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Current Status for TRR-II Cold Neutron Source

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Abstract

The Taiwan Research Reactor (TRR) project (TRR-II) is carrying out at Institute of Nuclear Energy Research (INER) from October 1998 to December 2006. The purpose of Cold Neutron Source (CNS) project is to build entire CNS facility to generate cold neutrons within TRR-II reactor. The objective of CNS design is to install CNS facility with a competitive brightness of cold neutron beam to other facilities in the world. Based on the TRR-II CNS project schedule, the conceptual design for TRR-II CNS facility has been completed and the mock-up test facility for full-scale hydrogen loop has been designed.

1. Introduction

The Taiwan Research Reactor (TRR) project (TRR-II) is carrying out at the Institute of Nuclear Energy Research (INER) from October 1998 to June 2006. One of TRR-II major tasks is to install various modern experimental facilities such as Cold Neutron Source (CNS) facility and material irradiation test facilities.

The purpose of CNS project is to install a current state-of-art CNS facility with a competitive brightness of cold neutron beam to other facilities in the world [1-5]. The specific functions of CNS system will provide the follows:

(1) A moderator is capable of slowing down thermal neutrons and producing an energy spectrum (and wavelength distribution) in the range of cold neutrons, a wavelength between 4 Å and 15 Å, as efficiently as possible.
(2) A two-phase thermosiphon for hydrogen loop is capable of removing the heat generated in moderator, moderator cell, and transfer tube to maintain operating pressure at 1.2 bar.
(3) A double containment barrier system for hydrogen loop is capable of maintaining separation of flammable moderator material and atmospheric air.
(4) An insulating vacuum is capable of isolating moderator and support system from surrounding environment.
(5) The barriers and buffer volume should ensure that a single component failure does not lead to fire, explosion, or the release of radioactive materials.

(6) A metal hydride storage system is capable of absorbing the total hydrogen gas inventory in a short time period.

The scope of this CNS project includes design, procurement, fabrication, testing, and installation of entire CNS facility to generate cold neutrons within TRR-II reactor. Based on the TRR-II CNS project schedule, the conceptual design for TRR-II CNS facility has been completed and the mock-up test facility for full-scale hydrogen loop has been designed. This report illustrates the current status of the TRR-II CNS facility.

2. System Description and Operating Conditions

The CNS system consists of a natural circulation hydrogen loop, a helium refrigerator loop to remove the heat load generated from the hydrogen loop, and auxiliary systems such as vacuum system, hydrogen supply system, metal hydride system, and nitrogen gas containment. The general layout of CNS system is shown in Fig. 1. The major design parameters of CNS system are listed in Table 1.

The hydrogen loop is a cryostat that includes a moderator cell, cold transfer tube, a condenser, and a buffer tank. The hydrogen loop is enclosed by heavy water tank or by light water in reactor pool. Figure 2 shows the schematic diagram of hydrogen loop.

The moderator cell has a cylindrical annulus shape, 130 mm in diameter, 300 mm in height, hollow structure with 17.5 mm thickness of liquid hydrogen layer, to moderate neutrons to an energy spectrum corresponding to an effective temperature around 50 K. The material of moderator cell is Aℓ6061-T6. The position of moderator cell is around 40 cm from the center of core. Its perturbed thermal flux is about 1.4×10^{14} cm^{-2} s^{-1}. It is close to the maximum thermal neutron flux area in D_2O tank to get the maximum possible brightness about 1×10^{12} n $cm^{-2}s^{-1}Å^{-1}sterad^{-1}$ at 4 Å with a tolerable heat load about 1200 W, acceptable impact on the reactor core, and a lifetime over ten years.

During normal operation, the cavity of inner shell will be filled with only hydrogen vapor, as any liquid will boil off, and the resultant pressure will not allow liquid to enter from bottom. This arrangement allows a large viewing area for beams, while reducing the total hydrogen inventory and mechanical stress effectively. The tube connecting two parts of moderator cell reduces normal liquid vapor interchange, and allows vapor to have a different ortho/para hydrogen ratio from liquid. (Normal hydrogen is 75% ortho, while the equilibrium ratio at 20 K is virtually 100% para.) For cold neutron efficiency, the vapor should approach equilibrium with nearly 100% para, while the liquid should be maintained at nearly 65% ortho, since the ortho form with spin 1 is a strong neutron scatter while para form with spin 0 is a weak scatter. While both the cylindrical and spherical shape and other details are not new to this source, and have shown to work satisfactorily in a hydrogen source at Saclay and NIST.

The cold transfer tube provides the transport routes of the liquid and gas hydrogen for the close two-phase thermosiphone loop. Its design requirement not only makes alignment simple but also fabrication easy. The design of cold transfer tube is a double wall concentric-pipes tube with the liquid and gas hydrogen route in the single inter-tube without flooding to simplify the transfer tube design. The liquid hydrogen from condenser along an inner tube, 45 mm OD with 1.2 mm thickness, flows down to moderator cell. The vapor hydrogen returns from moderator cell to condenser through the empty space of inner tube. The outer annulus is a vacuum tube (< 10^{-5} torr) for the heat transfer insulation and the barrier between moderator and reactor. The cold transfer tube comprises a straight section and a curved section. The straight section is vertically installed in reactor and directly above CNS with the outer vacuum tube, 156 mm OD, made from 6061-T6 aluminum with 8 mm thickness containing a moderator cell and a hydrogen line. The curved section of vacuum tube and hydrogen transfer line will allow easy to handle the thermal expansion of the transfer tube.

The preliminary design of hydrogen condenser is a shell and tube type heat exchanger connected to transfer tube, helium refrigerator, and buffer tank In the condenser, the hydrogen vapor flows upward through a vapor tube then flowing downward to liquid hydrogen tubes. The hydrogen vapor tube is 1200 mm in height, 25 mm in diameter with 1 mm thickness. There are 40 liquid hydrogen tubes and each tube is 1200 mm in height, 12 mm in diameter with 1 mm thickness. During normal operation, the pressure in condenser is around 1.2 bar. The cold helium gas enters condenser at pre-determined temperature. As helium passes through condenser, the flow direction of helium is controlled by baffle plate and the warmed helium returns to refrigerator at temperature approximately 18 K. The condenser is entirely surrounded by a vacuum chamber in order to insulate heat transfer from the reactor pool.

The buffer tank locates in reactor pool with 1.27 m^3 volume, 2500 mm in height, and 810 mm in diameter. The purpose of buffer tank is to provide an adequate hydrogen gas reservoir tank to hold the entire hydrogen inventory at a pressure less than 5 bar when the system is at 300 K. The buffer tank is entirely surrounded by a nitrogen blanket in order to prevent air from entering to hydrogen system. During normal operation, the pressure in the buffer tank is around 1.2 bar.

The helium refrigerator loop mainly consists of a cold box including a control heater, an oil screw compressor, two heat exchangers, two static gas bearing expanders, refrigerant transfer lines, a cooling water system, and a helium tank. The complete system provides refrigeration to an external heat load of 3 kW with a helium gas supply temperature of 14 K The refrigeration control shall be provided by electrical heater to operate in response to pressure sensors in hydrogen loop.

The auxiliary system includes vacuum system, hydrogen supply system, metal hydride storage system, and nitrogen gas containment. An insulating vacuum is capable of isolation of hydrogen loop and helium refrigerator loop from surrounding environment. The hydrogen supply system including hydrogen gas cylinders is used to supply hydrogen into hydrogen loop. A metal hydride storage system is capable of absorbing the total hydrogen inventory of hydrogen loop in less than 6 minutes at a pressure less than 3 bar. Nitrogen gas containment surrounds buffer tank in order to provide double containment to prevent air from entering hydrogen system.

The hydrogen loop including buffer tank is entirely closed. This eliminates further gas handling, and thus minimizes the possibility of inadvertent oxygen contamination. In addition, all hydrogen tubes are either within D_2O tank, or run in reactor pool to prevent air from entering to hydrogen-containing system. The cold hydrogen loop is immersed either in D_2O tank or in reactor pool. The buffer tank is completely surrounded by a 1.2 bar of nitrogen gas, maintained above atmospheric, so that there can be no in-leakage of air into the system, and thus no oxygen is available to combine chemically with hydrogen. The major controlled and monitored system parameter is the absolute pressure of hydrogen in buffer tank. The entire design philosophy is to rely on simple, passive safety features to minimize the possibility of a system failure or a procedural problem. With a closed system, the gas handling is minimized and the only charging is done at installation or after the system is opened for corrective maintenance. If the system must be emptied of hydrogen to allow maintenance of a component, the entire hydrogen inventory can be absorbed into the metal hydride system.

The normal operations of CNS system have three operation modes: shutdown mode, cool-down mode, and cold neutron production mode. The shutdown mode is entered only at reactor shutdown. Then, the reactor core decay heat has fallen sufficiently for moderator cell temperature stabilized below than 100°C without forcing cooling. The hydrogen loop pressure is stabilized at 3.3 bar for the shutdown mode of CNS system.

The cool-down mode of CNS system will always be started prior to the start-up of reactor. In this mode, the helium refrigerator system operates automatically and a heater in helium refrigerator is controlled by buffer tank pressure to ensure hydrogen temperature to not fall below 14 K for preventing the freeze of liquid hydrogen.

The transition from cool-down mode to cold neutron production mode is completed when the two-phase hydrogen loop stabilizes at their normal operating conditions of 1.2 bar with corresponding to a saturated hydrogen temperature around 20 K.

During cold neutron production mode, the heater in helium refrigerator is controlled by hydrogen loop pressure only. So, the system pressure will be automatically maintained at 1.2 bar by controlling the heater of helium refrigerator to compensate the small variation of nuclear heat load applied to moderator cell during reactor power transients.

3. Cold Source Design and Performance

In order to characterize the neutron performance of various cold neutron moderators for TRR-II, the Monte Carlo neutron and photon code, MCNP [6], was chosen for calculations. MCNP allows an exact representation of complex volumes bounded by segments of spheres, cylinders, and ellipsoids, etc.

None of the standard neutron sources contained in MCNP could be used to adequately represent a realistic distribution of neutrons entering the model. Thus a simplified core was developed to perform parametric studies of cold source as core design was proceeding, such as liquid hydrogen thickness, diameter, length, and D_2O gap between cold source, and beam tube. The gain and brightness of cold source were calculated after the realistic core design was finished and loaded with experimental apparatus.

It was necessary to model entire core for the generation of surface sources. The surface enclosed only the region of interest, in and around cold source and beam port, for gain calculations. The gain, depending on wavelength, is defined as the current of neutrons from cold source divided by the current without cold source. The cold neutron current was tallied using DXTRAN command across a plane at the entrance of a neutron guide, with direction cosines greater than 0.9997.

All criticality calculations require a large number of neutrons to be tracked in a number of cycles of fission generations to converge to eigenvalue k_{eff}. A number of cycles were skipped before the criticality calculation is started. In all generations of surface sources for parametric study, the first 20 cycles were skipped to converge to a stable source distribution in core and a total of 330 cycles were run with 5000 neutrons in each generation. For gain and brightness calculations, a total of 1220 cycles were run with the same neutrons in each generation.

As for the ortho content of liquid hydrogen, 65% was chosen [7] for all neutron performance calculations, although the early paper reported that ortho would convert to para due to the presence of radiation and low temperature stimulation [8].

Gain is defined as the ratio of cold neutron flux between CNS on and CNS off (D_2O there only). The gain of TRR-II CNS is plotted in Fig. 3, and is compared with the data from JRR-3M . The gain of such an annular type cold source of 17.5 mm thick liquid hydrogen is somewhat better than the JRR-3M cold source.

The brightness of a cold source is the most important parameter to judge the performance of a cold source. The cold neutron current of TRR-II CNS without the effect of BT-1was tallied at the entrance surface of cold guide with direction cosine 0.9997. The brightness showed in Fig. 4 is compared with the data of NIST sphere annulus cold source. The perturbed thermal flux averaged over CNS was 1.42×10^{14} n/cm^2/sec.

Based on the results of parametric study and performance calculation, a cold neutron source of cylinder annulus type was recommended. The outer shell of cold neutron source is 30 cm in length and 13 cm in diameter, and the inner shell is 26.37 cm in length and 9.37 cm in diameter. The liquid hydrogen will be filled in the gap of 1.75 cm between outer shell and inner shell. The length of cold neutron source recommended was 30 cm temporarily, but there is a possibility to reduce the length to 26 cm or 27 cm without significant effect to performance.

4. Thermal-hydraulic Analysis and Mockup Test Plan for Cold Hydrogen Loop

The schematic of the hydrogen system for TRR-II CNS is shown in Fig. 2. The cold hydrogen loop includes moderator cell, moderator transfer tube, and condenser. The heat generated by neutrons and gamma rays in liquid hydrogen and in the moderator cell, material Aℓ-6061-T6, is removed by the nucleate boiling of liquid hydrogen. The hydrogen vapor generated from the boiling of liquid hydrogen in moderator cell, flows upward to condenser through the moderator transfer tube. The vapor hydrogen condenses in condenser flows downward from condenser to moderator cell through the cold transfer tube. Thus, the hydrogen inventory circulates in cold hydrogen loop by means of two-phase thermosiphon. During normal operating conditions, the pressure of entire hydrogen system including buffer tank is around 1.2 bar and the moderator temperature at approximate 20 K.

The steady-state natural circulation in a closed two-phase thermosiphon is reached when the driving force is balanced to the flow resistance resulted from friction pressure drops of liquid hydrogen and hydrogen vapor in loop. One of design requirements of CNS is to provide stable operations, such as, keeping the liquid hydrogen level stable in the moderator cell and preventing a sudden bubbling during reactor power transients. A cold hydrogen loop with a closed two-phase thermosiphon is designed for this purpose [9]. Kawai, et al., had performed a series of analytical work on a closed two-phase thermosiphon for Kyoto University Reactor (KUR) cold neutron source [9-12]. Their approach is adopted to analyze the thermodynamic characteristics of two-phase thermosiphon for TRR-II CNS [13].

Recently, a single-tube type of transfer tube was designed by FRM-II CNS facility [14]. A single-tube will not only make design simple but also fabrication easy. With the similar design of FRM-II CNS, TRR-II must confirm that flooding does not occur in transfer tube during CNS operations. The Counter-Current Flow Limitation (CCFL) or flooding phenomenon is associated with carry-over of liquid flow caused by the interaction between an upward gas flow and a countercurrent falling liquid flow. The flooding in two-phase thermosiphon loop will prevent liquid falling back to moderator cell.

We have studied basic parameters for design of single transfer tube by using the well-known flooding correlations of Wallis and Kutateladze, respectively. The tube diameter of 50 mm is accessible for heat load up to 1500 W [13]. To prove the performance of two-phase thermosiphon and to investigate parametric effects on the onset of flooding, a series of mockup experiments is required to perform.

A full-scale hydrogen loop mockup testing represents a major step in the validation of TRR-II CNS conceptual design. The objectives of hydrogen loop mockup testing are :

(1) Validate a correct operation and thermosiphon heat removal in CNS hydrogen loop design ;
(2) Demonstrate no onset of flooding in a single transfer tube under CNS operating conditions; and
(3) Demonstrate the hydrogen loop system stability under normal and fault conditions.

The design features of mockup test facility include:

(1) Full-scale hydrogen loop ;
(2) Using R-11($CFC\ell_3$) as a fluid to reduce costs of mockup tests [15] ;
(3) Experiments with the same density ratio ($\rho_{Liquid} / \rho_{vapor}$) and scaling heat load to achieve the similarity of Wallis-numbers between CNS hydrogen and R-11 as shown in Table 2. Wallis-number is the most important scaling-number for simulating the onset of flooding [15] ; and
(4) Examination on the influence of incline angle upon the onset of flooding with a possible incline angle ranging between 0° and 10°.

In order to have a confidence that the design of CNS moderator cell is adequate, the mockup testing to observe the flow pattern in moderator cell with liquid nitrogen will be performed. A glass vessel and electrical heaters will be used for simulating the geometry and heat load of moderator cell, respectively. The major goals of the mockup tests are :

(1) Visualize the actual flow pattern in TRR-II CNS source geometry ;
(2) Evaluate the bubble growth and bubble size on a heated surface [16] for variation of heat flux and surface condition ; and
(3) Evaluate the bubbling correlation for nitrogen and hydrogen on a heated surface [17].

5. Safety Analysis Plans

The primary safety philosophy in CNS design is a defense-in-depth approach. The safety goal of CNS design is (1) personnel safety and (2) reactor safety wherever the maximum credible CNS accident.

The safety features in CNS design include: containment by multiple barriers to prevent hydrogen leakage, use of high quality material, fail-safe design, passive safety, simple to operate, and redundancy for safety consideration. CNS safety features are illustrated as the follows.

(1) Containment by Multiple Barriers -- Hydrogen will be contained by at least two barriers
- A vacuum surrounding is the inner barrier and a pool water surrounding is the outer barrier for cold hydrogen loop.
- A nitrogen gas blanket surrounding is the inner barrier and a pool water surrounding is the outer barrier for buffer tank.
- The vacuum level and nitrogen gas pressure are on-line monitored.

(2) Use of High Quality Material
- Hydrogen pressure boundary materials and the gases used in CNS will be at a very high quality level.
- All pressurized components will be designed to meet ASME Code and piping standards for governing the pressure boundary.

(3) Fail-safe Design Features

- The hydrogen pressure boundary will sustain the maximum credible detonation in hydrogen loop.
- A large volume buffer tank exists to hold the entire hydrogen inventory at a pressure less than 5 bar when CNS has loss of refrigerator at reactor shutdown.
- The helium refrigerant pressure will be higher than 5 bar. It does not allow hydrogen to reach refrigerator if any internal leakage of condenser occurs.

(4) Passive Safety Features

- The CNS design will use passive safety feature to achieve safety objectives. For no pressure relief anywhere, the hydrogen pressure boundary will withstand design basis detonation pressure. In the event of a refrigerator failure, CNS is completely passive returned to safe shutdown.

(5) Simple to Operate

- The hydrogen system will be filled once and sealed to minimize hydrogen handling.
- For easy operation, only one parameter of hydrogen pressure is used to control refrigerator at any reactor power level.

(6) Redundancy for Safety Consideration

- The redundant instruments related to the safety of CNS should be installed for the conservative consideration in safety system design.

The purpose of accident analysis is to show that the CNS system will not involve in any reactor safety problems. Analyze the following possible occurrence of hydrogen-related hazard to demonstrate not to cause any damage to reactor, cryogenic system, any safety system, or reactor confinement building itself.

- Hydrogen release in reactor confinement building
- Rupture of moderator cell
- Air contamination of hydrogen system and refrigerator system
- Air leakage in vacuum chamber
- Explosion of hydrogen gas in the vacuum chamber.

6. Schedule

The CNS project schedule is based on assumption that cold source component should be completely installed in TRR-II in advance of the first reactor critical in July 2006. The following factors will affect the schedule.

- Problems encountered in testing program,
- Efficiency of detailed design and procurement activities, and
- Quality and timing of review process.

The special concerns to the above mentioned factors would be made in the planning activities to minimize the risk of schedule delay. If TRR-II project schedule is modified, the schedule for this project should also be revised to meet the overall TRR-II project schedule.

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Table 1 Design Parameters of CNS

Parameter	Value
1. Hydrogen Loop	
Nominal Reactor Power	20 MW
Neutron Flux in CNS	2×10^{14} cm^{-2}s^{-1}
Size of Moderator Cell	300mm H × 130 mm ϕ
Material of Moderator Cell	Aluminum alloys (Aℓ6061-T6)
Moderator Cell: Mean Wall Thickness	0.65 mm
Volume of Moderator Cell	3.585 liters
Mass of H_2 in Moderator Cell	133 g
Total Hydrogen Mass	407 g
Temperature of Moderator Cell	20 K
Pressure in Moderator Cell	1.2 bar
Pressure in Warm H_2 System	3.3 bar
Volume of Buffer Tank	1.27 m^3
Heat Load	1164 W (823 W for nuclear heating and 341 W for non-nuclear heating)
2. Helium Refrigeration Loop	
Refrigeration Capacity	3.0 kW
Supply Helium(99.995%)	
•Pressure	5.5 bar
•Temperature	14 K
Return Helium	
•Temperature	18 K
Helium Flow	80 g/s

Table 2 Comparison of Operation Conditions between TRR-II CNS and Mockup Test

	TRR-II CNS (H_2)	Mockup Test (R-11)
Operating Pressure (kPa)	120	569
Operating Temperature (K)	20.8	356.5
Density Ratio (ρ_f/ρ_g)	44.4	44.4
Heat Load (kW)	1.2	8.0
Mass Flux (g/s)	2.7	51.3
Wallis Flooding Correlation		
($J_g^{*1/2} + mJ_f^{*1/2} = C$)		
Vapor (j_g^*)	0.19	0.19
Liquid (j_f^*)	0.0285	0.0285

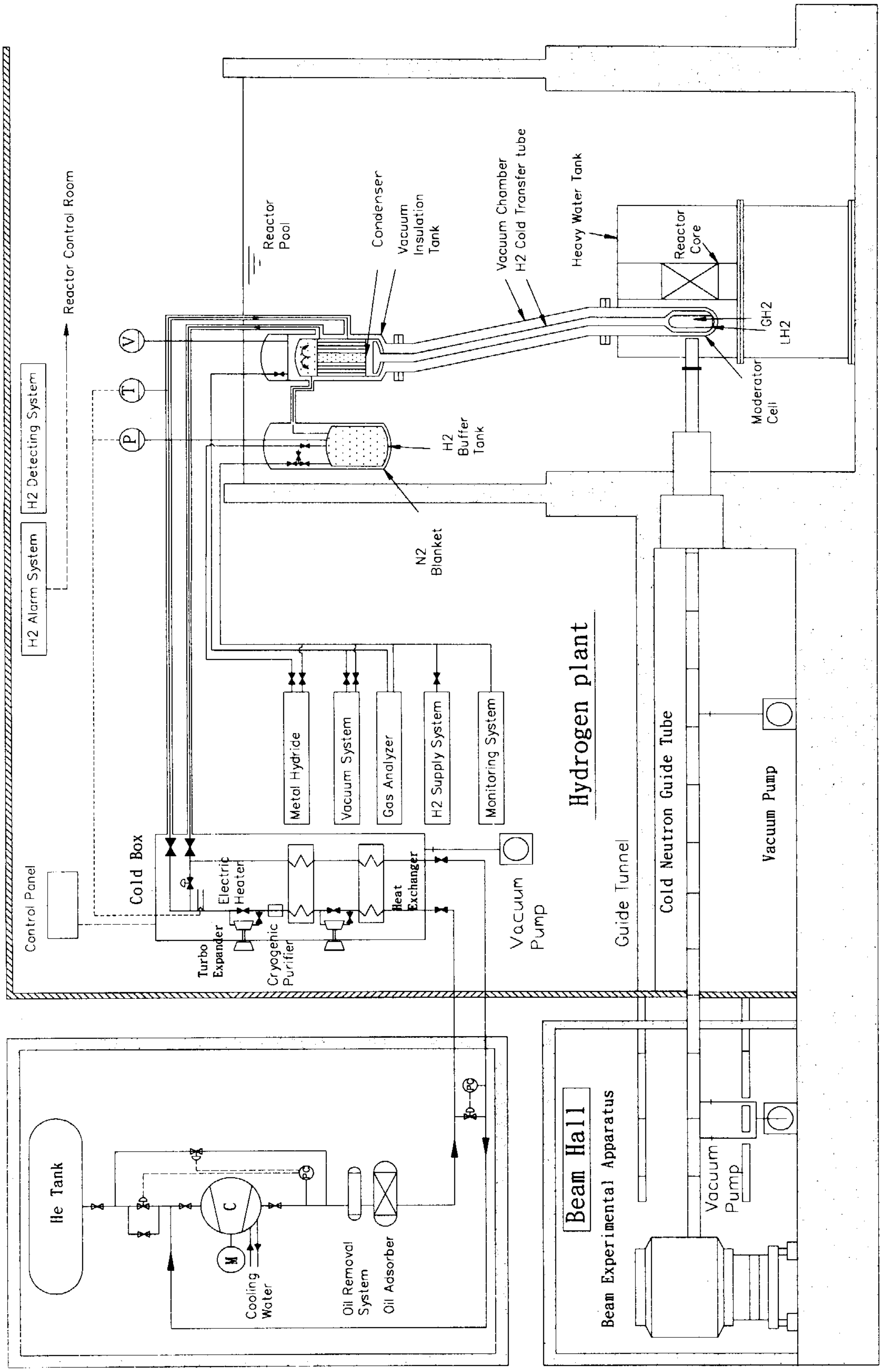

Fig. 1 Layout of TRR-II CNS Facility

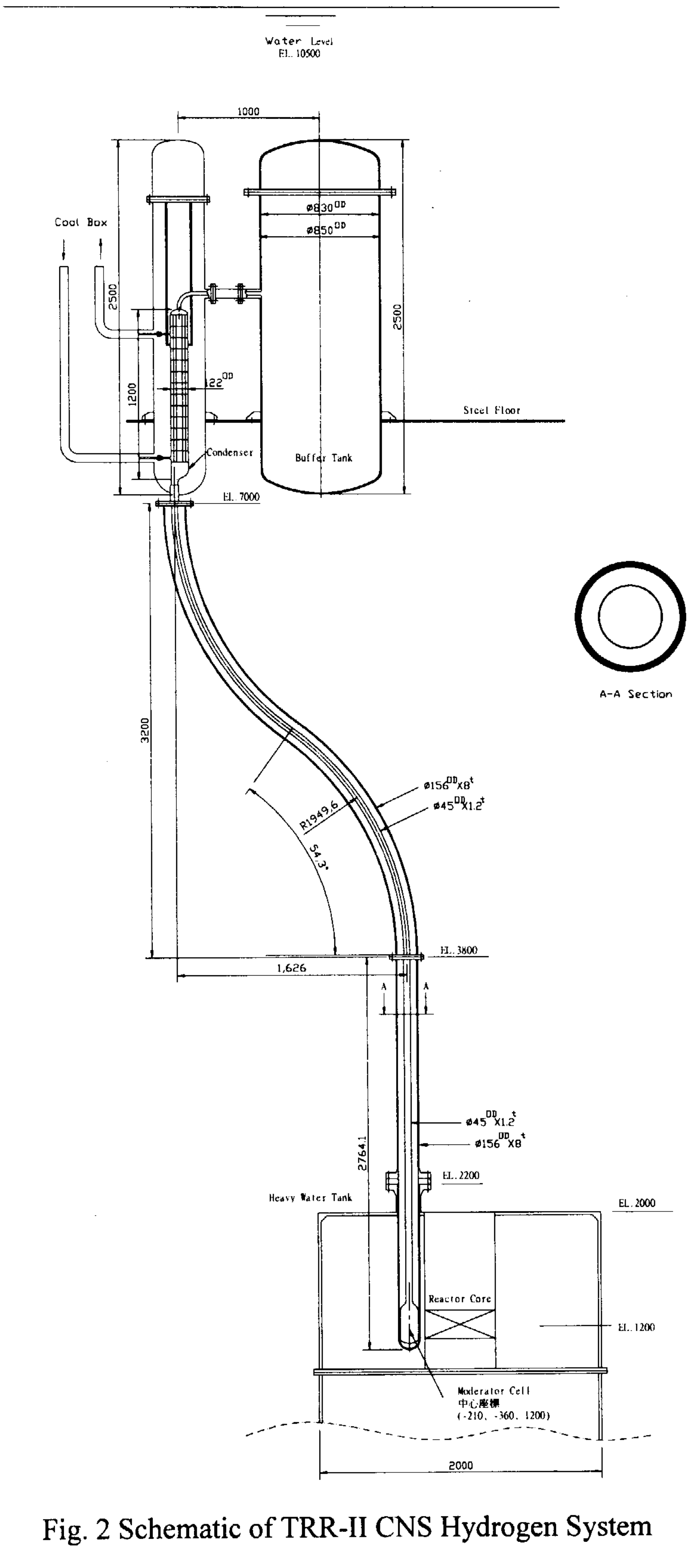

Fig. 2 Schematic of TRR-II CNS Hydrogen System

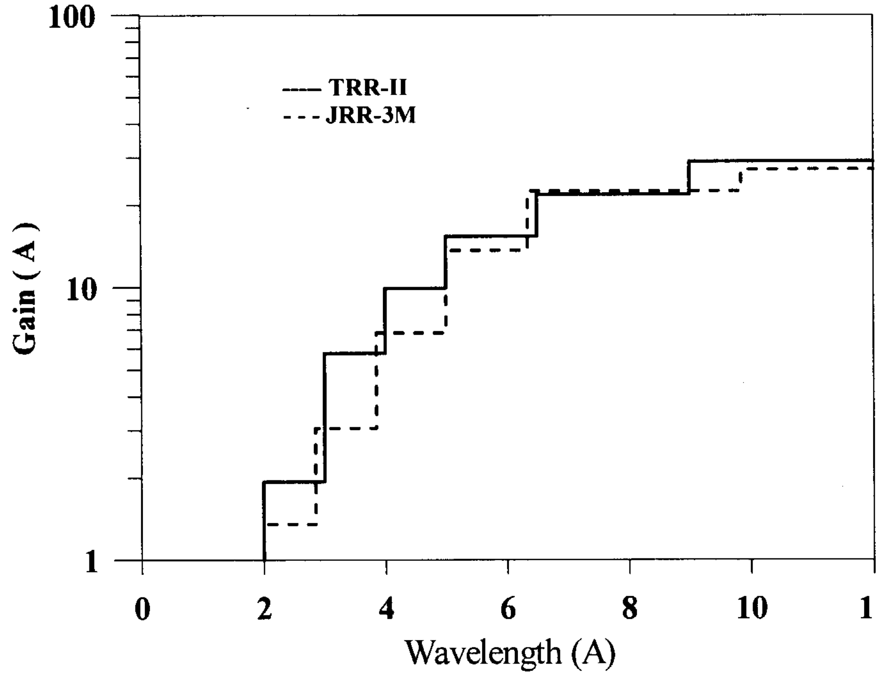

Fig. 3 Comparison of CNS Gain between TRR-II and JRR-3M

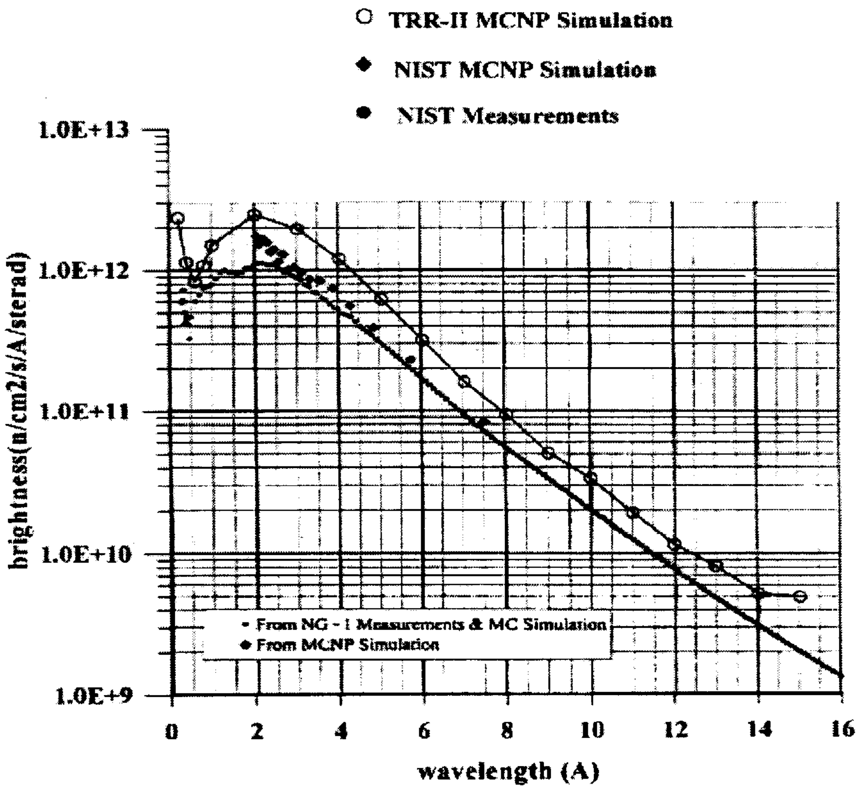

Fig. 4 Comparison of CNS Brightness between TRR-II and NIST