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SURVEY OF REACTOR FACILITIES FOR PRESSURE TUBE IRRADIATION

November 1968

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SURVEY OF REACTOR FACILITIES FOR PRESSURE TUBE IRRADIATION

Prepared for
US Heavy Water Reactor Base Program

By

P. A. Ard, E. N. Heck, C. H. McJilton

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PREFACE

This report was prepared for the U.S. Heavy Water Reactor Base Program. Its purpose is to review the status of technology in the subject area, and to identify required research and development for heavy water reactors and related systems.

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INTRODUCTION

This survey was made to determine available reactor space meeting the Heavy Water Reactor Program (HWRP) criteria for fast neutron irradiation of a zirconium alloy pressure tube and to define the requirements and costs of providing facilities for this irradiation. The HWRP goal is to operate a "full sized" zirconium alloy pressure tube at typical heavy water reactor conditions of pressure, temperature, and water chemistry to an equivalent 30 yr fast neutron fluence. The purpose of this irradiation will be to demonstrate reliability and performance of zirconium alloy pressure tubes exposed to 30 yr neutron fluence under typical heavy water reactor conditions. Also this test will expose a "full sized" pressure tube to advance reactor conditions to determine limits of operation.

Presently, there are approximately 1800 Zircaloy and 10 to 20 Zr—2.5 wt% Nb pressure tubes installed in water cooled nuclear reactors. In all approximately 40,000 ft of zirconium alloy pressure tubing has been fabricated excluding tubing for the new Canadian reactors. The technical basis for tube fabrication and predicting tube performance is based upon a large body of technology obtained from small sized zirconium alloy samples associated with thin-wall fuel cladding applications. This technology has limited application to the behavior of thick wall "full sized" pressure tubes. Available data and experience with actual pressure tubes and tubing is fairly extensive in some areas and lacking in others, such as, creep and stress rupture data under neutron irradiation and burst strength and ductility of irradiated tubular specimens. Technology generally has been acquired more to determine the feasibility of Zircaloy or Zr-Nb in a particular application than to qualify pressure tubes as a component of nuclear reactors.[(1)]

IRRADIATION TEST CRITERIA

The NWRP zirconium alloy pressure tube is to be irradiated under conditions specified by the following criteria:

Pressure Tube Size	>3 in. ID x 0.120 in. wall x 4 ft long
Coolant Temperature	518 to 572 °F (270 to 300 °C)
Neutron Fluence	>3 x 10^{21} nvt/yr (fast neutrons- E > 1 MeV)
Exposure Goal	>10^{22} nvt
Pressure Tube Design Stress	16,000 psi hoop tensile
Coolant	pH 10 (NH_4OH)
	O_2 - <0.1 ppm
	H_2 - 25 to 50 cm^3/kg
	High resistivity water

The high fast neutron fluence criterion of >3 x 10^{21} nvt/yr will require a reactor flux of 2 x 10^{14} nv assuming the reactor operating efficiency is 50%. To meet this criterion the tube must be placed in the reactor core. Thus the size of the core, access opening through the core and average fast flux become primary factors in selection of an irradiation facility.

The tube performance will be evaluated periodically by internal measurement and visual inspection during the irradiation, requiring access into the tube while in the reactor core unless the tube is removed from the reactor for this evaluation. However, it would be desirable if the evaluation could be made without removing the tube from the reactor.

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(1) *H. Harty. Heavy Water Reactor Program Plan, Pacific Northwest Laboratory, Richland, Washington, March 1, 1968.*

It is desirable that the tube during irradiation simulate as near as possible the conditions expected in a typical heavy water reactor. A preferred approach would be to have an inert gas insulation annulus around the tube, although, a controlled external cooling of the pressure tube would be acceptable.

REVIEW OF IRRADIATION SITES

With the use of information published by the AEC on nuclear reactors,[1] which summarizes present status and power ratings, ten reactors were chosen for further review based upon the power that would be needed to irradiate a tube of the proposed size withing the specified fast neutron flux. Reactors that operate solely for power purposes were excluded because of their low flux and because it would be difficult to schedule an experiment of this type into these reactors without disrupting their operation pattern and possibly their power output. Table 1 shows the results of the review of the ten reactors.

A review of Table 1 indicates that only the Advance Test Reactor (ATR) meets all the criteria outlined. The Engineering Test Reactor (ETR) meets all but the length requirement. The GETR, which has a good neutron flux and the same core length as the ETR, was further evaluated; however, the maximum pressure tube diameter which could be handled is approximately 2 in. The space can accommodate a tube with a 3 in. OD; however, this would be the maximum diameter of the shroud tube that would be required to insulate the pressure tube from the cooler reactor coolant. Due to the GETR short core and the small diameter tube that could be evaluated, no further consideration was given this reactor.

1. *Nuclear Reactors Built, Being Built, or Planned in the U. S., TID 8200. Prepared by Office of the Assistant General Manager, USAEC. June 30, 1967, 17th rev. Available from CFST 1, Springfield, Virginia.*

TABLE 1. Reactor Possibilities for HWRP Pressure Tube

Reactor	Power, MW	Core Size	Average Core Power Density, kW/l	Fuel Type	Core Positions	Pressure Tube Size, in.	Fast Flux, nv
ATR	250	28 x 28 x 48 in.	670	MTR Curved	NE Lobe E Lobe N Lobe	>3 ID >3 ID 2 1/2 OD	3.7×10^{14} max. 2×10^{14} max. $1.8\text{-}2.5 \times 10^{14}$ max.
ETR	175	30 x 30 x 36 in.	550	MTR Flat	J-12 (6 x 6) G-7 (6 x 9)	>3 ID >3 ID	2.5×10^{14} max. 2.2×10^{14} max.
GETR	30	2 ft diam x 36 in.	375	MTR Flat	Center Loop 2 Side Loops	2.93 OD 2.93 OD	5×10^{14} max. in-reactor
MTR	40	9 x 27 x 24 in.	400	MTR	L-42	2 OD	5×10^{13}
PRTR	70	6.46 in. diam x 7.3 ft	10.3	19 Rod or Concentric Tubes	Center Shroud Shroud Tubes Rings 3 & 5	6 in. 3 1/4 ID x 0.156 wall	5×10^{12} - 2×10^{13}
HFBRR	40	20 ft diam x 21 in.	470	MTR Flat	2 Center Holes (beam holes)	1.57 OD	Reactor 1.6×10^{15} max.
HFIR	100	17 in. OD x 5 in. ID x 20 in.	2000	Plates - Involute Shape	Center	5 OD	2×10^{15}
ORRR	30	21 x 12.7 x 24 in.	200	MTR	None Shown	---	Reactor 3×10^{14} avg
NASA Plum Brook	60	9 x 27 x 24 in.	600	MTR	None Shown	---	Reactor 1.3×10^{15} avg
EBR-II	62	19 in. diam x 14.2 in.		Pin Type			

Further consideration was given to the facilities available in the ETR and ATR as these reactors appear the most promising candidates for this irradiation test based on the criteria previously outlined.

REVIEW OF THE ETR TEST FACILITIES

GENERAL DESCRIPTION OF ETR

The Engineering Test Reactor (ETR) was designed to generate a very high thermal and fast flux in the core holes for use in performing engineering tests on fuel elements and components of nuclear plants. Nine openings are provided to accommodate experimental facilities in the core, consisting of one 9 x 9 in., one 6 x 9 in., three 6 x 6 in., and four 3 x 3 in. openings. These openings are illustrated in Figure 1 which shows a horizontal cross section above the core. The experimental facilities in the ETR are vertical and are placed inside the reactor vessel. The control rod drives are placed below the reactor to provide more room above the core for experimental facilities. Figure 2 shows a vertical cross section of the reactor. Access through the pressure vessel shell via the horizontal and angular nozzles and through the bottom head permit external connection of closed loop-type facilities and operational instrument leads.

Several areas are available in the ETR Building for placement of any required auxiliary equipment, i.e., pumps, heaters, pressurizers, and water sampling stations. The size and configuration of these areas vary; therefore, no recommendation can be made until a preliminary test design is established. Some radiation shielding exists in these areas; but it is likely that additional shielding would be required, depending upon the design.

3 x 3 in. Core Position

At least two 3 x 3 in. positions, J-12 and K-6, have peak fast fluxes in the range of 2 to 2.5 x 10^{14} and are now

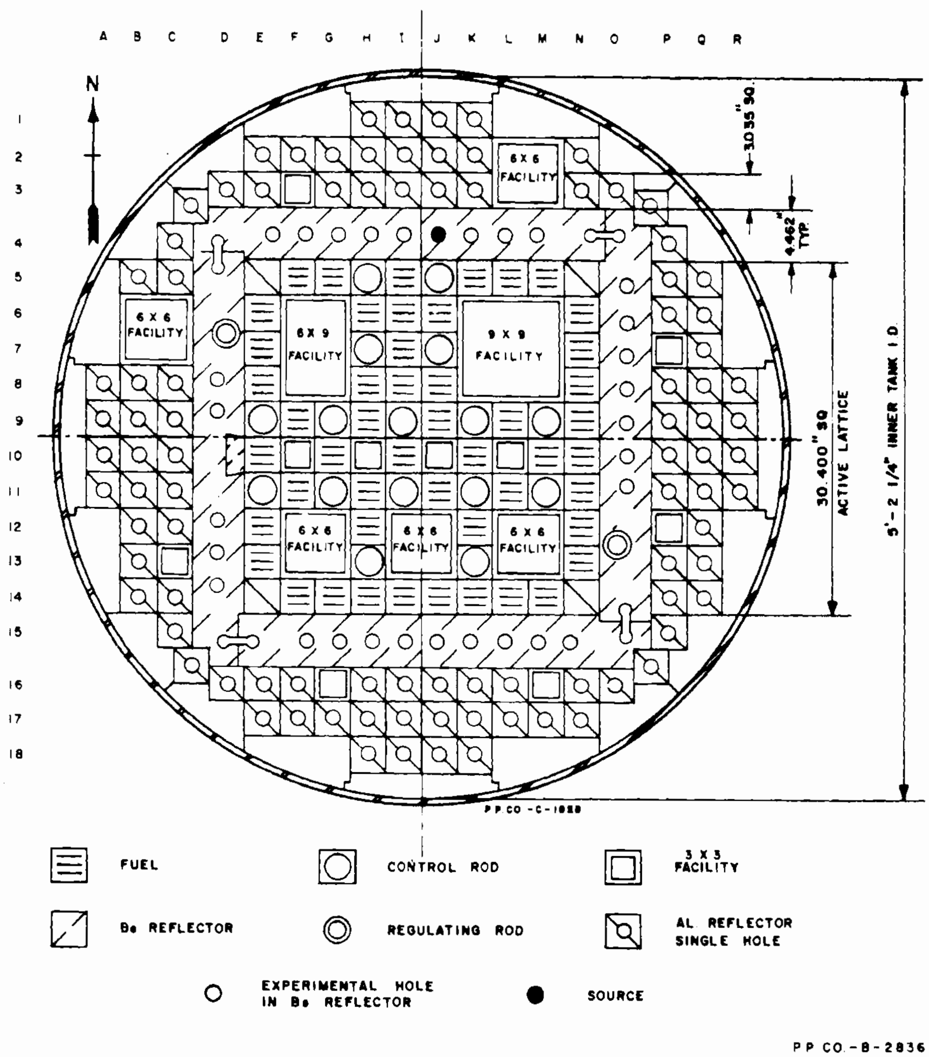

FIGURE 1. *ETR Lattice and Reflector Horizontal Cross Section Above Core*

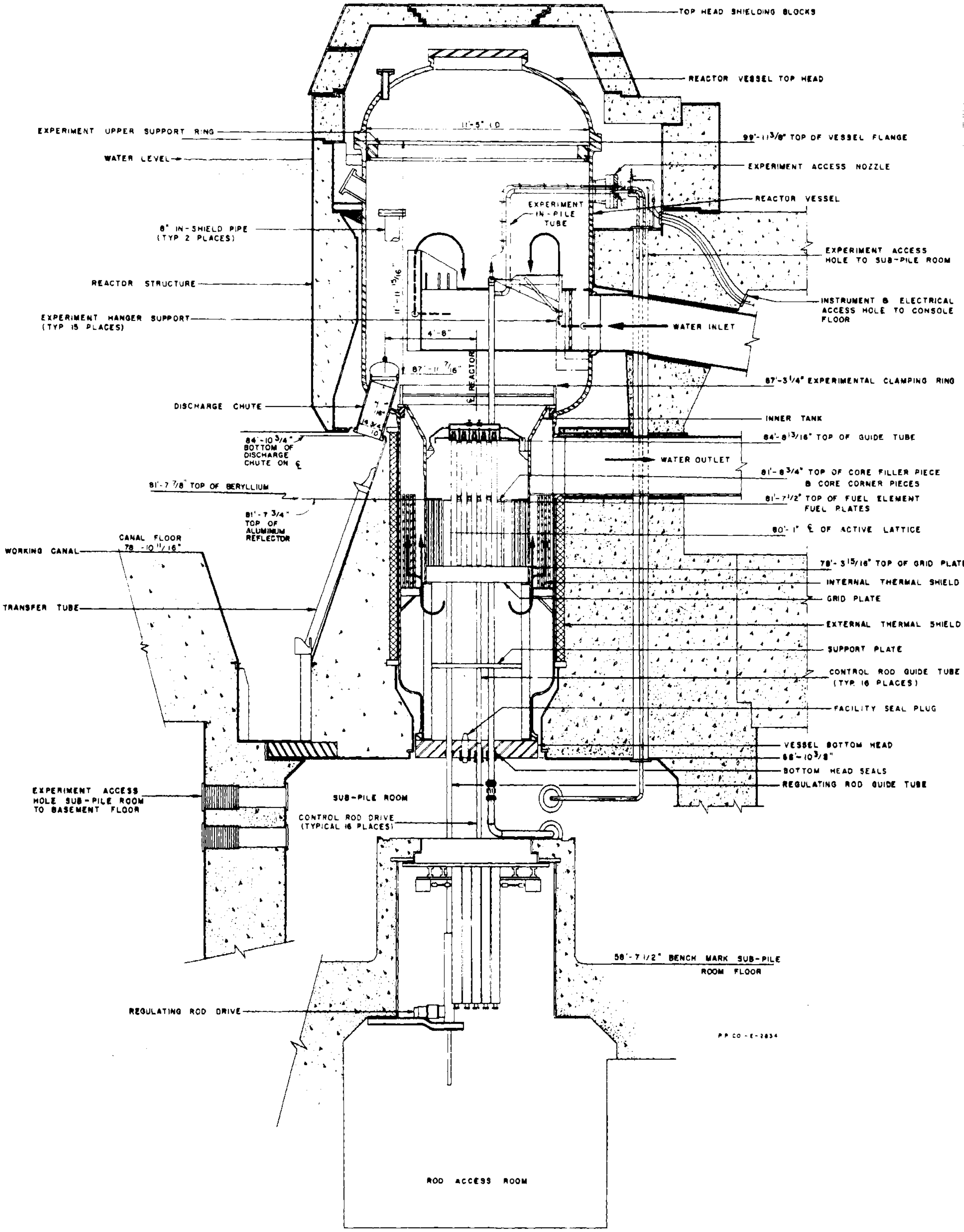

FIGURE 2. ETR Vertical Cross Section

available for experimental use. Figure 3 shows a horizontal cross section of the core indicating the magnitude of the fast flux for some positions in and around the core during a typical operating cycle. The core positions are designated by letter number coordinates indicated in both Figures 1 and 3. Like the GETR core positions described earlier, these 3 x 3 in. positions will only accommodate a tube of approximately 2 in. ID. Because this diameter does not meet the HWRP tube diameter criterion, these positions were not reviewed further. It is noteworthy to observe, however, that if meaningful data could be obtained with a smaller diameter tube, irradiation unit costs would be reduced to one-fourth the costs of the next larger 6 x 6 in. facility.

6 x 6 in. J-12 Core Position

The next largest test module which could be made available is the 6 x 6 in. J-12 position on the south side of the ETR. Since the test probably can be accommodated within a space of 4-1/2 x 4-1/2 in., it would be most economical to consider providing special filler pieces, as shown in Figure 4, so that the unused portion could be made available to other sponsors. The neutron charges then would be based only upon the 4-1/2 in. square portion. The J-12 position has a peak fast flux of 2.5×10^{14} nv (see Figure 5) and could be modified to accommodate a 3 in. or greater diameter tube. At present this position contains three 3 x 3 in. capsule irradiation facilities and one fuel element. The fuel element could be moved to a new position which would be determined by critical facility measurements. Several of the capsule holes are presently assigned on a long-term basis to Gulf General Atomics (GGA). However, discussion with them indicates that peripheral positions within the 6 x 6 in. space probably would be acceptable for their capsules.

The main disadvantage of this position lies in its present state of congestion with lead-type experiments and control rod

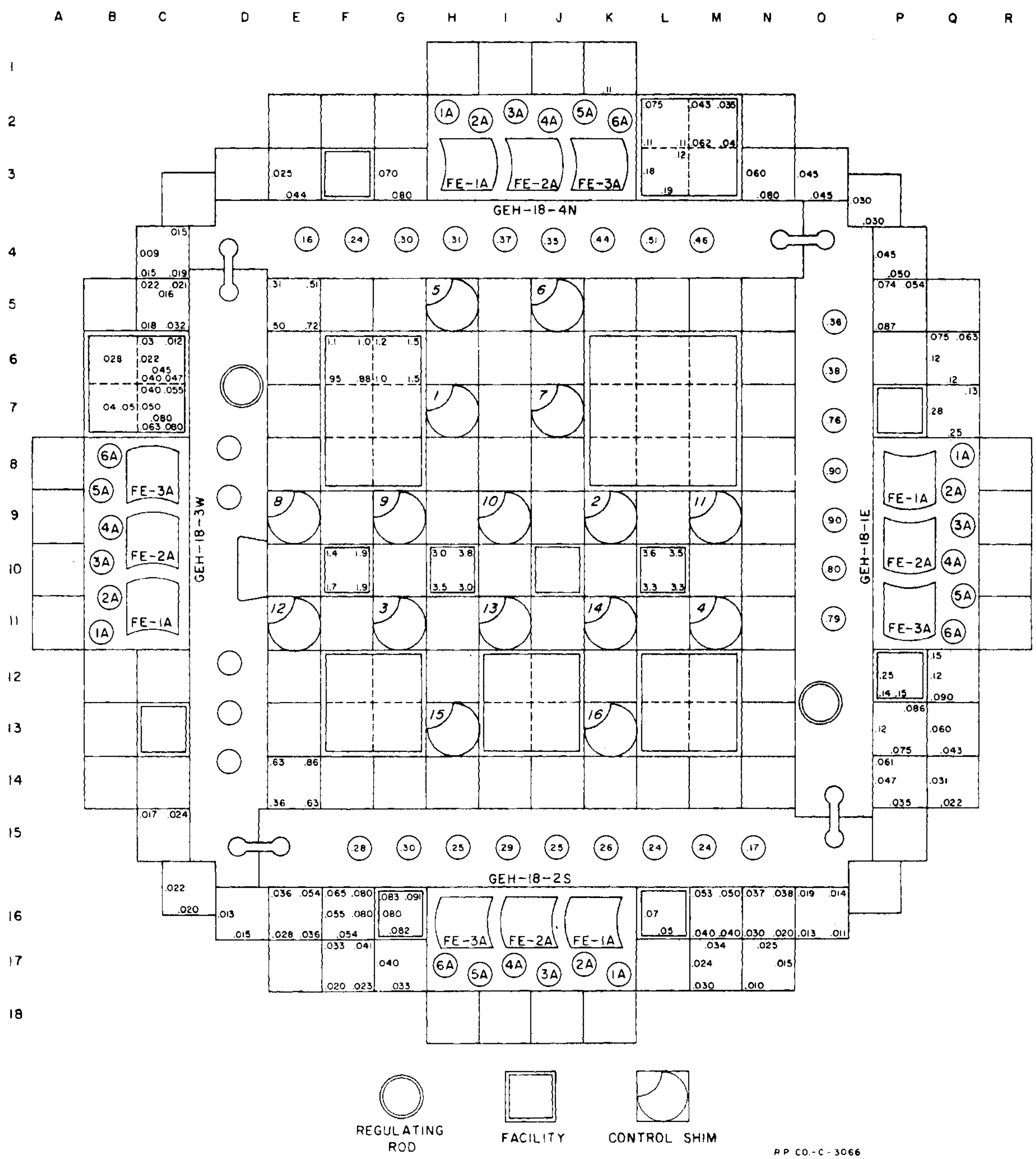

FIGURE 3. *ETR Cross Section Showing Fast Flux Magnitudes in and Around the Core During Cycle 27. Flux values are x 10^{14}.*

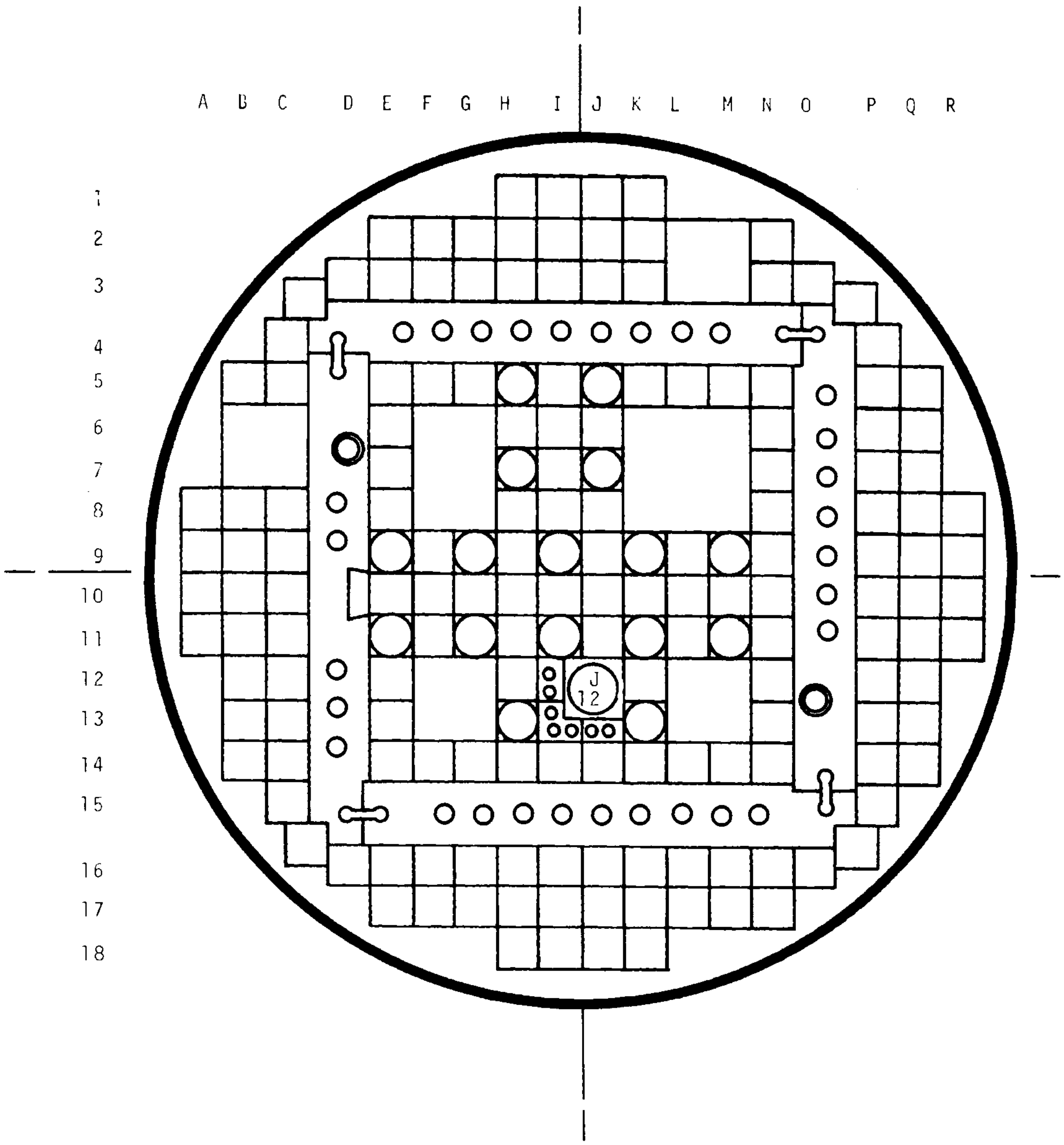

FIGURE 4. *Horizontal Cross Section of ETR Showing Proposed Filler Pieces in the J-12 Positions*

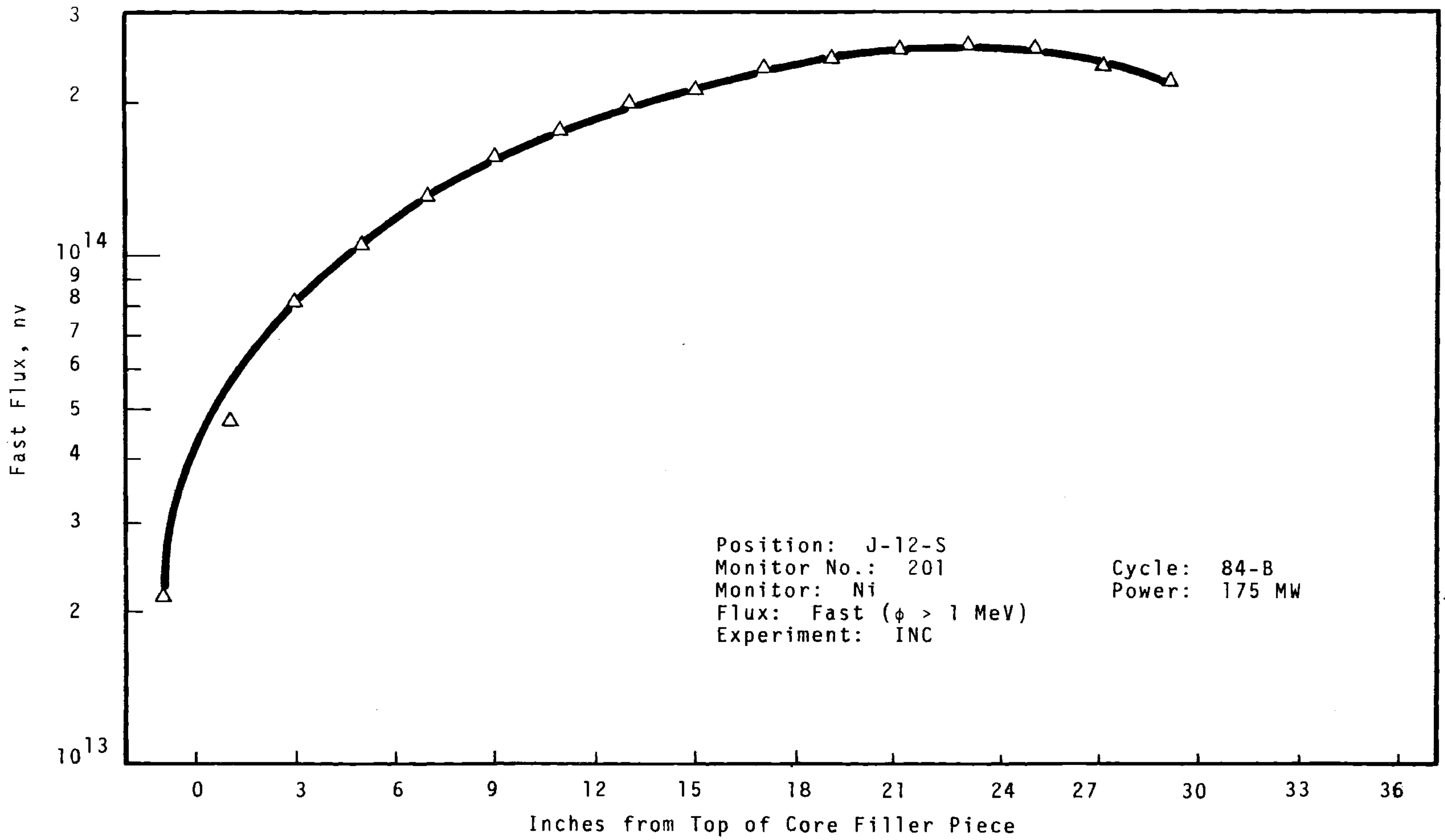

FIGURE 5. Vertical Plot of the Fast Flux in the ETR J-12 Position

guide tubes. Each of the presently operating experiments is equipped with an instrument lead tube which extends upward from the core with sufficient bends to permit clamping to the side of the reactor vessel, and to exit the vessel through one of the access nozzles at the top. Idaho Nuclear Corporation (INC) operating policy is to avoid disturbing or moving any operating lead experiment. Use of a portion of this facility will be contingent upon securing INC and GGA approval to move two experiments into the special filler pieces, based upon present GGA test schedules. The special filler pieces must be furnished by the Heavy Water Reactor Program.

Access into the reactor vessel above this position is presently restricted by the large number of lead experiments. Relief of this problem is expected by means of a tank extension with access flanges presently scheduled for delivery and installation in July 1968.

Piping and support design for an experiment in the J-12 position could not restrict access for refueling and handling adjacent experiments.

A penetration associated with the J-12 position to accommodate a through-tube is located in the ETR bottom head. However, it is offset about 6 in. to the south of the core position, and would require a dogleg in the tube below the reactor grid plate. Installation of such a tube would require fabrication of a split grid plate adapter, and removal of all adjacent core filler pieces and fuel to permit the necessary manipulation of components. For this reason, it is recommended that, in view of the existing congestion, this position be considered only for an experiment which requires top access, such as a lead capsule, or a re-entrant type loop with inlet and exit piping above the core.

6 x 9 in. G-7 LOOP FACILITY

There are no larger core facilities available, but consideration might be given to the possibility of fabricating a replacement Zircaloy-2 in-reactor tube for the 6 x 9 in. G-7 loop facility. This is a Battelle-Northwest loop currently in use for investigation of the effects of irradiation on structural materials under the GEH-20 program and is connected in parallel with the M-3 loop located in the ETR reflector. Both operate from a common pumping, pressurization, and purification system. Specific details pertaining to the design of such a pressure tube are given in a later section of this study.

The G-7 position will accommodate a through-loop tube with a slight offset below the core. The core section is placed within a 6 x 6 in. portion to take advantage of the maximum flux which is 2.2×10^{14} nv. As can be seen in Figure 6, the bulk of the tube material would be operating at a value somewhat less than the desired flux, with a consequent increase in the exposure time required to meet the test conditions. Figure 7 shows a vertical fast flux profile for the position with the maximum flux in the 6 x 6 in. portion of the 6 x 9 in. G-7 facility.

ETR IRRADIATION COSTS

Based upon current charging rates, annual Irradiation Unit (IU) costs would be approximately $1.2 million for the 4-1/2 x 4-1/2 in. J-12 facility, assuming 50% operation of ETR at full power. This corresponds to 42,000 IU.

The IU charges for the G-7 6 x 6 in. position are estimated at $1.4 million per year, based upon 50% operation. This facility is currently billed at long-term rate, which is $8.00 per IU less than the short-term rate which would be applied to any other facility. Assuming a fifty-fifty split with the present program sponsor the annual cost would be $0.7 million or $2.1 million for a 3 yr exposure.

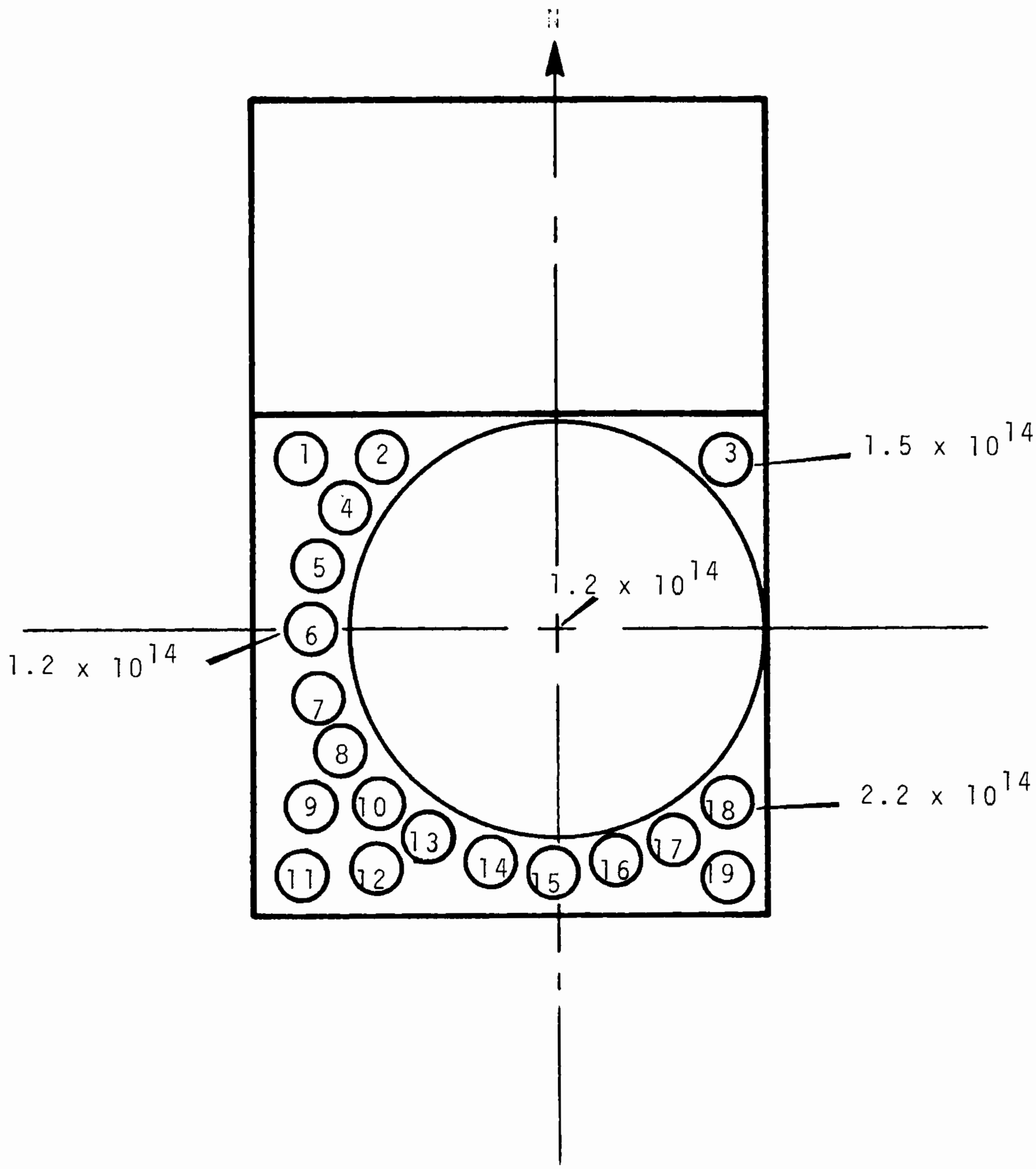

FIGURE 6. ETR 6 x 9 G-7 Facility Showing Weep Holes and Values for Fast Flux Measured During Cycle 57

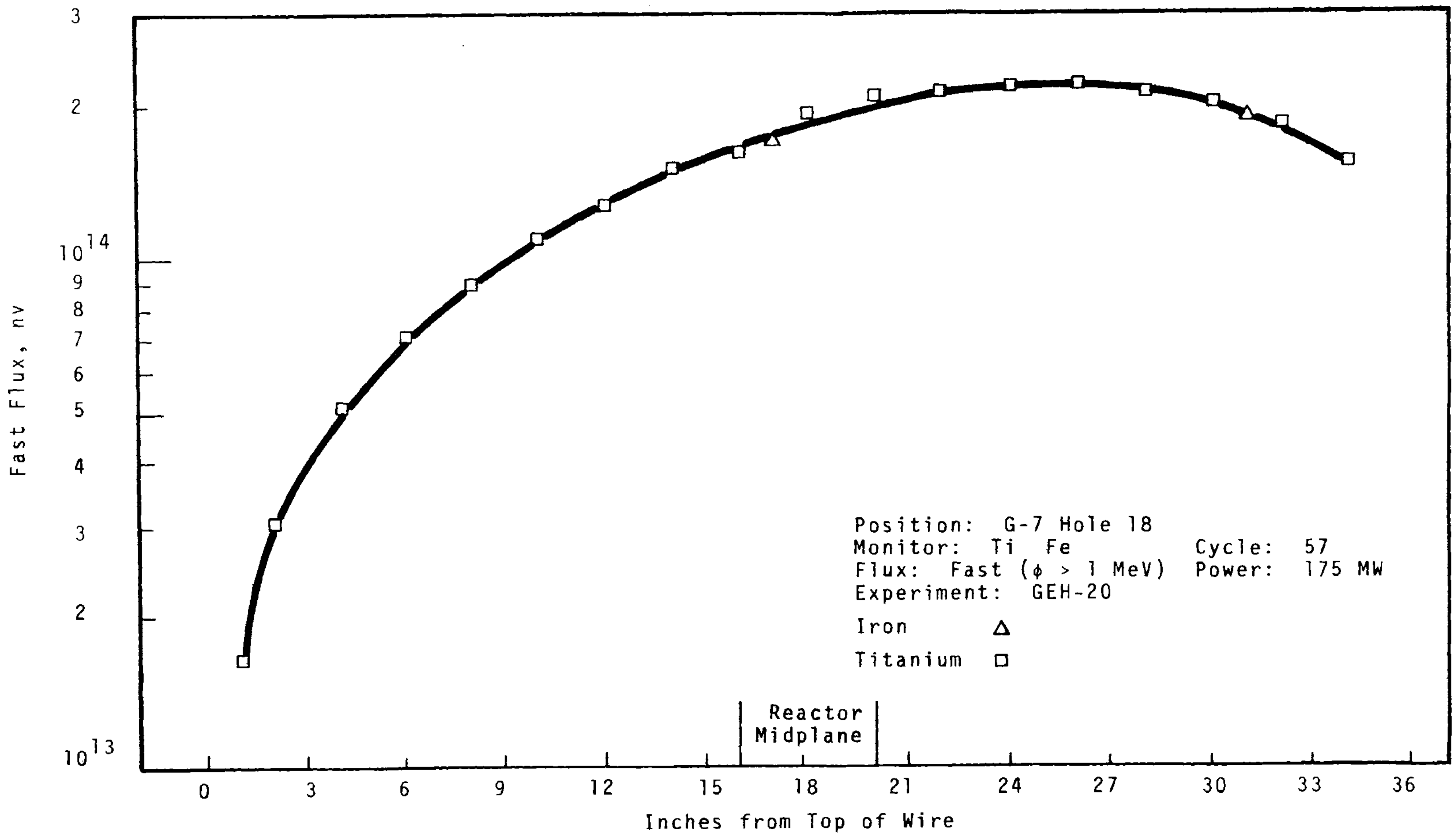

FIGURE 7. Plot of Vertical Fast Flux in the ETR G-7 Position

REVIEW OF ATR TEST FACILITIES

GENERAL DESCRIPTION OF ATR

The ATR has the fuel arranged in a serpentine geometry forming nine high-flux areas: four encircled lobes, four partially enclosed lobes, and a center test position. Figure 8 shows the location of the nine experimental lobes, or flux traps, and the designations of these lobes, which are identified by compass notation. Other test positions are located in the reflector, outside the rotating shims, but do not have sufficient flux to warrant consideration for the HWRP test. A cross-sectional diagram of the ATR core midplane is shown in Figure 9 which gives the predicted fast neutron flux at reactor power of 250 MW.

The flux traps will accommodate a circular assembly, the diameter of which is governed by the presence or absence of a safety rod in the test position as shown in Figure 9. The ATR safety rods are tubular in shape, and move vertically into and out of the core. For a position that has a safety rod, the size of a specimen must be small enough to permit unobstructed operation of the safety rod. For a position without a safety rod, the specimen could utilize the resultant vacant space. A 3 in. ID pressure tube would require a position without a safety rod.

The present ATR in-reactor tubes are designed with extensions that penetrate the upper head of the reactor so that access to the sample trains does not require removal of any vessel flanges. They also penetrate the bottom head and are designed for re-entrant flow which enters and exits the facilities in the subreactor room. Although the Gas-Cooled Loop was designed as a through tube with an upper tank penetration to avoid the loss of irradiation space caused by a re-entrant design, it is probable that a similar proposal for a new water loop in-reactor tube would be discouraged, in order to avoid any further complication of ATR handling requirements.

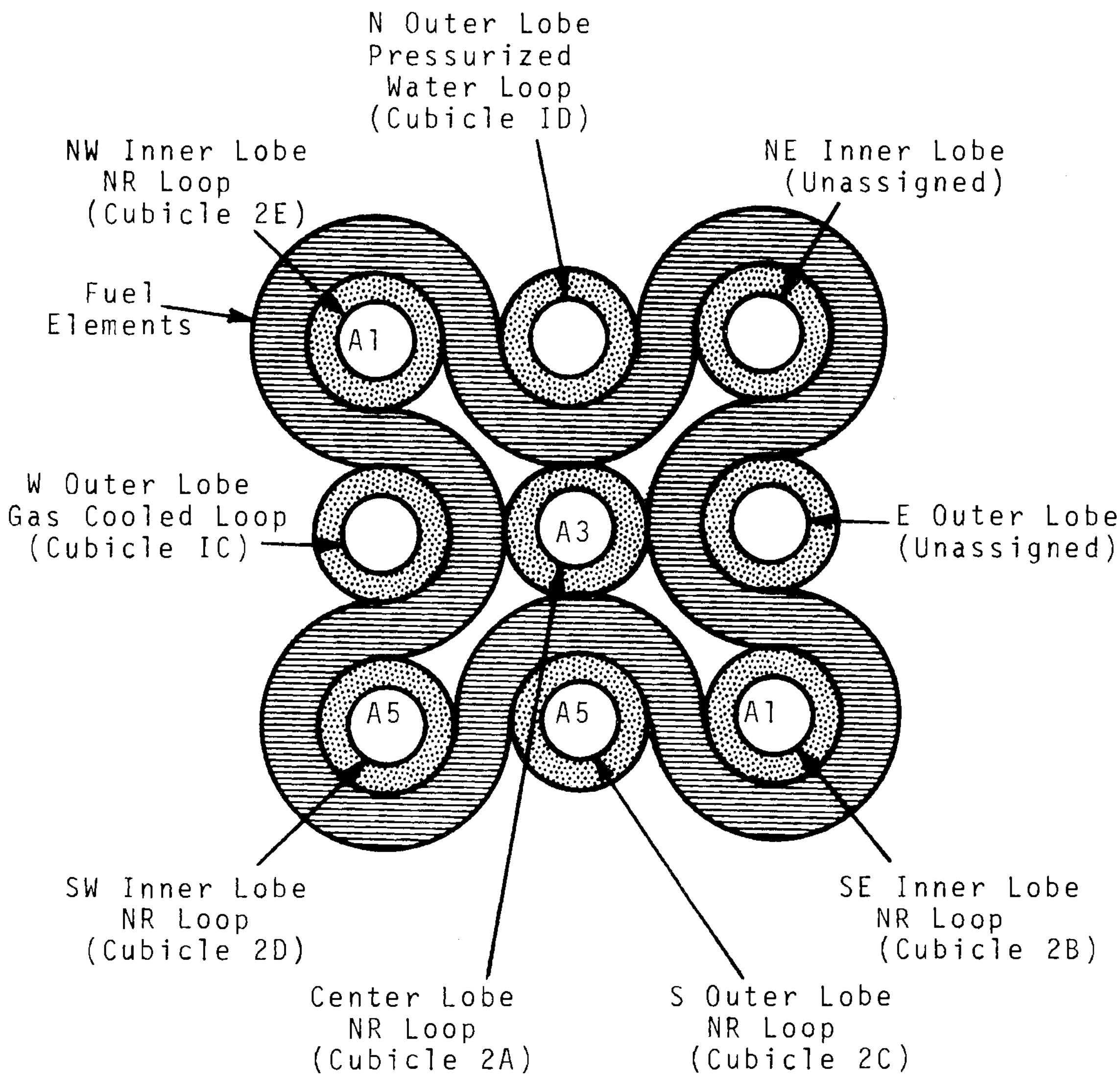

FIGURE 8. Cross Section of the ATR Core Showing Designation of the Nine Lobes

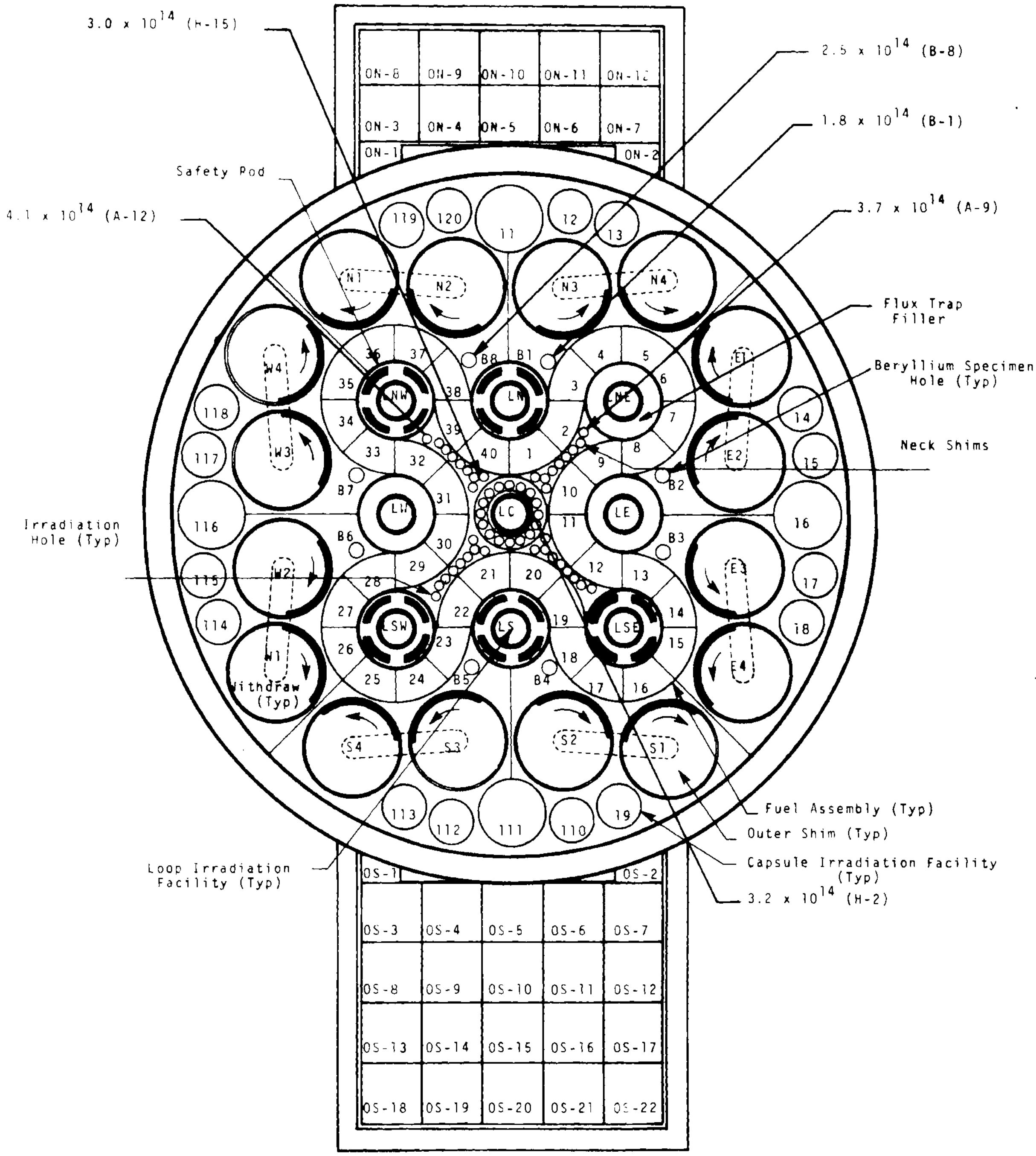

FIGURE 9. Cross Sectional Diagram of ATR Core Showing Some Values of Fast Neutron Flux at Reactor Horizontal Midplane for a Reactor Power of 250 MW

No announcements have been made concerning plans for installation and handling of lead-type experiments in the ATR. Presumably, these could be installed and removed in a manner similar to that used for ETR, with instrumentation and auxiliary lines enclosed by a lead tube which exits the reactor vessel via a flange at the top.

Present plans are to operate the ATR at a reduced power level of 175 MW for the initial 9 to 12 cycles. Assuming Cycle 1 begins in July 1968, this would mean July 1969, at the earliest for full power operation (250 MW). If the HWRP tube were to be irradiated in the ATR before this time, it would experience fluxes of approximately 70% of the values quoted earlier in this report. Should this period of reduced power be extended, fluxes in ATR position, other than the NE position would require approximately 3 yr to obtain the desired fluences.

NORTHEAST LOBE

The ATR-NE flux trap is an irradiation facility that would accommodate a 3 in. ID pressure tube. The estimated fast flux in this position is predicted to be in the range of 3 to 4×10^{14} nv at 250 MW reactor power (see Figure 9). Figure 10 shows an estimated vertical fast flux profile. These flux estimates are based on the ATR critical facility measurements and its accuracy has not yet been verified in the ATR. More accurate flux information should soon be generated by INC.

The position is presently unassigned and, therefore, contains a dummy in-reactor tube and flux trap filler. It would accommodate either a capsule or a re-entrant type loop. Reactor vessel access and equipment space are readily available.

EAST LOBE

The ATR-East flux trap is an irradiation facility identical to the NE flux trap, except that it has a lower flux level

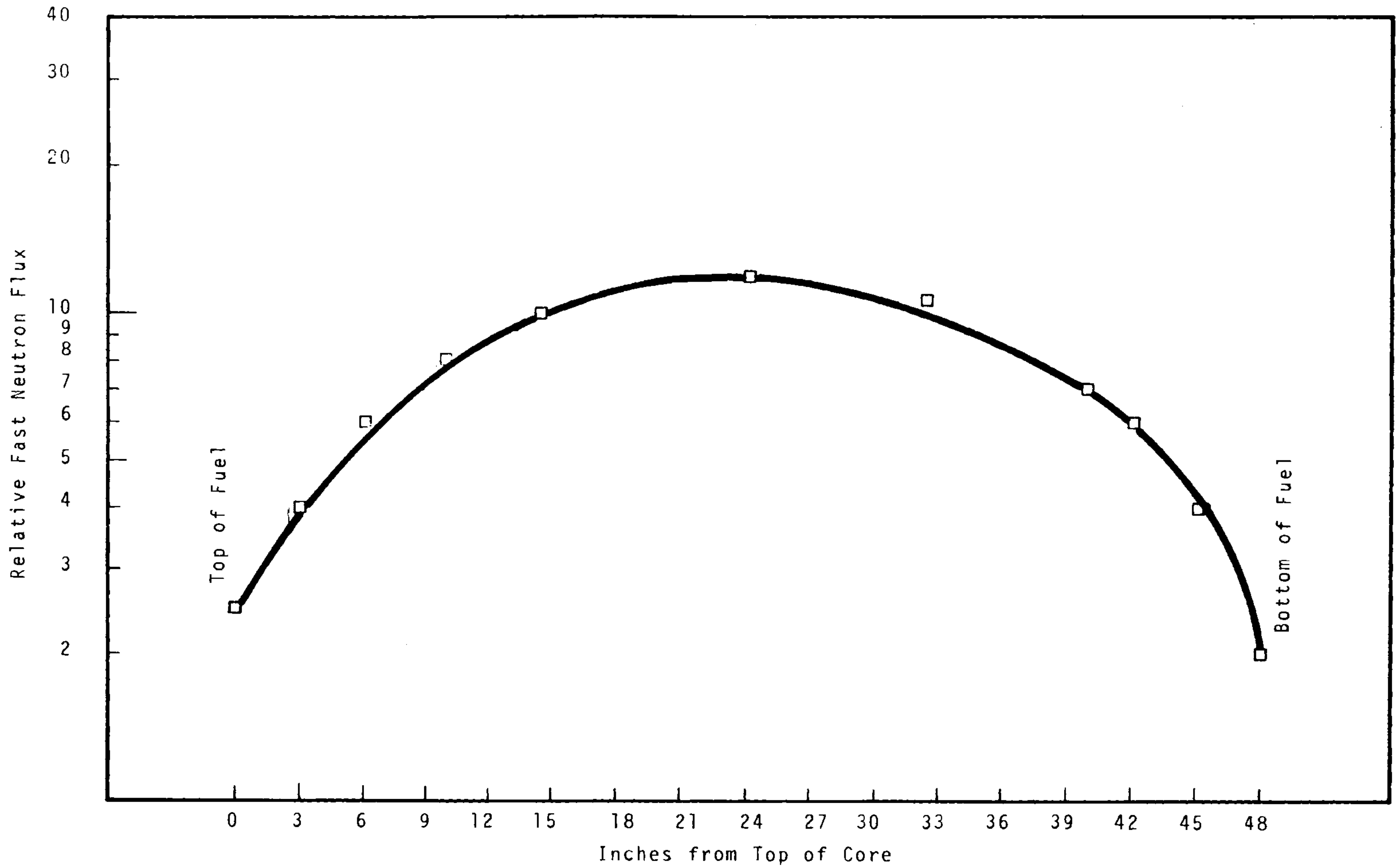

FIGURE 10. *Results of Preliminary ATRC Fast Flux Profile Measurements. (This data indicates that over a 36 in. length of tube in the ATR, exposure would be more uniform than in the ETR.)*

because it is only partially enclosed by fuel. The estimated fast flux is in the range of 1.8 to 2.5 x 10^{14} nv. This position is unassigned and has available equipment space and reactor vessel access.

Since this position offers no advantage over the NE position, it was dropped from further consideration.

NORTH LOBE

The ATR-North flux trap is an irradiation facility with fast flux levels in the same range as the East flux trap, i.e., 1.8 to 2.5 x 10^{14} nv. It will only accommodate a pressure tube with a 2.125 in. ID due to a safety rod and safety rod guide tube as shown in Figure 9.

This loop is presently assigned to Pacific Northwest Laboratory and planned utilization includes both fuel and structural materials irradiation. Design parameters for this loop are:

Temperature	600 °F maximum
Pressure	2000 psi
Flow	80 gal/min
Controlled water chemistry.	

ATR IRRADIATION COSTS

Based on the positions occupied, present plans call for the costs for the ATR to be shared between the respective test sponsors. Thus, assuming seven operating positions and 80% plant efficiency, annual costs are estimated to be $1.72 million. If any portion of the test was to be run during the initial 8 to 12 cycle period of reduced power operation (70% power), the time required to attain goal exposure would be extended accordingly, and the total irradiation cost would be increased.

In the ATR Northeast Lobe with the reactor operating at full power (250 MW) the goal exposure would be reached in about 16 months assuming an 80% plant efficiency. Thus the total costs would be $2.15 million. However, it must be pointed out that the 80% plant efficiency is a goal which may prove to be unrealistic. Probably a more realistic efficiency would be 50% which will be used for the subsequent analyses presented in this report.

GENERAL REQUIREMENTS FOR ETR AND ATR IRRADIATION TESTS

DESIGN CONSIDERATIONS

Normally INC policy is to require compliance to Section III of the ASME Boiler and Pressure Vessel Code for all new equipment inserted in the ETR or ATR. Since zirconium alloys have not been established as code materials, allowable stress at different temperatures would have to be established using the intent of Section III. Estimated design stress data is compiled and presented in BNWL-656, which is based on the ASME Nuclear Vessel Code, Section III. These curves, shown in Figure 11, were constructed from uniaxial tensile test data from various sizes of Zircaloy-2 specimens. These data can be considered as a basis for designing the pressure tube. Should the pressure tube stresses exceed acceptable operating allowables, it would be necessary to design the outer shroud tube to sustain a one-time application of operating pressure should the pressure tube fail. Full advantage can be taken of the greater strength of the shroud tube which results from being exposed to the cooler reactor coolant. If any desirable program information can be obtained, the shroud tube could be constructed of zirconium alloy.

CRITICAL FACILITY

Idaho Nuclear Corporation requires a critical facility mock-up for all in-core experiments. Parameters which should be duplicated include metal-to-water volume ratio and total cross section. Aluminum is an allowable substitute for zirconium as long as its distribution in the mock-up is representative of the zirconium distribution in the actual experiment.

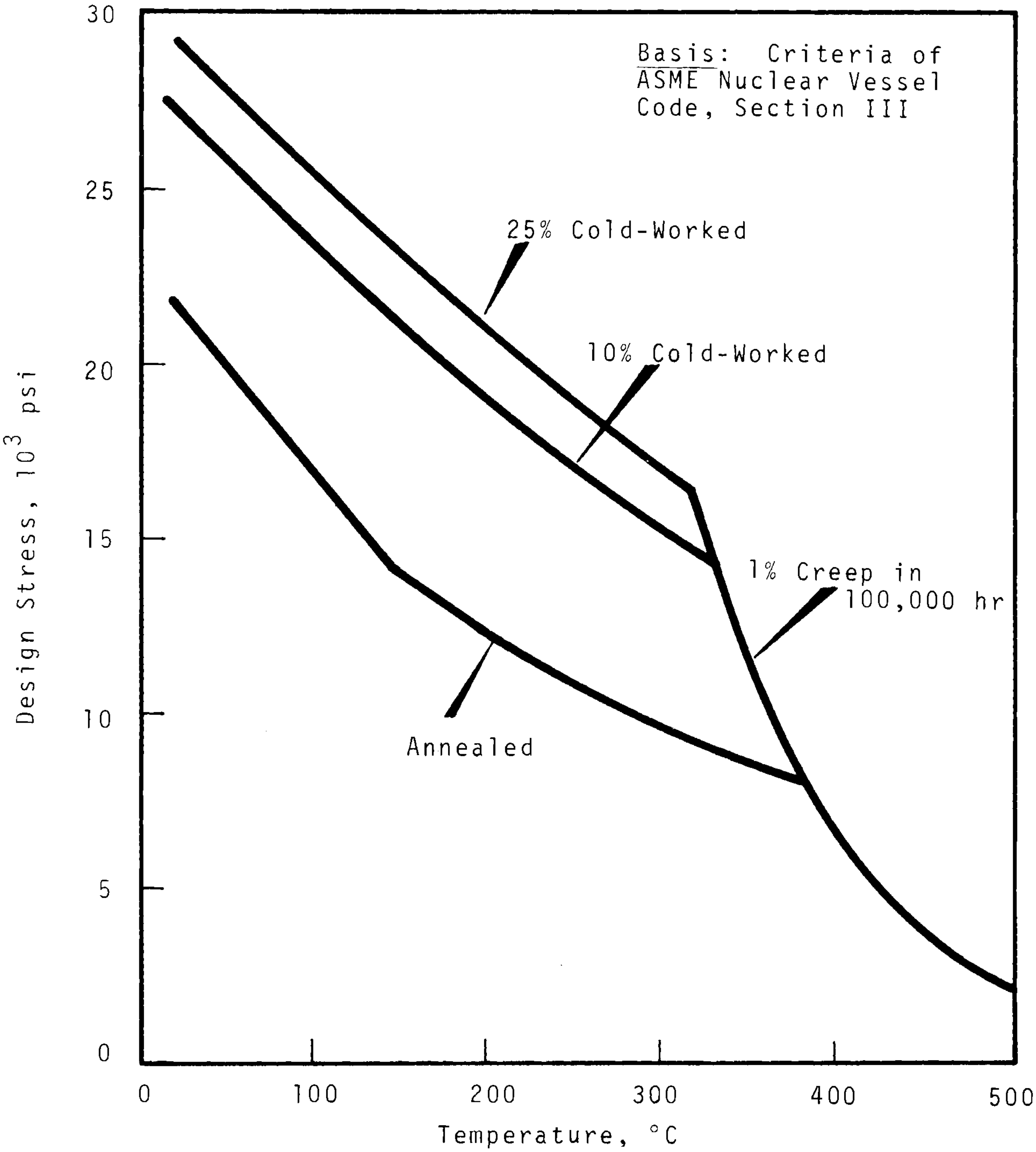

FIGURE 11. *Estimated Design Stress for Zircaloy-2 Pressure Tubes. These curves were constructed from uniaxial tensile test data from various sizes of specimens. (BNWL-656, HWR Program, March 1, 1968)*

ETR core changes that result in flux variations of 10% or more in any occupied experimental position require 6 months prior notice to all affected sponsors. Movement of a fuel element to gain access for a J-12 facility could cause this type of flux shift. Therefore, if this position is selected, a mock-up of the experiment would be required 8 months prior to test insertion. This would allow 2 months for critical facility measurements and data analysis. We would expect that lead time for an ATR mock-up would be considerably less due to the flexibility of the ATR to adjust for flux changes.

NUCLEAR SAFETY

Experiments which go into the reactor core must be evaluated from the standpoint of the effect of a core voiding accident on reactivity. This is probably only relevant for loop systems, or systems which have pressurized gas supplied to the experiment. In general, an unacceptable positive reactivity change can occur only if a substantial volume within the experiment can be voided. Therefore, if the test is designed with appropriate fillers, a potential difficulty may be avoided.

Determination of the reactivity effect is normally done by means of a test run in the critical facility.

INSERTION/REMOVAL EQUIPMENT

At present, capsule and specimen trains are removed from the ETR through a side discharge chute; therefore, no special equipment is required. In-reactor tubes, however, are removed through the reactor top into a cask. The same arrangements are planned for ATR. If the HWRP test is irradiated as a loop, its design would have to be compatible with the present removal cask design or else a special cask furnished.

IN-REACTOR PRESSURE TUBES

TYPICAL DESIGNS

Most of the pressure loops that pass through the core of a reactor operate at a temperature different from the reactor coolant (usually considerably higher). Thus they are insulated from the reactor coolant by placing a shroud tube around the pressure tube with an annulus of inert gas. This gas is normally pure helium. A section of such a system, the pressurized water loop in the N-Lobe of the ATR, is shown in Figure 12. The insulation ability of the gas annulus is dependent upon the gas mixture and width of the annulus. More heat is transferred from the outside of the tube with a narrow annulus and a rich helium mixture.

Other than the in-reactor tube, the principal equipment usually consists of the primary pumps, heat exchangers, line heaters, pressurizers, purification system, flow measuring devices, and valves.

GAMMA HEATING

A major problem encountered in the high neutron flux irradiation of the HWRP pressure tube is the high thermal gradient developed within the tube wall resulting from gamma heating during irradiation. The gamma heating in either the ETR or the ATR is expected to be between 8 and 18 W/g. This range can be narrowed when a reactor position is selected and measured actual ATR data are available rather than estimated ATR critical facility data which are being quoted. As a comparison, gamma heating of approximately 0.336 W/g is encountered in the PRTR when operating at 70 MW power[(1)] (flux $\sim 5 \times 10^{12}$ nv instead of 2×10^{14} nv expected in the ATR).

1. *C. A. Fick. Measurement of Gamma Heating in PRTR, Final Report Test 32, HW-82658. June 8, 1964. Available from CFST 1, Springfield, Virginia.*

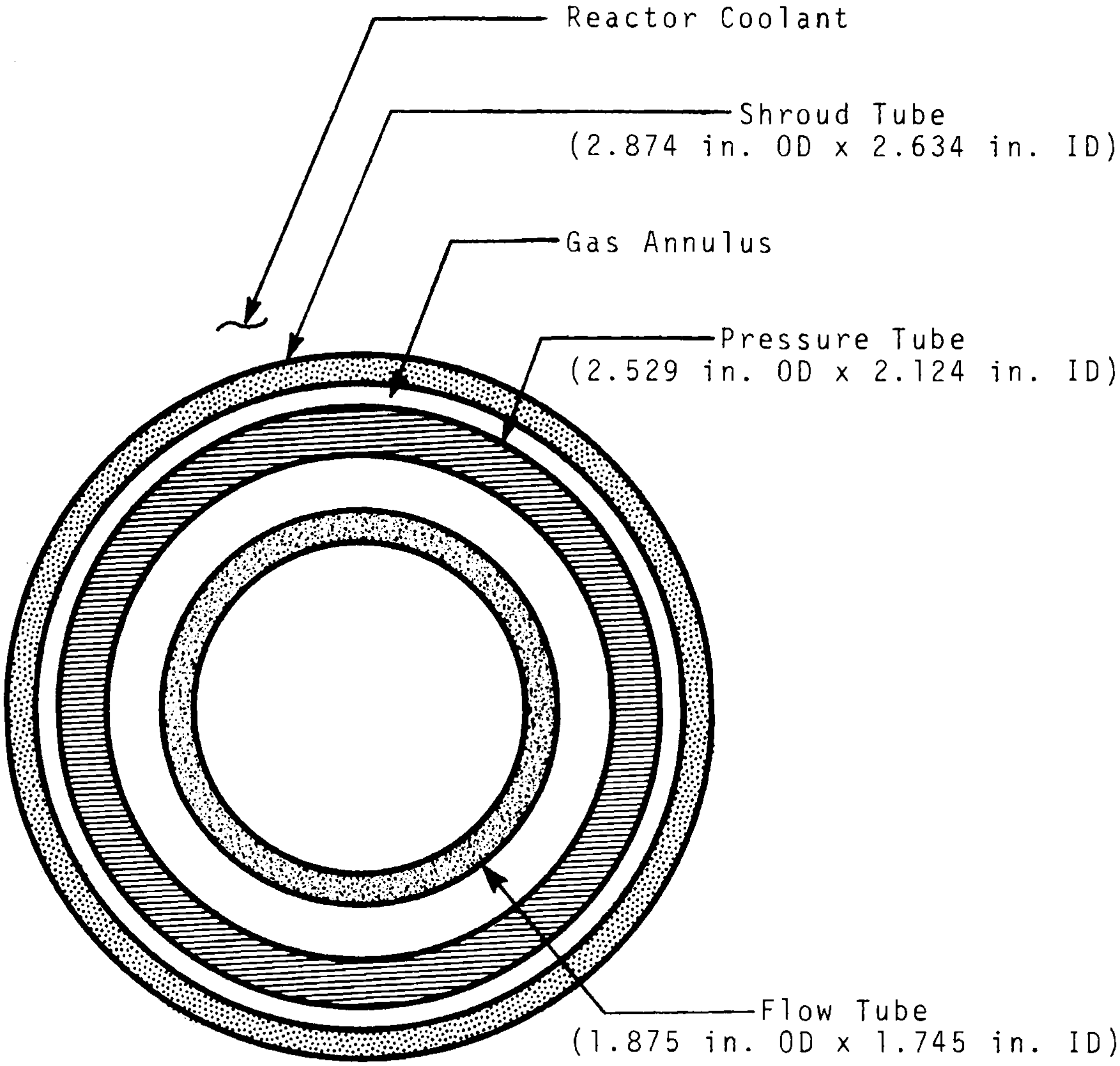

FIGURE 12. *A Cross Section of the In-Reactor Loop System of the Pressurized Water Loop in ATR N-Lobe. Section is in the active core portion of the loop.*

Figure 13 shows maximum wall Δt versus wall thickness for a 3 in. ID Zircaloy-2 tube with a gamma heating of 15 W/g. These data assume the tube is insulated on the outer surface which would be conservative as some heat is lost to the cooler shroud tube. Due to the large gamma heat generation in the ETR and ATR cores, the thermal stress induced in the in-reactor tubes may exceed the yield point. The cyclic nature of these stresses could result in a fatigue problem with the possibility of the growth of the tube diameter. Figure 14 shows a plot of the thermal tangential stress on the inner surface versus wall thickness for a 3 in. ID tube assuming 15 W/g gamma heating.

Accepted design theory[1] allows the application of a thermal stress which exceeds the elastic limit of the material because yielding produces a relaxation of the thermal stress. When cycled through the thermal stress range larger than the yield stress, combined with the stress from the internal pressure, the possibility exists that a progressive expansion (ratcheting) could occur. In the case of the HWRP pressure tube, both the thermal stress and pressure stresses are at a maximum at the inner tube surface.

TEST AND EXPERIMENTAL CONSIDERATIONS

A maximum thermal gradient of 50 °F was selected to produce data to more nearly simulate the gamma heating expected in typical heavy water reactors. The thermal gradient created by the high gamma heating of the tube wall can be controlled and the HWRP criteria met by one of the three following methods of cooling:

1) Cool the tube internally only and limit the wall thickness to the specified 0.120 in.

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1. *B. F. Langer. Design Values for Thermal Stress in Ductile Materials, WAPD-T-584, Rev. (1958).*

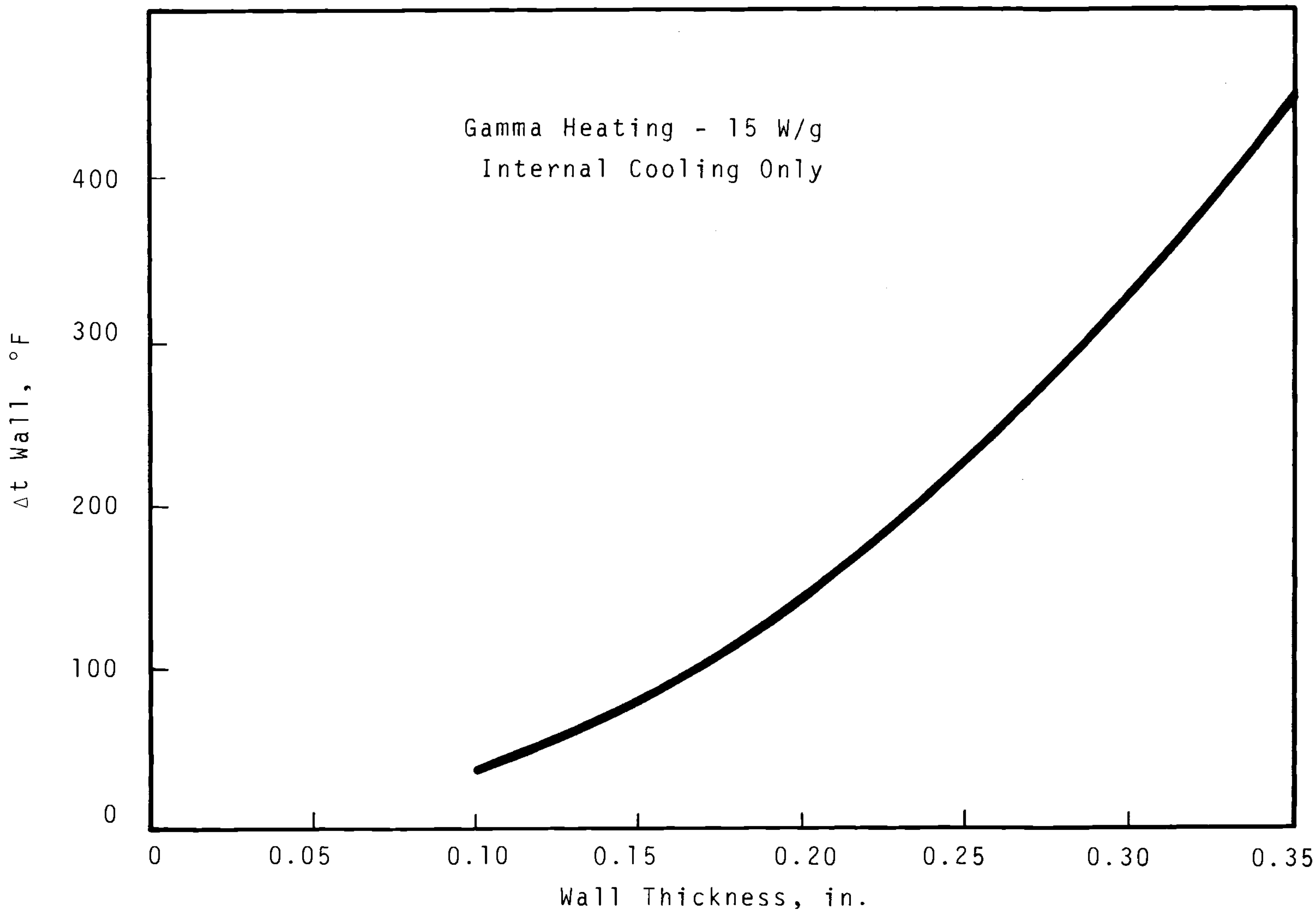
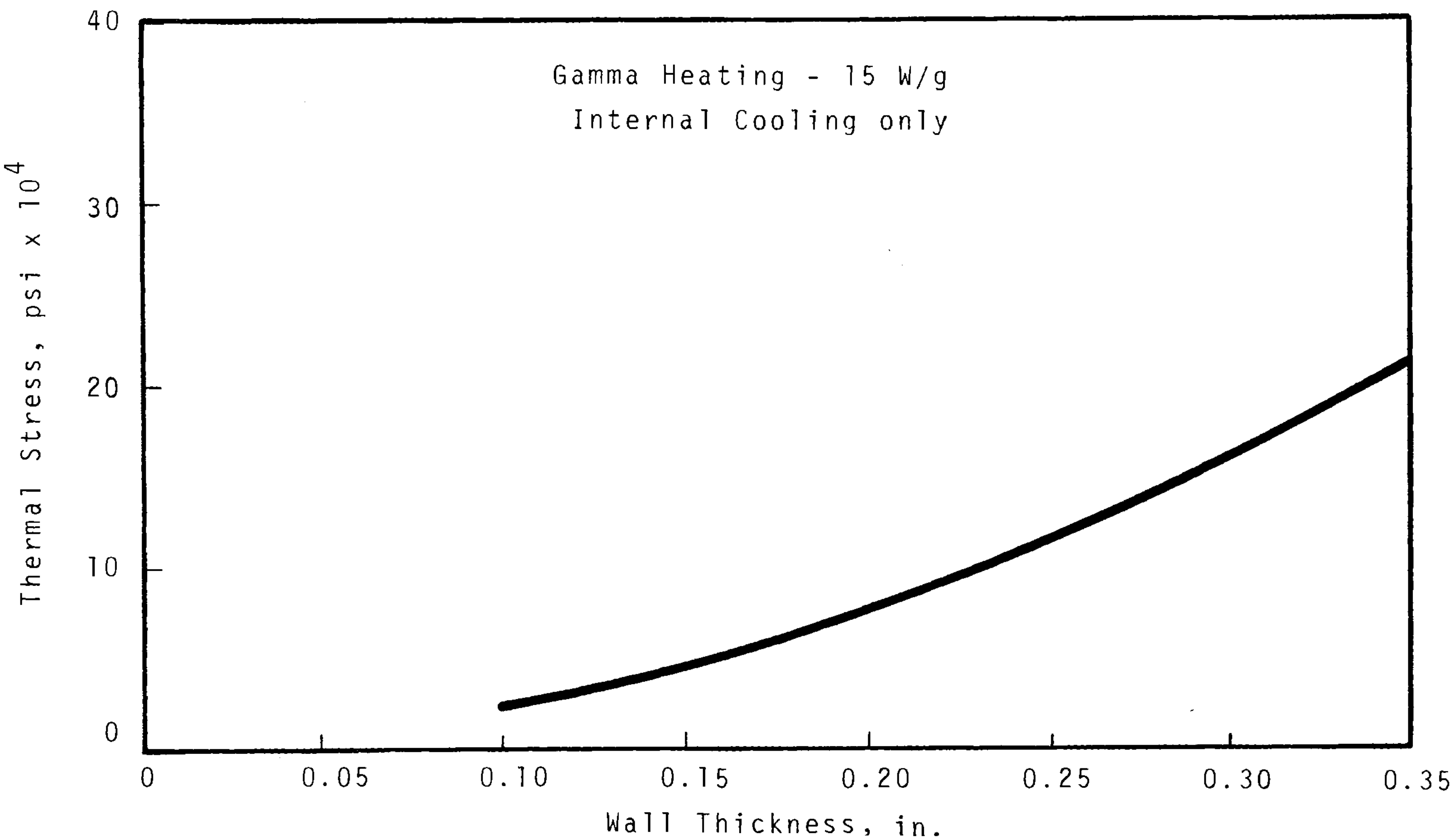


FIGURE 13. *Curve Showing Maximum Wall Δt Versus Wall Thickness for 3 in. ID Zircaloy-2 Pressure Tube Exposed to Gamma Heating*



<u>*FIGURE 14*</u>. *Curve Showing Maximum Thermal Tangential Stress Versus Wall Thickness for 3 in. ID Zircaloy-2 Pressure Tube Exposed to Gamma Heating*

2) Cool the tube externally only.
3) Cool the tube both internally and externally.

The first method would require that the loop be operated with a pressure differential across the 0.120 in. tube wall of approximately 1200 psi to produce the desired hoop stress. The ATR N-Lobe and the ETR G-7 loop now operate at 2000 psi. The second method of external cooling only would require internal pressurization and would be used if the pressure tube test was designed as an external cooled capsule irradiation. The third method of both internal and external cooling would allow the use of a higher internal pressure but would require two separate systems for cooling the inside and the outside of the tube. This method would allow the tube to be irradiated while serving as a pressure tube for other irradiations that require a high pressure water coolant. However, if water is the coolant, an external pressure of 800 psi or above would be required to prevent boiling if the coolant is maintained at the minimum specified temperature of 518 °F. Thus an internal pressurization of 2000 psi or greater would be required to produce the stress in the 0.120 in. wall pressure tube.

The later approach requiring two coolant systems would be difficult to incorporate into the flow re-entrant loops such as the ATR loops and the proposed ETR J-12 loop. The added costs of design and equipment together with added operational problems and control problems for the double cooling systems make this approach unattractive and thus it was not considered further.

Two basic systems exist to irradiate a pressurized Zircaloy-2 tube, either of which can be used in one form or another with any of the vacant facilities described earlier in this report. A capsule approach, if feasible, would involve a physically smaller and simpler system, and theoretically would be more economical. A loop approach requires larger, more sophisticated and more varied auxiliary equipment, and could, therefore, be expected to cost much more than a capsule to fabricate and require more effort to operate and maintain. There is a possibility, however, that a loop tube could be substituted for, or connected into an existing Battelle-Northwest facility. Should this prove feasible, then equipment costs would probably be comparable to a capsule.

CAPSULE FACILITIES

A capsule experiment is normally designed in such a manner that it operates at the desired conditions by transferring the heat generated directly to the reactor water through a thermal barrier. In some cases the thermal resistance is varied by adjustment of the ratio of a binary gas mixture in order to control the sample temperature over a range of power generation conditions.

Preliminary calculations were made to determine whether the HWRP conditions could be met by design of an encapsulated, pressurized Zircaloy tube, with a binary gas annulus for temperature control. The tube would be pressurized with water, and provision would be made for a slight purge in order to maintain the desired water chemistry. The calculations indicated that a helium gap on the order of 0.003 to 0.005 in. would be required in order to maintain the desired 300 °C on the tube surface. Considerable problems would be involved in the fabrication of a 3 or 4 ft long pressure tube assembly with this amount of radial clearance. It would be difficult or impossible to assure that uniform operating conditions could be maintained as portions of the inner tube could conceivably contact the cold annulus tube.

A large gas flow in the transition or turbulent region would be needed to provide flowing heat transfer coefficients adequate to meet the desired test conditions with a gas gap of more reasonable dimensions. Since the capsule design approach offers obvious cost advantage over a loop facility, consideration was given to the design of a capsule test that would use a vaporizing condensing system, instead of a gas annulus, that conceivably could accomplish the required heat transfer at the desired temperature. This approach would eliminate the requirement for the critical manufacturing and operating dimensional tolerances. A similar approach referred to as a reflex system has been used at General Electric Test Reactor at Vallecitos, California. This system consists of cooling the outside of a specimen with boiling water. The steam is taken off, condensed externally and recycled. The temperature of the coolant is controlled by the pressure of the system. This system would require that the coolant be insulated from the colder shroud tube.

For the HWRP test, a vapor cooled capsule system is envisioned where the colder shroud tube would serve to condense the vapor. The principle of operation would be analogous to a "heat pipe."[1] The vapor cooled capsule would provide concentric heat addition and heat rejection zones, instead of the linear arrangement requiring a capillary return of the condensate to the heat addition zone as is the case of the "heat pipe." The concentric capsule system would consist of the internal pressure tube enclosed by a shroud tube with two concentric annuli between these tubes. The inner annulus next to the pressure tube would be the vaporization zone while the outer annulus would serve as the condensation zone. An adiabatic sleeve would separate the two zones. The adiabetic sleeve would

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1. *K. T. Feldman, Jr. and J. H. Whiting. "Heat Pipe," Mechanical Engineering, vol. 89, p. 30. 1967.*

probably consist of two concentric tubes separated by a small annulus and sealed at both ends to form a vacuum wall. Passages at the bottom between the two zones would regulate the return of the condensate. Openings at the top above the heat zone, reactor core through the adiabatic wall, will allow the vapor to flow outward to the cooler shroud tube surface where condensation can occur. The condensate would return by gravity to the bottom of the annulus for recycling.

Vaporization schemes as described above would offer a number of advantages over other approaches. The primary advantage would be simpler control than the circulation systems thus cutting the cost of the out-of-reactor equipment while giving efficient heat transfer at essentially uniform temperature. The main disadvantage is the lack of knowledge or the amount of development necessary to establish control and stability aspects of these systems. Until further study and development can be undertaken, such systems cannot be shown to have a cost advantage over loop approaches. However, they may offer a solution to some existing capsule irradiation problems and the concept, as developed, could be used for future irradiations as well as this program.

The thermos tube type of capsule which does not depend upon vaporization cooling could also be considered. This approach has been tested successfully by PNL for short length pressure tube irradiations and consists essentially of two concentric tubes sealed at both ends with an annulus between. A vacuum is maintained in the annulus and thus the inner tube experiences the hoop tensile stress similar to a pressure tube when the capsule is exposed to a pressurized environment. However, the circumferential tensile stresses found in an internal pressurized tube are not produced. The outer tube, which is heavier, supports the inner tube and forms one side to the annulus. This type of capsule would have the same thermal gradient problems as the insulated pressure tube previously described. Therefore, the simulated pressure tube portion would need to be limited in thickness which in turn limits the pressure of the environment. Such a tube could be irradiated in the ETR G-7 position which operates at 2000 psi, but the annulus would need to be pressurized to produce the desired ΔP across the 0.120 in. wall pressure tube. The resulting pressure tube inside diameter would be only 2-1/2 in. which is smaller than the 3 in. desired.

FULL-SCALE LOOP FACILITIES

A loop type irradiation facility could be designed which would meet the HWRP criteria for irradiation of Zircaloy-2 tube material. This type of facility would be designed for heat removal by the internal pressurized circulating fluid. The tube would be insulated as efficiently as possible from the reactor water by enclosing the entire in-tank assembly with a shroud tube, and maintaining an inert gas in the annular space between the tubes.

High velocity flow is desirable within the tube to increase the heat transfer coefficient and minimize the temperature difference between the coolant and the tube. A high velocity may be attained in a large diameter tube by two methods: 1) by a large volume flow in an empty tube; or 2) to use lower volume flows with an added filler piece to restrict the cross-sectional flow area. If the inside volume of the tube is not needed for additional samples, the high velocity can be obtained by designing the tube for a re-entrant flow pattern. In this type of design, the flow is introduced into an annulus at either the top or bottom, and flows through the reactor core. At the end of the core the flow reverses and flows back to the same end through the center tube.

Since a full-scale loop requires a substantial amount of water, a volume chamber is required to accommodate the considerable expansion that takes place when the water is heated. This function is normally performed by a pressurizer vessel, which also serves to pressurize the circulating system by means of steam generation.

A pumping system of sufficient capacity for normal operating flow must be provided and have installed capability to provide cooldown flow in the event of pump failure. As a minimum two pumps would be required, either one of which must provide adequate flow to allow safe operating conditions in the event of failure of the other pump.

Additional auxiliary equipment necessary includes heat exchangers, heaters (if necessary), valves, water conditioning and sampling equipment, instrumentation for measurement and control of equipment for all primary and secondary systems.

A full-scale loop facility could be designed for any of the vacant positions. For the ETR J-12 position the loop would have to be of the re-entrant design with connections at the top. For the ATR position the loop probably would have to be re-entrant with the connections at the bottom. Auxiliary equipment requirements would be similar for any of the above locations.

A schematic diagram of a typical full scale loop can be seen in Figure 15 which shows the auxiliary primary coolant system for the ATR N-Lobe pressurized water loop. The loop is designed to operate with a coolant pressure of 300 to 2200 psig, coolant temperature of 200 to 600 °F and flow rates of 20 to 80 gal/min over the temperature range indicated. The principal out-of-reactor components are listed as follows:

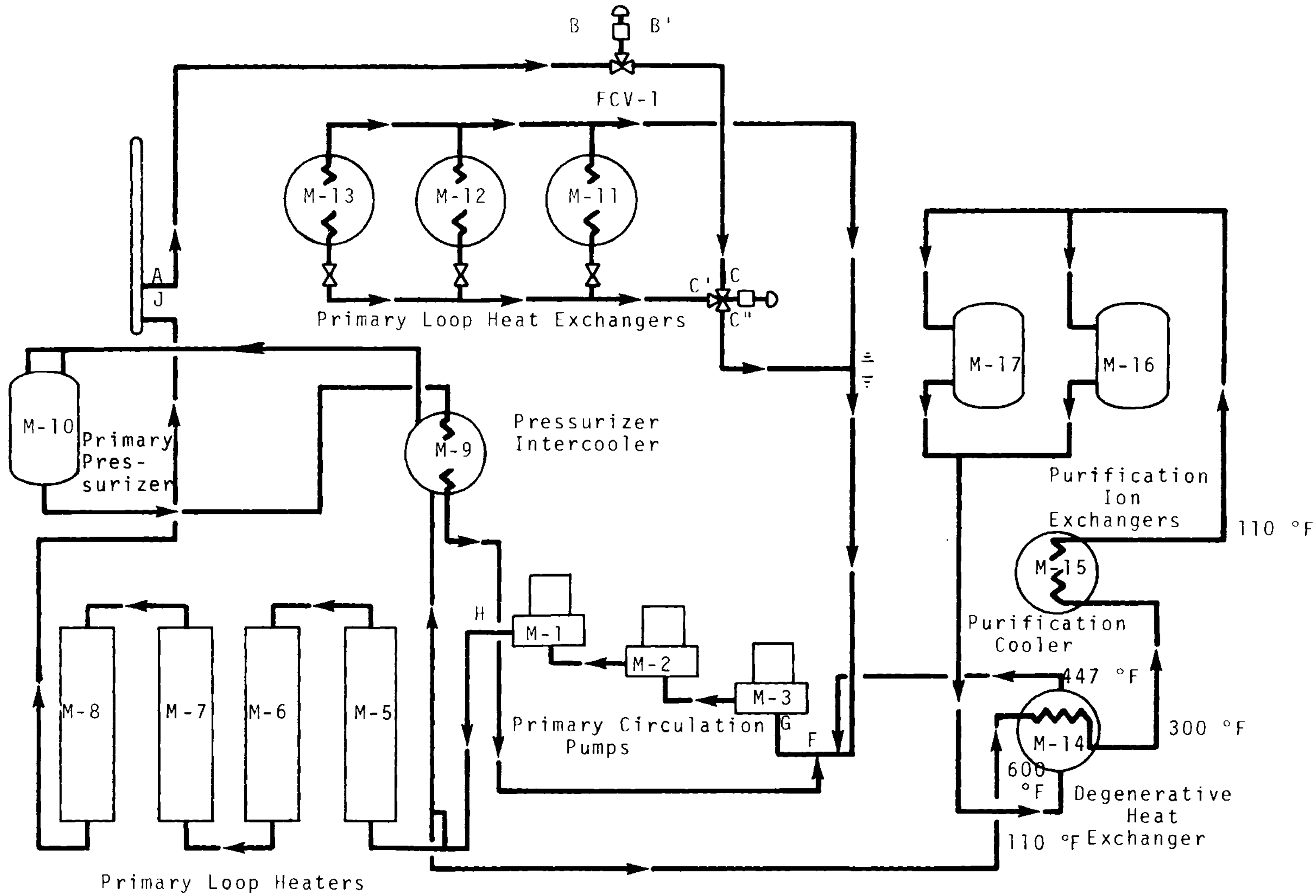

FIGURE 15. Schematic Diagram of a Full-Sized Pressurized Water Loop Installed in the ATR N-Lobe

Primary Loop

Primary Loop Heat Exchangers

Two 54 ft^2 units

One 11.6 ft^2 unit

Pressurizer (300 to 2200 psig)

Pressurizer Intercooler (2.85 gal/min - 70 to 404 °F)

Pressurized Water Heaters (60 kW)

Three Circulation Pumps (150 gal/min canned rotor pumps)

Four Primary Loop Heaters (54 kW each)

System Piping, Fittings, and Valves (348 SS)

Purification System

Sampling System

Two Ion Exchangers (6 gal/min)

Regenerative Heat Exchanger (11.6 ft^2)

Purification Cooler (11.5 ft^2)

Fill and Make-Up

Two Make-up Pumps (23 gal/min - 5150 psig)

Helium System

Instrumentation and Control

MINILOOP

The heat generation in a 0.120 in. wall pressure tube resulting from 15 W/g of gamma heat could be removed by a flow of approximately 20 gal/min under HWRP conditions with a bulk water temperature rise in the order of 30 °F. These conditions may not provide a normal margin of protection against boiling burnout and thus the heat transfer situation would need additional investigation.

Such a facility basically will contain the same equipment as described earlier for the full-sized loop but is attractive since the size and complexity of the auxiliary equipment could be reduced. This would result in substantial savings in initial cost over a full-sized loop. The miniloop, like a capsule, would be unable to operate with few if any additional tests within the tube.

The low flow in the large diameter pressure tube would require that a filler plug be included to raise the fluid velocity for adequate heat transfer unless designed for re-entrant flow where the center flow tube would act as the filler. This filler or center flow tube also could be a train of thermos elements. In any case this center filler device would require an additional coolant flow, the amount depending upon the filler volume and material.

One possibility would be to set up the low-flow pressure tube in parallel with one of the existing facilities (ATR N-Lobe, G-7 or P-7 loops) provided that the operating conditions would be compatible. The 2000 psi pressure at which these loops now operate would probably make this prohibitive due to a thick tube wall and resulting high thermal gradients as discussed earlier.

Capability for interim examination of the interior of the pressure tube could be provided in the same manner as for other systems, by design of a removable closure plug.

SUMMARY OF ETR AND ATR AVAILABLE IRRADIATION FACILITIES

A summary of the available study indicates that there are seven approaches which can be considered for irradiation tests of the HWRP pressure tube in the ETR and the ATR. These are as follows:

TEST APPROACHES

ETR G-7 Position

1. Irradiation of internal pressurized thermos tube in existing loop

ETR J-12 Position

2. Full-sized loop using P-7 loop out-of-reactor equipment (low pressure operated)
3. New full-sized loop (low pressure)
4. Miniloop (low pressure)

ATR NE-Lobe

5. Full-sized loop using N-Lobe out-of-reactor equipment (low pressure)
6. New full-sized loop (low pressure)
7. Miniloop (low pressure).

Consideration was given the possibility of replacing the existing G-7 pressure tube with the HWRP pressure tube. The loop now being used for the GEH-20 irradiations operates at 2000 psi and thus would require a wall thickness that would result in a high thermal gradient across the wall. Thus the most promising approach in this loop would be a large diameter internally pressurized thermos tube within the existing pressure tube and with the GEH-20 test placed within the thermos tube. This has the advantage of not requiring a major revision of the existing loop, but has the disadvantage that the HWRP thermos pressure tube ID would be about 2-1/2 in. instead of the desired 3 in. and would require redesign and rescheduling for the hardware and tests currently being irradiated.

The use of the J-12 position would require relocating some capsule experiments now occupying this position and would be a top re-entrant flow to avoid the dog-leg problem of passing through the core. A full-sized loop could be considered for this position. In the event that the P-7 loop was not in use, the P-7 loop out-of-reactor equipment could be used to cool a loop in the J-12 position, thus saving the cost of new out-of-reactor equipment. The in-reactor portion of the P-7 loop is now located in the reflector of the reactor.

The loop equipment would be operated at a pressure compatible with the HWRP pressure tube irradiation and could handle in addition up to two trains of nested thermos tubes. The miniloop (less than 50 gal/min) would accommodate cooling of the pressure tube and at most a small diameter thermos tube experiment.

The NE-Lobe is the most promising position in the ATR for the irradiation of the HWRP pressure tube. The loop would be a bottom re-entrant flow which could be a full-sized loop operated with the N-Lobe pressurized water loop out-of-reactor equipment or could be a complete new loop. The loop could accommodate a 3-1/2 in. diam in-reactor pressure tube and up to three trains of nested thermos tube capsules. A new full-sized loop in the ATR to cool the NE-Lobe irradiations would have out-of-reactor equipment similar to the equipment used for the N-Lobe which was described earlier under "Test and Experimental Considerations" on page 27. The miniloop would be similar to the one proposed for the ETR J-12 loop. Both the miniloop and a full-sized loop would be operated at conditions compatible to the HWRP irradiation test.

The reflux approach is not being considered here along with the self-cooled capsule approach although the reflux approach has been successfully used at GETR. Further study would be needed to prove the feasibility of both of these approaches for this test.

Table 2 lists the basic approaches under consideration and shows the compatibility to the HWRP criteria.

COST ANALYSIS

Following is a listing of the estimated set up costs for the suggested approaches. The reflux approach and the capsule approach are not included here as further study is required to determine the costs. These costs include design, capital equipment, in-reactor loop section, installation and checkout.

TABLE 2. Summary of Candidate Facilities for HWRP Pressure Tube Irradiation

	ETR			ATR	
	G-7	J-12		NE-Lobe	
	Thermos	Full-Sized Loop	Miniloop	Full-Sized Loop	Miniloop
Loop Tube Parameters					
Inner Diameter	2-1/2 in.	3 in.	3 in.	3-1/2 in.	3-1/2 in.
Length	3 ft	3 ft	3 ft	4 ft	4 ft
ID Measurement	Yes	Possible but difficult	Possible but difficult	Yes	Yes
Test Parameters					
Neutron Flux, nv	2×10^{14}	2×10^{14}	2×10^{14}	2×10^{14} (b)	2×10^{14} (b)
Time to 10^{22} nvt @ 50% Efficiency	3 yr	3 yr (a)	3 yr (a)	3 yr (a)	3 yr (a)
Temperature	277 °C	as desired	as desired	as desired	as desired
Pressure	2000 psi	as desired	as desired	as desired	as desired
Coolant Chemistry	OK	as desired	as desired	as desired	as desired
Loop Control	0-50% HWRP	HWRP	HWRP	HWRP	HWRP
Stability of Reactor Operation	Predictable	Predictable	Predictable	Unknown	Unknown
Installation Problems	Few	Difficult	Difficult	Few	Few
Thermos Specimen Capacity	3	3	6	9	3

(a) *Assumes 50% operating efficiency*

(b) *Assumes ATR operation at starting 70% power*

POSITION AND REQUIREMENTS

Position	Requirement	Cost $ x 10^6
ETR G-7	Insert HWRP Thermos Specimens	
	Funds required for gas pressurization and installing Zircaloy specimens.	0.15
ETR J-12	Connect Directly to P-7 Equipment	
	Funds required to construct in-reactor section and connect to present out-of-reactor equipment	0.50
	New Loop with Same Capacity as P-7 Loop Equipment Except Lower Pressure Capability	
	Funds required for both in-reactor and out-of-reactor portions of the loop.	1.5
	Miniloop	
	Funds required to construct low flow, out-of-reactor equipment and in-reactor portion of the loop.	1.1
ATR NE-Lobe	Connect Directly to N-Lobe Out-of-Reactor Equipment	
	Funds required for in-reactor loop section and cross-over to N-Lobe equipment.	0.5
	New Loop with Same Capacity of N-Lobe Equipment Except Lower Pressure Capability	
	Funds required for both in-reactor and out-of-reactor portions of the loop.	1.6
	Miniloop	
	Funds required to construct low flow, out-of-reactor equipment and in-reactor portion of the loop.	1.0

Detail costs analysis for these various approaches are given in Table 3 as total funds and in prorated costs per specimen-year where the construction, installation capital expenses, and irradiation and operating charges have been prorated over the specimen capacity of each facility being considered for a period of 3 yr. Each thermos specimen is considered to be about 1 ft long and the pressure tubes are evaluated in 1 ft lengths.

Table 3 indicates that Approaches 2, 5, and 6 are nearly equivalent in prorated costs, i.e., data efficiency, and being some lower than 3 and much lower than Approaches 1, 4, and 7. The efficiency of the facility is controlled mainly by the amount of data obtained and the IU costs. The capital equipment costs do not weigh nearly as heavily in the efficiency as the IU costs. Thus the miniloops which can handle only a few specimens compared to the larger loops is an inefficient approach the same as Approach 1, the thermos tube in the G-7 facility. Based on total costs, Approach 1 is the lowest by a considerable amount. This approach, besides showing a low data efficiency, produces only a single set of thermos tubes with a smaller than desired tube diameter. Approach 2 which has the next lowest total cost, $\$1.91 \times 10^6$ more than Approach 1, also shows a good data efficiency. The best approach in the ATR is 5 which gives the lowest total cost available in the ATR and provides the best efficiency of all approaches.

Results of the cost analysis indicate that the selection of an approach probably can be based on the types of funding available and the needs of the program in terms of rate of data accumulation without adverse effects on the efficiency in terms of data per test dollar.

TABLE 3. Cost Analysis of Candidate Irradiation Approaches for HWRP Pressure Tube

	Specimen Capacity		Funds Required $ x 10^6				
Facility	Loop Tube	Thermos Tubes	Capital	IU[a] (yearly)	Operating (yearly)	Prorated[b] (spec.-year)	Total Costs (3 yr period)
ETR G-7							
1. Thermos Tube	No	3	0.15	0.7[c]	0.01	0.25	2.28
ETR J-12							
2. P-7 Equipment	Yes (3)	6	0.5	1.2	0.03	0.16	4.19
3. New Loop	Yes (3)	(6)	1.5	1.2	0.03	0.19	5.19
4. Miniloop	Yes (3)	3	1.1	1.2	0.03	0.27	4.79
ATR NE-Lobe							
5. N-Lobe Equipment	Yes (4)	12	0.5	1.8	0.03	0.13	5.99
6. New Loop	Yes (4)	12	1.6	1.8	0.03	0.15	7.09
7. Miniloop	Yes (4)	4	1.0	1.8	0.03	0.27	6.49

(a) *IU - Irradiation Unit Charges*

(b) *Prorated Costs* $= \dfrac{\text{(1/3 capital) + Annual IU + Annual Operating}}{\text{No. of specimens}}$

(c) *Assumes HWRP shares loop and pays 50% of IU and operating costs*

RECOMMENDATIONS

Based on the desired irradiation test criteria and the cost per unit of data received, three approaches should be considered. These are: 1) the ETR J-12 position using the P-7 out-of-reactor equipment; 2) the ATR NE-Lobe position using the N-Lobe out-of-reactor equipment; and 3) the ATR NE-Lobe position with new out-of-reactor loop equipment. These three approaches will cost about $150,000/specimen-year compared to $190,000/specimen-year for one approach and $260,000/specimen-year for the other three approaches considered. They will meet all the required criteria except Approach 1, listed above, will irradiate a 3 ft long tube instead of a 4 ft length as specified. It must be understood that Approaches 1 and 2 above are subject to availability of the indicated out-of-reactor equipment and thus in the final analysis may not be candidates at the time of proceeding with the tests.

The above recommended approaches are all adaptable either to irradiating thermos specimens along with the pressure tube or sharing the loop with other sponsors with tests compatible with the HWRP test. Also, the facilities, at the conclusion of the irradiation, can be adapted to other programs for tests where a high flux would be desirable.

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