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FEASIBILITY STUDY FOR THE IPNS UPGRADE, A 1-MW PULSED SPALLATION NEUTRON SOURCE TARGET STATIONS

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ABSTRACT

This paper describes the design of target stations for the IPNS Upgrade Pulsed Spallation Neutron Source.

1. Background

In 1992, the U. S. Department of Energy commissioned a Panel on Neutron Sources chaired by Walter Kohn, to provide advice on the future of neutron sources and the related scientific and technological applications in the United States. Under Panel auspices, a Review of Neutron Sources and Applications was held at Oak Brook, Illinois in September 1992. About seventy experts convened to (1) review the status of advanced research reactors and spallation sources and (2) provide an update on scientific, technological and medical applications. The Panel's recommendations were published in January 1993[1] and the report of the Panel's findings was published in January 1994[2]. The Panel recommended:

1: Complete the design and construction of the Advanced Neutron Source[a] according to the schedule proposed by the project.

2: Immediately authorize the development of competitive proposals for the cost-effective design and construction of a 1-MW PSS ... .

The recommendation for studies of 1-MW Pulsed Spallation Sources (PSS) followed consideration of technical problems, costs and opportunities relating to accelerators and targets, and of accessible scientific applications.

After the Panel discussions, two workshops further evaluated accelerator prospects (Santa Fe, February 1993)[3] and scientific applications of a 1-MW PSS (Argonne, May 1993)[4]. In early 1993, the DOE asked Lawrence Berkeley Laboratory to host a design study for a 1-MW PSS, but major funding for this study has not yet been authorized. In early 1994, the Neutron

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[a] The Advanced Neutron Source (ANS) at Oak Ridge National Laboratory was to produce neutron fluxes 5 times those at ILL (Grenoble) and provide facilities for isotope production and materials irradiation at least as good as those at the existing Oak Ridge HFIR reactor. Although the conceptual design has been completed and documented, funding of the program has been terminated. The Total Project Cost of the ANS would have been about $3.0 B.

Keywords: Argonne, Upgrade, Pulsed Neutron Source, Targets

Scattering Society of America established a subcommittee to oversee the studies and nominated a steering group to guide the efforts.

Site-specific studies of 1-MW PSSs begun in 1992 are continuing under local laboratory sponsorship at Argonne National Laboratory[5] and Los Alamos National Laboratory[6] in response to the Panel recommendations. These are feasibility studies, a step preceding full-blown conceptual design studies, which normally follow DOE decision and higher-level funding. Both studies have been documented and have undergone review.

Brookhaven National Laboratory[7] has launched a study of a "green field" 5-MW source, which is at an early stage. Most of that work is on accelerator questions. The system includes a 600 MeV linear accelerator feeding two 3.6 GeV Rapid Cycling Synchrotrons operating at 30 Hz each and delivering pulses shorter than 3 μsec at 10 and 60 Hz.

Recently, in early 1995, the Department of Energy designated Oak Ridge National Laboratory the "preferred alternative site" for a 1-MW pulsed spallation source and requested funds to pursue its conceptual design.

2. IPNS Upgrade Feasibility Study

The development of the design and the preparation of the Feasibility Study greatly benefited from the expertise in the Advanced Photon Source project. The methodologies used for this study were essentially identical to those used for the APS document[8] which we believe greatly enhance the quality and reliability of this study. The study required about three years.

The Upgrade uses buildings and infrastructure of the former high energy physics Zero Gradient Synchrotron (ZGS) at Argonne. The ZGS Ring Building houses the synchrotron, about 200 meters in circumference, and has adequate radiation shielding to accommodate the 1-MW accelerator system. Two of the former high-energy physics experimental buildings house the two target stations and associated neutron scattering instruments. It is estimated that the use of existing buildings saves about $175 million in construction costs.

The Feasibility Study document is complete[9].

The IPNS Upgrade will be the fourth in a series of pulsed spallation sources constructed at Argonne. The ZGS Intense Neutron Generator Prototype (ZING-P), built in 1973, was a test in which all the essential components of the pulsed spallation neutron source came together for the first time. Based on the ZGS 200-MeV prototype Booster-I synchrotron, ZING-P eked out a beam power of 100 W. ZING-P', a second prototype that used the present IPNS 450 MeV Rapid Cycling Synchrotron, operated very productively from 1977 through 1980. It achieved 2 kW of beam power. The IPNS, operational since 1981, produces 7 kW of beam power incident on uranium or enriched uranium targets.

3. Accelerator and Target Station Parameters

The IPNS Upgrade uses a 2 GeV rapid cycling synchrotron (RCS) delivering a time-average beam power of 1 MW. The choice of proton beam energy is determined by several factors, including neutron yield, heat removal from the target, ease of machine construction and serviceability, and available space in the ZGS Ring Building. The design is also influenced by the distribution of the deposited heat and the distribution of produced neutrons. Most experience to date has been confined to energies below 1 GeV. Monte Carlo studies[10] show that the power density distribution, neutron production distribution, and total yield of neutrons favor energies higher than 1 GeV, at least up to about 3 GeV, the code-imposed limit of the study. The calculations confirm that the neutron production rate for constant beam power is approximately proportional to the proton beam power within the range of proton energies studied. Additional studies show that higher energies are preferable due to the lower peak power density at the upstream end of the target for a given beam power. These calculations indicate that proton energies above 1.5 GeV are equivalent with respect to the thermal and neutronic design of the target and moderator systems.

The choice of 30 Hz as the source repetition frequency was based upon a survey of scientific requirements and an evaluation of preliminary designs for neutron scattering instruments for a 1-MW pulsed source. Two categories of instruments emerged from the study of scattering instruments, those for which 30 Hz is preferable, and those that require a lower frequency, for which 10 Hz is satisfactory. Few of the instruments we considered could efficiently use frequencies higher than 30 Hz. Two targets that operate at different frequencies provide the flexibility to serve both classes of instruments and double the available number of beamlines and instruments. The accelerator delivers one out of three pulses to the low-frequency station at 10 Hz, and the high-frequency station receives the remaining two pulses of the 30-Hz pulse train. The high-frequency target is capable of using the full 1 MW of beam power, that is, all the pulses of the 30-Hz pulse train.

Our preference is to have the highest possible energy and lowest possible current to minimize the impact of beam losses at synchrotron injection. This does not affect the neutron production rate, since the rate is proportional to the proton beam power. We chose a linac delivering 400-MeV H^- beam for injection into the rapid cycling synchrotron (RCS). The synchrotron accelerates a time-average proton beam current of 0.5 mA to 2 GeV. Figure 1 shows a general view of the IPNS Upgrade.

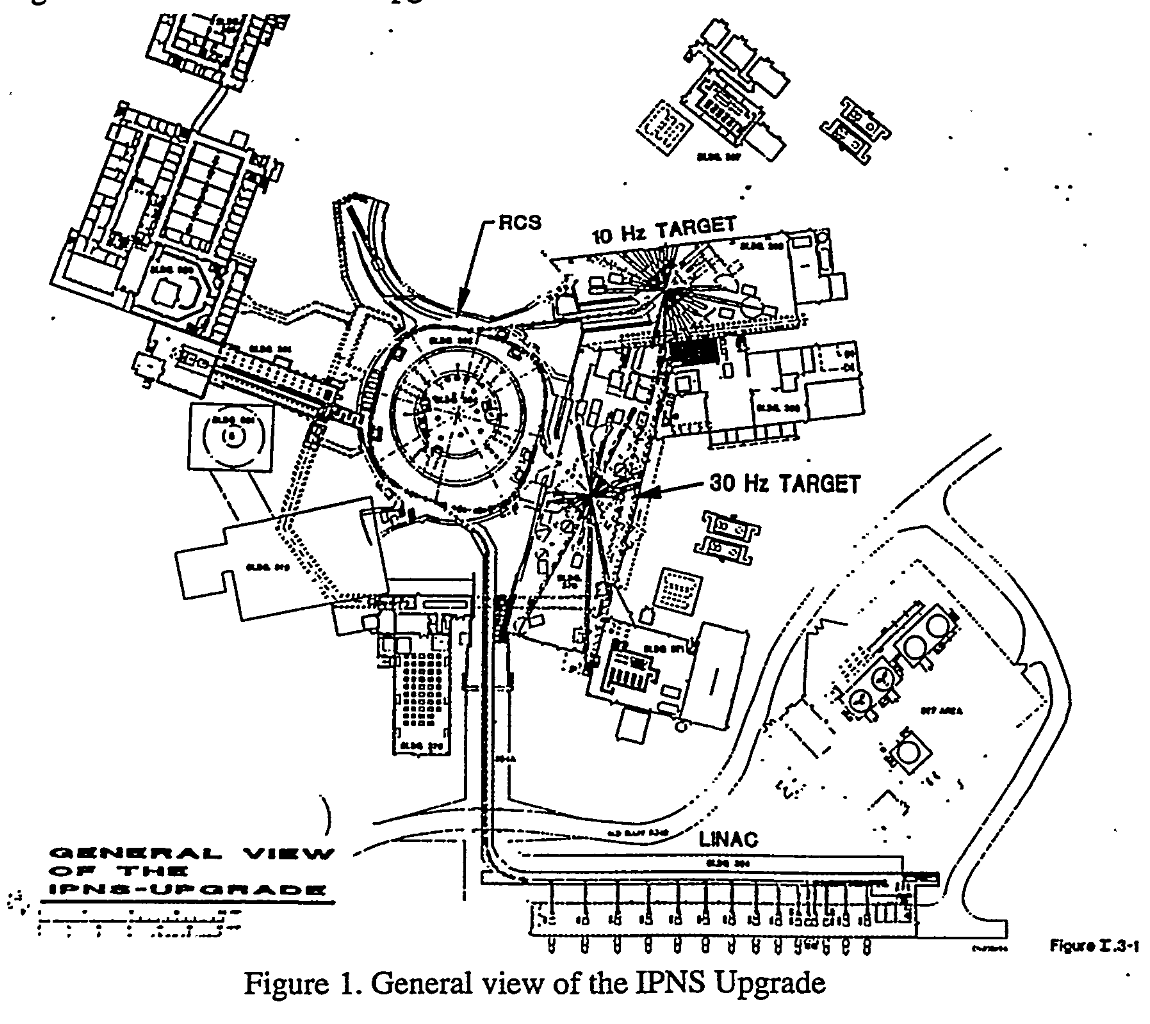

Figure 1. General view of the IPNS Upgrade

4. Accelerator Systems

The accelerator system is the subject of another paper in this conference. Table I summarizes the parameters of the IPNS Upgrade accelerator system.

Table I Accelerator Parameters

Parameters	Values	Units
Beam energy at extraction	2	GeV
Maximum beam energy attainable	2.2	GeV
Beam energy at injection	400	MeV
Beam average current	0.5	mA
Beam power	1.0	MW
Beam pulse length	<1	μsec
Synchrotron repetition rate	30	Hz
Synchrotron circumference	~200	m
Number of external proton beams	2	-
Number of extraction lines	2	-
Linac beam energy	400	MeV
Linac energy spread (95%)	±2.5	MeV
Linac repetition rate	30	Hz
Linac pulse current	44	mA
Linac pulse length	0.5	msec
Linac emittance (rms normalized)[a]	$1.0 \times 10^{-6} \pi$	m

5. Neutron Scattering Capabilities

Shielded proton beam transport lines carry two extracted proton beams to the two target stations. Each station contains a neutron-producing target consisting of water-cooled tungsten plates in two sections. Water, liquid methane, and liquid hydrogen moderators positioned close to each target slow down neutrons from the primary source energies (about 1 MeV) to useful energies (less than about 10 eV). Reflectors of beryllium metal or of beryllium and heavy metal surround the moderators to enhance the intensities of the neutron beams. Decouplers and heterogeneous poisons within the moderator-reflector system tailor the spectra and pulse characteristics of the neutron beams. Massive steel and concrete shields surround the targets and moderators and provide multiple levels of confinement of radioactive materials within. Because some components of the target have finite lifetimes and because changes need to be made over the years to accommodate changing demands of the instruments, each target station is equipped with a hot cell and remote handling equipment designed to facilitate moving and servicing the internal components. Figure 2 shows the target stations of the IPNS Upgrade.

Irradiation facilities for neutron activation and fast neutron materials irradiation applications are arranged close to the targets. These irradiation facilities do not interfere with the neutron scattering application. The irradiation facilities are accessible during operation.

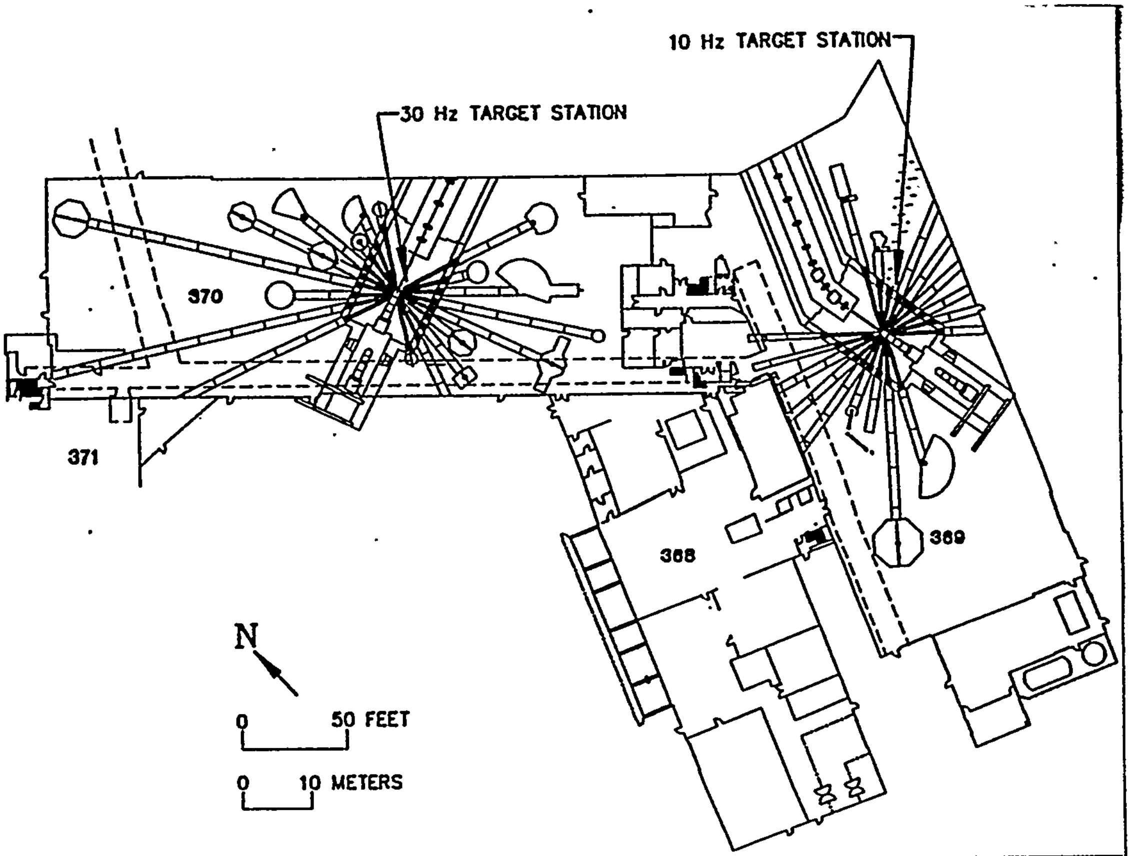

Figure 2. Target Stations and Reference Set of Instruments of the IPNS Upgrade

The IPNS Upgrade provides 36 beam ports for neutron scattering instruments, 18 each at the 30-Hz and 10-Hz target stations. Neutron beams for more than one instrument are extracted from a single beam port in some cases, so more than 36 neutron scattering instruments can be supported at this facility. There are a total of 12 moderators, one for every three beam ports, so the moderator characteristics can be optimized to the requirements of the individual instruments. The IPNS Upgrade provides 27 instruments for 24 of these 36 beam ports. The remaining 12 un-instrumented beam ports are available for later development and installation of new state-of-the-art instruments, as well as for the installation of specialized instruments developed by Participating Research Teams (PRTs). Chapter V of the IPNS Upgrade Feasibility Study outlines a reference set of 27 instruments that provide a well-balanced initial instrumentation complement. Tables II AND III briefly describe this reference set of instruments and indicate the wide range of neutron scattering science possible. This reference set of instruments has been used to select the target station parameters, lay out the locations of the target stations within the experiment halls, and provide the cost estimates. Up to 10 of the instruments that are presently operating at the IPNS would be refurbished and transferred to the IPNS Upgrade as part of this initial instrument complement. This approach provides a core of proven instruments ready for operation at startup. The neutron scattering instruments are located in existing experiment halls that provide internal space for beamlines up to 50 m long, as shown in Figure 1. Longer beamlines can be extended outside the buildings if necessary.

Most of the neutron scattering instruments use the neutron time-of-flight (TOF) principle for determination of neutron wavelengths. Of these instruments, the majority require good wavelength resolution. For such instruments, the IPNS Upgrade target stations provide 25-50 times the intensity available at the IPNS. However, for those instruments that do not require good wavelength resolution (for example, small-angle-scattering instruments), coupled liquid hydrogen moderators are used that provide 100-200 times the intensity available at the IPNS.

Table II Reference Set of Diffractometers and Reflectometers

Powder Diffractometers		Target	Moderator[a]	Range for d (Å)	Best Δ d/d (%)
VSPD	Very small samples (10-100 mg)	30-Hz	CH_4	0.2-17	0.35
SEPD[b]	High intensity	30-Hz	H_2O	0.2-17	0.35
GPPD[c]	Medium resolution (excellent at 90°)	30-Hz	H_2O	0.2-9	0.2
HRPD	High resolution	30-Hz	H_2O	0.2-5	0.08
RSD	Residual stress (12-m position)	30-Hz	H_2O	0.3-6	0.55
	(25-m position)	30-Hz	H_2O	0.2-3	0.30
Small-Angle Diffractometers		**Target**	**Moderator[a]**	**Q_{min} (Å^{-1})**	**Q_{max} (Å^{-1})**
SAND[b]	General purpose (wide Q range)	10-Hz	$C\text{-}H_2$	0.002	2
HRSAND	High resolution	10-Hz	$C\text{-}H_2$	0.0005	0.4
SPSAND	Re configurable for special purposes	10-Hz	$C\text{-}H_2$	Variable	Variable
Amorphous Materials Diffractometer		**Target**	**Moderator[a]**	**Range for Q (Å^{-1})**	**ΔQ/Q (%)**
GLAD[b]	Liquids and glasses	30-Hz	CH_4	0.07-120	1.2-10
Single-Crystal Diffractometers		**Target**	**Moderator[a]**	**Range for Q (Å^{-1})**	**ΔQ/Q (%)**
SCD[b]	General purpose	30-Hz	CH_4	0.9-17	0.6-0.9
HQSCD	High real-space resolution	30-Hz	H_2O	2-30	0.4
Reflectometers		**Target**	**Moderator[a]**	**Sample**	**Minimum Reflectivity**
POSY-I[c]	Polarized neutrons	10-Hz	H_2	Vertical	10^{-6}
POSY-II[c]	General purpose	10-Hz	H_2	Horizontal	10^{-7}
HIREF	High intensity	10-Hz	H_2	Horizontal	10^{-4}
GREF	Grazing incidence	10-Hz	H_2	Horizontal	10^{-7}

[a] Moderators are water at ~320 K (H_2O), liquid methane at ~95 K (CH_4), decoupled liquid hydrogen at ~18 K (H_2), and coupled liquid hydrogen at ~18 K ($C\text{-}H_2$). Moderator performance is shown in Figure I.2.2-1.

[b] Transferred from IPNS with little change.

[c] Transferred from IPNS with some modification.

The IPNS Upgrade source is sufficiently intense that it is no longer necessary that all instruments be based on TOF techniques. With moderators optimized for total neutron output rather than for sharp neutron pulse structure, time-averaged thermal or cold neutron fluxes are equivalent to those at a medium flux reactor. The reactor-equivalent cold neutron flux has been calculated to be ~5 x 10^{13} n/cm^2-sec for one of the liquid hydrogen moderators at the upgraded source. Thus, any instrument that works at a medium-flux reactor can be made to work at least as well at the IPNS Upgrade. Furthermore, even a moderator optimized for high time-averaged flux has a pulse width of less than one millisecond, and so has a duty factor of 1:30 or less at the IPNS Upgrade. This time structure can be used to significant advantage even on nominally steady-state instruments; for example, it can be used to reduce background and eliminate unwanted orders from crystal monochromators. A cold-neutron triple-axis spectrometer operating in this "quasi-steady-state" (QSS) mode is proposed as one instrument for the initial complement of IPNS Upgrade instruments.

Table III Reference Set of Inelastic Scattering Instruments and Component Development Instruments

Chopper Spectrometers		Target	Moderator[a]	Range for E_{inc} (meV)	$\Delta E/E_i$ (%)
HRMECS[b]	High-resolution general purpose	30-Hz	CH_4	4-2000	2-4
LRMECS[c]	Low-resolution general purpose	30-Hz	CH_4	3-2000	4-7
CNCS	High-resolution low energy	10-Hz	H_2	0.3-20	<1
SCCS	Excitations in single crystals	30-Hz	H_2O	50-2000	~1

Crystal-Analyzer Spectrometers		Target	Moderator[a]	Range for E (meV)	ΔE (meV)
TFCA	General purpose	30-Hz	CH_4	0-1000	0.5-30
QENS[c]	Quasielastic, medium resolution	30-Hz	CH_4	0-150	0.05-3
HRBS	Micro volt resolution	10-Hz	H_2	0-10	0.005-0.06
MICAS	Survey of single-crystal excitations	30-Hz	CH_4	0-20	variable
QSTAXC	Cold-neutron triple axis (QSS)[d]	30-Hz	C-H_2	variable	variable

Spin-Echo Spectrometer		Target	Moderator[a]	Resolution (meV)	ΔQ/Q (%)
TOFNSE	TOF spin-echo, cylindrical geometry	10-Hz	C-H_2	10^{-6} to 10^{-1}	1.5

Component Development Instruments		Target	Moderator[a]
REFD	Reflectometer development	10-Hz	H_2
DEVEL	General purpose development	10-Hz	H_2

[a] Moderators are water at ~320 K (H_2O), liquid methane at ~95 K (CH_4), decoupled liquid hydrogen at ~18 K (H_2), and coupled liquid hydrogen at ~18 K (C-H_2). Moderator performance is shown in Figure I.2.2-1.

[b] Transferred from IPNS with some modification.

[c] Transferred from IPNS with little change.

[d] Quasi-steady-state.

The facilities can be expanded to allow for a number of other research opportunities — including radiation damage studies, isotope production, neutron activation analysis, neutron radiography and tomography, muon spin rotation studies for materials science research, and neutrino physics — with minimum interference to operation as a dedicated neutron scattering source. These possibilities are discussed briefly in the IPNS Upgrade Feasibility Study Chapter V and Appendix C. Facilities for radiation damage studies, isotope production, and neutron activation analysis are included within the scope of the IPNS Upgrade project.

6. Targets, Moderators, Reflectors and Shields

The targets and shielding, and the reflector and moderator layouts are identical in the 10 Hz and 30 Hz stations, but moderators differ according to purpose. The targets are of split design, as shown schematically in Figure 3, but in a single piece. The split target, with the horizontal proton beam configuration, allows for "tall" moderators in the flux trap position, especially effective for powder diffractometer applications, and accommodates six differently tailored moderators.

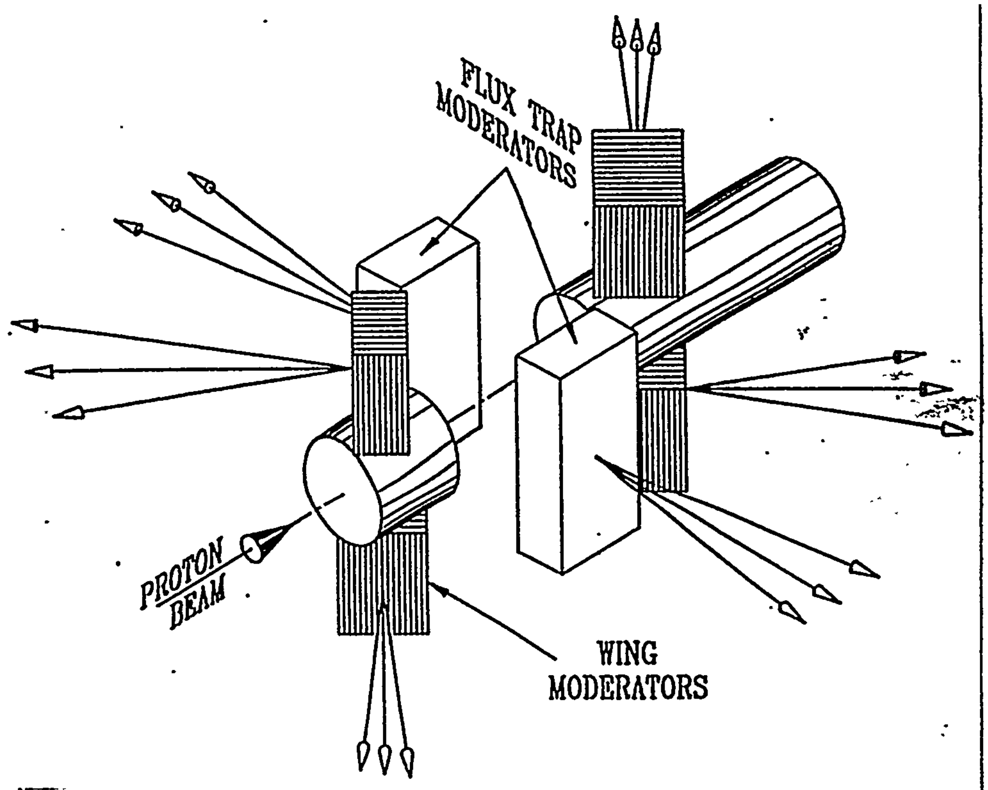

Figure 3. Schematic illustration of the split target and six moderators.

Figure 4 shows the one-piece split target. Water channels spanning the flux trap gap can serve as premoderators in some applications.

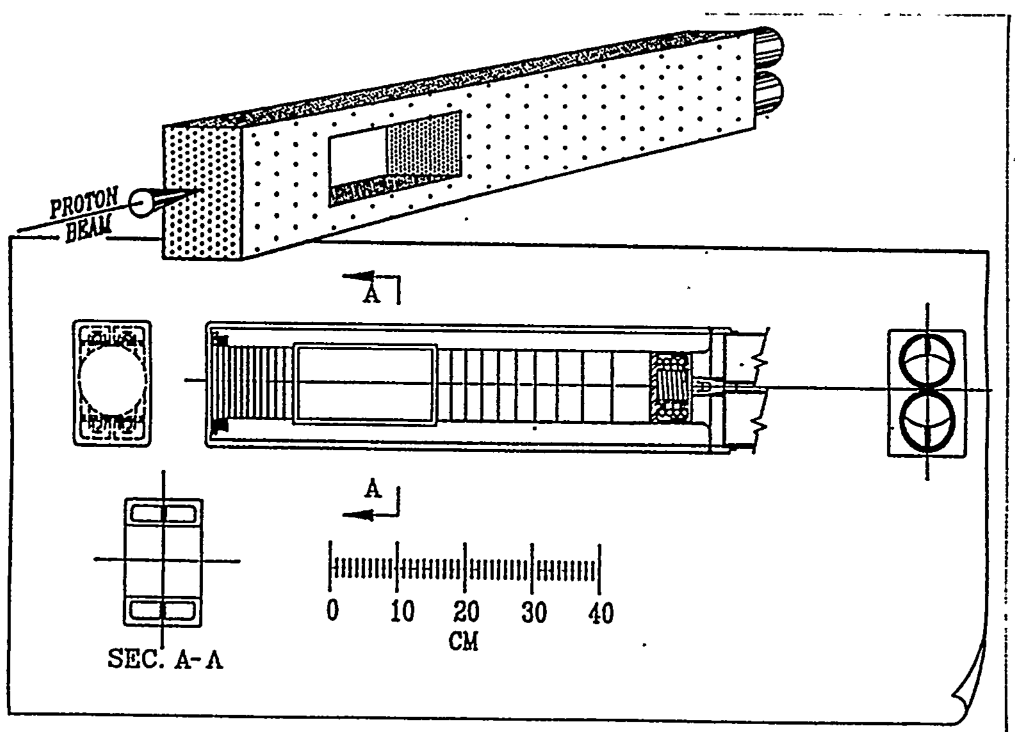

Figure 4. The one-piece split target.

Figure 5 shows how targets and moderators fit within the reflector. The arrangement allows the removal of parts for changes with minimal disturbance of other parts. The target moderator reflector assembly and attached shield roll downstream into a hot cell for servicing. The target module rests within a sealed aluminum tank filled with helium during operation.

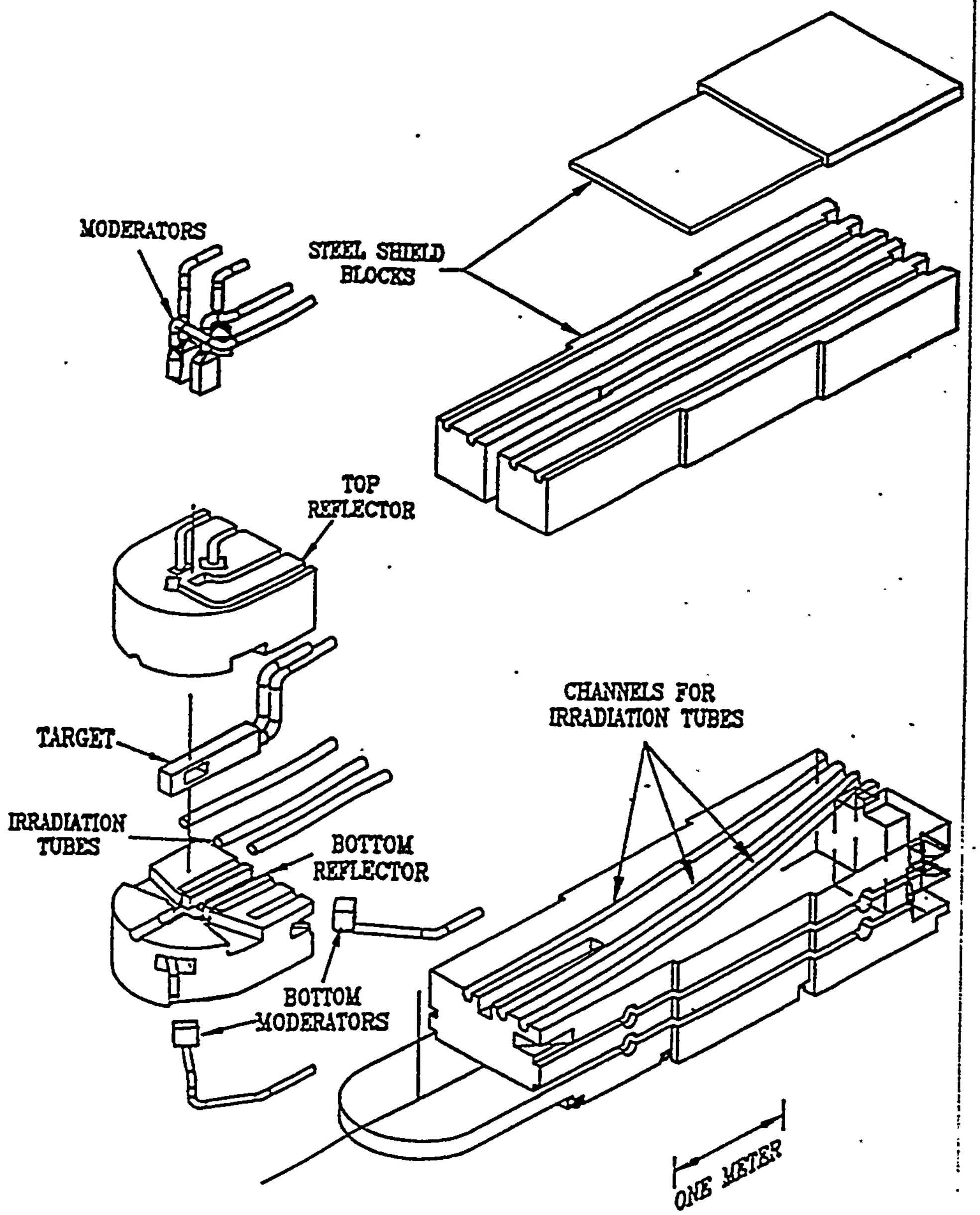

Figure 5. Target-moderator-reflector-shield assembly.

Figure 6 shows a cross sectional view of the shield. The shield consists of about 10,000 tonnes of stacked iron, approximately 5.5 meters thick, with 1 meter of exterior concrete. Two-meter-thick gates slide with precise alignment, driven by hydraulic actuators. The gates may contain guide sections or collimating elements. The core of the shield is sealed within an enclosure for confinement of radioactive gases. The shield rests on driven pilings set on bedrock about 30 meters below grade.

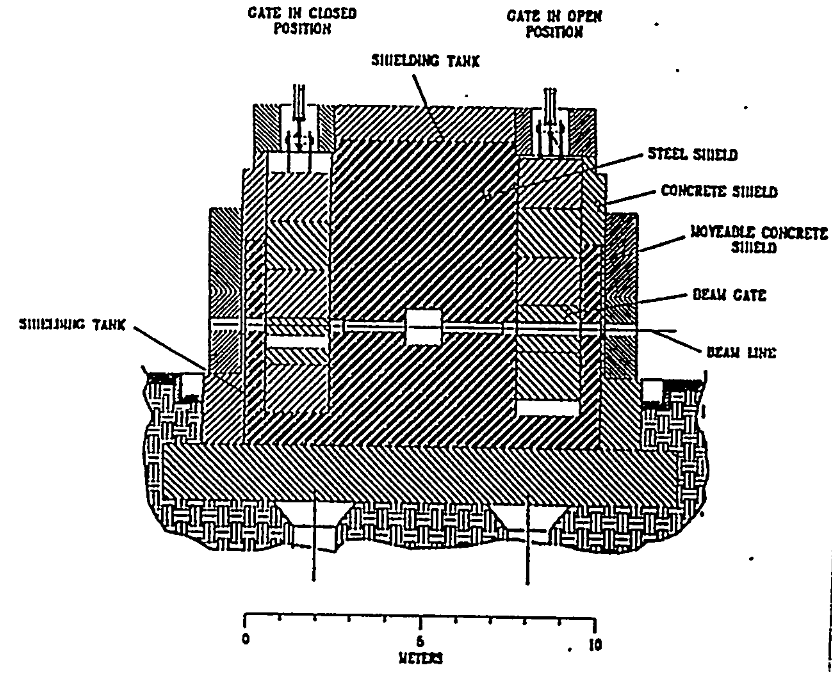

Figure 6. Cross sectional view of the shield taken perpendicular to the proton beam direction.

Figure 7 shows a plan view of the shield, beam tubes, gates, and hot cell. The proton beam enters horizontally through a water-cooled double-walled window and cooled tube, which can be dismounted from the accelerator side. Seals that isolate the target atmosphere and the inner shield atmosphere from the surroundings are made at the proton beam entry tube and at a seal sheet at the downstream end of the target train. Hands-on bayonet connectors provide for water, gas and cryogenic flows, accessible from behind the seal sheet.

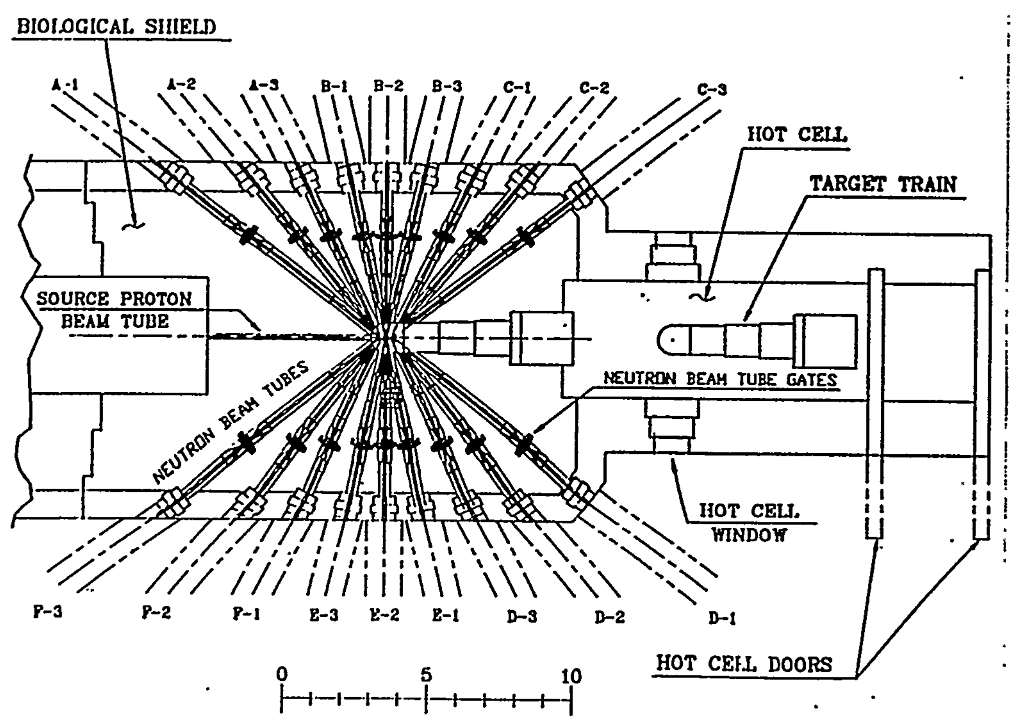

Figure 7. Plan view of the target station, showing the target train in the hot cell..

7. Summary Project Description

The major components of the IPNS Upgrade facility described here are an accelerator system, two target stations, and neutron scattering instruments. The accelerator system consists of a new, 400-MeV H^- linac and a new, 2-GeV rapid-cycling proton synchrotron (RCS). The RCS has a circumference of about 200 m and delivers a time-averaged proton current of 0.5 mA, for a total time-averaged power of 1.0 MW.

The 400-MeV injector linac, along with its associated technical equipment, is housed in a new building and tunnel. The 400-MeV linac beam is transported by a low-energy transport (LET) line to the RCS. The linac tunnel and klystron gallery are the only new buildings to be built for the IPNS Upgrade project. An extensive study was undertaken to choose a location for the new injector that would avoid interruption of present IPNS operation. A brief interruption of IPNS operation allows moving IPNS instruments to the IPNS Upgrade facility.

All other technical components are housed in approximately 55,000 m^2 of the former ZGS-complex space and use existing infrastructure. The synchrotron is located in the existing ZGS Ring Building. The power supplies for the RCS magnets, rf system, and beam transport systems are housed in the Center Building and other adjacent buildings. The target stations and instruments are located in existing large buildings that previously housed high-energy experiments at the ZGS, a use very similar to the new use. System control rooms, maintenance facilities, and a considerable amount of laboratory and office space for resident personnel and visitors are provided in existing buildings. The project uses water systems, cooling towers, main power and transformer systems, roads, sewers, and general infrastructure items that already exist. There is little need for constructing new conventional facilities. The cost estimate includes an allowance for refurbishing these existing buildings and facilities. Use of these existing buildings results in a very large savings in cost and construction time.

We expect that there is no need for land-use studies, such as wetlands accommodation and archaeological investigations, because construction takes place within existing buildings and in areas such as parking lots that are already graded. Altogether, these factors effect considerable cost and time savings.

If the project is initiated in FY 1997, the total estimated construction cost (TEC) is $478 million (in 1995 dollars), or $559 million in inflated dollars for the year in which they are spent. The facility commissioning is to start at the beginning of FY 2001. Construction of new components and refurbishment of existing facilities will not interfere with the present IPNS operations, except for reworking and relocation of the scattering instruments. An interval as short as a few months will be required to rework the scattering instruments and install them in their new locations. The accelerator commissioning period will be followed by commissioning of the target stations and instruments. Details of the cost and schedule appear in the IPNS Upgrade Feasibility Study document.

8. Upgrade ability

The IPNS Upgrade is a 1-MW source that can easily be upgraded to 5-MW by injecting the beam from the 2-GeV RCS into a 10-GeV RCS. Studies on this option have been underway since the 1-MW Feasibility Study was completed and a feasible concept, including siting, has been developed, the details of which are been worked on at the present time. This design has the large advantage of permitting full operation of the 1-MW source while the 10-GeV ring and target areas are under construction. Connecting the 2- and 10-GeV rings can be done quickly. In addition, no additional capabilities need to be built into the 1-MW facility for future enhancement to 5-MW, thereby avoiding any extra costs for the 1-MW source. The 10 GeV, 5-MW upgrade is the subject of a separate paper in this conference.

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