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Status of TRR-II Cold Neutron Source

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Abstract

The Taiwan Research Reactor improvement and the utilization promotion project (TRR-II) with a vertical Cold Neutron Source (CNS) is carrying out at the Institute of Nuclear Energy Research (INER). The CNS with a two-phase thermosiphon loop consists of an annular cylindrical moderator cell, a single moderator transfer tube and a condenser. A cylindrical annulus moderator cell with boiling liquid hydrogen at 1.2 bar and 20.7 K gives an optimum moderation for cold neutrons in the wavelength range between 4 Å and 15 Å. The moderator cell lies around 400 mm away from the core center. 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. An experimental study for thermal-hydraulic characteristics of the two-phase thermosiphon loop has been performed on a full-scale mockup loop using a Freon-11 as a working fluid. The objective of the mockup testing is to validate operation and heat removal capacity in CNS hydrogen loop design. Moreover, this loop will be used to demonstrate no onset of flooding and flow oscillations in a single transfer tube under CNS normal and abnormal conditions. The flooding limitation, the liquid level, and the void fraction in the moderator cell as a function of the initial Freon-11 inventory, the heat load, and the moderator cell geometry are also reported.

1. Introduction

The Taiwan Research Reactor improvement and the utilization promotion project (TRR-II) is carrying out by Institute of Nuclear Energy Research (INER) from October 1998 to June 2006. The TRR-II reactor is a pool type of the thermal power of 20 MW with a light-water coolant and a heavy-water moderator. One of the TRR-II major tasks is to install a Cold Neutron Source (CNS) with a competent brightness of cold neutron. The main part of the TRR-II CNS facility consists of a buffer tank of hydrogen gas, a hydrogen cold loop and the helium refrigerator. The specific functions of CNS system will provide the follow [1]:

(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.

Based on the TRR-II CNS project schedule, the conceptual design for TRR-II CNS facility has been completed and the mock-up testing for full-scale hydrogen loop has been performing. This report illustrates the status of the TRR-II CNS facility.

2. System Description

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 cold loop is composed of the condenser, the moderator transfer tube and the moderator cell. The hydrogen loop is enclosed by heavy water tank or by light water in reactor pool.

The moderator cell is an annulus cylindrical type, 130 mm in diameter, 300 mm in height, hollow structure with 17.5 mm thickness of liquid hydrogen layer, in which the inner shell with open in the bottom contains only hydrogen vapor and the outer shell liquid hydrogen. This arrangement allows a large viewing area for beams, while reducing the total hydrogen inventory and mechanical stress effectively. For extracting stable cold neutron flux from the CNS, the liquid level in the moderator cell should be kept stable without a sudden bubbling against the heat load disturbances [2-3].

A cold moderator transfer tube of a single tube, 45 mm OD, made from 6061-T6 aluminum with 1.2 mm thickness, provides the countercurrent two-phase thermosiphon without flooding. The liquid hydrogen liquefied at the condenser streams down into the moderator cell and the hydrogen vapor evaporated in the moderator cell is blowing up to the condenser. Its design requirement not only makes alignment simple but also fabrication easy. The vacuum tube, 156 mm OD, made from 6061-T6 aluminum with 8 mm thickness contains a moderator cell and a hydrogen line for the heat transfer insulation and the barrier between moderator and reactor.

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. 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. A vacuum chamber surrounds the condenser 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. A nitrogen blanket surrounds the buffer tank 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 at a pressure less than 5 bar. Nitrogen gas containment surrounds buffer tank in order to provide double containment to prevent air from entering hydrogen system.

3. Cold Source Performance and moderator cell heat load

The 4B Version of the MCNP code [4] and the cross section data set of para/ortho hydrogen developed by Los Alamos National Laboratory (LANL) were used for calculating the cold neutron performance of TRR-II CNS. The moderator cell lies around 400 mm away from the core center. The 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

In the calculation of the cold neutron fluxes entering the cold neutron guides, the ortho/para ratio of the hydrogen is assumed to be 65 % ortho and the void fraction in liquid hydrogen is assumed to be zero. The surface area of this model encloses only the region inside and surrounding the CNS and the BT-8 cold neutron tube which is touched with a CNS vacuum chamber through the 1mm thick heavy water. The surface sources were generated by the criticality calculations for representing the realistic neutron distributions and saving a CPU time. The cold neutron current was tallied by using DXTRAN command across a plane at the entrance of a cold neutron guide, with proper direction cosines greater than 0.9997. In TRR-II case, the entrance is 150 cm away from the center of the moderator cell. DXTRAN and F1 tally commands are used to count only neutrons entering the entrance surface within the solid angle subtended by the critical angles of the guide mirrors.

The brightness is defined as the number of neutrons per unit time, per unit area, per unit wavelength, per unit solid angle at the entrance of the cold neutron guide. Figure 2 shows that the brightness of TRR-II CNS is roughly about two times as that of NIST data [5], because thermal flux averaged over TRR-II CNS, 1.45×10^{14} n/cm^{2}sec, is roughly about two times as that of NIST.

The cold neutron gain factor depending on the neutron wavelength is defined as the current of neutrons from the CNS divided by the current without the CNS, that is, in case of heavy water being there. Figure 3 shows a comparison of the gain factor with those of NIST [5], ORPHEE [6], and JRR-3M [7]. The gain factor as a function of neutron wavelength is consistent with those of other facilities. 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.

High accurate estimation of the nuclear heating generated in the materials for the CNS is quite important since this heating must be removed by the closed counter current thermosiphon using hydrogen moderator. The prompt and delayed fission gamma rays from the core, secondary and decay gamma rays from the activated materials produced in all components, fast neutrons from the core, and decay betas from the disintegration of short-lived ^{28}Al are taken account into the calculation. The delayed fission gamma-rays production is not considered in the present MCNP calculation. Two special data sets were used for solving these problems. For the ^{235}U, the data set of LANL was modified to include the delayed fission gamma-rays production depending on energy as regular secondary gamma rays. For ^{27}Al, the data set of LANL was also modified to include decay gamma rays from the short-lived ^{28}Al as regular secondary gamma rays. The heat load of moderator cell is estimated to be 678 W of which 578 W is due to nuclear heating and 100 W from the non-nuclear heating.

4. Thermal-hydraulic Design and Mockup Tests for Cold Hydrogen Loop

The hydrogen cold loop is composed of the condenser, the moderator transfer tube and the moderator cell. A moderator transfer tube of the single tube provides the countercurrent two-phase thermosiphon in which the liquid hydrogen liquefied at the condenser streams down into the moderator cell and the hydrogen vapor evaporated in the moderator cell is blowing up to the condenser. For extracting stable cold neutron flux from the CNS, the liquid level in the moderator cell should be kept stable without a sudden bubbling against the heat load disturbances.

Recently, a single-tube type of transfer tube was designed by FRM-II CNS facility [8]. 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.

A full-scale hydrogen loop mockup testing represents a major step in the validation of TRR-II CNS conceptual design. The purpose of the mockup test is to validate the self-regulating characteristics [9] of a two-phase thermosiphon loop against thermal disturbances for the CNS design. Moreover, this loop will be used to demonstrate no onset of flooding in a single transfer tube under the normal and abnormal conditions.

The mockup equipment is a full-scale model, but a Freon-11 (R-11) is used as a working fluid for convenience. In order to visualize the flow patterns in the moderator transfer tube, two view ports are installed at the upper stream of the moderator cell and at the down stream of the condenser, respectively. Figure 4 shows a schematic diagram of the mockup test equipment composed of an annulus cylindrical moderator cell, a transfer tube, a condenser, and a buffer tank.

The Wallis's correlation equation is the most important factor for simulating the onset of flooding [10]. In order to do the relative evaluation regarding the Wallis correlation, the same density ratio ($\rho_{\text{Liquid}}/\rho_{\text{vapor}}$) and a relative heat load shown in Table 2 are applied to the test. The hydrogen density is that for the saturated hydrogen at the pressure of 1.2 bar, and a heat load is scaled up in case of R-11 so that the mass-fluxes of the liquid and the vapor in the Wallis correlation equation become equal to the hydrogen case.

Initial R-11 inventory was changed from 5.05 kg to 15.33 kg and the heat power was increased step by step until the onset of flooding. The onset of flooding is considered as the point at which the falling liquid film becomes a chaotic flow and a large amplitude wave appears at the interface. The constant pressure is maintained at 5.69 bar by adjusting the secondary water flow rate to keep the balance between the applied heat power and the cooling capacity of the condenser. Figure 5 shows the effect of heat power on the liquid level in the moderator cell in case of the initial inventory of 6.28 kg. The liquid level in the moderator cell begins to increase suddenly at the 1.6 kW heat power and at time lap of 750 s as shown in Fig. 5 (b). Then liquid level in the moderator transfer tube (see Fig.5 (c)) begins to increase rapidly at time lap of 1200 s, and this is considered, partly because some liquid is expelled from the inner shell into the outer shell.

Figure 5(a) shows that the heat power of the onset of flooding is 4.73 kW for R-11 corresponding to 710 W in case of liquid hydrogen. Figures 5(b) and 5(c) show the sharp decrease of liquid level in the moderator cell as well as the rapid increase of liquid level in the transfer tube at the flooding power condition. The decrease of liquid level in the moderator cell is also visualized from glass sight tubes at the moderator cell.

Figure 6 shows the effect of heat power on the local void fractions in the lower, middle, and upper regions of the outer shell at the same inventory. The average fluctuations of void fractions in the middle and upper regions are from 30 to 35 %. The average fluctuation of void fraction in the lower region is in the range of 20 to 25%. From Fig. 6 we could evaluate the distribution of void fractions in moderator cell being one of the important parameters for designing CNS.

In order to have a confidence that the design of CNS moderator cell with an inner shell only containing only hydrogen vapor and an outer shell containing boiling liquid hydrogen. A full-scale mockup test facility with liquid nitrogen as a working fluid was designed and made of glass for verifying the conditions to get the state mentioned above. The electrical heaters are used for simulating nuclear heat load of a moderator cell including hydrogen moderator. The liquid level in the inner shell will be measured directly as a function of the heater input. The visualization of the two-phase flow patterns in the cylindrical annuls and the void distribution in the liquid nitrogen of the outer shell against variations of heat load will be investigated.

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 case 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. To minimize the risk of schedule delay should be considered. If TRR-II project schedule is modified, the schedule for this project should also be revised to meet the overall TRR-II project schedule.

7. References

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Table 1 Design Parameters of TRR-II 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
Moderator cell Heat Load	678 W (578 W for nuclear heating And 100 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)	0.7	4.7
Mass Flux (g/s)	1.6	30
Wallis Flooding Correlation		
($J_g^{*1/2} + mJ_f^{*1/2} = C$)		
Vapor (j_g^*)	0.164	0.164
Liquid (j_f^*)	0.0248	0.0248

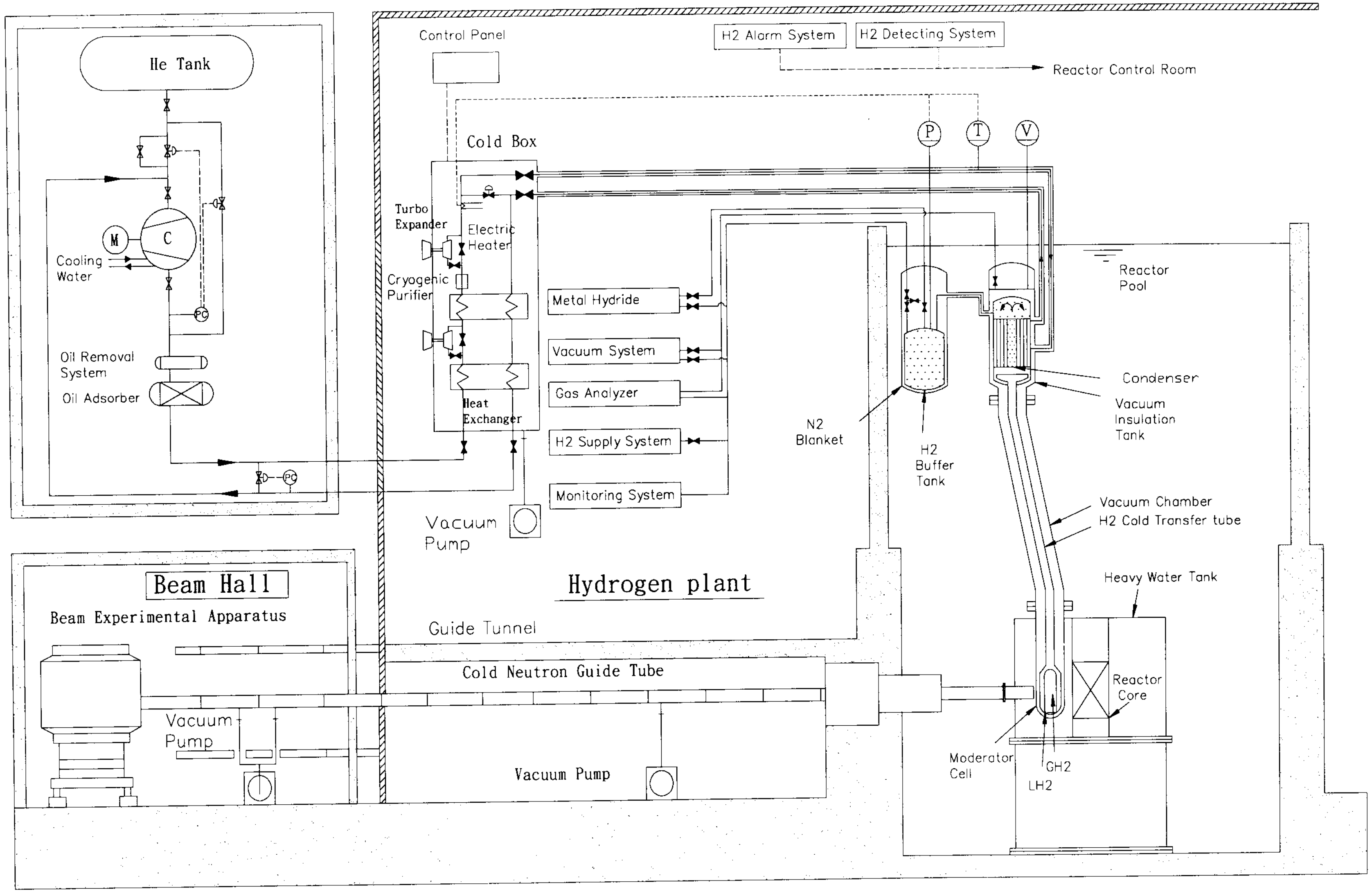


Figure 1. Layout of TRR-II CNS Facility.

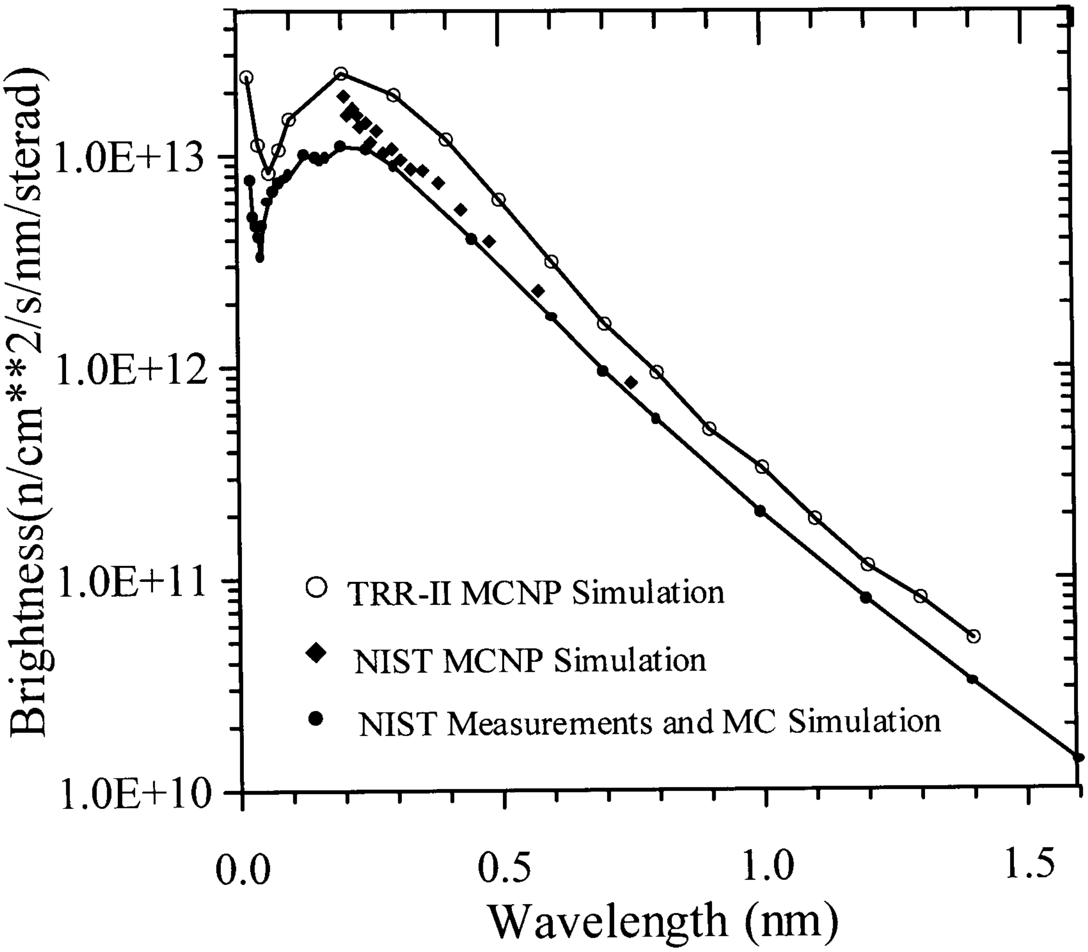


Figure 2. Comparison of CNS Brightness between TRR-II and NIST.

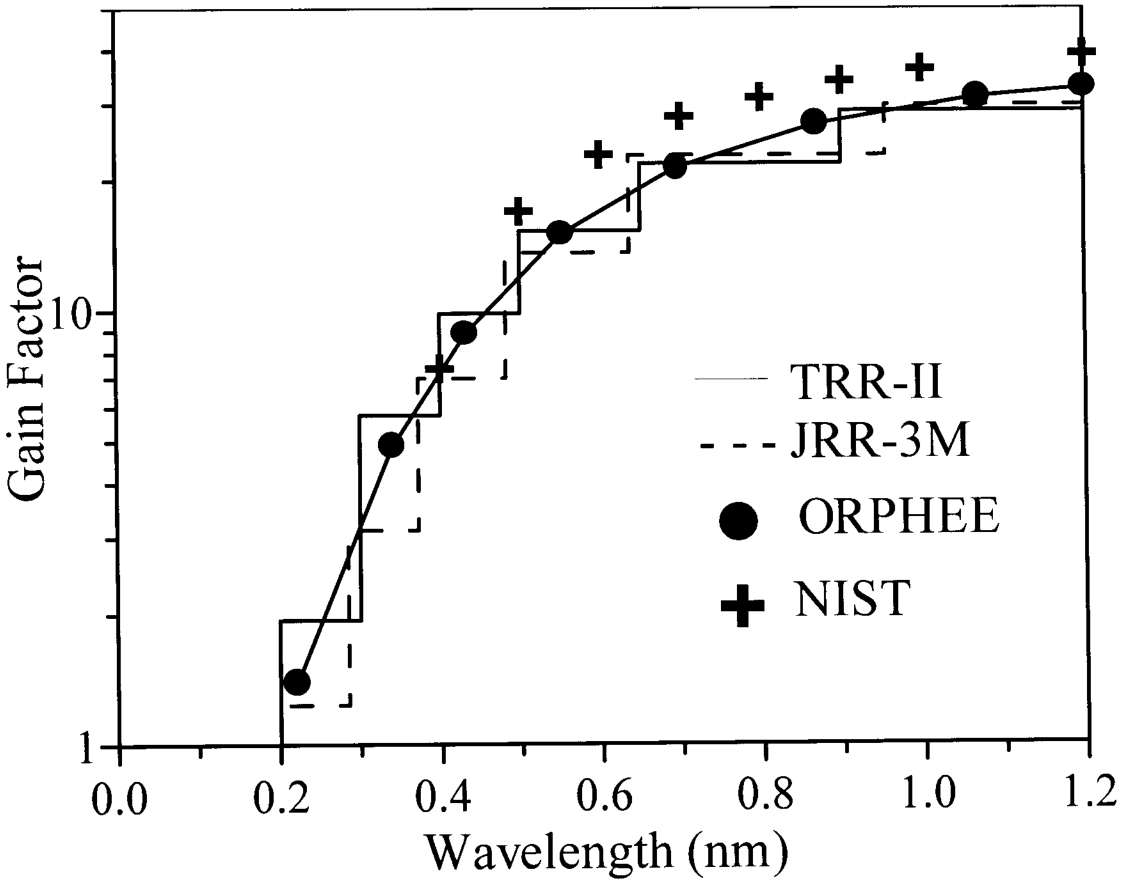
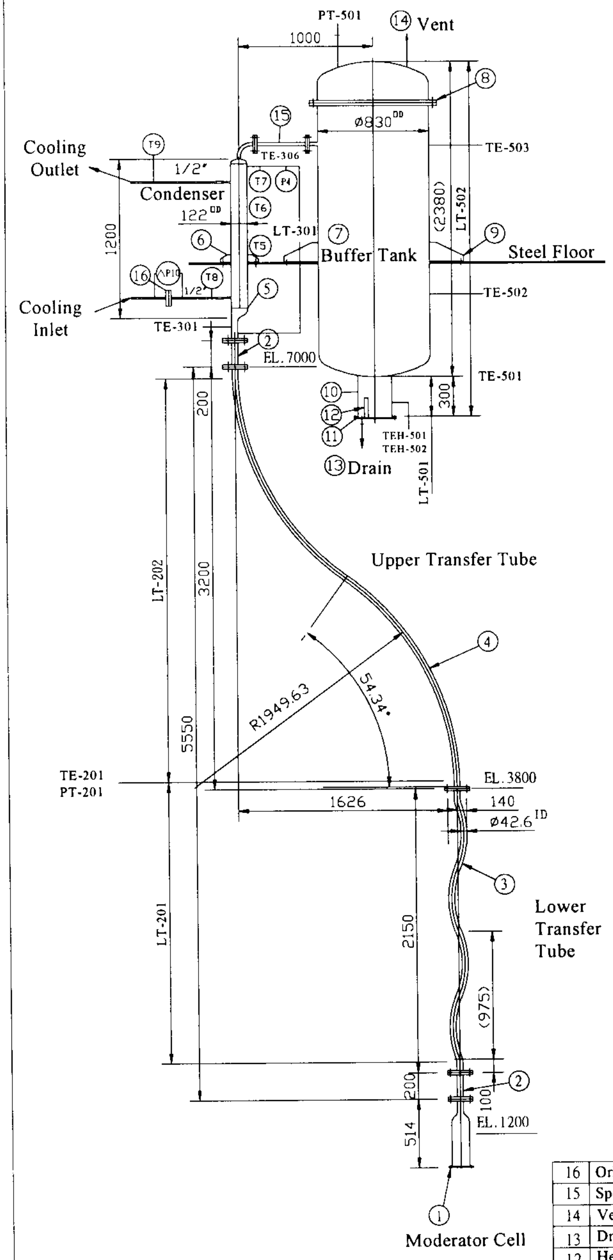


Figure 3. Comparison of TRR-II CNS Gain factor with JRR-3M, ORPHEE, and NIST.



16	Orifice		
15	Spool Piece Pipe	SUS 304	1 1/2" SCH 10S
14	Venting Pipe		1"
13	Drain Device		
12	Heater		30 kW
11	Sealing Gland		10" Flange
10	Heater Room		
9	Buffer Tank Supporting Frame	SUS 304	
8	Girth Flange		
7	Buffer Tank	SUS 304	Volume ~1.3 m3
6	Condenser Supporting Frame	SUS 304	
5	Condenser	SUS 304	
4	S-Type Transfer Tube	SUS TP304	1 1/4" SCH 10S, Type I, II
3	Transfer Tube	SUS TP304	1 1/4" SCH 10S, Type I, II
2	View Port	Glass	IDø42.6
1	Moderator Cell	SUS 304	
No.	Components Name	Materials	Memo

Figure 4. Schematic of mockup test facility for TRR-II CNS hydrogen loop.

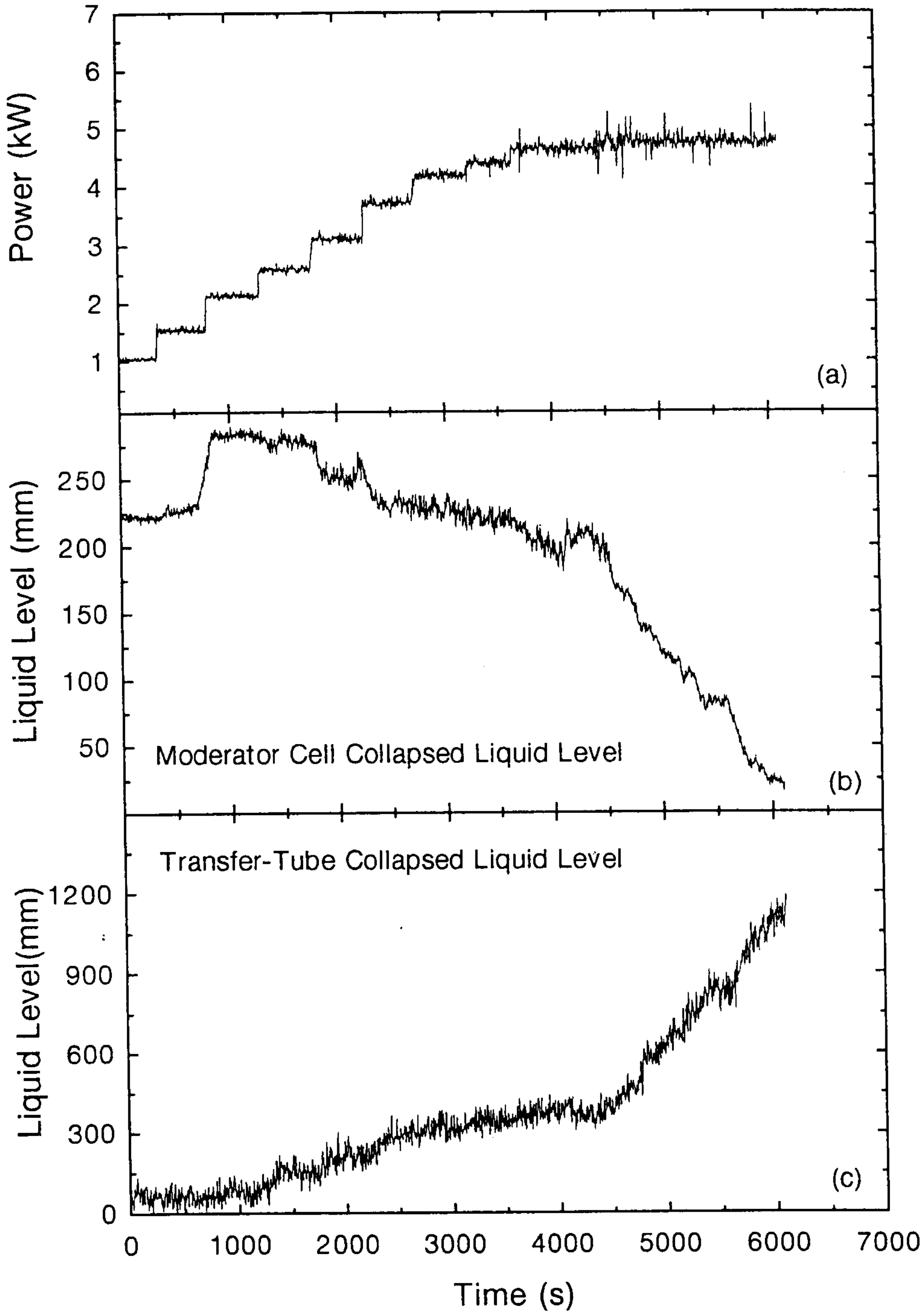


Figure 5. The effect of heat power on the collapsed liquid levels in moderator cell and transfer tube with the initial inventory 6.28 kg.

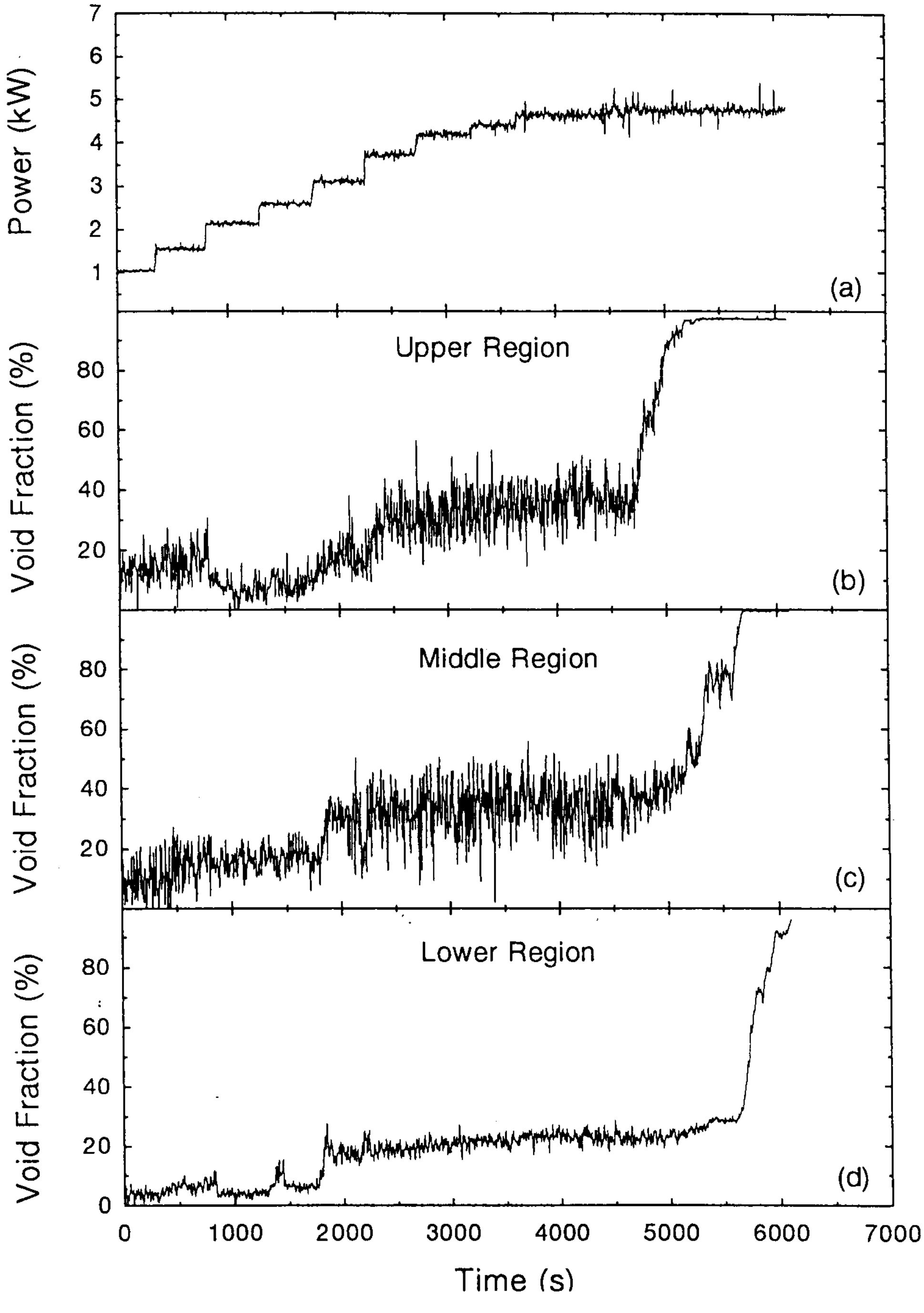


Figure 6. The effect of heat power on the moderator cell local void fractions with initial inventory 6.28 kg.