NUREG/CR-3849

Two-Phase 3x3 Rod Bundle Test Facility for Post-Critical Heat Flux Boiling

Prepared by K. Tuzla, C. Unal, O. A. Badr, S. Neti, J. C. Chen

Institute of Thermo-Fluid Engineering and Science
Lehigh University

Prepared for
U.S. Nuclear Regulatory Commission

NOTICE

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, or any of their employees, makes any warranty, expressed or implied, or assumes any legal liability of responsibility for any third party's use, or the results of such use, of any information, apparatus, product or process disclosed in this report, or represents that its use by such third party would not infringe privately owned rights.

NOTICE

Availability of Reference Materials Cited in NRC Publications

Most documents cited in NRC publications will be available from one of the following sources:

1. The NRC Public Document Room, 1717 H Street, N.W.
   Washington, DC 20555
2. The NRC/GPO Sales Program, U.S. Nuclear Regulatory Commission,
   Washington, DC 20555
3. The National Technical Information Service, Springfield, VA 22161

Although the listing that follows represents the majority of documents cited in NRC publications, it is not intended to be exhaustive.

Referenced documents available for inspection and copying for a fee from the NRC Public Document Room include NRC correspondence and internal NRC memoranda; NRC Office of Inspection and Enforcement bulletins, circulars, information notices, inspection and investigation notices; Licensee Event Reports; vendor reports and correspondence; Commission papers; and applicant and licensee documents and correspondence.

The following documents in the NUREG series are available for purchase from the NRC/GPO Sales Program: formal NRC staff and contractor reports, NRC-sponsored conference proceedings, and NRC booklets and brochures. Also available are Regulatory Guides, NRC regulations in the *Code of Federal Regulations*, and *Nuclear Regulatory Commission Issuances*.

Documents available from the National Technical Information Service include NUREG series reports and technical reports prepared by other federal agencies and reports prepared by the Atomic Energy Commission, forerunner agency to the Nuclear Regulatory Commission.

Documents available from public and special technical libraries include all open literature items, such as books, journal and periodical articles, and transactions. *Federal Register* notices, federal and state legislation, and congressional reports can usually be obtained from these libraries.

Documents such as theses, dissertations, foreign reports and translations, and non-NRC conference proceedings are available for purchase from the organization sponsoring the publication cited.

Single copies of NRC draft reports are available free, to the extent of supply, upon written request to the Division of Technical Information and Document Control, U.S. Nuclear Regulatory Commission, Washington, DC 20555.

Copies of industry codes and standards used in a substantive manner in the NRC regulatory process are maintained at the NRC Library, 7920 Norfolk Avenue, Bethesda, Maryland, and are available there for reference use by the public. Codes and standards are usually copyrighted and may be purchased from the originating organization or, if they are American National Standards, from the American National Standards Institute, 1430 Broadway, New York, NY 10018.

GPO Printed copy price: $4.25

NUREG/CR-3849
TS-843
R2

Two-Phase 3x3 Rod Bundle Test Facility for Post-Critical Heat Flux Boiling

Manuscript Completed: May 1984
Date Published: June 1984

Prepared by
K. Tuzla, C. Unal, O. A. Badr, S. Neti, J. C. Chen

Institute of Thermo-Fluid Engineering and Science
Lehigh University
Bethleham, Pennsylvania 18015

Prepared for
Division of Accident Evaluation
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555
NRC FIN No. B6794

TABLE OF CONTENTS

LIST OF FIGURES

ABSTRACT

This report describes the rod bundle post-CHF tests in progress and the test facility at Lehigh University. The mechanical and electrical design of the experimental facility and the iterative process used to arrive at the choices made for the design are described in detail. The test facility consists of a nine (3 x 3) rod bundle in a square shroud which form the test section together with the hot patches at the top and bottom ends. The rods and the hot patches are electrically heated while the shroud is radiatively heated. The test section includes instrumentation to measure the vapor superheat temperature and pressure drop upstream and downstream of a rod gap spacer. This is the first application of the hot patch technique for generating post-CHF conditions in a rod bundle and thus quasi-steady-state tests are being thought of as a backup procedure for conducting these post-CHF heat transfer tests.

The test section is part of a well instrumented recirculating loop to generate the desired post-CHF conditions. The other major components of the heat transfer loop include the surge tank, pumps, boiler, separation tank and condenser. The test facility also includes a versatile one hundred channel data acquisition system. The mechanical and electrical components in the facility have been chosen to have sufficient accuracy to yield meaningful results for the heat transfer coefficient in the rod bundle under various post-CHF conditions.

1. INTRODUCTION

Convective film boiling beyond critical-heat-flux (CHF) is encountered in a number of applications such as cryogenic systems, metallurgical processing, steam generators, and nuclear reactor loss-of-coolant accidents. In a number of these situations, post-CHF boiling occurs with very high void fractions wherein dispersed two-phase flow occurs in the heated channels. In this regime, termed convective film boiling, the two-phase mixture may exist in a nonequilibrium thermodynamic state with superheated vapor entraining drops or globules of saturated liquid. In this situation, the local actual-flow-quality (x_a) is not equal to the classical equilibrium quality (x_e). Analysis of this two-phase heat transfer problem requires solution of the vapor continuity and energy equations. A vapor volumetric source term, which represents the mass of liquid evaporated per unit time per unit volume, is involved in the above mentioned equations.

At the present time, the state of knowledge is lacking in the constitutive relations required to estimate the magnitude of this vapor source term, Γ. As noted by many researchers Chen, J. C. [1] and Groeneveld, D. C. and Rousseau, J. C. [2], the evaporative source intensity results from the simultaneous and competitive heat transfer between the hot wall surfaces to the vapor and liquid phases and between the liquid and superheated vapor phases. A few preliminary models for estimating Γ have been proposed, including those of Saha, P., Shiralkar, B. S. and Dix, G. E. [3] and of Webb, S. W., Chen, J. C. and Sundaram, R. K. [4]. The assessments of the available gamma models, and the development of improved models, are hampered by a lack of experimental data regarding the degree of thermodynamic nonequilibrium in convective film boiling.

In an effort to quantify the vapor source term Γ, a number of convective film boiling experiments have been conducted over the past twenty years. However, due to the extreme difficulty of measuring superheated vapor temperature in the presence of dispersed liquid, only a few attempts to quantify the degree of thermodynamic nonequilibrium have been reported. Mueller, R. E. [5] and Polomik, E. E. [6] obtained some limited data at high vapor qualities for internal flow in a tube. Hochreiter, L. E. [7] obtained some indication of vapor superheats in rod bundles, limited primarily to high vapor quality conditions (Loftus, M. J. et al.[8]). In previous work at Lehigh, Nijhawan et al. [9,10] successfully used an aspirated thermocouple probe to obtain measurements of vapor superheats at one axial location for convective film boiling in a tube. Gottula, R. C. et al. [11] extended Nijhawan's technique to obtain simultaneous measurements of vapor superheats at three axial locations for convective film boiling in a tube. A recently completed study at Lehigh University by Evans, D. C., Webb, S. W. and Chen, J. C. [12], extended the available data with slow moving quench front experiments in a vertical tube.

To date, there is only very limited data for nonequilibrium flow film boiling in rod bundle geometries. The present test facility has been designed to obtain such nonequilibrium flow film boiling data in a 3 x 3 rod bundle array. The vapor temperature, the wall temperature and the wall heat flux are the necessary measurements in such experiments. It is usually desirable to obtain time independent (steady-state) heat transfer data for comparison with analyses. In order to obtain steady-state heat transfer data in this kind of experiment, the quench front must be held at the test section inlet, which represents a major difficulty. Such steady-state post-CHF conditions have been achieved by several researchers, Nijhawan, S.

et al. [9], and Gottula, R. A. et al. [11] through the use of a hot-patch technique for single tube experiments. However, a recent Lehigh study (Evans, D. G., Webb, S. W. and Chen, C. J. [12]) showed that slow moving quench front experiments can be analyzed to obtain pseudo-steady state post-CHF data.

In the present test facility, the hot-patch technique will be attempted for the first time to a rod bundle geometry. It is hoped that the hot-patch design explained in the later sections of this report will successfully stabilize the quench front at the test section inlet. However, due to the first-ever nature of this design, there is no a priori assurance that the quench front can be successfully stabilized. For a back up procedure, the test facility is also designed for experiments with slow moving quench fronts, to permit quasi-steady-state tests.

These experiments will be conducted under the following conditions:

Mass Flux	7-27 kg/m^{2}s (5,000-20,000) lb/ft^{2}hr
Pressure	100-1000 kPa (15-150 psia)
Inlet Equilibrium Vapor Quality	5-50%
Heat Flux	3-30 kW/m^2 (10^3-10^4 Btu/Hr·ft^2)

These parametric ranges include conditions pertinent to reflood and quench phase of light water reactor accident analyses.

2. LOOP AND TEST SECTION DESIGN

This section describes the mechanical design of the experimental facility. The final design was obtained after many iterations in order to avoid various perceived operational and fabricational difficulties. Some of these difficulties will be briefly discussed along with their effect on the design. Types and locations of instruments are also described for better understanding of the experimental apparatus.

2.1 Test Loop

Two different concepts were considered for the two-phase loop:

- o steam-water injection loop
- o once through boiling loop

In the first concept, water and steam are mixed and injected into the test section. Upstream of this mixing location, liquid and vapor flows occur as single phases. Application of this concept to the present loop eliminates two-phase flow regimes upstream of the test bundle and reduces possible flow oscillations due to transitions in flow regimes. This concept requires a steam supply source, an accurate metering of steam flow rate, accurate control of steam pressure and a mixing chamber.

A once-through boiling loop starts with pure liquid and generates a desired two-phase flow by heat additions in various parts of the loop (mainly in the boiler and the test section). This type of loop usually has a preheater and a boiler before the test section. In practice, heating in the boiler is designed for moderate heat fluxes to avoid DNB and long boiler lengths are required. To avoid stratified flows the boiler is placed vertically and substantial head room is needed. This concept requires accurate metering of liquid flow rate and higher vertical space. After detailed comparisons of both concepts, the once-through boiling loop was selected for the present application of post-CHF experiments in 3 x 3 rod bundle. The main arguments that influenced this selection were:

- o Accurate metering of steam flow rate, required in case of a steam-water injection loop is a difficult task. Greater metering accuracy is possible for the liquid flow requirement of a once-through loop.

- o Steam-water injection raises concerns on the equilibrium of the phases after mixing.

- o Lehigh University's experience with once through boiling loop suggests that when the boiler section is placed vertically with upward flow, flow oscillations can be minimized. A suitable laboratory with three floors of total head space was located, permitting vertical placement of boiler and test section.

A schematic of the two-phase loop is shown in Figure 1. Water is pumped by a pair of metering pumps. The water temperature at this location is always below the saturation temperature. Flow rate is measured on the upstream side of the pump and the liquid is sent to the vertical tube boiler which provides various qualities of steam-water mixtures for the test bundle. The boiler and the test bundle are the main parts of the two-phase loop and they are described in detail in the following sections. The two-phase mixture at the outlet of the test section is sent to a tank where water and steam are separated. Water flows out to the condenser as it is collected at the bottom of the separation tank. The steam outlet is controlled by a back pressure regulating valve which senses the separation tank pressure. The regulating valve is of a diaphragm type and will be set to the test pressure. The remaining parts of the loop are a water cooled condenser and a surge tank.

In addition to flow rate measurement, fluid temperatures are measured at inlet and outlet to the boiler, at the inlet to the test section and at the outlet to the condenser.

2.2 Boiler

The boiler is specified for water at mass flow rate of 36 to 125 kg/hr (80-276 lb/hr), at inlet temperature and pressures of approximately 80°C and 1-10 bar respectively. The boiler is required to deliver wet steam of quality 0.35 to 0.70 for the above flow rates.

A single vertical tube design was chosen for the boiler. Direct Joule heating of the tube walls was selected in order to allow accurate measurement of boiler input power. The boiler tube dimensions were chosen to satisfy the following requirements:

a. The tube wall must have an electrical resistance capable of producing the required heat flux with manageable currents.

b. The tube must have sufficiently small cross section to avoid liquid flooding at low flow rates.

c. The tube must have sufficient surface area to reduce the input heat flux below DNB value.

d. The tube needed to avoid long lengths in order to reduce pressure losses and to avoid the use of any bends along the flow path.

e. The tube wall thickness must be sufficient to sustain mechanical stresses at operating temperatures.

f. The tube material should have good electrical resistance stability with temperature.

Inconel alloy 600 was selected as the tube material, due to its electrical resistance stability. To satisfy the requirements stated above the tube dimensions were chosen to be:

- o inside diameter 9/16"
- o outside diameter 11/16"
- o length 12'

Based on these dimensions it was calculated, Collier, J. G. [13] that:

- o Annular two-phase flow would be obtained in the boiler tube for quality higher than 0.05,
- o The critical (DNB) heat flux for the lowest flow rate and highest quality would be 412 kw/m^2, which is about three times larger than the anticipated maximum heat flux of the boiler tube,
- o Maximum velocity at the outlet of the boiler would be 224 m/s, which corresponded to a total pressure drop of 0.524 bar.

The boiler is to be insulated with 1" thick glass-wool and heat losses to the ambient will be determined experimentally prior to actual test runs.

2.3 Test Bundle

The dimensions of the rod bundle test section were chosen to be representative for pressurized water reactors. As shown in Figure 2, the bundle consists of nine rods of 9.5 mm (0.374") O.D. surrounded by a square shroud. The pitch was taken to be 12.6 mm (0.496"), which provides a rod-to-rod gap of 3.1 mm (0.122"). The distance between the shroud surface and the nearest row of rods was selected to obtain reasonably good similarity of thermal hydraulic conditions between the test section and a typical PWR core. Considering the different flow areas (as shown in Figure 2), a number of conditions have to be satisfied in order to achieve an ideal test section:

1. Equal pressure drops in all flow subchannels to minimize cross flows between subchannels.

2. Equal rates of heat addition per unit length and per unit flow mass in order to obtain equal vapor qualities in all subchannels at each elevation.

3. Similar velocity distributions to preserve equal wall shear stresses.

4. Similar temperature distributions in all subchannels.

Satisfying all of the above conditions was impossible. It was decided that the first two conditions were most important and had to be satisfied to avoid unrepresentative cross flows between subchannels. The requirement for equal pressure drops was satisfied by designing subchannels of equal hydraulic diameters. For the given rod diameter and pitch, this set the shroud inner width at 1.75 inches. Moreover, the corners of the square shroud were rounded with a radius of curvature of 0.381". Figure 2 shows the cross section of the rod bundle with the important dimensions. The requirement for equal rate of heat addition per unit length and per unit flow mass could be satisfied by requiring equal heat fluxes from the shroud and from the rods, as long as all subchannels have equal hydraulic diameters.

Schematic diagrams of the vertical cross section of the test bundle are shown in Figures 3a and 3b. The test section length between elevations A-B is 122 cm (48"). A spacer grid is located in the test section at 76.2 cm (30") elevation from the inlet (point A). Four instrumentation ports are located on one side of the shroud, for vapor temperature and pressure measurements.

A modified hot patch is incorporated at the inlet of the test section. This will be used to prevent quench front propagation into the test section during steady-state tests. Similarly, a top-patch is designed for the test section exit, to prevent any downward propagating top-quench. The inlet section is designed to provide uniform flow across the bundle (between the subchannels) before the flow enters the test section. Detailed information about the individual elements of the test bundle is given below.

2.3.1 Inlet Section

In order to hold the fuel rod simulators in place, to seal the lower end of the bundle and to provide uniform flow between the subchannels of the bundle, an inlet section is designed as shown in Figure 4. The inlet section has the same cross section as the test section. The lower end of the inlet section supports and seals the heater rods by rubber O-rings. The upper end of the inlet section is fastened to the hot patch. Two-phase flow from the boiler enters into the test section through a 1" diameter pipe. The inlet section contains a strainer to distribute the flow uniformly between the subchannels. The strainer is made of multilayer stainless steel screens. Two spacer grids are used in the inlet section for supporting the test tubes and for holding the strainer. The effectiveness of the strainer on uniformity was tested on a bench model. Visual observations of air and water tests have shown that flow is uniformly distributed between the subchannels.

2.3.2 Fuel Rod Simulators

The diameter of the fuel rod simulators (heaters) was selected to be 9.5 mm (0.374"), which is a typical PWR fuel rod diameter.

Two different designs of fuel rod simulators (test rods) were considered. The first option called for ohmic heating of thin Inconel tubes. Required strength for the tubes at operating temperatures and pressures necessitated tube wall thickness of 0.75 mm (0.030"). This would require 250 Amperes current for each rod in order to achieve the desired heat flux of 10 W/cm^2. For the nine rods, a total of 2,250 amps would be required. Difficult problems with buss-bars, electric isolation and arcing through the spacers were cause fc concern.

The second design utilizes internally heated rods, various versions of which are available on the market. By using high resistance internal ribbons, such heaters required much lower currents for equivalent surface heat fluxes. The best of these heaters used high thermal conductivity packing material (i.e. Boron-nitride) for electrical isolation between the heating element and the cladding. In addition it was found that up to 12 thermocouples could be placed at the inner surface of the clad in order to measure the rod surface temperatures.

Comparison of the above two options concluded that internally heated rods are technically superior. Thus, the selection was made in favor of internally heated test rods. A schematic sketch of the final rod design is shown in Figure 5. The heated length of the rod extends beyond the test length from both ends. The lower extension is 15 cm (6") long and its purpose is to prevent propagation of quench front into the test section. These lower extensions are referred to as "hot rods" and more information will be given in Section 2.3.3, in connection with the lower hot patch. Upper extension is approximately 12 cm (5") long and its purpose is to prevent top quenching.

Each fuel rod simulator is equipped with 12 thermocouples such that two thermocouples are in the lower extension, one thermocouple is in the upper extension and the remaining nine are in the test length. Thermocouples are placed into groves under the clad, with the junction tips in contact with the inner surface of 0.45 mm (0.018") thick stainless steel clad. Each heater rod has two heating coils. The upper heating coil is made of a 0.015" x 3/16" strip heating element and with an electrical resistance of approximately 3.3 ohms. The length of this coil is approximately 134 cm (53") which covers the entire test length and the upper extension. The lower coil is 15 cm (6") long and has an electric resistance of approximately 0.9 ohms. This lower coil covers the 15" inlet extension.

2.3.3 Lower Hot Patch

This is the inlet hot patch of the test section and its intended purpose is to arrest the CHF location at the test section inlet. The lower hot patch consists of two parts. The outer part surrounding the square shroud, as shown in Figure 6, is called the "hot patch." This piece is made of a copper block and heated by cartridge heaters with a total power capacity of 20 kW. A detailed drawing of the hot patch is given in Figures 7a and 7b. The second part of the lower hot patch, the inner part, consists of nine individual heater rods and these are referred to as "hot rods." Each hot rod is the lower 15 cm long heater extension below the test rods, as shown in Figures 5 and 6. These hot rods are manufactured with the test rods as a single piece with a common ground at the test section inlet. The resistance of each hot rod heater is 0.9 ohms. The nine hot rods are fed in parallel from a DC power supply. A thermocouple signal from the hotest point will be used to regulate the power. Surface temperature of the hot rods will be set to values 300-400°C higher than the fluid saturation temperature. In addition, an on-off temperature controller will be installed on each hot rod line to protect the individual heaters from local overheats. Bench experiments have shown that film boiling can be sustained on these hot rods for most of the proposed test conditions. However, it should be kept in mind that these working conditions, involving high temperatures and high heat fluxes, are almost at the operable limits for the heating elements. This use of hot rods in conjunction with the shroud hot patch is a first-time attempt to obtain fixed-quench-front conditions in post-CHF experiments.

2.3.4 Shroud

The dimensions of the shroud was determined from thermal-hydraulic similarity requirements as mentioned earlier. From these requirements, the shroud width was found to be 44.55 mm (1.754") and the shroud heat flux was determined to be equal to the test rod heat flux.

In the beginning, the shroud was designed to be heated by passing direct electric current of 3000 Amp through its walls. The walls had to be thin (0.030 inch) and accordingly could not take the fluid pressure (150 psi). Thus, the square shroud was to be surrounded by a circular steel pipe and the gap between the two was to be filled with a refractory powder which acts as a thermal and electrical insulator. At that stage, the rods had similar design, i.e. electrically heated thin wall tubes. To avoid arcing, the potentials of the nine rods and the shroud at any axial location were designed to be the same.

In a second design, the test rods were modified to minimize the fabrication and operational difficulties. The new design was based on the use of high resistance internal heating ribbons for both the test and hot rods. This meant that the only electrically hot part of the test section was the shroud; a fact which complicated the design especially from the viewpoint of electrically isolating the shroud from the rods. As a follow up to this modification, the idea of electric heating of the shroud was dropped. Other methods of heating the shroud (such as strip heaters, inductive heating, and radiative heating) were considered. In all these options the thickness of the shroud walls was not critical and there were only two constraints:

1. The shroud walls, with a maximum temperature of 1200°F, must withstand the fluid maximum pressure of 150 psia.

2. For transient experiments (moving quench front), the heat fluxes of both the shroud and test rods should be the same. This meant that shroud and test rods must have equal thermal masses per unit wetted perimeter.

In order to find the proper thickness and material which satisfy the above two conditions, we considered different materials and calculated the corresponding thickness based on the ASME codes for pressure vessels of noncircular cross section, Faupel, J. [14]. If the shroud were made from Inconel 625 square tube with sharp corners, the thickness would be 0.110 inch which made the thermal mass of the shroud much greater than that of test rods. The wall thickness required by stress considerations could be reduced if we used a shroud with round corners. Based on the equations given in Reference 14, stresses would be minimum if the radius of curvature of shroud corners was between 0.2-0.3 inch. Compromising with hydraulic considerations (equal pressure drops in flow subchannels), the radius of curvature was chosen to be 0.381 inch, which is very close to that for minimum stresses. Under such conditions and using Inconel 625, the necessary shroud wall thickness was found to be 0.077 inch. The resulting maximum deflection of the shroud due to hoop stress was calculated to be 0.014" at the center of each side for maximum operating pressure.

The shroud is to be made of two halves welded together along the axis, as shown in Figure 8. The welding joint was chosen to be at the zero stress line on the shroud walls. Moreover, the tolerances on the straightness, flatness, and twist of the shroud had to be very close in order to be able to center the vapor probe (0.098 inch O.D.) in the gap between the rods (0.122 inch). Twelve K-type thermocouples are to be externally brazed to one side of the shroud to monitor the wall temperatures.

Heat flux to the shroud will be supplied by radiation from a tubular furnace. The electrically heated furnace is 15 cm (6") ID and 120 cm (48") long. The furnace has a total power of 16 kw in its three independently controlled zones. The surface temperature of the furnace can reach up to 1200°C, which will provide the required radiation heat fluxes for the experimental range. The tubular furnace is made of two halves and hinged to a vertical stand. The split line allows the placement of vapor probes, pressure probes and thermocouples in to the shroud.

2.3.5 Upper Hot Patch (Top Patch)

This is the outlet hot patch of the test section and it is used to prevent top quench propagation into the test section. An assembly drawing of the top patch area is shown in Figure 9. Detailed drawings are shown in Figures 10a,b,c, and d. The top patch is made of two copper blocks which are heated with approximately 20 kw cartridge heaters. The lower piece of the top patch is brazed to the shroud upper end as shown in Figure 9. The upper piece provides additional superheated surface before the sealing of test heater rods. In addition to the heating of copper blocks, the portion of test rods in the top patch length are also heated at the same heat fluxes as the test rods.

2.3.6 Assembly of the Test Section

The hot patch and the lower part of the top patch are to be joined to the lower and upper ends of the shroud. The nature of the experiments require that these joints should have thermal conductivity which is comparable to solid copper and be free of bubbles or loose gaps. Otherwise, the areas of poor thermal contact would not be able to prevent local quenching of the shroud and result in propagation of a quench front into the test section. The present design was based on recent experience obtained at Lehigh University and EG&G. In this design, the hot patch is placed around the shroud with a gap of 0.1" and cast-brazed with high temperature silver alloy. A similar design is also applied to the lower part of the top patch. This casting process is a difficult task, requiring a controlled atmosphere furnace in order to prevent oxidation of the surfaces. The cast-brazing specification called for heating in a hydrogen furnace with a silver alloy of 1435°F melting point. At the date of this writing, the lower hot patch has been successfully brazed to the shroud. The upper hot patch joint encountered several problems related to leakages of the braze alloy from the ends of the top patch. At present, the top patch has a 0.7" high cast joint and the remaining portion of the gap (between the top patch and the shroud) has been packed with 100 m tungsten powder. The top of the shroud and the top patch was sealed with a nickel flange. Although all possible and reasonable precautions were taken in order to prevent bubble formation in the cast alloy, only actual test operations will demonstrate the degree of success obtained in this very difficult fabrication task.

2.3.7 Outer Frame

The test bundle, consisting of the test section, the hot patch, the top patch, the inlet section and the bottom and top sealing flanges, weighs approximately 1000 pounds. In order to support the above weight, without putting excess stress on the shroud, two supporting frames were designed. The lower support frame holds the inlet section at its top flange as shown in Figure 11. The hot patch, together with the shroud and the top patch, all sit on the lower frame and are fastened to the inlet section.

Since the shroud is the only supportive connection between lower and upper parts of the bundle, an upper frame was designed to release compression stresses on the shroud due to the weight of the upper bundle parts. A schematic diagram of this upper support is also shown in Figure 11. The upper frame guides the upper parts of the bundle to allow thermal expansion of the bundle, and balances the weight of the upper parts by its counter weights. As a result the shroud is placed under a slight tension during the hot experiments.

3. POWER SUPPLIES AND POWER METERING

3.1 Available Power

The space for this rod-bundle experiment is located in Whitaker Laboratory. Electric service of three phase 800 Amperes was installed in April 1983 for the project. The power panel has provisions for the following service:

Quantity	Current Rate Amperes	Phases
1	400	1
2	150	3
3	100	3
2	70	3
1	60	3

3.2 Power Supplies

Six power supplies are required for the different components of the rod bundle test loop; namely the test rods, hot rods, lower hot patch, upper hot patch, shroud furnace, and boiler. A list of the specifications for the power supplies is shown in the following table.

Specifications for Power Supplies

ITEM	TYPE	MAX. CURRENT AMPS	MAX. VOLT V	MAX. POWER Kw	REMARKS
Test Rods	DC	360	125	45	Heavy duty, silicon rectifier, saturable core reactor, with automatic proportional contol
Hot Rods	DC	500	60	30	Heavy duty, silicon rectifier, saturable core reactor, with automatic proportional control
Upper Hot Patch	AC Single Phase	50	120	6	Manually operated powerstat. In addition to this power, there will be extra 10 Kw provided by Cartridge heaters directly connected to line voltage
Lower Hot Patch	AC Single Phase	50	120	6	Manually operated powerstat. Similar to item 3, additional power is 15 Kw
Shroud Furnace	AC Single Phase	80	208	17	Zero Switching, silicon controlled rectifier, power controller
Boiler	AC Single Phase	1200	65	78	Variable reactance transformer

3.3 Power Metering

The power fed to all components, except the upper hot patch, will be measured by power transducers that give linear, analog output signals between 0-10V, where 10 volts correspond to full scale. The power range of the meters, the corresponding component heat fluxes, and specified accuracies are shown in the following table.

COMPONENT	POWER RANGE	ACCURACY	REMARKS
Test Rods	15-28 Kw ($4-7\ w/cm^2$)	2%-1%	Two power meters are used to cover the expected range of operation and to preserve accuracy of 2% or better
	7-15 Kw ($2-4\ w/cm^2$)	2%-1%	
Hot Rods	3.8-5.8 Kw ($9.3-13\ w/cm^2$)	1.5%-1%	Heat flux of hot rods is almost constant and corresponds to the best accuracy of the meter
Boiler	10-40 Kw	2%-0.5%	Two power meters are used to cover the expected range of operation (35% quality with maximum flow rate of 272 Lb/h or 70% with 136 Lb/hr) to preserve accuracy of 2% or better
	2.5-10 Kw	2%-0.5%	
Lower Hot	6 Kw	0.2%	The part of the power taken from the variac will be kept constant at about 6 Kw. Thus, accuracy is best. Variation of net power to hot patch is achieved by varying the number of cartridge heaters directly connected to the line voltage.
Shroud Radiation Furnace	4-16.5 Kw ($2-8\ w/cm^2$)	2%-0.5%	One power meter is good enough to cover the entire range of heat fluxes with accuracy of 2% or better.

Since there are three SCR power controllers feeding the three individually controlled heaters of the radiation furnace we had to use three power meters. However, the output of the three meters are connected to a load resistor box which provides one output signal 0-10V; the 10 volts correspond to the summation of the full scale powers of the three meters.

4. INSTRUMENTATION AND SYSTEM ACCURACY

4.1 Data Acquisition System

The data acquisition system (DAS) for the rod bundle post-CHF heat transfer experiment consists of a computer based system complete with a system multiplexer and voltmeter. A thorough survey of all commercially available systems was made as part of the DAS selection process. The major vendors evaluated included IBM, Digital Equipment Corporation (DEC) and Hewlett-Packard (HP). The HP system chosen for the present experiment has specifically been configured based upon the needs of the rod bundle setup.

The data acquisition system consists of a HP series 200 9816A computer, HP 3497A Data Acquisition/Control unit (multiplexer) and an HP3456A Digital Voltmeter with all the devices on a single HP-IB (IEEE 488) interface bus. Each of the devices listed above is described below individually and finally the overall system capabilities are summarized.

The HP Series 200 computer being used is a 16-bit computer based on a Motorola (MC68000) microprocesser with 32-bit internal architecture. Associated with this computer are 750 KB of internal memory, a 10 MB Winchester disk, a plain paper 100 characters per second impact printer and a plotter for generating the final results. The BASIC software for the 9816 computer is at least equivalent to ANSI FORTRAN in programming flexibility together with the capabilities for the interfacing of the rest of the DAS on the HP-IB bus. In addition this computer is compatiable with the instrument control software for the multiplexer and voltmeter described below.

The multiplexer (3497A) system has been configured to have a total of 100 channels. Eighty of these channels (4 cards) are to be used for thermocouple measurements and the rest are for various other transducers such as mass flow rate and pressure. The system is expandable to a total of 1000 channels if necessary. The four thermocouple cards each consisting of twenty channels each includes a hard wired reference junction compensating electronics to enhance the speed of temperature data acquisition. The relay multiplexer assemblies used here employ a "tree switch" to minimize capacitance effects resulting in the best possible measurements. The thermocouple multiplexer assemblies employ isothermal connector blocks to enable proper temperature measurements. All the features of the 3497A can be controlled from the computer through the HP-IB bus with coded commands that are fairly easy to program.

The 3456A Digital Voltmeter (DVM) is the heart of the data acquisition system. This is a high resolution, high accuracy versatile instrument offering variable speed and precision. The voltmeter is capable of 100 nanovolt sensitivity at 100 mV to detect small changes of temperature or it can be operated at speeds of up to 300 channels per second at lower resolution. The built-in buffer memory of the voltmeter can store up to 350 readings with programmed time delay to make efficient use of the computer time. The voltmeter includes digital averaging, filtering and variable integration times and it is expected that these capabilities will result in stable and repeatable measurements.

The overall DAS will be used in monitoring the heat transfer flow loop before the start of the experiment as well as to take the data when desired. The process of acquiring data requires (1) the setup of the voltmeter, (2) closing of the desired channel (one of hundred), (3) taking a reading, and (4) transferring the reading to the computer. Based on the DAS configuration described above, the time required to finish the above sequence can vary from 13 msec to 99 msec resulting in data rates of approximately 75 to 10 channels per second. The 3456A voltmeter and 3497A channel controller (scanner) can be synchronized with the scanner advance signal and the voltmeter reading complete signal to give analog scanning rates of about 300 channels per second at lower (4½ digit) voltmeter resolution.

The signals to be measured in the experiment are all (transducer as well as TC) DC voltages. For such signals the accuracies expected are about ± 0.1 percent of the reading in the 0.1 volt range. The accuracies expected for the temperature measurements with type K thermocouples are expected to vary from ± 1° to 2°C for the fast scan (4½ digit) in the range of 20 to 1200°C. In the slower scans (5½ digits) maximum uncertainties of ±0.9°C are expected in the same temperature range. The uncertainties given above include errors from reference junction compensation (±0.3°C), temperature difference along terminals, thermal offset, voltage to temperature conversion errors and the DVM accuracy specified earlier. The voltage to temperature conversion follows NBS125 definition with eight third order polynomials that are continuous at the end points.

Data acquired with the above described system will be stored in the 10 MB Winchester disk or the 256 KB floppy disks (for archival). The computer system described above will also be used to plot the results of the experiments for reporting purposes.

4.2 Individual Measurements and Accuracy

Instrumentation of the two-phase loop consisted primarily of thermocouples, pressure transducers, power metering devices and flow meters. A description of individual measurements and their accuracies are given below.

Temperature Measurements

Standard grade K type thermocouples are used for temperature measurements. Limits of error due to impurity of thermocouple materials is ±2.2°C or ±0.75 percent of reading. Additional uncertainties are ±0.9°C due to data acquisition system and ±2°C due to thermal contact resistance between the thermocouple and the surface if it is measuring a surface temperature (i.e. wall thermocouples). The thermocouples which measure the saturation temperature and the fluid temperatures at boiler inlet will be calibrated with reference thermometers to give an accuracy of [illegible]°C. The wall thermocouples then will be calibrated with reference to the thermocouple which measures the saturation temperature. After this calibration it is expected that maximum uncertainty on wall temperature measurements will be ±2°C.

Vapor temperature measurements include additional uncertainties due to strip chart reading and the quality of vapor probe response. These uncertainties, as discussed in Evans, D. G., Webb, S. W. and Chen, J. C. [12], ranges from ±10°C to ±30°C.

Pressure Measurement

The pressures to be measured in the rod bundle experiment consist of the test section absolute pressure and the differential pressure for the pressure drop between the pressure taps on the shroud walls. All the above data are recorded using Validyne variable reluctance type pressure transducers. There are a total of four pressure taps on the test section and a couple of these are multipurpose in nature. They are to be used for vapor probe insertion as well as pressure measurement. A brief description of the pressure measurement system is given below.

The test section pressure (0 to 120 psia) is to be measured with a Validyne AP10-54 absolute pressure transducer. This is a transducer well suited for liquids as well as gaseous media. The pressure sensing element is a flat diaphram of magnetic stainless steel welded between the two halves of the transducer in a symmetric assembly. The sensing coils are covered with non-magnetic stainless steel, thus providing a completely stainless steel pressure cavity. One side of the diaphram is exposed to an evacuated and welded reference chamber. The electronics for this transducer are described in one of the following paragraphs.

The differential pressure (Δp) transducers (Validyne DP15) are similar in construction with an all stainless steel pressure cavity. The diaphrams in these transducers are sealed with O-rings thus providing for removable diaphrams that could be used at different Δp ranges. One of the difficulties in choosing the range of these transducers lies in the fact that the test section had to be designed to be full of water though the experiment will not operate like this most of the time. Thus the Δp cells had to have enough of a range to accommodate the head of water between the pressure taps. The DP15 transducers have a total range of 560 mm of H_2O head with a maximum line pressure of about 3000 psia.

The principle of operation for both the above transducers is the same. The diaphram of magnetically permeable material completes a magnetic circuit with two E-shaped cores. The diaphram deflection with the application of pressure increases the gap in the magnetic flux path of one core and decreases the gap equally in the other. These changes are measured in an AC bridge circuit in which an output voltage proportional to pressure is obtained. The final demodulated output is a DC voltage linearly proportional to the pressure.

All the four transducers above 3Δp and one absolute will have electronics in one 4 channel demodulator; Validyne CD280-4-RM4 with a switch selectable pressure display and continuous 4 channel 0 to 10V DC output for the computer data acquisition. The pressure transducers as well as the demodulator have linearities of ±0.5 percent of full scale with less than 0.5 percent zero shift for 200 percent overpressure. The line pressure effect for the Δp cells are expected to be less than one percent full scale zero shift at 1000 psig. The hysteresis effects are guaranteed to be less than 0.5 percent per excursion for all the transducers. Thus the transducer and demodulator arrangements described above are expected to be quite suitable for the intended pressure measurements.

Power Metering

A description of power metering devices and their accuracies was given in Section 3. Additional uncertainties are due to the data processing system and due to the calibrations of heat losses to the ambient where applicable. The uncertainty due to data acquisition system is 0.06 percent of full scale.

Heat losses from the boiler, from the shroud furnace and from the hot patch are less than 180 W, 1700 W and 120 W respectively. Estimated uncertainties on the above heat losses are 9 W, 51 W and 6 W respectively. Thus, total uncertainties of power measurements will be as follows.

o Test rod power	7-15 kW range	± 159 W
	15-28 Kw range	± 297 W
o Hot rod power	3.8-5.8 Kw	± 60 W
o Boiler power	2.5-10 kW range	± 65 W
	10-14 kW range	± 233 W
o Hot patch power	0-5.8 kW	± 22 W
o Shroud furnace power	4-16.5 kW	± 130 W

Flow Rate Measurement

Flow rates are measured with variable area flow meters. Two flow meters with different flow ranges (0-150 lb/hr and 150-300 lb/hr) are used for better accuracy. The uncertainty for the flow meters, including the erorrs due to flow meter electronics, is ±0.54 percent of full scales. Additional uncertainty due to data acquisition system is 0.06 percent of full scales. Final uncertainties of flow meters are then,

0-68 kg/h (0-150 lb/h) range	±0.41 kg/h
68-136 kg/h (150-300 lb/h) range	±0.82 kg/h

Saturation Temperature

The saturation temperature is measured with a thermocouple at test section inlet. Another measurement for saturation temperature is obtained from the test pressure measurement. Both instruments will be calibrated for maximum accuracy. The estimated uncertainty on saturation temperature is expected to be ±0.5°C.

Specific Enthalpy of Vaporization

Based on measured inlet pressure the enthalpy of vaporization uncertainty is less than ±1 kJ/kg.

Test Section Axial Position

Uncertainty of vapor probe position is approximately 3 mm due to thermal expansion of the test section. Uncertainty of shroud or test rod wall thermocouple position is the sum of the expansion error, 3 mm, and an initial position error of 3 mm, for a total uncertainty of 6 mm.

4.3 Uncertainty Analysis for Equilibrium Quality

The rate of heat input to the fluid up to elevation z in the test section is

$$Q_z = Q_o + Q_B + Q_{HP-HR} + Q_{TR} + Q_{SH} \qquad (1)$$

where

- Q_o : Rate of heat brought in by the enthalpy of water inlet to boiler
- Q_B : Rate of heat transferred to fluid in boiler measured as electric power input to boiler
- Q_{HP-HR} : Rate of heat supplied by hot patch and hot rods, measured as electric power input to hot patch and hot rods
- Q_{TR} : Rate of heat contribution by the test rods, measured as electric power input to test rods
- Q_{SH} : Rate of heat transferred from shroud, measured as electric power input to shroud furnace

Equilibrium enthalpy of the fluid at elevation z can be calculated from Equation (1) as

$$h_z = h_f + x_z \cdot h_{fg} = \frac{Q_z}{m} \tag{2}$$

where

h_f = enthalpy of saturated liquid at test pressure

h_{fg} = latent heat of fluid at test pressure

m = mass flow rate of fluid

Combining Equations (1) and (2) will give the equilibrium quality as

$$x_z = \frac{Q_z}{m \cdot h_{fg}} - \frac{h_f}{h_{fg}}$$

or

$$x_z = \frac{h_o}{h_{fg}} - \frac{h_f}{h_{fg}} + \frac{1}{mh_{fg}} [Q_B + Q_{HP-HR} + Q_{TR} + Q_{SH}]$$

where, h_o is the fluid enthalpy at inlet to boiler. Each term on the right hand side can be represented by $(\Delta x)_i$, thus,

$$x_z = \Delta x_{ho} - \Delta x_{hf} + \Delta x_B + \Delta x_{HP-HR} + \Delta x_{TR} + \Delta x_{SH} \tag{3}$$

where

h_o is determined for measured temperature and pressure at inlet to boiler

h_f is determined for saturation temperature in the test section

h_{fg} is determined for saturation temperature in the test section

m is measured mass flow rate

Q_B is measured boiler input after heat losses

Q_{HP-HR} is measured heat inputs of hot patch and hot rods after heat losses

Q_{TR} is measured heat inputs of test rods

Q_{SH} is measured heat input of the shroud after heat losses

Average uncertainty in x_z can be calculated from Equation (3) as follows

$$[\Delta x_z]^2 = [\Delta(\Delta x_{ho})]^2 + [\Delta(\Delta x_{hf})]^2 + [\Delta(\Delta x_B)]^2 + [\Delta(\Delta x_{HP-HR})]^2 + [\Delta(\Delta x_{TR})]^2 + [\Delta(\Delta x_{sh})]^2 + [\Delta(\Delta x_m)]^2 \quad (4)$$

Each term on the right hand side can be calculated individually. Sample calculations of average experimental uncertainties for equilibrium qualities at the hot-patch inlet, at the second vapor probe location and at the test section outlet are given in the following subsection.

Sample Uncertainty Calculations

Sample calculations at the four extreme cases are presented below.

Common Test Parameters for All Sample Cases

Test pressure	p = 138 ±3 kPa (20 psia)
Boiler inlet temperature	$T_{b,i}$ = 60 ±0.5°C
Boiler inlet enthalpy	h_o = 251 ±2.1 kJ/kg
Saturation enthalpy	h_f = 456.5 ±1.4 kJ/kg
Enthalpy of vaporization	h_{fg} = 2233 ±0.88 kJ/kg
Second vapor probe location	z = 610 ±6 mm
Test section length	z = 122 ±6 mm

Sample	Low G Low x	High G Low x	Low G High x	High G High x
Parameter				
(at test section inlet)	0.05	0.05	0.50	0.50
m (kg/hr)	35	125	35	125
G(kg/m²s)	7.68	27.4	7.68	27.4
δm (kg/h)	0.41	0.82	0.41	0.82
δG (kg/m²s)	0.09	0.18	0.09	0.18
Q_b (w)	5542	19729	15294	54622
δQ_b (w)	65	233	233	309
q_{HP-HR} (w/cm²)	13	16	7	13
Q_{HP} (w)	3120	3840	1680	3120
δQ_{HP} (w)	22	22	22	22
Q_{HR} (w)	5200	6400	2800	5200
δQ_{HR} (w)	60	60	60	60
q_{TR} and q_{SH} (w/cm²)	1.6	6.5	0.8	3.25
Q_{TR} (w)	6100	24400	3050	12200
δQ_{TR} (w)	159	297	159	159
Q_{SH} (w)	3200	12800	1600	6400
δQ_{SH} (w)	130	130	130	130

Uncertainty at Hot Patch Inlet

x_e	0.05	0.05	0.50	0.50
$\Delta(\Delta x_{ho})$	0.00094	0.00094	0.00094	0.00094
$\Delta(\Delta x_{hf})$	0.00063	0.00063	0.00063	0.00063
$\Delta(\Delta x_b)$	0.00300	0.00299	0.01076	0.00400
$\Delta(\Delta x_m)$	0.00083	0.00046	0.00230	0.00128
Total x_e	0.00331	0.00323	0.01106	0.00435

Uncertainty at Second Vapor Probe Location

($\Delta(\Delta x_{ho})$, (Δx_{hf}) and (Δx_b) same as above)

x_e	0.74	0.51	0.92	0.83
$\Delta(\Delta x_{HP-HR})$	0.0040	0.0011	0.0040	0.0011
$\Delta(\Delta x_{TR})$	0.0073	0.0020	0.0073	0.0020
$\Delta(\Delta x_{SH})$	0.0060	0.0017	0.0060	0.0017
$\Delta(\Delta x_m)$	0.0097	0.0040	0.0118	0.0060
Total Δx_e	0.0145	0.00586	0.0192	0.0078

Uncertainty at Test Section Outlet

x_e	0.97	0.77	35°C superheat	0.96
$\Delta(\Delta x_m)$	0.0125	0.0057	0.0132	0.0069
Total Δx_e	0.0165	0.0071	0.0201	0.0085

The above maximum uncertainties are calculated for the worst case of all errors in the same direction. It is clear that average experimental uncertainties will be less than these maximum values. Furthermore, it is possible to decrease the above maximum uncertainties by using additional metering devices. The present metering devices (i.e. flow meters and power meters) were selected for optimum cost and accuracies. The uncertainties of these meters are proportional with their full scale ratings. During the selection of these meters, a wide range of experimental parameters were considered. We will find out the exact capabilities of the test set up when the experiments start. Then, it is possible to decrease the above uncertainties by using intermediate range metering devices.

SUMMARY

The rod bundle post-CHF test facility at Lehigh University consists of the two-phase loop, the test section and associated instrumentation. The two-phase loop is designed as a once through boiling loop. The flow is held at constant rates by a pair of metering pumps. Electrically-heated, vertical tube boiler is to be used to obtain desired qualities at the test section inlet. The outlet of the test section is connected to a separation tank where the test pressure is to be controlled with a back pressure regulating valve.

The test section incorporates a nine (3 x 3) rod bundle in a square shroud, with bottom and top hot patches. The rod diameter and spacing were chosen to be representative for PWR's, with a total length of 122 cm. The fuel rod simulators are electrically heated, and each rod contains 12 thermocouples for surface temperature measurements. The test facility is designed to cover the following parametric ranges:

o Mass Flux	7-27 kg/m^2s
o Pressure	100-1000 kPa
o Inlet Equilibrium Quality	5-50%
o Heat Flux	3-30 kW/m^2

The instrumentation for the two-phase loop and the test section include the following major items:

- o Liquid phase flow meters
- o Test section total pressure transducer
- o Test section differential pressure transducers
- o Vapor superheat probes
- o Approximately 200 thermocouples for various temperature measurements
- o Separate power supplies for boiler, hot-patch, hot-rods, test rods, shroud furnace and top patch
- o Individual power meters for each power supply with exception of the top-patch power
- o Various temperature controllers

The test facility also includes a versatile, one hundred channel data acquisition system. The DAS has a capability of contiuous recording of 100 channels in approximately 2 seconds, with required accuracy.

REFERENCES

1. J. C. Chen, "Some Phenomenological Questions in Post-Critical Heat Flux Heat Transfer," NATO Advanced Research Workshop on Two-Phase Flows and Heat Transfer, Spitzingsee, F. R. Germany, August-September, 1982.

2. D. C. Groeneveld, and J. C. Rousseau, "CHF and Post-CHF Heat Transfer: an Assessment of Prediction Methods and Recommendations for Reactor Safety Codes," NATO Advanced Research Workshop on Two-Phase Flows Heat Transfer, Spitzingsee, F. R. Germany, August-September, 1982.

3. P. Saha, B. S. Shiralkar, and G. E. Dix, "A Post-Dryout Heat Transfer Model Based on Actual Vapor Generation Rate in Dispersed Droplet Regime," ASME Paper 77-HT-80.

4. S. W. Webb, J. C. Chen, and R. K. Sundaram, "Vapor Generation Rate in Nonequilibrium Convective Film Boiling," 7th International Heat Transfer Conference, Munich, 1982.

5. R. E. Mueller, "Film Boiling Heat Transfer Measurements in a Tubular Test Section," EURAEC-1971/GEAP-5423, 1967.

6. E. E. Polomik, "Transition Boiling Heat Transfer Program-Final Summary Report for Feb/63-Oct/67," GEAP-5563, 1967.

7. L. E. Hochreiter, "NRC/Westinghouse/EPRI FLECHT Low Flooding Rate Skew Axial Profile Results," presented at the 5th Water Reactor Safety Information Meeting, Washington, D.C , 1977.

8. M. J. Loftus, L. E. Hochreiter, C. E. Conway, E. R. Rosal and A. H. Wenzel, "Non-Equilibrium Vapor Temperature Measurements in Rod Bundle and Steam Generator Two-Phase Flows," Proceedings OECD (NEA) CSNI Third Special Meeting on Trans. Two-Phase Flow, Pasedena, California, CSNI Report No. 61, 1981.

9. S. Nijhawan, J. C. Chen, R. K. Sundaram and E. J. London, "Measurements of Vapor Superheat in Post-Critical-Heat-Flux Boiling," Transactions ASME, Journal of Heat Transfer, Vol. 102, pp. 465-470, 1980.

10. S. Nijhawan, "Experimental Investigation of Thermal Non-Equilibrium in Post-Dryout Steam-Water Flow," Ph.D. Dissertation, Lehigh University, 1980.

11. R. C. Gottula, R. A. Nelson, J. C. Chen, S. Neti, and R. K. Sundaram, "Forced Convective Nonequilibrium Post-CHF Heat Transfer Experiments in a Vertical Tube," ASME-JSME Thermal Engineering Conference, Honolulu, March, 1983.

12. D. G. Evans, S. W. Webb and J. C. Chen, "Measurement of Axially Varying Nonequilibrium in Post-Critical-Heat-Flux Boiling in a Vertical Tube" NUREG/CR-3363, TS-831-I, Vol. 1, 1983.

13. Collier, J. G., "Convective Boiling and Condensation," McGraw-Hill, New York, 1972.

14. Faupel, J., "Pressure Vessel and Piping Codes," ASME Trans., J. Pressure Vessel Technology, Vol. 101, pp. 255-267, 1979.

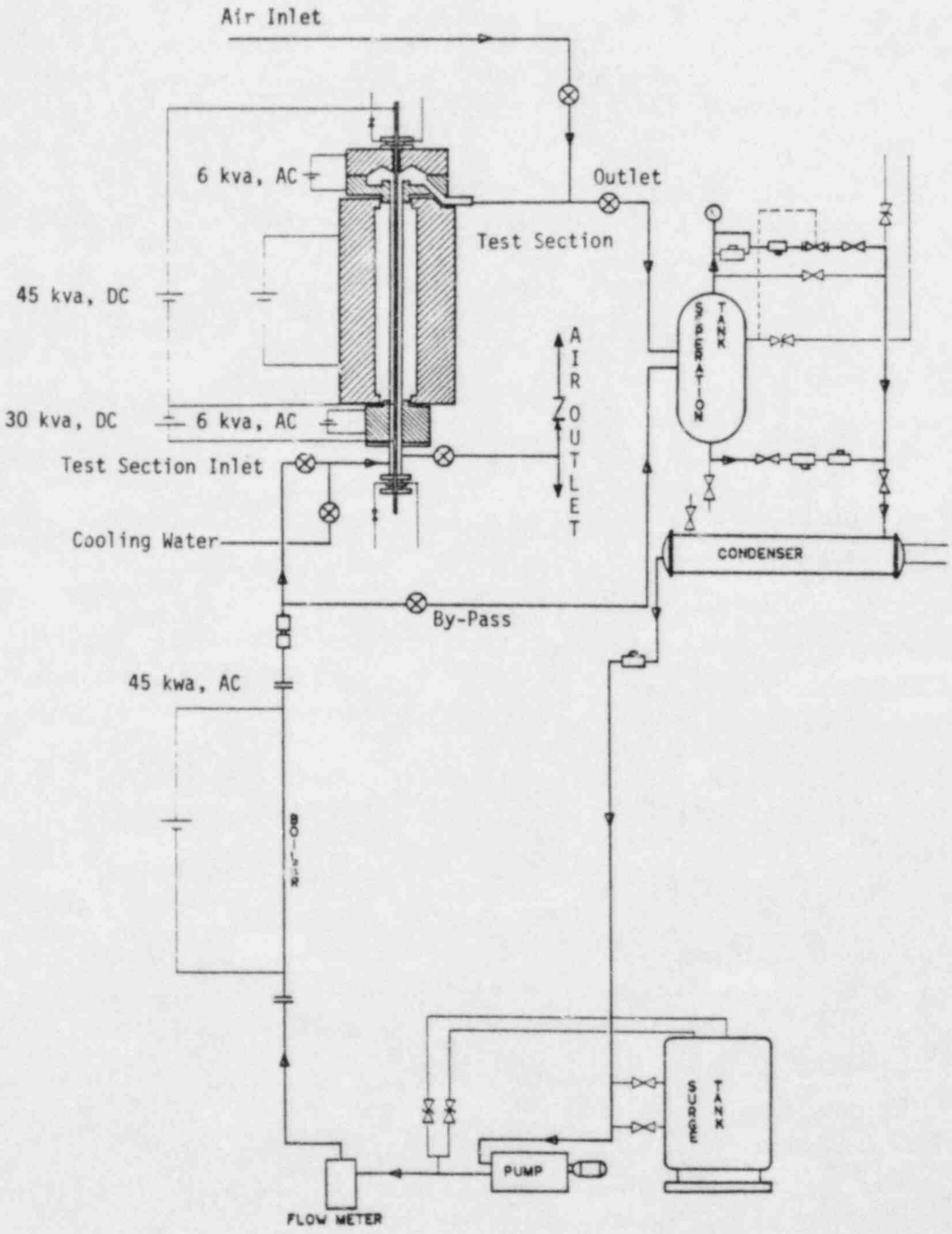


Figure 1. Schematic of Lehigh University Rod Bundle Test Loop

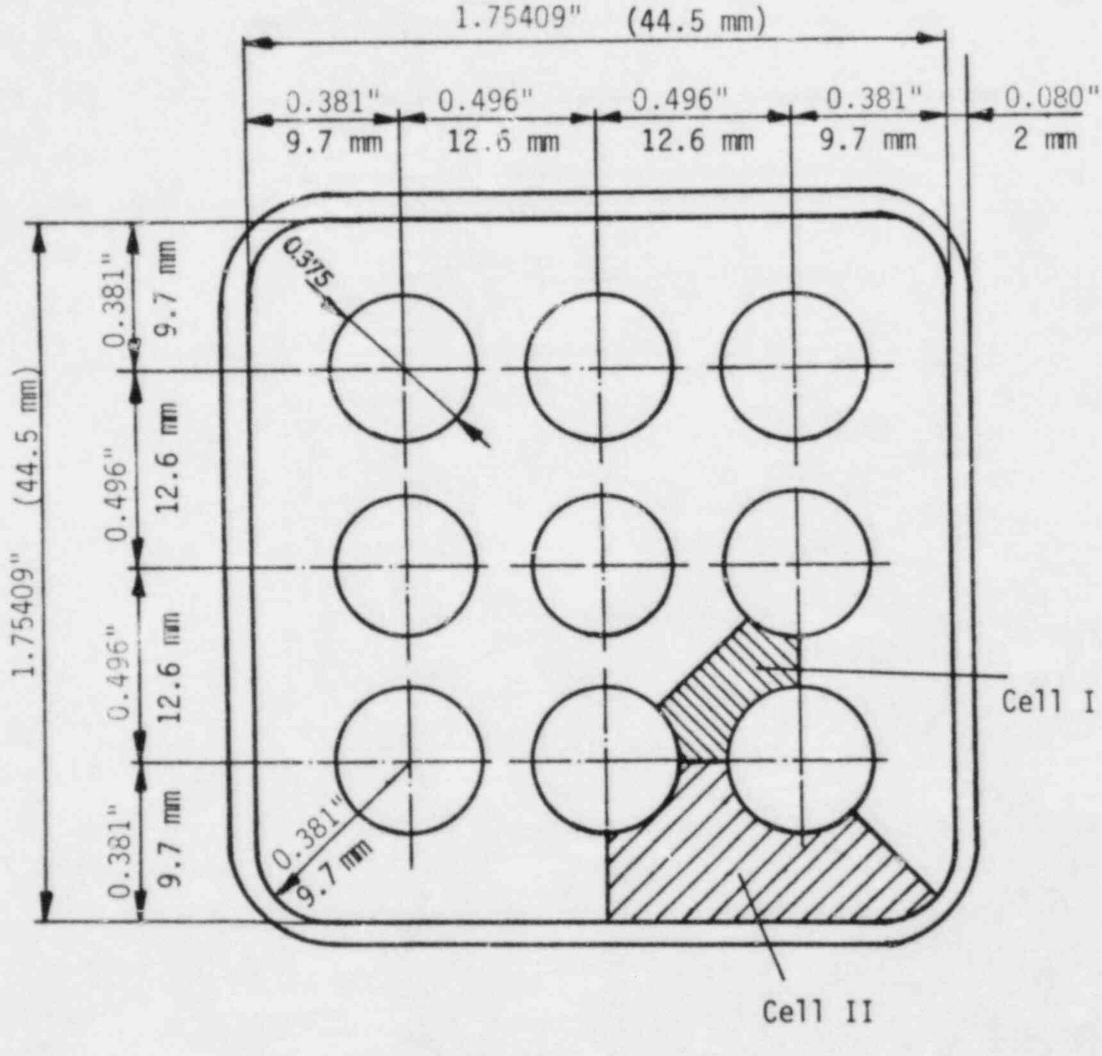


Figure 2. Cross-sectional View of the Test Bundle

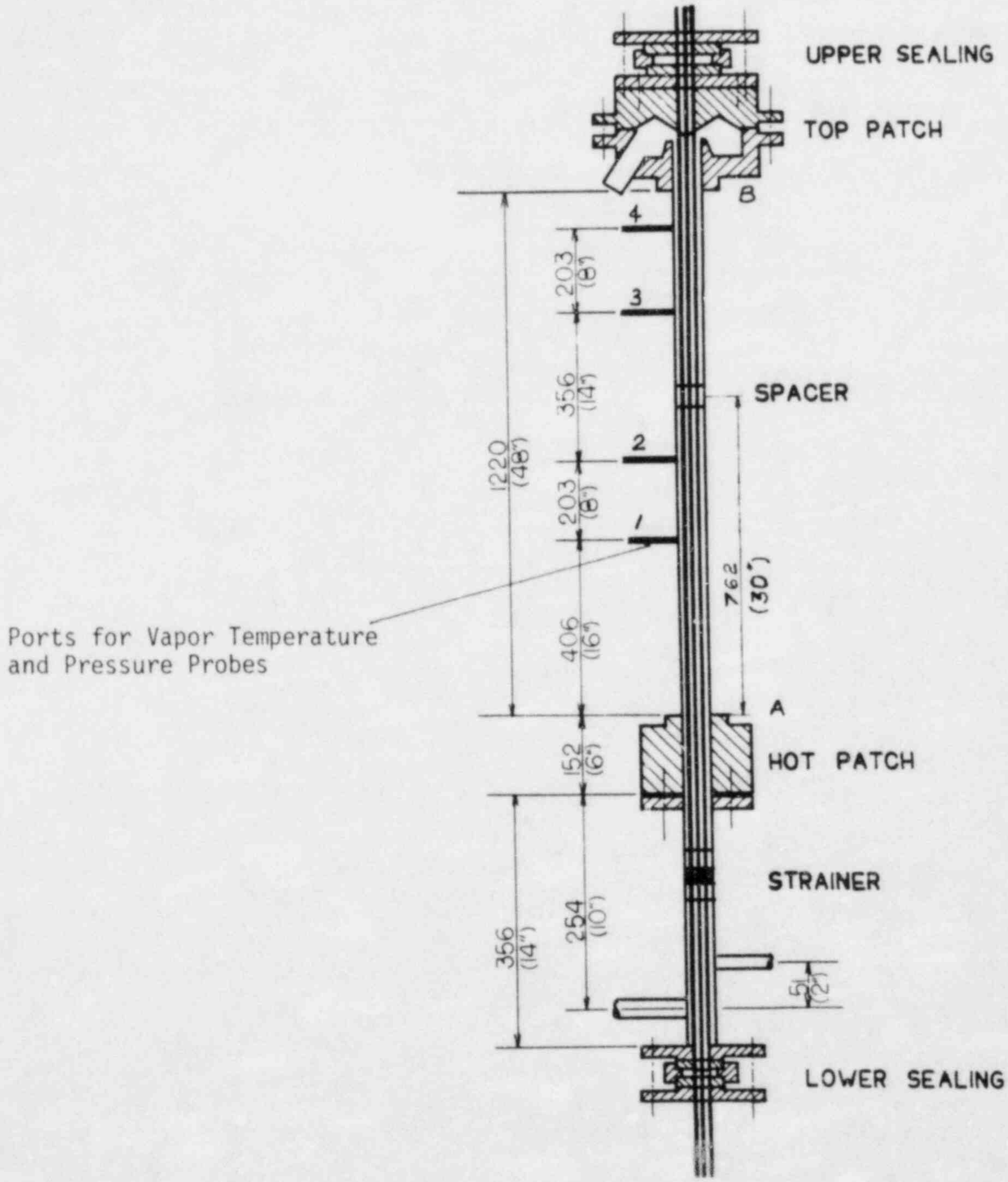


Figure 3a. Schematic of the Test Bundle

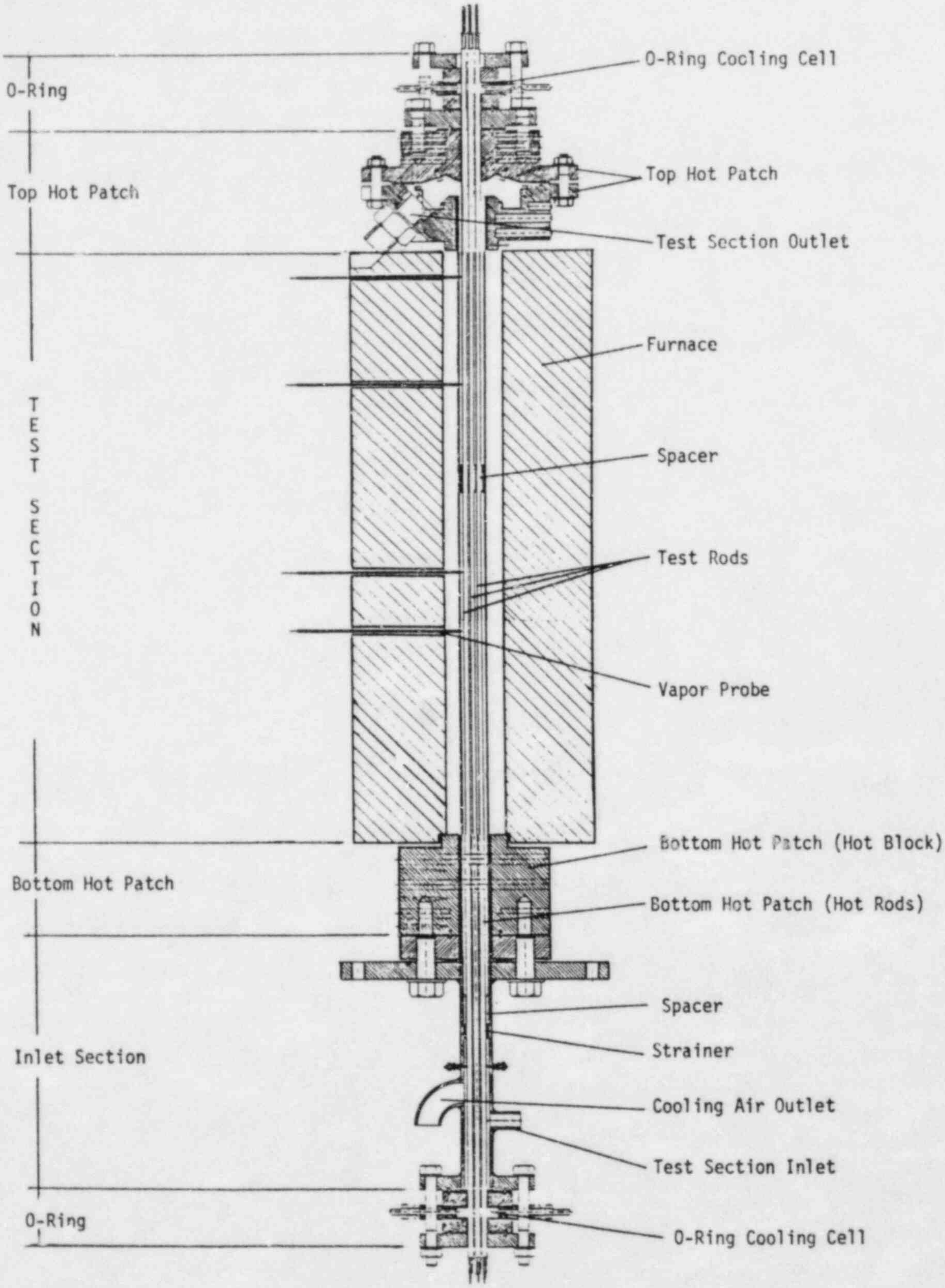


Figure 3b. Schematic of the Test Bundle

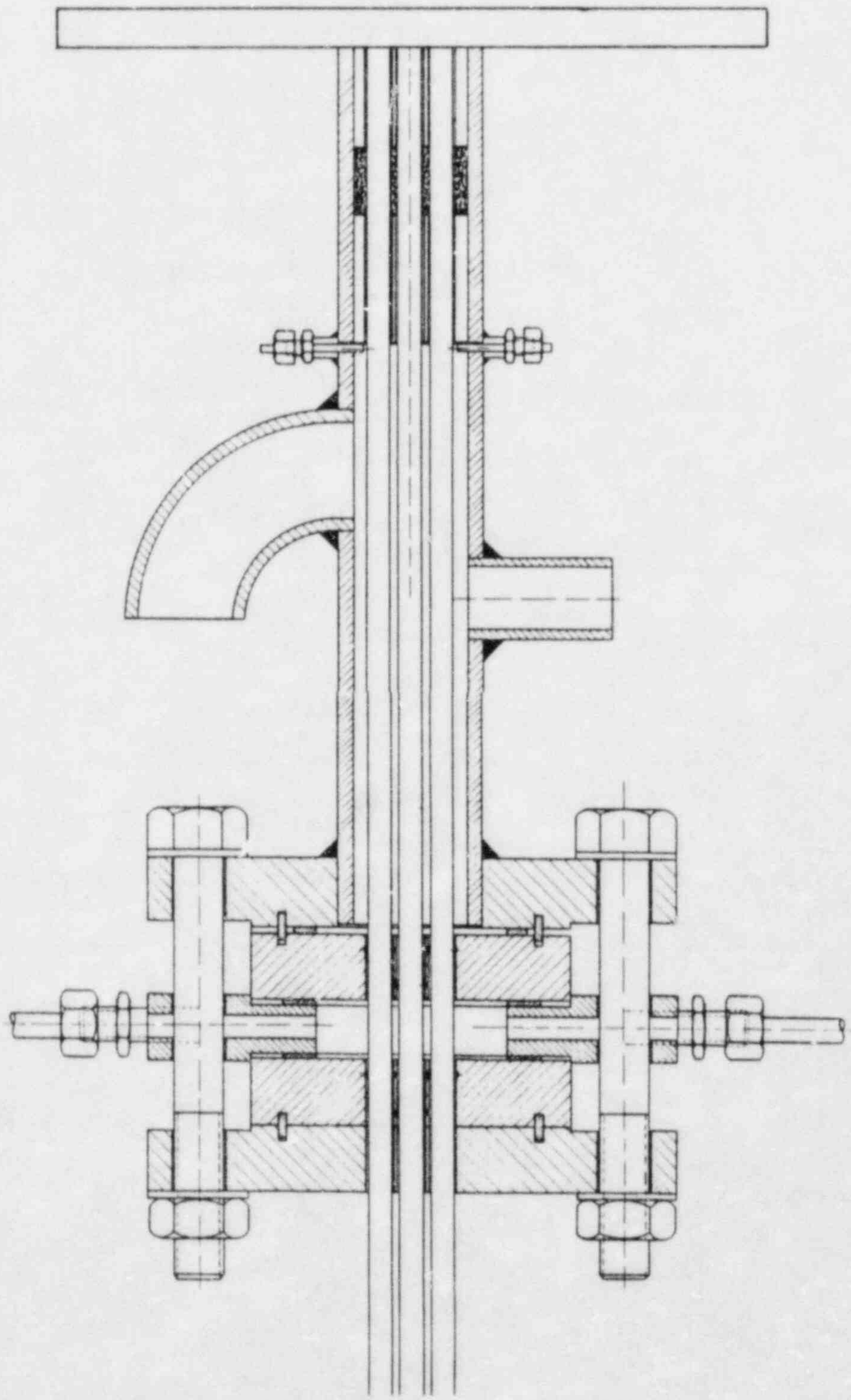


Figure 4. Inlet Section and Lower Sealing Assembly

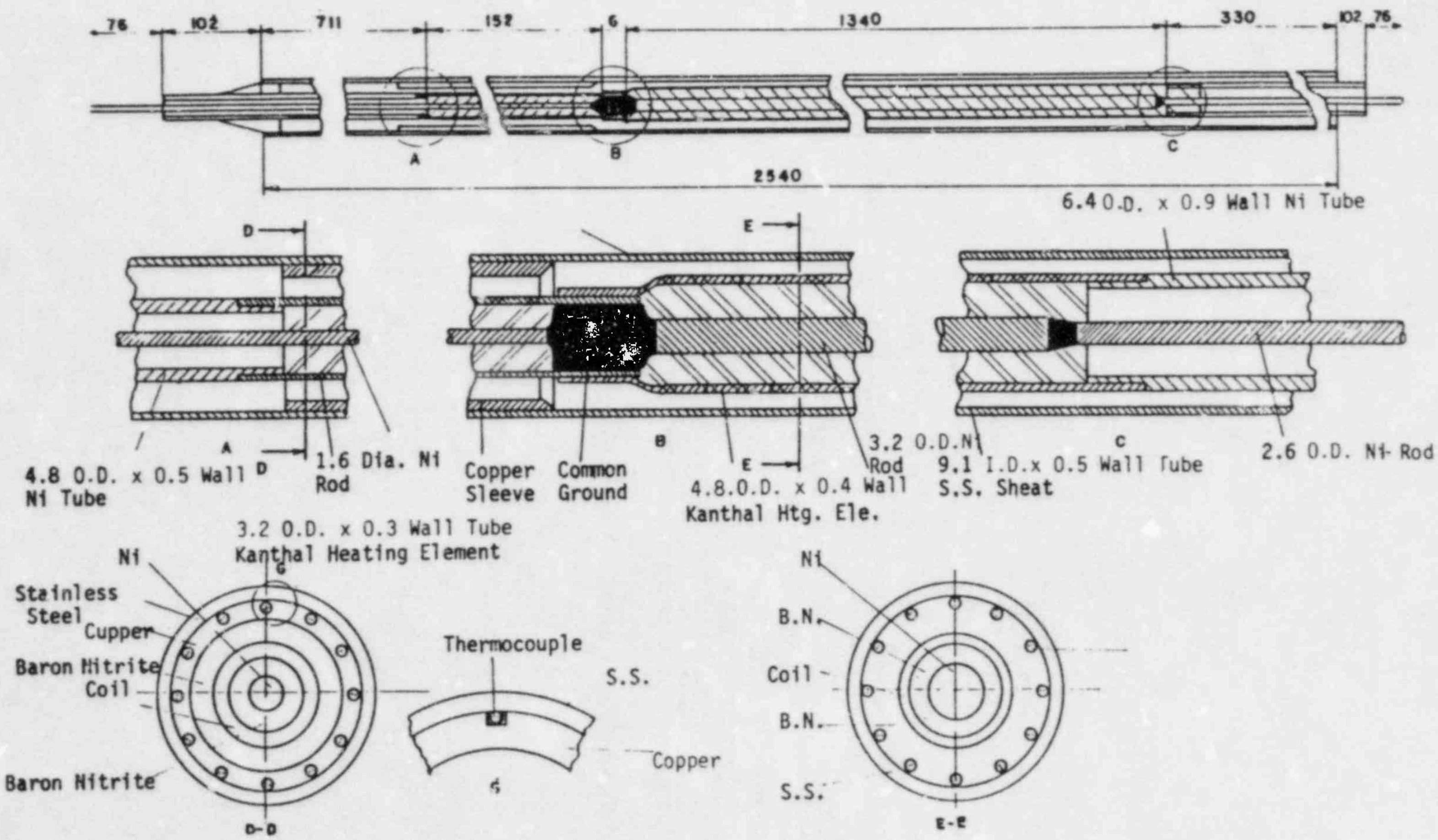


Figure 5. Schematic of the Fuel Rod Simulators

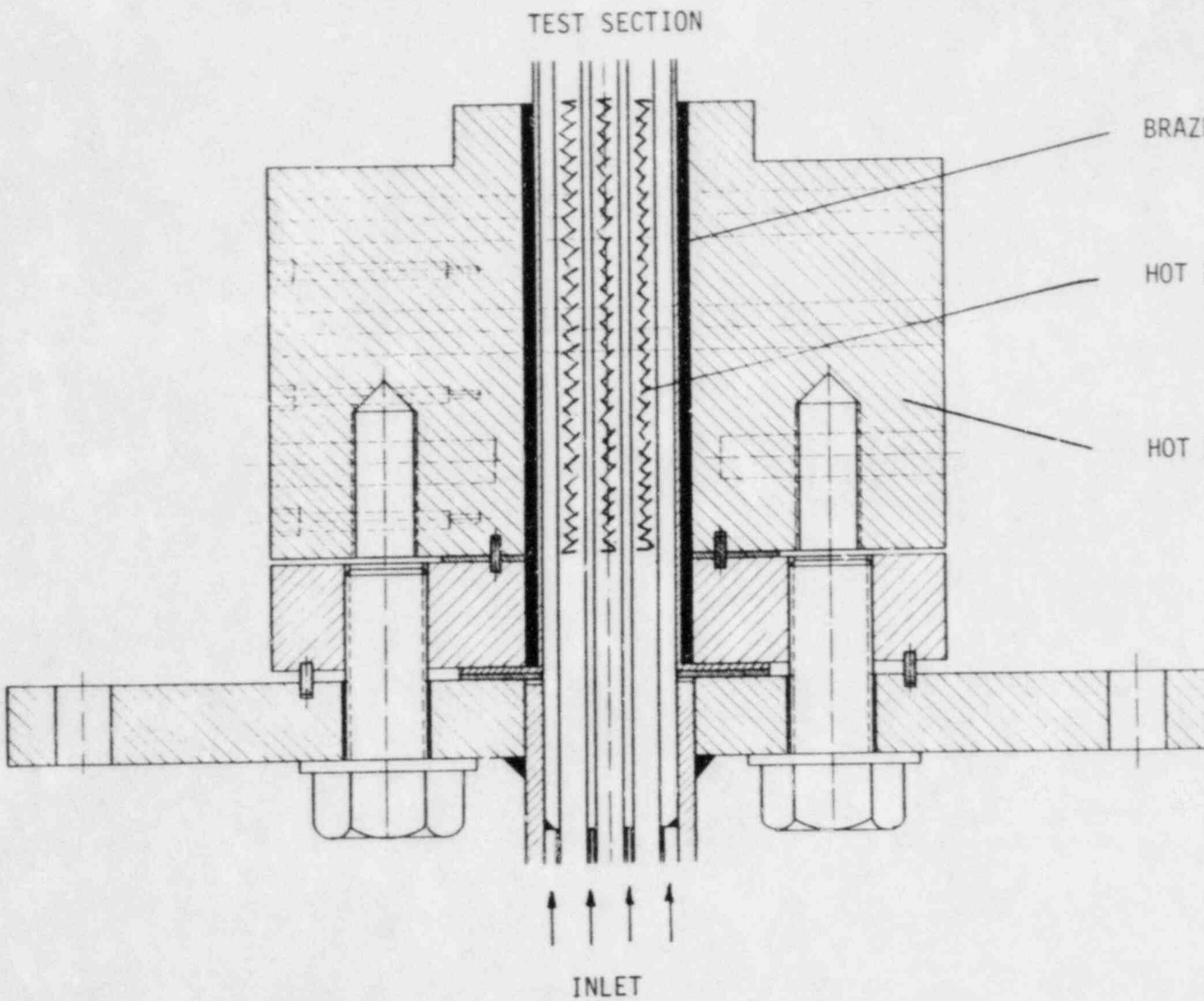
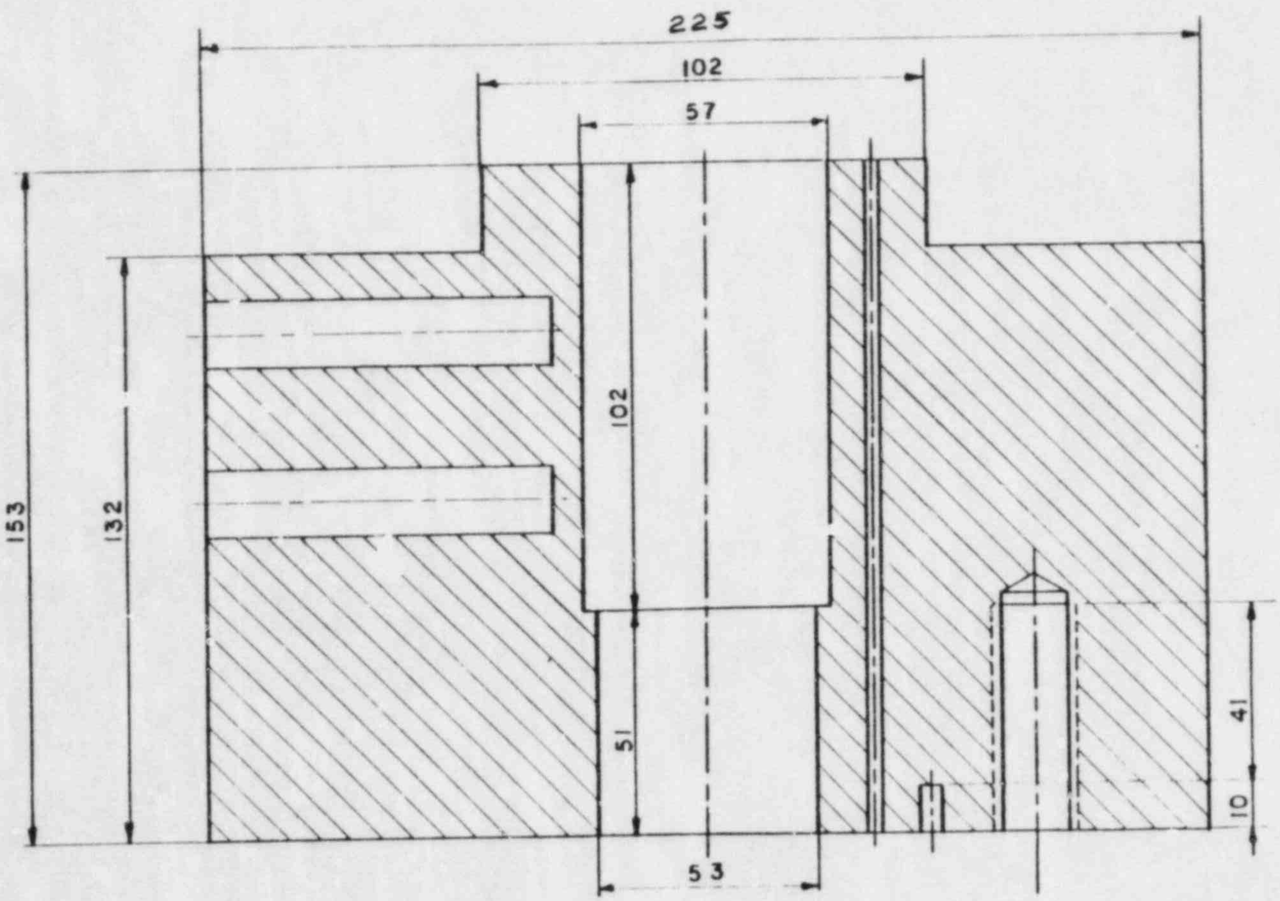


Figure 6. Lower Hot Patch Assembly



A–A

Figure 7a. Vertical Cross Section of the Hot-Patch

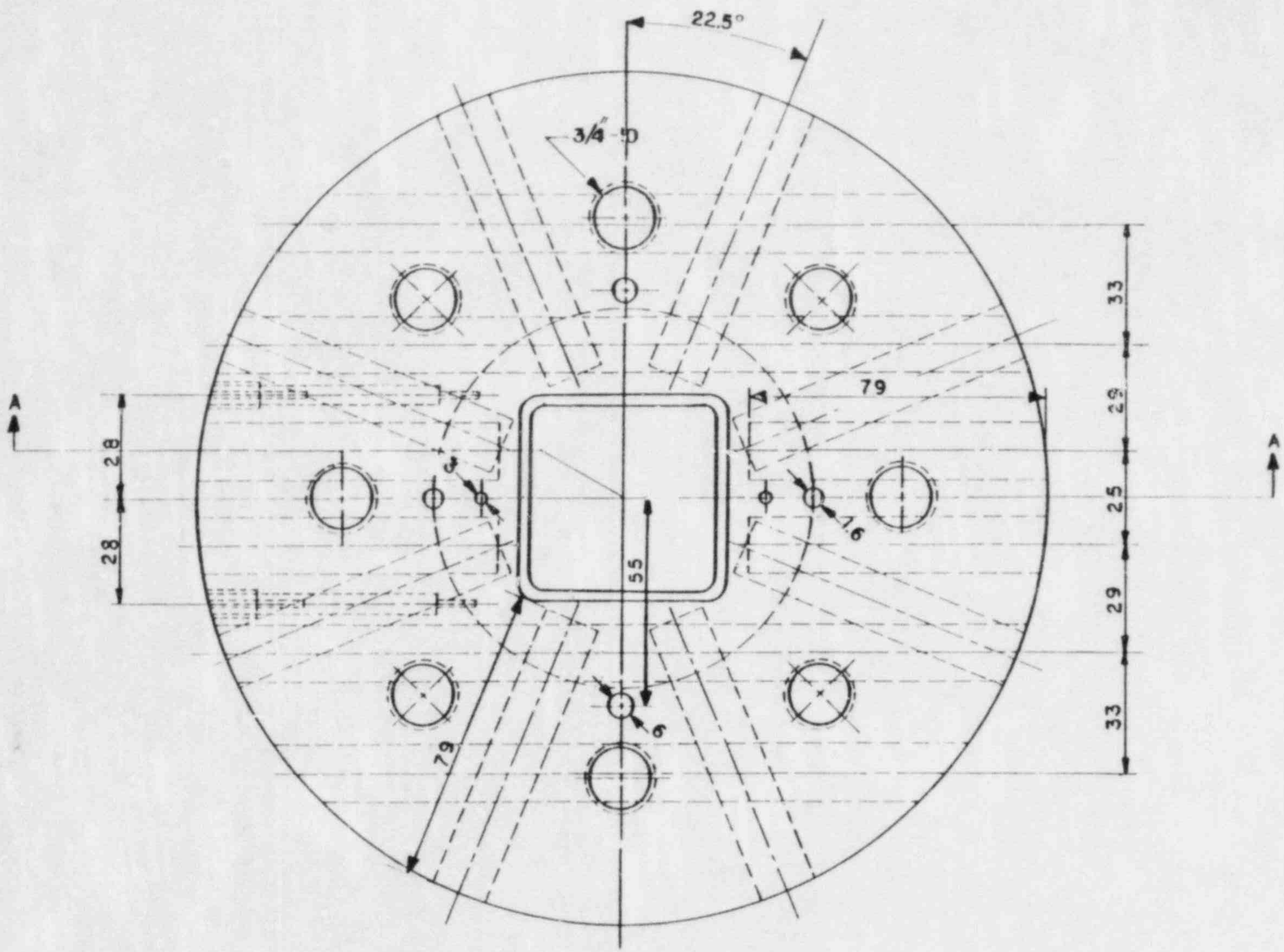


Figure 7b. Top View of Hot-Patch

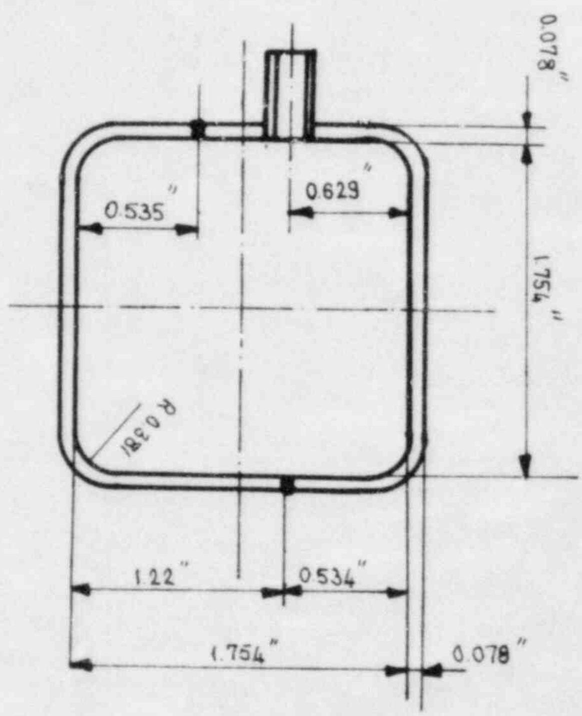


Figure 8. Schematic of the Shroud's Cross Sectional View

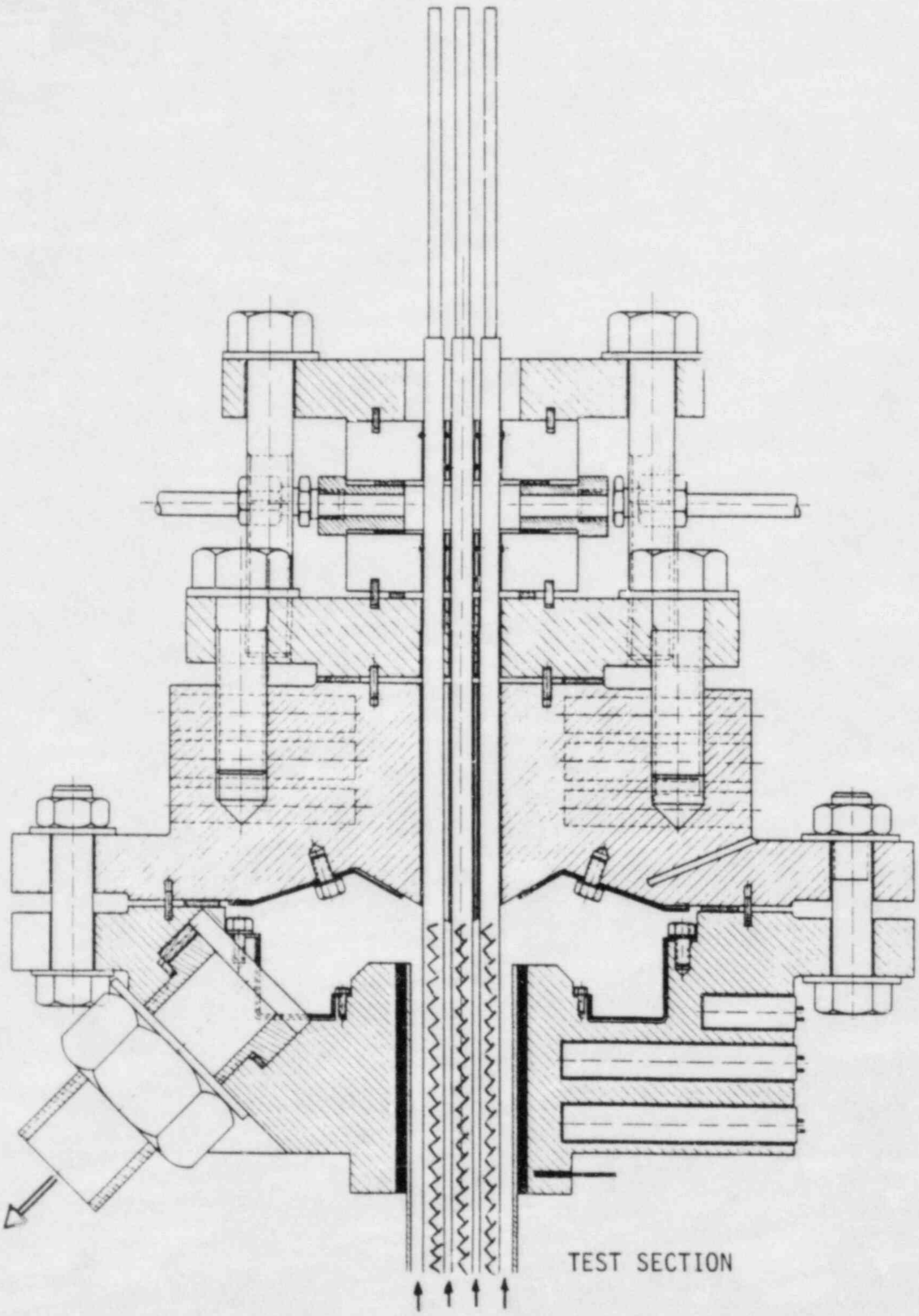


Figure 9. Top-Patch and Upper Sealing Assembly

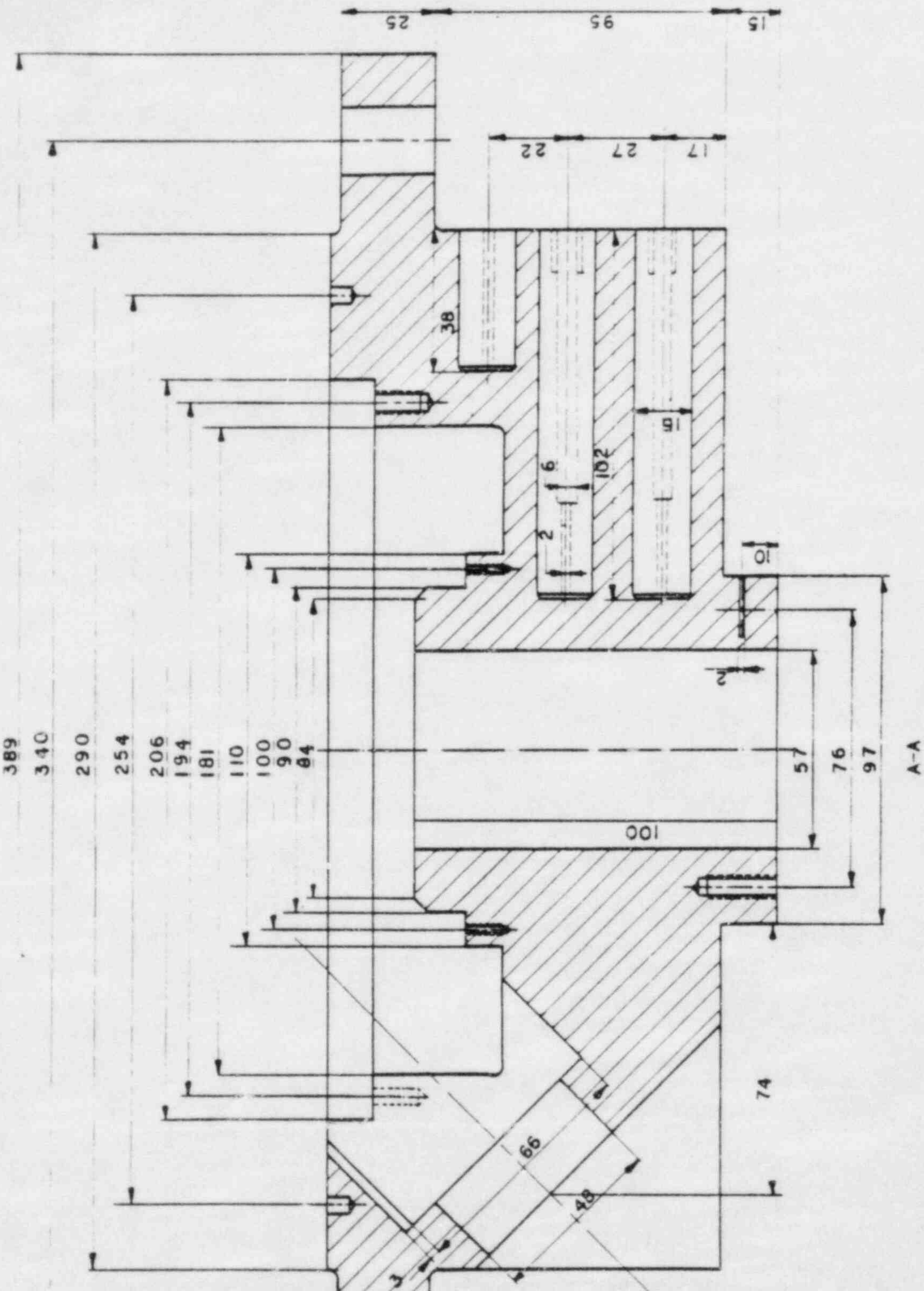


Figure 10a. Lower Piece of the Top Patch (Vertical View)

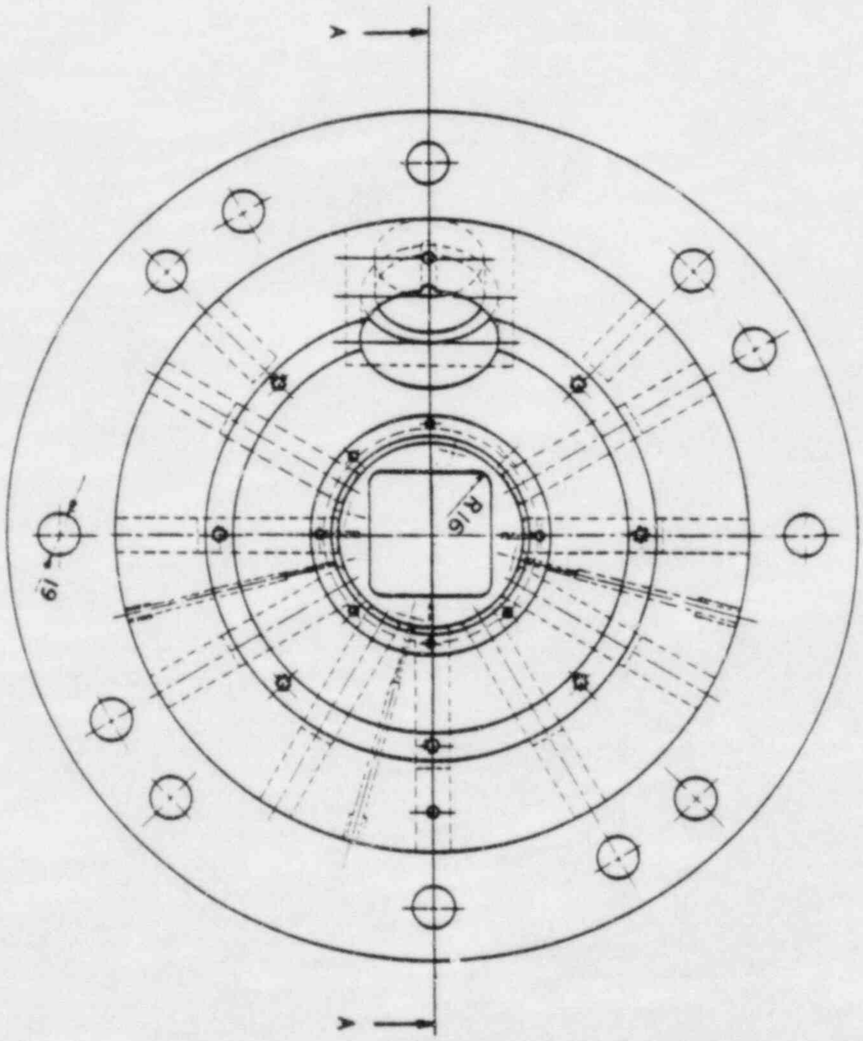


Figure 10b. Lower Piece of the Top Patch (Top View)

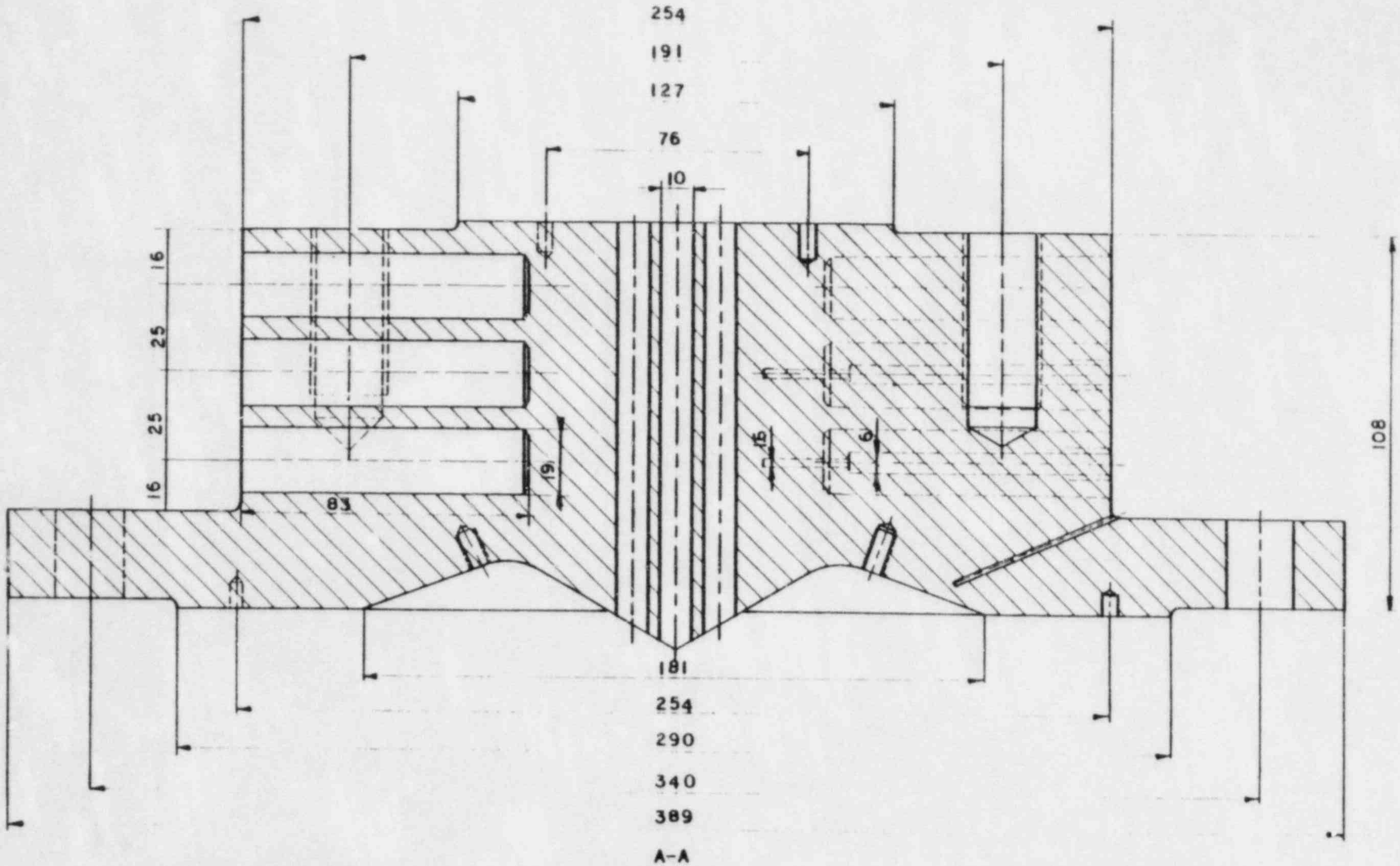


Figure 10C. Upper Piece of the Top Patch (Vertical View)

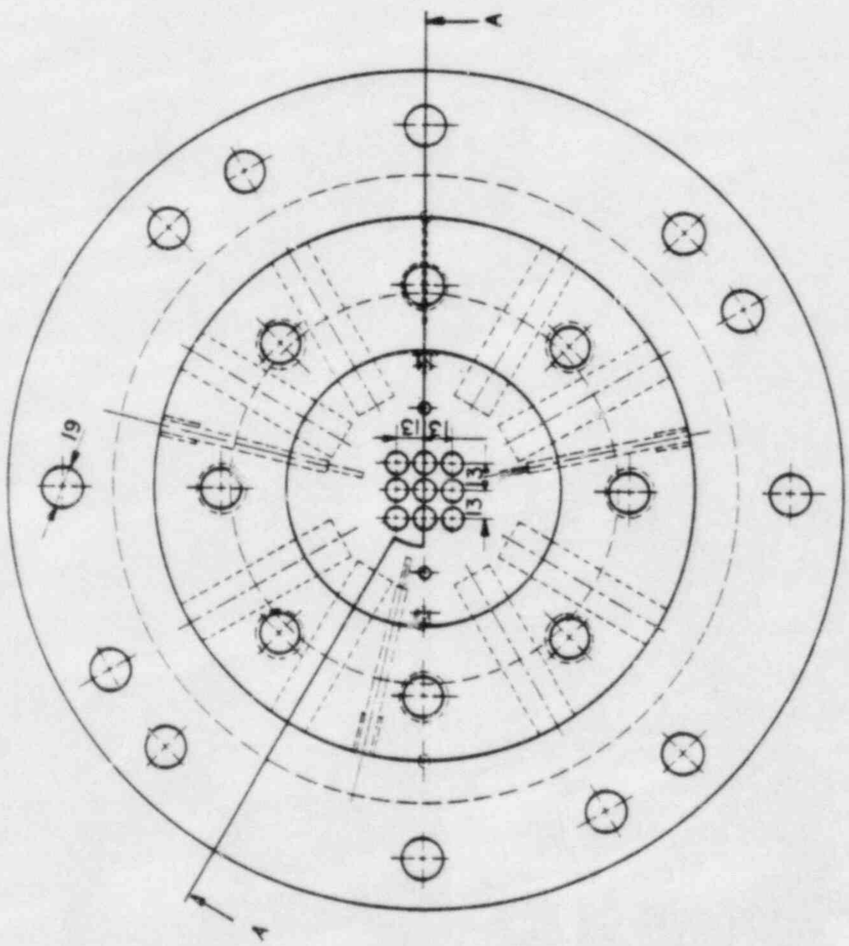


Figure 10d. Upper Piece of the Top Patch (Top View)

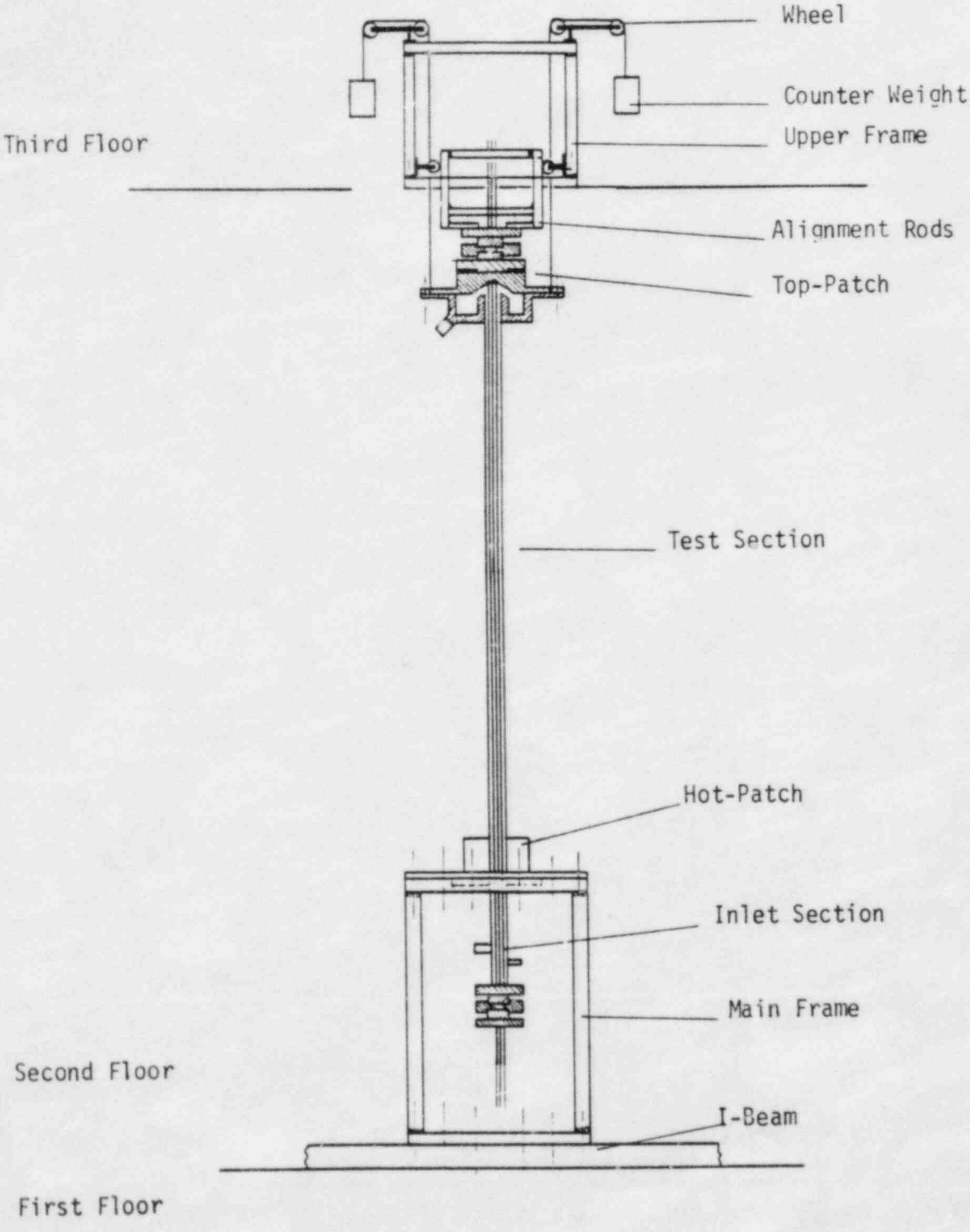


Figure 11. Schematic of the Test Section Supports

NRC FORM 335 (6-83)

U.S. NUCLEAR REGULATORY COMMISSION

BIBLIOGRAPHIC DATA SHEET

1. REPORT NUMBER (Assigned by TIDC, add Vol. No., if any)

NUREG/CR-3849
TS-843

2. Leave blank

3. TITLE AND SUBTITLE

TWO PHASE 3x3 ROD BUNDLE TEST FACILITY FOR POST-CRITICAL HEAT FLUX BOILING

4. RECIPIENT'S ACCESSION NUMBER

5. DATE REPORT COMPLETED

MONTH	YEAR
May	1984

6. AUTHOR(S)

Kemal Tuzla, Cetin Unal, Osama A. Badr, Sudhakar Neti and John C. Chen

7. DATE REPORT ISSUED

MONTH	YEAR
June	1984

8. PERFORMING ORGANIZATION NAME AND MAILING ADDRESS (Include Zip Code)

Institute of Thermo-Fluid Engineering and Science
Lehigh University
Bethleham, Pennsylvania 18015

9. PROJECT/TASK/WORK UNIT NUMBER

10. FIN NUMBER

FIN no. B6794

11. SPONSORING ORGANIZATION NAME AND MAILING ADDRESS (Include Zip Code)

Division of Accident Evaluation
Office of Nuclear Regulatory Research
U. S. Nuclear Regulatory Commission
Washington, D. C. 20555

12a. TYPE OF REPORT

Design Report

12b. PERIOD COVERED (Inclusive dates)

May 1982 - May 1984

13. SUPPLEMENTARY NOTES

14. ABSTRACT (200 words or less)

This report describes the rod bundle post-CHF tests in progress and the test facility at Lehigh University. The mechanical and electrical design of the experimental facility and the iterative process used to arrive at the choices made for the design are described in detail. The test facility consists of a nine (3 x 3) rod bundle in a square shroud which form the test section together with the hot patches at the top and bottom ends. The rods and the hot patches are electrically heated while the shroud is radiatively heated. The test section includes instrumentation to measure the vapor superheat temperature and pressure drop upstream and downstream of a rod gap spacer. This is the first application of the hot patch technique for generating post-CHF conditions in a rod bundle and thus quasi-steady-state tests are being thought of as a backup procedure for conducting these post-CHF heat transfer tests.

The test section is part of a well instrumented recirculating loop to generate the desired post-CHF conditions. The other major components of the heat transfer loop include the surge tank, pumps, boiler, separation tank and condenser. The test facility also includes a versatile one hundred channel data acquisition system. The mechanical and electrical components in the facility have been chosen to have sufficient accuracy to yield meaningful results for the heat transfer coefficient in the rod bundle under various post-CHF conditions.

15a. KEY WORDS AND DOCUMENT ANALYSIS

Post-CHF
Convective Film Boiling
Non-thermodynamic Equilibrium Heat Transfer
Rod Bundle post-CHF

15b. DESCRIPTORS

16. AVAILABILITY STATEMENT

Unlimited

17. SECURITY CLASSIFICATION (This report)

Unclassified

18. NUMBER OF PAGES

19. SECURITY CLASSIFICATION (This page)

Unclassified

20. PRICE

$

UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D.C. 20555

OFFICIAL BUSINESS
PENALTY FOR PRIVATE USE, $300

FOURTH CLASS MAIL
POSTAGE & FEES PAID
USNRC
WASH. D.C.
PERMIT No. G 67

120555078877 1 1AN1R2
US NRC
ADM-DIV OF TIDC
POLICY & PUB MGT BR-PDR NUREG
W-501
WASHINGTON DC 20555

NUREG/CR-3849

TWO-PHASE 3x3 ROD BUNDLE TEST FACILITY FOR POST-CRITICAL HEAT FLUX BOILING

JUNE 1984