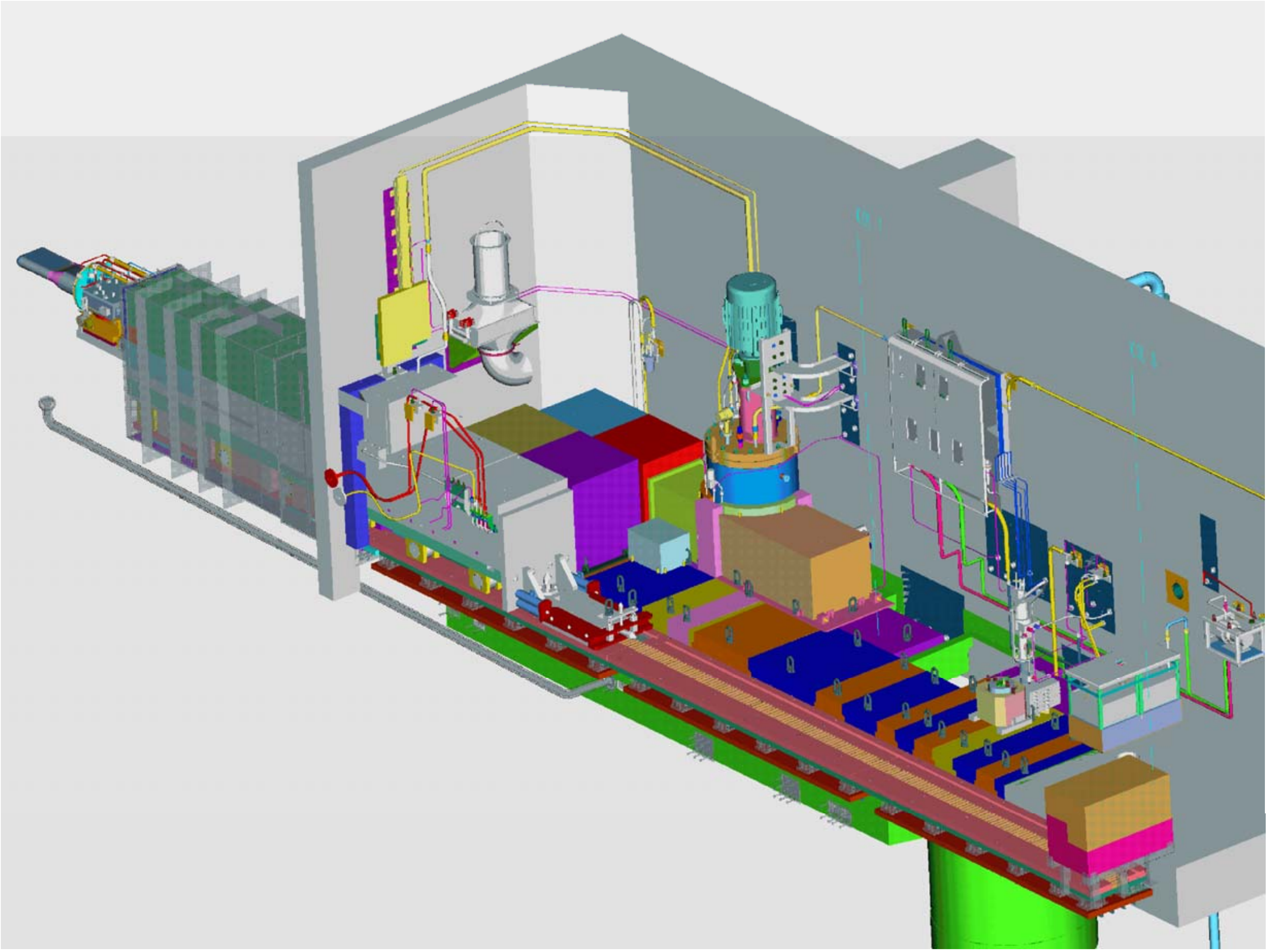


Fig. 5.2-15. Isometric of process bay showing mercury loop shielding with target plug carriage inserted into the monolith in operational position [the part of target service bay to south (left) of carriage tracks omitted for clarity].

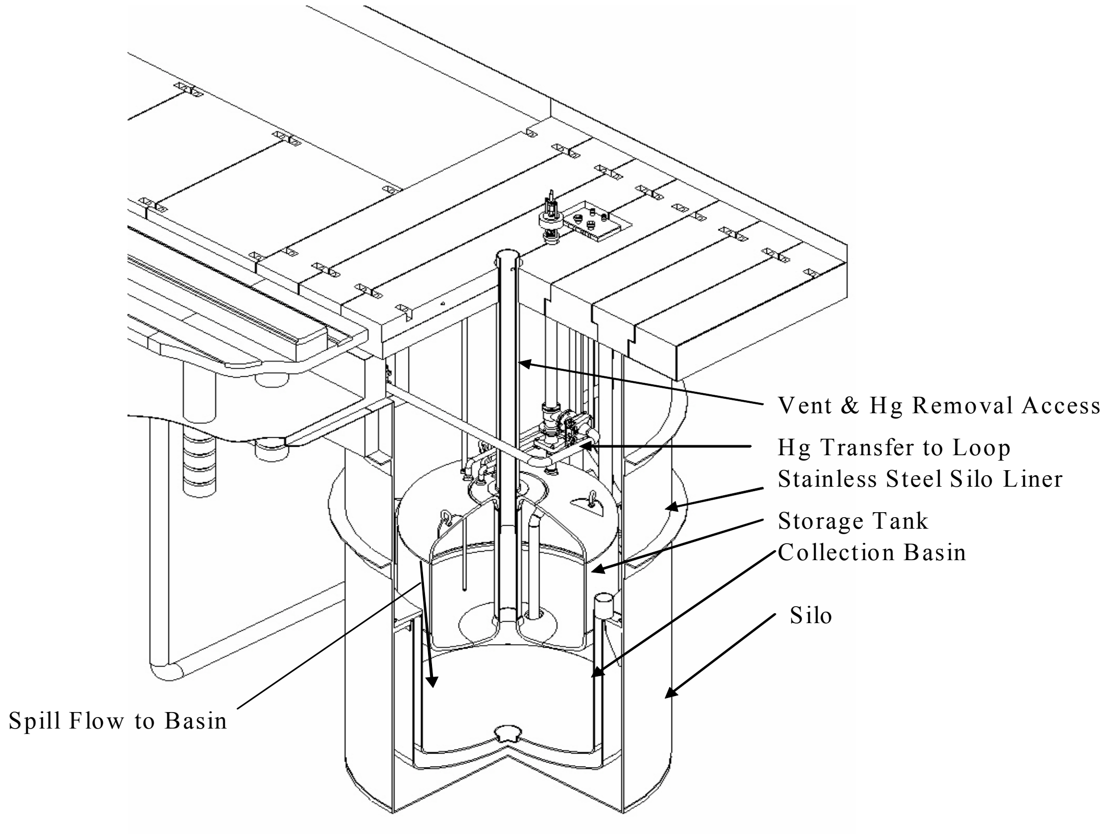


Fig. 5.2-16. Storage and collection silo general arrangement.

This feature provides mitigation for a loss of mercury confinement event by minimizing the surface area of mercury exposed to air and the duration of time it is exposed as it is draining to the collection basin. The drainage feature is a passive credited engineered control.

Figure 5.2-17 shows the drainage areas and directions of floor slope. The carriage track area, i.e., the southern ~5-ft-wide by 48-ft-long section of the process bay, is sloped north toward a trough that is ~48 feet long by 2 inches wide by ~9 inches average depth and is sloped toward the notch between the track area and the collection basin. The floor of the carriage tunnel is sloped east to direct leaks in the tunnel back toward the carriage track area and collection trough. The floor of the sunken heat exchanger pit is sloped to the east, toward the collection basin.

The steel shielding that surrounds the mercury loop is an additional feature of the mercury process system and target service bay that would help minimize the extent of contamination following a mercury spill event. This includes the ~12-inch-thick steel beams that cover the trench in which the heat exchanger and collection basin are located, as well as the "doghouse" shielding cabinets made of ~4-inch-thick steel that encloses the pump discharge (cold leg) piping and part of the hot leg piping (i.e., before it turns down through a hole in the 12-inch shielding to enter the trench on its way to the heat exchanger). The purpose of this shielding is to minimize background radiation in the target service bay during operation so that electrical cables, etc., can have an adequate service life. The safety benefit is that leaks/breaks in the mercury loop would occur inside a largely closed space inside the target service bay. Figure 5.2-15 illustrates the mercury loop with shielding installed. Another benefit of this shielding would come about

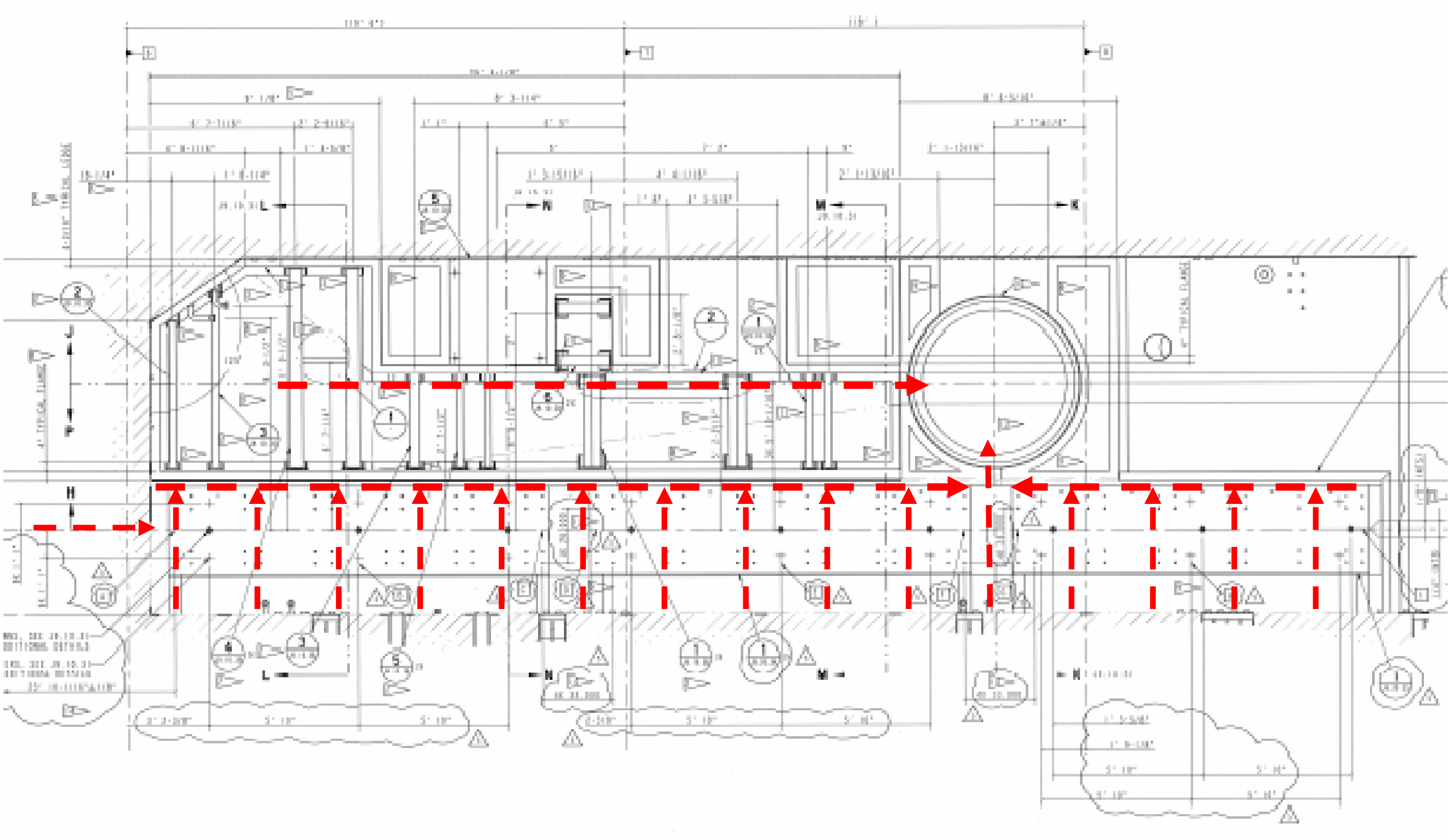


Fig. 5.2-17. Target service bay process bay spill drainage directions and areas.

In the highly unlikely event of a significant fire in the target service bay, whereby the radiation shielding would provide thermal shielding for the mercury loop piping inside. The “doghouse” shielding cabinets that cover the 6-in. piping will not be installed during initial zero- and low-power operations since they are necessary only for operations at significant beam power.

Double-wall heat exchanger design. The mercury-to-water heat exchanger uses a robust double-wall heat exchanger design to minimize the risk of contaminating the cooling water with the highly radioactive target mercury. Figure 5.2-18 shows the double-wall arrangement during fabrication. The target mercury flows inside the tubes, essentially; unirradiated mercury resides between the concentric tube walls; and cooling water flows outside the tubes. Although the interstitial mercury is described as “unirradiated,” it is recognized that the unirradiated mercury will absorb stray neutrons and eventually become slightly radioactive. Calculations indicate that the degree of radioactivity will lead to dose rates only on the order of a few millirem/hour on contact. To achieve the heat transfer benefit of interstitial mercury, the gap has sufficient width to allow the filling to ensure that bubbles and gas pockets are minimized.

During normal operations, the interstitial mercury is maintained at a higher pressure than the circulating, irradiated mercury and the cooling water. Because of the pressure differential, a through-wall failure of the inner tube would result in transfer of interstitial mercury into the circulating, highly radioactive mercury. Likewise, a through-wall fault of the outer tube would result in the loss of interstitial mercury into the cooling water. Simultaneous faults of both inner and outer tube would result in transfer of cooling water into the irradiated mercury since cooling water is kept at a higher normal pressure than the circulating, irradiated mercury. The heat exchanger integrity surveillance program relies on periodic measurements of the ability of the interstitial space to retain pressure and/or vacuum and frequent surveillance of the available interstitial mercury instrument indications.

5.2.1.2 Installation and testing

All components of the mercury loop have been installed, and the design flow rate of 380 gallons/minute of mercury was demonstrated on January 6, 2006, with the target in the operating position in the core vessel and the inflatable seal functioning. The loop was run at up to 60ºC, which is the target design inlet temperature for operation at 2 MW. The first target module is designed for up to 1-MW beam operation, and all other components are designed for up to 2-MW of beam operation at the demonstrated flow rate. Design water flow rates have been demonstrated in the water-cooled shroud and in the secondary side of the mercury heat exchanger, with operating leak detection systems in the interstitial region of the heat exchanger. The mercury loop has also been operated continuously for up to three days and with all water loops operating. Normal draining and filling operations have been demonstrated multiple times.

Remote-handling testing has demonstrated the target replacement process. Remote-handling testing has also been completed for all other components that are expected to require replacement.

A summary of the major system and integrated system tests is given in Table 5.2-1. A summary of the overall mercury flows is given in Table 5.2-2. Figures 5.2-19 through 5.2-23 are representative installation pictures.

Table 5.2-1. Major target assembly testing

SST1.6.1-5	Water test of mercury loop	7/20/05	Demonstrated loop operation with water
SST1.6.1-6	Target seal testing	9/30/05	Demonstrated inflatable seal operation
SST1.6.1-8	Mercury loop operation with mercury	1/19/06	Full operation with mercury for up to 3 days at nominal flow rates for 2-MW beam
Full integrated operational testing	Mercury loop run with all other	4/23/06	Integrated testing of all systems to simulate beam operation

systems

Table 5.2-2. Comparison of measured and calculated mercury flows

Nominal Mercury Flow Condition	SNS Data (410 rpm) taken 4/17/2006	FATHOM Model
Total Supply Flow (gpm)	380	382
Return Flow (gpm)	391*	382
Window Flow (gpm)	30	27
Pump Discharge Pressure (psig)	43	43
Pump Head (psid)	40	41

*****Actual return must equal supply – differences due to measurement tolerances.

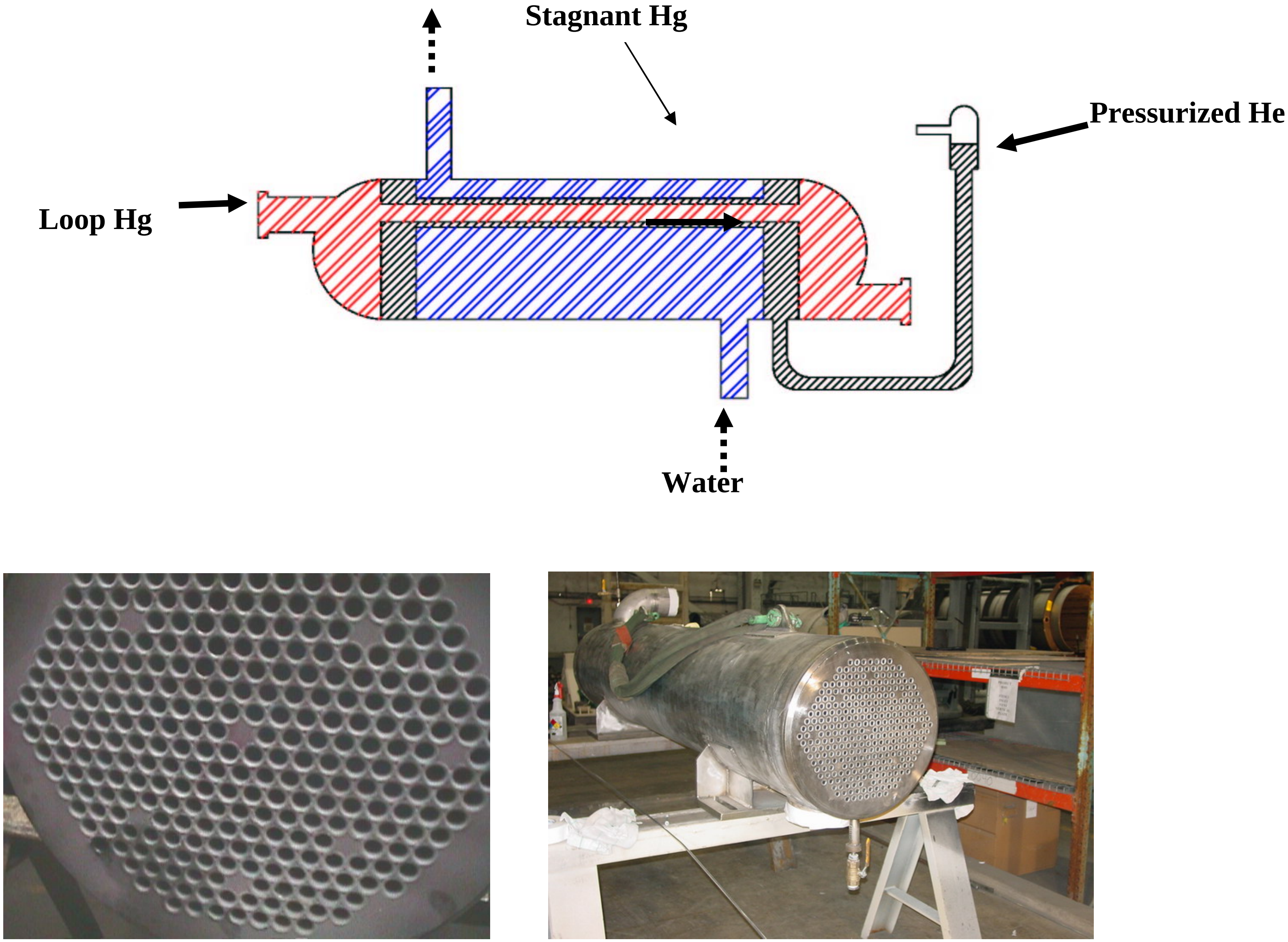


Fig. 5.2-18. Double-wall mercury-water heat exchanger schematic and fabrication prior to welding end caps.

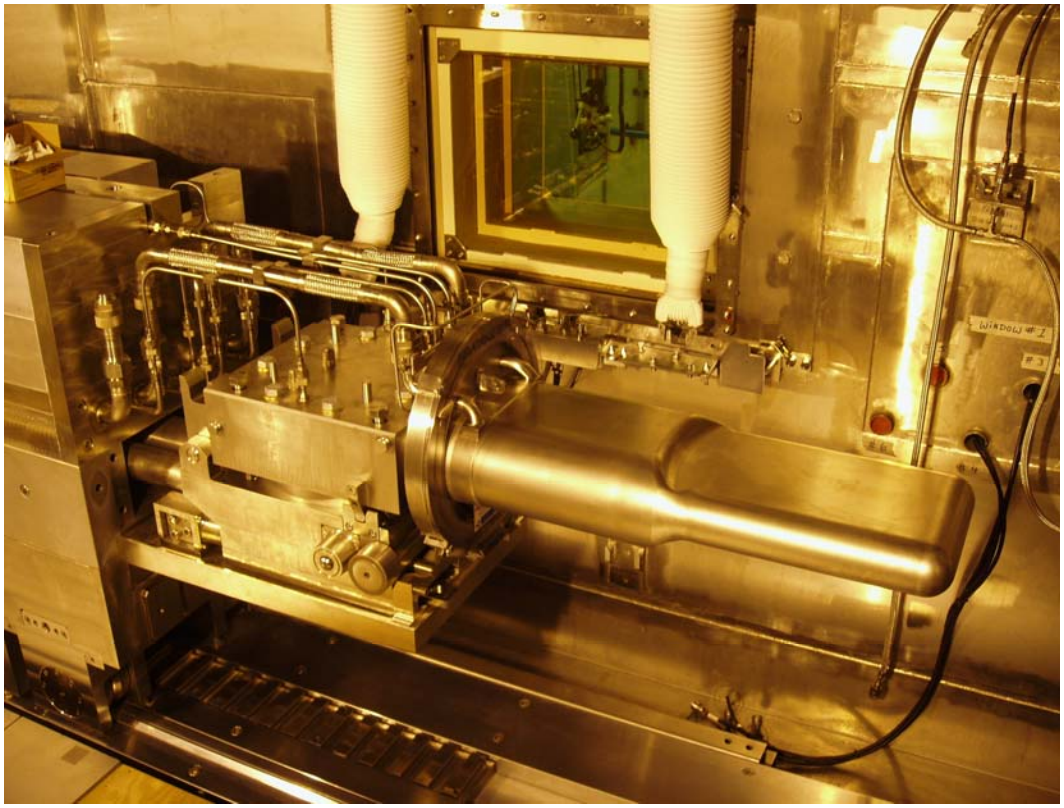


Fig. 5.2-19. Target module installed on front of carriage assembly (7/7/05).

Fig. 5.2-20. Target carriage in operating position and mercury pump.

Fig. 5.2-21. Mercury collection basin and mercury storage tank installed in collection basin.

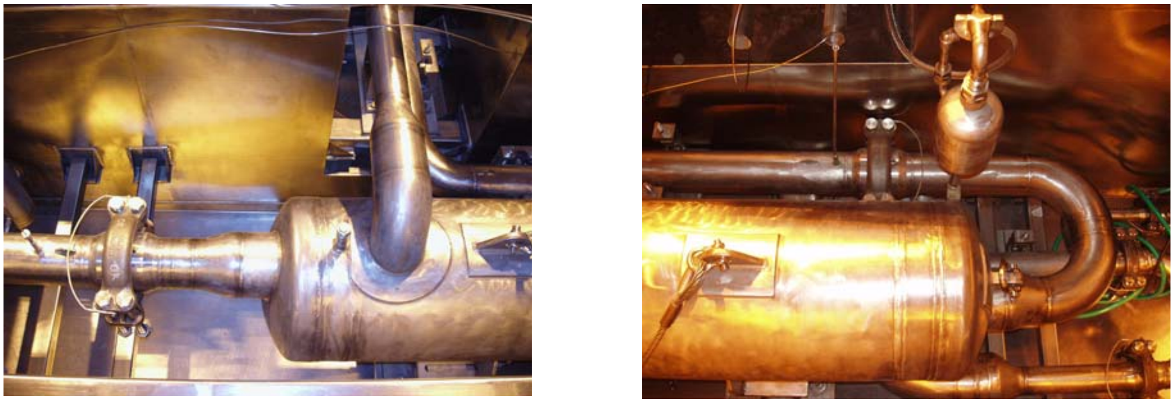


Fig. 5.2-22. Two ends of the installed mercury heat exchanger.

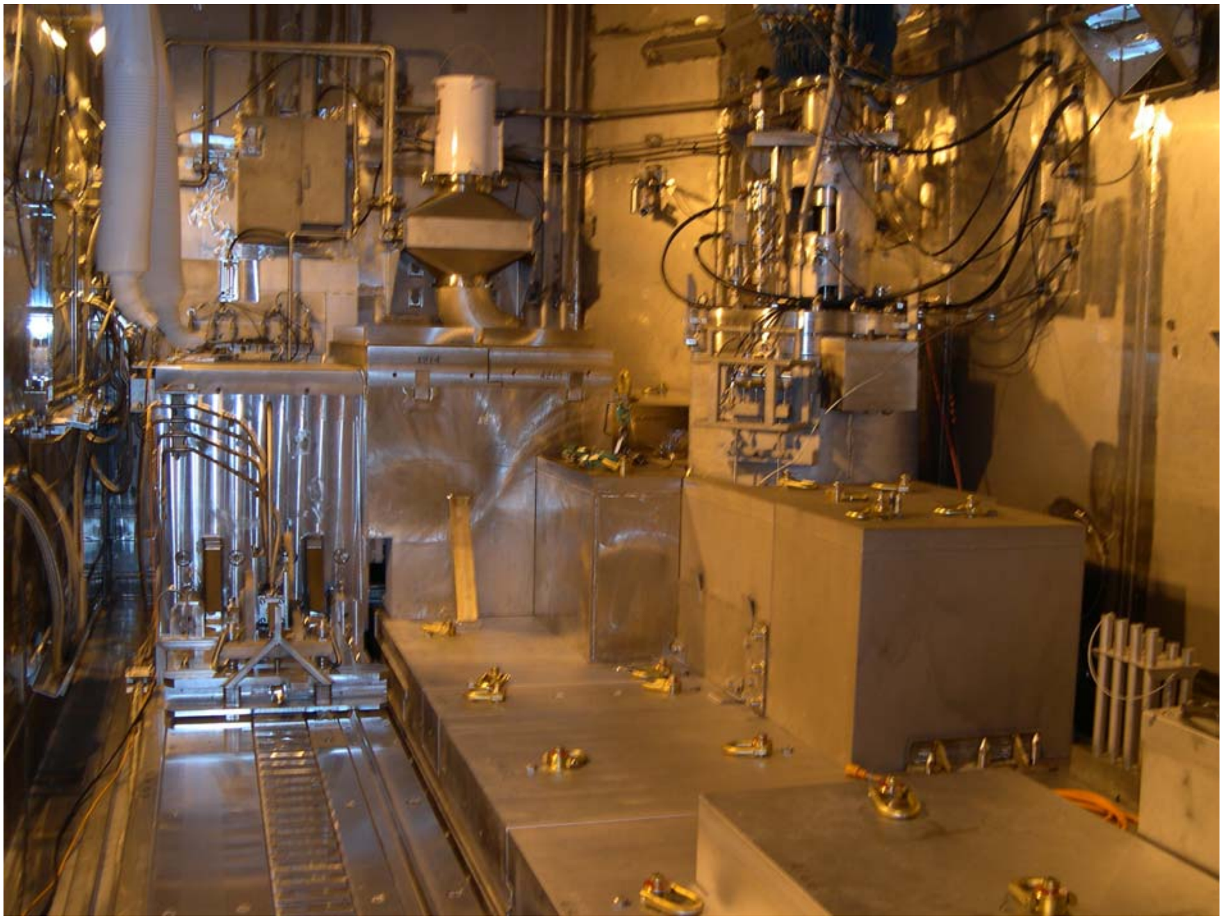


Figure 5.2-23. Target Service Bay with above floor shielding installed.

5.2.1.3 CD-4 Performance and additional capability

The target assemblies system is capable of 1-MW beam operation. For the CD-4 neutronic measurement, the mercury target produced adequate neutrons to allow the measurement of greater than 5×10^{-3} neutrons/proton/steradian from a moderator. To aid in alignment of the proton beam for this measurement, a phosphor viewscreen was attached to the front of the target as shown in Fig. 5.2-24.

The first target has been designed, fabricated, and operationally tested for up to 1-MW proton beam operation. The remainder of the system—including the pump, heat exchanger, piping, and shielding—has been designed, fabricated, and operationally tested to show it is capable of 2-MW beam operation (see Table 5.2-1).

5.2.2 Core Vessel and Internals

5.2.2.1 System description

The core vessel (Fig. 5.2-25) contains the target module, the moderators, reflector material, and shielding elements that require active cooling. The operating environment inside the vessel will be either helium at slightly subatmospheric pressure (~14 psia) or rough vacuum.

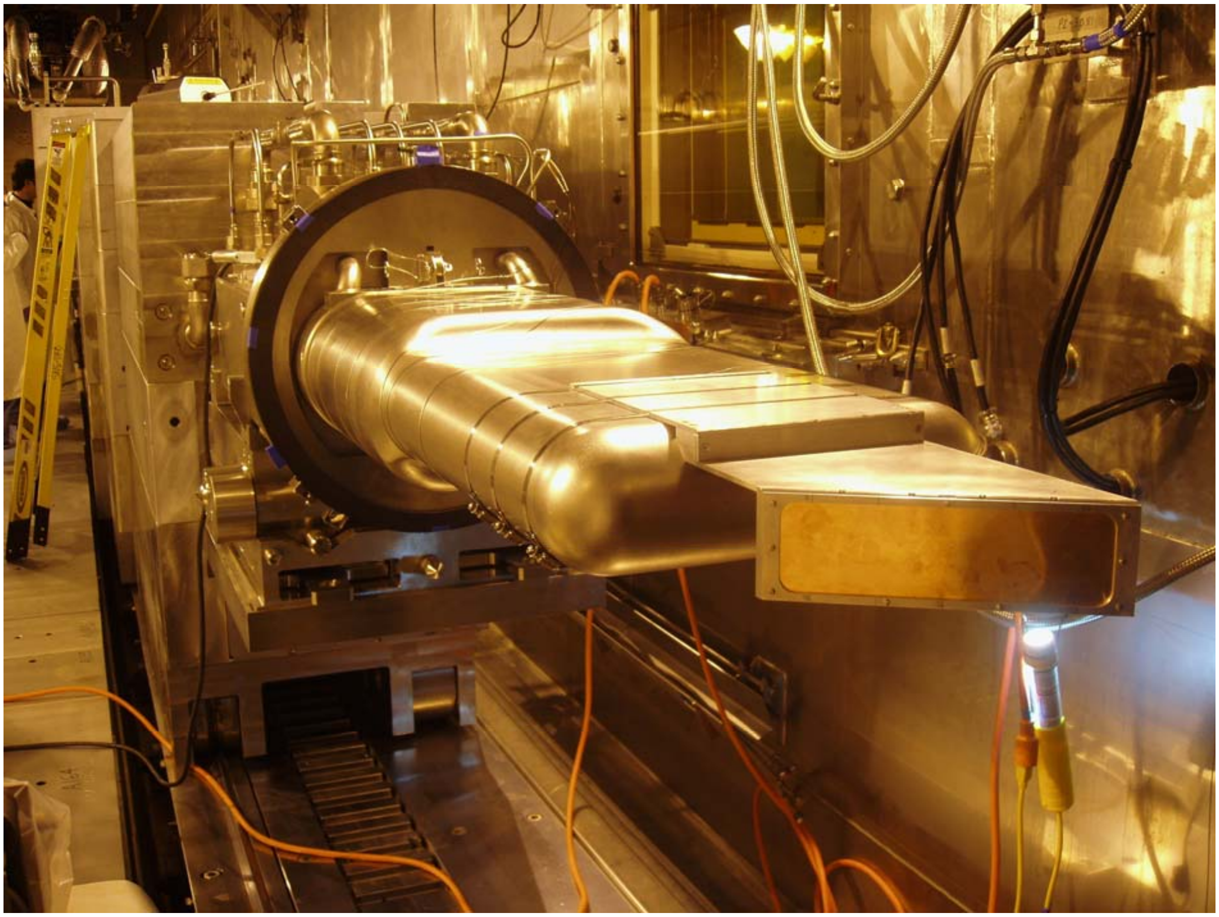


Fig. 5.2-24. Phosphor viewscreen installed on front of target module.

The 316 stainless steel core vessel has been designed and fabricated to requirements guided by the *American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel (B&PV) Code*, Section VIII. The vessel is protected from overpressure by a rupture disc. In the event of an overpressure within the core vessel, the rupture disc opens and the vessel is vented to its inert gas-purged vent line. The hydrogen-safe vent must be designed to accommodate release of helium, hydrogen, and/or air from the core vessel. The core vessel is designed to withstand either vacuum or an overpressure of 1 atm (i.e., internal pressure between ~0 and 2 atm). In operation, however, the core vessel rupture disc is set to actuate at ½ atm pressure over atmospheric.

The core vessel drain line allows removal of any liquids spilled into the core vessel. As shown in Fig. 5.2-26, the drain line terminates in a standpipe that is closed with a blind flange to facilitate closure and contamination control in the target service bay. The standpipe is designed so that it can accommodate the maximum feasible spillage of mercury into the core vessel without overflowing mercury into the target service bay when the blind flange is removed.

The core vessel provides credited confinement functions. These include retaining liquid mercury that could be spilled inside the core vessel and maintaining a confinement barrier against release of mercury vapor into the monolith bulk shielding after a spill. An approximately 0.7-m^3 (183 gal) void volume at the bottom of the vessel provides the liquid retention function. The mercury vapor leakage minimization function is provided by the core vessel itself, the neutron beam windows, the gas-pressurized seals, and the passive seals around penetrations.

The core vessel has 20 ports: 18 neutron beam ports, a proton beam port, and a target port. The neutron beam windows, which are part of the core vessel inserts, provide the pressure boundary at the inlets of the neutron beam ports. The vessel inserts are sealed to the vessel port with a double metal vacuum o-ring. Studs in the core vessel flanges and remotely installed nuts secure the core vessel inserts to the vessel flanges and provide the necessary sealing force. The neutron beam windows are aluminum to enhance neutron transmission. The proton beam window and the target module are sealed to the vessel using inflatable-metal seals. These two inflatable seals use an active system that relies on an inert gas-pressurized stainless steel bellows to maintain contact with the vessel-sealing surface.

Proton beam window. The proton beam window separates the helium or rough vacuum environment inside the core vessel from the high vacuum inside the proton beam line. The window is a double-walled, Inconel 718 (or equivalent) shell with active water cooling. The proton beam window will be replaced periodically because of accumulated material damage caused by proton fluence. To facilitate replacement of this intensely heated and irradiated structure, pneumatic (inert gas) seals and a vertical assembly and removal path are incorporated into the design. The expected service life of the proton beam window assembly is estimated to be about one year at maximum beam power.

Inner reflector plug. The inner reflector plug is composed of three elements: (1) the upper inner plug, (2) the intermediate inner plug, and (3) the lower inner plug. The moderator vessels are integrated with the lower inner reflector plug. The inner reflector plug will be replaced periodically as a unit, including the moderator vessels, coolant lines, and cryogenic transfer lines.

The lower inner reflector plug consists of an aluminum shell that holds beryllium reflector material and stainless steel shielding. The intermediate and upper inner reflector plugs are stainless steel. The neutron beam channels for the top and bottom upstream moderators are cadmium lined for neutron physics reasons.

The inner reflector plug has specially designed structures to provide the following:

- Chambers that hold the moderator vessels in place.
- Channels for cryogenic and coolant lines.
- An opening for target module insertion and an open pathway for the proton beam to reach the target module.
- Open channels for the neutron beams.

The lower inner and intermediate inner reflector plugs are designed to be heavy-water-cooled. The upper inner reflector plug is passively cooled by conducting heat to the actively cooled plugs. Maximum operating heavy water pressure is approximately 50 psig.

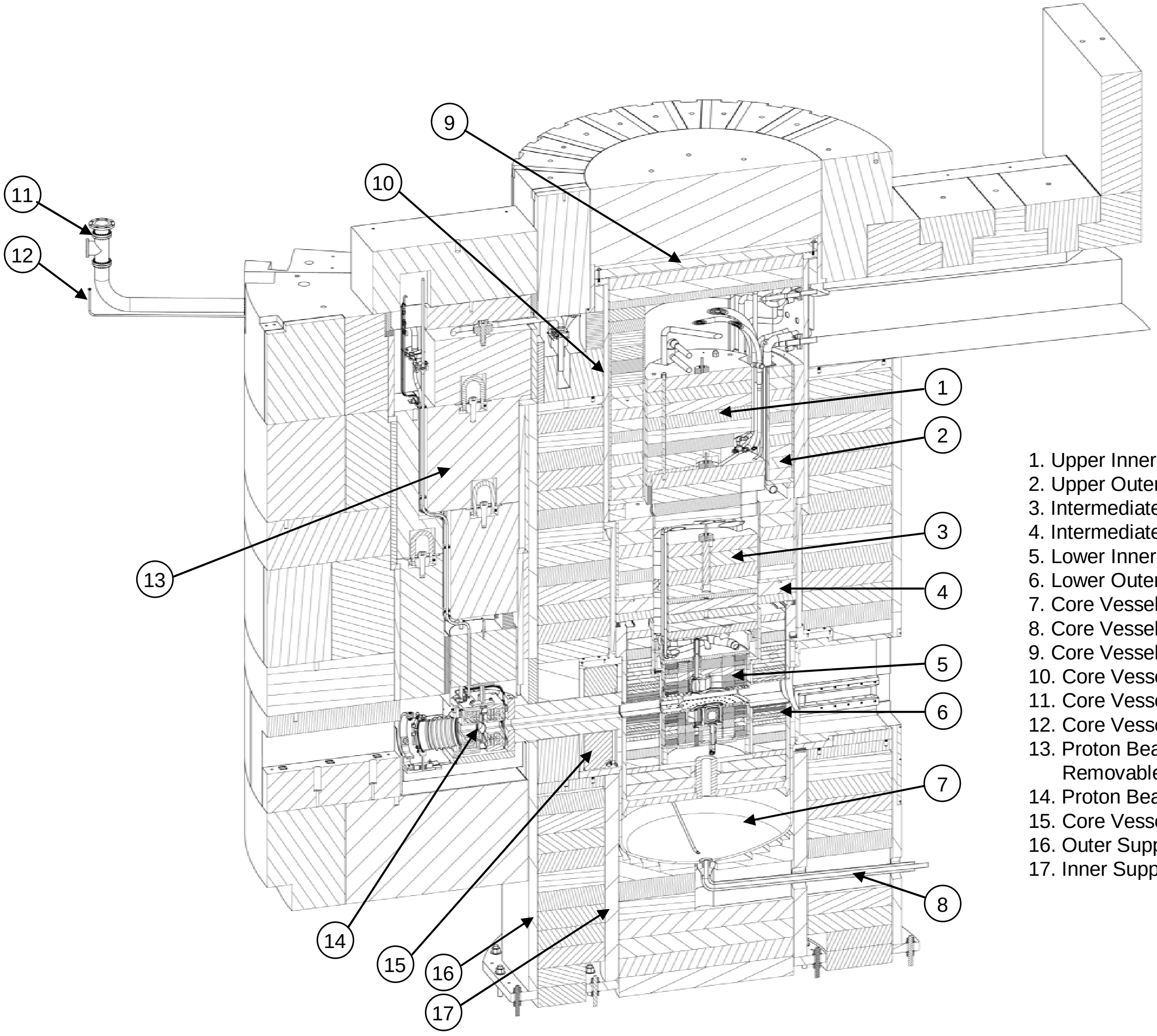
The inner reflector plugs are connected so they can be installed as one unit. They are designed with removable connecting bolts between the sections so that it can be removed in pieces sized for shielding containers. The inner reflector plug may be changed out as research priorities change, but probably no more frequently than on the order of once per three years at maximum beam power on account of irradiation damage considerations.

Outer reflector plugs. The outer reflector plug is composed of three elements: (1) the lower outer plug; (2) the intermediate outer plug; and (3) the upper outer plug.

The lower outer plug is made of stainless steel. The intermediate and upper outer plugs are stainless steel and stainless steel-encased carbon steel.

The lower and intermediate plugs are heavy-water-cooled. The upper outer plug relies on conduction to the actively cooled components.

Core vessel atmosphere control. Controlling the atmosphere inside the core vessel is necessary for operational purposes to prevent the formation of corrosive nitrogen compounds and to minimize formation of volatile radionuclides for ALARA purposes. The operating environment inside the vessel will be either helium at slightly subatmospheric pressure (~14 psia) or rough vacuum [less than one torr (133.3 Pa)]. Controlling the atmosphere inside the core vessel is not a safety requirement because the cryogenic moderator system hydrogen boundary is credited with preventing hydrogen release inside the core vessel. The cryogenic moderator system vacuum boundary is the second credited control against hydrogen release and possible formation of combustible hydrogen air mixture in the core vessel. These credited safety functions are discussed further in Sect. 5.



1. Upper Inner Reflector Plug
2. Upper Outer Reflector Plug
3. Intermediate Inner Reflector Plug
4. Intermediate Outer Reflector Plug
5. Lower Inner Reflector Plug
6. Lower Outer Reflector Plug
7. Core Vessel Ullage Volume
8. Core Vessel Drain Line
9. Core Vessel Lid
10. Core Vessel Chimney
11. Core Vessel Vacuum Line
12. Core Vessel Helium Suction Line
13. Proton Beam Window Removable Shielding
14. Proton Beam Window
15. Core Vessel Lower Section
16. Outer Support Cylinder
17. Inner Support Cylinder

Fig. 5.2-25. Core vessel and internals.

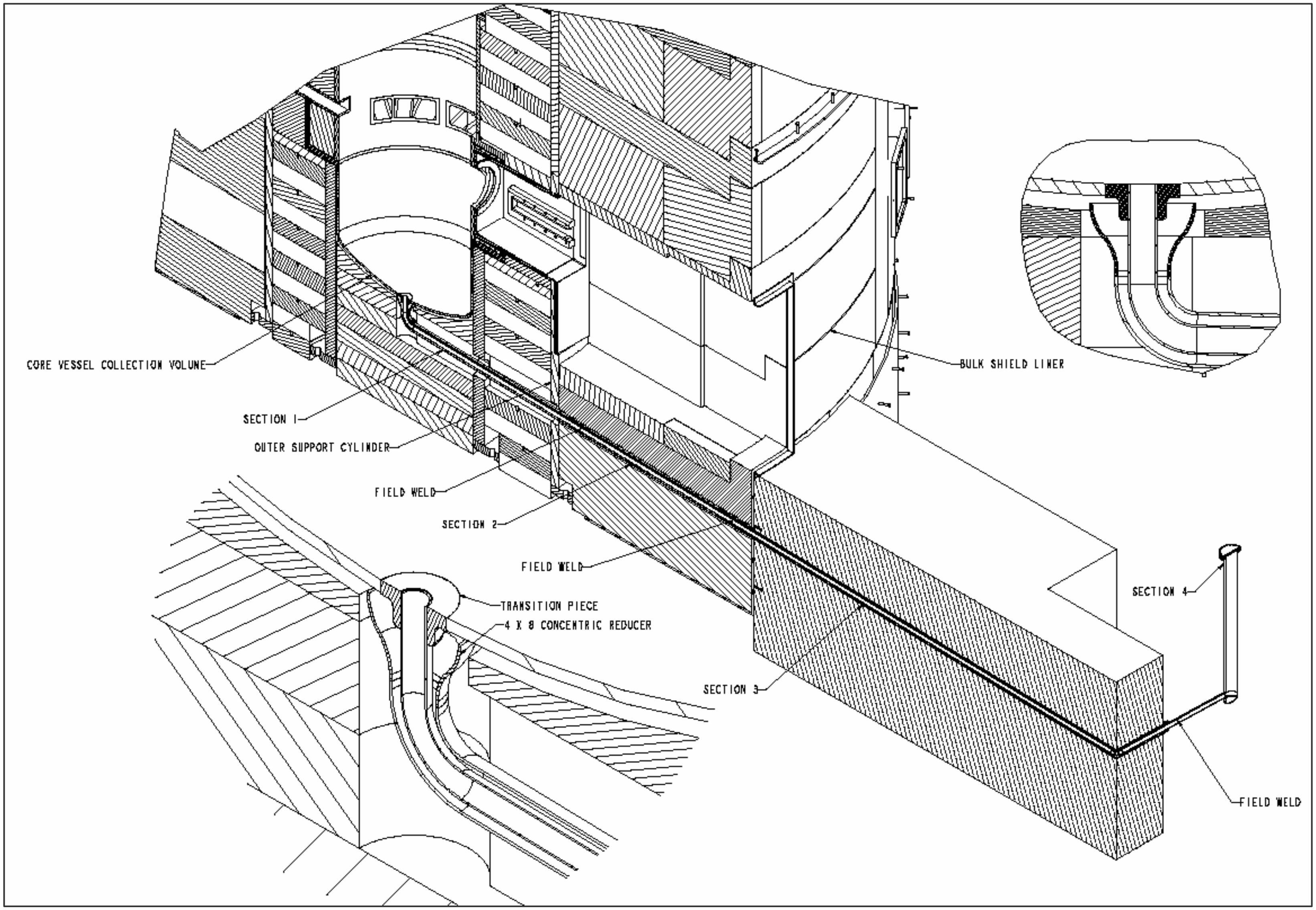


Fig. 5.2-26. Core vessel drain line.

Although an inert or vacuum atmosphere is required only for operational purposes, it provides an uncredited layer of safety by normally excluding significant oxygen from the core vessel. In the highly unlikely event that both the cryogenic moderator hydrogen and the vacuum boundaries [both credited engineering controls (CECs)] should fail and leak hydrogen into the core vessel, the resulting atmosphere inside the core vessel would not be combustible.

The vacuum pumps (capacity limited to ~150 feet^3/minute) exhaust to the primary confinement exhaust system upstream from the sulfur-impregnated charcoal filters (these are technically adsorbers). The charcoal filters will prevent excessive mercury release in the unlikely event of leakage of mercury to the core vessel under vacuum conditions when the vacuum pump exhaust could be transporting mercury vapor.

5.2.2.2 Installation and testing

The core vessel, proton beam window, inner reflector plug, and outer reflector plug have all been installed and successfully completed all functional testing. The core vessel was installed early in the construction of the monolith in two sections, the lower vessel and the chimney. Figure 5.2-27 shows the lower section at the vendor and being installed, and Fig. 5.2-28 shows the chimney installed and also completion of all permanent shielding. Representative pictures are shown in Figs. 5.2-29 through 5.2-32 for installation of the proton beam window, outer reflector plug, and inner reflector plug.

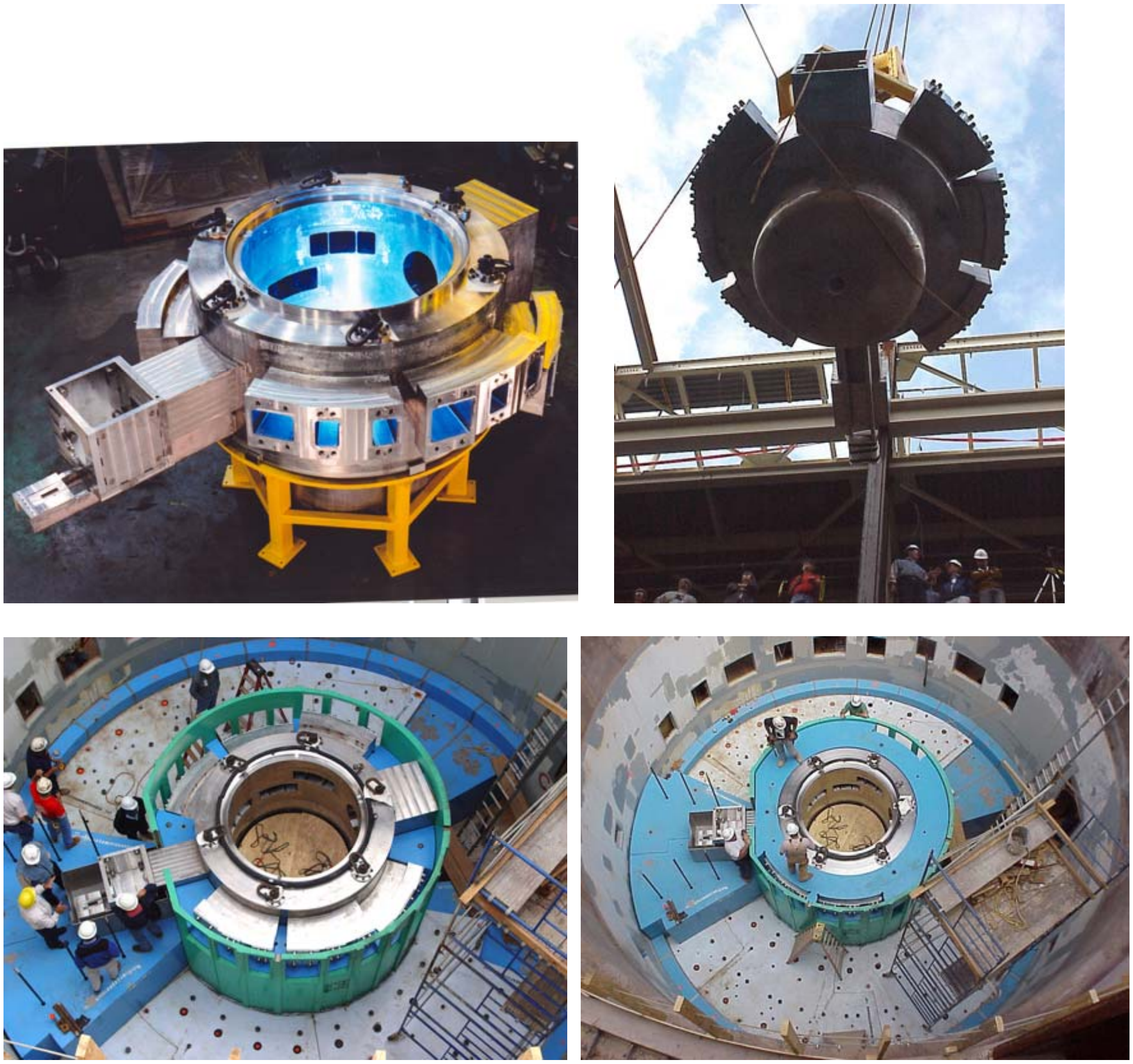


Fig. 5.2-27. Lower core vessel and initial installation.

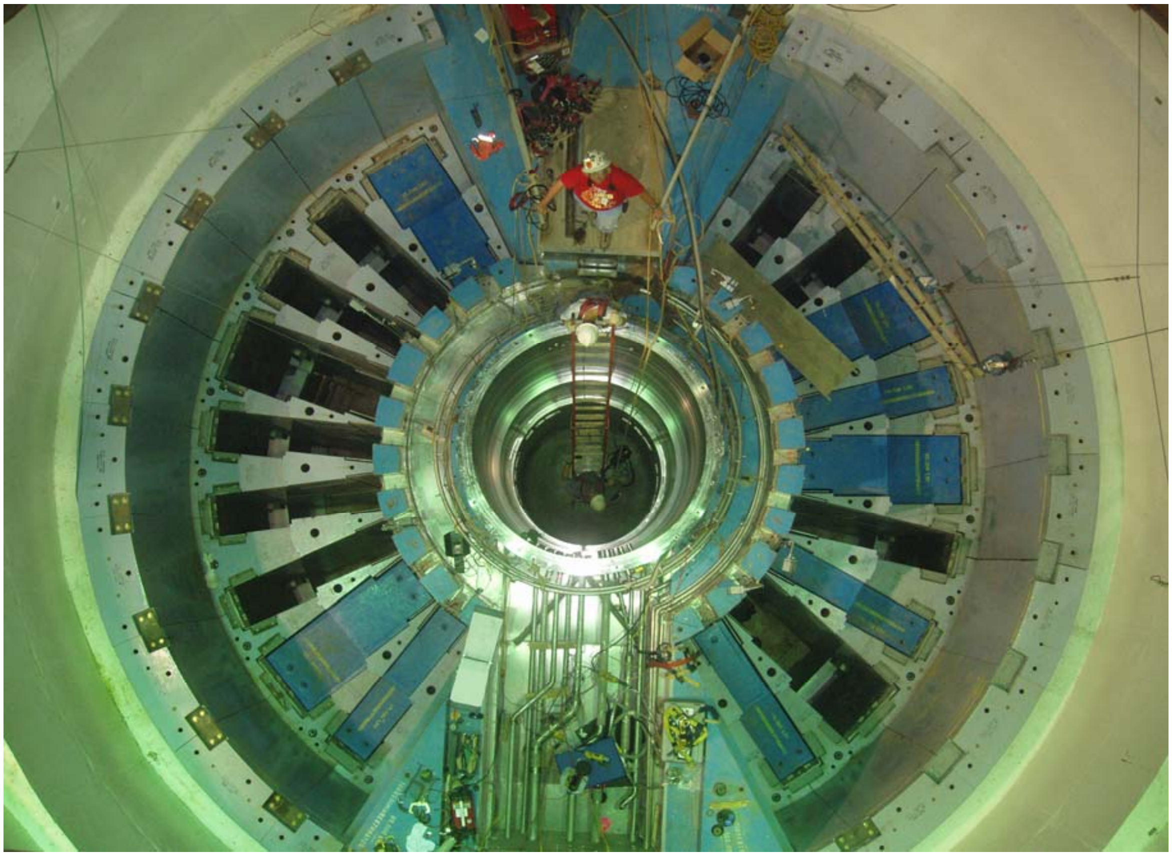


Fig. 5.2-28. Core vessel chimney installed and all permanent monolith shielding.

Fig. 5.2-29. Lower proton beam window assembly before and after installation.

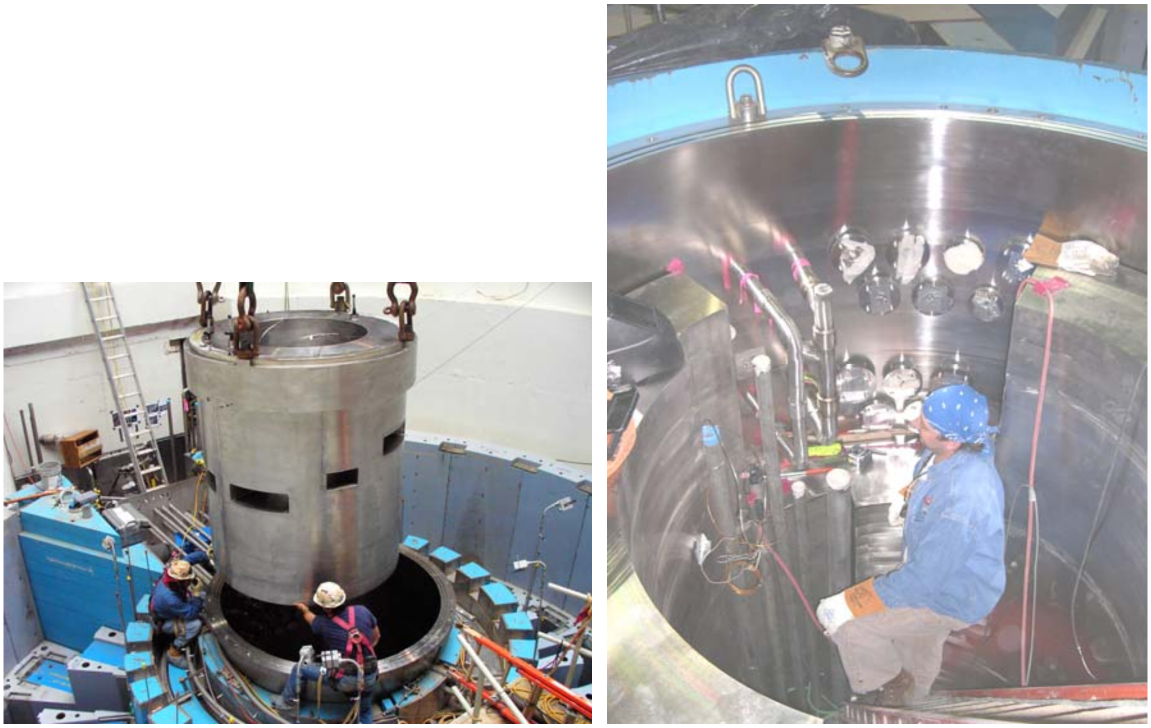


Fig. 5.2-30. Installation of lower outer reflector plug completed April 2005.

Fig. 5.2-31. Inner reflector plug just before installation.

Fig. 5.2-32. Inner reflector plug installed with water lines connected, and transfer lines welded.

Functional testing of the cooling and gaseous systems for the core vessel, proton beam window, and reflector plug assemblies were completed, and the summary is discussed in section 5.2.6. The core vessel has been tested for operation in the vacuum mode or helium mode and with all cooling flows required for beam operation at 2 MW. The vessel will be operated in the helium mode with the first inner reflector plug.

5.2.2.3 CD-4 performance and additional capability

The core vessel, proton beam window, and outer reflector are all designed for operation at 2 MW beam power and have been tested with cooling system flows, which are anticipated for 2 MW beam operation. The Inner Reflector Plug was also designed for 2 MW operation, but the as-built configuration has resulted in a reduction in cooling capacity to 1.4 MW.

5.2.3 Moderator Systems

The primary hydrogen boundary of the cryogenic moderator system (CMS), including its pressure relief function, performs a credited safety function. The vacuum boundary and its pressure relief also perform a credited safety function that provides an additional layer of safety. For both the primary and secondary hydrogen boundaries, the safety function is to prevent the release of hydrogen into the core vessel. This section explains how the inherent design characteristics of the CMS function to prevent significant oxygen from accumulating inside the system, and how the hydrogen is vented without operator action in the event that heat transfer conditions become degraded. The 19-bar maximum design pressure of the CMS hydrogen boundary ensures robust hydrogen containment inside the core.

Three of the four moderator systems employ cryogenic supercritical hydrogen controlled during normal operations to temperatures close to 20 K. One ambient moderator system is included for research applications that require higher-energy neutrons. The ambient moderator vessel contains water that is circulated between the moderator vessel and heat exchangers in the basement as part of cooling loop 3.

Cooling for the hydrogen system is provided by a 7.5 kW helium refrigeration system. The principal components are the warm helium compressor and oil removal skids located in a separated building just outside the Target Building, and the cold box that includes the turbine system located on top of the RTBT shielding in the Target Building high bay.

5.2.3.1 Cryogenic Moderator System

Figure 5.2-33 shows the four moderator vessels (three cryogenic and one ambient temperature) arranged above and below the target inside the core vessel. Figure 5.2-34 shows the location of the CMS components and transfer line in the Target Building. The innermost boundary confining the cryogenic hydrogen (primary confinement barrier) is enclosed within the vacuum boundary (secondary confinement barrier). The outer cooling water layer is present for the moderator vessels and in cryogenic transfer lines in the lower part of the core vessel (not shown). As described below, a CMS cannot physically be operated with a degraded vacuum layer because the resulting heat-up of the system will result in discharge of the hydrogen inventory to the outdoors through the spring-loaded relief valve or rupture disc.

The CMS consists of three separate CMSs of essentially the same design. These systems provide three volumes of supercritical hydrogen at 20 K, which yields a neutron spectrum that is well matched to many research needs. Connections are provided among the three systems to allow a mode of operation in which the circulator for one system provides motive power for two systems. The systems are intended to be interconnected only in the event that a circulator fails; sufficient flow could then be obtained with one circulator powering two systems.

Each system comprises a moderator vessel inside the core vessel; a coaxial stainless steel transfer line to carry the cryogenic hydrogen to and from major components; and, in the hydrogen utility room (HUR), a circulator, a heat exchanger, and an accumulator. The HUR is discussed below. Since hydrogen in the CMSs is maintained at ~20 K and above the critical pressure, it is technically correct to refer to it as "supercritical" rather than "liquid" hydrogen, although the density is close to that of liquid hydrogen. The circulator provides motive power to move the supercritical hydrogen around its circuit between the heat exchanger (in the HUR) and the moderator vessel in the core vessel. Cryogenic helium circulated through the heat exchanger removes heat that the cryogenic hydrogen absorbs from surroundings and from incident gamma rays and neutrons (significant in regions near the target module).

The accumulator has stainless steel bellows to accommodate expansion associated with normal and anticipated off-normal operational swings in temperature without the need to add or subtract hydrogen to or from the system. The purpose of the accumulator is to minimize pressure swings that would otherwise accompany temperature changes. For example, the circulator outlet pressure is nominally about 15 bar (for an approximately 14-bar inlet pressure), with the system at temperature with the proton beam not on, but increases only to 16 bar when the beam reaches full power owing to the action of the accumulator.

The moderator vessel and several meters of the transfer line inside the core vessel receive significant neutron and gamma irradiation. CMS boundaries in this zone that are not in direct contact with the cryogenic hydrogen are cooled to maintain temperatures within normal design range. This is accomplished by a water jacket that surrounds the outer helium layer. The outer helium layer provides a protective buffer for the vacuum layer in the core vessel by minimizing the possibility of in-leakage of contaminants (water or air, for example). The water jacket also performs a neutron pre-moderation function by helping slow down the neutrons before they reach the cryogenic hydrogen. Cooling water for all three cryogenic moderators and for the ambient (water only) moderator is provided by cooling loop 3.

The following functions are needed for operation of the CMS:

- Gas management—vacuum and helium purging, hydrogen filling.
- Normal operation—circulation, cooling, and pressure control (accumulators).
- Hydrogen venting—spring-loaded safety valves and rupture discs that discharge to the inert gas-purged vent line for discharge to the atmosphere above the Target Building roof. It should be noted

that the hydrogen does not become significantly activated during operation, so this discharge path is a negligible accident or environmental source term.

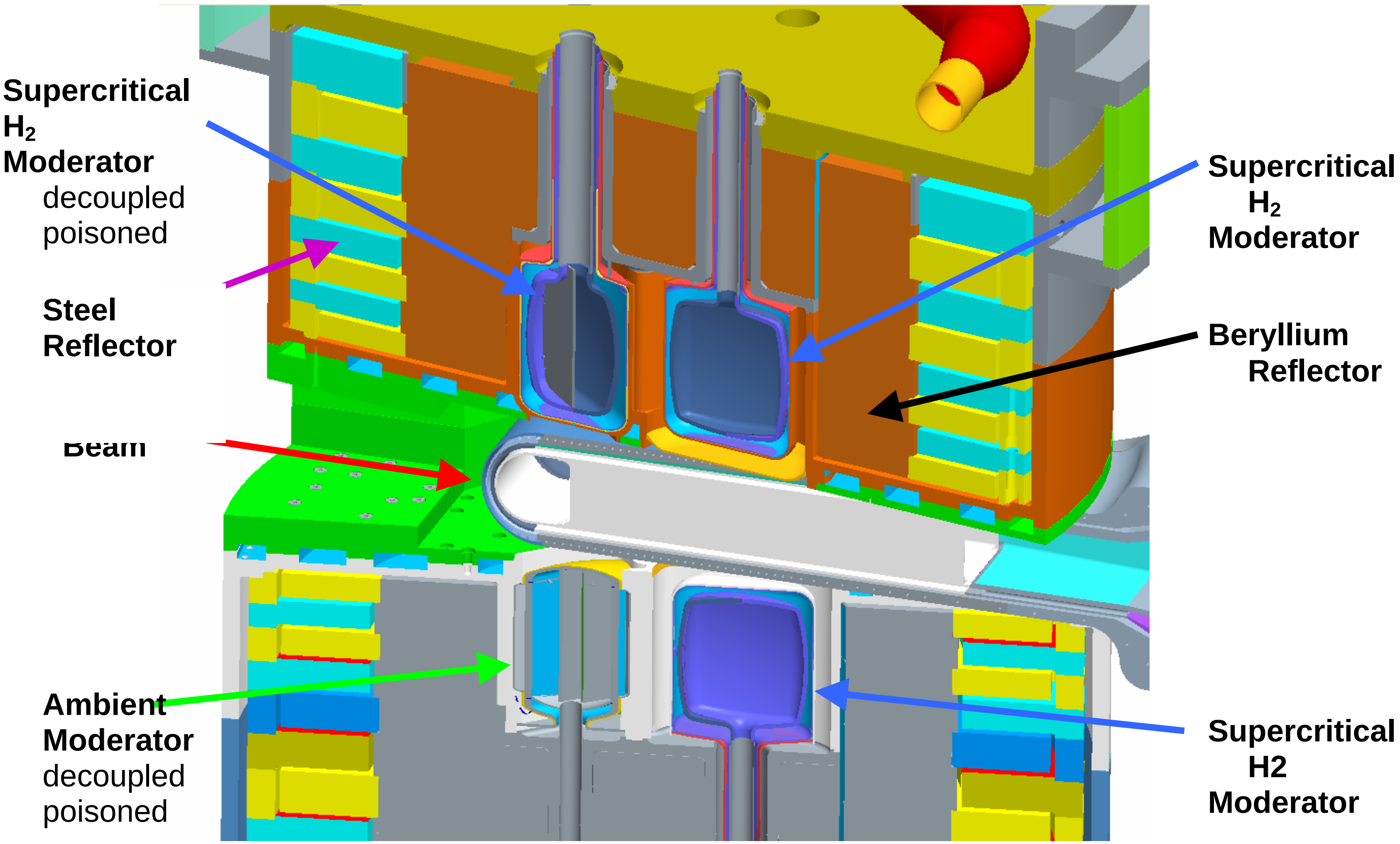


Fig. 5.2-33. Configuration inside the core vessel of the moderator vessels above and below the mercury target.

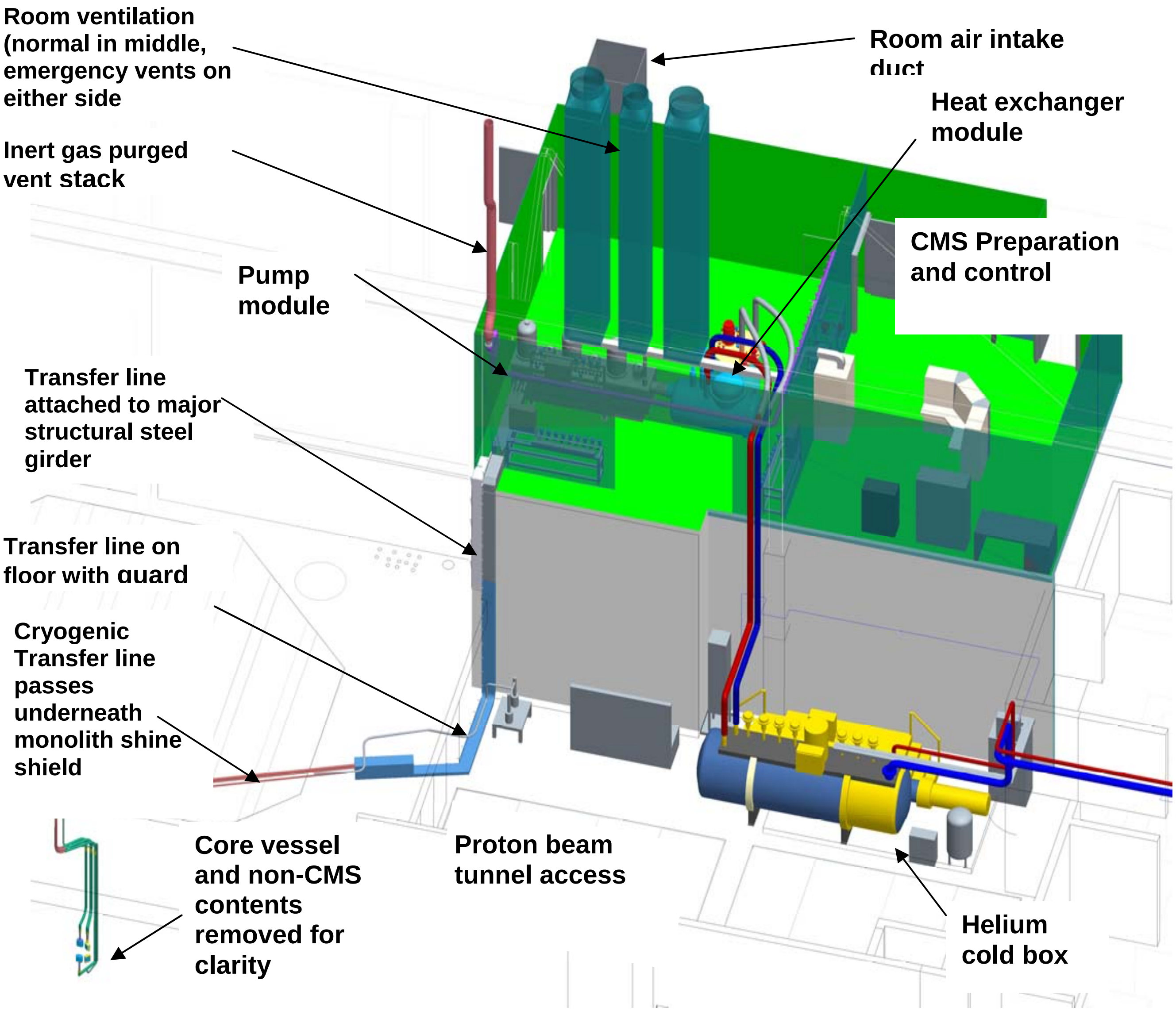


Fig. 5.2-34. Hydrogen system layout.

All the active functions are located in the HUR except for control valves in the hydrogen supply cabinets, which are located inside the helium compressor building. In the HUR, the three heat exchangers (i.e., of each of the three CMS subsystems) are held inside a vacuum vessel called the heat exchanger module. The three pumps and three accumulators are inside the pump module. The pump module and heat exchanger module are interconnected by the vacuum system. The vacuum system for these modules is separate from the vacuum for the transfer line and moderator vessel. Thus, a hydrogen leak inside the pump or heat exchanger module cannot flow through the vacuum layer down into the core vessel.

No instrumentation or control devices are located inside the core vessel. The instrumentation is indicated on control panels in the room adjacent to the HUR and is made available to the EPICS digital information bus for remote read-out.

The system must be charged with hydrogen before cryogenic operation is achieved. The charging operation is initiated starting at ambient temperature by purge and vent cycles: vacuum pump-down followed by helium fill to remove residual oxygen from all parts of the system. After this is completed, the hydrogen piping on the suction side of the circulator is connected to the hydrogen supply by opening three isolation valves. A pressure regulating valve in the ambient hydrogen supply line controls the hydrogen supply pressure during filling to the desired 14-bar system operating pressure. As the initially ambient temperature system cools, the pressure decreases slightly and the pressure regulator automatically admits more ambient hydrogen to hold pressure close to 14 bar. A major leak in the ambient hydrogen charging line would have a potential to release a significant quantity of hydrogen into the HUR in a short period of time. Thus, a flow orifice is incorporated in the charging line near the cylinder manifold to limit the maximum break flow to within the ventilation capacity of the HUR ventilation fans (see HUR discussion below).

When cooldown to the desired operating temperature is complete, the three isolation valves are closed, cutting off the connection with the hydrogen supply. The system now operates on this inventory of hydrogen until a major maintenance shutdown necessitates discharge of the hydrogen from the system by releasing it to the atmosphere. This is achieved by turning off the helium refrigerator and opening an isolation valve to allow a 14-bar regulating valve to vent the hydrogen to the inert-gas-purged vent stack for discharge to the environment above roof level. This mode of controlled venting maintains 14 bar at the circulator inlet to ensure supercritical conditions during the return to ambient temperature. After the system reaches ambient temperature, another valve is opened to allow the system to reach atmospheric pressure. If a more rapid venting needs to be accomplished, the regulating valve can be bypassed. Multiple vacuum pumpdown and inert gas purging cycles remove residual hydrogen from the system before it is opened for maintenance.

A major key to reliable operation of the CMS is the ability to maintain a high-vacuum envelope to provide effective thermal insulation around all parts of the system that contain cryogenic hydrogen. The ability to hold ~20 K hydrogen temperature is very sensitive to the heat input and, therefore, to leakage of gases into the vacuum insulating layer. The vacuum utilities are designed to provide pump-down to the required ($\sim 10^{-6}$ torr) vacuum range. Highly engineered barriers with all-welded connections minimize the chance of leakage. Any significant leakage of hydrogen or helium into the vacuum barrier allows greater than normal heat transfer and causes hydrogen temperature to increase. If sufficient leakage brought the vacuum into the range of 10^{-2} torr or greater, rapid temperature and pressure increase would occur, requiring venting to control the pressure. System pressure would be controlled without operator intervention by the 18-bar spring-loaded relief valves and/or the 19-bar rupture discs, discharging into the inert-gas-purged vent line.

A major key to the safety of the CMS is the provision of redundant barriers against hydrogen release and the protection of the barriers against internal over-pressurization, as well as external threats. The hydrogen boundary is the primary barrier, and the vacuum boundary is the secondary barrier against uncontrolled hydrogen release. The hydrogen primary boundary and the vacuum boundary are code-stamped vessels, designed and built according to applicable requirements of Section VIII of the American Society of Mechanical Engineers (ASME) *Boiler and Pressure Vessel (B&PV) Code*. The all-welded assembly of the cryogenic loop piping helps minimize the probability of leakage. Pressure relief features (i.e., in addition to manual venting capability) are listed as follows:

- Hydrogen boundary: 19-bar rupture disc bar and 18-bar spring-loaded relief valve
- Vacuum boundary: 2-bar rupture disc
- Helium boundary: 2-bar rupture disc

Within each of the three CMSs, the hydrogen and vacuum, volumes are contiguous throughout. This enables the relief device to relieve pressure buildup at any point in the entire volume, including points within the core vessel that are farthest away from the relief device. The design provides relief for each of the following pressure buildup conditions:

1. Sudden and total loss of vacuum to one atmosphere (helium or air)—expanding hydrogen is relieved through 18-bar spring-loaded relief valve and/or 19-bar hydrogen rupture disc within acceptable pressure for hydrogen boundary (no hydrogen leakage to vacuum layer).
2. Leakage of cryogenic hydrogen into vacuum space—relief through hydrogen and vacuum rupture discs accommodated within the design pressure of hydrogen and vacuum boundaries and within allowable combined thermal and pressure stress limits of vacuum boundary that sees rapid temperature decrease due to contact with cold hydrogen.

Protection of the hydrogen boundary is important to safety throughout the system. The hydrogen boundary is credited as a hydrogen confinement barrier. Although the hazardous material safety concern is with escape of hydrogen into the core vessel, the hydrogen boundary is designated to high quality standards throughout the cryogenic system (inside and outside the core vessel). The reason for crediting more than just the boundary inside the core vessel is the possibility that hydrogen leaking into the vacuum volume could escape into the core vessel if the vacuum boundary were also leaking. In order to provide a credited, independent (secondary) barrier against uncontrolled leakage of hydrogen into the core vessel, the vacuum boundary is designated as a credited engineered control. The crediting extends to the hydrogen rupture discs and the vacuum region rupture discs.

Outside the core vessel, the line is protected at the PC-3 level against seismically induced failure modes (crimping, crushing) that could prevent the flow of hydrogen from inside the core vessel to the rupture discs in the HUR. Other failure modes (e.g., shearing, leakage) are not of radiological safety concern outside the core vessel.

Figure 5.2-34 shows the location in the Target Building of the CMS hydrogen boundary components and transfer line from the core vessel through the monolith, up along the south wall of the high bay, and into the HUR. The transfer line for each CMS traverses the high bay so that it is protected against inadvertent impacts from operational activities (forklifts, cranes, etc.). This is facilitated by routing the transfer line near major structural elements such as the large steel girder it follows up to the HUR. The hydrogen boundary inside the core vessel is seismically protected at the PC-3 level against all failure modes. The line is supported as needed, and the path inside the core vessel is protected by its installation in slots in the large metallic reflector and shielding segments inside the core vessel.

5.2.3.2 Hydrogen utility room

The major hazard in the HUR is inadvertent hydrogen combustion. Design features included to mitigate the hazard are described and evaluated in the Target Building Fire Hazards Analysis (FHA). The summary information is given below. Although the cryogenic hydrogen moderator does not become significantly activated in service, it may become contaminated in service. Therefore, appropriate surveys are performed as needed to control radiological hazards when equipment must be opened up for maintenance.

The HUR houses active components of the CMS, including circulators, valves, and heat exchangers. The HUR has its own ventilation system, including redundant active exhaust paths. The normal exhaust path and blower operate continuously during normal operation. The two emergency vent paths (one blower in each) remain in standby for actuation on detection of excessive hydrogen in the HUR. Loss of exhaust air flow is indicated in the target control rooms.

The HUR is located on the truss level above the south instrument hall of the Target Building. The north wall of the HUR forms part of the south wall of the high bay. The floor is reinforced concrete; the walls are gypsum-based drywall and extend so that the metal decking roof of the building forms the ceiling of the HUR. The nearest personnel access to the truss level is from the stairwell on the southwest side of the building. The HUR includes two personnel doors, one communicating directly with the truss level and the other with the adjacent preparation and control instrumentation room that, in turn, opens to the truss level.

The HUR is a Class I, Division 2, Group B space, defined by the National Electric Code as a space in which the flammable gases are normally confined within closed containers or closed systems from which they can escape only in case of accidental rupture or breakdown of such containers or systems. The HUR is designed to follow the applicable requirements of National Fire Protection Association (NFPA) 50A, 50B, 69, and 70. If the hydrogen sensors detect a hydrogen release, an alarm is activated and the emergency exhaust blowers are energized to vent the HUR at an enhanced rate to maintain the room below 60% of the lower flammability limit for hydrogen (i.e., below 2.4% by volume). The cryogenic hydrogen inventory can also be transferred outside the facility by remote manual operator actions from the control room.

Instrument and electrical connections inside the control room are of a hydrogen-safe design per NFPA-70. Valve operators are pneumatic and employ nonincendive controls. The room ventilation system is designed to prevent hydrogen explosions per NFPA-69, therefore, the building is not equipped with blowout panel(s).

As provided by the ORNL work smart standards (WSS) for engineering design, the SNS project has prepared an equivalency determination from the DOE authority having jurisdiction to support the following desired design feature:

- The doors of the room may be located such that they allow access to and from the interior of the Target Building. The equivalency is discussed further in the Target Building FHA.

The HUR is seismically qualified to withstand a PC-3 earthquake without causing a failure of the CMS venting capability. This is a hazardous material safety requirement, the reason for which is explained above. Since the HUR normal and emergency (forced) ventilation could be lost during a PC-3 seismic event, the CMS hydrogen boundary in the HUR is qualified against failure resulting from a PC-3 earthquake. The HUR is required to have ceiling vents to prevent buildup of hydrogen after a PC-3 seismic event. The two emergency exhaust vents provide a hydrogen vent path even though the blowers would, presumably, not be running after a PC-3 seismic event. The PC-3 seismic design of the CMS hydrogen boundary ensures that any post-seismic-event leakage would not exceed the capability of the ceiling vents to passively vent the HUR.

5.2.3.3 Ambient moderator system

One ambient moderator system is included for research applications that require higher-energy neutrons. The ambient moderator vessel contains water that is circulated between the moderator vessel and heat exchangers in the basement as part of cooling loop 3.

5.2.3.4 Installation and Testing

All components for the helium refrigeration system and the moderator systems have been installed and tested. Initial system testing was done with the Design Validation and Training Module (DVTM) which simulated one loop with a circulator, accumulator, representative pipe lengths, and a heater. The testing verified the accumulator performance with simulated beam heating and trips. Circulator performance was also verified. During the DVTM testing the refrigeration system capacity was evaluated. The capacity at 20 K was found to be approximately 4 kW instead of the 7.5 kW required in the specification. The 4 kW capacity is adequate for 1.4 MW beam operation based on the measured heat loads without beam and the calculated neutronic heating. A repair to increase the capacity to the specified value will be planned during a future shutdown. An initial test of all three loops was performed in March 2006. For this test the three transfer lines were not connected to the Inner Reflector Plug, but were “jumpered” near the monolith. Stable operation at 20 K and design flow rates for all three loops was demonstrated. A second full integrated operational test was performed after installing the inner reflector plug. Again all three loops were operated at design flows and temperatures for more than 48 hours with all other target systems operating. This test also included the design flows for the ambient moderator. The test summary is shown in Table 5.2-3. Representative installation pictures are shown in Figs. 5.2.35 through 5.2-41.

Representative pictures from the Experimental Physics and Industrial Control System (EPICS) control screen during testing are shown in Figs. 5.2-42 and 5.2-43.

Table 5.2-3. **Major Moderator System Testing**

SST 1.6.2-6	DVTM testing	11/16/05	Accumulator control system demo and refrigeration system test
SST 1.6.2-7	Full Hydrogen system test	3/13/06	First run with all 3 loops
Full integrated operational testing	Hydrogen system run with all other systems	4/23/06	Integrated testing of all systems to simulate beam operation

Fig. 5.2-35. Moderators being installed in the inner reflector plug.

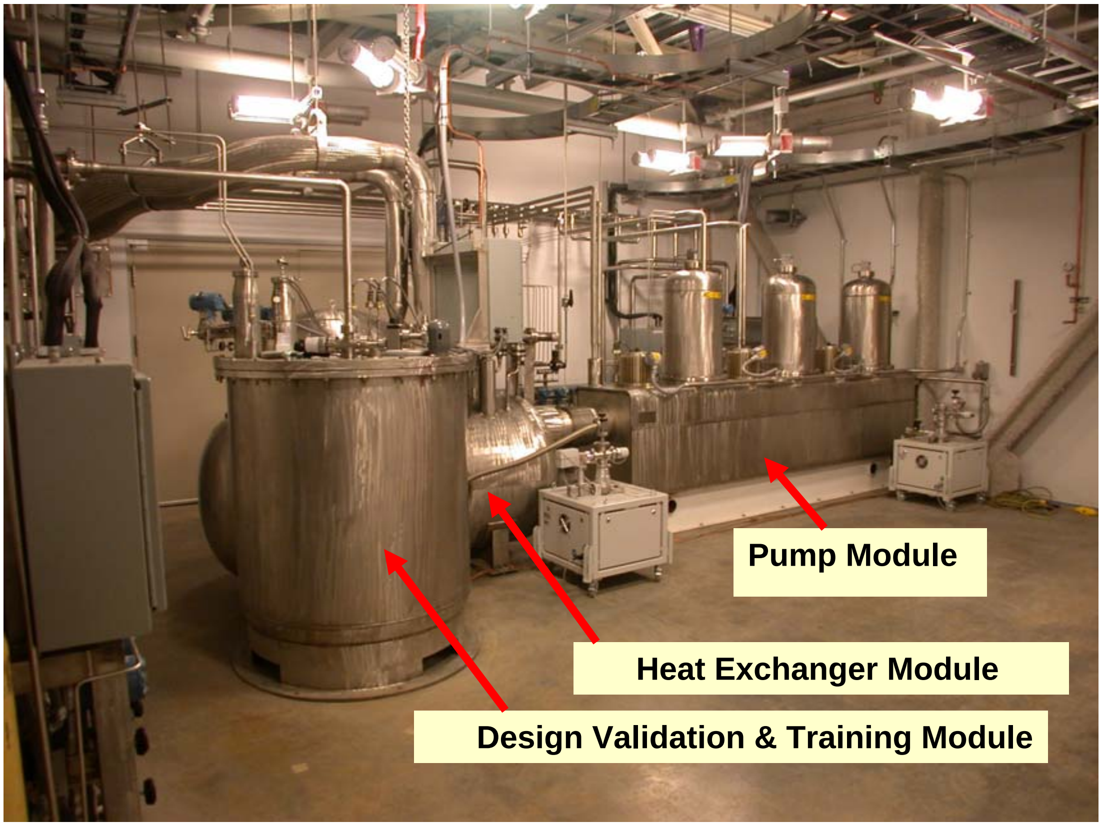


Fig. 5.2-36. CMS system components in hydrogen utility room.

Fig. 5.2-37. Helium refrigerator cold box in RTBT location.

Fig. 5.2-38. Compressor Building and helium buffer tank to left.

Fig. 5.2-39. Hydrogen gas cabinet in Compressor Building.

Fig. 5.2-40. Helium compressor.

Fig. 5.2-41. Oil removal skid for helium compressor system.

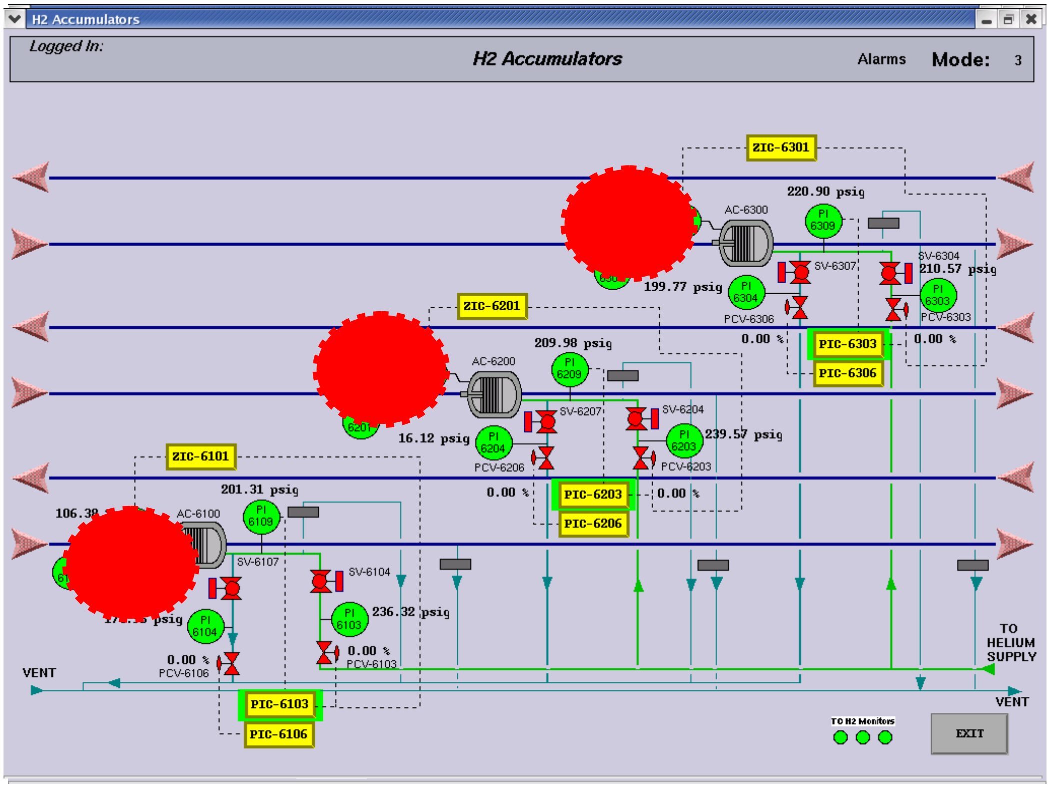


Fig. 5.2-42. 20-K hydrogen circulator outlet temperatures for all loops.

Fig. 5.2-43. Hydrogen design flows demonstrated for all loops.

5.2.3.5 CD-4 performance and additional capability

The overall capacity for the moderator system as installed will support 1.4 MW beam operation. The present limit is the capacity of the helium refrigeration system. The demonstrated hydrogen system flows would support 2 MW beam operation or greater if the helium refrigeration system capacity was increased to 7.5 kW.

5.2.4 Target Monolith

The target monolith includes the shielding and shutter equipment external to the core vessel assembly (~168 inch diameter) extending out to the interface with the instrument halls at the chopper archways at ~408 inch diameter and includes the removable “shine shield” beam at the interface with the high bay. The design accommodates major interfaces such as the cooling water systems, the ring-to-target proton beam line, and the instrument halls. Figure 5.2-44 depicts a half-section of the monolith and core vessel in the direction parallel to the plane of the incident proton beam.

The monolith design includes a drain for potential liquid accumulation in the liner. The drain line is located at the center low point of the monolith liner and leads down and radially outward to a cavity in the concrete monolith pedestal where it can be accessed from the utility vault in the basement. The cavity in which the drain line terminates is a small pit sized to accumulate approximately 1 m^3 of liquid before reaching the level of the door that separates the cavity from the basement. This door is also a fire barrier. Instruments are provided on the drain line termination so operators can tell if liquid is present inside the drain line. These instruments are designed to distinguish between water and mercury. It should be noted that the mercury in the drain line is a very low-probability event that would require failure of multiple independent boundaries. It has been postulated that a severe seismic event could cause such failures. The cavity and fire door are PC-3 seismically qualified structures.

Figure 5.2-45 shows the bulk shielding drain line configuration in schematic form and the initial installation. To initiate removal of fluid from the drain line, operators would, after satisfactory radiation and contamination surveys, open the cavity door and make drain line connections to route the fluid to the desired destination.

5.2.4.1 Shutters

The shutter system is an integral part of the target monolith. The shutters are a system that provides a safe, non-obtrusive method to close a beam line so that downstream parts of the neutron beam line(s) can be accessed. The shutters have an indication feature that is part of the instrument PPS so that certain unsafe activities will cause alarms and/or proton beam shutdown. These activities include opening the door to the instrument cave and removing interlocked shielding. Controlling the position of a shutter is normally an instrument PPS activity.

There are two broad types of shutters. The single channel gates serve a single instrument and consist of single large steel fabrication weighing about 30 tons. The multichannel shutters are wider and are composed of three major steel segments weighing a total of about 50 tons. Multichannel shutter gates can serve two or more instruments. Both types of shutters operate in exactly the same manner. Figure 5.2-46 locates typical shutters in the monolith. A typical single-channel shutter gate is shown on Fig. 5.2-47 in both the operational and closed position. Some of the principal features of the shutter gate system are labeled in the figure. Installation is shown in Fig. 5.2-48. A typical shutter drive system on top block is shown in Fig. 5.2-50.

The shutters have a vertical stroke of about 20 inch and move upward to close the beam. This operation was carefully chosen because the shutter insert "floats" in an oversize cavity in the shutter gate. In the operational position, the shutter insert is supported on kinematic mounts that very accurately align the insert with the core vessel insert. This preserves the neutron guide alignment configuration and greatly increases the neutron flux on samples.

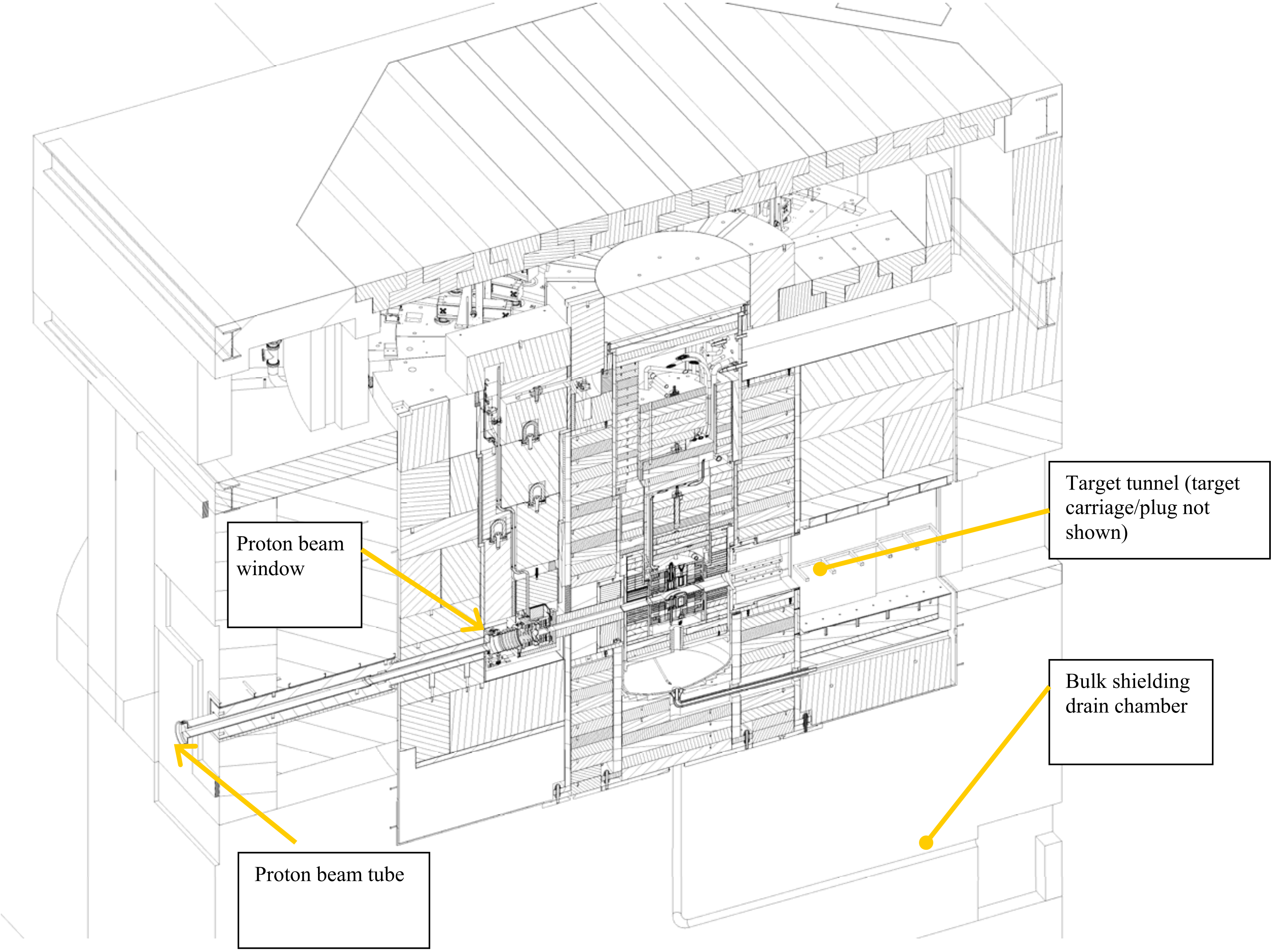


Fig. 5.2-44. Target monolith cross section view, sheet 2: 0° and 180° to proton beam direction.

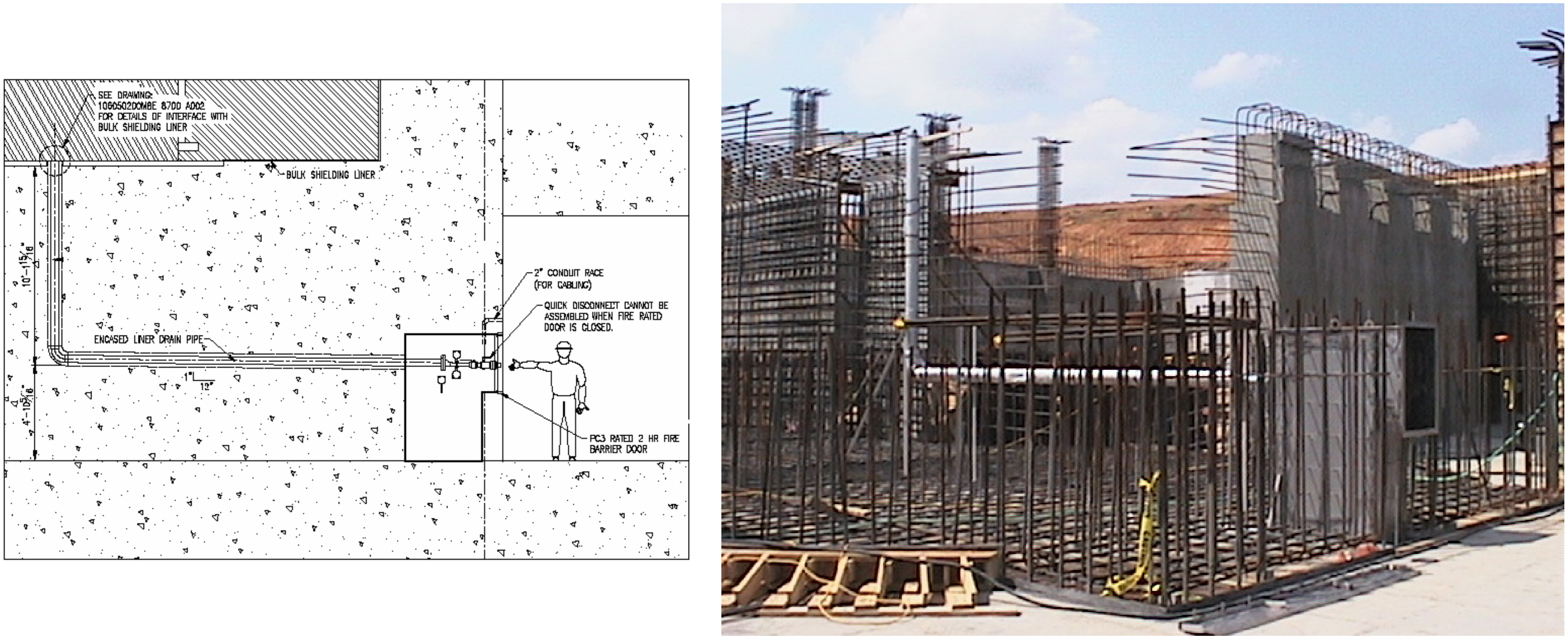


Fig. 5.2-45. Schematic diagram of bulk shielding liner spill drainage provision and initial installation.

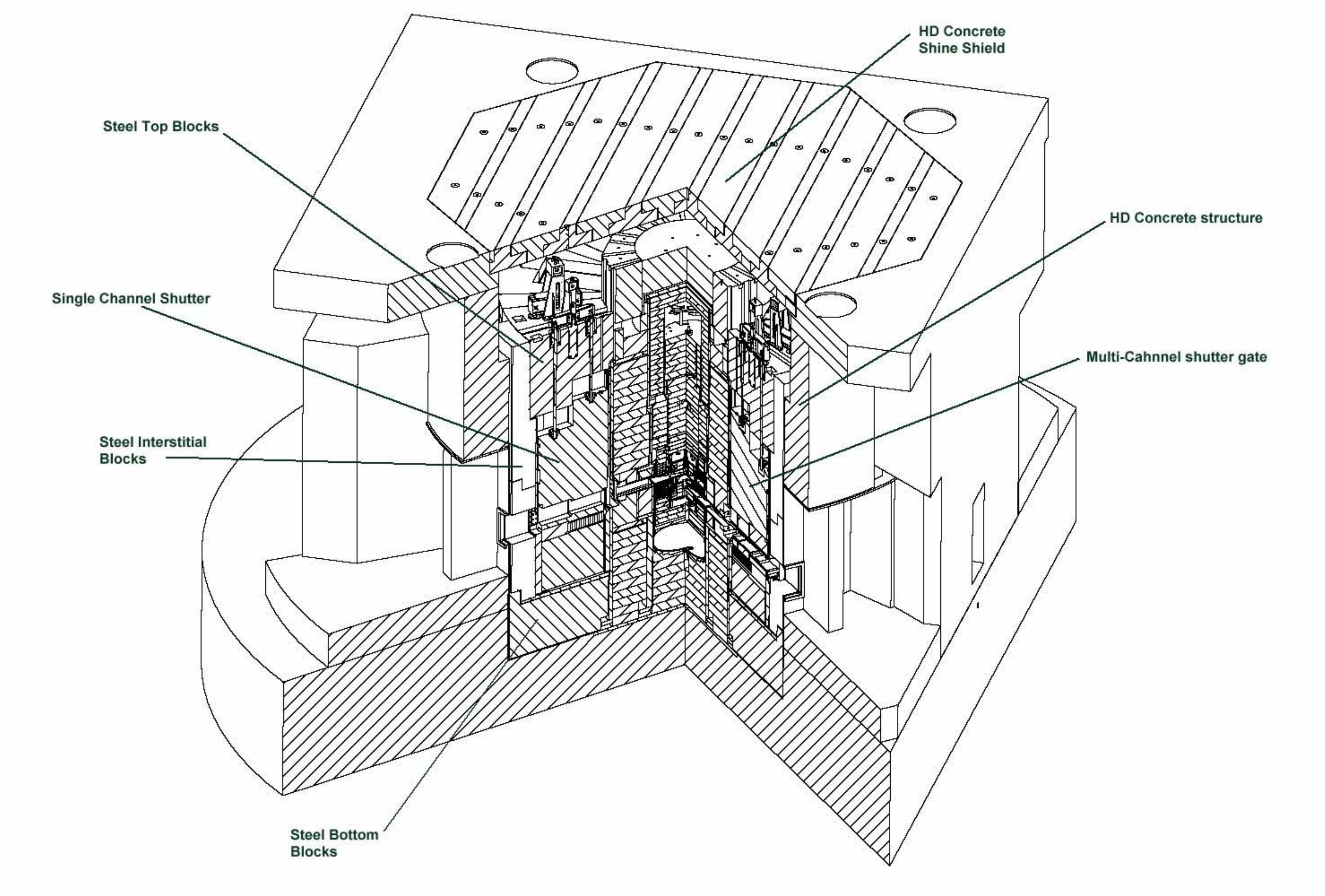


Fig. 5.2-46. Location of shutters in context of monolith structure.

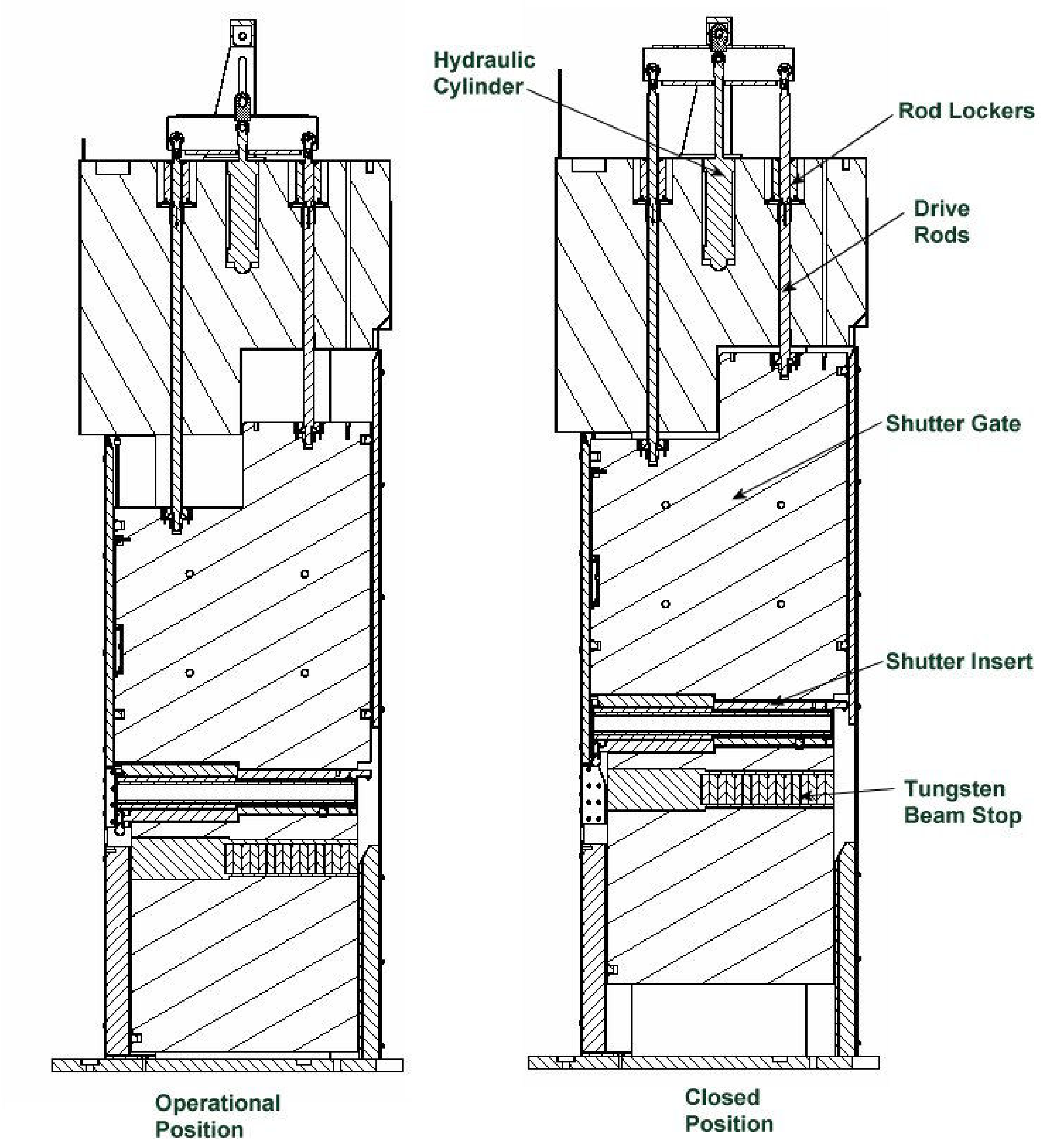


Fig. 5.2-47. Typical shutter.

Fig. 5.2-48 Installation of a typical shutter.

The hydraulic system that powers the hydraulic cylinders uses water. The use of water as hydraulic fluid is possible because the system is designed for a relatively low pressure at 2250 psi and a relatively slow stroke speed at 20 inches/minute. It is desirable to control the amount of flammable liquid near the target. The rod lockers located at the top of the drive rods are designed to clamp the drive rods when the hydraulic system pressure falls below set pressure. This means that a shutter can be placed in the closed position (up), the hydraulic system can be depressurized, and the shutter will still remain in the closed position. In addition, there is a manual safety pin that can be used to lock the drive system in the closed position and can be used for "lock out tag out" procedures.

The independent indicator switches and indicator rod are shown in Fig. 5.2-49. This equipment is part of the instrument personnel protection system (PPS). It is has no function for control of the shutters. The indicator rod has no loads on it other than the force of the switch actuators. It is firmly fixed to the shutter. If a shutter failed to return to the closed (up) position in response to an instrument PPS close signal, a fault signal would be automatically generated for the PPS to cut off the proton beam.

5.2.4.2 Installation and testing

All planned monolith components have been installed. This includes 11 operating shutters and 7 concrete shutter plugs and the hydraulic drive system for the shutters. Figure 5.2-28 shows the installation completion for all the permanent monolith shielding. Representative installation pictures are shown in Figs. 5.2-51 through 5.2-53.

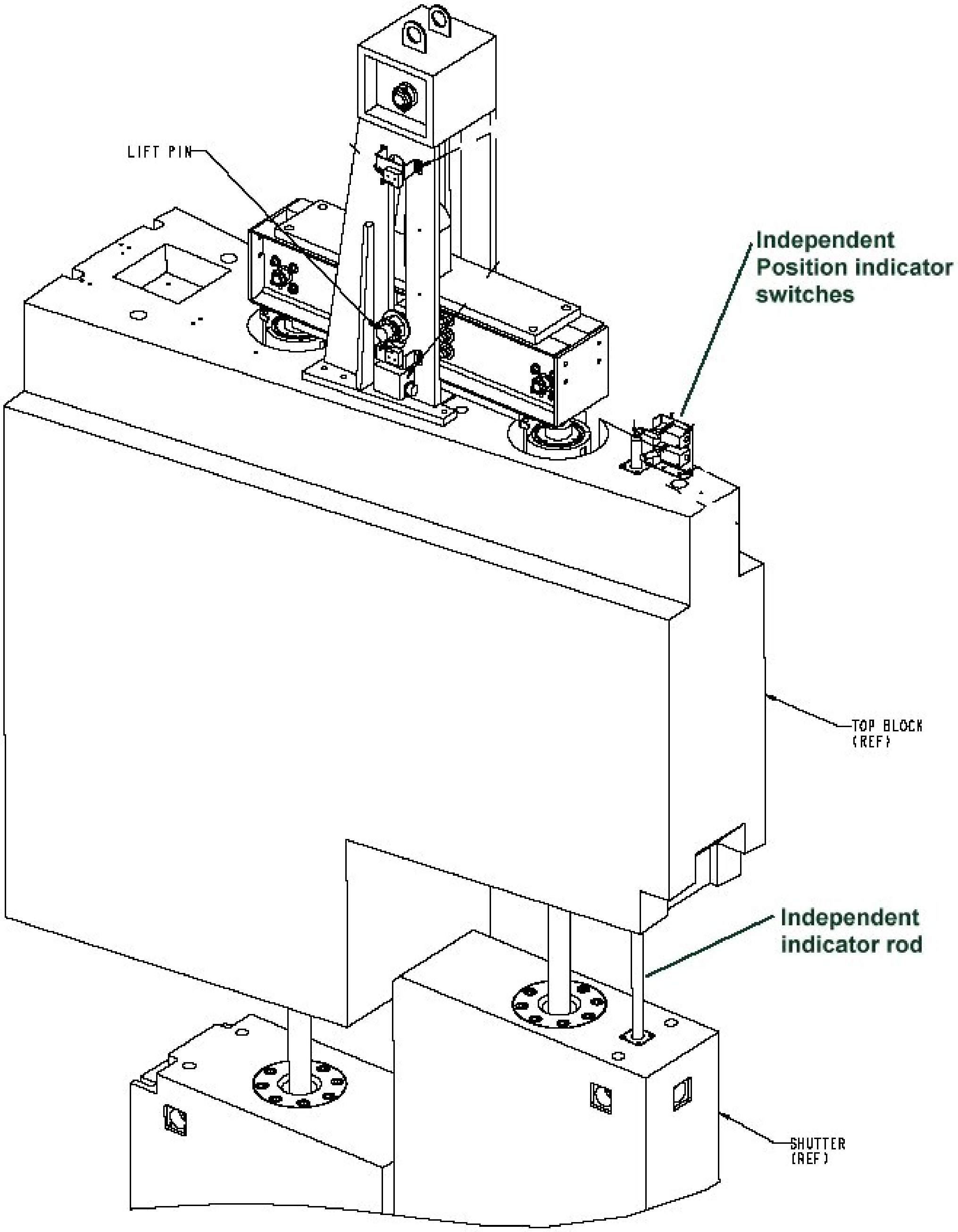


Fig. 5.2-49. Shutter position indicators.

Fig. 5.2-50. Typical shutter drive system on top block.

Fig. 5.2-51. Hydraulic power unit for the shutter drive system.

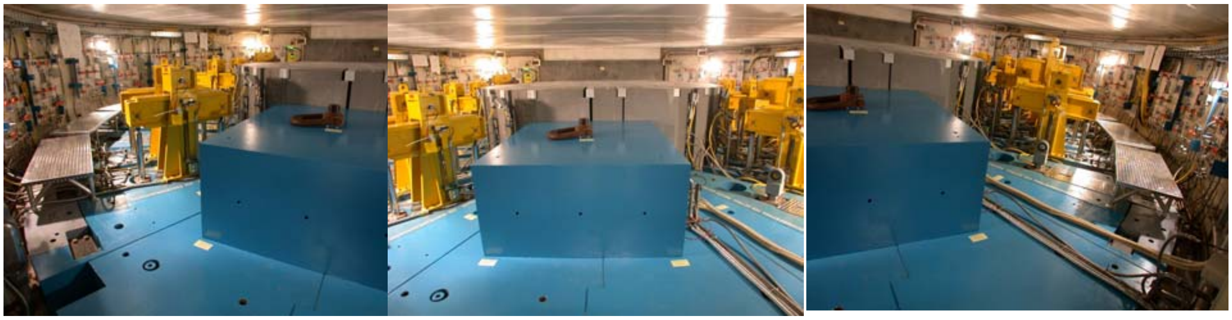


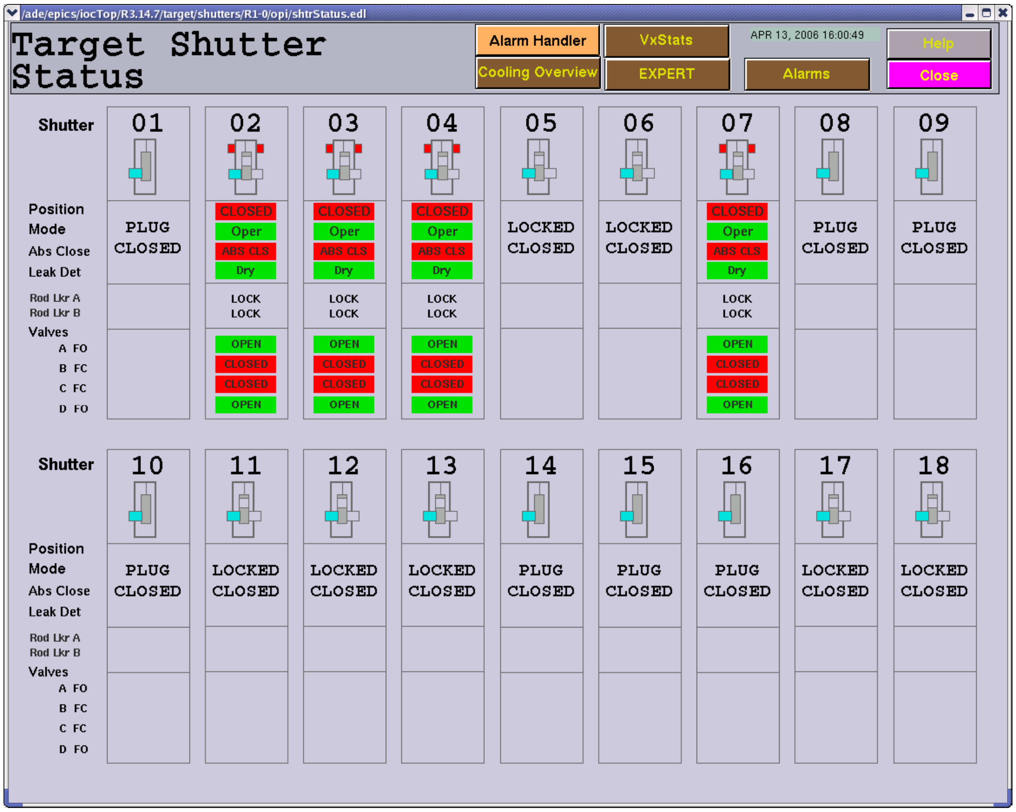
Fig. 5.2-52. Shutter drive room views (north side, center, south side).

The shutter hydraulic power unit has been tested, and all 11 operating shutters have been successfully tested. The time to raise or lower a shutter is approximately 1 min. A typical EPICS view screen is shown in Fig. 5.2-54.

5.2.4.3 CD-4 performance and additional capability

The monolith shielding has been designed and evaluated for 2 MW beam operation. Higher beam power may be possible, but this would require additional analysis and may require some localized additional shielding.

Fig. 5.2-53. Shine shield “T” beams installed.



Shutter	01	02	03	04	05	06	07	08	09
Position	PLUG CLOSED	CLOSED	CLOSED	CLOSED	LOCKED CLOSED	LOCKED CLOSED	CLOSED	PLUG CLOSED	PLUG CLOSED
Mode		Oper	Oper	Oper			Oper		
Abs Close		ABS CLS	ABS CLS	ABS CLS			ABS CLS		
Leak Det		Dry	Dry	Dry			Dry		
Rod Lkr A		LOCK	LOCK	LOCK			LOCK		
Rod Lkr B		LOCK	LOCK	LOCK			LOCK		
Valves									
A FO		OPEN	OPEN	OPEN			OPEN		
B FC		CLOSED	CLOSED	CLOSED			CLOSED		
C FC		CLOSED	CLOSED	CLOSED			CLOSED		
D FO		OPEN	OPEN	OPEN			OPEN		

Shutter	10	11	12	13	14	15	16	17	18
Position	PLUG CLOSED	LOCKED CLOSED	LOCKED CLOSED	LOCKED CLOSED	PLUG CLOSED	PLUG CLOSED	PLUG CLOSED	LOCKED CLOSED	LOCKED CLOSED
Mode									
Abs Close									
Leak Det									
Rod Lkr A									
Rod Lkr B									
Valves									
A FO									
B FC									
C FC									
D FO									

Fig. 5.2-54. EPICS view screen for target shutter status.

5.2.5 Target Service Bay and Remote Handling Systems

Figure 5.2-55 shows the location of different parts of the target service bay complex. Figs. 5.2-56 and 5.2-27 show additional views of the process bay.

5.2.5.1 Target service bay

The target service bay is built to prevent unintentional escape of radioactivity through the barriers provided by its design configuration and by waste/emissions collection systems that serve the target service bay. Figures 5.2-59, 5.2-60, and 5.2-61 present various cross section and cut-away views of the target service bay.

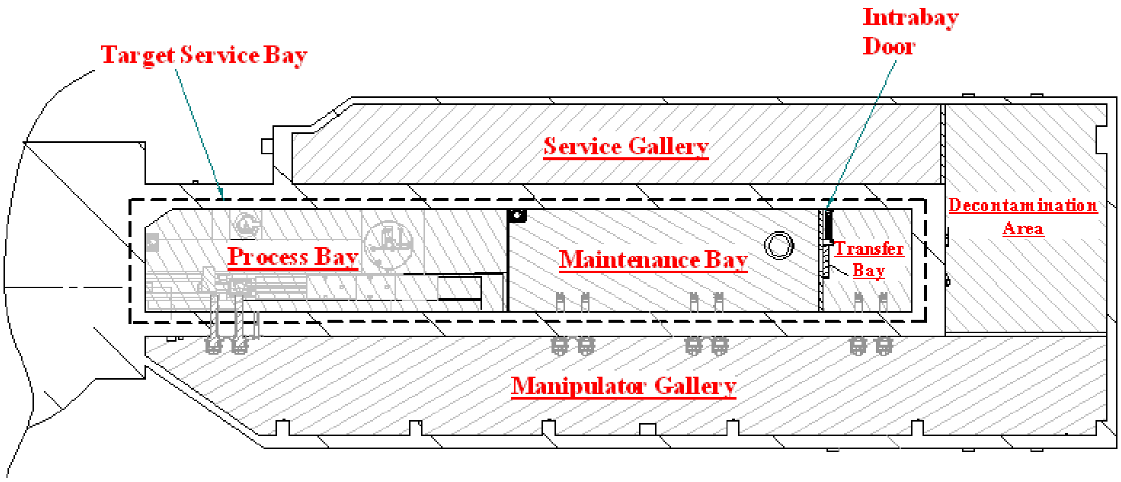


Fig. 5.2-55. Location of functional areas of the target service bay complex.

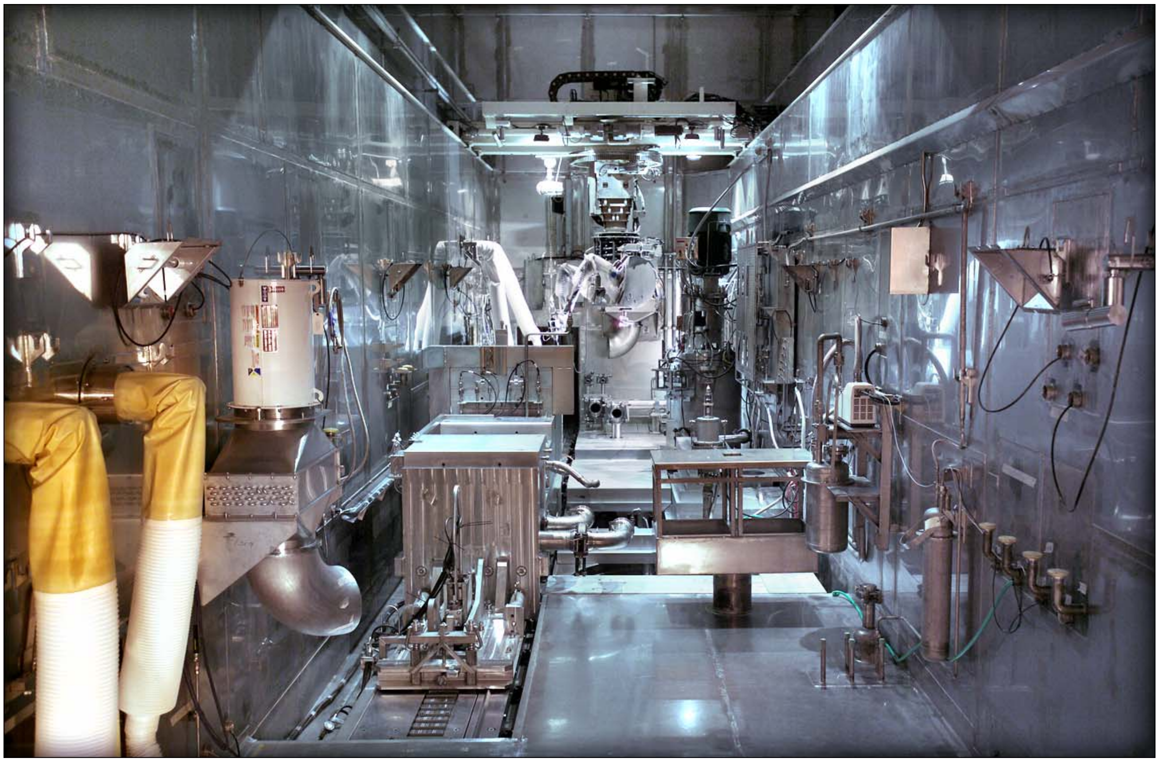


Fig. 5.2-56. Process bay.

Fig. 5.2-57 View from transfer bay to maintenance bay.

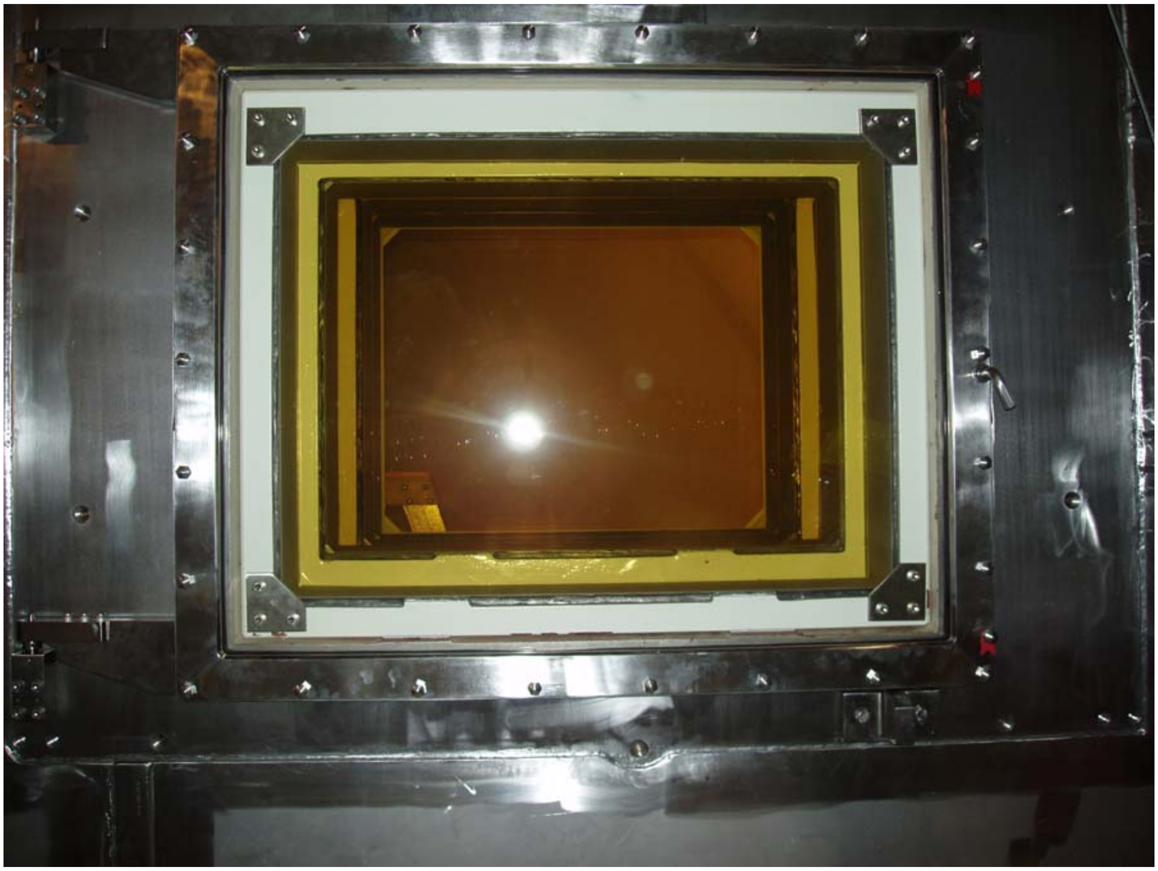


Fig. 5.2-58. Typical window as viewed from inside target service bay.

The target service bay has a continuous stainless steel liner over the concrete to keep radioactive constituents, particularly activated mercury, from leaching into the concrete.

Bay penetrations for utilities (piping, electrical, etc.) include features such as remotely operable disconnect assemblies on the inside of the bay and flanged connections on the outside of the bay. Spare piping and electrical penetrations are installed through the shielded bulkheads so that future needs can be accommodated without compromising the bay confinement integrity.

The bays have equipment transfer systems that allow air lock transfers for small items, helping to keep worker exposure to radiation ALARA and minimize the potential for spread of contamination. The bay manipulator workstations each have one lead glass shielding window that matches or exceeds the shielding provided by the bay shield walls and allows visual observation for remote operations while minimizing/eliminating exposure (see Fig. 5.2-58). The bay windows are designed for removal from the cold side for maintenance.

The design confines liquids that may be contaminated with radioactivity within the target service bay until operators decide to make the transfer. The process bay of the target service bay is designed to confine and collect any liquid mercury spills. In this area, the stainless steel-lined concrete floor is sloped to direct spills to the collection basin that is able to hold 100% of the mercury.

Each of the service bays in the target service bay has a liquid collection sump that has no direct liquid removal outlet from the target service bay. Normally-capped lines in the target service bay provide a connection to the low-level liquid waste system. To remove liquid from the target service bay, one of these drain lines must be remotely uncapped and connected to a sump pump. It is possible that liquid mercury and/or water could be spilled into one of the sumps (particularly the collection basin, which is the sump in the process bay). Therefore, the piping configuration and pump used are configured so that liquid mercury could not be inadvertently discharged into the low-level liquid waste (LLLW) system by this means.

Additionally, there is a waste handling bay for processing and packaging contaminated or activated waste items generated in the target service bay for disposal.

5.2.5.2 Remote handling and material transfer systems

The target service bay complex is divided into two bays, as illustrated in Fig. 5.2-55: (1) the target service bay itself with its process and maintenance functional workspaces, and (2) the single bay transfer bay. Figure 5.2-59 shows a cut-away isometric view, while Figs. 5.2-60 and 5.2-61 depict cross-sectional views of the target service bay from side and end.

The process bay holds the mercury process system, including related water cooling, instrument, and utility systems. The maintenance bay is designed to handle, size, and package used equipment and other waste items. This bay is also used to hold replacement components and packaged waste. All operations inside the process and maintenance bays are designed to be performed remotely; no personnel will enter this area without a major cleanup operation.

The transfer bay is separated from the higher radiation levels of the process and maintenance bays by the intrabay shielding door. Personnel may enter the transfer bay for contact maintenance or inspection of items such as the bridge crane or gantry servomanipulator. The sequence for such operations involves first opening the intrabay door, remotely moving the crane or other item into the transfer bay, closing the intrabay door, then opening the personnel access door for worker entry. An automatic interlock on the transfer bay personnel access door and intrabay doors ensures worker protection.

The transfer bay is intended to be maintained as a “clean” area for in-bay crane and servomanipulator hands-on maintenance. It is also a decontamination area for some of the materials (contact-handled wastes, samples for analysis, tooling for repair, etc.) removed from the maintenance bay, before they are removed from the bay environment. The flow of air is maintained from the transfer bay into the maintenance bay during all operational conditions to minimize airborne spread of contamination from the maintenance and process bays into the transfer bay.

5.2.5.3 Remote handling systems

The target service bay has two basic tooling systems: (1) four shield window work stations; and (2) bridge-mounted tooling. Both are monitored and supported by a remote handling control room located outside the manipulator gallery.

The south wall of the target service bay is equipped with four separate WWSs. Each WWS includes a leaded-glass shield window, a pair of through-the-wall manipulators, a video monitoring console, and a bank of utility services (compressed air, electrical, and high-pressure water). This wall is partially depicted in cut-away in Fig. 5.2-59. Figure 5.2-62 shows workstations 2 and 3.

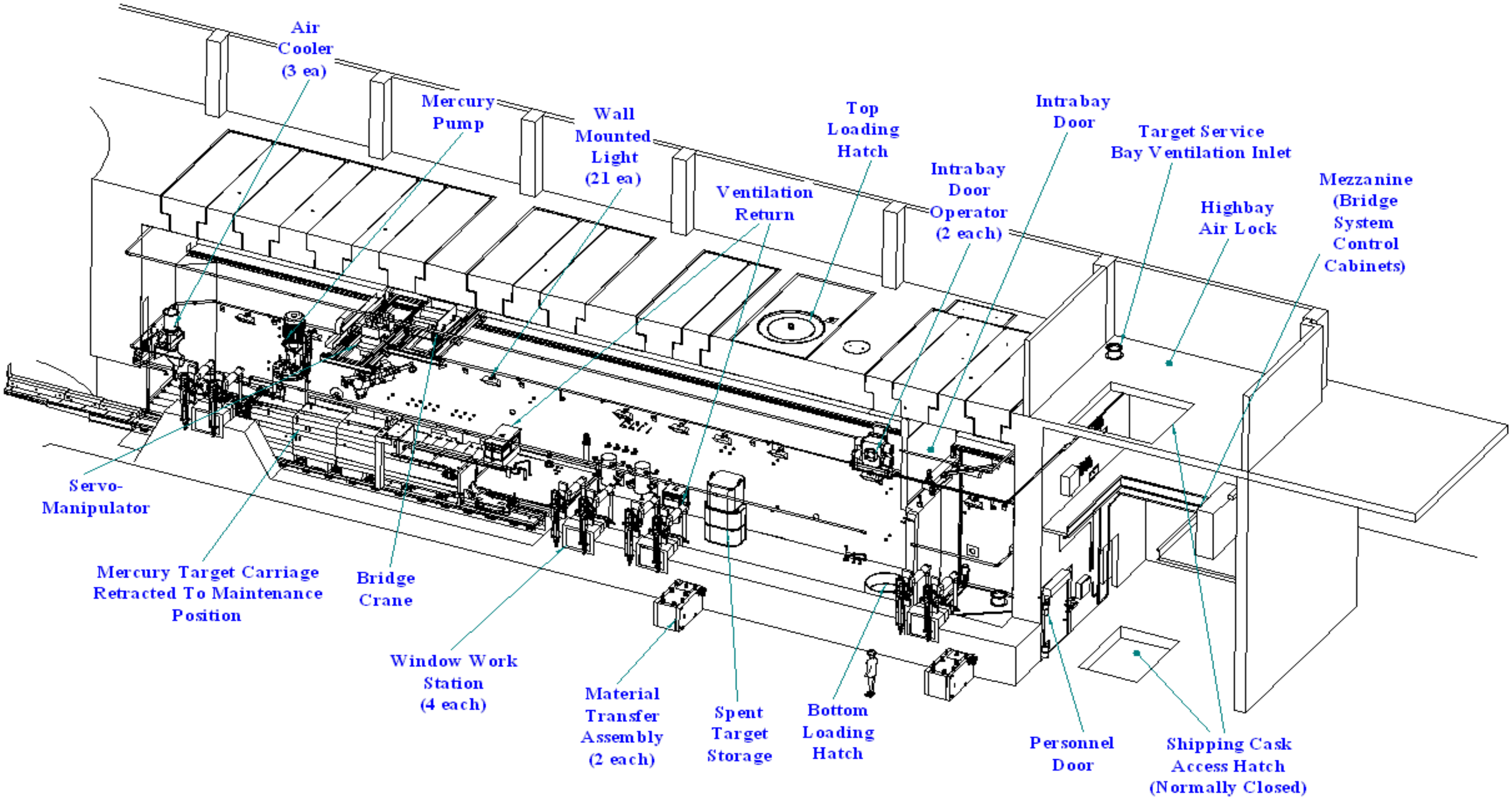


Fig. 5.2-59. Cut-away view of target service bay from the southeast (target carriage in withdrawn position).

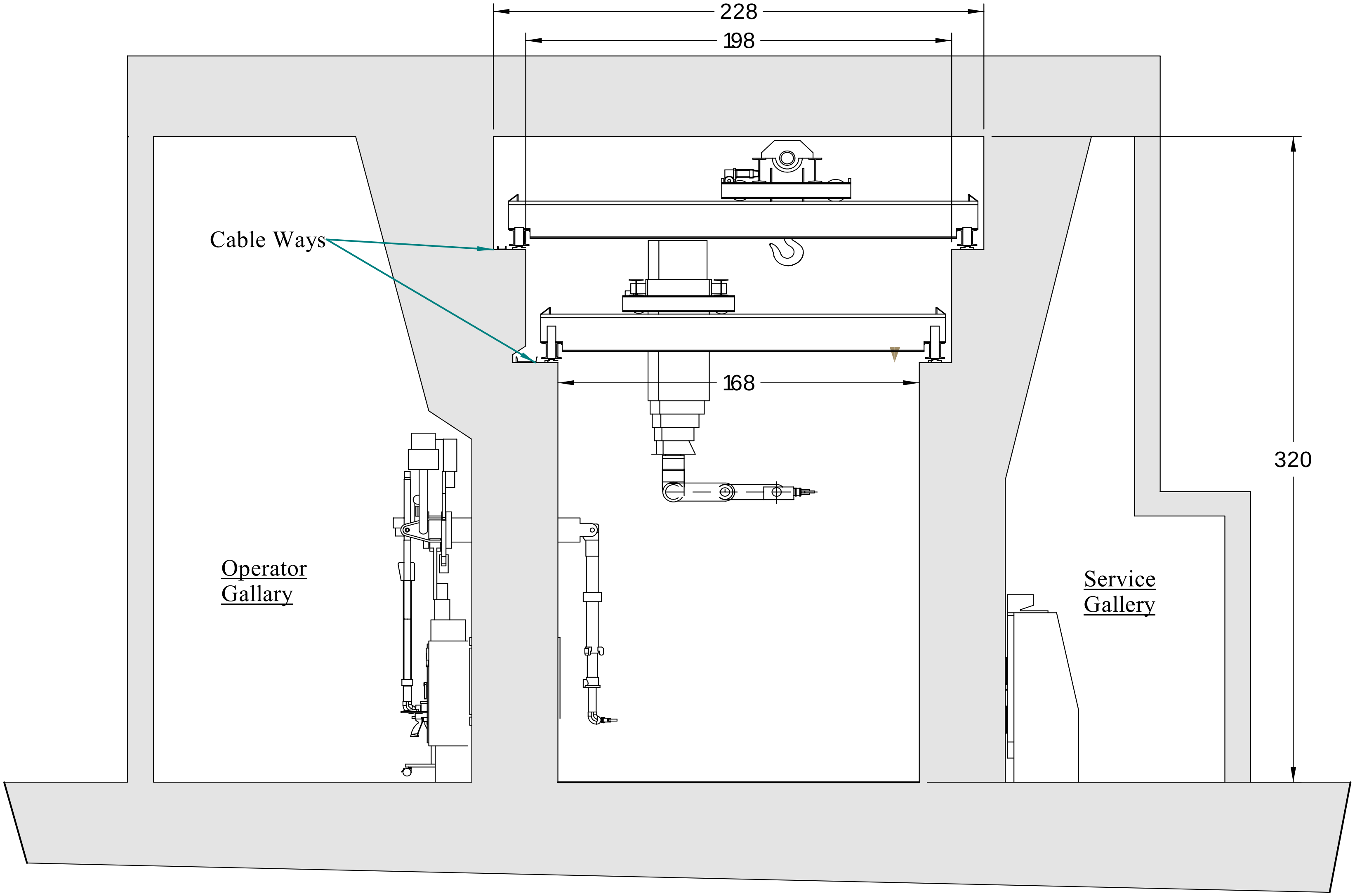


Fig. 5.2-60. Cross section view of target process bay and galleries.

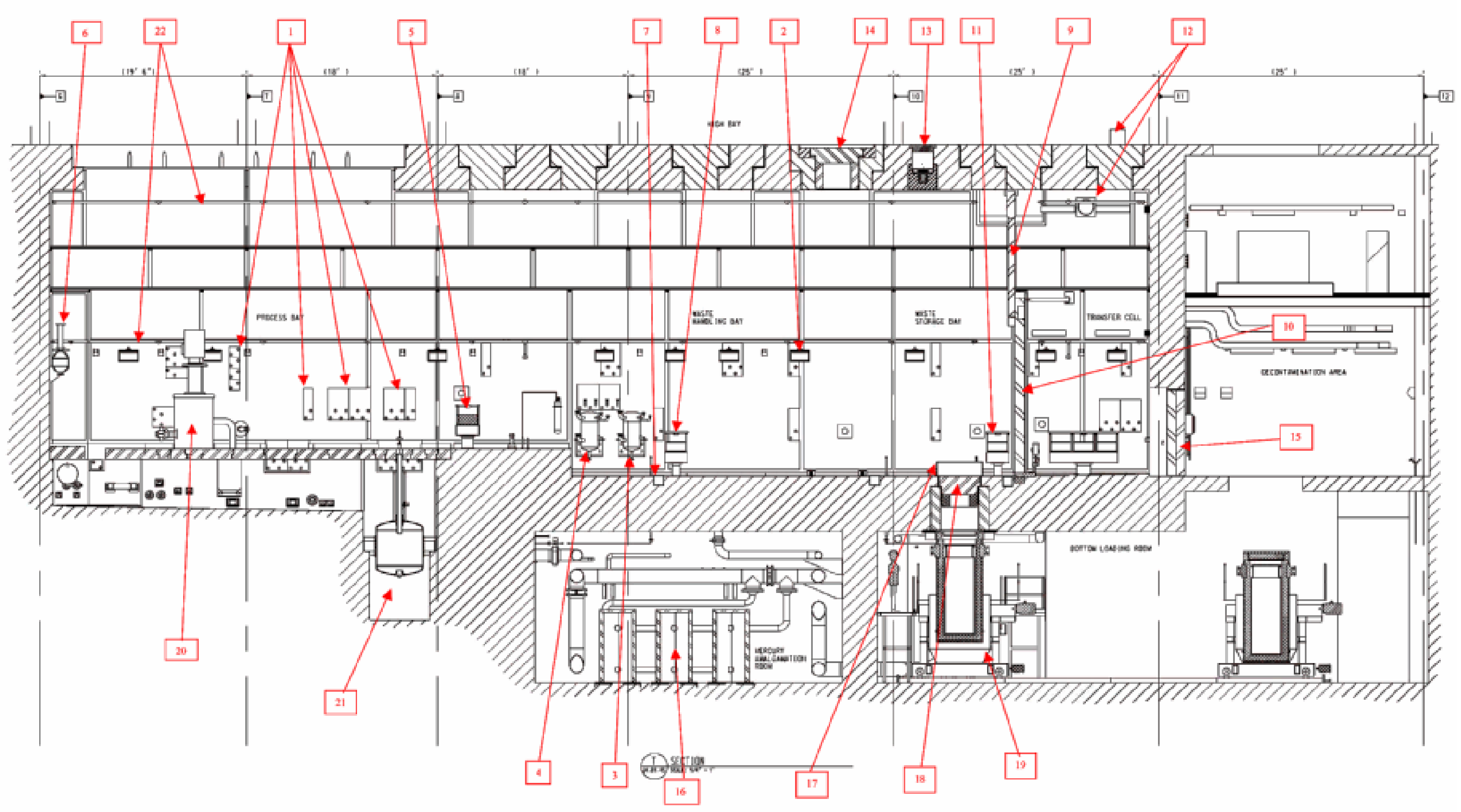


Fig. 5.2-61. Target service bay cross section view (shielding beams above process bay shown removed, a very rare nonoperational configuration).

Fig. 5.2-61. (continued)

Key to numbered items:

Note: the target service bay (i.e., the "maintenance" bay) is divided into the process bay and the maintenance bay. The transfer bay is part of the target service bay, but it is labeled separately because of the intent to maintain it in a relatively contamination-free state to facilitate infrequent worker entry. The transfer bay is separated from the maintenance bay by movable steel shielding doors (items 9 and 10 on the drawing and in the list).

1. Penetration banks, typical of 50 within the target service bay. Both electrical and piping penetrations are shown.
2. Light fixture, typical of multiple light fixtures within the target service bay.
3. Deferred low temperature condenser (for use only during regeneration of the gold amalgamation bay exhaust treatment medium, will not be installed for initial operation).
4. Deferred water-cooled condenser (to be used only during regeneration of the gold amalgamation bay exhaust treatment, will not be installed for initial operation).
5. Process bay PCE system exhaust port (each exhaust port fixture holds a HEPA filter).
6. In-bay air cooler, typical of three within the target service bay (service bay air recirculates through each water-cooled heat exchanger).
7. Floor sump, typical of three within the maintenance bay.
8. PCES exhaust port, typical of two in maintenance bay.
9. Upper rotating intrabay shielding door (~8 in.-thick steel).
10. Lower rolling intrabay shielding door (~11 in.-thick steel).
11. PCES exhaust port.
12. PCE system air intake for target service bay (air enters transfer bay first).
13. Upper intrabay shielding door latch.
14. Large component port.
15. Personnel door.
16. Deferred PCE system gold amalgamation air treatment stages (shown in place in the basement but will not be initially installed. Items 3 and 4 support this item and will also not be installed for initial start-up).
17. Curb structure for bottom-loading port (prevents maximum credible water accumulation from leaking out of the target service bay).
18. Bottom-loading port (shield plug is stored inside storage bay when removed for use of the port).
19. Shipping container cart for the bottom-loading port with TN-RAM cask.
20. Mercury pump.
21. Mercury storage tank and collection basin.
22. Water mist system spray distribution piping.

Fig. 5.2-62. Workstations 2 and 3 showing windows, CRL manipulators, and video monitors.

The through-the-wall manipulators are operated by workers occupying the manipulator gallery as shown in Fig. 5.2-62. Two types of manipulators are installed: seven Central Research Laboratories (CRLs) Model F (or equivalent) mechanically linked master-slave manipulator pairs and one CRL Model E. The manipulators are to be used for in-bay tasks requiring high dexterity, such as handling wrenches and small fixtures; positioning bridge and servomanipulator-held components; and performing inspections with swipes or closed-circuit cameras. The maximum capacity of the manipulators is ~50 lb. The reach of the WWS manipulators is limited to the immediate vicinity of the stations.

Two overhead, in-bay, remote handling systems are provided: a 7.5-ton, in-bay bridge crane, and a servomanipulator. The telerobotic servomanipulator system is mounted on the end of a telescopic boom that is mounted on a traversing bridge (gantry). The servomanipulator arms are rated for a maximum load of ~100 lb. The system will be used throughout the bay to handle tools, lift fixtures, and other loads. The manipulator can be fitted with conventional parallel pinch grips and hook and tool holding hands. The servomanipulator has a vertical travel allowing activities between floor level and approximately 13 ft above the bay floor over the full floor area of the bay. Figure 5.2-63 shows the manipulator, and Fig. 5.2-64 shows a typical target change operations with the bridge and CRL manipulators working together.

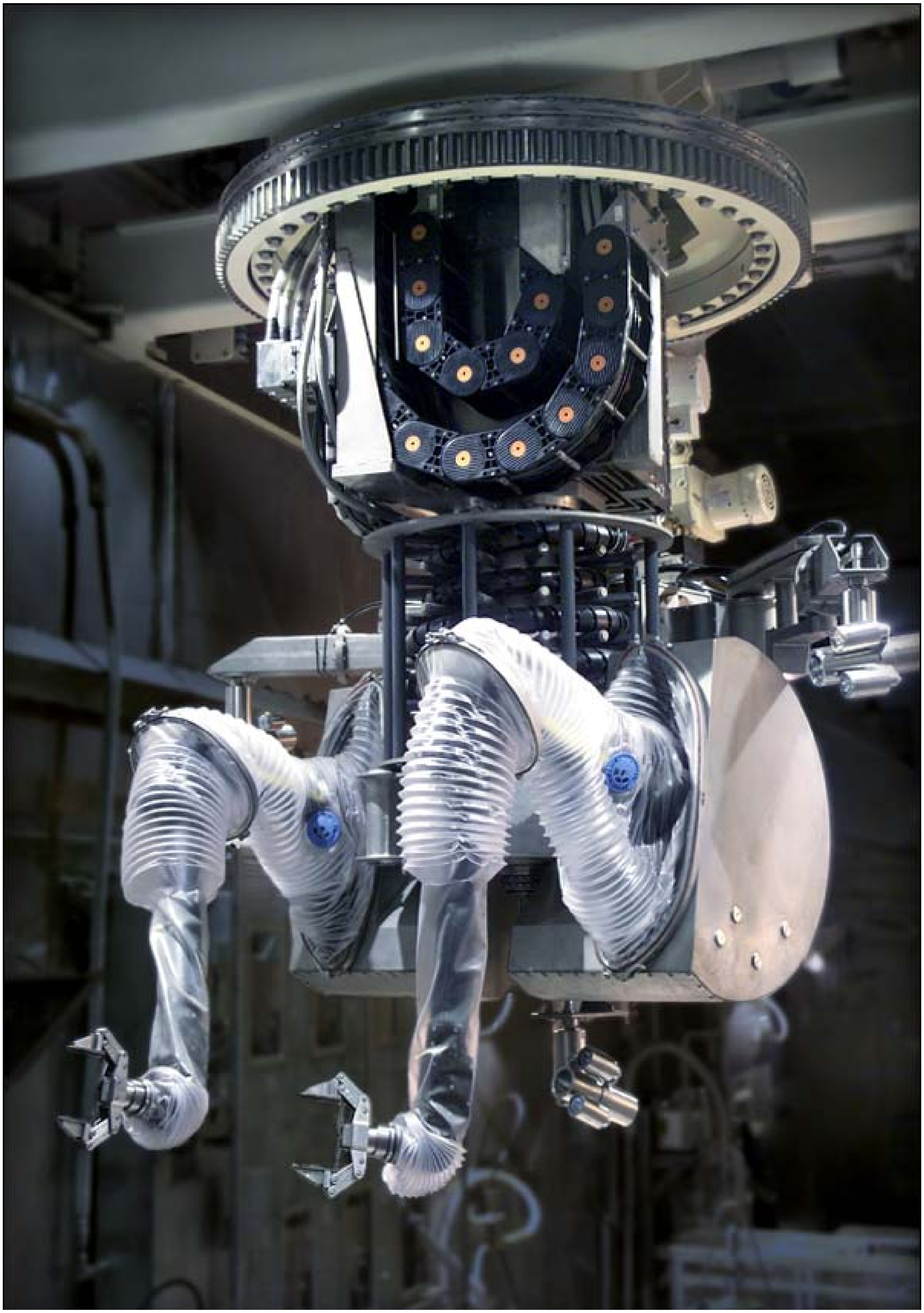


Fig. 5.2-63. Telerobotic servomanipulator system.

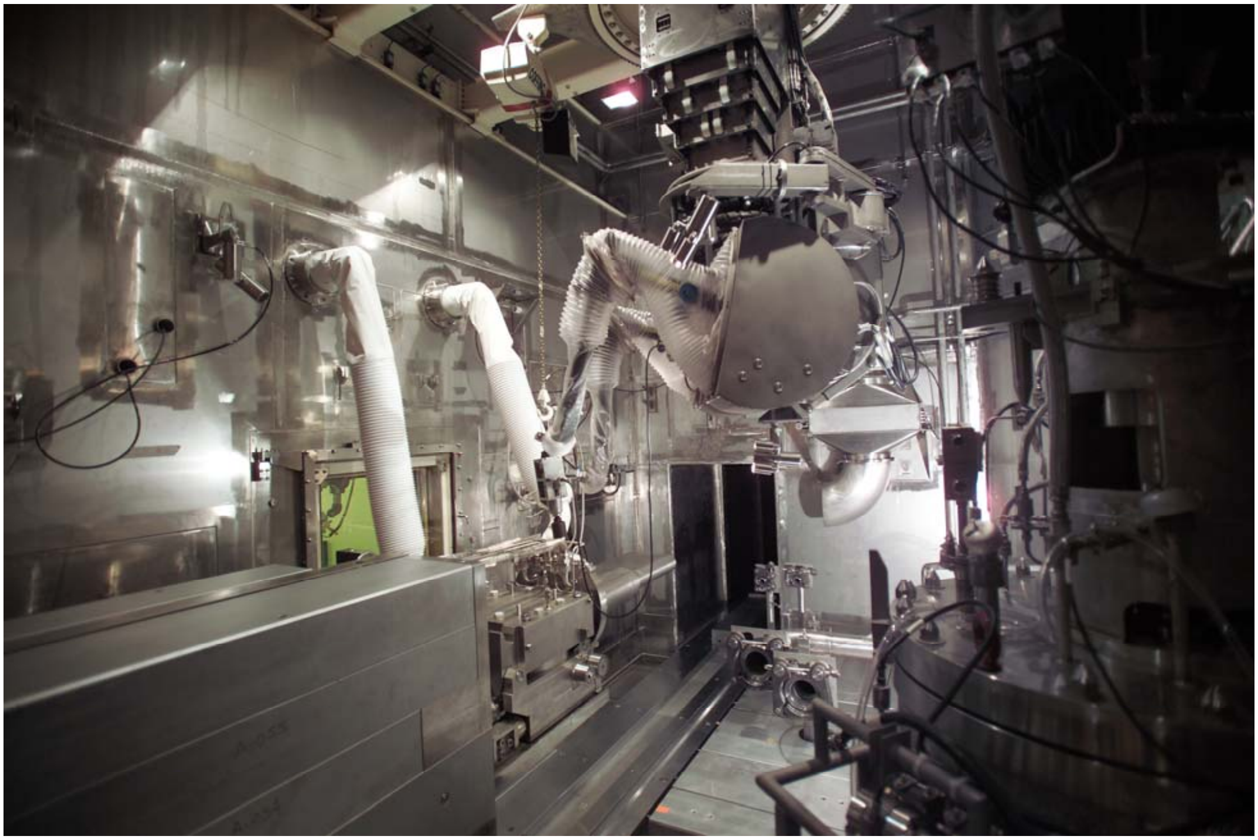


Fig 5.2-64. Telerobotic and through-the-wall manipulator access to target.

The 7.5-ton overhead bridge crane is mounted above the servomanipulator to handle most loads inside the target service bay. Generally, this includes only components with lifting attachments designed to mate with the crane hook. Identified loads include shield blocks, used mercury process components, waste-handling containers with and without loads, spent target assemblies, proton beam window modules, and new and used filters. The vertical hook travel of the crane is approximately 35 ft. This allows it to lower loads into a shielded cask docked at the bottom loading hatch, or to reach a load in the collection basin/storage tank pit (i.e., the crane is designed to reach below the target service bay floor level for these required activities). The hook can approach to within ~12 in. of all the bay walls.

The remote handling control room houses the main control stations for the crane, servomanipulator, and video systems. Fig. 5.2-65 shows the servomanipulator station.

Other systems operated from the control room include the intrabay door, air coolers, and lights. Because of the size of the target service bay, video cameras are required to provide viewing for the operators. Video cameras (initial installation of 11) are mounted on the walls and bridge systems throughout the target service bay. The cameras will provide viewing throughout the bay and supplement direct viewing though the four shield windows. The video systems may also be operated and viewed from the four WWSs and the remote handling control room.

5.2.5.4 Material transfer systems

Four paths have been provided for loading materials into and out of the target service bay; each designed to accommodate a specific range and type of component or tool.

Fig. 5.2-65. Servomanipulator station in remote-handling control room.

Bottom-loading port: A bottom-loading port is mounted in the floor of the maintenance bay and will normally be used to move wastes out of the bay via the bottom loading room in the basement. Some contaminated and activated materials loaded out will be packaged in liners prior to load-out into a waste liner located in the cask. Other waste materials too large to package will be loaded directly into the waste liner. The bottom-loading port is designed for loading the shipping cask tentatively selected for certain irradiated SNS materials (e.g., the TN-RAM shielded shipping cask). The in-bay bridge crane will be used to move items through the bottom-loading port into the cask.

Top loading port: The top loading port located in the ceiling of the maintenance bay of the target service bay is used for the insertion of irradiated, potentially contaminated components such as the spent proton beam window or core vessel inserts from the high bay. These components will be disassembled and packaged for loading into the TN-RAM shipping cask.

Input enclosures: Two input enclosures are provided, one at WWS 3 and one at WWS 4 (these are shown on Fig. 5.2-59, labeled as “Material Transfer Assembly” and Fig. 5.2-66). Each input enclosure is a shielded pass-through device mounted at floor level that allows small items to be passed in and out of the target service bay. A curb is built into the structure of the pass-through to make it impossible for the greatest water spill event to allow contaminated water to flow out of the target service bay through this device.

Transfer bay personnel door: New equipment will enter the target service bay primarily through the transfer bay. The transfer bay has a shielded personnel door at the instrument floor level that opens into the decontamination area, which functions as an air lock when the door is open (see Fig. 5.2-67).

Fig 5.2-66. Input enclosure near workstation 3.

Fig. 5.2-67. Personnel door leading to transfer bay.

The ventilation system is designed to maintain a negative pressure in the target service bay so that the flow of air is into the target service bay with the personnel door open. New equipment to be loaded into the bay may be positioned inside the bay with a lift truck or transfer cart. A small sample cask may be positioned within the bay for loading out samples of the target module or other materials for analysis. Crane bridge and manipulator bridge maintenance will occur from a man-lift platform loaded into the transfer bay on an as-needed basis. Servomanipulator arm maintenance will occur from the transfer bay floor level. Operational procedures and a keyed interlock system will prevent entry into the transfer bay when the inter-bay shielding door is open, and this is backed up by a radiation monitor that is interlocked with the intra-bay door and with visual and audible alarms. Figures 5.2-68 through 5.2-70 show additional view of the control room and service bay areas.

5.2.5.5 Installation and Testing

All Remote handling equipment has been installed and testing. Integrated system testing has been performed to demonstrate all required remote handling operations on the mercury loop components and other equipment installed in the target service bay. Table 5.2-4 lists these tests and completion dates. Representative Installation and testing pictures are shown subsequently.

Table 5.2-4 Remote Handling Integrated System Tests

Test	Date Completed
Remove and install pump motor (IST1.6.7-6)	1-Nov-05
Demo hdlg of wall mounted video camera(IST1.6.7-15	30-May-05
Demo ziplift oper Inside HC (IST 1.6.7-18)	1-Sep-05
Demo removal & install of shld blks(IST1.6.7-13)	1-Nov-05
Demo hot cell filt.chgeout(in-cell)(IST1.6.7-20)	4-Oct-05
Demonstrate Target Module Replacem.(IST1.6.7-1b)	1-Dec-05
Demo pump greasing with tooling (IST1.6.7-12)	1-Feb-06
Demo hdlg of wall mnted light/bulb (IST1.6.7-14)	2-Aug-05
Demo access to vacuum pump (IST1.6.7-23)	1-Nov-05
Demo Hot Cell Cooler Maintenance (IST1.6.7-21)	1-Nov-05
Demo chge-out of a penetration serv(IST1.6.7-16)	14-Nov-05
Demo target cart retract mechanism (IST1.6.7-4)	4-Nov-05
Chk access/view&hdlg of valve panels(IST1.6.7-11	15-Nov-05
Demo/chk access&view.of all Hg joints(IST1.6.7-9	18-Nov-05
Dis-&re-engage pump disch pipe fitt.(IST1.6.7-8)	18-Nov-05
Demo/chk access & viewing heat exch(IST1.6.7-10)	23-Nov-05
Dem RH of Hg dmp valv(IST1.6.7-7)	7-Dec-05
Changeout safety related instrum. (IST1.6.7-3)	14-Dec-05
Demo compl.target chgout;multi.times(IST16.7-1b)	26-Jan-06
Demo Mercury Pipe Handling (IST1.6.7-26)	7-Feb-06
Demo Handling Upper Floor Shields	26 Apr 06

5.2.5.6 CD-4 performance and additional capability

The target service bay and equipment has been designed and evaluated for operation at 2 MW. The window workstations have adequate shielding to allow continuous occupancy with a target exposed to a 2 MW beam for 1250 hours in front of the window. All equipment required to support > 1 MW beam operation and target replacement has been installed and tested.

5.2.6 Cooling Water Loops, Vacuum, and Helium Systems

5.2.6.1 Water cooling systems

The target systems are cooled by four independent cooling loops. The cooling loops supply and control the distribution of cooling water to the various target components. The cooling loops remove approximately 2 MW of heat when the target is operating at the 2-MW full proton beam power. Three of the cooling loops use light water, and the fourth uses heavy water (Table 5.2-5).

The cooled components are located in the target service bay, core vessel, or monolith shielding area. Active components, e.g., pumps and motor-operated valves, are generally located in the basement-level utility vault. A similar design approach has been followed for each loop. Generic design information is presented below to avoid repetition.

A simplified block flow diagram representing the primary components in each cooling water loop is depicted in Fig. 5.2-71. Components or features not included in or unique to individual loops are not identified. Light water loop 1e does not have a delay tank because the water is not activated.

Fig. 5.2-68. Remote-handling control room and manipulator in target service bay.

.

Cooling loops 2, 3, and 4r each pass directly through intense neutron fields emanating from the target. In addition, the full proton beam passes through loop 2cooling water in the proton beam window and in the water-cooled shroud. The water and entrained impurities will become significantly activated. These loops are equipped with delay tanks designed to provide the holdup time needed to allow short-lived isotopes such as N-16 (7.1 second half-life) to decay. Cooling loop 1 is unique in that the water will not be significantly radioactive. It circulates water through the mercury heat exchanger located in the target service bay. Because the water of cooling loop 1 is removed from direct neutron exposure, it is not expected to have significant activity.

During normal operation, water circulates in a closed loop. During shutdowns, the water may be drained to the drain tank. Each of the target cooling loops rejects heat to a secondary cooling water system through a heat exchanger. At least two boundary failures would be required to contaminate tower water with activated water. In addition, during normal operations, differential operating pressures are maintained so that tower water is at a higher pressure in the heat exchanger where cross-contamination could occur. Consequently, any leakage through the barriers that separate the fluids would be from the tower water side to the target cooling loop side of the heat exchanger.

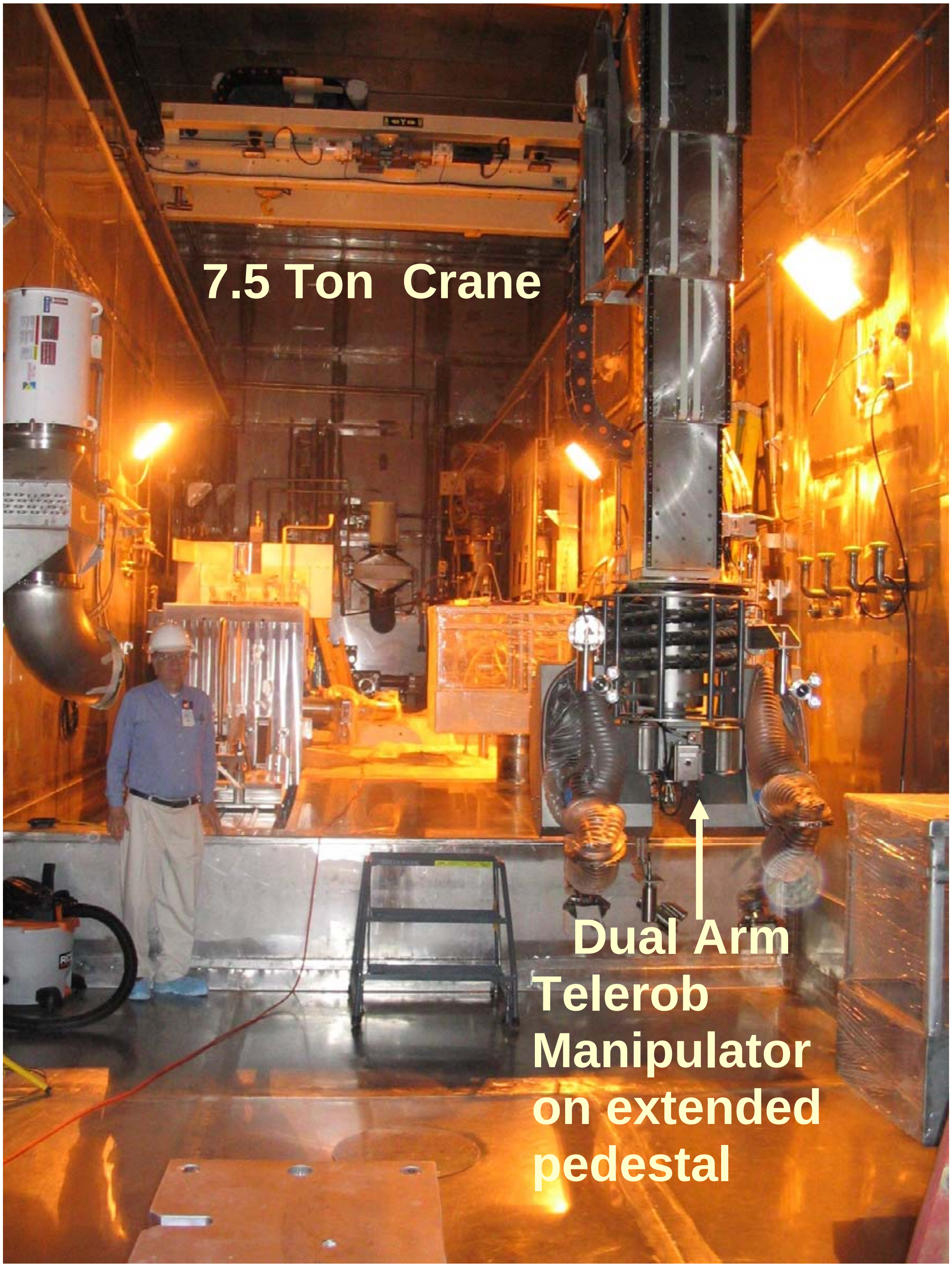


Fig. 5.2-69. Target service bay with manipulator and 7.5-ton crane.

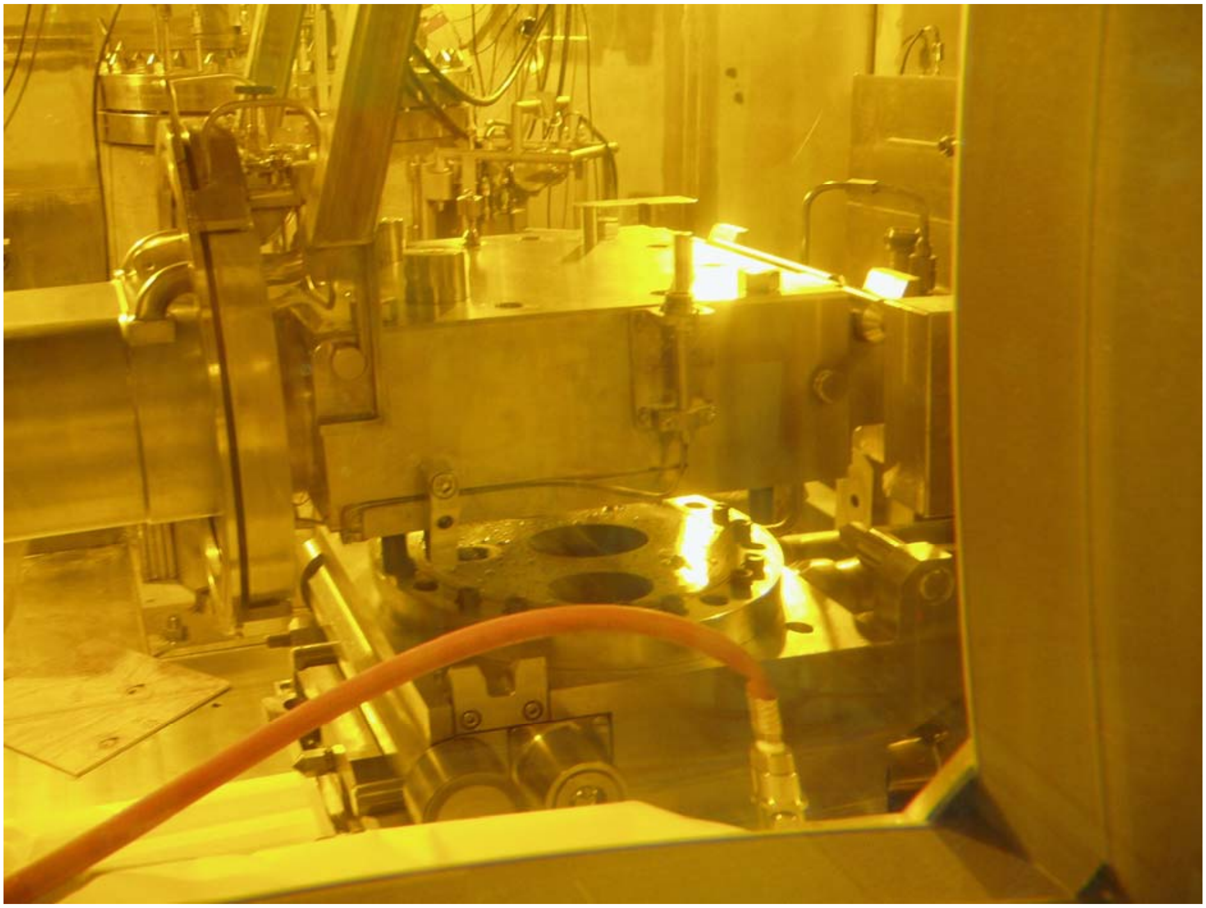


Fig. 5.2-70. Remote-Handling test of target change after loading mercury.

Table 5.2-5. Coolant loops and approximate estimated heat loads

Cooling water loop	Main component(s) served	Design basis heat load
1 (light water)	Mercury heat exchanger	1547 kW
2 (light water)	Proton beam window and target shroud	130 kW
3 (light water)	Moderators, shutters, and inserts	73 kW
4 (heavy water)	Reflector plugs	755 kW

Delay tanks are employed in the return line of each activated water loop to facilitate localized decay of some of the short-lived water activation products. The delay also reduces the potential for neutron activation of components located downstream in areas to which access must be provided for maintenance. Localized shielding is provided, as required, to address the anticipated deposition of the longer-lived radionuclides (e.g., Be-7) in system components (e.g., heat exchangers, ion exchange units, or filters). Separation of gases generated in the water loops due to spallation and/or the radiolytic decomposition of water is achieved in a gas/liquid separation tank to be located at the high point in the cooling loop. Inert purge gas is supplied as needed to maintain the long-term buildup of hydrogen or deuterium concentration in the gas/liquid separator tank headspace to below the lower flammable limit. The separator tank head space vents to the hot off-gas (HOG) system.

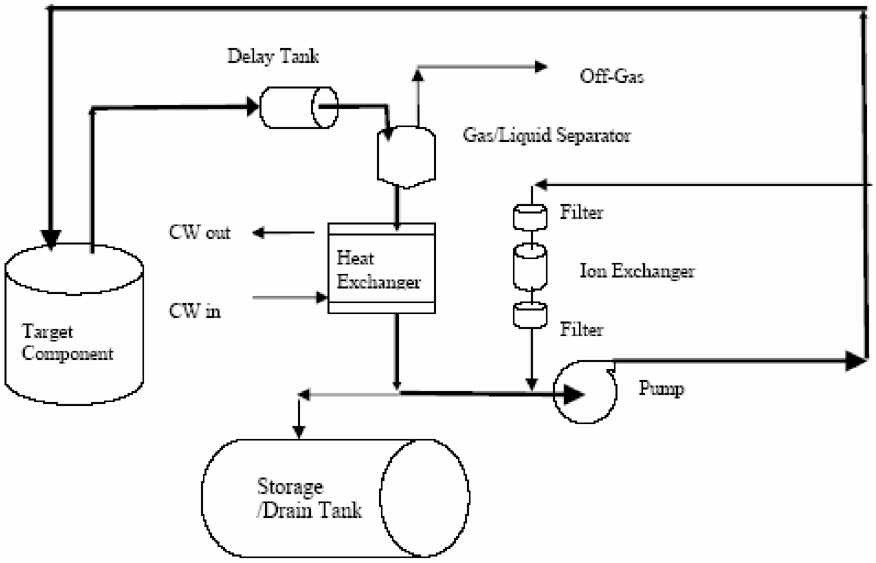


Fig 5.71. Generic schematic illustration of cooling loop components.

Water quality is maintained by bypassing a fraction of the total flow through particulate filters and ion exchange columns. Based on periodic sample results, cooling loop water can be periodically discharged to the LLLW system, as required, to ensure loop tritium concentrations do not exceed the LLLW waste acceptance criteria. Spent resin columns and filters will be replaced as needed based on either component dose rate or water quality. Each cooling loop is instrumented to allow operators to monitor appropriate operational parameters.

The water in loop 1 will not be activated by direct exposure to either protons or neutrons but could become contaminated with mercury if the heat exchanger leaks. To minimize the potential for cross-contamination, the mercury/water heat exchanger design employs double-walled tubes as described in Sect. 5.2.1.

The heavy water cooling loop 4 removes heat from the vessel wall, proton beam window box, and reflector plugs. Heavy water is used to optimize neutron characteristics. The heavy water will be replaced periodically, as needed, to replace losses or to control tritium concentration. Alternatively, light water may be used in cooling loop 4 with no impact on safety.

5.2.6.2 Vacuum systems

The vacuum systems serve numerous purposes. For example, the vacuum systems are used to remove air from target station components prior to backfilling with an inert gas, and to activate seals employed between the target vessel and both the proton beam window and the target plug. Vacuum systems that exhaust to the primary confinement exhaust system (PCES) are also provided to evacuate the core vessel and mercury process equipment.

5.2.6.3 Helium distribution

Helium is used as a cover gas in areas exposed to high-energy radiation to minimize the air activation (high-energy protons can also cause production of corrosive NO radicals in air) and for other purposes. A gas distribution system is provided, as necessary, to facilitate its supply to its various uses.

5.2.6.4 Installation and Testing

All the Utility systems have been installed and tested. Heavy water loading for loop 4 has been postponed and initial operation will be with light water. All the water loops have been run at design flow rates required for a 2-MW operation. Table 5.2-6 gives the design and measured flow rates for the principal technical components from the last set of integrated tests.

The core vessel has been operated in both the vacuum and helium modes with the proton beam window and target module inflatable seals installed and operating. A base pressure of 9 mTorr was achieved in the vacuum mode. All the vacuum and gaseous systems have been tested and run under design conditions. A summary listing of all utility system testing and completion dates is shown in Table 5.2-7. Typical EPICS screens showing operation at design conditions from the Full Integrated System Test are shown in Figs. 5.2-72 through 5.2-76. Representative installation pictures are shown in Figs. 5.2-77 through 5.2-79.

Table 5.2-6. Comparison of design and measure water flow rates

Loop	**Technical Component**	**Design Flow Rate** gpm	**Measured Flow** gpm
1	Mercury Heat Exchanger	401	405.8
2	Proton Beam Window	40	42.6
2	Target Shroud	50	49
3	Ambient and Bottom Downstream moderators	15.8	16.2
3	Top Moderators	15.8	16.1
3	Single& Multi Channel Inserts total	26.9	31.9
4	Lower IRP Inner bottom	60	64.4
4	Lower IRP Inner middle	15	15.5
4	Lower IRP Inner middle (2)	15	16.5
4	Lower IRP Innertop	60	59.8
4	Inermediate IRP Inner	8.2	10.4
4	Inermediate IRP outer	1.8	2
4	Lower Outer bottom	50	46.1
4	Lower Outer	30	34.5
4	Core Vessel wall	23.2	23.6

Table 5.2-7. Utility system testing

TEST	**Completion Date**
Hot cell distribution (N2) (IST 1.6.6-35)	27 JUN 05
ORP pneumatic pres test (Incl with TG06110060)	01 JUL 05
Reservoir pump (He) (IST 1.6.6-43)	26 JUL 05
Hg reservoir (He) (IST 1.6.6-45)	15 JUL 05
Hg loop vacuum system (IST 1.6.6-20)	03 JAN 06
PBW inflatable seals vacuum system (IST 1.6.6-23)	01 FEB 06
He/N2 Supply Pnls Testing Tgt Bld (IST 1.6.6-30A)	01 MAR 06
Loop #2 test (IST 1.6.6-2)	22 SEP 05
Loop #1 test (IST 1.6.6-1)	03 OCT 05
CV rough vacuum sys with Tgt(partial IST 1.6.6-25	30 SEP 05
TC inflatable seal vacuum system (IST 1.6.6-22)	05 JAN 06
Hg storage tank (He) (IST 1.6.6-44)	10 JAN 06
TC inflatable seal (He) (IST 1.6.6-46)	20 JAN 06
RID Loop Test (IST 1.6.6-5)	06 JAN 06
IRP pressure test (incl ORP test TG06110057)	21 OCT 05
Loop #4 test (IST 1.6.6-4)	01 FEB 06
PBW inflatable seals vacuum system (SST 1.6.6-23)	16 DEC 05
Loop #3 test (IST 1.6.6-3)	01 FEB 06
Core vessel rough vacuum system (IST 1.6.6-25)	01 FEB 06
Tunnel sweep air (IST 1.6.6-93)	21 NOV 05
RIBS gas sampler (IST 1.6.6-90)	04 JAN 06
RIBS vacuum system (IST 1.6.6-21)	05 JAN 06
Inserts vacuum system (IST 1.6.6-24)	12 JAN 06
Beam stop enclosure (He) (IST 1.6.6-48)	23 JAN 06
Core vessel He system (IST 1.6.6-50)	01 FEB 06
Delay tank cavity drain syst Test (IST 1.6.6-91)	01 FEB 06
Bulk shldng liner drain syst Test (IST 1.6.6-91)	01 FEB 06
Instrument air to core vessel Test (IST 1.6.6-92)	01 FEB 06
Core vessel low vac sys (He mode) (IST 1.6.6-26)	23 FEB 06
Core Vessel vent stack Test (IST 1.6.6-75)	01 MAR 06
Full Integrated System Test	23 APR 06

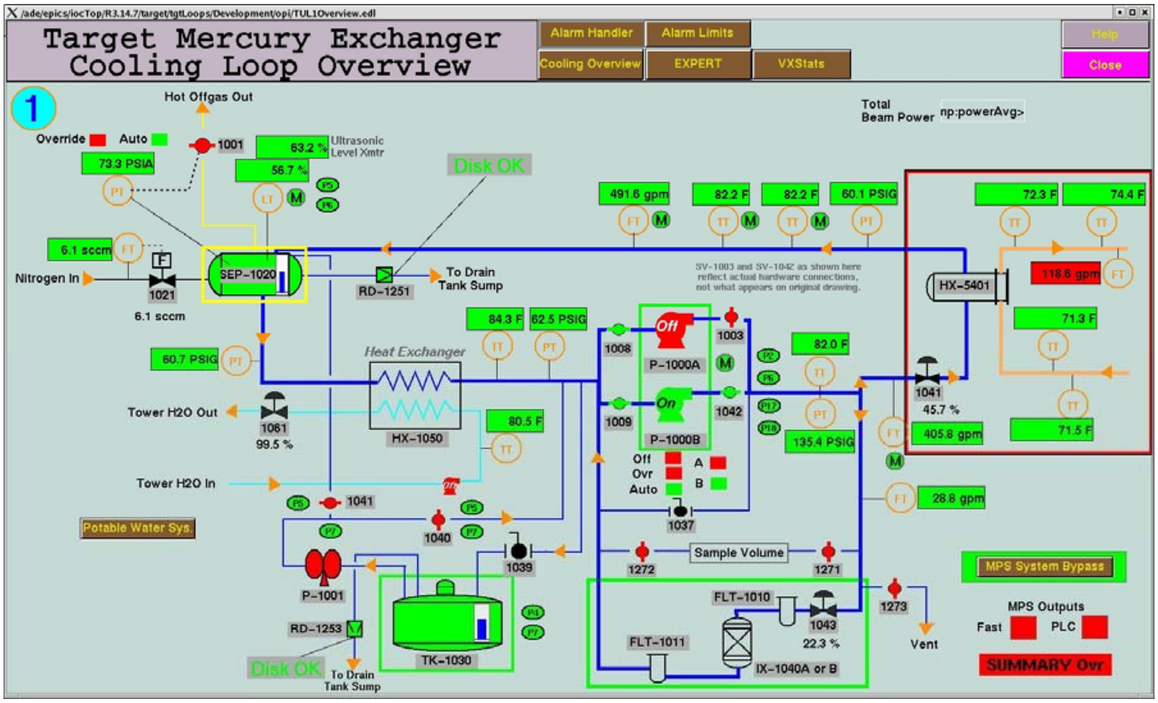


Fig. 5.2-72. Loop 1 EPICS Screen during full integrated system testing (FOIST) with design flows and pressures.

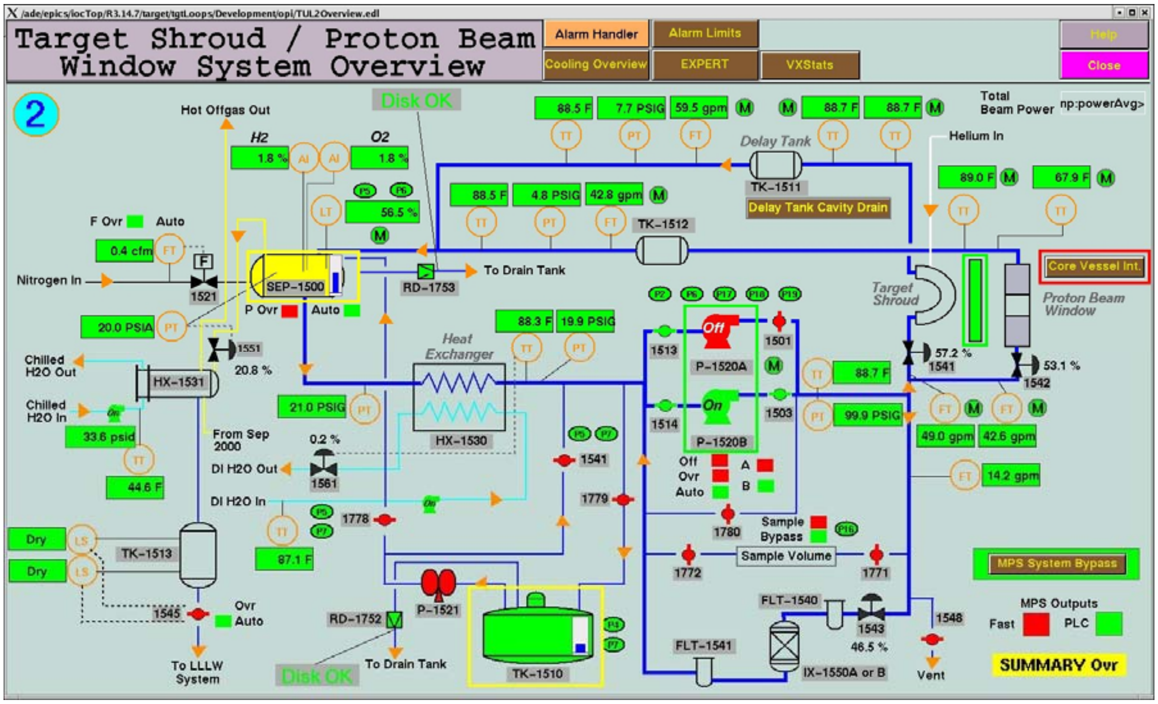
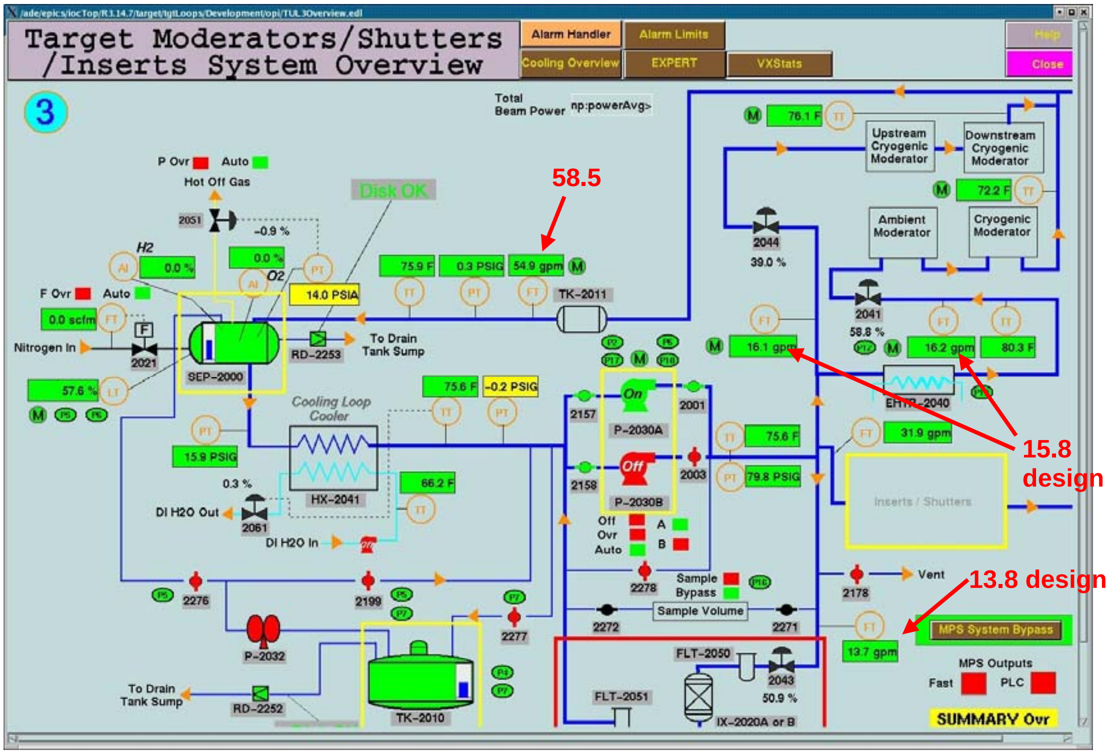


Fig. 5.2-73. Loop 2 EPICS Screen during FOIST with design flows and pressures.



58.5

15.8 design

13.8 design

Fig. 5.2-74. Loop 3 EPICS screen showing flows at 2-MW design values.

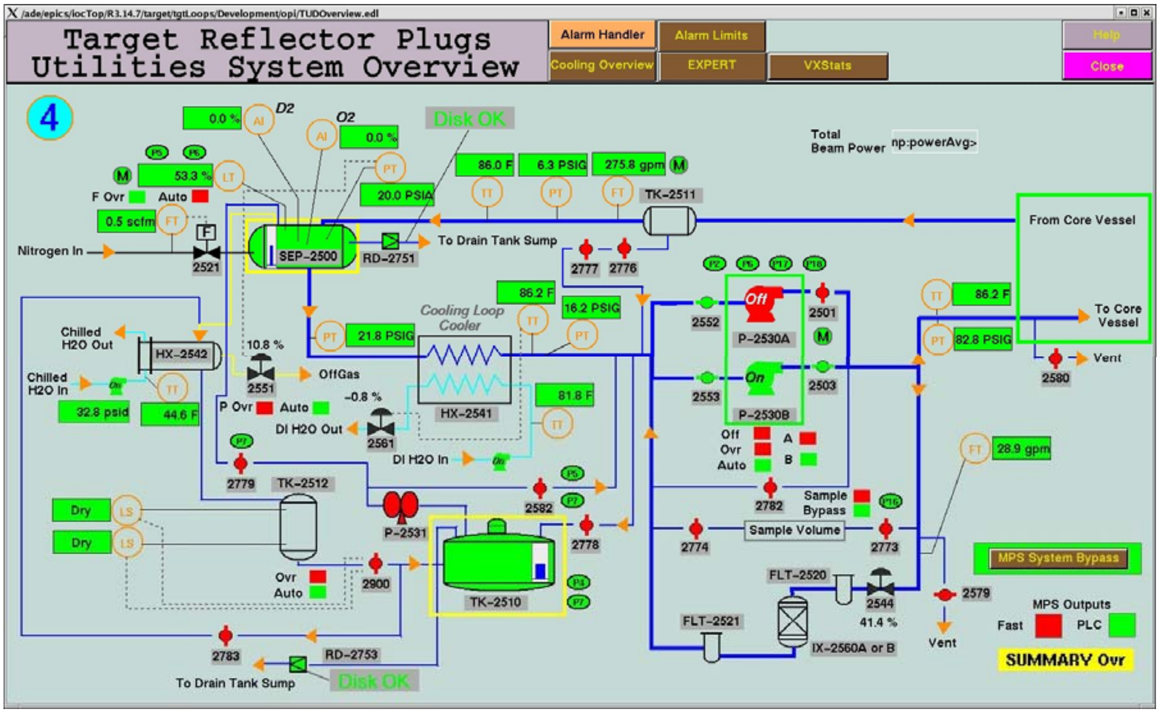


Fig. 5.2-75. Loop 4 EPICS Screen during FOIST with design flows and pressures.

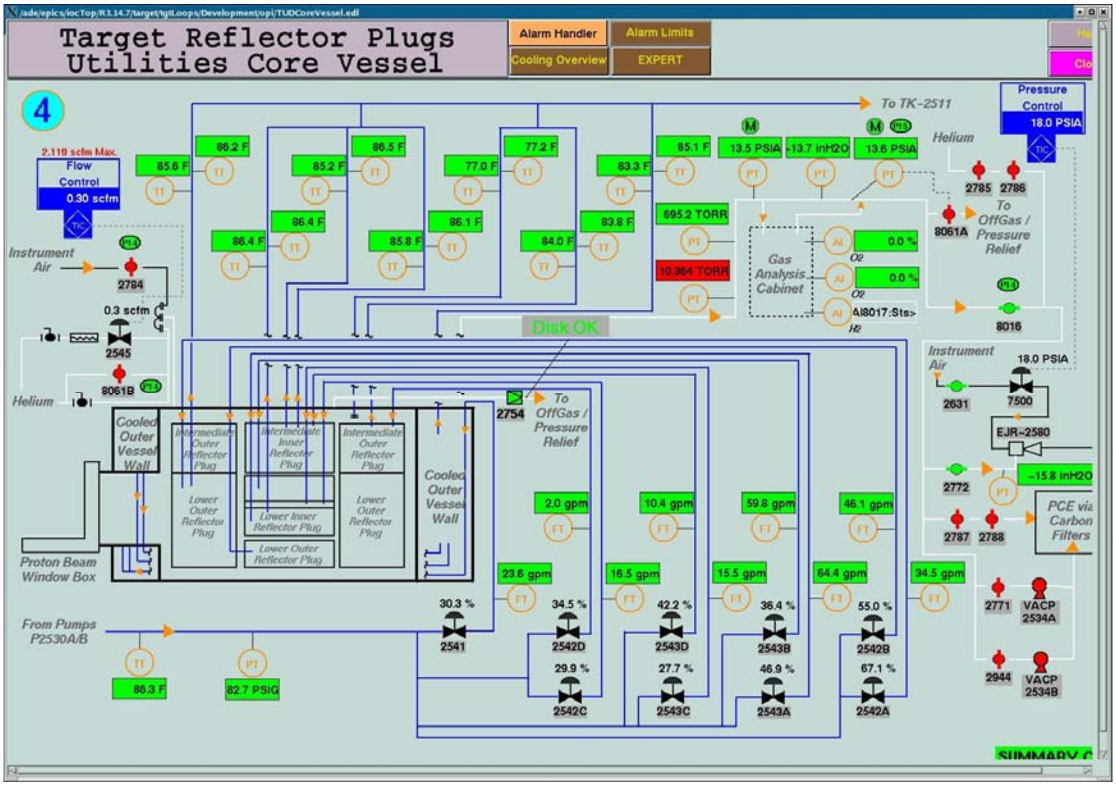


Fig. 5.2-76. Loop 4 EPICS Screen during FOIST with component design flows and pressures.

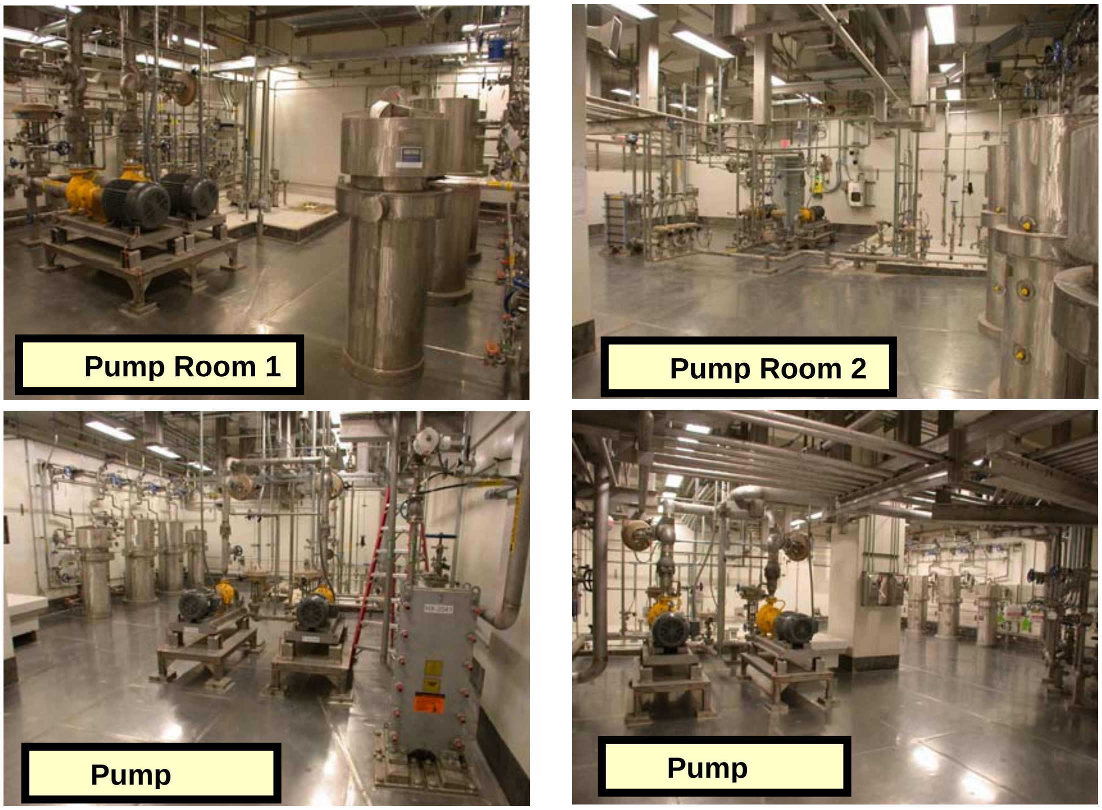


Fig. 5.2-77. Four pump rooms after installation complete.

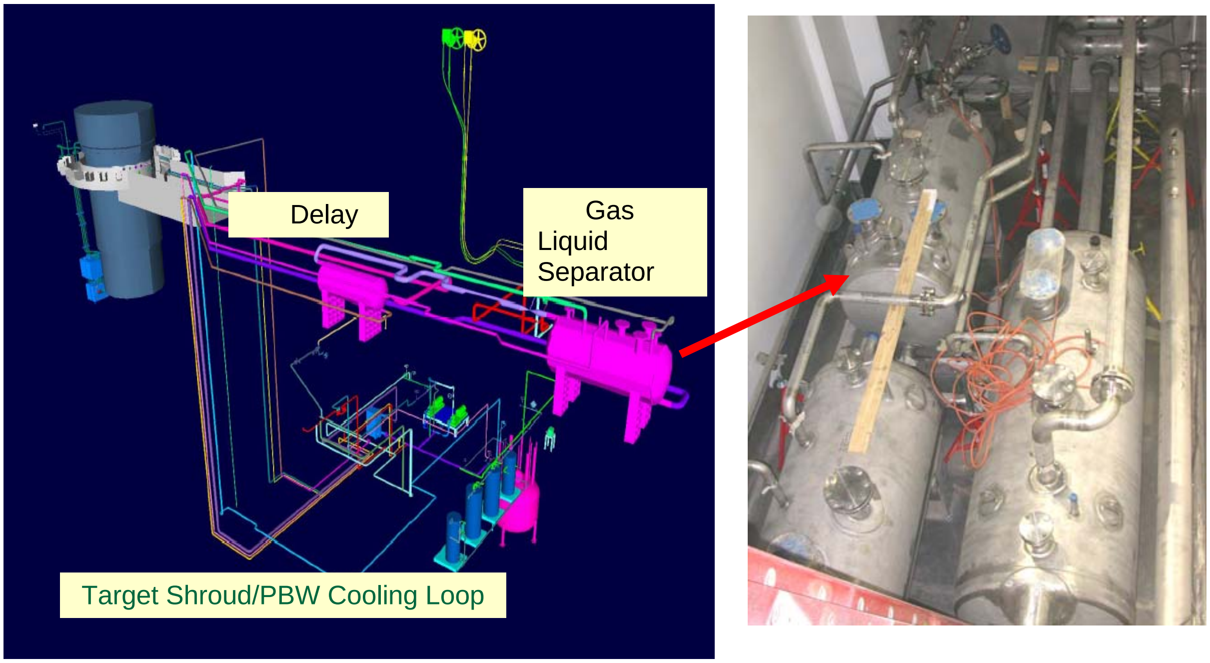


Fig. 5.2-78. Typical loop model and installed gas liquid separator tanks.

Fig. 5.2-79. Core vessel vacuum pumps.

5.2.6.5 CD-4 performance and additional capability

The water cooling systems and other utilities have been designed to support 2 MW beam operation. Since each loop was designed with some margin the actual total design heat removal capacity is 2.5 MW. Future studies may indicate additional capacity.

5.2.7 Mercury Off-Gas Treatment System

Helium purge or other inert cover gas that is in contact with mercury is routed through the mercury off-gas treatment system (MOTS), which is located in the target service bay and tritium removal room areas. It removes mercury, noble gases, iodine, and tritium from the target off-gas. Other target service bay process exhausts that are not significantly mercury-contaminated (i.e., other than the target service bay exhaust) are routed directly to the HOG system. The MOTS consists of the following elements (see Fig. 5.2-80 for diagram):

1. Two gold amalgamation adsorbers in series.
2. A CuO/dessicant oxidation/adsorption system.
3. A cryogenically cooled charcoal adsorber.

The gold adsorber (Al_2O_3 pellets containing a gold impregnant) is sized to hold the quantity of mercury that would exit into the off-gas during the anticipated operational period (the preliminary estimate is 50 g of Hg/year).

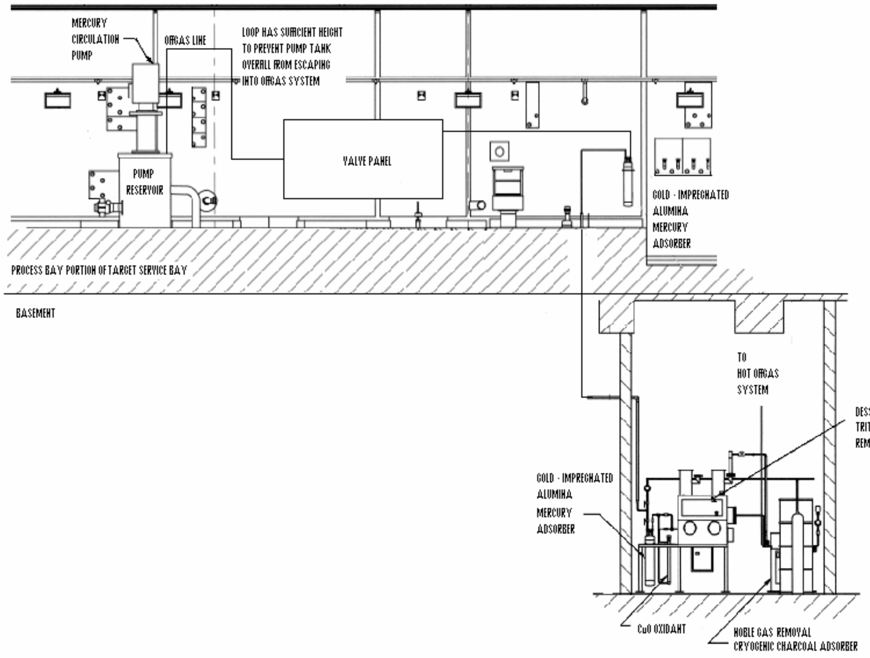


Fig. 5.2-80. Mercury target off-gas system schematic.

The CuO bed is the next component in the system. It functions to oxidize tritium in the gas stream. It operates at a temperature on the order of 250°F. The CuO supplies oxygen to react with tritium; it becomes reduced to copper metal in the process and therefore requires periodic regeneration. The regeneration is expected to be performed during shutdowns for target module maintenance, when the off-gas system is not operating. Because mercury is known to decrease the effectiveness of CuO catalyst, monitoring of the bed condition and periodic replacement of the bed is required. The bed is designed for periodic catalyst replacement. Loss of catalyst activity should be detectable as a radiation dose rate increase of the CuO bed, since the mercury is radioactive. Elemental tritium that penetrates the CuO and molecular sieve bed system should be trapped in the carbon bed. Since the quantity of hydrogen isotopes is expected to be small, capacity loss should not be an issue until the bed is completely deactivated.

Downstream of the CuO bed is a set of desiccant beds filled with a molecular sieve (Linde 5A). The hydrogen oxides are removed in this bed, and the beds are discarded periodically. Approximately 2,000 curie (Ci) of tritium is expected to be produced by spallation of mercury during a three-month period at the 2-MW full beam power. The bed may, therefore, require change-out during the campaign to maintain the quantity of tritium on an individual bed below 1,000 Ci if the proton beam is operated consistently at full beam power.

The last component in the treatment system is a cryogenically cooled charcoal bed. This component is present to remove noble gas spallation products (principally xenon) from the off-gas stream. The bed requires shielding but should never require replacement. The charcoal bed also serves to remove residual mercury and tritium from the gas stream.

There are two gold adsorbers in the system, one located in the target service bay and the other in the tritium recovery room. The desiccant beds are located inside a glove box in the tritium recovery room. The charcoal bed is located in a separate shielded area also in this room.

Helium is admitted into the mercury storage tank to force mercury to flow up into the pump tank when the process loop is being filled with mercury. Typically about 40 to 50 gal. of mercury remain in the storage tank after the loop is filled. Excess helium pressure would force a greater than normal quantity of mercury into the pump tank. An automatic alarm and interlock are provided to isolate the helium in the event that the pump tank reaches an abnormally high mercury level. If the pump tank were overfilled significantly, its rupture disc would actuate, allowing mercury to flow onto the target service bay floor. A loop seal is provided in the line that connects the off-gas system to the pump tank to provide positive assurance that a pump tank overfill event could not result in the transfer of mercury out of the target service bay. The top of the loop seal (see Fig. 5.2-80) is at a high enough elevation that it would prevent mercury from escaping from the target service bay. The loop seal arrangement is a CEC.

5.2.7.1 Installation and Testing

All equipment has been installed and tested. Integrated system testing has been performed to demonstrate functionality of all components of the MOTS in concert with the mercury loop operations. A listing of tests and approximate completion dates are listed in Table 5.2-8. Representative installation photos are shown in Figs. 5.2-81 and 5.2-82.

Table 5.2-8. MOTS system testing

TEST	Completion Date
Verify Vessels filled with sorbent	4/3/06
Verify Glove Box ready for operation	4/20/06
Verify Instrumentation Operation	4/21/06
Pressure leak test system	4/20/06
Verify liquid nitrogen fill/drain	4/3/06
Verify helium flowrate from mercury loop	4/3/06
Operate MOTS with mercury loop	4/21/06

Fig. 5.2-81. Gold adsorber in service bay.

Fig. 5.2-82. MOTS after installation complete.

5.2.7.2 CD-4 Performance and Additional Capacity

The MOTS was designed to support 2 MW beam operations or higher since the total helium flow from instrumentation or pump seal purging does not change relative to beam power level increases. Some additional capacity may be possible with minor design changes to the molecular sieve adsorber beds. Target design changes which might require significant helium flow increases are not supported.

5.2.8 Target Protection System and Target System Controls

Monitoring and control of the mercury process system and related support systems are accomplished through three systems: the target protection system (TPS); the target service bay differential monitoring/evacuation system; and the target control system that is part of the integrated control system (ICS).

The TPS and target service bay differential pressure monitoring systems are credited controls. The TPS is the credited engineered control that trips the proton beam when necessary to prevent overheating of the mercury by the proton beam. The service bay differential monitoring system provides the credited alarm on inadequate target service bay negative pressure.

Instrumentation and controls for the remaining target systems (water loops, vacuum systems, shutters, etc.) were installed and tested as part of each sub system.

5.2.8.1 Target protection system

The three process inputs to the TPS are differential pressure across the mercury pump (indicative of mercury flow), power utilization by the mercury pump, and mercury temperature at the mercury heat exchanger outlet leg. The mercury differential pressure signal cuts off the beam on low mercury loop flow; the heat exchanger exit temperature signal cuts off the beam on high mercury temperature; and pump power trip causes a beam cutoff when power to the pump is below the established set point. The TPS also includes a manual cutoff in the target and CLO control rooms.

The TPS is an analog system with two-channel architecture. Proton beam trip is generated when either of the two redundant channels receives an out-of-bounds input signal. The trip devices are permissive based, which means they must remain powered to permit continued operation. Anything that interrupts power to the trip devices in the accelerator Front End will cause the proton beam to be cut off. This and other features such as monitoring for out-of-bounds input signals provide the fail-safe design concept of the TPS.

On receipt of a low mercury flow signal, a high mercury temperature signal, a loss of power to the mercury circulation pump signal, or an input signal that is out of the identified acceptance range (i.e., possibly indicating a faulty instrument), the TPS actuates a proton beam cutoff in the front-end area of the accelerator by two redundant, independent, and diverse channels:

- Channel 1—Interrupts the power supply to the ion injector (front end building)
- Channel 2—Interrupts the ac power input to the radio frequency quadrupole (klystron building adjacent to the front end building)

Success by either channel shuts down the proton beam. Utilizing these two diverse cutoff mechanisms helps ensure reliability. A bypass feature for the flow trip in the TPS allows the accelerator to be tested when the target has no mercury flow. This operating bypass is implemented by monitoring and controlling power to the 15° bending magnet (identified as DH-13) between the ring and the ring extraction dump that directs the proton beam to the target or to the ring extraction dump. When this magnet is de-energized, the proton beam is directed to the dump; when it is energized, the protons are directed to the target. Each TPS channel monitors the position of redundant power disconnects. Channel 1 monitors the position of the disconnect in the ac power to the 15° magnet power supply, and Channel 2 monitors the position of the disconnect in the dc output of 15° bending magnet power supply.

The bypass is actuated manually from the CLO control room after the disconnect is opened by closing a “bypass-initiate” switch in each channel. In order for the TPS to go into bypass mode, both channels indicate bending magnet power “off,” and the “bypass-initiate” switch in each channel must have been manually closed. Establishing either the ac or dc power to the bending magnet or opening either channel’s “bypass-initiate” switch automatically removes the trip bypass. That is, any one of four conditions not satisfied would throw the TPS out of bypass mode. The disconnect monitor is fail-safe on loss of power because it removes the TPS bypass.

The TPS electronic circuits incorporate fail-safe features designed to ensure that a beam cutoff would occur in the event of damage to a circuit or other anomaly in the circuit. For example, if a lead became disconnected or severed, or a short circuit occurred in one channel, a proton beam cutoff would be initiated by that channel. Since the architecture is one-out-of-two, a trip condition in either channel cuts off the proton beam.

The TPS mercury high temperature cutoff circuit employs redundant resistance temperature detectors mounted in wells that protrude into the mercury pipe that connect the heat exchanger outlet to the pump tank inlet. The mercury differential pressure cutoff circuit employs differential pressure transmitters with connections to the pump suction and discharge piping.

The TPS includes status indicators in the target control rooms that indicate the status of each TPS channel. These provide positive indication to the operators whenever the TPS has actuated. The manual cutoff provides a means for diverse shutdown, however, a manual cutoff is not a required action for any accident. In addition, electronic or electro-optical isolation devices are used to connect the TPS to EPICS) The outputs of the isolation devices connected to EPICS are not safety grade; however, they prevent a malfunction in the non-safety system from propagating in the TPS system. They are used to provide alarm and data archive information using EPICS. The EPICS alarms do not provide a required safety function.

The TPS actuators that trip the proton beam are located in the front end building and the Klystron Gallery, the trip bypass equipment is located in the RTBT service building and the “bypass-initiate” switches in the CLO control room, the operator indicators and manual shutdown switches are on panels located in the main and target control rooms, and the TPS process modules for Channel 1 are located in the target control room and for Channel 2 in the Service Gallery. The inherent characteristics of the accelerator are such that the proton beam cannot continue to operate following a seismic event of greater than PC-1 severity or in the event of a serious fire. The permissive-based trip logic is designed to trip the proton beam on an out-of-range signal, which would include loss of signal, open circuit, short, or off-normal signal, ensuring beam trip in the event of damage to the TPS due to a natural phenomena event or internal event such as fire.

5.2.8.2 Target Service Bay Differential Pressure Monitoring System

The Target Service Bay Differential Monitoring System alarms are initiated by a programmable logic controller (PLC)-based logic that uses two input channels for each differential pressure. Since either channel can provide the required alarm, only one channel need be operable at any given time.

Differential pressure is monitored for the two highest occupancy areas adjacent to the Target Service Bay: (1) differential pressure between the Target Service Bay and the manipulator gallery; and (2) differential pressure between the Target Service Bay and decontamination room. When the personnel door to the Target Service Bay is open, flow in the PCE system is monitored instead of the differential pressure. If either of these areas has inadequate differential pressure, or there is inadequate flow with the personnel door open, the Target Service Bay Differential Pressure Monitoring System initiates the evacuation alarm in the six areas that could potentially be occupied by workers and affected by loss of Target Service Bay vacuum: (1) manipulator gallery; (2) service gallery; (3) decontamination room; (4) bottom loading hatch room (basement); (5) high bay area above Target Service Bay process bay; and (6) high bay area above accelerator tunnel.

The Target Service Bay Differential Pressure Monitoring System interfaces with non-safety instruments, but the design includes provisions to protect the Target Service Bay Differential Pressure Monitoring System from faults in the systems to which it is interfaced.

5.2.8.3 Installation and testing

The Target Protection System and the Target Service Bay Differential Pressure Monitoring System were tested using SNS certification procedures after the equipment installation was completed. A photograph of the TPS logic and signal conditioning cabinet for channel B of the TPS, which is in the Service Gallery, is shown in Fig. 5.2-83. The TPS cabinet in the CCR is shown in Fig. 5.2-84.

5.2.8.4 CD-4 performance and additional capability

The TPS and Target service bay differential pressure monitoring system have been fully installed and tested and will support beam operation to at least 2 MW.

Fig. 5.2-83. TPS CAB5500B located in the Target Building service gallery.

Fig. 5.2-84.. TPS cabinet CAB5501A/B located in the Central Control Room.

5.3 SNS INSTRUMENTS (ANL/ORNL)

The definition of completion for the SNS project instruments is governed by the SNS PEP, Milestone 18 in Appendix B, in the section on Level 2 Milestone Definitions (2005 revision):

> "Instrument Systems Complete Subproject Acceptance Test–Milestone is defined as the completion of at least 3 instruments installed and tested, and procurements for the last 2 project instruments will have been placed, but components not necessarily received. This milestone will be complete upon notification of the project office via memorandum from the target division director and the experimental division director that this condition exists."

In addition, each instrument has been designed to be "best in class" as far as performance goes.

The three instruments to be completed before CD-4 are the Backscattering Spectrometer, Magnetism Reflectometer, and Liquids Reflectometer. The last two instruments, to be completed after CD-4, are the Small-Angle Neutron Scattering (SANS) Diffractometer and the Powder Diffractometer. Receipt of remaining components and installation for these last these last two instruments is expected to be complete before the end of FY 2007. The following sections give brief descriptions and the completion status of each of these five instruments.

5.3.1 Backscattering Spectrometer–Beamline 2

5.3.1.1 Operation and performance

The SNS Backscattering Spectrometer is a near backscattering, crystal-analyzer spectrometer designed to provide extremely high-energy resolution at the elastic peak ($\delta\omega = 2.2 - 2.7\ \mu\text{eV}$), with an unprecedented dynamic range near the elastic peak of $-258\ \mu\text{eV} < \omega < 258\ \mu\text{eV}$. For experiments that require the full dynamic range available at comparable reactor-based instruments, this spectrometer is expected to have an effective count rate ~60 times that of the current best spectrometers, so this is definitely a *best-in-class instrument*. This instrument will enable studies of dynamical processes such as rotational and translational diffusion on time scales as long as $\sim 10^{-9}$ sec.

This instrument uses the Bragg reflection from perfect silicon crystals in near backscattering geometry to allow only neutrons scattered from the sample and having a wavelength of 6.267 Å to reach the detectors. The time of arrival of a neutron at a detector gives the total time of flight (TOF) from moderator to sample to silicon crystal and back to the detector, and this time in turn can be used to deduce the wavelength of the incident neutron. Knowledge of both incident and scattered wavelengths, along with the scattering angle that comes from the location of the detector detecting the event, provides complete kinematic information about the scattering event. Carrying out this process for a large number of incident neutrons builds up a pattern that shows the probability of scattering as a function of both the momentum transfer and energy transfer in the scattering process.

This instrument is optimized for the study of quasielastic scattering, which occurs for incident wavelengths near the scattered wavelength of 6.267 Å. For such measurements, the bandwidth of 0.78 Å transmitted through the bandwidth choppers results in a range of energy transfers of $\pm 258\ \mu\text{eV}$. The various uncertainties in the measurement result in a quasielastic energy resolution of $2.2 - 2.7\ \mu\text{eV}$, depending on sample size. Operating near 6.267 Å means that one is operating in the 9th frame, so the neutrons being measured left the moderator 9 pulses earlier and there are nine similar bunches of neutrons currently traveling down the guide with some separation between each bunch.

5.3.1.2 Instrument description

Figure 5.3-1 shows a three-dimensional view of the spectrometer design as seen from the downstream end looking back towards the target/moderator assembly. Although the sample end of this spectrometer (as seen in Fig. 5.3-2) is very similar to that found in a reactor-based instrument, the initial flight path is very long (84 m) in order to provide the required resolution on the incident neutron energy. This flight bath is too long to fit inside the Target Building, so a satellite building connected by a passageway to the Target Building was constructed to house the balance of the spectrometer.

Neutrons from the decoupled and poisoned H_2 moderator are transported to the sample position at an 84-m distance via ~82 m of supermirror neutron guide (Fig. 5.3-3). The first ~74 m of this guide have a cross-section of 10×12 cm^2. The first ~1 m of this guide is in the core vessel insert and extends to within ~1 m of the moderator face. The next ~2 m are in the primary shutter in the target monolith. This shutter guide and the next ~27 m of guide are curved with a radius of curvature of 1000 m. This design gives a line-of-sight distance for the fast neutrons of ~31 m. The next ~45 m are straight with the same cross section and the final 8 m of guide taper from this cross section to a final cross section of 3×3 cm^2. The last ~2.7 m of this tapered guide are located inside the evacuated scattering chamber.

Three single-disk neutron bandwidth limiting choppers (Fig. 5.3-4) are located at distances of 7 m, 9.2 m, and 50 m from the moderator. The openings in these chopper disks are sized to provide a bandwidth of 0.78 Å when operated at the design speed of 60 Hz. This 0.78-Å band can be centered at any desired wavelength by changing the chopper phasing, and by adjusting this phase this instrument can be used for quasielastic scattering or for inelastic scattering at energy transfers up to ~18 meV.

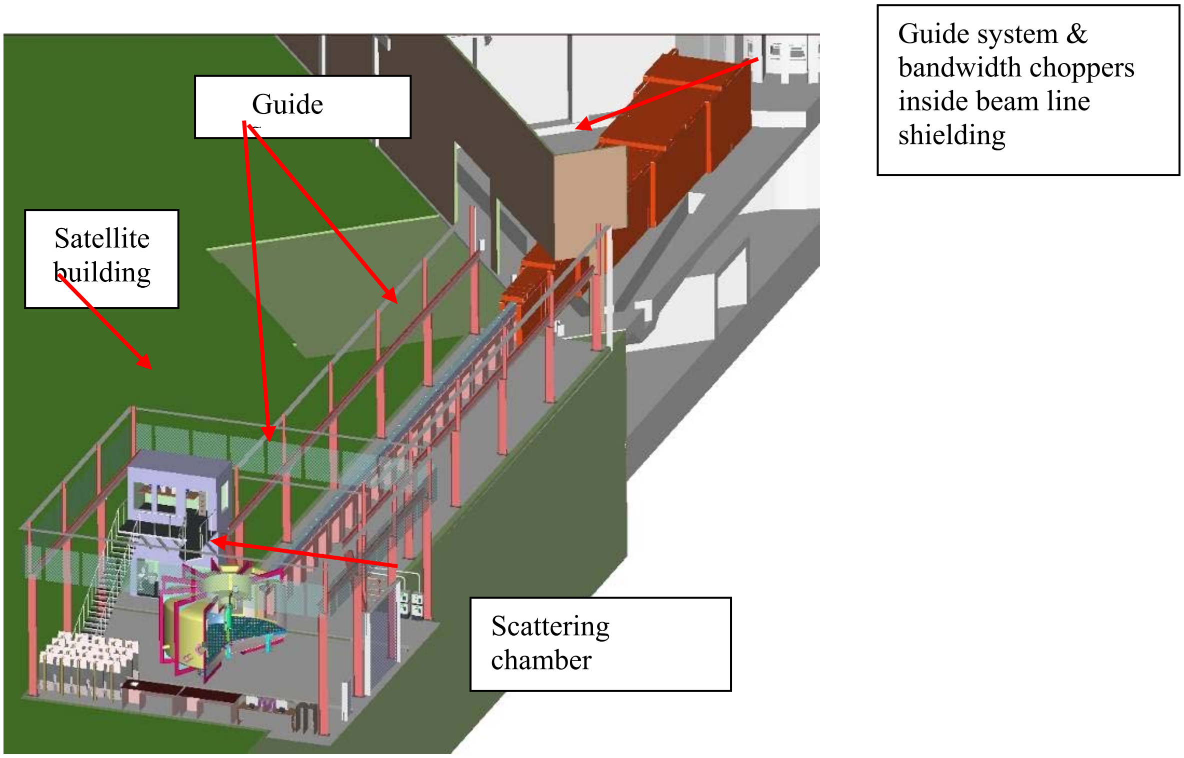


Fig. 5.3-1. The evacuated scattering chamber at the near end of the instrument is ~6 m in diameter, and is housed in the center of a 15- × 15-m satellite building.

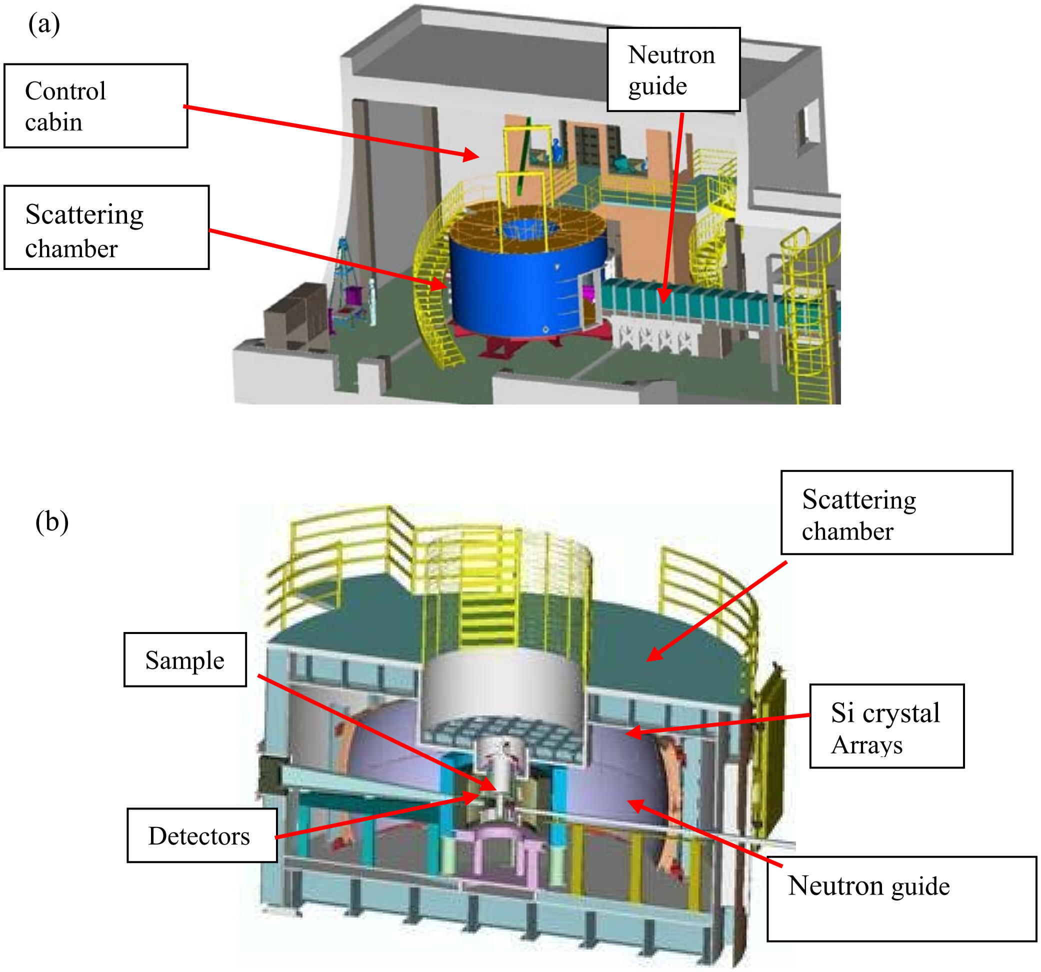


Fig. 5.3-2 .Scattering chamber: (a) shows a view of the scattering chamber inside its satellite building; (b) shows the technical equipment located inside the evacuated scattering chamber, including the final portion of the incident neutron guide directed toward the sample position at the center of the chamber, the Bragg analyzing crystals, and the neutron detectors. Scattered neutrons are Bragg reflected by the analyzing crystals located on the periphery of the chamber and directed back towards the center of the chamber where they are detected by ^{3}He detectors located above and below the scattering plane.

This incident beam line also contains a secondary shutter linked to the Instrument Personnel Protection System (IPPS) and a low-efficiency beam monitor. The incident beam line, including secondary shutter, beam monitor, and all three choppers, is surrounded by a massive shielding (Fig. 5.3-5) made of steel, heavy concrete, and normal concrete in proportions optimized to provide the desired shielding characteristics. This shielding is designed to reduce radiation doses at its surface to below 0.25 mrem/h when the facility is operating at 2 MW.

The secondary section of the spectrometer is housed inside an evacuated scattering chamber (Fig. 5.3-6) of ~3 m radius and ~4 m height. Neutrons from the guide are incident on the sample located at the center of this chamber, and a fraction are scattered. An array of silicon crystals (Fig. 5.3-7) is located near the outer wall of the scattering chamber at a radius of 2.5 m from the sample. The silicon crystals are mounted on spherical loci and focused to Bragg diffract 6.267-Å neutrons from the Si 111 planes in near-backscattering at a Bragg angle of 88° to arrays of linear-position-sensitive ^{3}He detectors located above and below the sample (Fig. 5.3-8) at a radius of ~0.3 m from the scattering chamber axis. These detectors record the position and TOF of any detected neutrons. A state-of-the-art data acquisition system, located in a cabin near the scattering chamber [Fig. 5.3-2(a)], collects and organizes the data from the detectors to present this information. A radial collimator between the silicon crystals and the detector minimizes extraneous scattered neutrons, which otherwise could contribute to the background. Figure 5.3-2(a)shows this scattering chamber geometry. The initial instrument provides a full complement of silicon crystals and detectors to cover scattering angles of 5° to 160° on one side of the scattering chamber. The other side of the scattering chamber is initially left open as a future upgrade path.

All user access is from the top of the scattering chamber [Fig. 5.3-2(a)]. A sample chamber well with thin aluminum windows is located in the center of the scattering chamber. Samples and sample environment equipment are lowered into this sample well from the top. A small monorail crane facilitates this process. This sample chamber serves to separate the sample vacuum from the scattering chamber vacuum, allowing much higher quality sample vacuum and short pumpdown times associated with insertion of different sample environment equipment. Utilities to support a wide range of sample environment equipment are installed in easily accessible panels and manifolds at the top of the scattering chamber.

An IPPS linked to the primary and secondary shutter ensures that personnel do not enter areas with dangerous radiation levels. The IPPS can direct closure of the secondary shutter and can also force shutdown of the accelerator to prevent unsafe radiological conditions.

5.3.1.3 Components

The figures in this section show representative views of the major components of the backscattering spectrometer in various stages of installation.

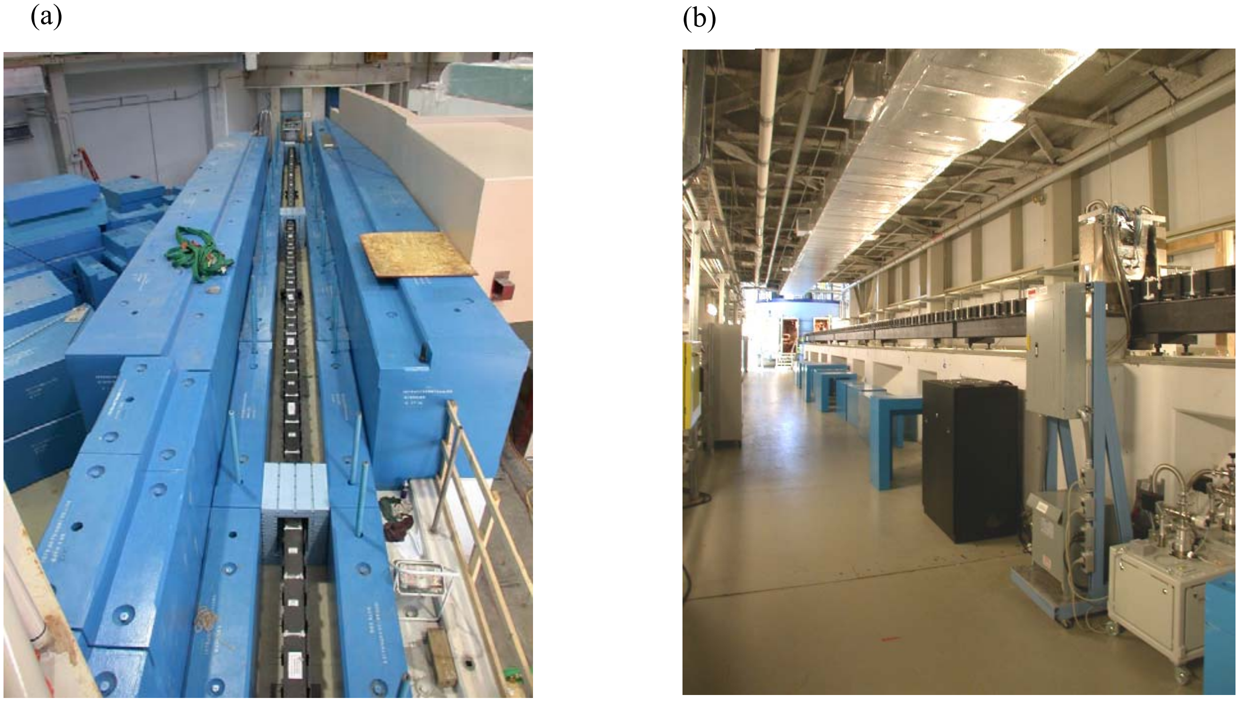


Fig. 5.3-3. Neutron guide system: (a) view of the partially shielded curved guide looking back toward the monolith; (b) view of straight guide and third chopper looking toward the scattering chamber.

Fig. 5.3-4. First two choppers.

Fig. 5.3-5. Beam line shielding: (a) heavily shielded initial curved guide section; (b) lighter shielding beyond the fast neutron line of sight.

Fig. 5.3-6. Evacuated scattering chamber.

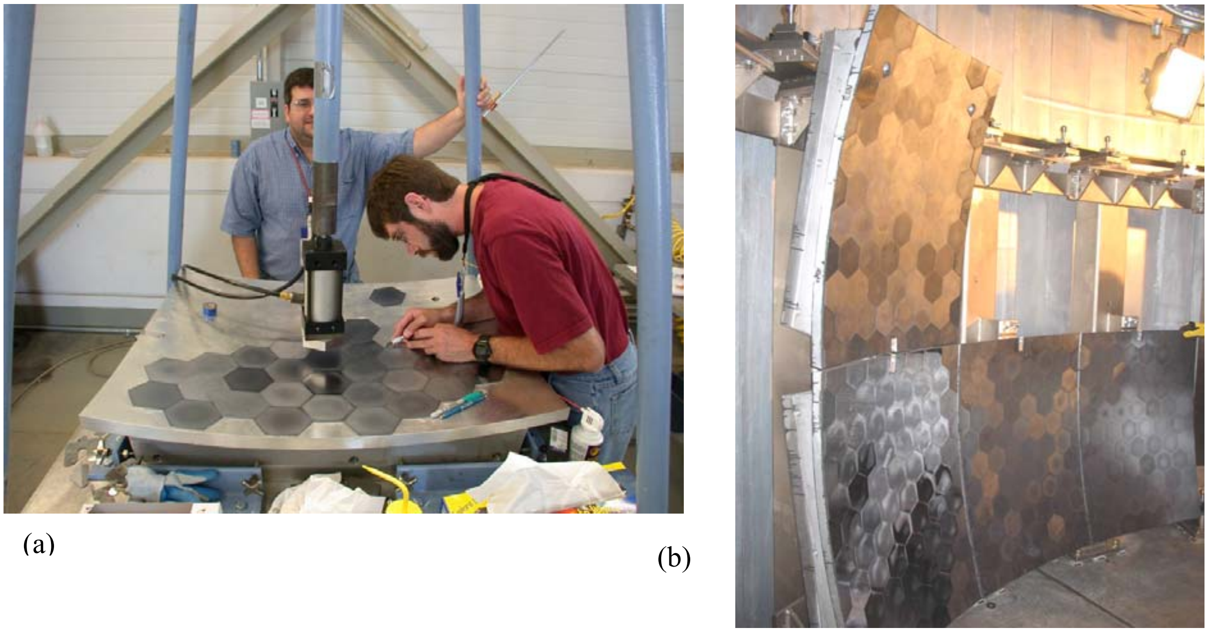


Fig. 5.3-7. Silicon crystal arrays: (a) gluing crystals to one panel; (b) four panels mounted in instrument.

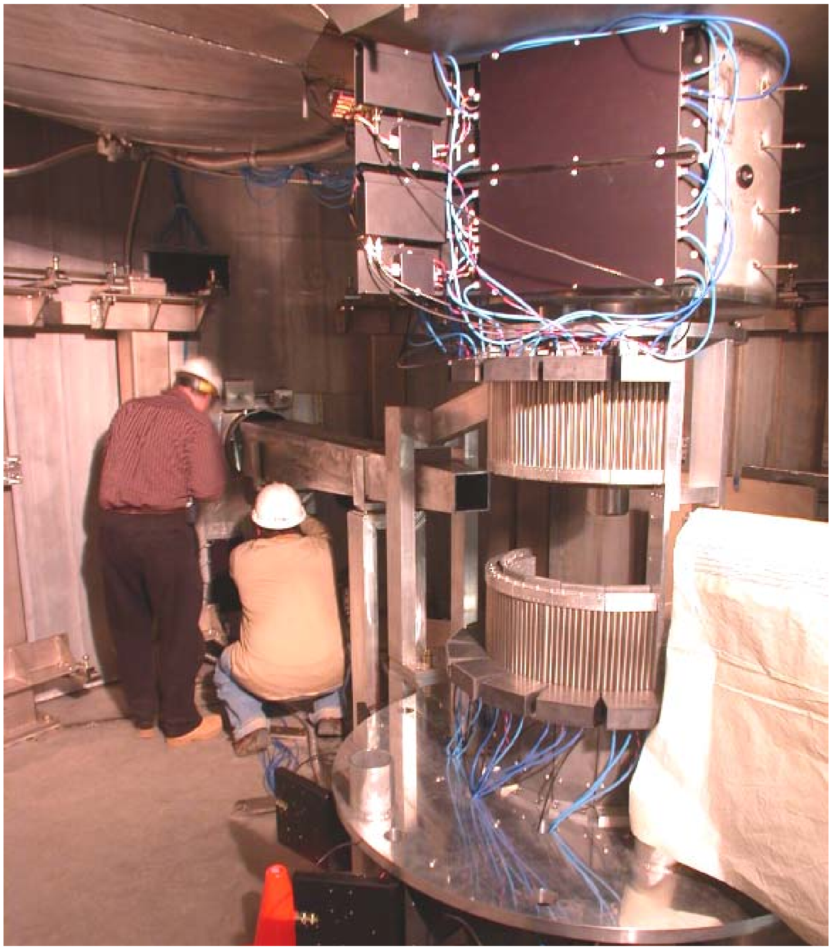


Fig. 5.3-8. Neutron detectors and electronics installed in instrument.

5.3.1.4 Completion status

All components/systems necessary to operate the instrument safely and at the specified performance level have been installed and tested. In addition, on Friday, May 19, 2006, the backscattering spectrometer received operational approval (Figs. 5.3-9 through 5.3-10). The primary shutter was opened that afternoon, and the instrument measured cold neutrons from one of the cryogenic hydrogen moderators guided to the sample through the neutron guide. The commissioning program continued on Tuesday, May 23, 2006, with measurement of the diffraction pattern from a sample of fluorphlogopite, a synthetic mica (Fig. 5.3-11). These data were collected with four helium detector tubes in 820 seconds at an average proton power on target of approximately 185 W. On Wednesday, May 31, 2006, the instrument measured the energy resolved scattering from a sample of 4-methyl pyridine (N-oxy γ-picoline) at a sample temperature of 3 – 4 K. In addition to a strong elastic response whose width in energy was determined by the instrument resolution, the series of expected tunneling peaks was observed. This spectra was collected using 25% of the current detector/analyzer system in 3 hours at an average proton power on target of 5 kWatts.

Fig. 5.3-9. Experimental Facilities Director Ian Anderson and Backscattering Spectrometer lead instrument scientist Ken Herwig during the instrument commissioning.

Fig. 5.3-10. The Backscattering Spectrometer instrument team.

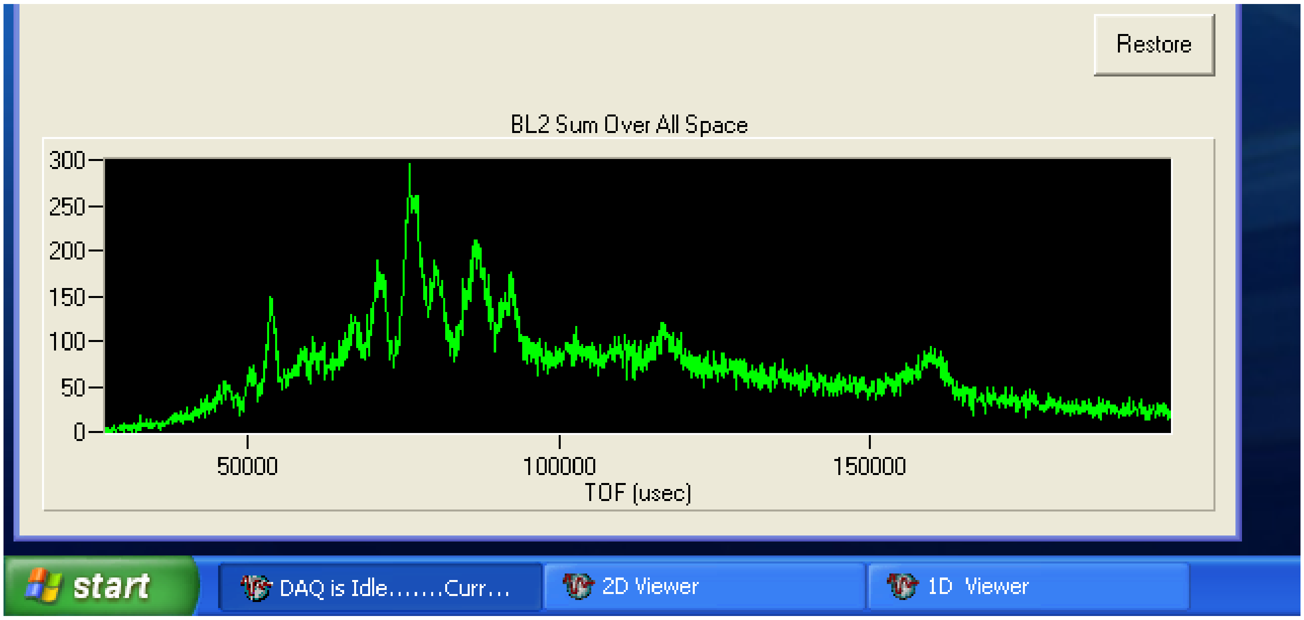


Fig. 5.3-11. Data from the Backscattering Spectrometer commissioning showing the 118k neutrons counted and the neutron diffraction peaks.

5.3.2 Magnetism Reflectometer–Beamline 4A

5.3.2.1 Operation and performance

Two independently operated reflectometers share a single beam port at SNS: the Liquids Reflectometer is optimized for studies on liquid surfaces; the Magnetism Reflectometer is optimized for magnetism studies on thin films. The resulting configuration in shown in Figs. 5.3-12 and 5.3-13. The instruments view the same moderator through a single primary beam line shutter. The primary shutter is designed to accommodate two individual optics for beam extraction. The result is a pair of highly integrated instruments that can be independently operated.

The Magnetism Reflectometer is a neutron-scattering instrument optimized for measurement of atomic-scale magnetic structures at surfaces and interfaces and for high-angle diffraction studies on magnetic thin films and surfaces. This instrument can perform such reflectivity measurements at Q values up to ~1 $Å^{-1}$ and can make diffraction measurements up to Q values of ~5 $Å^{-1}$. Typical reflectivity measurements down to reflectivities of ~10^{-6} can be made in a matter of minutes. The ultimate goal for this instrument is to be able to measure reflectivities down to a few times 10^{-10} for many systems, although measurements to this level will be quite difficult and will take much longer. Over the entire reflectivity range, data collection times are factors of 10 to 100 faster than for the best current instruments, making this instrument truly *best-in-class*.

The nominal sample orientation is with the sample surface in the vertical plane (normal to surface is in horizontal plane), so the reflection/scattering plane is horizontal. Although this instrument is optimized for the study of magnetic samples, the availability of polarized neutrons and the polarization analysis capability suggests that the instrument will also be used for specific studies on nonmagnetic thin film samples. Examples for the latter cases include contrast variation, incoherent background reduction, and phase determination for direct inversion of reflectivity data into real-space, scattering-length density profiles.

For reflectivity measurements, neutrons from the guide are directed onto the sample surface at a shallow angle near the critical angle for reflection from this surface. The neutrons can then be specularly reflected from the surface, scattered off-specularly within the scattering plane (plane normal to the surface), scattered perpendicular to this plane, or transmitted through the sample.

This instrument can also be used with larger angles of incidence relative to the sample surface and with quite large scattering angles. In this case, it functions as a diffractometer to measure atomic spacings of layers deposited on the sample substrate. In either case, the time of arrival of a neutron at a detector gives the total TOF from moderator to sample to detector; and this time in turn can be used to deduce the wavelength of the incident neutron. Knowledge of the incident angle comes from the sample geometry relative to the beam, while the scattering angles both in the scattering plane and perpendicular to this plane come from the location of the neutron detection event within the two-dimensional detector area. These parameters provide complete kinematic information about the scattering event. Carrying out this process for a large number of incident neutrons builds up a pattern that shows the probability of scattering as a function of the momentum transfer in the reflection or scattering process.

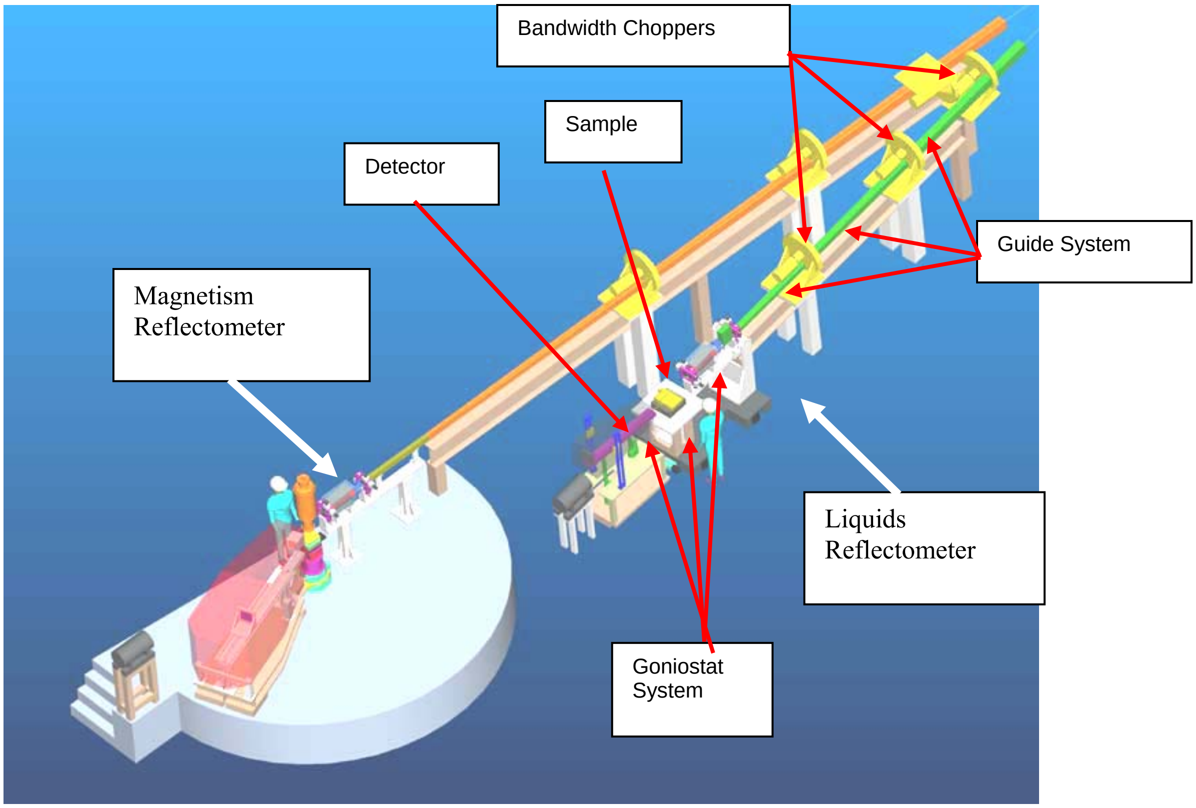


Fig. 5.3-12. SNS reflectometry beam lines: the upper beam line represents the Magnetism Reflectometer, the lower the Liquids Reflectometer. For clarity in the figure, all shielding and enclosures have been removed. Major components of the Magnetism Reflectometer are labeled.

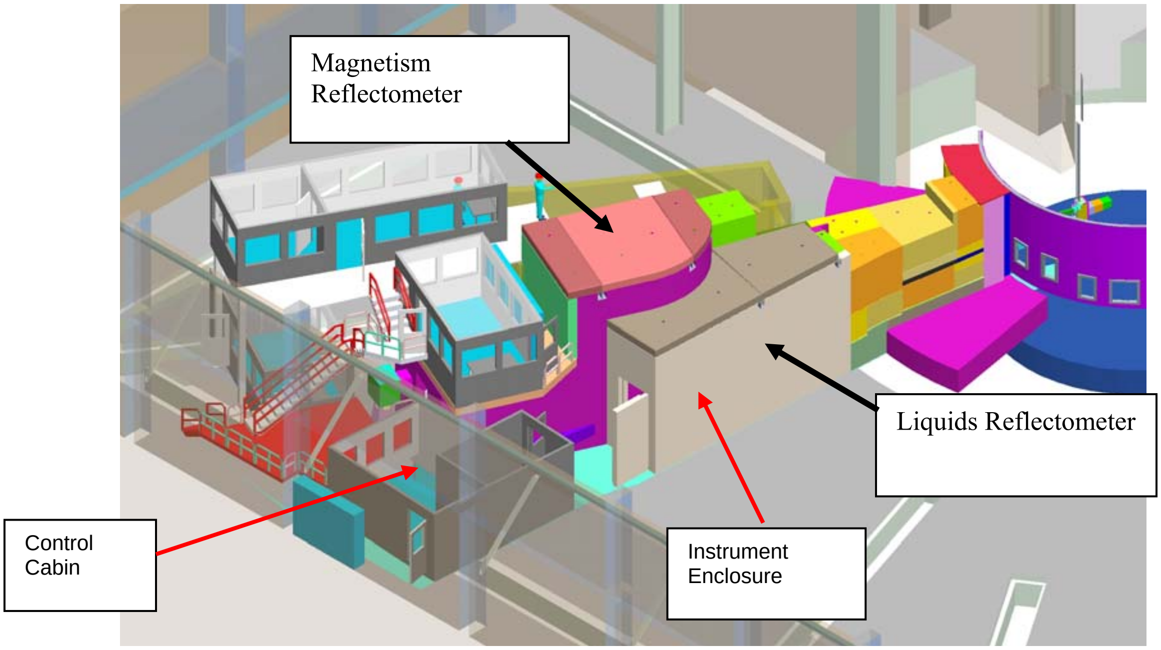


Fig. 5.3-13. The SNS reflectometry beam lines with shielding, enclosures, and control cabins installed. Major components of the Magnetism Reflectometer are labeled.

5.3.2.2 Instrument description

The basic layout of the Magnetism Reflectometer is shown in Fig. 5.3-12. Neutrons from the coupled H_2 moderator are guided to the sample position at 18.64 m from the moderator via a combination of a short channel beam bender and a tapered neutron guide (Fig. 5.3-14). The bender is effectively four narrow curved supermirror neutron guides in parallel, with very thin supermirror-coated septa between the adjacent guides. This arrangement allows the guides to have a relatively short radius of curvature (~135 m) while still transmitting neutrons down to fairly short wavelengths. Each of the parallel guide channels has a cross section of ~1.3 × 8 cm^2. The first ~2 m of the bender are in the primary shutter in the target monolith, while the remaining ~3 m of the bender are downstream from the shutter. The bender is followed by a 9.8-m-long tapered guide that reduces the total beam cross section from ~5.5 × 8 cm^2 to 2.5 × 2.5 cm^2. The combination of bender plus tapered guide results in a line-of-sight distance of ~10.5 m from the moderator for fast neutrons.

Three single-disk neutron bandwidth-limiting choppers (Fig. 5.3-14) are located at distances of 6.2 m, 8.0 m, and 10.32 m from the moderator. The openings in these chopper disks are sized to provide a nominal bandwidth of 3.14 Å at a detector-moderator distance of 20.97 m when operated at the design speed of 60 Hz. This 3.14-Å band can be centered at any desired wavelength by changing the chopper phasing, and by adjusting this phase this instrument can use the wavelength range ~1.7 Å to 3.14 Å (first frame), 3.14 Å to 6.28 Å (second frame), or even higher frames depending on the need of the particular experiment. Additionally, by reducing the speed of the choppers, pseudo 30-Hz (or lower) operation can be realized with correspondingly wider wavelength bandwidth.

This incident beam line also includes a 50-cm-long secondary shutter (Fig. 5.3-14) starting at ~8.93 m from the moderator and linked to the IPPS. The secondary shutter contains part of the tapered guide, which is rotated out of the beam when the shutter is closed. A low-efficiency beam monitor in the incident beam provides wavelength spectrum data for the incident neutrons. The incident beam line, including secondary shutter, beam monitor, and all three choppers, is surrounded by massive shielding (Fig. 5.3-15) made of steel, heavy concrete, and normal concrete in proportions optimized to provide the desired shielding characteristics. This shielding is designed to reduce radiation doses at its surface to below 0.25 mrem/h when the facility is operating at 2 MW.

The neutron guide system transports the beam to a shielded instrument enclosure (Fig. 5.3-16). This enclosure houses a goniometer assembly (Fig. 5.3-16) that includes slits to control the size of the neutron beam, polarizing neutron optical elements (polarizer and spin flipper) to select the spin-state incident on the sample (Fig. 5.3-17), and polarization analyzing optics to determine the spin state after reflection or scattering from the sample (Fig. 5.3-18). The goniometer assembly provides motors to position these components and to position the neutron detector and to provide some of the sample angular positioning. A hexapod sample positioner (Fig. 5.3-16) provides the remainder of the motions necessary to properly position the sample and any associated sample environment equipment.

Neutrons that are reflected/diffracted by the sample are counted by a two-dimensional multidetector (Fig. 5.3-18) at ~20.97 m distance from the moderator (the actual position of the detector is variable). This detector is a ^{3}He proportional counter with an active area of 20 × 20 cm^2 and a resolution of ~1.5 mm. A state-of-the-art data acquisition system, located in a cabin near the instrument enclosure (see Fig. 5.3-13), collects and organizes the data from the detector to present this information.

There is access from the top of the instrument enclosure to insert heavy equipment into the sample position. Some samples may also be inserted from this position. However, the primary user access will be through a shielded door into the instrument enclosure. An IPPS linked to the primary and secondary shutter ensures that personnel can enter the instrument enclosure only when the one or both of these shutters is closed. The IPPS can direct closure of the secondary shutter and can also force shutdown of the accelerator to prevent unsafe radiological conditions.

5.3.2.3 Components

The figures in this section show representative views of the major components of the Magnetism Reflectometer in various stages of installation.

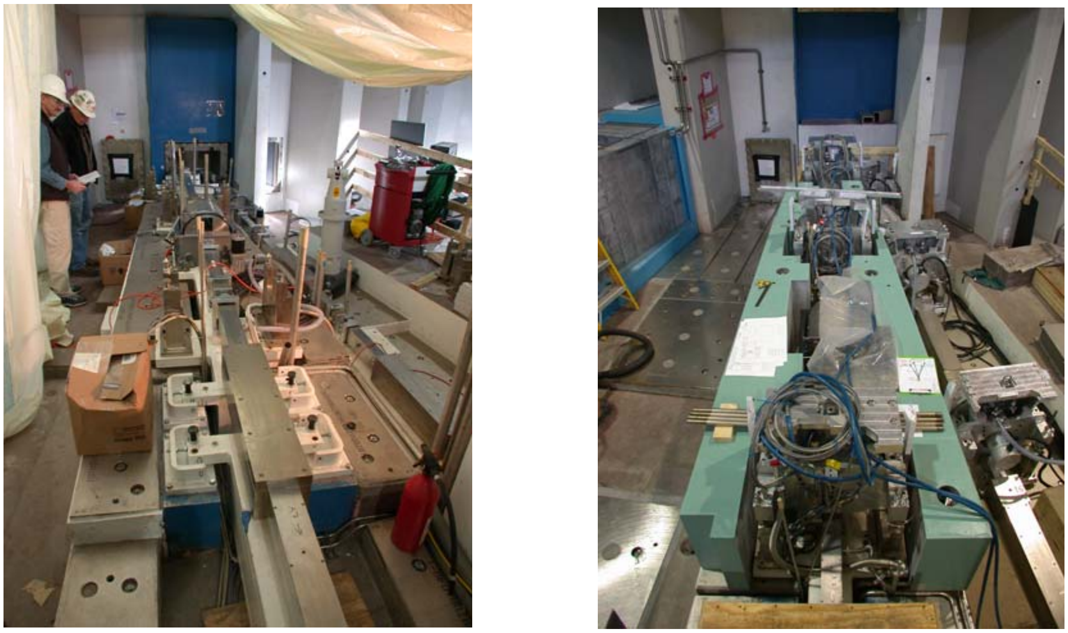

(a) (b)

Fig. 5.3-14. Guide system and choppers: (a) guide system and secondary shutter installed, (b) choppers installed in guide openings and first shielding pieces in place.

Fig. 5.3-15. Final shielding being installed on Magnetism Reflectometer and Liquids Reflectometer incident beam line.

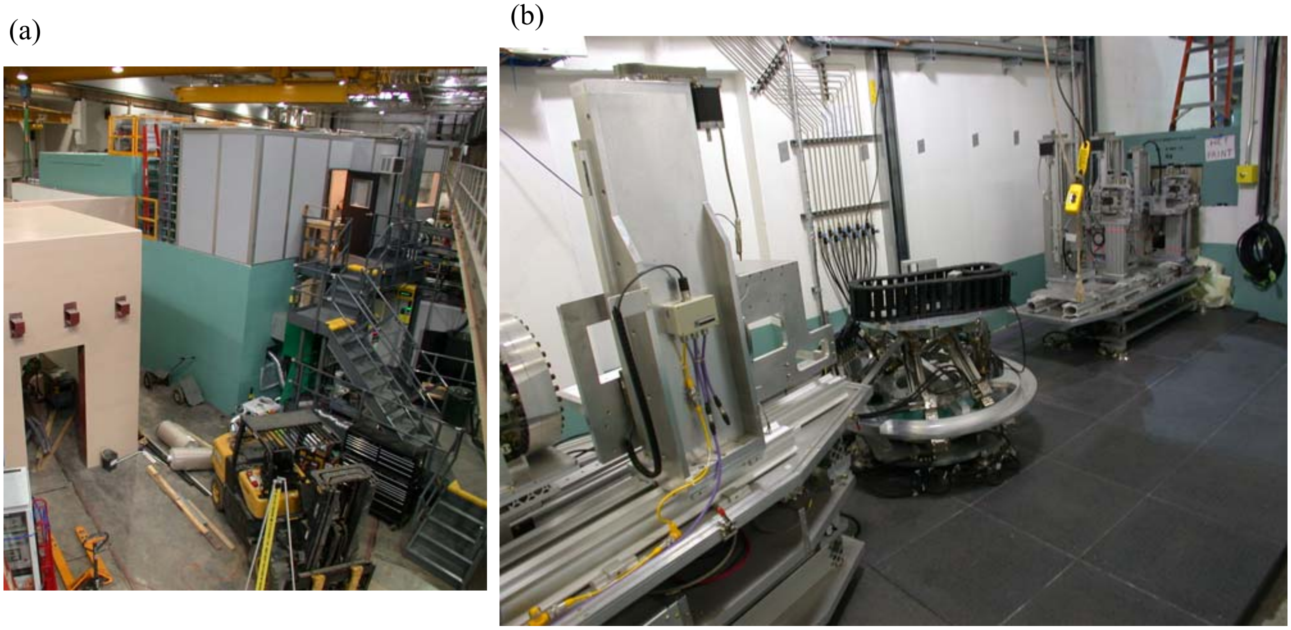


Fig. 5.3-16. Shielded enclosure: (a) external view, (b) internal view, showing goniometer assembly that moves on air pads over the granite floor, and the hexapod that supports the sample.

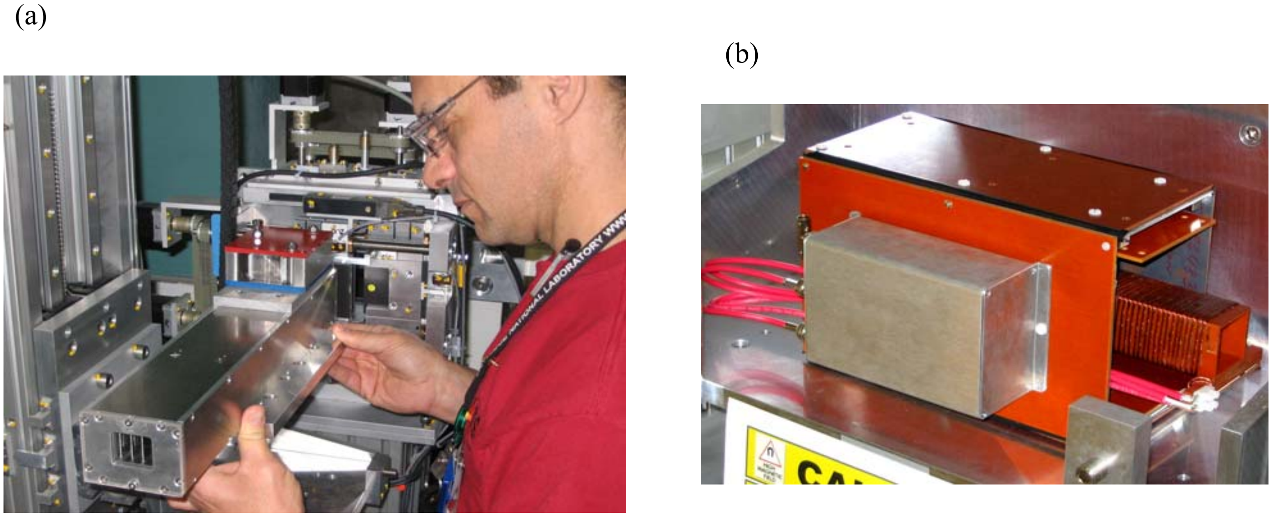


Fig. 5.3-17. Incident beam polarization: (a) polarizer, (b) spin flipper.

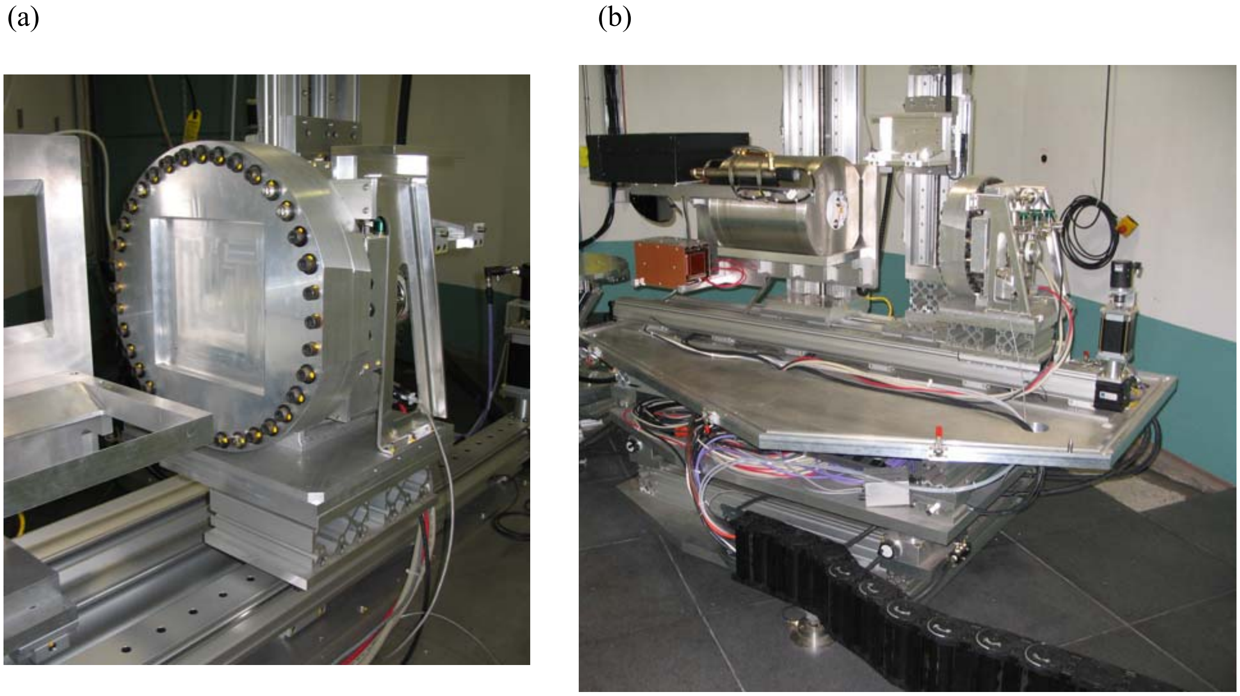


Fig. 5.3-18. Scattered beam: (a) ^{3}He area detector, (b) ^{3}He polarization analyzer and neutron detector installed on goniometer system.

5.3.2.4 Completion status

All components/systems necessary to operate the instrument safely and at the specified performance level have been installed and tested.

5.3.3 Liquids Reflectometer–Beamline 4B

5.3.3.1 Operation and performance

Two independently operated reflectometers share a single beam port at SNS: the Liquids Reflectometer is optimized for studies on liquid surfaces; the Magnetism Reflectometer is optimized for magnetism studies on thin films. The resulting configuration in shown in Figs. 5.3-14 and 5.3-15. The instruments view the same moderator through a single primary beam line shutter. The primary shutter is designed to accommodate two individual optics for beam extraction. The result is a pair of highly integrated instruments that can be independently operated.

The Liquids Reflectometer is an instrument optimized for the measurement of atomic-scale structures at surfaces and interfaces of both liquids and solids. However, it is designed especially to accommodate the unique requirement for reflectivity measurements from liquids—namely that the liquid surface must be horizontal. This instrument can perform such reflectivity measurements from liquid surfaces up to Q values of ~0.5 Å^{-1} and can reach higher Q values (~1 Å^{-1}) for solid surfaces. Typical reflectivity measurements down to reflectivities of ~10^{-6} can be made in a matter of minutes. The ultimate goal for this instrument is to be able to measure reflectivities down to a few times 10^{-10} for many systems, although measurements to this level will be quite difficult and will take much longer. Over the entire reflectivity range, data collection times are factors of 10 to 100 faster than for the best current instruments, making this instrument truly *best-in-class*.

For reflectivity measurements, neutrons from the guide are directed onto the sample surface at a shallow angle near the critical angle for reflection from this surface. Since a liquid surface cannot be tilted, variation of the angle of incidence is achieved by lowering (raising) the sample surface and adjusting the beam-defining apertures so that the neutrons strike the surface at a greater (smaller) angle of incidence. The neutron can then be specularly reflected from the surface, scattered off-specularly within the scattering plane (plane normal to the surface), scattered perpendicular to this plane, or transmitted through the sample. The time of arrival of a neutron at a detector gives the total TOF from moderator to sample to detector, and this time in turn can be used to deduce the wavelength of the incident neutron. Knowledge of the incident angle comes from the sample geometry relative to the beam, while the scattering angles both in the scattering plane and perpendicular to this plane come from the location of the neutron detection event within the two-dimensional detector area. These parameters provide complete kinematic information about the scattering event. Carrying out this process for a large number of incident neutrons builds up a pattern that shows the probability of scattering as a function of the momentum transfer in the reflection or scattering process.

5.3.3.2 Instrument description

To accommodate reflections from liquid surfaces, the nominal sample orientation is with the sample surface in the horizontal plane (normal to surface is in vertical plane), so the reflection/scattering plane is vertical. To provide a neutron beam with a small angle of incidence to the horizontal surface, the incident beam line is inclined downward at a 4° angle. The basic layout of the instrument is illustrated in Fig. 5.3-12 Neutrons from the coupled H_2 moderator are guided to the sample position at ~13.6 m from the moderator via a combination of a short channel beam bender and a tapered neutron guide (Fig. 5.3-13). The bender is effectively four narrow curved supermirror neutron guides in parallel, with very thin supermirror-coated septa between the adjacent guides. This arrangement allows the guides to have a relatively short radius of curvature (~156 m) while still transmitting neutrons down to fairly short wavelengths. Each of the parallel guide channels has a cross section of ~1.15 × 8 cm^2. The first ~2 m of the bender are in the primary shutter in the target monolith, while the remaining ~3 m of the bender are downstream from the shutter. The bender is followed by a 4.9-m-long tapered guide that reduces the total beam cross section from ~4.5 × 8 cm^2 to 3 × 1.75 cm^2. The combination of bender plus tapered guide results in a line-of-sight distance of ~10 m from the moderator for fast neutrons.

Three single-disk neutron bandwidth limiting choppers (Fig. 5.3-19) are located at distances of 5.7 m, 7.5 m, and 9.6 m from the moderator. The openings in these chopper disks are sized to provide a bandwidth of 3.8 Å when operated at the design speed of 60 Hz. This 3.8-Å band can be centered at any desired wavelength by changing the chopper phasing, and by adjusting this phase this instrument can use the wavelength range of ~1.8 Å to 4.4 Å (first frame), 4.4 Å to 8.7 Å (second frame), or even higher depending on the need of the particular experiment. Additionally, by reducing the speed of the choppers, pseudo 30-Hz (or lower) operation can be realized with correspondingly wider wavelength bandwidth.

This incident beam line also includes a 50-cm-long secondary shutter starting at ~6.8 m from the moderator and linked to the IPPS. The secondary shutter contains part of the bender, which is rotated out of the beam when the shutter is closed. A low-efficiency beam monitor in the incident beam provides wavelength spectrum data for the incident neutrons. The incident beam line, including secondary shutter, beam monitor, and all three choppers, is surrounded by massive shielding (Fig. 5.3-15) made of steel, heavy concrete, and normal concrete in proportions optimized to provide the desired shielding characteristics. This shielding is designed to reduce radiation doses at its surface to below 0.25 mrem/h when the facility is operating at 2 MW.

The neutron guide system transports the beam to a shielded instrument enclosure (Fig. 5.3-20). This enclosure houses a goniostat assembly (Fig. 5.3-20) that includes slits to control the size of the neutron beam, along with all the motions necessary to adjust the sample height and tilt, and to position the detector over a range of scattering angles. Neutrons that are reflected/diffracted by the sample will be counted by a two-dimensional multidetector (Fig. 5.3-20) at ~15.6-m distance from the moderator. This detector is a ^{3}He proportional counter with an active area of 20 × 20 cm^2 and a resolution of ~1.5 mm. A state-of-the-art data acquisition system, located in a cabin near the instrument enclosure (see Fig. 5.3-20), collects and organizes the data from the detector to present this information.

User access will be through a shielded door into the instrument enclosure. An IPPS linked to the primary and secondary shutters ensures that personnel can enter the instrument enclosure only when the one or both of these shutters is closed. The IPPS can direct closure of the secondary shutter and can also force shutdown of the accelerator in order to prevent unsafe radiological conditions.

5.3.3.3 Components

The figures in this section show representative views of the major components of the Liquids Reflectometer in various stages of installation.

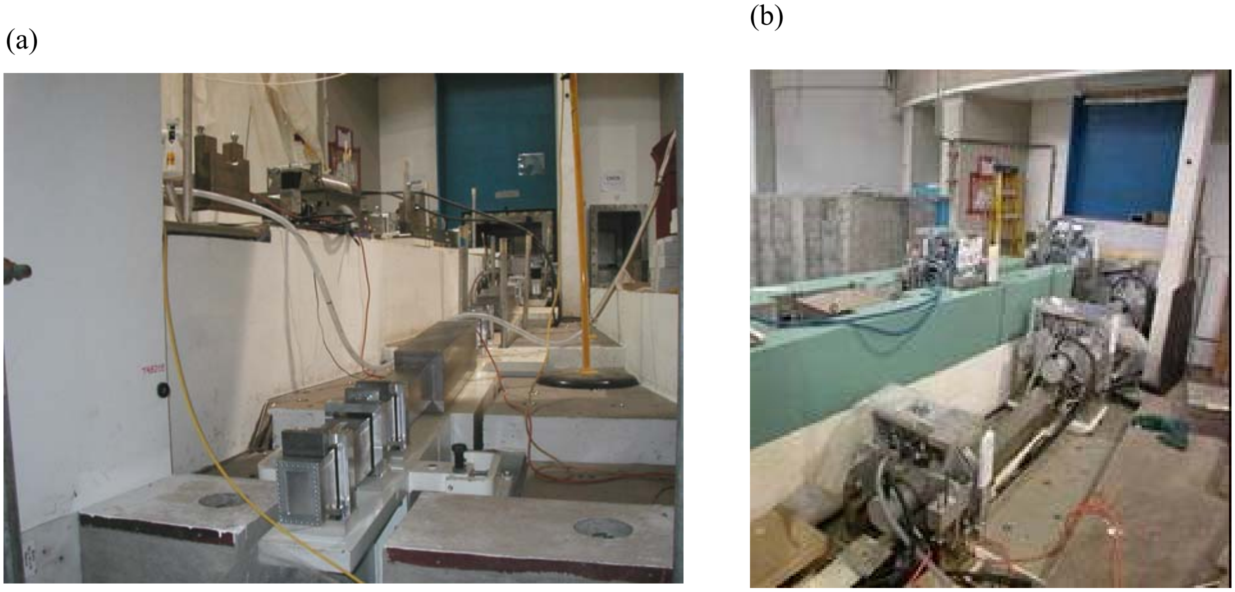


Fig. 5.3-19. Incident beam: (a) neutron guide system installed on downward-inclined beam line; (b) three choppers installed in spaces in guide system.

5.3.3.4 Completion status

All components/systems necessary to operate the instrument safely and at the specified performance level have been installed and tested.

5.3.4 Small-Angle Neutron-Scattering Instrument–Beamline 6

5.3.4.1 Operation and performance

The SANS instrument has a high useable flux and a wide Q coverage unmatched by any other SANS instruments. For the SNS SANS instrument, the smallest accessible Q value is 0.003 Å^{-1},while the largest Q value accessible with the baseline instrument is 3.8 Å^{-1}. The design allows for an upgrade to provide additional detectors at higher scattering angles to access even higher Q values if desired. Because of this broad Q range, the SANS instrument is also referred to as the extended-Q SANS. The useable flux at the sample position for comparable resolution will be as high or higher than at any existing SANS instruments. This, together with the uniquely wide Q range, makes this a *best-in-class instrument*.

This instrument will open many exciting opportunities for new science. An example is the study of protein-membrane interactions, where protein signals appear at low Q, while lipid signals show up at high Q. Other applications include engineering materials, where simultaneous monitoring of domain small-angle scattering and crystal diffraction is of great interest.

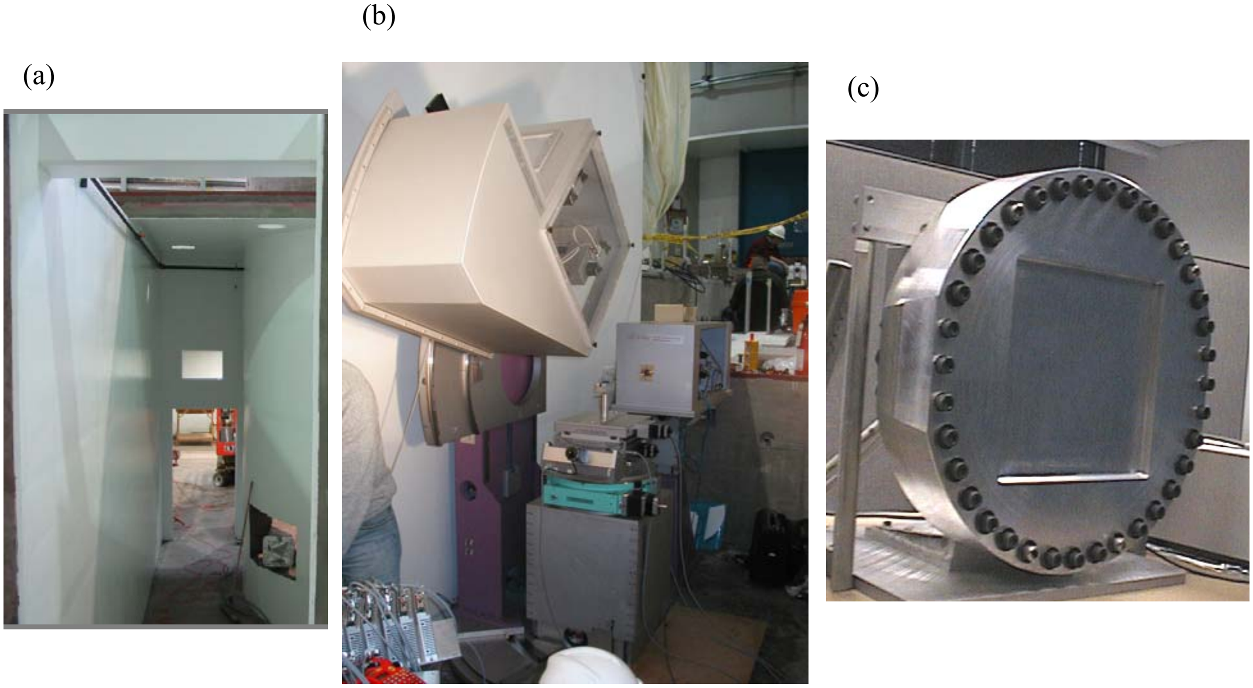


Fig. 5.3-20. Scattered beam: (a) shielded enclosure; (b) goniometer system installed inside enclosure; (c) area detector prior to installation.

The minimum accessible Q value on the extended-Q SANS is obtained when the low-angle detector is at its maximum distance of 22 m (8 m detector-to-sample), giving a minimum Q value of ~ 0.003 $Å^{-1}$ when 9-Å neutrons are used (3rd frame). The maximum usable Q value of ~3.8 $Å^{-1}$ is given by the use of 1-Å neutrons at the highest detector angle of the moveable two-dimensional detector array, which varies between ~81° and ~10° as the detector is moved between 1 and 8 m from the sample. This Q value can be extended by adding detectors at higher angles in a future upgrade. Many samples have time-dependent properties of interest (e.g., kinetics of phase transitions, chemical reactions, or aggregation of smaller particles), and the ability to simultaneously collect data over all the required Q range is often a prerequisite for studying these systems.

Data collection time depends both on scattering properties of the sample and on the required Q range. For strong scatterers, such as polymers at high concentrations, collection of a single data set within one minute will be possible for all accessible Q ranges. For weak scatterers, such as proteins in dilute solutions, per data set collection time less than 10 min will be possible when Q down to 0.003 $Å^{-1}$ is needed.

For SANS measurements, neutrons from the guide are scattered by the sample. The time of arrival of a neutron at a detector gives the total TOF from moderator to sample to detector, and this time in turn can be used to deduce the wavelength of the incident neutron. Knowledge of the scattering angle comes from the location of the neutron detection event within the two-dimensional detector area. These parameters provide complete information about the momentum transfer Q in the scattering event. Carrying out this process for a large number of incident neutrons builds up a pattern that shows the probability of scattering as a function of the momentum transfer in the scattering process.

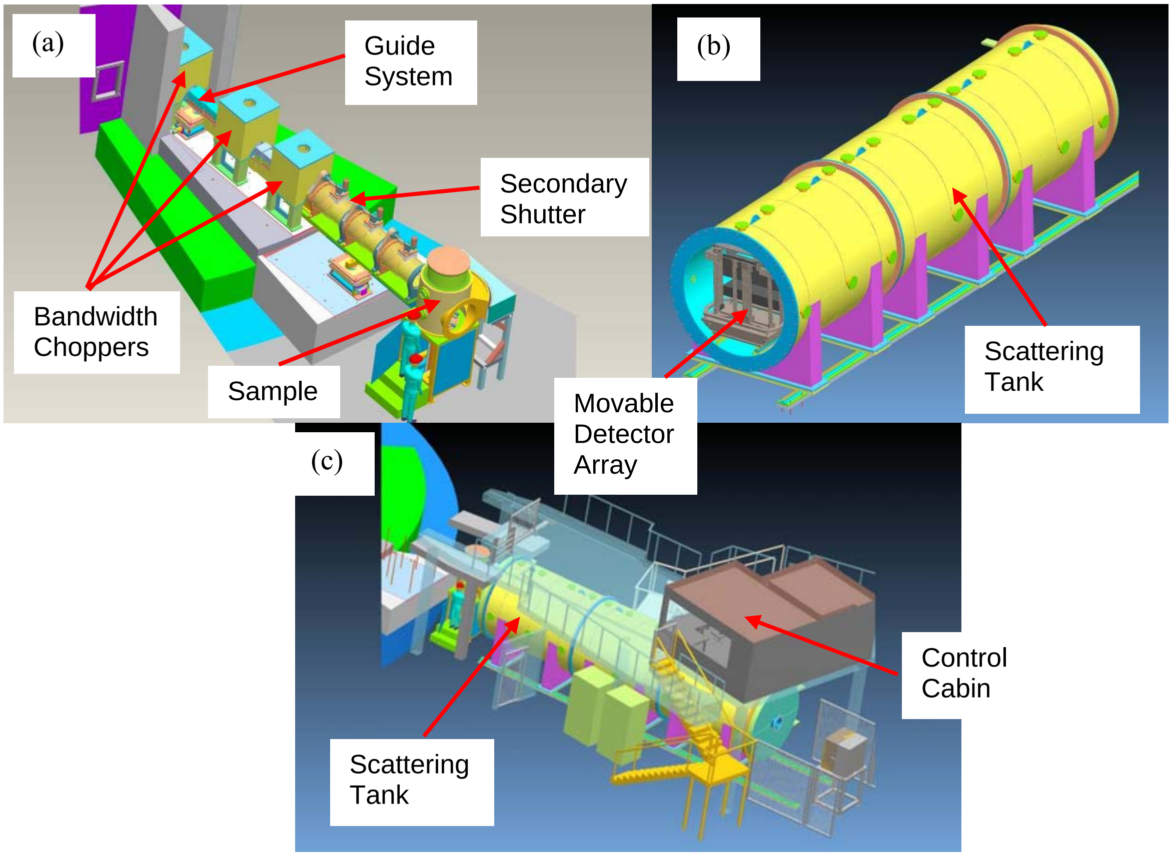


Fig. 5.3-21. (a) SANS incident beam line, including sample area but with most shielding removed for clarity; (b)evacuated scattering tank; (c) integrated view showing sample area, scattering tank, platform above scattering tank, instrument control cabin, and sample preparation area.

5.3.4.2 Instrument Description

The basic layout of the instrument is illustrated in Fig. 5.3-21. Neutrons from the coupled H_2 moderator are guided to the sample position at 14 m from the moderator via a combination of a short channel beam bender and a straight neutron guide. The bender is effectively nine narrow curved supermirror neutron guides in parallel, with very thin supermirror-coated septa between the adjacent guides. This arrangement allows the guides to have a relatively short radius of curvature (~68 m), while still transmitting neutrons down to short wavelengths. Each of the parallel guide channels has a cross section of ~0.4 × 4 cm^2. The first ~2 m of the bender are in the primary shutter in the target monolith, while the remaining ~1 m of the bender are downstream from the shutter. The bender is followed by a 5-m-long straight guide. The combination of bender plus straight guide results in a line-of-sight distance of ~7 m from the moderator for fast neutrons.

Two single-disk neutron bandwidth limiting choppers are located at distances of 5.3 and 7.8 m from the moderator, and a dual-disk neutron bandwidth limiting chopper is located at 9.8 m. The openings in these chopper disks are sized to provide a bandwidth of 4.4 Å (3.0 Å when detector is at 22 m from moderator) when operated at the design speed of 60 Hz, varied to match the frame bandwidth between for detector positions between 15 and 22 m from the moderator. This band can be centered at any desired wavelength by changing the chopper phasing, and by adjusting this phase, this instrument can use the wavelength range ~1 Å to 4 Å (first frame, when detector is at 15 m), ~4 Å to 8 Å (second frame), or even higher frames depending on the need of the particular experiment. Additionally, by reducing the speed of the choppers, pseudo 30-Hz (or lower) operation can be realized with correspondingly wider wavelength bandwidth.

This incident beam line also includes a 100-cm-long secondary shutter starting at ~10 m from the moderator and linked to the IPPS. The secondary shutter contains beam transport optics or apertures, which are rotated out of the beam when the shutter is closed. A low-efficiency beam monitor in the incident beam provides wavelength spectrum data for the incident neutrons. The incident beam line, including secondary shutter, beam monitor, and all three choppers, is surrounded by massive shielding made of steel, heavy concrete, and normal concrete in proportions optimized to provide the desired shielding characteristics. This shielding is designed to reduce radiation doses at its surface to below 0.25 mrem/h when the facility is operating at 2 MW.

The neutron guide system transports the beam to a sample position. Slits upstream from the sample position control the size and the angular divergence of the neutron beam incident on the sample. Neutrons that are scattered by the sample are counted by a two-dimensional detector array located in an evacuated scattering tank downstream from the sample (Fig. 5.3-21). This detector is made up of an array of ^{3}He proportional counters with a total active area of 100 × 100 cm^2 and a resolution of ~8 mm. This detector array can be moved along the scattering tank between ~15 and ~22 m from the moderator. The instrument design includes room for a future upgrade to include a high-angle detector array to extend the Q range. A state-of-the-art data acquisition system, located in a cabin on the instrument platform (Fig. 5.3-21), collects and organizes the data from the detector array(s) to present this information.

The primary user access will be through a gate into the controlled instrument area. An IPPS linked to the primary and secondary shutter ensures that personnel can enter the controlled instrument area only when the one or both of these shutters is closed. The IPPS can direct closure of the secondary shutter and can also force shutdown of the accelerator in order to prevent unsafe radiological conditions.

5.3.4.3 Completion status

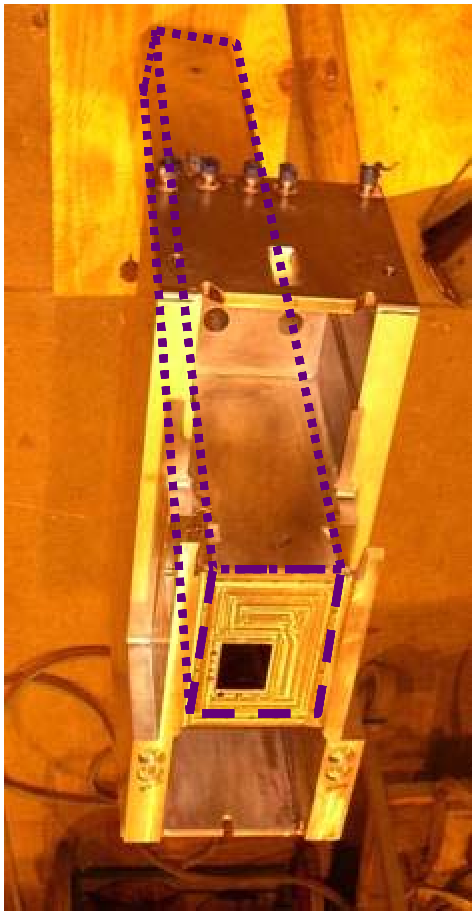
Only a few technical components/systems have been received (Fig. 5.3-22). The remaining technical components/systems necessary to operate the instrument safely and at the specified performance level have been ordered. Most of the conventional structures (instrument enclosures, control cabins, etc.) will be provided as part of the installation process, which is to be carried out after CD-4 using SNS operating funds.

5.3.5 Powder Diffractometer–Beamline 11A

5.3.5.1 Operation and performance

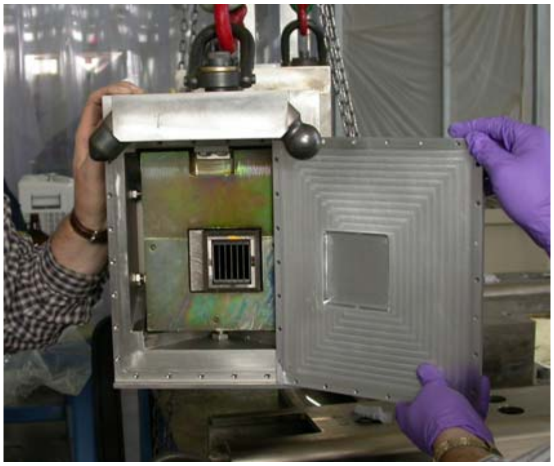
The high-resolution, general-purpose Powder Diffractometer is a TOF neutron-scattering instrument designed for crystallographic studies of polycrystalline materials. This instrument can collect high-resolution diffraction data over d-spacings of 0.4 to 6 Å (with a resolution $\delta d/d$ of 0.0015 at d = 1 Å) in a single diffractogram, a capability unique in the world . For complex crystal structures, the high-resolution and high-count rate will allow diffraction data suitable for precise structural refinement to be collected in as short as 2 to 5 min, which is as fast or faster than other instruments with much poorer resolution. Adjusting the phase of the bandwidth choppers can move the wavelength bandwidth incident on the sample to allow measurement of d spacings up to 16 Å, which is particularly useful for the study of magnetic and micro/mesoporous crystal structures. For small samples (<0.5 g) and time-dependent studies, the intensity can be increased at the expense of resolution to reach data collection times of 1 to 3 seconds per diffractogram for studies of materials having relatively simple crystal structures. The high degree of flexibility, broad range of d spacings accessible, high resolution, and high data rates make this instrument unique and certainly *best-in-class*.

5.80 (a)



5.80 (b)

5.80 (c)



5.80 (d)

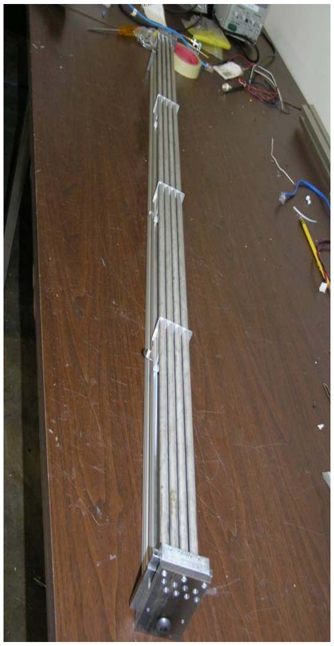


Fig. 5.3-22. SANS components: (a) core vessel insert; (b) guide section for core vessel insert; (c) shutter insert with bender inserted; (d) module containing 8 1-m long x 8-mm diameter 3He detectors, the first of a number of similar modules .

For diffraction measurements, neutrons from a long incident-beam neutron guide are scattered by the sample to an array of position-sensitive detector modules. The time of arrival of a neutron at a detector gives the total TOF from moderator to sample to detector, and this time in turn can be used to deduce the wavelength of the incident neutron. Knowledge of the scattering angle comes from the location of the neutron detection event within the detector area. These parameters provide complete momentum transfer Q information (which is simply related to the d spacing between atomic planes) about the diffraction event. Carrying out this process for a large number of incident neutrons builds up a pattern that shows the probability of diffraction as a function of the momentum transfer or d spacing in the scattering process.

5.3.5.2 Instrument description

Neutrons from the decoupled and poisoned H_2 moderator are transported to the sample position at 60 m distance via ~44 m of fixed and 5 m of interchangeable straight supermirror neutron guide. The 60 m distance is too long to fit within the Target Building, so the scattering part of this spectrometer is housed in a nominally 60- × 60-ft^2 satellite building attached to the Target Building. This satellite building contains a 10-ton bridge crane to facilitate manipulation of instrument components for maintenance and upgrade activities. The layout of this secondary diffractometer inside the satellite building is shown in Fig. 5.3-23.

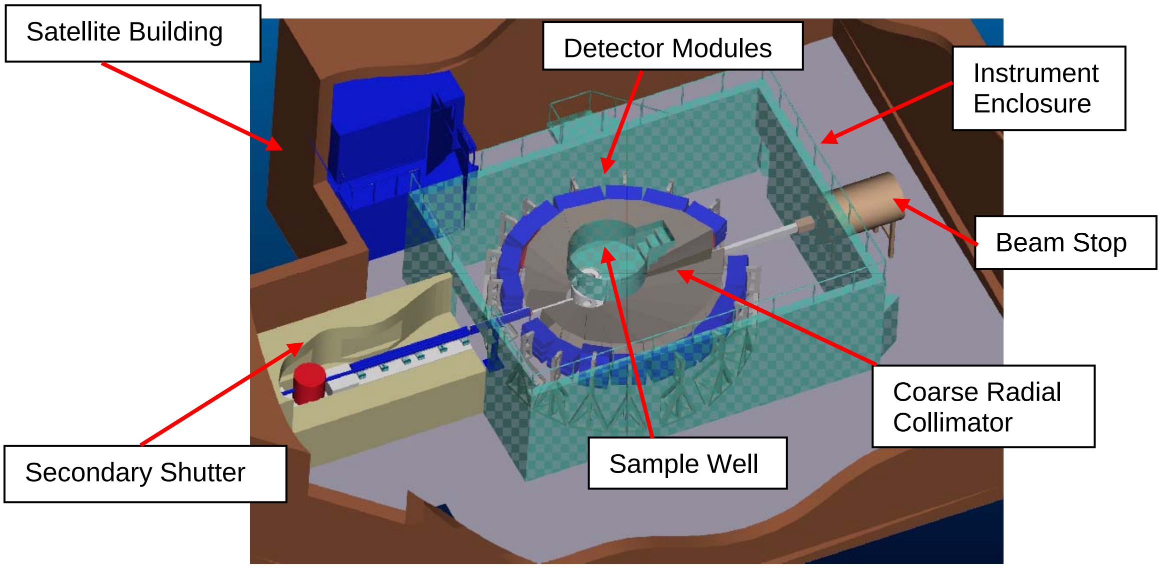


Fig. 5.3-23. Satellite building for the Powder Diffractometer, cut away to show the final portion of the incident flight path and the secondary diffractometer with instrument enclosure, sample chamber, detectors, and coarse radial collimator. Only a portion of the detector module arrays shown are provided as part of the baseline instrument.

The requirements of high flux at the short wavelengths, $\lambda < 1.5$ Å, and a homogeneous distribution of incident neutrons on the sample can only be satisfied with a straight geometry for the guide. The fixed portion of the guide starts at 8 m from the moderator and extends to 52 m from the moderator. The first 22 m of this guide has a cross section of 1.4 × 8.7 cm^2. The remaining 27 m of guide tapers from this cross section to a final cross section of 1.4 × 4.4 cm^2. Two versions of the last 5 m of this tapered guide can be interchanged to adjust the incident beam divergence to match the needs of particular experiments. The principal operating neutron wavelengths of this instrument are $0.5 \text{ Å} < \lambda < 7.0 \text{ Å}$, with primary emphasis in the $\lambda < 1.5$ Å region. The guide interchange translation table is sized to accommodate three different 5-m sections of supermirror guide. The translation table is automated such that a user or computer may choose any of the three interchangeable guide sections, and a linear translation stage(s) will precisely move the translation table aligning the selected guide section at the neutron beam transportation position. Initially the interchange table will accommodate high-resolution and high-intensity guide sections. Space on the translation table is reserved for a third interchangeable guide section that may be purchased and installed as part of a later instrument upgrade.

Three single-disk neutron bandwidth limiting choppers are located at distances of 6.7 m, 7.9 m, and 49.98 m from the moderator. The openings in these chopper disks are sized to provide a bandwidth of 1.02 Å when operated at the design speed of 60 Hz. The bandwidth choppers can also be operated at a speed of 30, 20, or 10 Hz with a corresponding wavelength bandwidth of 2.04 Å, 3.05 Å, or 6.1 Å. Any of these wavelength bands can be centered at any desired wavelength by changing the chopper phasing. Because the beam line is straight, this instrument also requires a massive T_0 chopper at 6.3 m from the moderator phased to block the prompt pulse to cut out the prompt pulse fast neutrons that could contaminate the data and contribute significantly to background.

This incident beam line also contains a 1-m-long secondary shutter centered at a distance of 50.5 m from the moderator and linked to the IPPS, a low-efficiency beam monitor, and a set of slits to adjust the beam size. The secondary shutter when closed must reduce the dose rate at the sample position to less than 2 mrem/h. The incident beam line, including secondary shutter, beam monitor, adjustable slits, bandwidth choppers, and the T_0 chopper, is surrounded by a massive shielding made of steel, heavy concrete, and normal concrete in proportions optimized to provide the desired shielding characteristics. This shielding is designed to reduce radiation doses at its surface to below 0.25 mrem/h when the facility is operating at 2 MW.

The secondary section of the diffractometer is housed inside an instrument enclosure built inside the satellite building. Neutrons from the guide are incident on the sample located in a sample chamber inside this enclosure, and a fraction are scattered. An array of area-position-sensitive scintillation detector modules is placed around the sample on a smooth locus optimized to match instrument resolution to experimental requirements. The spatial resolution for each module is ±3 and ±25 mm along the horizontal and vertical directions, respectively. Distance between the sample and the detectors varies between ~1.6 m and ~5 m, depending on scattering angle. The initial complement of detectors will cover ~4 m^2 of this locus, but the instrument is designed to accommodate upgrades ultimately leading to ~50 m^2 of detector coverage. A state-of-the-art data acquisition system, located in a control cabin on the mezzanine level (Fig. 5.3-23), collects and organizes the data from the detector array(s) to present this information.

The sample is centered in a relatively small evacuated sample chamber with large ribbed thin aluminum windows on either side. The thin windows allow the scattered neutrons to travel to the detector modules with minimum attenuation. A coarse collimator between the sample chamber and the detectors minimizes extraneous scattered neutrons, which otherwise could contribute to the background. The beam stop is located externally and immediately adjacent to the instrument enclosure, blocking access to the neutron beam transmitted through the sample. The beam stop is constructed so as to limit radiation dose rate levels to <0.25 mrem/h on contact. It is sufficiently long such that neutrons that scatter from its end have a minimal likelihood of reentering the sample chamber. Figure 5.3-23 shows this secondary diffractometer geometry.

All user access is from the top of the instrument enclosure (see Fig. 5.3-23). A well leads down to the top of the evacuated sample chamber. Samples and sample environment equipment are lowered into this sample chamber from the top. Utilities to support a wide range of sample environment equipment are installed in easily accessible panels and manifolds at the top of the instrument enclosure.

An IPPS linked to the primary and secondary shutter ensures that personnel do not enter areas with dangerous radiation levels. The IPPS can direct closure of the secondary shutter and can also force shutdown of the accelerator to prevent unsafe radiological conditions.

5.3.5.3 Completion status

Only a few technical components/systems have been received for this instrument (Fig. 5.3-24). The remaining technical components/systems necessary to operate the instrument safely and at the specified performance level have been ordered. Most of the conventional structures (instrument enclosures, control cabins, etc.) will be erected as part of the installation process, which is to be carried out after CD-4 using SNS operating funds.

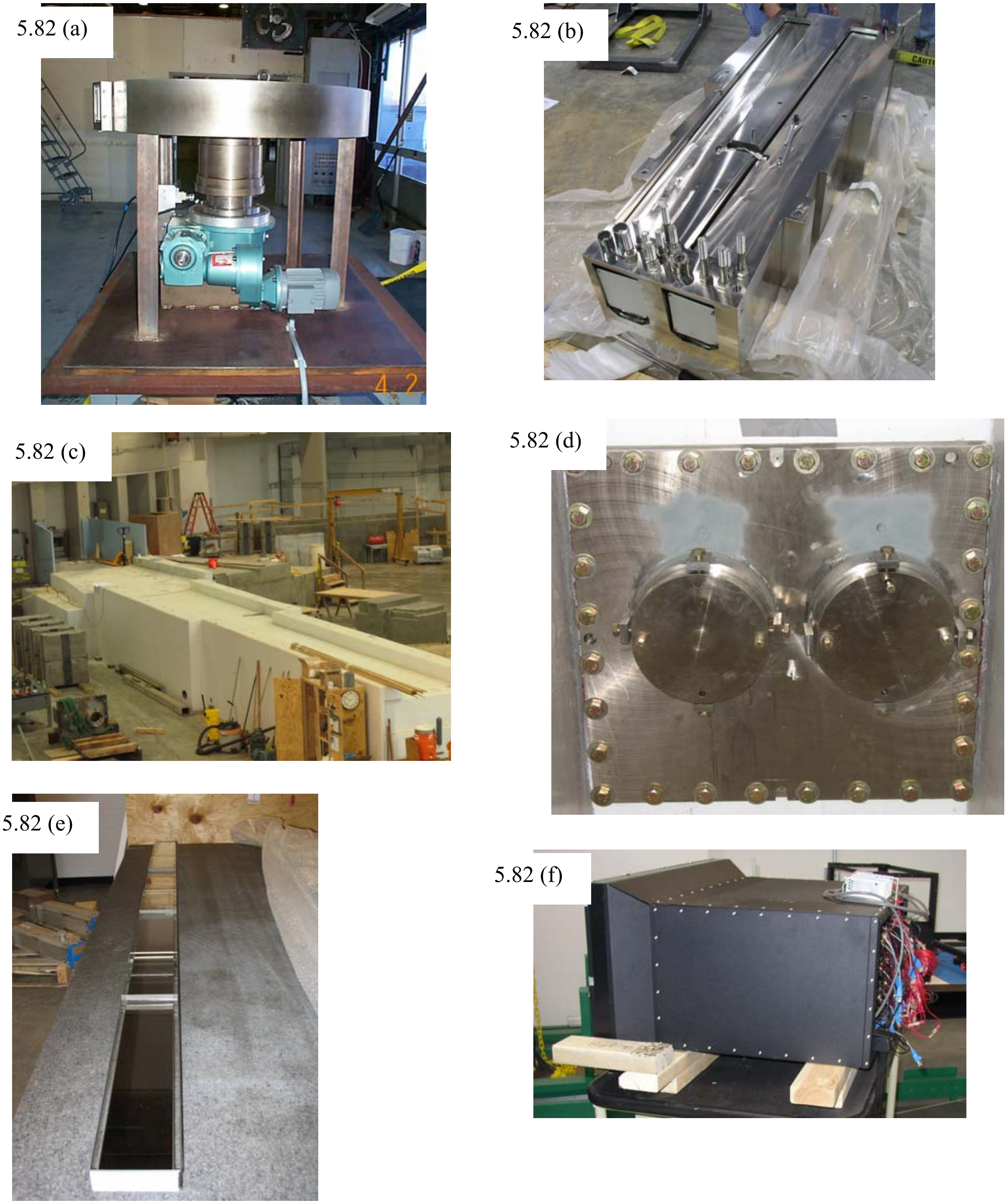


Fig. 5.3-24. Components for the Powder Diffractometer: (a) secondary shutter; (b) insert for secondary shutter; (c) poured-in-place shielding; (d) bulk shield insert; (e) section of guide; (f) first detector module.

5.3.6 Summary for SNS Neutron-Scattering Instruments

Installation and testing of the first three SNS project instruments is complete and is documented (documentation summaries: Backscattering Spectrometer, SNS 107040000-TL0001-R00; Magnetism Reflectometer, SNS 107050000-TL0001-R00; Liquids Reflectometer, SNS 107060000-TL0001-R00). All major technical components of the remaining two SNS Project instruments are in place or have been ordered, consistent with the SNS PEP requirements (documentation summaries: SANS, SNS 107080000-TL0001-R00; Powder Diffractometer, SNS 107100000-TL0001-R00). All five of these instruments are designed to be *best in class*, and the components, including shielding, are designed for 2-MW operation.

5.4 SNS INTEGRATED CONTROL SYSTEM

The primary objective of the SNS ICS has been to integrate into one seamless, easily-operable system all of the major components and subsystems that make up the SNS facility. These include not only the accelerator systems (front end, linac, ring and transfer lines) but also the CHL, target, and conventional facilities. Integrating conventional facilities into the accelerator controls system was an important but unusual SNS innovation that has already paid operational dividends.

Integration of these diverse elements was complicated by the fact that, like the SNS itself, the SNS control system was built by a collaboration of partner laboratories. In order to ensure close integration with subsystem designers, the approach was to have the control system for each major component designed by the laboratory delivering that subsystem. Eventually distributed throughout the SNS facility, these are known as the “distributed systems.” The systems common to all were developed at BNL (the timing system) and ORNL (the communications network, MPS), and Control Room). These are known as the “global systems.” The PPS, only loosely connected to the control system, was also developed at ORNL and included in the scope of the ICS.

Two key decisions—one administrative and one technical—made this complex integration possible. Administratively, the ICS was made a Level 2 WBS element responsible for all of the control systems, wherever developed. This provided the financial authority to enforce technical standards and procedures. Standards that were effectively instituted and thereby facilitated integration included standard electronics racks, standard PLCs, standard IOCs, a standard device and signal naming convention, a central software repository and configuration management tool, a color standard for operator displays, and a well-defined interface point between the control system and the subsystems controlled. The most important and effective standard, however, was the choice of the EPICS Toolkit for all aspects of the ICS.

5.4.1 EPICS

EPICS is a control system toolkit developed collaboratively in the early nineties at LANL and ANL. It was made freely available to not-for-profit institutions with an invitation not only to use it but also to further develop it and resubmit changes and improvements. This model proved both attractive and effective, and both the toolkit and its community of users and collaborative developers grew rapidly. By the time SNS selected EPICS as the basis of its control system (1997), there were well over 100 user-laboratories worldwide (mostly accelerators but also tokamaks, telescopes, and some industrial applications), and EPICS had become the unchallenged system of choice for new accelerators everywhere. It was already used for other projects by SNS collaborators at LBNL, LANL, ANL, and JLab.

Users of EPICS select from a variety of tools for various control system functions including archivers, an alarm handler, save and restore facilities, a sequencer, database configuration tools, several display managers, and many others. Two elements are not optional, however, and together they make up the core of EPICS. The first is the EPICS database, which is distributed among a number of IOCs. It is not a relational database but rather a “flat” configuration database that fully describes all the components of the control system in linked records—one or more for each process variable—and is, in a sense, executable. The second mandatory element is the EPICS network protocol known as "Channel Access" that defines all interprocessor communication. If you have both of these elements, you have EPICS; and you are free to select as needed from the toolkit. If you are missing one element or the other—you're on your own.

5.4.2 Architecture

EPICS is based upon a "flat" control system architecture, meaning most messages go directly from source to destination without passing through another computer. Communication is on a single communication medium—in the case of EPICS, transfer control protocol/internet protocol (TCP/IP) over Ethernet. At the top (if there can be said to be a "top" in a flat architecture) are the EPICS clients—servers for operator consoles, communications, archivers, physics and engineering applications, configuration databases and more. At SNS, commercial servers and commodity PCs configured for their specific functions and running the Linux operating system are used for these functions.

Below the clients are the distributed IOCs that communicate on the same network with the clients and among themselves and communicate to the equipment and equipment controllers being monitored and controlled. The IOCs for most equipment consist of a standard VME or VXI crate (housing) and a processor, which for SNS is a Power PC—MVME 2100 or MVME 5100 are the selected standards. These IOCs run EPICS under a widely-used commercial real-time operating system (kernel) called VxWorks©. (It is currently operating the Mars Rovers, for example.) A second type of IOC is the SoftIOC, which runs as a task along with other SoftIOCs under Linux in a PC-based SoftIOC server. The extensive use of SoftIOCs was an innovation at SNS.

The IOCs for most beam instrumentation are PC-based, and are dedicated to only one instrument each. These IOCs are referred to as network attached devices (NADs), because each device is directly attached to the network. They run EPICS under Windows© with a Labview© front end and appear to the system exactly like the other IOC types.

SNS uses five common ways of connecting IOCs to equipment controllers:

- directly from the IOC to a controller on the Ethernet
- directly from an input/output (I/O) module in the IOC (this case includes the NADS)
- using a fieldbus driven from the IOC
- from an I/O module in a PLC connected to the Ethernet
- using a fieldbus driven from a PLC connected to the Ethernet

These possibilities are all shown in Fig. 5.4-1, a high-level representation of the SNS architecture.

5.4.3 Distributed Systems

The IOCs and PLCs of the distributed systems that control individual subsystems (see the lower level in Fig. 5.4-1) were developed at the SNS partner laboratories following agreed standards. Software was committed to a configuration management software repository at the SNS site in Oak Ridge so that all software was loaded into the field processors from the local repository and therefore demonstrably compatible with the local software environment. This procedure worked well (its value was quickly evident whenever it was bypassed.) Altogether, the SNS controls distributed subsystem layer includes 462 IOCs, distributed as shown in Table 5.4-1.

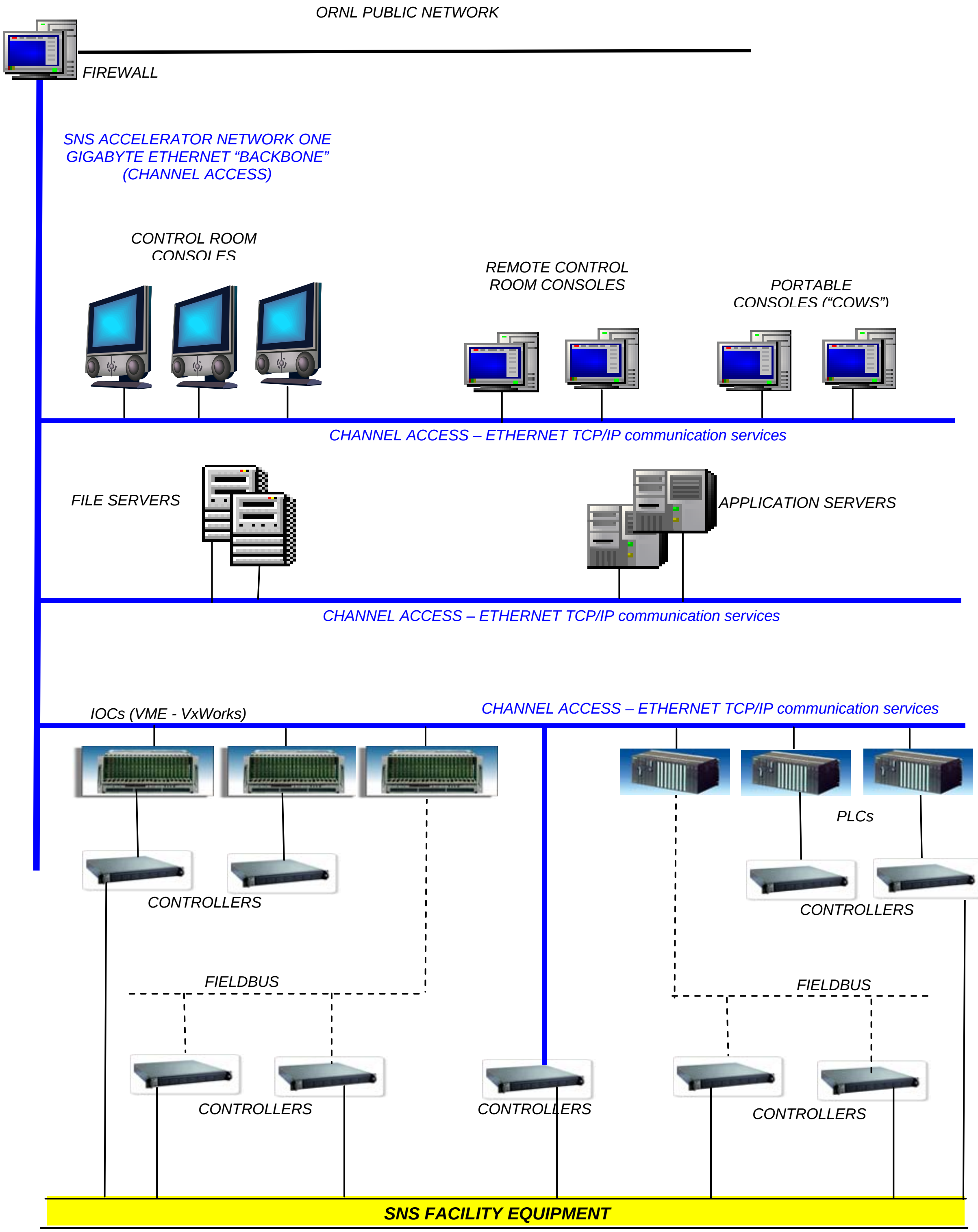


Fig. 5.4-1. SNS control system from 50,000 ft.

Table 5.4-1. IOC count

				VME/VXI VxWorks-Based IOCs				
	Vacuum	**RCCS**	**Power**	**HPRF**	**LLRF**	**Diagnostics**[a]	**Misc**[b]	**Total**
FE	**1**						**4**	**5**
MEBT			**1**		**2**			**3**
RFQ				**1**	**1**			**2**
DTL	**2**	**2**	**1**	**1**	**4**	**3**		**13**
CCL	**1**	**1**	**4**	**2**	**4**	**2**		**14**
SCL	**3**		**9**	**7**	**42**	**4**	**1**	**66**
HEBT	**1**		**1**			**2**	**2**	**6**
Ring	**1**		**7**	**1**	**5**	**4**	**8**	**26**
RTBT	**1**		**1**			**2**	**1**	**5**
ICS							**6**	**6**
							Total VME/VXI on accelerator domain	146
Cryo							**12**	**12**
Target							**3**	**3**
CF							**4**	**4**
PPS							**3**	**3**
							Total VME/VXI on other domains	22
Totals	**10**	**3**	**24**	**12**	**58**	**17**	**44**	168
						Linux-based “soft” IOCs	**46**	46
				Windows-based diagnostic IOCs (“NADs”)				
	BPMs	**BCMs**	**WS**	**LW**	**FBLM**	**Misc**		
Linac	**60**	**10**	**20**	**9**	**0**	**12**		**111**
HEBT	**35**	**5**	**6**	**0**	**2**	**0**		**48**
Ring	**45**	**2**	**1**	**0**	**8**	**1**		**57**
RTBT	**18**	**5**	**5**	**0**	**2**	**2**		**32**
								248
			Total number of IOCs					462

[a] BLMs and neutron detectors are packaged in VME crates

[b] Timing, MPS, water

Contributions from the partner laboratories were extensive. Teams at LBNL (for the ion source and front end systems), LANL (for the warm Linac and all the Linac RF systems) and BNL (for the ring and transfer lines) provided IOC and PLC hardware, software, and engineering displays for vacuum, cooling, RF, magnet power supply, and ancillary systems. Vacuum system controls for the SCL were provided by JLab. The cryogenic system controls—both for the CHL and for the superconducting linac (SCL) cryomodules—were developed by controls personnel at ORNL. Software and hardware for the NADs were developed by beam instrumentation teams at LANL, BNL, and ORNL, Distributed controls for the conventional facilities and the target subsystems were contracted to a commercial company (Sverdrup) that used the same tools, in particular EPICS, and followed the same standards and procedures, resulting in easily-integrated subsystems. The intimate integration of conventional and target controls with the accelerator and their implementation by industry were each successful SNS innovations.

It is difficult to establish the total number of I/O signals that are handled by these IOCs. It is difficult indeed even to know what to count. What is easily counted, and therefore what is generally quoted for

EPICS-based control systems, is the number of database records in the distributed EPICS database. SNS has ~395,000 such records. A reasonable rule-of-thumb estimate might be that each real signal or channel results in approximately 4–5 database records, resulting in an estimate for SNS of ~80,000 to ~100,000 I/O signals. As measured by process variables, database records, or IOCs, SNS has the largest installed EPICS-based control system in the world.

All of these channels are controlled and/or monitored from the CCR on more than 1000 available displays (screens). Many of these screens are intended primarily for subsystem experts. Figure 5.4-2 includes a small sample of available screens chosen from a variety of systems (linac, ring, RTBT) and subsystems (RF, power).

5.4.4 Global Systems

The distributed subsystem controls are knit together by the global systems that are common to all. In addition to the Control Room and the client servers, these include the communications infrastructure, a machine protection system (MPS) (developed at ORNL), and a timing and synchronization system (developed at BNL).

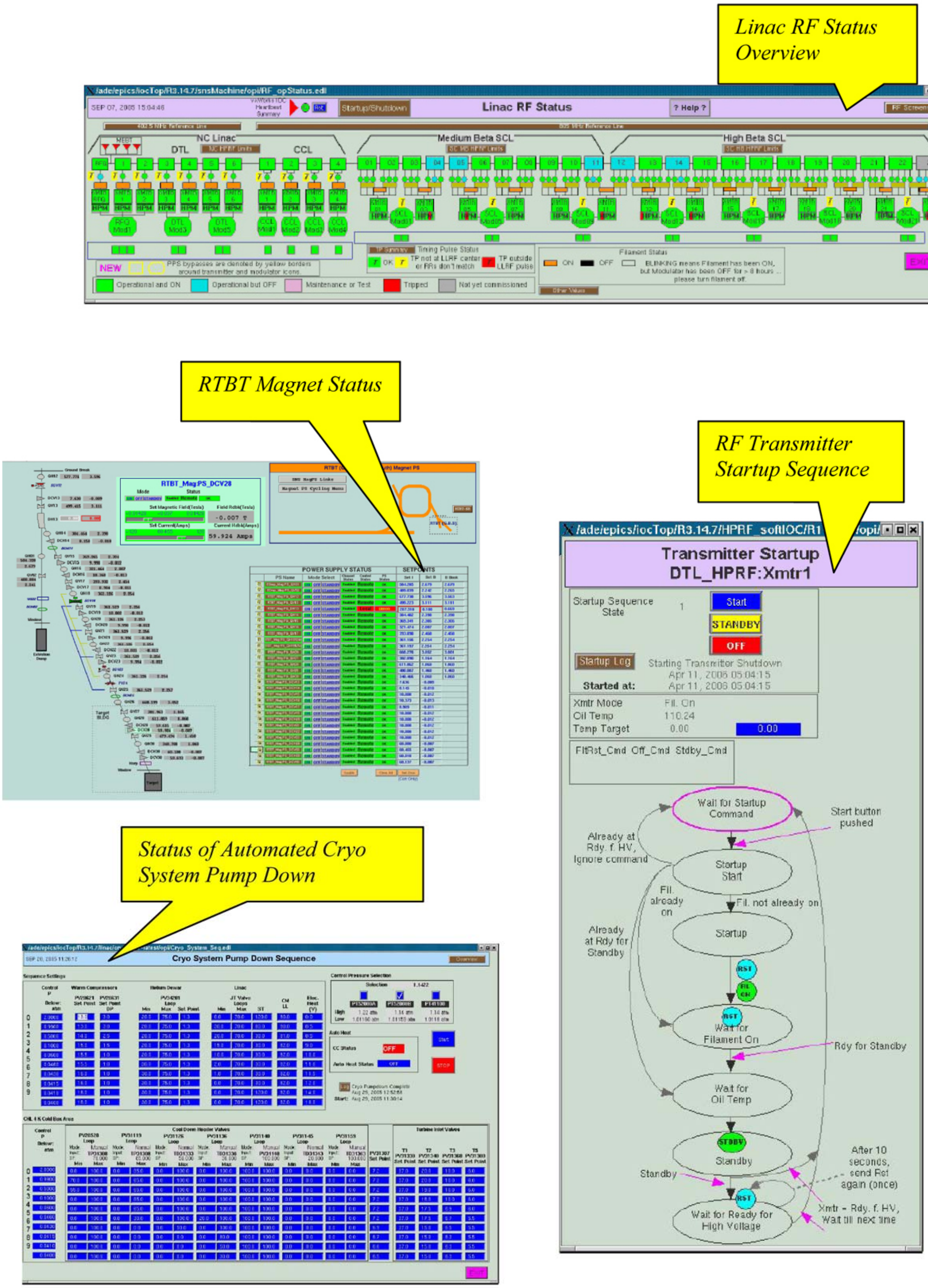
Servers, operator interfaces, Control Room. Operator access to the equipment on the distributed systems is through OPerator Interfaces (OPIs) or consoles. The CCR, located in the CLO, features 11 general purpose operator stations, 9 of which have 6 screens and 2 of which have 3, as well as a PPS station (see Fig. 5.4-3). In addition to the CCR, there are smaller control rooms in the CHL, the Central Utilities Building (CUB), and the Target Building. Finally, there are 17 portable “consoles on wheels” (COWs) that can be located wherever there is an accelerator network Ethernet port across the facility. Including these COWs, there are 30 OPIs altogether. All of these operator stations are functionally identical and can in principle be used to access any parameter in the system. Special software (Channel Access Security) is used to control who can do what from where and under what operating conditions.

In addition to the OPIs, there are 39 server-class control system computers running client applications in UNIX, Windows, and Mac Operating System environments. Many of these are located in the Central Equipment Room adjacent to the CCR. The servers and OPIs are listed in Table 5.4-2.

As an example of a server, the primary archive server is archiving an average of six gigabytes of data per day and has thus far stored 4.2 terabytes of archived accelerator data. These data are frequently referred to analyze machine behavior (and malfunctions) and can be accessed both from the control room(s) and/or remotely, using a web-based viewer.

Communications. The accelerator communications infrastructure is based upon a 1-gigabit fiber-optic Ethernet backbone. The fiber plant was installed using blown fiber technology, in which fiber is literally blown with a small air pump from source to destination through special pre-installed conduit. Savings are realized by initially installing only a small fiber overcapacity because additional fiber can be easily and economically installed (blown) later as required and where required (provided adequate conduit was installed). At the heart of the network are two redundant high-capacity Cisco™ switches with automatic fail-over for reliability. The backbone then goes to 17 mid-level switches located in communication rooms distributed about the site. From these the network extends to 108 edge switches located in equipment racks close to the IOCs, PLCs, smart controllers, and other technical equipment on the network.

The accelerator network is isolated from the SNS Office network by a firewall, and a strict IP registration protocol ensures that only recognized and authorized computers can attach to the network. A security plan is maintained and reviewed by ORNL information technology security personnel. Network traffic is constantly monitored, and on-line tools are available for traffic analysis and diagnosis. As low-power operation began, the network was operating safely below capacity.



Linac RF Status Overview

RTBT Magnet Status

RF Transmitter Startup Sequence

Status of Automated Cryo System Pump Down

Fig. 5.4-2. Sample of available screens from various distributed systems.

Fig. 5.4-3. Central Control Room.

Timing. The same fiber infrastructure used for controls communication is used also for the timing and machine protection systems. The timing system consists of two links that are distributed to all IOCs from a timing master IOC located in the ring service building. The event link distributes numbered events at predetermined times in each machine cycle. These events are shown in the timeline of Fig. 5.4-4. The event link is decoded at each IOC, each of which in turn produces triggers for local equipment after software programmable delays. In this way all activities are synchronized across the facility with a resolution of ~30 ns. The real-time data link (RTDL) is also distributed to most IOCs and carries, again for each machine cycle, information for decoding and use by the IOCs. Examples include the time-of-day, which allows acquired data to be time-stamped and/or correlated for archival purposes, the operating mode of the accelerator, and whether the last machine pulse was terminated normally (used by feed-forward learning algorithms).

Machine protection. The MPS is responsible for preventing beam-related damage to accelerator equipment. It does so by turning off the beam at the front end in the event of equipment failure, excessive beam loss, power supply trips, vacuum leaks, and many other conditions. There are a total of 923 inputs to this system, each of which results in beam turn-off in less than 20 μs. Inputs to this system are located in ORNL-designed MPS chassis distributed in equipment racks throughout the facility along with the IOCs. The chassis and their inputs are arranged in seven MPS chains corresponding to the seven geographically-defined operating modes of SNS, which in turn correspond to the seven possible places the beam can be stopped: MEBT beam stop, CCL dump, Linac dump, injection dump, ring (unextracted), extraction dump, and target. Table 5.4-3 shows the number of inputs in each of these chains. In each operating mode, all of the inputs up to and including that chain are active.

Table 5.4-2. Servers, OPIs, and IOCs

Domain	Admin	ACCL	Cryo	CF	Tgt	PPS	Total
			Servers				
Domain servers		**2**	**1**	**1**	**2**	**2**	**8**
Physics servers		**4**					**4**
Archive servers	**3**		**1**			**1**	**5**
Soft IOC servers		**5**	**1**				**6**
Administration[a]	**8**						**8**
Diagnostics servers[b]	**8**						**8**
							39
			Consoles (OPIs)				
Console OPIs		**12**	**5**	**3**	**3**		**23**
COWs		**14**			**3**		**17**
							30
			Input/Output Controllers				
IOCs (VxWorks)		**146**	**12**	**4**	**3**	**3**	**168**
Soft IOCs (Linux)		**39**	**7**				**46**
NADs (Windows)		**248**					**248**
							462

[a]DHCP/DNS (2), network monitoring (2), one-time password login (1), backup (1), relational DB (1), remote data (1),

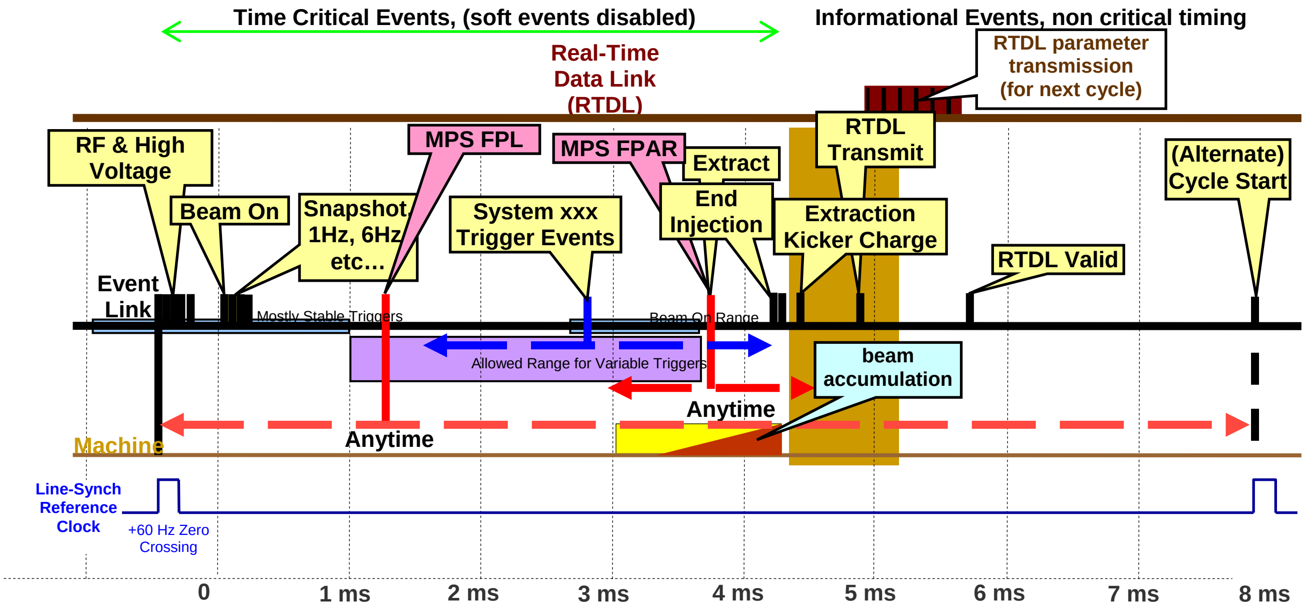


Fig. 5.4-4. Event timeline.

Table 5.4-3. MPS chassis count and inputs

	MEBT	CCL	LDmp	IDmp	Ring	EDmp	Tgt	
Chassis	7	21	28	7	30	6	6	**105**
PS	11	15	52	31	143	32	25	**309**
RF	11	26	98		8			**143**
BLM		62	120	39	69	16	24	**330**
Diag	5	33	2	7	2	2	4	**55**
Other	27	16	21	5	4	10	3	**86**
Total inputs	**54**	**152**	**293**	**82**	**226**	**60**	**56**	**923**

Each of these seven chains consists of two separate MPS fiber links. Inputs to the "latched" chain are latched when activated, holding the accelerator off until operator intervention. This would be used, for example, in the case of a power supply failure. Inputs to the auto-reset chain are automatically reset before the next beam pulse. In the case of beam losses detected by the BLMs, this has the effect of shortening beam pulses that would otherwise result in excessive spill and allowing continued tuning while minimizing component activation and serving an ALARA function. An example screen showing BLM data for the last section of the SCL and the HEBT along with corresponding MPS limits (set points) is shown in Fig. 5.4-5.

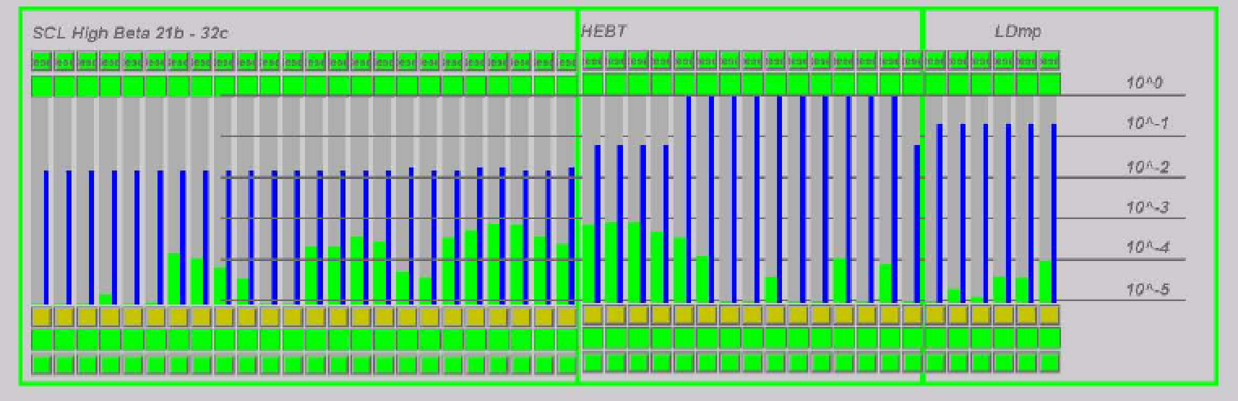


Fig. 5.4-5. Partial BLM status display with MPS limits.

<u>Lessons Learned:</u> Modern high beam power accelerators such as the SNS require a functional control system to commission and efficiently and safely. The SNS control system was ready and tested on time to support each of the series of commissioning runs, and thereby made an essential contribution to the success of the project as a whole. Below are listed a few brief comments on lessons learned, both positive and negative.

- The post-CDR decision to elevate Controls to a level 2 WBS greatly facilitated interactions with the partner laboratories. Controlling the money is essential to successful standardization, even though that "stick" never had to be wielded in practice.
- The early decision to use EPICS everywhere was critical to success.
- The early decision to use standardized PLCs everywhere, and to impose that choice even on vendors, contributed to successful integration.
- The use of a local "rack factory" greatly facilitated controls installation. All controls racks were ready on schedule. (This approach was suggested by the DOE Review Committee.)
- The original cost estimates for controls – based primarily on "rules-of-thumb" – came very close to the mark.

- The approach of integrating controls team members with "customer" engineering groups to improve the interface was extremely successful where it was accepted. Integrating controls test plans with those of the controlled subsystems was also successful and efficient where accepted.
- Notwithstanding the failings of the naming convention, SNS did better on standardized names than most similar facilities. As applied to lattice devices, they are a total success.
- The approach of integrating the target and conventional facilities into the accelerator controls network and to extend the use of EPICS to these systems, while not without issues, has been a success and should be pursued in future projects.
- The use of industry to provide complete EPICS-based control systems for some subsystems while following SNS standards has proven a successful approach to address staffing issues. Close oversight is required.
- Not enough controls effort was placed on Oracle Database activities early in the project. At least two Controls specialists should have been assigned to this task at the outset in order for maximum benefit to be realized. Other groups – Physics, Diagnostics and Operations – did better.
- The original plan to have an increasing controls staff to support early (pre) operations should have been followed. The entire group effort was required to meet installation goals, and adequate support was not available to (pre)operations. The areas that suffered most were production of suitable operator-oriented screens with summary displays (as opposed to screens designed for design and maintenance engineers) and deployment of a useful alarm handler.
- The first approved standard for SNS controls was the device and signal naming standard. In principle the standard works well, but there was a failure to communicate the ideas behind the standard and the result, in spite of good intentions, was many incorrect names. Enforcing a naming standard requires constant oversight and effort which the SNS Controls Group Leader failed to provide.
- The SNS control system incorporates more PLCs than is traditionally the case in accelerator control systems. Responsibility for these PLCs – both hardware and software – was ambiguous and varied across the systems. Better would have been to assign the scope for PLCs and traditional instrumentation unambiguously to the controls WBS and then to staff accordingly.

5.4.5 Summary

The Integrated Control System was a collaborative effort including significant contributions from LBNL, LANL, BNL, JLab and ORNL. The control system was ready for each pre-commissioning ARR as installation and commissioning of each section of the accelerator progressed. The final Level 2 Milestone – "Global Controls Ready for Target" – was met on schedule.

5.5 CONVENTIONAL FACILITIES

The SNS site is located atop Chestnut Ridge, ~1.75 miles (2.8 km) northeast from the center of ORNL and is accessible by Chestnut Ridge Road across from the 7000 Area at ORNL. The facilities include the Front-End Building, Klystron Building, Linear Accelerator Tunnel, Central Helium Liquefier (CHL) Building, RF Facility, HEBT, Ring, and RTBT Tunnels, Ring Service Building, RTBT Service Building, Target Building, Beam Dumps, CLO, Central Cooling Tower, CUB, Central Exhaust Facility, and are shown in Fig. 5.5-1.

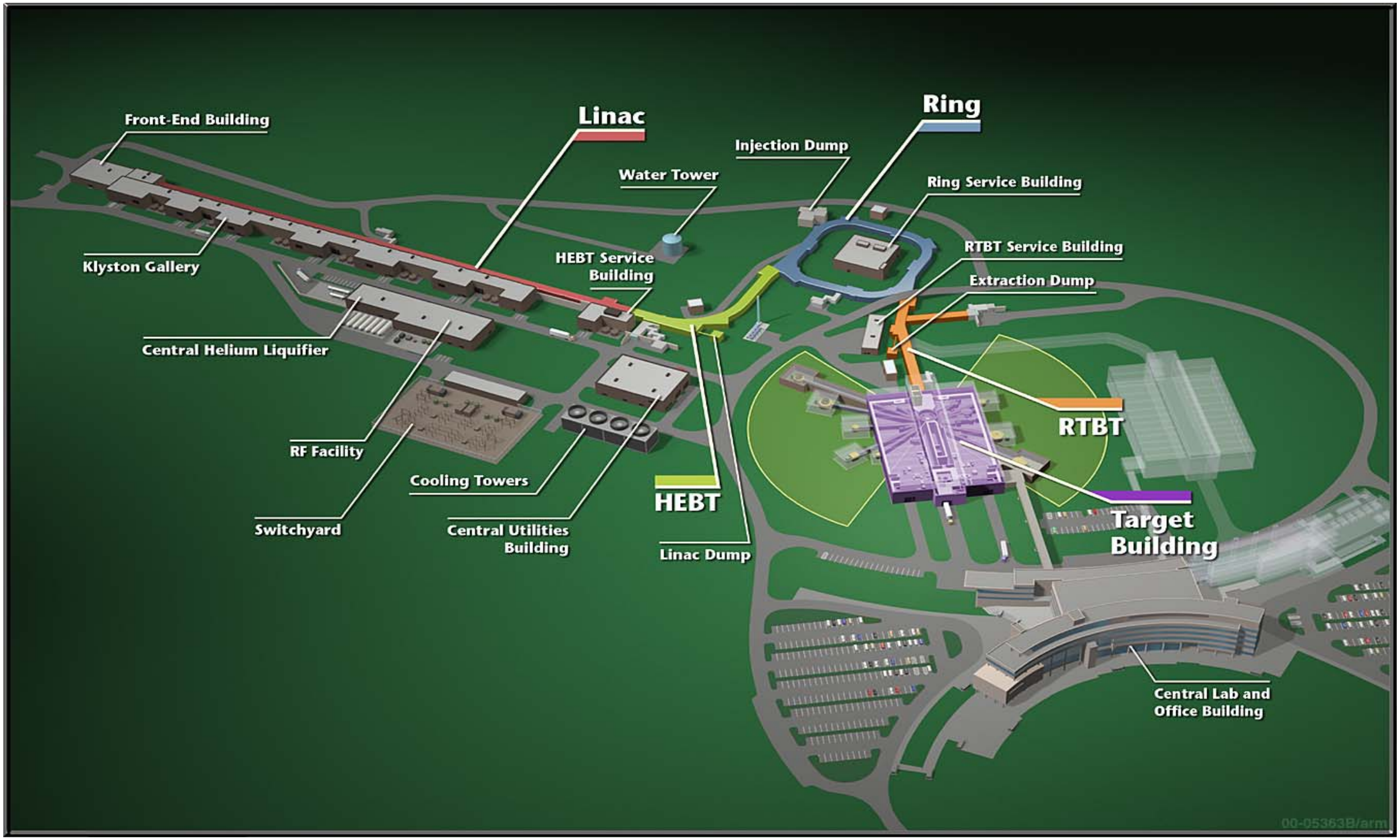


Fig. 5.5-1. Spallation Neutron Source site facilities.

5.5.1 Front-End Building

The Front End Building (Fig. 5.5-2) is an above grade, steel frame, structure with an interior clear height of approximately 12 ft. Its intended use is to house the accelerator Ion Source, low-energy beam transport line (LEBT), RFQ, MEBT and the first 30 ft of the DTL. To accommodate these components and related support equipment, the building consists of 15,562 ft^2. The floor area is 12,337 $ft^2$and the mezzanine 3,225 ft^2. Floor elevation is at the same level as the Linac Tunnel with the beam centerline elevation at 50 in. above finish floor. The building height is 31 ft–8 in. Normal access to the Linac Tunnel is through the Front End Building and PPS Room. However, for proper smoke removal and confinement ventilation, a wall separates the Front End from the Linac tunnel. The final wall closure contains a Lexan® window for viewing of the Linac tunnel. Interior walls are reinforced concrete block or gypsum board over metal studs. The concrete floor slab is constructed sufficiently flat to accommodate forklift traffic for moving equipment.

Interior access to the Klystron Building is provided by way of an interior stair located on the east wall. Movement of material and equipment between the Front End and Klystron Building is achieved by means of a vertical equipment lift adjacent to the stair. The interior stair continues up to serve a heating, ventilation, and air-conditioning (HVAC) equipment mezzanine located above the DTL. A second means of egress from this mezzanine is provided to the north at grade.

The exterior skin of the Front End Building is a metal panel insulated with thermal insulation supported by the steel structure. The roof is a composite built-up roof with rigid insulation over metal deck.

Equipment access is provided by means of an overhead truck door. An access road and parking apron are provided and sized sufficiently to allow for truck turnaround. Personnel access doors are provided as required by code. Proximity badge readers control entry into the Front End Building. Other exterior doors leading to service rooms are keyed entry or exit only. In all cases, installation of such door control devices is done to maintain a “Fail-Safe” building environment. Meaning that in event of power loss or emergency, all building occupants are able to exit freely without special keys or knowledge to operate door hardware as defined by the building code.

5.5.2 Linear Accelerator Tunnel

The Linear Accelerator Tunnel houses the majority of the linear accelerator components (Fig. 5.5-3 shows an aerial view of the accelerator facilities). These components consist of the DTL, CCL, and the superconducting frequency (SRF) medium and high beta modules. The tunnel itself is constructed entirely of reinforced concrete. Interior tunnel dimensions are 14 ft wide and 10 ft high. Beam height is 50 in. above finish floor, and all necessary utilities, ductwork, and other equipment are routed overhead. The tunnel consists of a floor area of 14,711 ft^2. The Linac tunnel egress consists of 704 ft^2. A draft curtain is provided at the Front End/Linac interface point, to limit the movement of smoke in the event of a fire. The depth of this curtain is estimated to be a minimum of 18 in. Tunnel floor elevation is the same as the Front End Building, and a drainage trough is located along the inside of the beam line against the tunnel wall. This drainage trough is to collect any ground water seepage that may enter the tunnel as well as leakage from beam line equipment.

The interior of the tunnel walls is painted a light color. An epoxy system suitable for decontamination has been applied to the floors, and a semigloss acrylic enamel paint has been applied to the walls and ceiling surfaces. An embedded vertical Unistrut® channel from floor to ceiling is provided along the south wall of the tunnel and the ceiling for greater ease of installing carrier arms and attachment points of mounted equipment and cable trays. Oxygen Deficient Hazard (ODH) vent shafts have been provided in the Superconductor portion of the tunnel. Such vent shafts also serve a dual function in removal of smoke from the tunnel.

Fig. 5.5-2. Eastward view of the Front-End Building.

Fig. 5.5-3. Aerial view of the accelerator facilities.

A single vertical alignment pipe through the roof of the Linac tunnel has been provided. A second is located through the mezzanine portion of the Front End Building that is positioned above the tunnel section. There are four additional pipe chases 24 in. and 18 in. (1–24 in., 3–18 in.) in diameter for the LHe transfer lines between the CHL Building and the tunnel.

Access to the tunnel for both personnel and heavy equipment is through the Front End Building on the west and a large equipment plug and personnel door located to the east off the HEBT Tunnel. Soil shielding is estimated to be a minimum of 17 ft thick around the Linac tunnel and when combined with the fixed concrete shielding is sufficient to protect the surrounding buildings and its occupants. An exit tunnel and stair are provided near the center point of the Linac tunnel, which will discharge to a building enclosure at grade.

The amount of soil shielding over the roof of the Linac tunnel increases rapidly from a minimal amount adjacent to the Front End Building to its normal thickness of 17 ft for the remainder of the tunnel. Perforated drain lines are provided along the tunnel foundation to intercept groundwater, which permits monitoring for potential contamination. A spray waterproofing was applied directly to the tunnel exterior as a final waterproof barrier. A multilayered waterproofing system was buried near the surface of the berm to intercept surface water and divert it away from the tunnel before it percolates into the soil.

Actual entry into the Linac is controlled through the PPS room. The doors to and from this room are interlocked and are monitored by SNS personnel in the control room. In the event of a power loss or emergency, these doors will remain locked, but all occupants are able to exit freely without special keys or knowledge to operate door hardware as defined by the building code.

5.5.3 Klystron Building

The Klystron Building and the HEBT Service Building (Fig. 5.5.4) house the 402.5-MHz Klystrons, 805-MHz Klystrons, waveguides and associated water loads, power supplies, electronics, as well as other required instrumentation supporting the Linac. The HEBT Service Building is located on the east end of the Klystron Building (Figs. 5.5-4 and 5.5-5) and designs of the buildings are the same. They are positioned 15 ft-10 in. clear from the exterior face of the Linac Tunnel with finish floor set at 9 ft-0 in. above the Front End Building and Linac Tunnel floors. The common rear wall is also designed to serve as a concrete retaining wall to support the earth shielding that surrounds the Linac Tunnel. This retaining wall extends approximately 25 ft-6 in. above finish floor elevation with a waterproofing membrane applied to the exterior face. The balance of the buildings is a steel frame structure with an interior clear height of approximately 22 ft-6 in. The first 15 ft-6 in. is reserved for technical equipment, the remaining approximate 7 ft-0 in. is for Conventional Facilities building infrastructure of mechanical, electrical and structural systems. The floor area is 49,171 ft^2, 48,787 ft^2 on Level 1 and 384 ft^2 on Level 2. The building height is 25 ft-6 in. Utility chases for routing of mechanical system piping, electrical cabling, and the RF waveguides has been installed between the Klystron Building and Linac Tunnel. There are approximately 81 such chases 24 in. and 30 in. in diameter The pipe material is of fiberglass reinforced plastic. A stair located on the west end of the building provides direct access to the Front End Building. Material and equipment movement is provided by means of an adjacent vertical lift. The south face of the Klystron Building is provided with several equipment access doors to accommodate movement of equipment into and out of the building. Deionized (DI) water is provided for the equipment in the building by DI treatment facilities in large utility rooms along the south face of the Klystron Building. These utility rooms are sized to accommodate not only the DI water equipment but also HVAC system and electrical motor control centers. Electrical switchgear and power supplies serving the building loads and the equipment loads are located on the exterior to the building.

The interior of the Klystron Building is separated into two sections to limit the potential financial loss due to fire by a 2-h fire rated wall. The interior concrete floor slab has been constructed to accommodate forklift and air pallet traffic for moving equipment. Based on site and grading conditions, the exterior walls are exposed concrete retaining walls with a medium sandblast finish and applied water repellant, or a flat or corrugated insulated metal panel. The roof is standard asphalt-ply built-up roofing with gravel ballast on rigid insulation boards, over an unfilled metal deck.

Fig. 5.5-4. Aerial view of the RF Building (left), the Klystron Service Building, and Klystron Building (right).

Fig. 5.5-5. Westward view of the Klystron Building.

Personnel proximity badge readers control entry. Other exterior doors leading into the utility rooms require key entry. In all cases, installation of such door control devices is done to maintain a “Fail-Safe” building environment so in the event of an emergency, all building occupants are able to exit freely.

5.5.4 Central Helium Liquefier Building

The CHL Building (Figs. 5.5-6 and 5.5-7) is an above grade, steel frame structure with a sunken area and mezzanine. The building floor area is 13.978 ft^2, 12, 641 ft^2 on the main level and 1,337 ft^{2}on the mezzanine. The building height is 34 ft-3 in. It’s intended to house the equipment that provides super fluid helium to the cryogenic components located in the Linac tunnel. To accomplish this, the building houses two refrigeration systems. The first refrigerator cools the helium to 4.5K and the second from there to 2.1K. The adjoining compressor room houses the helium compressors for the refrigerators, the vacuum pumps, the Cryogenic Test Facility (CTF), and all associated mechanical and electrical systems. Although hearing protection is required in the Compressor room it is isolated from adjoining spaces by sound absorbing walls capable of reducing the high intensity noise in the room to 75dB. Exterior louvers are also designed as sound baffles. Trenches are provided in the floor of the compressor room to house the helium lines and tower water supply and return piping.

The floor elevation is 7 ft-0 in. above the Linac Tunnel floor, and the sunken area is 8 ft-6 in. below the building floor. A grated walking surface is located over the sunken area. Interior walls are of gypsum board over metal studs. The concrete floor slab is constructed sufficiently flat to accommodate forklift and air pallet traffic for moving equipment.

Interior flooring is sealed concrete, with vinyl flooring in the office and toilet areas and painted gypsum walls. Additionally, the office/control area has sound-absorbent material in the walls and above the ceiling to mitigate noise generated by adjoining equipment. The underside of the roof structure is exposed and unfinished.

An interior stair serves the Control room mezzanine that also contains an open area for electrical equipment. A second means of egress from this mezzanine is also provided. Overhead truck doors and loading areas provide equipment access. Adjoining outdoor areas are provided for helium storage tanks and processing equipment. The Compressor room is served by a 7 1/2-ton overhead crane with a minimum hook height of 21 ft-0 in. A 500-lb Jib crane is located in the loading dock area.

The exterior skin of the CHL Building is a metal panel system with thermal insulation supported by steel tube columns and horizontal girts. The roof is a composite built-up roof over rigid insulation on an unfilled metal deck. Access to the roof is by an internal roof ladder and through a hatch.

Personnel access doors are provided as required by code or operational needs.

Liquid nitrogen and helium Dewar tanks are located on the exterior of the CHL Building at the main floor elevation. A portion of the Dewar tank projects into the Cold Box portion of the CHL, so that controls, instrumentation, and points of connections associated with the Dewar tank, are in an interior environment. Access is provided for tube trailers to service the Dewars.

5.5.5 RF Facility

The RF Building (Figs. 5.5-4 and 5.5-7) is used to test the 402.5-MHz and 805-MHz Klystrons, RF-power components, and warm accelerating structures. It also supplies power to the test cave in the RF facility. Modulator repairs are performed in this area in addition to RF testing and development. Klystron test areas, an RF test lab, electrical and instrumentation shops, storage area, and a test cave are areas also provided.

The RF Building is an above grade steel frame structure. The building consists of 13,436 ft^2, 12,176 ft^2 on the main level, and 1,260 on the mezzanine level. The building height is 34 ft-3 in. The floor of the building is sealed concrete, and the roof underside is exposed and unfinished. Vinyl flooring and standard lay-in acoustical ceiling tiles are provided in the Tech and Lab areas with a ceiling height of 10 ft-0 in. Appropriate electrical power is provided to office and bench locations.

Fig. 5.5-6. Eastward view of the CHL Building.

The exterior skin of the RF Building is a metal panel system with thermal insulation supported by steel tube columns and horizontal girts. The roof is a composite built-up roof over rigid insulation on an unfilled metal deck. Access is from the roof of the CHL Building.

Personnel access doors are provided as required by code or operational needs.

5.5.6 SRF Buildings

The SRF Test facility provides shop and office space for the cryogenic and RF groups. A 12,317-ft^2 one-story building extension, roughly 109 ft × 113 ft is located on the east side of the existing structure.

The building is an above grade steel frame structure the same height as the RF Building. The floor of the building is sealed concrete, while the underside of the roof is exposed and unfinished. Vinyl flooring and standard lay-in acoustical ceiling tiles are provided in the rest room area only. Appropriate electrical and mechanical utilities to support cavity F&D and cryomodule maintenance are provided.

The exterior skin of the RF Building is a metal panel system with thermal insulation. The roof is a metal panel system with thermal insulation. Access is from the roof of the RF Building.

Roll-up and personnel doors are located between the RF and SRF Buildings and to the exterior as required by code and operational needs.

Fig. 5.5-7. Aerial view of the CHL and RF facilities.

5.5.7 RTBT Service Building

The RTBT Service Building (Figs. 5.5-8 and 5.5-9) is an above grade, steel frame, structure with an interior clear height of approximately 16 ft. The height of the building is 22 ft-1 in. and consists of 2,834 ft^2. The exterior skin of the building is constructed of insulated metal panels over steel frame. The roof is a composite built-up roof over rigid insulation on a corrugated metal deck. Equipment access is from an adjacent parking apron in front of the building. The apron is located and sized to accommodate general access to the building. Personnel access doors are provided as required by code and sized sufficiently to accommodate the movement of equipment within the building.

5.5.8 HEBT, Ring, and RTBT Tunnels

The below grade tunnels are constructed entirely of concrete (Fig. 5.5-10). Interior tunnel dimensions were developed based on the required beam height of approximately 50 in. above finish floor as well as accommodating necessary utilities and other equipment being routed overhead. Included in this equipment is a paired monorail to be used throughout the tunnels to maintain and remove equipment and draft curtains to limit the movement of smoke in the event of a fire. One paired monorail travels in the south segment of the Ring Tunnel, and a second paired monorail traverses through the HEBT, Ring, and RTBT Tunnels. The 12.5- and 15-ton cranes are to be a single girder, under hung traveling cranes with a span of approximately 10 ft-8 in. and a hook height of 8 in.-7 1/2 in. Runway length is approximately 1400 ft long. Crane bridge, trolley, and hoist drive controls are to be variable speed with creep speed capability for precise locating of sensitive equipment. The cranes are to be used for transporting collimators, magnets, and other beam line instruments. The Ring Tunnel has a cross-sectional area that measures 17 ft wide by 13 ft high and has a circumference of 248 m.

Fig. 5.5-8. Aerial view of the RTBT Service Building. The RTBT Service Building is on the left in front of the Target Building.

Fig. 5.5-9. Westward view of the RTBT Service Building.

A drainage trough is located to the inside of the beam line against the tunnel wall. This drainage trough is used to take away any ground water seepage, which may enter the tunnel as well as leakage from beam line equipment. Such is collected in the drain trough and manually removed.

The HEBT tunnel has a height of 17 ft-0 in. and consists of 12,765 ft^2. The height of the RTBT Tunnel is 15 ft-3 in. and consists of 8,341 ft^2. The Ring Tunnel consists of 18,153 ft^2. Access to the tunnels is through large equipment plug doors and adjacent personnel access-ways. These accesses are adequately shielded and located per the System Requirements Document (SRD). Soil shielding is estimated to be a minimum of 17 ft thick around the tunnels and when combined with the fixed concrete shielding is sufficient to protect the surrounding service buildings and its occupants. Perforated drain lines are provided along the tunnels foundation to intercept ground water that might otherwise seep into the interior of the tunnel. A rubberized-asphalt sheet waterproofing membrane is provided around the tunnels. Due to the nature of the existing soil, which exerts a slight horizontal hydrostatic pressure when water is present in the soil, a drainage panel sheet in lieu of a protection board has been applied as a cover to the waterproof membrane. The tunnel roofs are constructed of reinforced concrete.

The interior of the tunnel walls is painted a light color. An epoxy system suitable for decontamination has been applied to the floors, and a semi-gloss acrylic enamel paint has been applied to the walls and ceiling surfaces.

5.5.9 Ring Service Building

The Ring Service Building (Figs. 5.5-11 and 5.5-12) is an above grade, steel frame, structure with an interior clear height of approximately 17 ft-10 in. It houses the RF and instrument control rooms. The exterior skin of the building is constructed of insulated metal panels over steel studs. The roof is a composite built-up over rigid insulation and metal corrugated deck.

Soil and fixed shielding between the Ring Service Building and the adjacent tunnels are sufficient to appropriately limit the radiation in the Ring Service Building. Conduit banks are provided from the Ring Service Building to two quadrants of the accumulator ring. The height of the building is 26 ft-2 in. and consists of 16,344 ft^2, 3,761 ft^2 on Level 2, 10,783 ft^2 on Level 3, and 1,800 ft^2 on the mezzanine level. The roof is a composite built-up roof over rigid insulation on a metal deck.

Equipment access is provided by means of an overhead truck door. An access road and parking apron is located and sized sufficiently to allow for truck turnaround. Personnel access doors are provided as required by code. The Ring Pump Building contains the pumping and heat exchange equipment for the separate ring magnets and collimator cooling water loops and is positioned as a basement below the Ring Service Building. Construction of the pump building exterior walls, floor, and floor/ceiling assembly is of concrete.

Personnel access is by exterior stairs at the Ring Service Building. A floor sidewalk hatch is provided for vertical transport of equipment. In the Instrumentation Room of the Ring Service Building, a mezzanine for placement of electrical equipment is also provided.

The Pulse Forming Network Building is an extension of the Ring Service Building, and the interior walls of this building are clad in metal and also separated from the Ring Service Building.

Perforated drain lines are provided along the foundation to intercept ground water that might otherwise seep into the interior. A waterproof membrane is provided on the outside of the walls to further mitigate water intrusion from the earth shielding.

5.5.10 Target Building

The Target Building is an above grade, steel frame, structure with an interior clear height which allows for a 30-ton bridge crane with a clear hook height of 30 ft. Its intended uses are to support the neutron scattering research programs by providing the experiment facilities for the scattering instruments; meeting their space and utility requirements; providing proton beam line shielding and a Target Service Bay complex used for the target systems; and housing the electrical, cooling, waste, and HVAC systems used to support the proton target, neutron moderators, and experimental facilities in an appropriately shielded and serviceable environment. To accommodate these components and related support equipment, a floor area of approximately 65,000 ft^2 is provided at the Instrument Level, 40,000 ft^2 is provided at the Basement Level, and 14,000 ft^2 is provided at the High Bay. The floor elevations are +76 ft-11 in. at the Basement Level, +96 ft-11 in. at the Instrument Level, and +128 ft-11 in. at the High Bay, with the beam centerline elevation at approximately 78 in. above the Instrument Level floor elevation. A Mezzanine Level at elevation +113 ft-3 in. connects to the pedestrian bridge structure from the CLO. It also provides an Observation Area and a perimeter walkway connecting any future Lab/Office module construction above the individual instruments. A Truss Level walkway and platform system at elevation +138 ft-9 in. provides space for placement of 10 air handling units to service the facility. A 50-ton bridge services the high bay for target and monolith related maintenance activities.

A number of CECs are an essential part of the Target Building. The CECs function to prevent exposure of personnel to mercury vapor under off-normal and accident conditions including seismic events and fires. CECs include robust fire barriers around the mercury source, a robust crane, robust fire protection systems, confinement of the mercury, and robust ventilation systems.

Fig. 5.5-10. HEBT, Ring, and RTBT tunnels.

Fig. 5.5-11. Aerial view of the Ring Service Building.

Fig. 5.5-12. Southward view of the Ring Service Building.

The SNS Final Safety Assessment Document for Neutron Facilities concluded that structures, systems, and components (SSC) of the Target Building associated with preventing potential post–seismic fires from allowing the release of mercury to the public must be designed as Performance Category 3 (PC-3). One such element is the firewall around the Target Service Bay. Even though many of the building's other structural components do not have a PC-3 level safety function, to ensure that their collapse would not adversely affect the safety functions of other, truly PC-3 SSCs, these structural components were designed such that these would not collapse when subjected to a PC-3 level earthquake. The Target Building is PC-2 for wind/tornado because a fire is not a credible post-tornado event. The Target Building is a large (approximately 200 ft x 290 ft in plan and about 98 ft tall) reinforced concrete and steel structure with a 5 ft thick reinforced concrete foundation mat supported by 914 drilled piles (11 ¾ inch outer diameter concrete filled steel pipes) that reaches the bedrock at about 135 ft below the soil surface (Fig. 5.5-13).

The design of the Target Building started in 1999. At that time, the primary DOE document that provided the requirements for natural phenomena design was DOE-STD-1020-94 (with Supplement 1). The structural analysis and design included dead and live loads, crane loads, and wind and snow loads. Wind design was in accordance with ASCE 7-95, and is based on a wind speed of 96 mph with exposure "C" and an importance factor of 1.07. Snow loads are per ASCE 7-95. Seismic demands were determined per site specific seismic response spectra for both PC-2 and PC-3 structures. The steel and concrete design and construction included requirements from those industry's nuclear codes, AISC-N690 and ACI 349, respectively. For more information regarding the concrete and steel codes, see SNS document 102040000-QA0002, "Recommended Quality Assurance Requirements Relative to Structural Design and the Selective Use of ACI 349 and AISC N690 on Design and Construction of the SNS Target Building." The analytical methods used to determine the seismic response and member demands of the Target Building are in accordance with ASCE 4-98, "Seismic Analysis of Safety-related Nuclear Structures and Commentary. DOE-STD-1020 required that the design basis seismic loads for a PC-3 SSC be determined considering the effects of soil-structure-interaction (SSI). It also required that an independent peer review be performed to evaluate the seismic design adequacy of the PC-3 structure. A summary of the Target Building structural design is described in more detail in document number 1080700-DA-0004-R0 entitled "SNS Target Building Structural Design Report".

The seismic design was also reviewed by DOE personnel who reviewed the Preliminary Safety Analysis Report. DOE-HQ personnel raised the question as to whether the Target Building would meet more current seismic hazard methodologies, namely USGS, which is used in IBC. This concern was resolved by means of a Ruggedness Assessment calculation (DAC 108030700-TD005), which concluded that the seismic design is conservative, and would meet USGS seismic methodologies.

Personnel can access the Target Station at the Basement Level through the east elevator/stair tower, at the Instrument Level through a lobby and the north stair tower, and at the Mezzanine Level via the bridge connection from the Central Lab and Office Building.

Interior walls are reinforced, painted concrete block, reinforced cast-in-place concrete, or standard metal stud and drywall construction. The latter will generally be located around areas not subjected to forklift or air pallet traffic. The concrete floor slab is constructed sufficiently flat with a hard, smooth finish to accommodate forklift and air pallet traffic for moving equipment between the two main areas of the Instrument Level. Figures 5.5-14 and 5.5-15 show the Target Building during installation of the target monolith and the hot cell.

The exterior skin of the building is constructed of insulated metal panels with moderate articulation in the form of reveals and profiles (Fig. 5.5-16). The window system is prefinished, extruded aluminum with insulated glazing panels, located at the upper section of the Instrument Level wall. Louvers are located at the upper section of the High Bay wall. The roof is a gravel ballasted built-up roof system with a 20-year warranty.

Equipment access is provided by means of three insulated steel overhead truck doors, one at the Basement Level and two at the Instrument Level. Personnel access doors are provided at all three overhead doors, as required by code. These doors and frames are prefinished extruded aluminum or insulated hollow metal assemblies. Figure 5.5-17 shows the completed Target Building; Fig. 5.5-18 shows the interior of the completed building with construction of the first four SNS instruments.

Access roads are provided to both the Basement and Instrument Levels at the overhead door locations. Parking is available in a lot located to the northeast.

Fig. 5.5-13 Target Building construction--getting ready for concrete pilings.

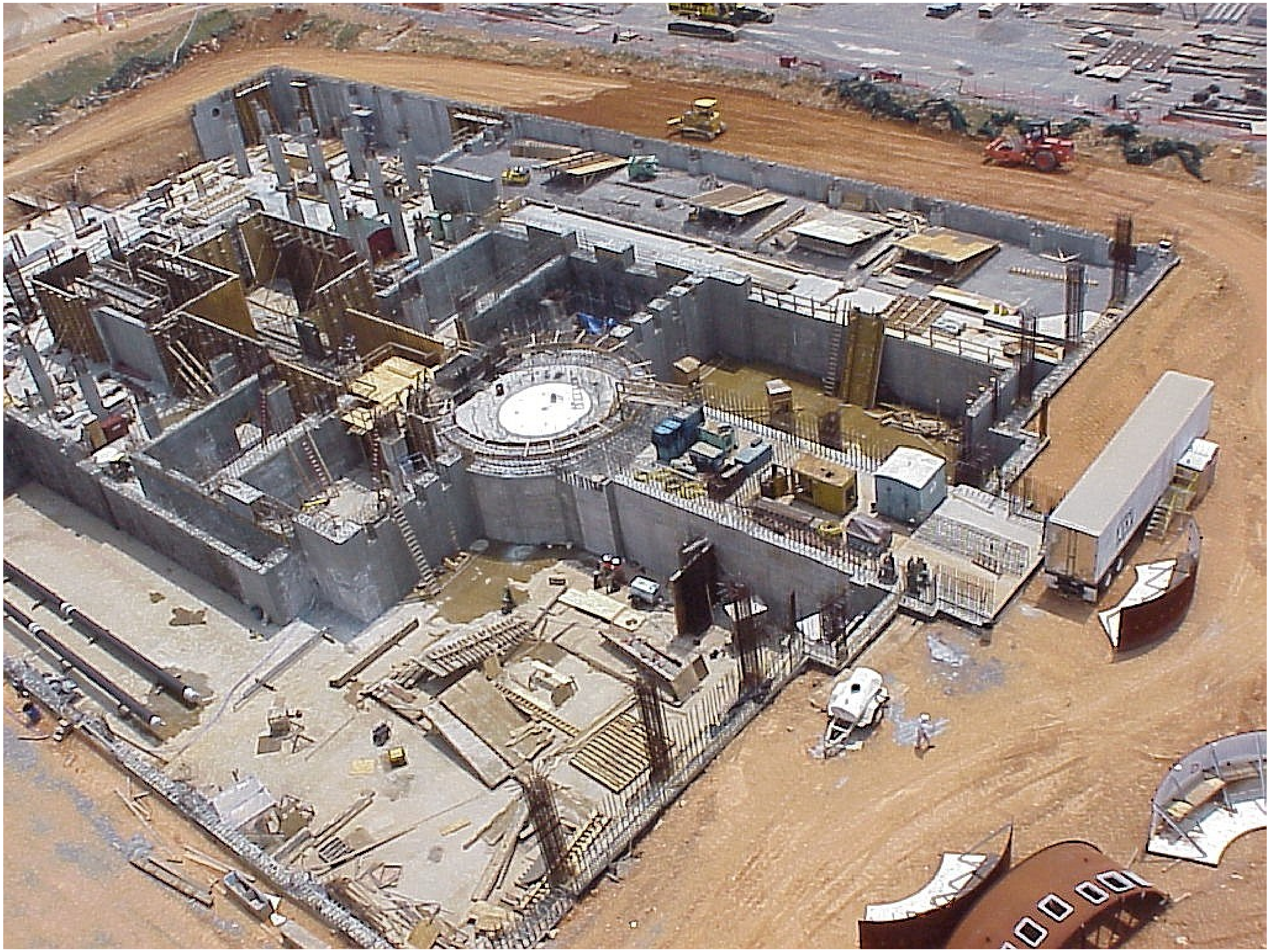


Fig. 5.5-14. Target Building construction as the target monolith is installed.

Fig. 5.5-15. Target Building construction as the target monolith and surrounding structure are installed.

Fig. 5.5-16. Target Building and Backscattering Spectrometer Building construction.

Fig. 5.5-17. Completed Target Building

Fig. 5.5-18. Interior of the completed Target Building showing construction of the first four instruments.

Fig. 5.5-19. Northward view of the completed Target Building.

5.5.11 Beam Dumps

The Ring Injection Beam Dump Building (Fig. 5.5-20) houses the beam dump target and its shielding, and the mechanical, electrical and utility systems, in an appropriate serviceable environment. The service areas are located at grade level, adjacent to the below grade Beam Stop Pit. The Linac and Extraction Beam Dump Buildings are passive dumps housing only the beam dump target and shielding in a Beam Stop Pit similar to the vault described below for the Injection Beam Dump. No mechanical, electrical, or utility systems or the space for these systems is provided for the Linac and the Extraction Beam Dumps.

The Beam Stop Pit is a below grade vault constructed of 2-ft-thick reinforced cast-in-place concrete walls, surrounding the metal shielding of the dump target. The Beam Stop Pit extends approximately 34 ft below finished grade and has an area of ±360 ft^2. There is a 3-ft-thick concrete ceiling on the pit, with a 6-ft^2 access hatch. The Ring Injection Dump has a Dump Vault room above the Beam Stop Pit, which has a 6- ft by 9-ft roof hatch that provides crane access to the hatch in the ceiling of the Beam Stop Pit.

The Mechanical/Electrical Room, for the Ring Injection Dump, is constructed of a steel frame covered by a preformed metal wall system and concrete retaining walls where the finish grade is above the floor level. A pair of hollow metal service doors and a single hollow metal door provides access from the exterior. The floor is concrete with a hard, smooth, liquid tight finish system. An air lock with 5-ft-wide doors is provided between the Mechanical/Electrical Room and the adjacent Dump Vault room and the Utility Vault.

The Utility Vault, for the Ring Injection Dump, is enclosed with 30-in.-thick concrete shield walls. The concrete floor is sloped to facilitate detection and clean up of spills and is covered with a stainless steel liner that turns up 12 in. onto the base of the wall. A 9 ½ ft by 12 ½ ft by 11 ¼ ft-deep Tank Pit with a stainless steel lining, is provided below the Utility Vault. The Tank Pit is accessed through a floor hatch. The roof is constructed of 28-in. cast-in-place concrete.

The Ring Injection Dump roof is gravel ballasted built-up roof system with a 20-year warranty and with a minimum of ¼-in. per foot slope. The exposed exterior walls are cast-in-place architectural concrete. The building consists of 3,768 ft^2, 813 ft^2 on Level 1, and 2,955 ft^2 on Level 2.

Fig. 5.5-20. Aerial view of the ring injection beam dump.

5.5.12 Central Laboratory and Office Building

The CLO (Figs. 5.5-21 through 5.5-23) is a mixed use facility providing the office, laboratory, conference, food service, and shop space necessary to operate the SNS facility. The 249,950-gross ft^2 building is comprised of a six-story, curved office “bar” connected to a four-story shop and lab “block” by a three-story circulation atrium.

There are two primary building entry points, the main entry for employees and guests to the west, on Level 1 and an additional entry to the east on Level B1. A bank of two elevators, and toilet cores, serving six floors of the building, are located at the west entrance for the public. A bank of two elevators serving six floors is located at the east. There is a bridge connection from the CLO Level 2 to the Target Building mezzanine level. The CLO has a service access with a four-bay truck dock located on Level B1 at the north side of the shop and lab block. A freight elevator links the dock area with the three lab floors and a mechanical room.

All of the spaces intended for public use are organized around the Main Entry Lobby. The 355-person auditorium is directly accessed from the Main Entry Lobby. The Lobby also provides a break-out space for functions held in the auditorium. The Meeting Rooms, Coat Room, and toilets for public use are accessed from an atrium, which is an extension of the Main Entry Lobby. The atrium is located between the south office wing and the laboratory block. An ornamental stair in the Main Entry Lobby provides a formal connection to the future Cafeteria and Gallery office area on Level B1 and to the balcony level of the auditorium on Level 2. The ornamental stair can also be used for public tours enroute to the Target Building from the Level 1 to Level 2. At Level B1, outdoor terraces are provided adjacent to the future Cafeteria Dining Room for dining and conference-related functions. A patio area outside the CLO will accommodate a temporary tent for conference functions.

While a small number of offices are located in the basement level, primarily for the Support and Administrative Services, the majority of SNS staff offices are located in the curved office portion of the building on Levels 2, 3, and 4. The future Executive Conference Room, the Observation Deck, and the mechanical room for the offices are located on Level 5. The office and office support spaces are based on a standard 120-ft^2 module. In cases such as conference rooms and executive offices, several modules have been combined to create larger rooms. Many offices in the office bar are enclosed offices, each with glass side lights adjacent to the office doors. The User Work Stations, located in the north office wing on Level 2 are based on an 80 ft^2 module. Other open office areas for staff are located on Level 3 of the lab block. Office support spaces and conference rooms are centrally located on each office floor within the interior office zone. A “suite of offices” for the Office of the Director is located on Level 4.

The plan and structural grid of the four story shop and lab “block” is based on a 20-ft × 20-ft, 400-ft^2 lab module. Level 2 is planned to be comprised of five groups of eight modules, with each group being served by a dedicated mechanical shaft. Level 3 is planned to be comprised of five groups of labs that total 21 modules. User offices are located along the north perimeter for access to natural light and view. All of the heavy-duty Technical Support Shops and the Material Handling Area, which require truck access and a minimum ceiling height of 14 ft-6 in. are located on Level B1. Other building service spaces requiring ground level access such as the Plant Shop, are located on Level B1. The large Technical Support Labs are located directly above the shops on Level 1. The CCR located on Level 1 has direct access to an emergency service vehicle parking area. The Control Room features a mezzanine overlook at Level 2 for public tour viewing. The subbasement, Level B2, provides space for electrical and telecommunications functions.

The exterior skin of the building is insulated metal panels and precast concrete panels, with moderate articulation of reveals and profiles. Window systems are prefinished, thermally broken, extruded aluminum with insulated glazing panels. Exterior entrance doors are prefinished, thermally broken, extruded aluminum with single glazing panels. Truck dock doors are insulated steel overhead coiling doors, and exterior man doors are insulated hollow metal doors and frame assemblies. The roof is composite built-up asphalt roofing and insulation over concrete and metal deck.

The floors finish of the CLO is carpet for the office, assembly, and circulation areas. The Main Entry Lobby, Atrium and ornamental stair finish floor surface is polished concrete. Floor finishes in the Labs and Lab corridors are Vinyl Composition Tile (VCT). Shower rooms, and all toilet rooms are ceramic tile.

The interior partitions and shaft walls for the CLO office, assembly, and lab areas are painted drywall on metal studs. The ceilings for the CLO office areas, meeting rooms, circulation, some labs and bridge are suspended acoustical lay-in panels (2 ft-0 in. × 2 ft-0 in.). The shops and most labs are exposed structure. The assembly areas, lobby, toilet rooms, cafeteria, kitchen, dining room, and stairs are suspended drywall with a painted finish.

5.5.13 Central Cooling Tower

The Central Cooling Tower (Figs. 5.5-24 and 5.5-25) is designed to supply water at a temperature of 82°F during periods of when design temperatures are achieved. The cooling tower has four cells with a capacity of 6250 gal/min each. One cooling tower cell is dedicated for heat rejection from water-cooled equipment throughout the facility, two cells are dedicated for heat rejection from the chilled water plant's condenser water, and one cell is able to function in either capacity. The cooling tower sits over a reinforced concrete basin of 400,000 gal.

The cooling tower is located to the South of the CUB. Associated circulation pumps are located within the CUB. Make-up water to the cooling towers is from the site process water system. Water quality within the cooling tower system is maintained to prevent corrosion and fouling of heat exchanger surfaces.

Cooling tower piping above ground is painted black steel utilizing either welded or grooved connections. Cooling tower piping underground is steel, jacketed with a non-corrosive fiberglass or HDPE (High Density Polyethylene) coating. Cooling tower capacity control is achieved by utilizing fan cycling in conjunction with a variable speed drive (VSD) fan. There is a VSD enclosure between the CUB and the Cooling Towers. In addition, to achieve freeze protection, fan motors are reversible and electric immersion heaters are provided in each basin.

Fig. 5.5-21. Northeastward aerial view of the CLO.

Fig. 5.5-22. Southward evening view of the CLO.

Fig. 5.5-23. Southwest end of the CLO.

Fig. 5.5-24. Aerial view of the Central Utility Building and central cooling tower.

Fig. 5.5-25. Northward view of the central cooling tower.

5.5.14 Central Utility Building

The CUB (Fig. 5.5-26), located to the south of the HEBT Service Building, is an above grade, steel frame structure with an interior clear height of approximately 25 ft. Its intended use is to house the tower water, chilled water, boilers, and compressed air systems serving the SNS site. To accommodate these components and related support equipment, the building has a floor area of 14,548 ft^2, 10,276 ft^2 on Level 1, and 4,272 ft^2 on Level B1. A 12-ft depressed area of approximately 4,300 ft^2, within the building, is designated for the cooling tower pumps. The associated cooling towers are located to the south side of the building. Electrical transformers are also to the south side. The building height is 31 ft-3 in.

Interior walls are of metal stud with gypsum board. The “office core” area of restrooms, communications room, and offices, are of metal stud construction. Fire-rated walls are provided to separate hazardous equipment/operations where desirable or required to ensure life/safety and minimize potential loss due to fire. HVAC equipment, which serves the office, communications, and restroom areas, is located over the office area. Some acoustic separation is provided to mitigate sound into the office area itself, and hearing protection is required outside these areas. The concrete floor slab is designed to safely support the heavy equipment associated with these systems.

The exterior skin of the building is a horizontal metal ribbed siding with insulated panels over a steel frame structure. The roof is a composite built-up over rigid insulation and metal deck. Roof drainage is located along the building perimeter by way of internal roof drains and rain water leaders connected to the site storm system. Overflow scuppers are provided at the roof parapet.

The equipment housed in the CUB includes four 1200-ton chillers, two 200-Hp gas-fired boilers, a 560-SCFM air compressor, and associated pumping and distribution systems.

Equipment access is provided by means of two overhead truck doors, one to access the refrigeration machinery room and one to access the main pumping room. An access road and parking apron is located and sized sufficiently to allow for truck turnaround.

Personnel access and egress doors are provided as required by code.

Fig. 5.5-26. Westward view of the CUB.

5.5.15 Central Exhaust Facility

The Central Exhaust Facility (Fig. 5.5-27) contains 288 ft^{2}and has a height of 12 ft. The building is fabricated of self-framing steel with insulated metal siding. The roof consists of insulated steel panels. This facility houses the exhaust stack as well as the central exhaust fan.

The central exhaust system conveys exhaust air from the tunnels, a ring injection beam dump and Target Building to the central exhaust stack. To prevent particulate fall out within the ducts, a design velocity of 1800 to 3000 FPM is utilized. Underground duct material is fusion-welded HDPE pipe. The nonmetallic material is utilized for longevity, and to eliminate the need for cathodic protection. Above ground Duct is of 304L stainless steel construction.

The exhaust stack is located to the east of the HEBT Tunnel. The exhaust stack is 80 ft in height and 48 in. in diameter and is of prefabricated, free-standing, all welded, carbon steel construction. The design includes a ladder and platform to provide access to monitoring equipment mounted a minimum of ten diameters above any duct connections. The stack is designed for a discharge velocity of 3000 FPM.

Exhaust fan assemblies are located on a concrete slab on grade. Exhaust fans serving the tunnels are separated from other systems. This minimizes the potential for any cross contamination, as well as reduces fan energy because this exhaust stream is unfiltered. Similarly, the exhaust stream from the ring injection beam dump is separated from the Primary Confinement Exhaust (PCE) system, the Secondary Confinement Exhaust (SCE), and HOG Exhaust streams in the Target Building.

The exhaust system serving the Target Building conveys confinement ventilation consisting of the HOG system, the PCE system, and the SCE system.

All exhaust systems are provided with redundant fan units and are supplied from the emergency power system. A single fan unit runs continuously, with the second fan unit on stand-by. Variable frequency drives are utilized for fan capacity control, thus maintaining a constant negative static pressure in the exhaust ductwork.

Fig. 5.5-27. Central exhaust facility.

5.5.16 SNS Electrical Delivery

During the early stages of SNS, discussions were held with the Tennessee Valley Authority (TVA) to discuss schemes for delivering power to SNS and to explore the possibility of TVA providing some portion of the electrical distribution system. Based on these discussions, a Letter of Intent between DOE and TVA was signed in December 1999 to begin planning and design for the SNS electrical power delivery system.

In May 2002, DOE and TVA signed an agreement where TVA would finance, design, and construct the SNS electric power delivery system. This consisted of two new 161kV line connections, the 161kV transmission system and the SNS substation. TVA further agreed to operate the switchyard.

DOE purchased all substation real property from TVA for $1.75M. This property included the switch house, foundations, fencing, underground structures and grounding. DOE provided right-of-way for the transmission lines, switchyard and switch house and agreed to operate the low voltage (13.8kV) portion of the switch house. DOE also agreed to repay the $5.4M capital cost of the switchyard (transformers, switch gear, etc.) over a ten year period. At the end of the ten years, DOE has the option of taking ownership of the equipment. Figure 5.5-28 shows the Oak Ridge electrical distribution system and power delivery to SNS.

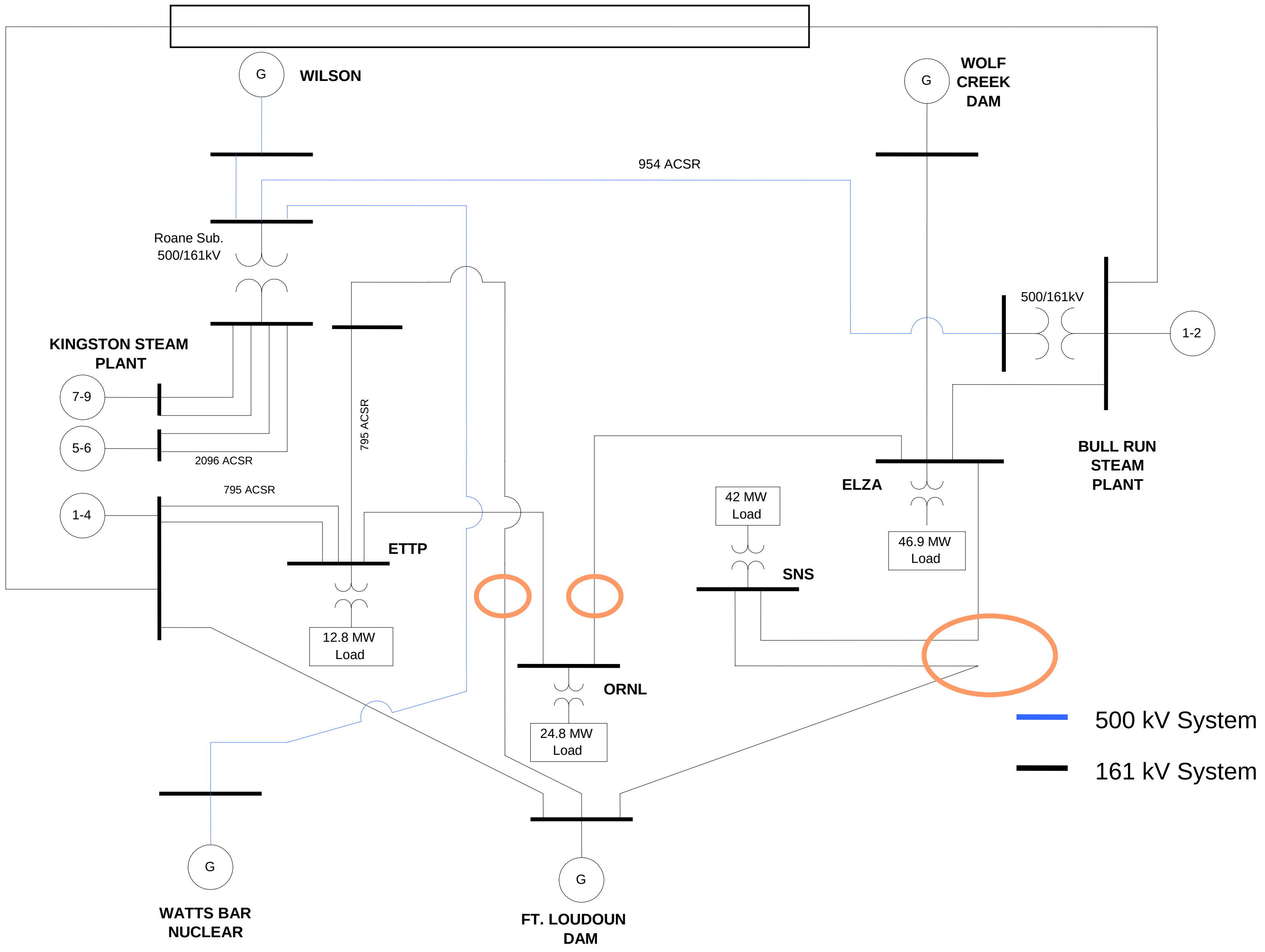


Fig. 5.5-28. TVA Oak Ridge area power system diagram.

5.6 CHANGES FROM THE CDR TO FINAL CONSTRUCTION

Since its inception, the SNS design has undergone a series of internal reviews and replanning efforts to ensure that all the needs of the user are met in the final configuration in an efficient and cost effective manner. More formal reviews were also held by DOE on an annual and semiannual basis to validate the design concept. Of the many considerations one such factor was the physical size of the building. One indication of the overall change in SNS since the CDR is a comparison of the size of the building identified in the CDR and as it was finally constructed. Building size has changed over time to ensure that the basic functional requirements of the users needs were met. Table 5.6-1 compares the building sizes as originally proposed in the CDR and the final size as constructed in 2006. Note that the final configuration which has a fewer number of multifunction buildings is in contrast to the early proposal that had a large number of primarily single function structures designed to support the major functional elements of SNS. The approach changed from single function shops and associated buildings, such as a front end shop adjacent to the Front End Building, to a multifunction building containing shops, administrative space and labs. The CLO contains the vacuum shop, alignment shop and user office space, etc. for all Divisions. There are exceptions. Most notably the shops to support the Klystron operation are in the SRF/RF Building. The table lists the size of the buildings in square feet as proposed in the CDR and as they were finally constructed in 2006.

Table 5.6-1. Building sizes proposed in the CDR and final size as constructed in 2006 (FT^2)

Building	CDR	As Constructed
Accelerator Buildings		
Front End Building	10,000	15,562
Linac Tunnel	21,042	14,711
HEBT Tunnel	9,972	12,765
Ring Tunnel	13,140	18,153
RTBT Tunnel	8,136	8,341
Linac Tune Dump	1,600	365
Neutral Dump	1,600	2,982
Ring Tune Dump	1,600	365
Klystron and HEBT Service Building	50,336	49,171
Ring Service Building	6,400	16,344
Ring DI Water Building	1,100	0
RTBT Service Building	1,960	2,834
Central Helium and Liquefier Bldg	0	13,978
RF Building	0	13,436
SRF Building	0	12,317
	Subtotal 126,886	**Subtotal 181,324**
Target Building		
Instrument floor	49,490	61,265
High bay transfer area	9,800	0
Basement	16,120	9,800
Support labs and Shops	7,000	0[1]
Mezzanines	0	41,170
Instrument Buildings	0	12,189
Target Helium Bldg	0	1,163
	Subtotal 82,410	**Subtotal 125,587**

Table 5.6-1. Building sizes proposed in the CDR and final size as constructed in 2006 (FT^2)

Administrative/Lab/Shop Space		
Central Lab and Office Bldg	-	-
Offices	0	43,000
Shops/Labs	0	63,000
Mechanical/Electrical	0	27,000
Common/Support Space	0	116,950
Administrative Office Bldg	17,175	0[1]
Front End Shop	12,000	0[1]
Linac Shop	8,000	0[1]
Linac and Klystron Shop	24,000	0[1]
Ring Shop	8,000	0[1]
Central Change House	300	0[1]
Central Receiving	9,000	0[1]
User Office Building	18,560	0[1]
Central Control Building	9,000	0[1]
	Subtotal 106,035	**Subtotal 249,950**
Support Buildings		
Central Utilities Building	9,420	14,548
Hot Shop	8,000	0
Support Buildings	4,000	
Make-up Air Bldg West	0	1,249
Make-up Air Bldg East	0	1,252
Central Exhaust Facility	0	288
Potable Water Pump Bldg	0	350
Diversion Tank Bldg	0	552
Staging/Storage/Warehouses	14,000	25,092
	Subtotal 31,420	**Subtotal 43,331**
Total Site Building Area	**Grand Total 350,751**	**Grand Total 600,192**

[1] ***Buildings were not built and space was incorporated into Central Lab and Office Building***

5.7 ROADS, GROUNDS, AND LAND IMPROVEMENTS

Land Improvements include the site work necessary for access, construction, and operation of the SNS. These activities include: (1) roadwork, walks, plazas, and paved areas, (2) site characterization, (3) site preparation and grading, (4) storm water management, (5) the groundwater interceptor system, (6) retaining walls, (7) landscaping, (8) fencing, (9) excavation disposal areas, and (10) construction support such as temporary utility services, roads, parking, lay down areas, and other similar support. See Fig. 5.5-29 and 5.5-30 for aerial views of the entire SNS site.

Roadwork, walks, plazas, and paved areas provide temporary and permanent access for vehicular and pedestrian traffic to, from, and throughout the site and its facilities. It includes roads, parking lots, and walkway and plaza areas connecting buildings to roads, parking, and other buildings.

Site characterization includes the land characterization and site analysis to explore and define surface and subsurface characteristics of the site. These were used as the basis for overall site and building design.

Site Preparation and Grading includes demolition or removal of existing interferences to the grading operations; clearing and grubbing of existing vegetation, as well as protection of existing vegetation to remain in place; excavation and backfilling for building constructions, including stockpiling of reusable materials and disposal of excess and undesirable materials; finish grading in preparation for landscaping, walks, roads, etc., and provision of temporary erosion and sediment controls during construction.

The Storm Water Management system collects surface runoff from the site and controls its discharge downstream into the infrastructure catchment's area. This activity includes surface and sub grade collection systems, as well as detention facilities for control against flooding and any monitoring required by National Pollutant Discharge Elimination System (NPDES) permitting.

Fig. 5.5-29. Eastward aerial view of the SNS site.

Fig. 5.5-30. Westward aerial view of the SNS site.

6. ACCELERATOR READINESS REVIEW

The accelerator readiness review process was initiated in 2000 to assure project personnel, DOE, and the user community that SNS met the technical baseline requirements and was ready for safe commissioning and operations. The process was based on the requirements of the DOE Accelerator Safety Order, DOE Order 420.2A (now 420.2B) and governed by 10 CFR 835, and ORNL WSS/SBMS. The approach was to perform substantive self-assessments, objective detailed reviews by knowledgeable in-house experts, analysis of issues and concerns and appropriate action, and finally independent review by recognized professionals.

The reviews were conducted in modular increments with one preceding each phase of accelerator commissioning. The SNS PSADs and later SADs contained the specific operating and safety envelopes for each phase of commissioning. The ARR process guaranteed that all documentation and control processes were in place to support that operation.

Seven Accelerator Readiness Reviews have been held:

- Front End: October 2002
- Drift Tube LINAC Tank 1: August 2003
- Drift Tube LINAC Tanks 1-3: March 2004
- Drift Tube LINAC Tanks 4-6 and Coupled Cavity LINAC Modules 1-3: August 2004
- Coupled Cavity LINAC Module 4 and Superconducting LINAC: July 2005
- High Energy Beam Transport Beam line and Ring to Extraction Dump: December 2005
- Ring to Target Beam Transport Beam line and Target: April 2006

The ARR Committee consisted of subject matter experts currently or recently associated with SLAC, Fermilab, Brookhaven National Laboratory, Argonne National Laboratory, NIST, LANL and one member from ORNL. The final committee report from each review was the basis for the DOE Project manager to document the approval for permission for operation.

All Pre-Start and Post-Start Action Items for the Accelerator Readiness Reviews required for CD-4 have been closed out and documented. This documentation can be found in the SNS document management system.

Key Documents in the ARR process included:

- Commissioning Program Plan, SNS 100000000-PN0004
- Accelerator Readiness Review (ARR) Plan Of Action, SNS 100000000-PN0005
- 2 Safety Assessment Documents (SADs)
    - Proton Facilities - Front End, LINAC, and Ring and Beam Transport Systems, SNS 102030103-ES001
    - Neutron Facilities - Target Building (target and instruments), SNS 102030103-ES0016
- Accelerator Safety Envelope, SNS-OPM 2.B-1

7. ENVIRONMENT, SAFETY, AND HEALTH

7.1 NATIONAL ENVIRONMENTAL PROTECTION ACT

The Spallation Neutron Source was evaluated in an EIS "Construction and Operation of the Spallation Neutron Source." Following publication of the Draft EIS, comments were resolved, and a Final EIS was published. A Record of Decision was published in the *Federal Register* Vol. 64, No. 125, on Wednesday, June 30, 1999, approving construction and operation of the SNS.

Five areas of concern requiring mitigation were identified in the Record of Decision, and a Mitigation Action Plan was developed.

Impacts to wetlands were identified as a concern. Avoiding wetlands to the degree possible was a design and siting criterion, and a Wetlands Mitigation Plan was submitted to the Tennessee Department of Environment and Conservation to address unavoidable impacts. The Plan was accepted, and wetlands in excess of five times the area affected by SNS construction were restored in an area close to the SNS.

The potential to affect protected species of plants and animals was identified during the siting process. Following final site selection, the areas were surveyed by an independent expert. No protected species were located, and no significant habitat was noted.

Cultural resources could have been affected by construction activities. All known sites were located, marked, included in every construction package, and carefully avoided during construction activities. No additional cultural resources were identified by independent experts during construction.

Transportation concerns were raised during the comment period. The SNS activities were included in discussions with the Tennessee Department of Transportation, and the SNS entry included access lanes and on-demand traffic lights in 2001.

The possibility that dust, water vapor, and exhaust could impact the long-term climatic research at the nearby Walker Branch Watershed area was raised. Discussions with the affected scientists were held to determine the magnitude of the potential impacts and evaluate the options to minimize the effects. The selected alternative was to fund an alternative data-collection tower at a location with features similar to Walker Branch but outside the zone of potential impacts for SNS activities. A location was identified, and a research facility was installed in 2003.

In general, the inherent design of SNS and its associated operations preclude the potential for significant releases of liquids that pose a threat to the environment. However, SNS operations have the potential for inducing radioactivity in the shielding berm surrounding the linac, accumulator ring, and/or beam transport lines. A principal concern is the potential for water infiltrating the berm soils to transport radionuclide contamination to saturated groundwater zones. Because the potential for activation of soil beneath portions of the facility is significant, SNS has implemented facility design and construction features to minimize the mobility of activation products in the site hydrologic system. The SNS groundwater protection program incorporates engineering-designed controls to address concerns associated with the spallation and neutron activation of soils in the shielding berm. Specifically, the shielding berm has been designed and constructed to isolate radionuclide contamination generated by the SNS particle beam and to provide radiation protection for outside areas around the beam and ring tunnel. The amount of such activation is minimized by beam loss control and passive shielding. Nevertheless, the berm is constructed of compacted native soils and is engineered to isolate activation products by minimizing the amount of water infiltrating the berm. The SNS berm groundwater study estimates that the planned berm construction of compacted indigenous clay renders it relatively impermeable to water (compacted clay Darcy permeability much less than 1e-05 cm/s). Furthermore, a flexible membrane liner coupled with a drainage net is included in the design to provide an additional degree of control against water penetration. The berm design incorporates a groundwater interceptor system to collect any water that penetrates the engineered berm. This water will be sampled routinely and analyzed for radionuclides. If radioactivity is present, the water will be managed appropriately with respect to the amount of radioactivity present. Otherwise, the water will be released to the retention basin.

Although the major objective of SNS engineering controls is to prevent any migration of radionuclides to groundwater, another key programmatic element of the SNS groundwater protection program was the implementation of a baseline groundwater monitoring program (2004-2006), and the subsequent implementation (2006-ongoing) of an operational groundwater monitoring program. The ultimate purpose of these programs is to ensure that any releases of contaminants from the facility do not cause an unacceptable impact to groundwater or surface water on, or adjacent to, the site.

7.2 ACCELERATOR SAFETY ORDER

SNS has been designed, constructed, and commissioned in compliance with the DOE Accelerator Safety Order 420.2B. An assessment was conducted in 2005 to evaluate compliance with the requirements of 420.2B. This assessment determined that the SNS complies with the Order.

SNS has segmented the safety documentation, with a Safety Assessment Document for Proton Facilities and a Safety Assessment for Neutron Facilities. These documents have been submitted to the DOE Federal Project Director for review, and comments have been addressed. The safety documents are revised as necessary to address issues associated with changes in the SNS. Credited Engineered Controls identified to protect workers from incidents and releases from the SNS have been identified and are maintained under configuration management. With each commissioning phase, an Accelerator Safety Envelope was developed and approved by the DOE Federal Project Director for approval.

The detailed safety analysis verifies that the design of the SNS facility effectively mitigates hazards, primarily through the use of passive design features. A rigorous and comprehensive process was employed to identify hazards and to assess the potential impacts of those hazards. This process resulted in the identification and evaluation of a wide spectrum of potential accidents. The analyses show that there is no credible mechanism, with the energy sources available (including the proton beam, a massive earthquake, potential fires, and combustion of hydrogen in the neutron moderator system), for enough mercury or any other radioactive material to be driven from the facility to cause a significant offsite impact. The maximum off-site radiological dose under the most severe physically plausible accident scenarios was shown to be well under 1 rem.

Changes in the SNS are evaluated under the unreviewed safety issue (USI) process to ensure compliance with the Accelerator Safety Order. The USI process is documented and archived. The current revision of the safety documentation, the approved accelerator envelope, and the USI determinations comprise the SNS safety basis.

7.2.1 External Reviews

An external Accelerator Safety Review Committee, composed of accelerator and operational experts from across the DOE complex, has provided reviews of the SNS safety documentation (the Safety Assessment Document for Proton Facilities and the Safety Assessment Document for Neutron Facilities) as well as performed the independent Accelerator Readiness Reviews. The results of these reviews are recorded in transmittals to both the SNS Project and to the DOE Project Director.

7.3 FIRE PROTECTION

The SNS is designed and constructed in compliance with the applicable building code and NFPA standards. Fire safety features have been provided at the SNS to protect the occupants, property, operations, safety systems and components, and the environment from the risks and impacts of a fire.

Facility-specific fire hazards, maximum possible fire loss (MPFL) potentials, and fire protection mitigation features in SNS facilities have been detailed in the various SNS building Fire Hazards Analyses (FHA). Fire detection and suppression systems are installed to protect against the fire hazards identified in the FHA.

The SNS site-wide fire alarm system is linked to the SNS CCR and the ORNL Fire Department Alarm Center. The SNS building fire alarm systems and fire sprinkler systems are maintained by ORNL personnel. Firefighting support is provided by the ORNL Fire Department. A number of drills have been held, and response time to SNS alarms has been excellent, with support arriving within 10 min. SNS routinely participates in ORNL Fire Department drills.

7.4 RADIATION MONITORING

SNS complies with the ORNL radiation protection program, which has been evaluated and meets the requirements of 10 CFR 835. Trained radiation protection professionals are supplied to the SNS, and the individuals are supplied with appropriate SNS site-specific training.

Radiation monitoring is performed in areas occupied or accessible during operations, as well as on the stack effluent and water releases. The radiation emitted by the SNS was conservatively estimated, and monitoring systems designed to detect releases and ensure compliance with applicable requirements. Air from facilities with the potential to become activated is routed through filters and then to the central exhaust facility. The Central Exhaust Facility is monitored and sampled, and the releases are projected to be well under the National Emission Standards for Hazardous Air Pollutants.

Staff with the potential to receive doses from SNS operations are fitted with personal dosimeters. In addition, areas are routinely surveyed for radiation levels, and postings and access control is modified as required to ensure protection of the SNS population.

7.5 EFFLUENT MONITORING

The SNS uses natural gas to heat facilities and supply hot water as needed. As required by the SNS permits, the amount of natural gas used by the boilers is continuously measured and reported to the Tennessee Department of Environment and Conservation. Emissions from the boilers are estimated using conservative factors based upon the boiler type and size. Other regulated emissions are routed through the Central Exhaust facility, which is monitored to demonstrate compliance with the air permit.

The SNS has an NPDES permit for cooling tower blowdown waters, and an operational effluent monitoring program to ensure compliance with the respective permit. The cooling towers operations commenced in December 2004, and since that time there have been no violations of the NPDES permit.

The SNS has also undertaken development and implementation of a baseline groundwater monitoring program. The monitoring of groundwater commenced in 2004 and continued through April 2006 providing approximately 2 years of data to establish the respective baseline prior to commencement of operations. In April 2006, the baseline groundwater program was completed and transitioned to an operational groundwater monitoring program.

7.6 WASTE SYSTEMS

The generation of wastes from the SNS is minimized as a result of the facility design and operation. At the earliest stages, Waste Management Plan SNS-102030000-TR0002 was developed to identify potential waste streams and estimated amounts. As designs evolved, the plan was revised to ensure the information is correct and that current processes and waste estimates are available for evaluation. As identified in the Plan, wastes generated at the SNS are segregated and routed to the appropriate system for treatment or disposal. Most liquid wastes are transferred to the ORNL sewage treatment facility; liquids requiring other treatment or disposal are segregated, packaged, and transported to the appropriate facility.

Hazardous wastes are treated in compliance with ORNL waste management requirements. As the facility evolves, waste generation rates are predicted to increase, but continuous evaluation of processes and waste streams is conducted to minimize the amounts of wastes generated.

Radioactive waste streams have been evaluated, and a disposal method identified. The facility was designed to minimize the amounts of rad wastes generated. An example is the liquid mercury target. Approximately 40,000 lb of liquid mercury serves as the source of neutrons at the SNS. The mercury will remain for the life of the facility, with only the stainless steel shell requiring disposal. Other spallation sources use solid targets, which result in thousands of curies of radioactive materials being disposed of at every target replacement. The target shells and other radioactive materials will be held on-site for a period of time to allow for the decay of short-lived nuclides, and then disposed of in commercial facilities.

7.7 PROTECTION SYSTEMS

The SNS has a series of automated systems to detect machine interruptions and cease operations before dangerous conditions evolve. The MPS is designed to detect beam irregularities and shut off the beam before damage or excessive activation of components occurs.

The PPS is a Credited Engineered Control that provides protection from prompt radiation. The PPS uses highly qualified detectors, under rigorous configuration control, to detect radiation levels that exceed set points in areas that could be occupied. Upon detection of elevated levels of radiation, the PPS shuts the beam off within 2 s. The PPS also consists of interlocked doors and entrances that shut off the beam if an individual attempts to access restricted areas of the SNS while the beam is operating. Access to the tunnel is controlled in a series of modes, and accelerator operations are linked to the access mode.

The TPS is a Credited Engineered Control that provides protection from high levels of radiation from the target. The TPS uses highly qualified detectors, under rigorous configuration control, to detect flow or temperature conditions within the target that could lead to releases of mercury vapor. The TPS shuts the beam off within 2 s, and does not allow the beam to reach the target if the target is not in position to accept beam, or if mercury flow and temperature readings are not within specifications.

7.8 OCCUPATIONAL SAFETY DURING CONSTRUCTION

During the SNS project, there were 4.3 million construction hours worked with 0 lost workday (away) cases, 22 DART (restriction) cases, and 78 recordable illness injuries. In addition, there were 3.6 million nonconstruction hours with 2 lost workday (away) cases, 4 DART (restriction) cases, and 21 recordable illness injuries. Figure 8.1 shows a poster commemorating reaching 1 million construction hours without lost workday case. Key factors in construction safety are discussed in Sect. 10 and in SNS 102000000-LL001-R00, *Safety Lessons Learned for the Spallation Neutron Source*.

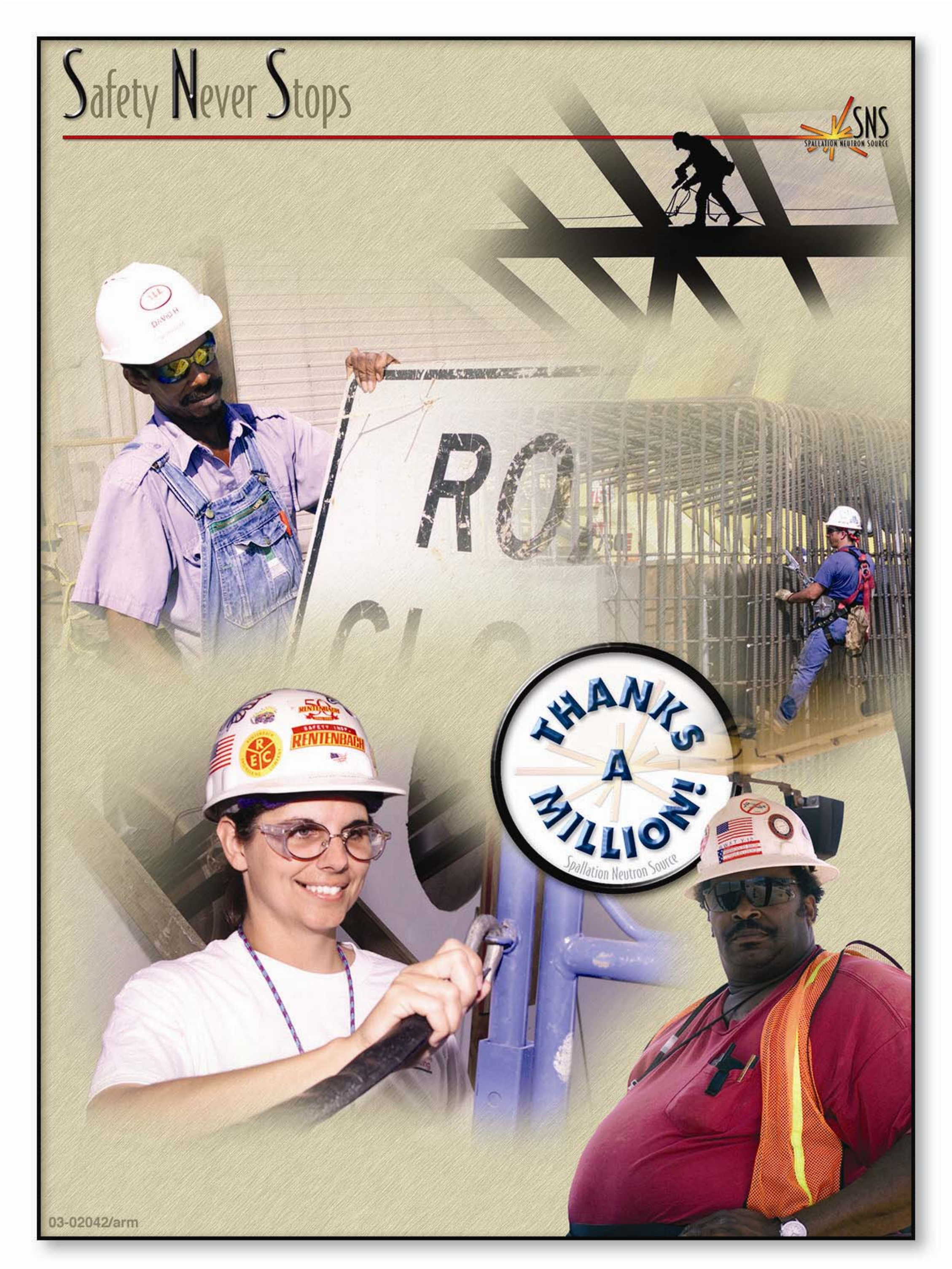


Fig. 8.1. SNS poster commemorating reaching 1 million construction hours without lost workday case.

8. PROJECT MANAGEMENT

Project management activities for the SNS project were performed by ORNL (contractor), with oversight from the DOE Project Office, which reports administratively to the DOE Oak Ridge Office. Programmatic direction was provided by the DOE Office of Science (DOE-SC). Project organization, responsibilities, and processes are described in the SNS PEP.

From November 1999 through May 2006, the project submitted monthly reports to DOE that included cost/schedule performance information. Numerous reviews were conducted by DOE, as well as Accelerator Advisory Committee and Experimental Facilities Advisory Committee reviews.

Integrated systems were used to manage the cost, schedule, and technical performance of the project. Some of the key systems follow:

1. ***Earned Value Measurement Reporting***—An earned value system that was consistent with the ANSI standard EIA-748, was utilized.

2. ***Risk management***—Risk management was implemented during the SNS construction project on a continuing basis to help ensure that

   - risk identification was completed and had the appropriate rigor,
   - risk issues were made visible early and stayed in focus, and
   - thorough, credible mitigation plans were prepared.

3. ***Contingency Management***—Thorough reestimates of the cost and schedule to complete, including contingency analysis, were performed routinely from the bottom up.

   Appendix F shows contingency use throughout the project.

4. ***Procurement planning***—Roughly 50% of the total estimated cost was composed of major (>100K) procurements. Advanced procurement plans (APPs) were used as a planning tool for SNS management. An APP was prepared for all anticipated procurements of >$100K (and all critical path procurements), indicating procurement strategy, sources for the bid list, and key milestones including planned solicitation issue and award dates. The APPs were revalidated before the start of each fiscal year. Procurement staff were dedicated to the project full time and were collocated with other project staff.

5. ***Quality assurance***—SNS prepared and maintained a QA manual, the *SNS Quality Manual*, SNS 102040000-QA0001-R04. This manual provided the requirements applicable to all activities conducted by or for SNS. Additional information about the QA program is described in Sect. 8.1, “Quality Assurance.”

8.1 QUALITY ASSURANCE

The SNS project quality assurance (QA) requirements come from DOE Order 414.1B. As provided in the order, the SNS quality program relies on a graded approach to determine the degree of QA effort needed. The other notable emphasis is the acceptance criteria listing process used for QA of equipment quality. Quality professionals were assigned to each subproject and to the AE/CM to provide advice, services, and oversight. The project operated under QA plans, as listed subsequently.

The QA staff have been involved in all major procurements by evaluation of vendors' QA programs and acceptance of equipment. They were involved in records systems; calibration of equipment; procedure development and use; inspection coordination; and many other aspects of project work. The quality manager regularly led audits of the partner labs and the AE/CM.

At Oak Ridge, ASD and Experimental Facilities Division (XFD) quality representatives have also provided assistance with planning and obtaining appropriate mechanical inspections, physical properties testing, and other inspections and tests.

QUALITY ASSURANCE PLANS

The *SNS Project QA Plan*, SNS-QA-P01, implements the DOE Quality Assurance Order (O 414.1B), and the *Target Systems Quality Assurance Plan*, SNS-TS-P00, provides additional requirements for Target Systems. Although SNS as an accelerator facility is excluded from 10 CFR 830, this plan was developed and followed to achieve a level of safety equivalent to a nuclear facility. The plan assures that the target and associated systems were designed and constructed substantially in accordance with 10 CFR 830 requirements.

GRADED APPROACH

The graded approach was crafted to support a variety of systems, components, and activities. Quality-assuring actions were applied commensurate with needs. Three grade levels (quality levels) were defined to cover the range of needs from the most serious items with safety implications to normal commercially available components.

8.1.3 OVERSIGHT

Quality professionals were assigned in each subproject and in the AE/CM to provide advice, services, and oversight. The QA staff have been involved in all major procurements by evaluation of vendors' QA programs and acceptance of equipment. They were involved in records systems, in calibration of equipment, in procedures development and use, inspection coordination, and many other aspects of project work. The Quality Manager regularly led audits of the partner labs and the AE/CM. At Oak Ridge, Accelerator Systems Division and Experimental Facilities Division quality representatives have also provided assistance with planning and obtaining appropriate mechanical inspections, physical properties testing, and other inspections and tests. An important tool used throughout the project was the Acceptance Criteria Listing (ACL) process that was used for assurance of equipment quality. The ACL's were created by the responsible engineers before fabrication or procurement, and approved by their QA representatives. They became the record of inspection and tests. The ACL records and attachments associated with acceptance of the equipment are filed in the project records system. Where discrepancies were found in the acceptance process, the ACL files also contain the records of rework, repair, or replacements made.

9. OPERATIONS PLANNING

The *Operations Execution Plan* (OEP) serves two basic functions. First, it satisfies the requirement for an SNS operational plan, as outlined in the Energy Policy Act of 2005, and supports the Office of Science Long-Range Plan and the ORNL agenda. Second, it establishes the basis for SNS operations and activities for the initial planning cycle (CD-4 through FY 2010) and serves as the primary reference document for all SNS activities. Additional SNS plans and policies and procedures for science programs, future upgrades, instrument development, risk management, environment, safety, health, and quality (ESH&Q), resource management, performance assessment and reporting, etc., all flow down from the OEP.

9.1 SPARES PLANNING

As part of the design and procurement process for technical systems at SNS, a number of required spare parts were identified. These spare parts are required to ensure that the startup, commissioning, and operation of SNS facilities are not interrupted because of the unavailability of critical spares. The initial complement of spares was recommended by the partner laboratories and the technical group leaders in Oak Ridge, based on engineering judgment, and the experience of the engineers and scientists who designed the systems. This list was prioritized based on the total number of installed systems and the anticipated mean time between failure in various components and systems. Also considered was the projected time to acquire the spare and the economics of purchasing the spare with the construction production run for the installed components. If the recommended spare required special manufacture or had long lead times to acquire in the future, it was given a higher priority. Spares were then grouped into high, medium, and low priority, and this list was reviewed by SNS management.

DOE-Oak Ridge Operations (ORO) budget guidance instructs that the initial complement of spare parts required by project design criteria be included in the project using capital funds. The SNS project budget included the initial complement of high-priority spares meeting this guidance.

9.2 ATTAINING AND TRAINING OPERATIONS STAFF

To date, the ASD Operations staff consists of twelve chief accelerator operators, including Accelerator Operations management staff and one accelerator operator, all of whom are trained and qualified. The Training and Qualifications are specified ant tracked in the ASD Operations Training Matrix. Two more accelerator operators have been hired and have assigned report-to-work dates. Two more operators will be hired in FY 2006, and three more will be hired in FY 2007. This staffing ramp-up is the approved staffing plan for ASD Operations which will result in full staffing in FY 07. All chief operators have a minimum of four years experience in operation of high-powered particle accelerators. The actual number of years of experience varies, but it is as high as fifteen years in some cases. All accelerator operators have a minimum of three years experience in operation of high-powered particle accelerators. Training and accelerator operation training records management is conducted by accelerator operations management staff.

The ramp-up of Accelerator Operations staff began early in the project with the installation, testing and commissioning of the Front End Systems and has continued through to the commissioning of the RTBT-to-Target systems. This schedule has provided the opportunity for ASD Operations Staff to participate in all phases of commissioning and pre-operation running as well as the development of policies and procedures which define the operations envelope for the facility.

XFD operations staff can generally be categorized into the following groups:

- Technical facilities managers and systems engineers
- Operations shift technicians
- Facility support technicians
- Remote-handling technicians
- Instrument hall and instrument floor coordinators
- Research mechanics
- Clerical and support staff

This staff is being populated according to an approved staffing plan. Staff required for startup and commissioning was in place for initial operation. Staffing will continue according to plan and will meet the operational requirements as neutron-scattering instruments become operational and the number of users increase. Initial hires for each of these categories had a large amount of relevant experience, more than 10 years in most cases. Beginning with an experienced staff helped to minimize mistakes and directional changes typical with the startup of a complex facility. This allowed us to meet the aggressive startup schedule for the SNS.

The highly experienced staff was desirable to understand the need for and be able to create the documentation infrastructure of appropriate rigor and discipline necessary to operate a complex DOE facility. Initial operation required creation of operating policies and procedures, safety documentation, training programs, work control and maintenance programs, startup and testing procedures, alarm response procedures, emergency response procedures, and all other required documentation and programs.

Operations shift technicians (persons who operate the target and support systems) were hired before completion of construction. This hiring schedule provided the opportunity for them to be involved in the installation, testing, and initial operation of the systems. This proved an invaluable training tool and has given the operating staff a strong experience base.

Remote-handling personnel were employed before critical remote-handling activities. This was essential to proving the remote-handling hardware, processes, and procedures.

Design engineers continued through the construction phase and into the startup and initial operation phase. Their role has transitioned to that of systems engineers. Some of these staff have moved to and will remain in the Operations organization, and the remainder will be matrixed from the ORNL Engineering organization.

The instrument hall coordinator and the instrument floor coordinator, whose primary function will be to deal with users and user support, are in the process of being placed and will be ready when users arrive.

All XFD personnel received the ORNL basic required training, with additional training as defined by position. These position-dependent training requirements are based on the work assigned for that position.

Managers and engineers typically have the lowest number of additional training requirements. These requirements consist of primarily institutional training, which deals with hazards that could be encountered in Target Building operations. Such training includes both hazard awareness and how to work with these hazards present (e.g., RadWorker I or II training).

On the other end of the training spectrum, the Operations shift technicians go through an exhaustive qualification program based on a qualification standard. The standard requires training on each operating system (both classroom and practical factors), written and oral exams, proficiency evaluations, and console operation time. Qualification requires a minimum of three months but typically requires six.

console operation time. Qualification requires a minimum of three months but typically requires six.

10. KEY LESSONS LEARNED

Key lessons learned from the SNS project follow.

1. **A clear mission need and program support are imperative.**

High-cost projects will always be challenging, but it is essential that support from DOE-SC, Congress, and the scientific community never wavers.

1. **Build a strong, effective project management organization early**.

It is imperative that the project management team have a project (vs program) mentality. Although some managers may have success in building the mission need, it does not necessarily ensure success in execution. The transition from conceptual design to project execution must be considered when filling key roles. In addition, the project management team must consist of experienced professionals, project and team builders, chief schedule drivers, and communicators; these people must be able to plan the staffing transitions at the end of the project. Early establishment of effective project leadership will establish the right vision and will attract qualified staff. In addition, project leadership must have the authority to make decisions in a timely manner.

3. **Multilaboratory partnerships with clear responsibilities and centralized budget authority can be successfully used for new, big-scale projects.**

One of the keys to the success of the SNS was being able to use resources at partner labs, which extended the range of expertise and achieved a better product and allowed a slower, deliberate operations staff rampup. (see staffing chart in Appendix G). The success of a collaboration project in general, however, depends on the following:

- Strong leadership in the lead lab that will ultimately operate the facility. This is necessary to establish and enforce workable rules for collaborating, monitoring, and encouraging progress with all subprojects and for arriving at management decisions that equally respect the needs of the overall project and each of the subprojects.
- Technical expertise and strong systems integrator capability by the lead lab to manage integration and interfaces.
- Excellent communications between all partners with frequent and well-organized meetings, using state-of-the-art media technology.
- Strong support and commitment by the top management of each of the partner lab to accept institutional ownership and accountability, allocate adequate support (largely dedicated workforce), and help achieve project goals.
- A virtual single-site organization/approach; a structured agreement (memorandum of agreement) should be used to describe how the project will work.
- Influence by the lead lab on the partner labs’ performance fee and key staff evaluations.

4. *Many* project management tools and processes are needed to manage project performance, but processes alone are not sufficient to effectively manage project performance.

Constant, unrelenting control of costs and scheduling using disciplined management systems is a must. This should include:

A. Maintaining and measuring against an aggressive schedule.
B. Planning work to fully use the annual budget authority.
C. Ensuring that the project's annual funding profile is appropriate from the beginning.
D. Obtaining competent, independent assessment and advice is imperative:

    i. using ad hoc reviews as needed for specific problems and
    ii. using routine, disciplined peer review processes on all aspects of the project. This ensures that lessons learned from other projects are routinely incorporated, and it is an excellent tool for understanding and managing risks and vulnerabilities.

E. Ensuring that vendor management is performed by experienced personnel.
F. Planning carefully, anticipating problems, actively managing changes, and staying on top of the details.
G. Keeping an eye on things such as EAC and risk; planning for known risks and unknowns to achieve performance objectives.
H. If a collaboration, managing contingency centrally; this is an important risk mitigation approach.
I. Establishing and incentivizing performance for risk minimization, such as incentive contracts (especially civil construction) and creation/retention of reserves by partners.

5. Planning for commissioning and operations should take place early.

Early planning for commissioning is needed to ensure cost estimates are within the TPC and to recruit operations staff. Additionally, the facility long-range upgrade strategy should be established early on between DOE and the Lab in enough detail to guide design decisions and facilitate future scope enhancements.

6. Innovative HR programs are key for successful recruiting and retention of staff.

During the early several years of the project, there were difficulties in recruiting candidates and securing rapid acceptance and relocation. Candidates perceived that the Project could be subject to cancellation and were unwilling to leave stable employment and/or to lose compensation including pay and/or benefits. The DOE-SC chartered a team, the Working Group, to develop a proposal for assisting SNS in recruiting. The team was composed of representatives from the Headquarters and Operations Offices and contractors with expertise in project management, compensation with expertise in variable pay plans, benefits with expertise in retirement plans, and recruiting. As a result, the DOE-SC director approved implementation of the SNS Project's Human Resources (HR) Working Group's recommendations which became known as the SNS HR toolkit. The toolkit included variable pay options, service-based benefits, and nonqualified tax-deferred retirement plan. SNS has experienced success in recruiting and retaining highly skilled staff to fill over 300 positions to date with an acceptance rate of about 85% and a turnover rate of about 4%. The SNS HR toolkit contributed to this success and effectively minimized issues associated with attracting highly qualified individuals to fill key positions. The toolkit use mitigated perceived differences in vacation and retirement benefits and eliminated the need to grant exceptions, base pay increases, and other actions that result in inequities. The cost impact of using these tools is negligible and in some cases recurring cost were avoided.

7. Safety requires the unrelenting attention and commitment of management and labor.

It is extremely important to place emphasis on a rigorous safety culture from the beginning. The safety program must be “Workforce friendly”. SNS’s approach to this included an on-site nurse’s station for quick attention to work-related injuries which was also available for non-work related injuries. This helped maintain an environment that encouraged event reporting. Frequent “celebrations” were used to recognize workers with good safety performance. In addition, crafts participated in the Job Hazard Analyses and work process development.

The safety program must also be “Management driven”. There must be a commitment from DOE, Laboratory management, the Construction Manager, and the subcontractors that safety is #1 priority. Actions by SNS included:

A. Only contractors with good safety records could bid.
B. “White Hat” oversight was utilized.
C. Safety inspections were made by the Construction Manager’s corporate and insurance company.
D. A Master ES&H plan was used for all site work.
E. Precursor events were tracked and trended.

Specific lessons learned related to construction management can be found in the, *SNS Site Services Lessons Learned,* SNS 108010200-LL0001; specific lessons learned related to safety can be found in SNS 102000000-LL0001-R00, *Safety Lessons Learned for the Spallation Neutron Source*.

11. REFERENCE DOCUMENTS

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Spallation Neutron Source Standards for Design and Construction, 108030000-ST0001-R00, Spallation Neutron Source, Oak Ridge, Tenn., September 1999.

Target Systems Quality Assurance Plan, SNS-TS-P00,

APPENDIX A: PROJECT CHRONOLOGY

5/06	CD-4 Declaration and Draft Project Completion Report Submitted to DOE
5/06	Instrument Acceptance Test (3 Installed + 2 Procured)
5/06	SC Semi-Annual Project Review Validates Project Completion Status
4/06	First Beam-on-Target and CD-4 Performance Test Accomplished
4/06	RTBT & Target Readiness Review and Authorization for Beam Operation
4/06	Global Controls Installation and Testing Complete
3/06	Instrument Readiness Review Conducted for the Backscattering Spectrometer
3/06	Electrical Arc Flash Near-Miss Occurs in Target Building
3/06	Target Inner Reflector Plug (IRP) Repaired & Installed
3/06	Target Service Bay (TSB) Floor Shield Blocks Plated & Received & Staged in the TSB
2/06	Target Service Bay (TSB) Floor Shield Blocks Caught in Fire at Plating Vendor in Nashville
2/06	Central Laboratory & Office Building Draft Request for Equitable Adjustment (REA) Submitted by General Construction Subcontractor
2/06	Began Build Out of the RF Building & Klystron Gallery Extensions
2/06	Completion of Central Exhaust Facility Ends Required Civil Construction
2/06	Target Inner Reflector Plug (IRP) Leaks Discovered
2/06	Ring Commissioning Complete
2/06	Reprogramming Returns $4.5 Million from SNS-OPC to SING
1/06	Demonstrated Remote Target Change Out
1/06	Successfully Completed 72 hr Mercury Loop Flow Test
1/06	First Neutron Shutter Lifted Hydraulically
1/06	Beam Accumulated in Ring and Extracted to Dump
1/06	Authorization Granted to Run Beam to the HEBT/Ring/RTBT
12/05	$417K Rescinded From FY06 SNS Line Item Appropriation
12/05	Began Build Out of the CLO Auditorium
12/05	Mercury Loaded into the Target System

12/05	Ring and Transport Systems Accelerator Readiness Review
11/05	SC Semi-Annual Project Review
10/05	Inner Reflector Plug Assembly Installed in Target Monolith
10/05	Mercury Delivered to Target Building
9/05	Completed linac commissioning; Operated at 960 MeV
8/05	Flags (US, TN, SNS) Raised at CLO for First Time
8/05	Last of 18 Top Shield Blocks Installed in Target Monolith
8/05	$4.5 Million Reprogrammed from SING to SNS-OPC
8/05	Ring Crane Disassembly and Removal Completed
8/05	Installed Proton Beam Window in Target Monolith
8/05	Secretary of Energy Bodman Tours SNS Target Building
7/05	Neutron Guide for Backscattering Instrument Installed
7/05	Full Energy Linac Accelerator Readiness Review & Authorization to Begin Commissioning
7/05	Target Inner Reflector Plug Delivered to the Site
6/05	Target Module Installed on Target Trolley
6/05	SC Semi-Annual Project Review
6/05	Particle Accelerator Conference (PAC) Held in Knoxville
5/05	First Target Module Delivered to the Site
5/05	Site "Hand-Off" from Knight-Jacobs to ORNL
4/05	Beneficial Occupancy of the Target Building
4/05	Target Cryogenic System Cooled to Operating Level; 20K
3/05	IG Completes Audit Begun in 10/04 with Letter Report; No Recommendations
3/05	Last Cryomodule Delivered to Site from Jlab
3/05	May 04 Event, Originally Recorded as the First Construction Lost Workday Away, was Reclassified to Non-Work Related
1/05	Beneficial Occupancy of the Central Lab & Office Building (CLO)

1/05	First Non-Construction Lost Workday Away Recorded; Parking Lot Fall
1/05	Completed Warm Linac Commissioning
12/04	First Cryomodule Cooled to 4K
12/04	2K Cryogenic System First Operated
11/04	SC Semi-Annual Project Review
10/04	IG Audit Begun; Project Completion & Transition to Operations
9/04	Linac Smoke Alarm for Smoldering Steel Shot Bags Near Cryogenic Heater
9/04	Accelerator Systems Advisory Committee Meeting
9/04	Target Carriage Placed in Service Bay
8/04	First Proton Beam through Warm Linac (DTL & CCL)
8/04	Mercury Pump & Heat Exchanger Installed in Target Service Bay
8/04	Last (of 32) Ring Half-Cells Delivered from BNL
8/04	Target Completion Review Conducted
8/04	Initial Cool Down of 4k Cryogenics System
7/04	First High-Beta Cryomodule Delivered to Oak Ridge
7/04	RTBT Backfill Placed to Complete Settlement Load
7/04	First Core Vessel Insert Installed in Target Monolith
6/04	Project Office Staff Relocated to Central Lab Office (CLO) Building
6/04	All Warm Linac Structures (DTL 1-6 & CCL 1-4) Placed in Tunnel
5/04	First Construction Lost Workday Away Case Recorded; Slip & Fall
5/04	SC Semi-Annual Project Review
5/04	Two Million Non-Construction Hours Without Lost Workday Away
5/04	Three Million Construction Hours Without Lost Workday Away
5/04	Last of 4 CCL Modules Arrives on Site
5/04	Earned Value Certification Review Successfully completed
4/04	Los Alamos SNS Division Dissolved

4/04	Completed ARR for DTL 1-3 and Accelerated First Beam
3/04	Began Instrument Installation – Placed Backscattering Tank
2/04	Civil Engineering Research Foundation Review of SNS
12/03	Awarded Last Multi-$Million Procurement; Target Inner Reflector Plug
12/03	Began Commissioning Cryogenic Systems
12/03	First 5MW Klystron Arrives on Site
11/03	1mA Beam Accelerated through DTL Tank 1; Supports 1MW SNS Power
11/03	First of Four CCL Module Arrives on Site
11/03	SC Semi-Annual Project Review
10/03	Installed Target Core Vessel
10/03	Review of Jlab Cryomodule Production Difficulties
9/03	Site Transitioned to Permanent Utilities with Final CUB Turnover
9/03	Hurricane Isabel Interrupts Jlab Cryomodule Production
9/03	RATS I Building Vacated; Staff and Equipment Relocated to Site
9/03	Target PSAR Update No. 3 Reviewed
9/03	Accelerator Systems Advisory Committee Meeting
9/03	Neutron Scattering Workshop for Chemistry, Chemistry/Biology Interface, and Sample Environment held at Florida State University
8/03	Transported First Proton Beam through DTL Tank 1
8/03	Completed Design of the Accumulator Ring
8/03	Began Ring Equipment Installation
7/03	Secretary Abraham Visits SNS Construction Site
7/03	DOE Review of the “End Game Plan”
6/03	Completed Design of the Target System
6/03	First Cryomodule from Jlab Delivered to Oak Ridge
6/03	Hosted PARS Workshop in Oak Ridge
6/03	TVA Substation Dedicated

6/03	Beneficial Occupancy of the Ring Tunnel
5/03	SC Semi-Annual Project Review
4/03	Accumulated 2,000,000 Construction Hours without Lost Workday Case
4/03	Open House for Local Community
4/03	Began Target Equipment Installation
4/03	Began Linac Equipment Installation
4/03	CFO Agrees with SNS Position on 11/01 Inspector General Audit Report
3/03	DOE Issues Project Management Manual 413.3
3/03	ASAC finds DTL Recovery, High Power RF, and Staffing Levels Need Particular Attention
1/03	Beneficial Occupancy of the Full Linac Tunnel
1/03	Beneficial Occupancy of the Klystron Building
1/03	“ProjectWise” replaces “iMAN” as Official Project Records System.
1/03	BCP-03-1 Accumulated Changes at Levels 1 & 2 Across the Project
12/02	First Proton Beam Accelerated in Front End System RFQ (2.5MeV)
12/02	Beneficial Occupancy of Full Linac Tunnel
12/02	Beneficial Occupancy of the CHL/RF Building
11/02	SC Semi-Annual Project Review
11/02	Begin Commissioning of the Front End System
10/02	Beneficial Occupancy of Linac & Klystron Buildings to 225MEV
10/02	Beneficial Occupancy of the Front End Building
10/02	First High Voltage Converter Modulator Delivered to Site
10/02	DOE Approval of the Front End Accelerator Readiness Review
10/02	Project Conventional Facilities Staff Relocated to the Construction Site
10/02	FSAD for the FELK Approved
10/02	ASAC Recommends and Project Implements LLRF Management Change; LANL to ORNL/LBNL/LANL

10/02	FY 03 Budget Stalled in Congress - No Impact from Extended Continuing Resolution
10/02	Liquid Mercury Target Retained Based on Resolution of Pitting Issues
9/02	"Begin Linac Installation" (Level 2 Milestone) Missed Because of Drift Tube Manufacturing Issues
9/02	Completed Design of the Global Control System
9/02	BCP-02-4 Growth in Target Building and CLO Cost Estimates
8/02	RATS Building (RATS-II) on Construction Site Placed into Operation
8/02	Celebrated 1,000,000 Construction Hours without Lost Workday Case
8/02	PSAR Update 3 Reviewed and SER Approved, Resolved Seismic Question
7/02	Setup Operation of the Manitowoc Ring Crane
7/02	Subcontract Award for Target Bldg. General Construction
7/02	Subcontract Award for CLO General Construction
6/02	Instrument Development Team (IDT) with Canada
6/02	Established Web-Based Project Action Tracking System
6/02	CMCIP Carrier Change after September 11 Terrorist Attack
6/02	LBNL Delivers the Front End System to Oak Ridge
6/02	SNS Users Meeting in Knoxville; American Conference on Neutron Scattering
5/02	SC Semi-Annual Project Review
5/02	MOU Signed with TVA to Supply Site Power
4/02	Open House for Local Community
4/02	BCP-02-3 Revise Ring Schedule Milestone
4/02	BCP-02-2 Accumulated Changes to Conventional Facilities
3/02	Experimental Facilities Division Management Change; Mason (Gabriel Acting) to Anderson
3/02	SNS Construction Experiences a 100-Year Rain Event
3/02	BNL Management Change; Weng to Wei
1/02	Bevatron Shield Blocks Arrive at the SNS Site

1/02	Subcontract Award for Ring and Service Bldg. General Construction
12/01	Project Disagrees with 11/01 Inspector General Audit Report
12/01	Subcontract Award for Site Utilities General Construction
12/01	Subcontract Award for CHL/RF General Construction
12/01	BCP-02-1 Accumulated Level 2 Changes Across the Project
11/01	SC Semi-Annual Project Review
11/01	Subcontract Award for CUB General Construction
11/01	Inspector General Issues Scope Audit Results
11/01	Subcontract Award for HEBT, Ring, RTBT Concrete
10/01	FY 02 Congressional Budget of $291.4M Equals Request
10/01	Project-Wide Estimate to Complete Analysis
10/01	Microframe Program Management (MPM) Adopted as Project Cost Module
10/01	BCP-01-5 Accumulated Changes to the Linac
9/01	Subcontract Award for FELK General Construction
9/01	BES Grant to Instrument Development Team (IDT) at California Institute of Technology
8/01	BES Grant to Instrument Development Team (IDT) at Penn State
7/01	Subcontract Award for Target Bldg. Substructures
7/01	Sextupole Magnets added to the Ring Scope
5/01	SC Semi-Annual Project Review
5/01	Accelerator Systems Division Change; Kustom to Holtkamp
5/01	Open House for Local Community
5/01	Deputy Project Director Named; Strawbridge
5/01	SNS Conventional Facilities Management Change; Etheridge to Chargin
4/01	Subcontract Award for Front End and Linac Concrete
4/01	Inspector General Begins Project Scope Audit
3/01	BCP-01-4 Accumulated Level 2 Changes Adopted at Level 1

3/01	BCP-01-3 Accumulated Level 2 Changes
3/01	Project “Re-Integrated “with ORNL; Project Director/Associate Lab Director
3/01	SNS Project Management Change; Moncton to Mason
2/01	Receiving, Acceptance, Test, and Storage (RATS) Building Occupied
2/01	EPICS Extended to Conventional Facility Control System
12/00	SC Semi-Annual Project Review (Part 2)
10/00	BCP-01-2 Accumulated Conventional Facilities Changes
10/00	BCP-01-1 Adopted 1:1 RF Architecture to the Linac
10/00	SC Semi-Annual Project Review (Part 1)
10/00	DOE Issues Project Management Order 413.3
10/00	FY 01 Congressional Budget \$278.0M vs \$278.5M Request TPC: \$1,411.7+0.0 = \$1,411.7; Complete: 6/06+0 = 6/06
10/00	Conventional Facilities Title I Estimate Drives Cost Reduction Effort
9/00	BCP-00-9 adding Target Building Micropiles
9/00	High-Speed Video Network Established for Multi-Site Communication
9/00	Steel Pipe Pile Subcontract Awarded for Target Building Foundation
8/00	LANL Management Change; Miller to Rej
5/00	SC Semi-Annual Project Review
5/00	CMCIP Insurance Program Strategy Adopted
5/00	SNS Users Meeting in Washington DC
5/00	Inspector General Audit Finds SNS Management Systems In-Place
5/00	BCP-00-7 Superconducting Linac Adopted
4/00	BCP-00-8 for Ring Upgrade to 1.3GeV
4/00	BCP-00-6 Revisions to CLO Building
4/00	BCP-00-5 Revisions to Project Support Planning
4/00	BCP-00-4 Removing Sales Tax; TPC \$1440M - 28.3 = \$1411.7M
4/00	BCP-00-3 for FY00 Budget Shortfall

4/00	Open House for Local Community
4/00	ORNL Contractor Change from Lockheed Martin to UT-Battelle
3/00	SC Semi-Annual Project Review; Management Restructuring Viewed as Complete
2/00	BCP-00-2 Revised Schedule Milestones
2/00	Baseline Change Proposal (BCP-00-1) for Target System Changes
2/00	Project Team Relocated to 701 Scarboro Bldg.
2/00	“iMAN” Implemented as Official Project Records System.
2/00	First PSAR Reviewed and SER Approved
1/00	Revised Ring Layout from “α” to “Ω” Design
1/00	Jefferson Laboratory Joins the SNS Lab Partnership
12/99	SNS Site Clearing Begins
12/99	SNS Ground Breaking; Speeches by the Vice President, Governor, & Others
12/99	OMB Approves Project Funding Profile Plan for FY 01-06; FY 00 Congressional Budget $117.9M vs $241.0M Request TPC: $1,360M + 80 = $1,440.0M; Complete: 12/05+6 = 6/06
12/99	Superconducting RF Linac Potential Presented to ASAC
11/99	Critical Decision 3 (Start Construction) Approved by Science Director Krebs
11/99	House Science Subcommittee on Energy and Environment recognizes Progress on SNS Issues and Supports Continued Line Item Funding
11/99	SNS Conventional Facilities Division Director Named; Etheridge
10/99	Began Receipt of Duratek Shielding Blocks
10/99	Established Web-Based Project Change Control System
10/99	Chartered OFCCP Megaconstruction Project Oversight Committee
10/99	DOE Project Manager Change; Watkins to Price
9/99	Implement SNS Human Resources Working Group Recommendations
8/99	LANL Management Change; Hartline to Miller
7/99	SC Semi-Annual Review and Level 1 Baseline Established/Validated

7/99	Upgraded Technical Performance Goal to 2MW
6/99	EIS Record of Decision Signed by Secretary Richardson
5/99	Safety Strategy Chosen (Nuclear Facility SAR and Accelerator SAD)
4/99	Final Environmental Impact Statement Published
3/99	House Science Subcommittee on Energy and Environment reports Project Management and Financial Difficulties
3/99	SNS Project Management Change; Appleton to Moncton
1/99	SC Semi-Annual Project Review
11/98	LANL Management Change; Jason (Hardekopf Acting) to Hartline
11/98	Users Meeting in Oak Ridge; SNS Neutron Instrumentation Workshop and Oak Ridge Neutron Users Meeting
10/98	FY 99 Congressional Line Item Approved ($130M vs $157.0M Request) TPC: 1,332.8+27.2 = $1,360.0; Complete: 9/05+3 = 12/05
6/98	SC (Energy Research) Project Readiness Review
3/98	Architect-Engineer/Construction Manager RFP Issued.
3/98	Neutron Science Symposium in Washington D.C.; “Symposium on the Scientific and Industrial Opportunities”
1/98	DOE Project Manager Selected; Watkins
12/97	Project Execution Plan (Base Document) Approved by Secretary Peña
12/97	Critical Decision 2 (Project Baseline) Approved by Secretary Peña
10/97	Validation of FY 1999 Line Item Budget Request by SC
10/97	Congress Appropriates $23M in FY98 for Project Preparation
10/97	LBNL Management Change; Gough to Keller
9/97	Independent Cost Estimate (ICE) Completed by Burns & Roe
9/97	EIS Public Scoping Period Completed
7/97	EIS Notice of Intent Published
7/97	Integrated Project Controls Broken Out as Separate WBS Level 2 Element
6/97	SC (Energy Research) Review of Conceptual Design Report (CDR:6-Yr to Sept 04 @ $1,266M) (Revised: 7-Yr to Sept 05 @ $1,332.8)

5/97	Conceptual Design Report Completed
1997	Tennessee Appropriates $8 Million and Begins Conceptual Design of the Joint Institute of Neutron Science
11/96	Neutron User Workshop in Oak Ridge; “Workshop on Instrumentation Needs and Performance Metrics”
10/96	Congress Appropriates $8 Million to Complete Conceptual Design
8/96	Critical Decision 1 (Mission Need) Approved
8/96	Pre-Conceptual Estimates of $1 billion and 6 years Established
1996	EPICS Identified as the Integrated Controls System
1996	Five Laboratory Collaboration Established
1996	Basic Energy Sciences Advisory Committee Report(Russell Panel) Supports New Short Pulsed Accelerator-Based Neutron Source
10/95	Congress Appropriates $8 Million for Conceptual Design
2/95	President’s Budget Cancels ANS; Proposes SNS as Alternative
1994	Nobel Prize in Physics to Clifford Shull & Bertram Brockhouse for Neutron Scattering Materials Investigation
1993	Basic Energy Sciences Advisory Committee Report(Kohn Panel) “Neutron Sources for America’s Future” Stating Need for Both Reactor & Accelerator-Based Neutron Sources
1984	Seitz-Eastman Report “Major Facilities for Materials Research and Related Disciplines” Stating Need for New Neutron Source

APPENDIX B: EAC BY WBS LEVEL 2

Table B-1. SNS May 2006 estimate at completion ($M)

WBS		May 2006
LINE ITEM		
1.02 Project Support		70.9
1.03 Front End Systems		20.9
1.04 Linac Systems		310.6
1.05 Ring & Transfer System		147.3
1.06 Target Systems		116.5
1.07 Instrument Systems		66.2
1.08 Conventional Facilities		401.9
1.09 Integrated Control Systems		57.9
Subtotal		1192.3
OTHER PROJECT COSTS		
R&D		99.9
Pre-Ops		113.0
Subtotal		212.9
TOTAL PROJECT		
EAC		1405.2
Undistributed Budget in Pre-Ops		6.1
FY06 Rescission		0.4
	Total	1411.7

APPENDIX C: COST BREAKDOWN BY PARTICIPANT

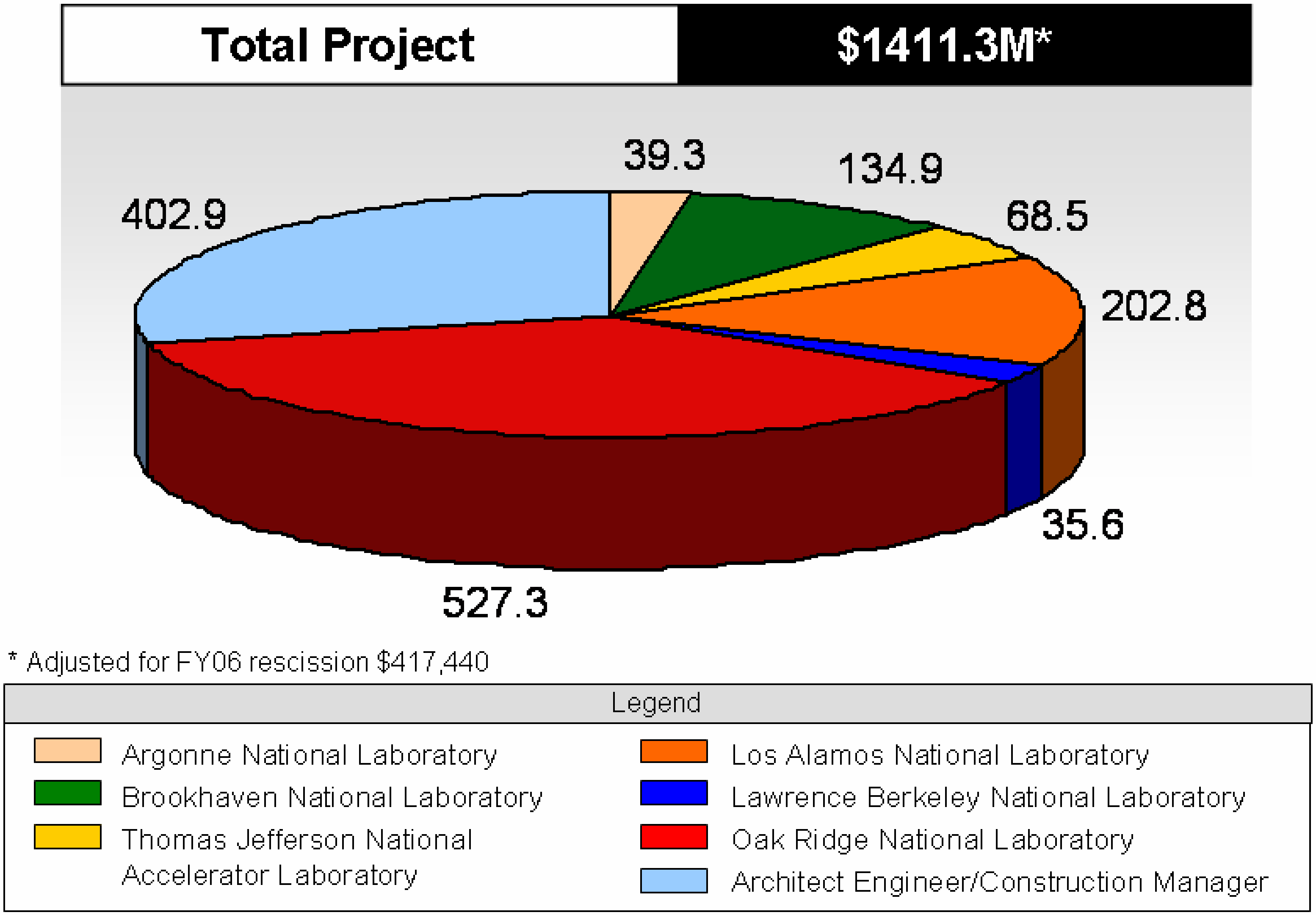


Fig. C-1. Allocation of budget authority ($M).

Table C-1. SNS participants annual funding ($M)

Laboratory	Prior	FY 1999	FY 2000	FY 2001	FY 2002	FY 2003	FY 2004	FY 2005	FY 2006	Total
Argonne National Laboratory	1.3	$3.9	$9.2	$8.5	9.9	7.4	-0.7	-0.3	0.2	39.3
Brookhaven National Laboratory	5.2	11.6	17.2	26.9	29.4	28.6	10.5	5.5		134.9
Thomas Jefferson National Accelerator Laboratory	0	0	11.8	22.4	22.6	6.7	4.1	0.9		68.5
Los Alamos National Laboratory	7.7	18.3	30.3	61.1	57.9	23.5	3.7	0.3		202.8
Lawrence Berkeley National Laboratory	5.2	6.4	8.0	9.2	4.6	1.5	0.4	0.3		35.6
AE/CM		13.1	39.1	83.5	91.1	63.5	62.9	24.1	25.6	402.9
Oak Ridge National Laboratory	19.2	76.7	2.3	66.4	75.9	93.8	61.4	86.8	44.9	527.3
Total	38.6	$130.0	$117.9	$278.0	291.4	225.0	142.3	117.6	70.7	1411.3

APPENDIX D: EAC IN TERMS OF EDIA

Table D.1. EAC in terms of EDIA

		Burdened, escalated $M					
TOTAL ESTIMATED COST, TEC		**EAC**	**EDI**	**PM**	**Procure**	**Labor**	**Install**
1.2	**Project Support**	70.9	-	46.3	24.7	-	-
1.3	**Front End Systems**	20.9	7.2	3.4	6.6	3.1	0.6
1.4	**Linac Systems**	310.6	38.4	23.1	185.6	37.0	26.5
1.5	**Ring and Transfer System**	147.3	28.6	9.2	56.2	41.0	12.3
1.6	**Target Systems**	116.5	30.3	8.4	58.6	0.7	18.6
1.7	**Instrument Systems**	66.2	23.8	8.2	29.2	1.9	3.1
1.8	**Conventional Facilities**	401.9	51.7	16.4	332.0	1.3	0.6
1.9	**Integrated Control Systems**	57.9	25.9	4.8	17.5	4.4	5.2
	Subsystem Subtotals	**1,192.3**	**206.0**	**119.7**	**710.3**	**89.3**	**66.9**
	Contingency	**0.0**					
	FY06 Rescission	**0.4**					
	TEC	**1,192.7**			EDI = 23.8% of Procurement, Labor, and Installation EDIA = 37.6% of Procurement, Labor, and Installation		
OTHER PROJECT COSTS, OPC	**R&D/PreOps**	**212.9**					
	Remaining Undistributed	**6.1**					
	Total Project Cost, TPC	**1,411.7**					

APPENDIX E: COST ESTIMATE HISTORY

Table E.1 Cost estimate history ($M)

WBS ELEMENT	**CDR** **06/97**	**CD-2; 1st DOE Baseline** **12/97**	**DOE Review** **06/98**	**DOE Review** **01/99**	**1st SC Baseline** **07/99**	**DOE Review** **03/00**	**DOE Review** **10/00**
1.2 Project Support	47.6	53.4	54.5	35.6	50.5	70.2	75.5
1.3 Front End	17.5	20.0	17.2	14.3	18.4	18.3	19.2
1.4 Linac Systems	267.1	276.4	260.0	267.4	222.0	239.7	256.8
1.5 Ring Systems	136.4	142.0	139.9	131.4	125.3	127.5	130.5
1.6 Target Systems	84.9	91.1	79.3	77.7	79.9	85.9	91.9
1.7 Instruments	47.6	49.5	46.4	45.6	97.3	92.6	93.0
1.8 Conventional Fac.	315.7	321.4	287.0	279.7	256.6	266.0	300.3
1.9 Control Systems	Distributed Above	Distributed Above	60.7	62.9	54.4	56.9	58.3
Subtotal	916.8	953.8	945.0	914.6	904.3	957.1	1,025.5
Sales & Use Tax	Distributed In R&D & Line Item	Distributed In R&D & Line Item	41.4	35.4	Distributed 1.0 OPC 27.3 LI	0.0	0.0
Contingency	179.3	185.0	167.3	219.7	255.2	235.6	167.2
TEC	1,096.1	1,138.8	1,153.7	1,169.7	1,159.5	1,192.7	1,192.7
Pre-Project and R&D	86.6	98.0	108.9	100.5	99.5	104.1	107.8
Pre-Operations	62.3	70.7	70.2	89.8	101.0	114.9	111.2
Contingency	21.0	25.3	0.0	0.0	0.0	0.0	0.0
OPC	169.9	194.0	179.1	190.3	200.5	219.0	219.0
TPC	1,266.0	1,332.8	1,332.8	1,360.0	1,360.0	1,411.7	1,411.7
Project Complete	9/04	9/05	9/05	12/05	12/05	6/06	6/06

WBS ELEMENT	DOE Review 05/01	DOE Review 11/01	DOE Review 05/02	DOE Review 11/02	DOE Review 05/03	DOE Review 11/03
1.2 Project Support	75.3	72.3	75.7	75.7	75.7	75.9
1.3 Front End	19.3	19.3	21.0	21.1	20.8	20.8
1.4 Linac Systems	264.3	272.4	292.1	301.3	304.9	314.6
1.5 Ring Systems	145.3	146.2	150.9	147.9	147.3	142.1
1.6 Target Systems	93.0	95.3	101.9	103.2	106.4	108.1
1.7 Instruments	60.0	62.3	63.4	63.3	63.3	63.3
1.8 Conventional Fac.	307.5	310.7	323.6	345.1	355.3	376.9
1.9 Control Systems	57.5	58.6	59.5	59.6	59.6	59.6
Subtotal	1,022.2	1,037.0	1,088.1	1,117.2	1,133.4	1,161.4
Sales & Use Tax	0.0	0.0	0.0	0.0	0.0	0.0
Contingency	170.5	155.7	104.6	75.5	59.3	31.3
TEC	1,192.7	1,192.7	1,192.7	1,192.7	1,192.7	1,192.7
Pre-Project and R&D	103.7	103.8	101.2	101.2	101.2	101.9
Pre-Operations	115.3	115.2	117.8	117.8	117.8	117.1
Undistrib. Budget	- -	- -	- -	- -	- -	- -
OPC	219.0	219.0	219.0	219.0	219.0	219.0
TPC	1,411.7	1,411.7	1,411.7	1,411.7	1,411.7	1,411.7
Project Complete	6/06	6/06	6/06	6/06	6/06	6/06

WBS ELEMENT	DOE Review 05/04	DOE Review 11/04	DOE Review 06/05	DOE Review 11/05	DOE Review 05/06	Final EAC
1.2 Project Support	75.6	75.1	72.1	71.4	70.8	70.9
1.3 Front End	20.8	20.8	20.8	20.9	20.9	20.9
1.4 Linac Systems	316.9	316.8	314.9	314.3	310.4	310.6
1.5 Ring Systems	142.0	142.4	143.9	146.7	147.3	147.3
1.6 Target Systems	108.2	109.0	114.8	115.3	116.1	116.5
1.7 Instruments	63.3	63.5	63.8	64.5	65.7	66.2
1.8 Conventional Fac.	378.9	379.9	391.1	395.8	400.4	401.9
1.9 Control Systems	59.8	59.8	59.8	58.5	57.9	57.9
Subtotal	1,165.5	1,167.4	1,181.4	1,187.4	1,189.5	1,192.3
Sales & Use Tax	- -	- -	- -	- -	- -	- -
Contingency	27.2	25.3	11.3	5.3	2.7	0
Rescission					0.4	0.4
TEC	1,192.7	1,192.7	1,192.7	1,192.7	1,192.3	1,192.7
Pre-Project and R&D	100.0	100.0	100.0	100.0	99.9	99.9
Pre-Operations	119.0	119.0	104.6	107.9	113.5	113.0
Undistrib. Budget	- -	- -	14.4	11.1	5.6	6.1
OPC	219.0	219.0	219.0	219.0	219.0	219.0
TPC	1,477.7	1,411.7	1,411.7	1,411.7	1,411.7	1,411.7
Project Complete	6/06	6/06	6/06	6/06	5/06	5/06

APPENDIX F: USES OF CONTINGENCY

End of Fiscal Year	% Project Complete	TPC $(K)	Line Item Contingency $(K) Remaining
FY 98	2	1,333,000	$200,000
FY 99	7	1,360,000	$252,000
FY 00	14	1,411,700	$184,000
FY 01	30	1,411,700	$156,000
FY 02	50	1,411,700	$67,300
FY 03	72	1,411,700	$31,300
FY 04	87	1,411,700	$18,000
FY 05	93	1,411,700	$5,300
FY 06[1]	100	1,411,700	$0

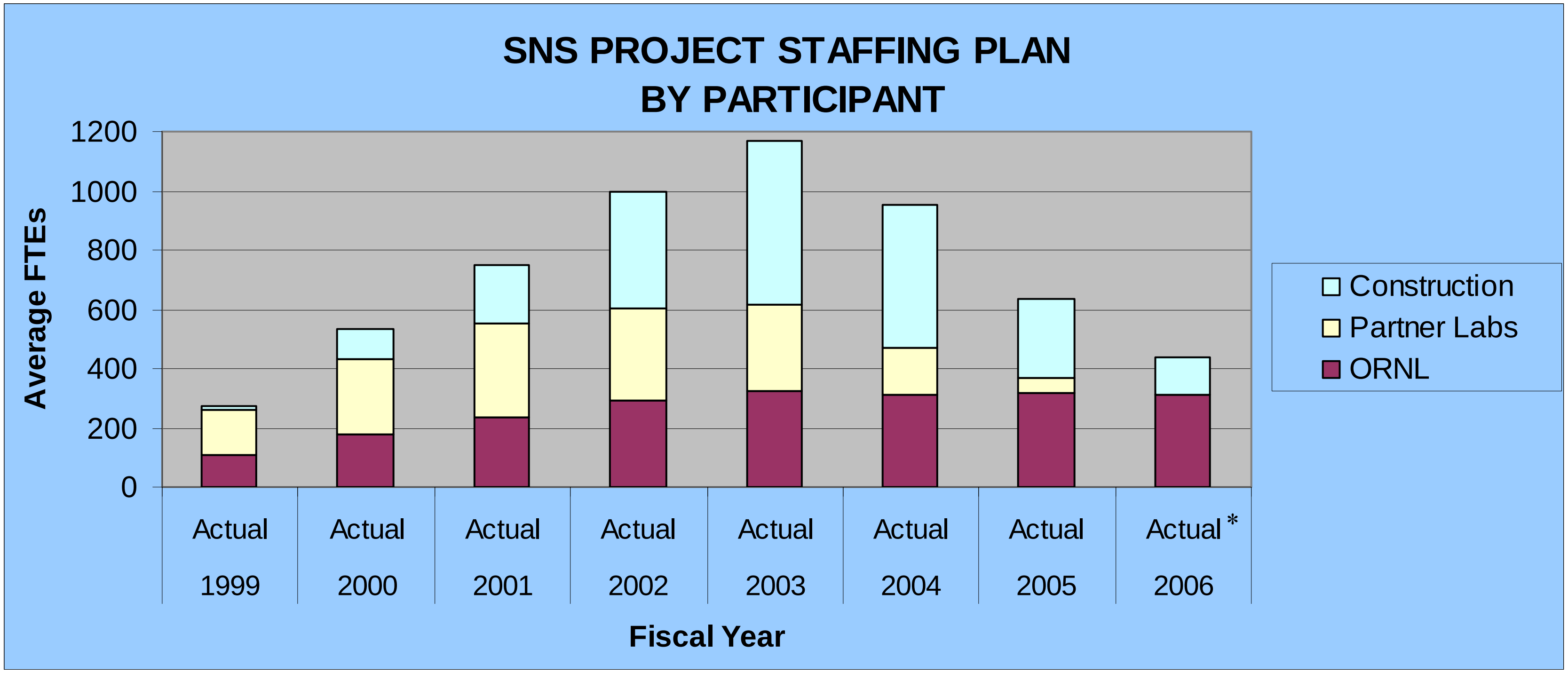
NOTE: Contingency on TEC.

[1] FY06 based on May 2006 EAC.

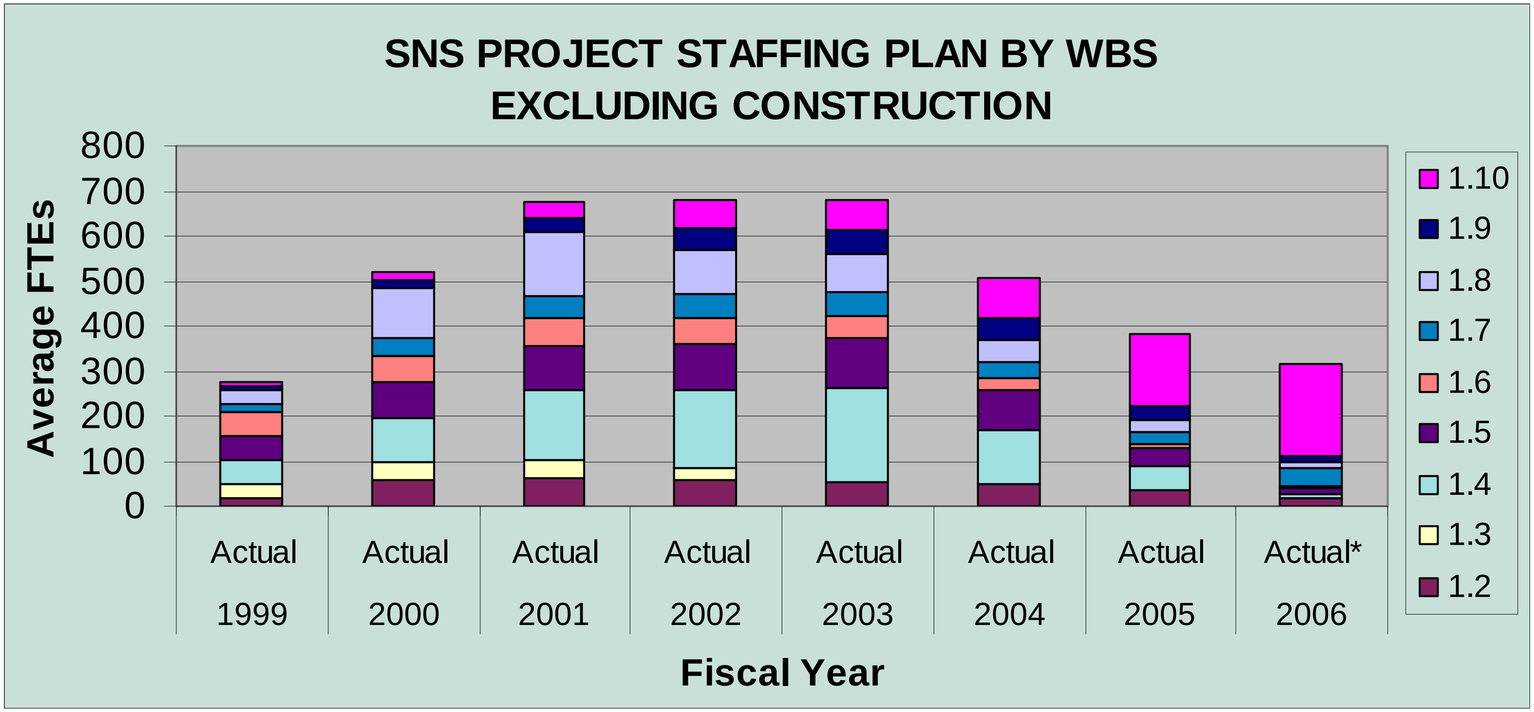
WBS	July 1999 BAC	May 2006 EAC	Major uses of contingency
LINE ITEM			
1.02 Project Support	50.5	70.8	Underestimating of needs along with added project management costs as a result of the collaboration
1.03 Front End Systems	18.4	20.9	Installation/Start-up
1.04 Linac Systems	226.8	310.4	~50% due to change to Superconducting linac; DTL and SCRF cavity production problems; underestimate of installation costs
1.05 Ring & Transfer System	125.3	147.3	~50% design changes; underestimate of installation costs
1.06 Target Systems	80.1	116.1	~50% design changes; ~15% contract awards; underestimate of installation costs
1.07 Instrument Systems	97.3	66.2	Retreat from aggressive goals to a level well in excess of the CDR estimate
1.08 Conventional Facilities	256.6	401.9	~35% of increase due to contract awards higher than baseline budget;~30% increased work scope; ~10% based on differing site conditions; additional staff needs; fees (incentive/insurance/claims)
1.09 Integrated Control Systems	54.3	57.9	Superconducting linac
Subtotal	909.3	1192.3	
Contingency $	250.2	0.0	
TOTAL	1159.5	1192.3	
OTHER PROJECT COSTS			
R&D	103.9	99.9	
Pre-Ops	96.6	113.0	Commissioning staff and spares
Undistributed	0.0	6.1	
TOTAL	200.5	219.0	
FY06 Rescission		0.4	
TPC	1360.0	1411.7	

Note: July 1999 used as reference since it was the first DOE-SC baseline.

APPENDIX G: STAFF SUMMARY



*Through April 30, 2006



*Through April 30, 2006

APPENDIX H: MAJOR EXTERNAL REVIEWS

Table H-1. Major External Reviews

No.	Date	Sponsor	Review Topic/Report	Purpose
1.	6/97	DOE-ER	Review of the NSNS	CDR Approval
2.	6/97	DOE-ER	Independent Cost Estimate (Burns and Roe)	CDR Validation
3.	6/98	DOE-ER	Technical, Cost, Schedule, and Management Review	Readiness for Title I Design
4.	9/98	DOE-ORO	DOE Project Review	Readiness for FY99 Funding
5.	1/99	DOE-ER	Technical, Cost, Schedule, and Management Review	Status Review
6.	1/99	DOE-FM	External Independent Review of the SNS (EG&G)	Hse Rpt 105-271
7.	3/99	GAO	SNS Management Assessment Letter Report 141297	Congressman Sensenbrenner Report
8.	7/99	DOE-SC	Baseline Review	DOE Level 1 Baseline Review
9.	10/99	DOE-ECM	Independent Review of the SNS (Burns and Roe)	FY 2000Appropriations Report
10.	12/99	DOE-SC	Mini-Review of Project Management Systems	Post CD-3 Commitment
11.	2/00	DOE-IG	Management of SNS Letter Report ER-L-00-04	Management Systems Audit
12.	3/00	DOE-SC	Technical, Cost, Schedule, and Management Review	Status Review
13.	5/00	DOE-SC	Conventional Facilities Mini-Review	Action Status From 3/00 Review
14.	10/00	DOE-SC	Technical, Cost, Schedule, and Management Review	Status Review
15.	5/01	DOE-SC	Technical, Cost, Schedule, and Management Review	Status Review
16.	11/01	DOE-SC	Report DOE/IG-0532	Project Audit

17.	5/02	DOE-SC	Technical, Cost, Schedule, and Management Review	Status Review
18.	6/02	DOE-IG	Technical, Cost, Schedule, and Management Review	System Audit
19.	11/02	DOE-SC	Technical, Cost, Schedule, and Management Review,	System Audit
20.	5/03	DOE-SC	Technical, Cost, Schedule, and Management Review	Status Review
21.	7/03	DOE-SC	End-Game Plan Mini-Review	Action from 5/03 Review
22.	11/03	DOE-SC	Technical, Cost, Schedule, and Management Review	Status Review
23.	5/04	DOE-SC	Technical, Cost, Schedule, and Management Review	Status Review
24.	5/04	DCMA	Earned Value Management Review	EVMS Certification
25.	7/04	GAO	Target Completion Review	Action from 5/04 Review
26.	7/04	GAO	DOE Contract Management for Major Projects GAO-05-123	Congress
27.	11/04	DOE-SC	Technical, Cost, Schedule, and Management Review	Status Review
28.	11/04	DOE-IG	Progress of the SNS Project Report OAS-L-05-05	Project Audit
29.	6/05	DOE-SC	Technical, Cost, Schedule, and Management Review	Status Review
30.	11/05	DOE-SC	Technical, Cost, Schedule, and Management Review	Status Review
31.	4/06	GAO	Cost and Schedule Changes on Major Projects	Revision Causes
32.	5/06	DOE-SC	Technical, Cost, Schedule, and Management Review	Validate Project Completion

APPENDIX I: LETTERS RELATED TO PROJECT COMPLETION

OAK RIDGE NATIONAL LABORATORY
MANAGED BY UT-BATTELLE FOR THE U.S. DEPARTMENT OF ENERGY

SNS

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Associate Laboratory Director
for the Spallation Neutron Source

May 31, 2006

Mr. Lester K. Price
Project Director
Spallation Neutron Source
U.S. Department of Energy
Oak Ridge Operations Office
Bethel Valley Road, Building 8600
Oak Ridge, Tennessee 37831-6476

Dear Les:

The goal of the Spallation Neutron Source (SNS) project was to design, construct, and commission into operation an accelerator-based, pulsed neutron research facility for studies of the structure and dynamics of materials that is substantially better than any other facility in the world. Key requirements, captured in the Level-0 baseline, were to complete a facility capable of ≥1 MW at a total project cost of $1,411.7M by the end of June 2006. This goal has been not only achieved but exceeded.

I am delighted to report that the SNS construction project was completed today, May 31, 2006, at an estimate at completion (EAC) of $1,405.2, meeting all of its performance milestones with a scope that exceeds what was originally envisaged at the time the project was approved.

Sincerely,

Thomas Mason

Thomas E. Mason

TEM:kfr

cc: I. S. Anderson
J. R. Haines
S. D. Henderson
N. R. Holtkamp
J. R. Lawson
J. B. Roberto
C. N. Strawbridge
J. Wadsworth

Department of Energy

Oak Ridge Office
P.O. Box 2001
Oak Ridge, Tennessee 37831

Date: June 1, 2006

To: Patricia M. Dehmer, Director
Office of Basic Energy Sciences, SC-22

Subject: **SPALLATION NEUTRON SOURCE (SNS) PROJECT COMPLETION**

I am pleased to inform you that the SNS Project has successfully met all the requirements for Critical Decision 4 (CD-4) Project Completion.

The technical scope, cost, and schedule baseline requirements for CD-4 are specified in the Project Execution Plan (PEP) and summarized below.

Level 0 Baseline	Requirement	Achieved
Technical Scope	Facility capable of at least 1 MW proton beam on target	1.4 MW facility capability
Total Project Cost	$1,411.7 million	$1,405.2 million
Completion Schedule	June 2006	May 2006

All project facility systems have been installed and tested and site infrastructure is in place. Over 4.3 million hours of construction work were completed without a lost workday injury. Safety documentation and accelerator readiness reviews, conducted in accordance with the Accelerator Safety Order, DOE O 420.2B, are complete. ORNL operating staff and procedures are in place. System performance testing on April 28, 2006, exceeded the PEP requirements of 1x10^{13} protons per pulse and 5x10^{-3} neutrons per steradian solid angle per incident proton.

The attached table presents in more detail how the lower tier PEP requirements were met. In addition, the Project Completion Report will provide a comprehensive summary of the as-built facility and demonstrate in detail how the requirements have been not only met, but in many cases, exceeded. A draft of that report has been provided separately. SNS will indeed be one of the world's premier science facilities.

If you have any questions, please call me at (865) 576-0730.

Les Price

Les Price
DOE Federal Project Director
Spallation Neutron Source

Attachment: SNS Project Completion Requirements

cc w/attachment:
J. Hoy, SC-223/GTN
D. Lehman, SC-1.3/GTN
B. Kong, ME-90/FORS
G. Boyd, M-1, ORO
G. Malosh, SC-10, ORO
M. Crow, AD-42, ORO
T. Mason, SNS

SNS PROJECT COMPLETION REQUIREMENTS

Technical Baseline	Status
Acquisition Executive (Level 0)	
Accelerator-based neutron scattering facility providing ≥1 MW proton beam power on target.	All facilities and equipment in place required to operate the SNS at 1.4MW proton beam on target.
DOE SC Program Office (Level 1)	
Facility Performance Test:	
1×10^{13} protons per pulse	1.75×10^{13} proton pulse delivered to the target
5×10^{-3} neutrons per steradian solid angle per incident proton measured viewing a moderator face.	42×10^{-3} neutrons per steradian solid angle per incident proton measured at beamline 7 moderator face.
Initial Complement of Five Instruments (3 to be installed; 2 to be procured):	
Backscattering Spectrometer	Installed and ready for experiment measurements.
Magnetism Reflectometer	Installed and ready for experiment measurements.
Liquids Reflectometer	Installed and ready for experiment measurements.
Small Angle Scattering Instrument	Partial installation with all components ordered.
Powder Diffractometer	Partial installation with all components ordered.
DOE ORO Project Office (Level 2)	
Final Safety Documentation	Final Safety Assessment Documents Proton Facilities – approved June 2005 Neutron Facilities – approved April 2006 Accelerator Safety Envelope Initial operations – approved April 2006
Facility Documentation (As-Built Drawings, and Operating and Maintenance Procedures, Manuals, etc)	Drawings and manuals recorded in SNS “ProjectWise” database.
Trained and Qualified Operating Staff	Approximately 450 staff in place; fully trained and qualified

Schedule Baseline	Status
Project Completion by June 2006	Completion Criteria Satisfied - May 2006

Cost Baseline	Status
Total Project Cost $1,411.7 million	Projected final total cost, based on estimated cost plus commitments thru May 2006 - $1,405.2 million

Department of Energy
Office of Science
Washington, DC 20585

Office of the Director

MEMORANDUM FOR CLAY SELL
DEPUTY SECRETARY

THROUGH INGRID A. C. KOLB
DIRECTOR
OFFICE OF MANAGEMENT

Ingrid Kolb

FROM: RAYMOND L. ORBACH
DIRECTOR
OFFICE OF SCIENCE

Raymond L. Orbach

SUBJECT: **<u>ACTION</u>:** Approval of Critical Decision 4 (CD-4), Project Completion, for the Spallation Neutron Source (SNS) project at Oak Ridge National Laboratory (ORNL)

ISSUE: The SNS project has successfully achieved all of its CD-4 objectives (technical, cost, and schedule). Thus, the project is ready for CD-4 to be approved by the Secretarial Acquisition Executive.

BACKGROUND: The purpose of the SNS project is to provide the Nation with an accelerator-based, pulsed neutron research facility for studies of the structure and dynamics of materials that is substantially better than any other facility in the world. Once it is fully operational, the SNS facility is expected to be used by 1,000-2,000 researchers each year and meet the U.S. need for neutron science capabilities well into the 21st Century.

The SNS project was executed over a period of about 10 years by a multi-laboratory partnership led by the SNS Project Office at ORNL. The other partners were Argonne National Laboratory, Brookhaven National Laboratory, Lawrence Berkeley National Laboratory, Los Alamos National Laboratory, and Thomas Jefferson National Accelerator Facility.

Briefly, the SNS facility consists of: (1) a Front End System, where a pulsed beam of negative hydrogen ions is produced; (2) a Linear Accelerator or Linac System, where the beam is accelerated to an energy of 1 billion electron volts; (3) a Ring and Transfer System, where the negative ions are converted into protons and then stored in very short, high intensity pulses and then directed onto; (4) a liquid mercury Target System, where neutrons are generated by spallation reactions and then moderated to lower energies; (5) Instrument Systems, which receive the neutrons through beam guides and where experiments are conducted; and (6) Conventional Facilities and site infrastructure, including a Central Laboratory and Office Building.

The Mission Need for SNS was approved in August 1996, followed by over three years of design and research and development activities. The Level 0 technical, cost, and schedule baselines were established when the SNS Project Execution Plan (PEP) was approved in December 1997, and the Start of Construction was approved in November 1999. The first major system, the Front End, was installed and commissioned in 2002, followed by the Linac during 2003 – 2005, and the Ring and Target during 2004 – 2006.

The SNS Level 0 baseline calls for all capital facilities necessary to achieve a proton beam power on target of at least 1 MW to be installed and certified to operate safely, a Total Project Cost of $1,411.7 million, and project completion by June 30, 2006.

As documented in the attached memo from the SNS Federal Project Director, and verified by the final DOE status review of the SNS project in early May 2006, these Level 0 baseline objectives have been achieved. In fact, the project was completed one month early, slightly under budget, and with no lost workday injuries in over 4 million construction work hours. Likewise, all of the lower level baseline objectives listed in the PEP have been attained, and the project was considered to be complete as of May 31, 2006. An SNS Project Completion Report is being prepared and will be submitted to the Office of Science in early June 2006.

SENSITIVITIES: None.

POLICY IMPACT: This action does not impact Department policy.

RECOMMENDATION: It is recommended that you approve CD-4 for the SNS project.

Approve: Clay Sell

Disapprove: __________

Date: 6/5/2006

Attachment

cc:
D. K. Garman, US
J. T. Campbell, Acting CF-1
J. S. Shaw, EH-1
J. A. Rispoli, EM-1
D. R. Hill, GC-1
R. L. McMullan, MA-50
M. P. Fischetti, MA-60
L. F. Brooks, NA-1
T. P. D’Agostino, NA-10
D. R. Lehman, SC-1.3
J. F. Decker, SC-2
P. M. Dehmer, SC-22
P. A. Montano, SC-22.3
J. C. Hoy, SC-22.3