DP-988

AEC RESEARCH AND DEVELOPMENT REPORT

CONTROL OF THE DISSOLVED GASES IN THE MODERATOR OF THE HEAVY WATER COMPONENTS TEST REACTOR

L. M. Arnett
H. P. Olson

Savannah River Laboratory

Aiken, South Carolina

Printed in USA. Price $2.00
Available from the Clearinghouse for Federal Scientific and Technical Information, National Bureau of Standards, U. S. Department of Commerce, Springfield, Virginia

664381

DP-988

Reactor Technology
(TID-4500, 45th Ed.)

CONTROL OF THE DISSOLVED GASES IN THE MODERATOR OF THE HEAVY WATER COMPONENTS TEST REACTOR

by

L. M. Arnett
H. P. Olson

Approved by

L. M. Arnett, Supervisor
HWCTR Task Force

November 1965

E. I. DU PONT DE NEMOURS & COMPANY
SAVANNAH RIVER LABORATORY
AIKEN, SOUTH CAROLINA

CONTRACT AT(07-2)-1 WITH THE
UNITED STATES ATOMIC ENERGY COMMISSION

ABSTRACT

Unexpected variations in the nuclear reactivity during the initial mode of hydraulic operation in the Heavy Water Components Test Reactor were traced to the appearance and disappearance of helium bubbles in the moderator. Three mechanisms, aspiration, entrainment, and supersaturation, were each identified, and mechanical and procedural modifications were installed to eliminate the void formation. The investigation of the mechanism for supersaturation of the moderator is of general interest because the problem could arise in other reactors that are pressurized with an inert gas.

CONTENTS

LIST OF FIGURES

CONTROL OF THE DISSOLVED GASES IN THE MODERATOR OF THE HWCTR

INTRODUCTION

The Heavy Water Components Test Reactor[1] (HWCTR) was built and operated for the United States Atomic Energy Commission by the Du Pont Company at the Savannah River Plant to test prototype fuel elements and other reactor components for power reactors that are moderated with heavy water and fueled with natural or slightly enriched uranium. The reactor core is in the lower 10 feet of a 30-foot pressure vessel. The core contains 24 positions for driver fuel, 12 positions for test fuel, 18 positions for control rods, and 6 positions for safety rods. All of these components are cooled with liquid D_2O that flows downward from the region above the top shield. The D_2O is discharged at the bottom of the core components and then flows upward through the moderator space. The heat produced by the core is removed in two loops, each containing a circulating pump and a steam generator. H_2O steam produced in the generators is discharged to the atmosphere. Sufficient helium gas is maintained in the top of the pressure vessel to prevent boiling of the liquid D_2O at all points, except possibly for some nucleate boiling on the surfaces of the fuel.

Nominal operating conditions of the HWCTR are: power = 50 MW, pressure = 1200 psig, and moderator temperature = 250°C.

This report describes the program that was required to define the cause and to devise corrective measures for the unexpected variations in nuclear reactivity that were found to be associated with variations in hydraulic operation.

SUMMARY

The unexpected variations in nuclear reactivity that accompanied changes in the mode of hydraulic operation during the initial critical experiments in the HWCTR were found to result from the appearance and disappearance of gas bubbles in the moderator. Three mechanisms, aspiration, entrainment, and supersaturation, all contributed to various extents to the formation of helium bubbles in the D_2O moderator. Appropriate changes in the physical structure of the reactor and in the operating procedures successfully eliminated all the causes of bubble formation and the undesirable variations in nuclear reactivity.

Gas was aspirated into the moderator through the control and safety rod assemblies. The flow of D_2O through these original assemblies was unduly restricted, with the consequence that they ran dry when the total D_2O flow was at the nominal operating value. Under these conditions, gas entered the tops of the assemblies, which extended into the gas space above the D_2O, and passed into the moderator at the bottom of the assemblies. This undesirable condition was corrected by increasing the size and number of entrance orifices in the rod assemblies so that under all flow conditions the assemblies were filled with liquid.

Gas was entrained by vortex formation on the surface of the D_2O only when the level of D_2O above the core was lowered to about two feet above the D_2O inlet nozzles. This difficulty was corrected by specifying in operating procedures a minimum safe D_2O level.

Gas was evolved in the core whenever the concentration of helium exceeded the saturation concentration at core conditions. This condition could exist at normal operating conditions because the helium was more soluble in D_2O at the gas-liquid interface in the upper non-nuclear portion of the reactor vessel than in the moderator region. A combination of structural and procedural modifications corrected this situation by limiting the concentration of helium in the D_2O in the upper portion of the vessel to about 60 percent of saturation. The three structural modifications were: (1) installation of a stilling baffle about 30 inches under the surface of the D_2O, (2) introduction of the gas carried out of the reactor in the D_2O purge back to the high pressure gas space rather than into the circulating D_2O, and (3) introduction of excess D_2O from the seal system into the main D_2O circulating system rather than overflowing through the gas space. All of these changes minimized the contact of D_2O in the main circulating system with the high pressure gas. Limits on the gas concentration were prescribed in Operating Procedures.

The maximum amount of reactivity that could be held in gas voids, when all three mechanisms of bubble formation were operative, was estimated to be 0.0082 $\Delta k/k$. After the aspiration and entrainment were eliminated, the maximum amount of reactivity held in voids was observed to be 0.0014 $\Delta k/k$. This latter value is in excellent agreement with that calculated from the amount of voids that could arise from solubility effects and the calculated reactivity effect of voids.

DISCUSSION

DESCRIPTION OF THE PROCESS SYSTEM

The pertinent features of the HWCTR process system, as-built, are shown in Figure 1.

The primary circulating system consists of two identical loops, each containing a pump and a steam generator. The pumps are mounted vertically and have mechanical seals. Each pump circulates 5000 gpm of D_2O at a TDH of 150 feet when driven by the AC motor, or about 2000 gpm of D_2O at a TDH of about 15 feet when driven by the DC motor. The D_2O flows from the pump through the steam generator and into the reactor through a nozzle located about $6\frac{1}{2}$ feet below the D_2O surface. The D_2O flows around and through a cylindrical flow distribution baffle and enters the fuel channels through openings in the top shield. The D_2O is discharged into the moderator space through holes at the bottom of each fuel assembly, and then flows upward and out of two nozzles located below the top shield. About 240 gpm of D_2O passes through other openings in the top shield and about 360 gpm of D_2O flows through the control and safety rod assemblies.

Clean D_2O is supplied to the mechanical seals on the pumps and the rod drives by an Aldrich Triplex pump with a capacity of 10 gpm. The D_2O is taken from the return line from the purification system and pumped to an elevated seal head tank that provides a constant head to the seals, which normally take less than 2 gpm. The extra overflows from the seal head tank to the reactor. The seal pump operates continuously during normal operation.

The D_2O is maintained at a constant level in the reactor by outflow of D_2O through a purge line attached to the reactor vessel about four feet below the D_2O surface. The purge flow is controlled by a valve that is positioned by a signal from the D_2O level instrument. At constant temperature, the purge flow is equal to the overflow from the seal head tank plus the seal inleakage. Another Aldrich pump, the make-up pump, can supply 30 gpm of D_2O to the reactor to counteract D_2O shrinkage when the temperature decreases, or to counteract a D_2O leak. The purge valve can accommodate the flow rate of the seal pump and make-up pump (40 gpm) so that a constant D_2O level can be maintained with both pumps operating. The D_2O level is normally maintained 10 feet above the top shield.

The reactor is pressurized by a helium blanket above the D_2O surface. Helium can be added to this space from high pressure (2000 psig) storage banks. The gas space in the reactor is connected to the gas space above the D_2O surface in the seal head tank. The volume of the two gas spaces and piping is about 96 ft^3.

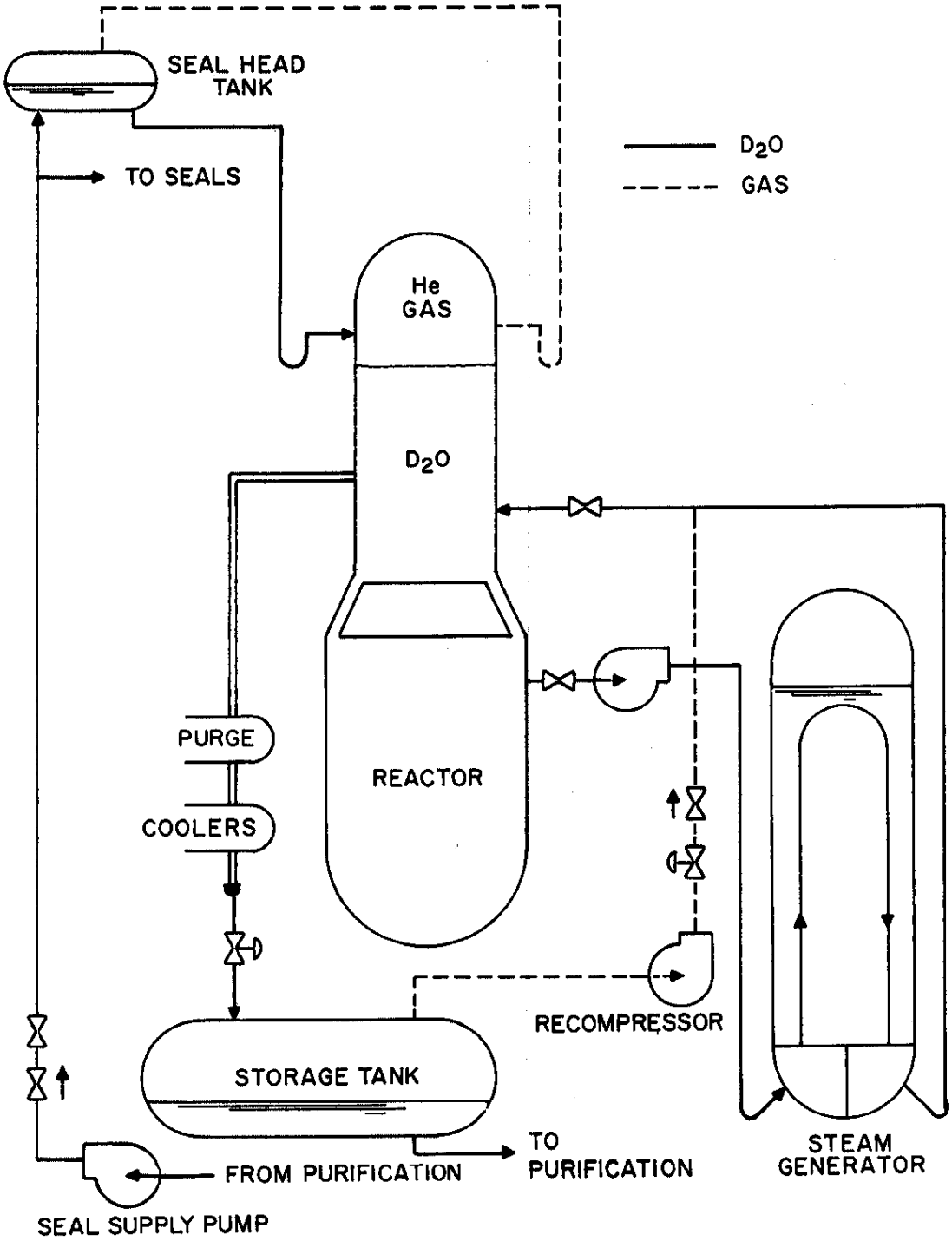


FIG. 1 HWCTR PROCESS SYSTEM
(as-built)

The D_2O that flows from the reactor through the purge line is cooled and depressurized and then flows into the top of the holdup tank, a vertical cylinder about one foot in diameter. This holdup tank is connected by lines both at the top and bottom to the storage tank. The dissolved gas that evolves is compressed by a four-stage piston compressor and returned to the high pressure system. As originally built, the return line for the compressed gas was connected to the 10" D_2O line between the steam generator and the reactor. The D_2O either flows to the storage tank or is pumped through filters and deionizers to remove particulate matter or ionic impurities.

RELATIONSHIP BETWEEN NUCLEAR REACTIVITY AND HYDRAULIC OPERATION

Among the series of low power physics tests[2] performed during the startup program were certain tests at the expected operating temperature of the reactor.[3] The desired temperature of about 240°C was attained by heating the D_2O with the energy that resulted from full flow of 5000 gpm through each of the main circulating pumps. The secondary sides of the steam generators were dry to minimize heat losses. The seal pump was operated intermittently to provide only enough D_2O for the mechanical seals and to avoid the addition of cold D_2O to the reactor through the overflow from the seal head tank. The level of D_2O in the reactor was maintained constant by a purge flow equal to the inleakage through the mechanical seals.

The reactor was made critical for this first experiment at a high temperature at the following conditions:

Reactor power	~1 KW
Moderator temperature	243°C
Reactor pressure	800 psig
D_2O flow	10,000 gpm
D_2O level	5 ft below normal

When the nominal zero power condition was achieved, flux oscillations were noted on each of the nuclear instruments. These oscillations are shown in Figures 2 and 3. The oscillations were observed for about 30 minutes, after which the conclusion was reached that they were related in some manner to the hydraulic operation at the reduced D_2O level. To test this hypothesis the circulating pumps were stopped and the effect on the flux oscillations noted.

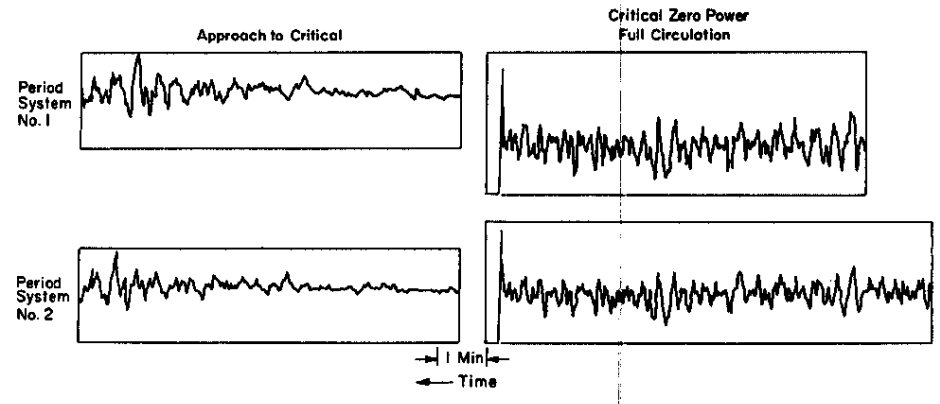


FIG. 2 FLUX VARIATIONS INDICATED BY PERIOD INSTRUMENTS (full flow)

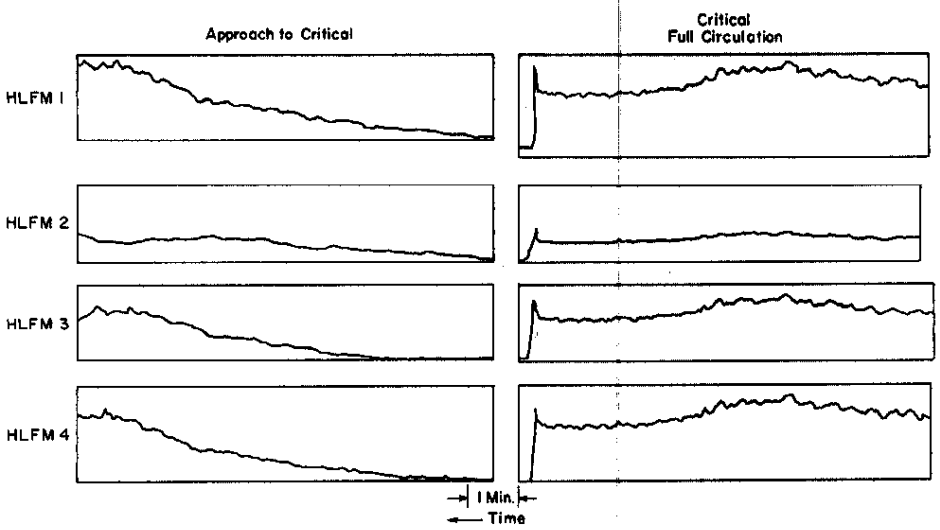


FIG. 3 FLUX VARIATIONS INDICATED BY LINEAR INSTRUMENTS (full flow)

Coincident with the shutdown of the pumps, a fast nuclear shutdown (scram) resulted from short periods on both of the log N-period instruments. The recorder charts on both instruments indicated a period of 25 seconds compared to the scram set point of 15 seconds. However, in this case, the recorder response time was too long to permit the recorder to indicate the full magnitude of the fast transient.

When the reactor was made critical again at the same D_2O level, but without D_2O circulation, no flux oscillations were observed. Criticality was achieved with less control rod withdrawal than in the previous case, indicating that more reactivity was available with no D_2O circulation. The difference in reactivity between the two critical rod configurations, corrected for temperature difference, was 0.00824 $\Delta k/k$. Figures 4 and 5 show reproductions of the nuclear instrument recorder charts for the no-flow condition, and show the absence of the flux oscillations that occurred when the D_2O was circulating. The physics experiment in progress was completed without difficulty and the reactor was shut down.

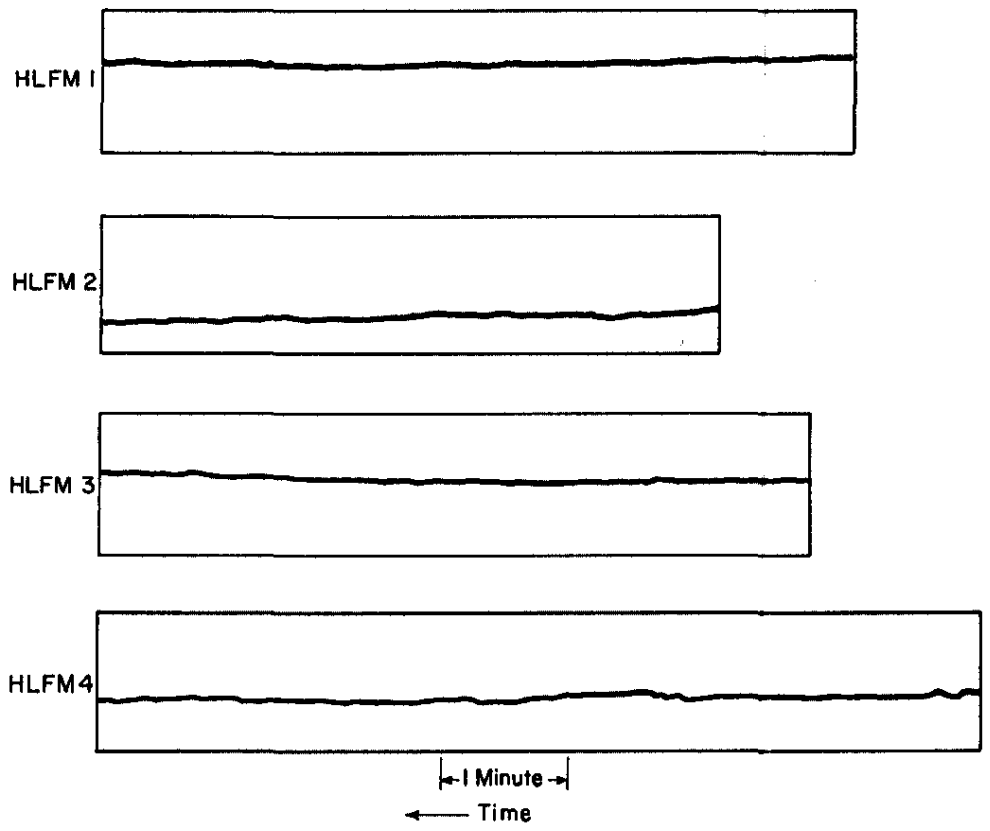


FIG. 4 FLUX VARIATIONS INDICATED BY LINEAR INSTRUMENTS (no flow)

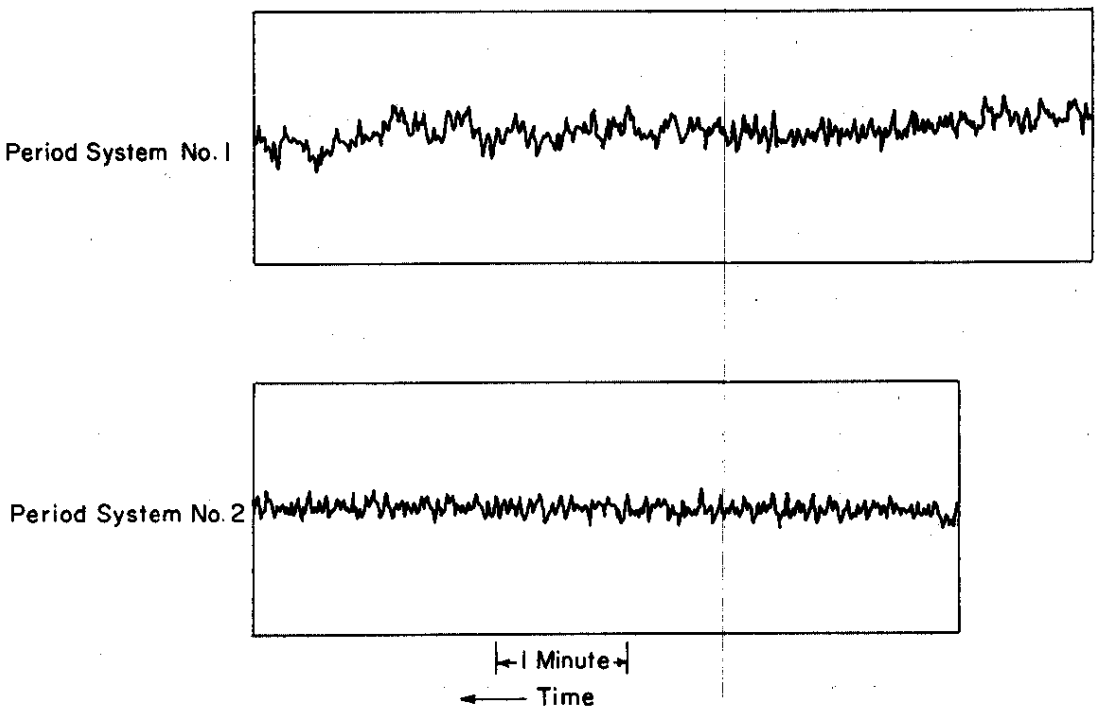


FIG. 5 FLUX VARIATIONS INDICATED BY PERIOD INSTRUMENTS (no flow)

The unexpected relationship between nuclear reactivity and hydraulic operation prompted a more intensive examination of certain unexplained phenomena that had been observed earlier during hydraulic tests. No explanation had been formulated to account for the fact that the D_2O level in the reactor rose by six to eight inches when the D_2O circulation rate was increased from zero to 10,000 gpm and fell an equal amount when the flow stopped. The D_2O level also changed at intermediate flow rates but the changes were smaller and erratic. These changes were noted when the D_2O was at the normal level in the reactor. When the six central control rods were withdrawn from the reactor in which full flow existed, the level of the D_2O fell five or six inches.

From the observed effects of flow changes on the D_2O level and the nuclear reactivity, the postulate was formulated that the moderator contained gas voids when the D_2O was flowing at the maximum rate and that these voids disappeared when D_2O flow was stopped. Disappearance of voids would cause the reactivity to increase because in the HWCTR the void coefficient of reactivity is negative.

POSSIBLE MECHANISMS FOR VOID FORMATION

The HWCTR system was analyzed to determine the various ways that gas voids might be introduced into the moderator. Three mechanisms of void formation appeared to be possible, viz., 1) aspiration of gas through the hollow control and safety rods, 2) entrainment of gas in the D_2O flowing through the fuel elements, and 3) evolution of gas dissolved in the D_2O. Subsequent tests demonstrated that all three mechanisms were operative under attainable reactor conditions. Aspiration and entrainment were possible because of the mechanical design of the reactor and components and the pressure gradients in the system. The mechanism of gas evolution, however, was related to the physical properties of helium and D_2O, as well as to the mechanical design and operating conditions. For this reason, gas evolution is a more basic problem, involving not only the design peculiarities of the HWCTR, but more generally the concept of gas pressurization of pressurized water reactors.

Aspiration

The control and safety rods travel vertically inside guide tubes that are made in two parts. The upper guide tube hangs from the top guide plate and is open to the gas space in the top of the reactor. The lower guide tube is supported in a cup at the bottom of the core. The bottom of the upper guide tube and the top of the lower guide tube are positioned radially by the sleeve in the top shield, with a gap between the two guide tubes. The mechanical arrangement is shown in Figures 6, 7, and 8.

The D_2O coolant flows into the guide tube assemblies at the elevation of the top shield through holes in the lower portion of the upper guide tubes of the six central rods, and through the gap between the upper and lower guide tubes of the other rods. After flowing a short distance along the annulus between the rod and guide tube, most of the coolant enters holes in the control rods and flows down the center of the rod. At the bottom of the rods the coolant flows out through holes in the rod into the annulus and then into the moderator space through holes in the bottom of the lower guide tube. These flow paths are shown in Figures 7 and 8.

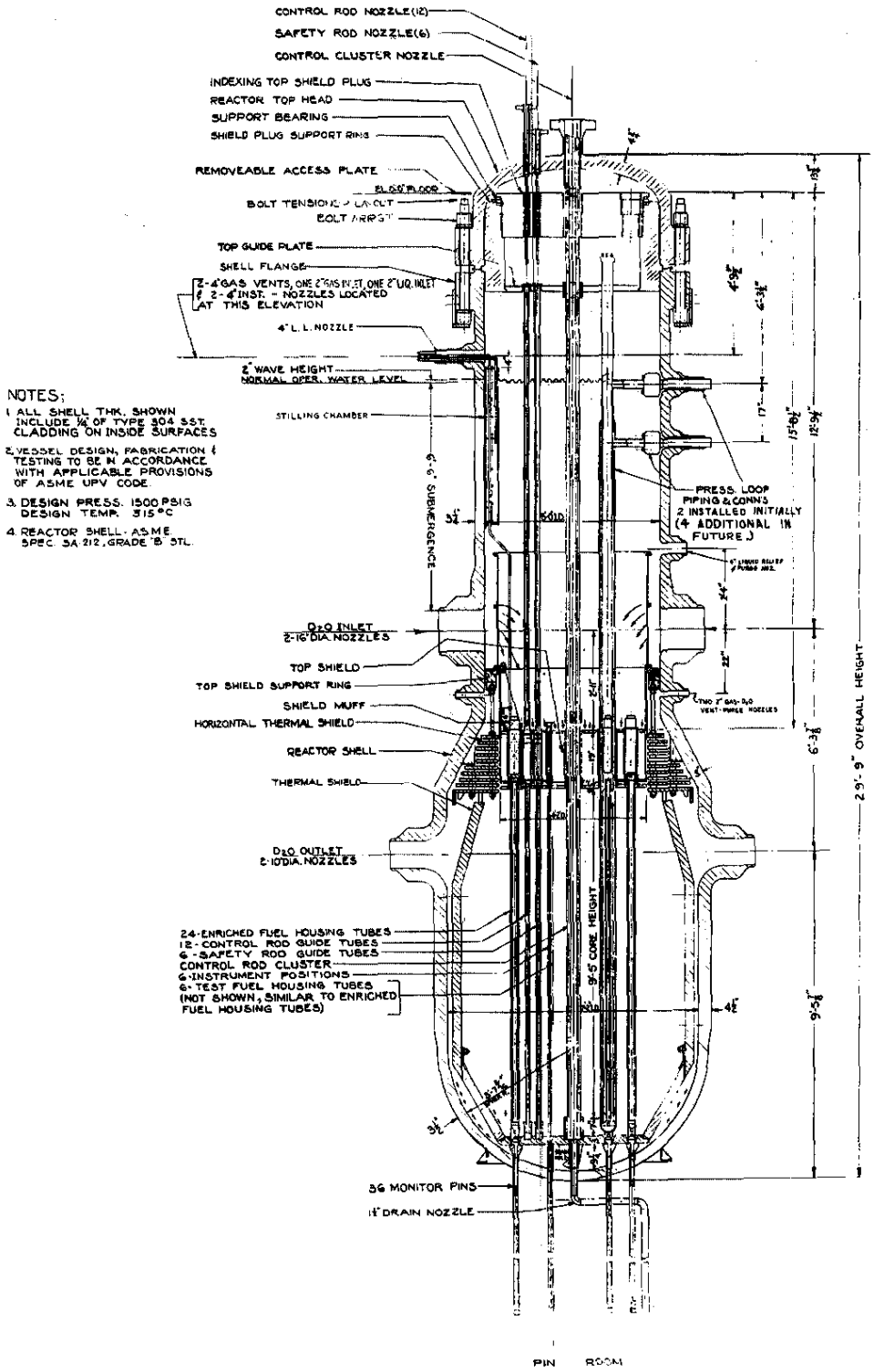


FIG. 6 CROSS SECTION OF REACTOR

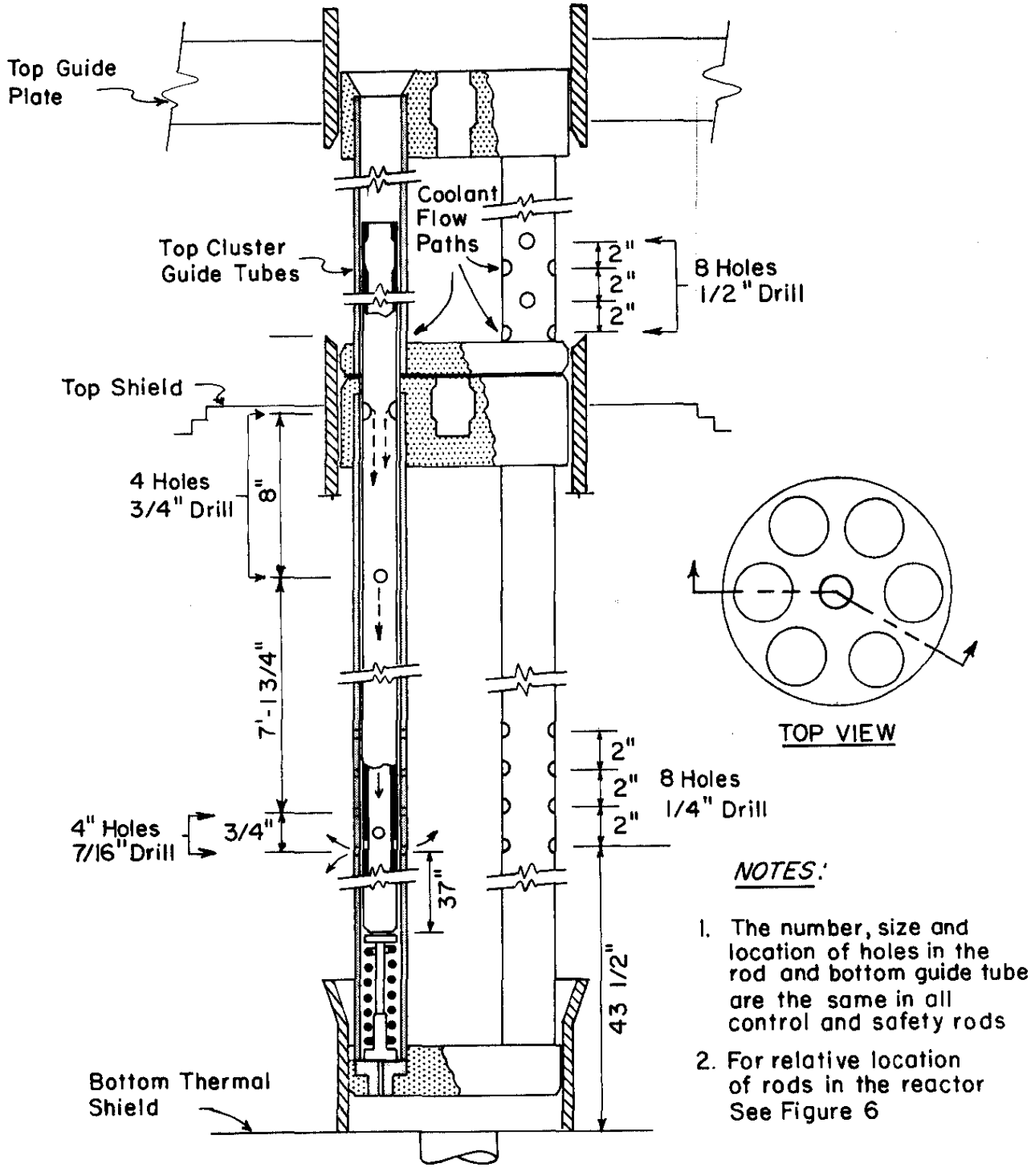
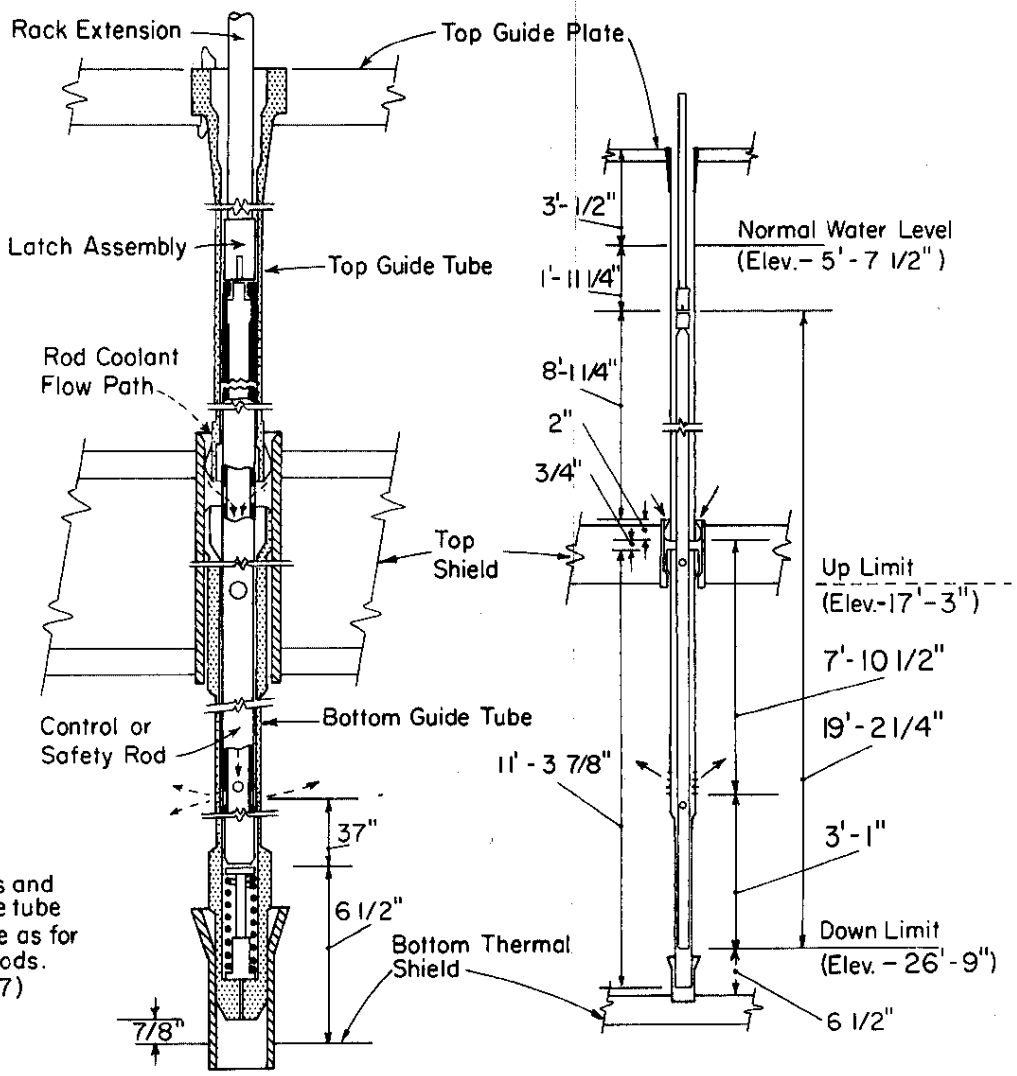


FIG. 7 CLUSTER ROD GUIDE TUBE ARRANGEMENT



NOTE:

Holes in rods and bottom guide tube are the same as for the cluster rods. (see Figure 7)

FIG. 8 CONTROL AND SAFETY ROD GUIDE TUBE ARRANGEMENT

The height of D_2O inside of the hollow rods depends upon the difference between the pressure inside the bottom portion of the rod and the pressure in the gas space. The pressure inside the bottom portion of the rod is the sum of the pressure at the bottom of the reactor and the pressure loss caused by D_2O flowing through the holes in the rod and guide tube. When there is no flow of D_2O in the reactor, the pressure at the bottom of the reactor is equal to the pressure in the gas space plus the hydrostatic pressure of D_2O in the reactor; the height of D_2O in the rods is equal to the height of D_2O in the reactor. When D_2O is pumped through the fuel at the rate of 10,000 gpm, the pressure in the bottom of the reactor is less than the gas space pressure by about 46 feet of D_2O. Under these conditions, the pressure loss caused by D_2O flowing through the holes at the bottom of the rod and guide tube must be greater than 46 feet of D_2O to maintain a positive level of D_2O inside the rod. For this reason, the flow of D_2O through the rod and annulus fixes the height of D_2O in the hollow rod.

The flow of D_2O through a rod assembly depends upon the resistance to flow offered by the entrance holes, the holes in the rod, and the length of annulus the flow must traverse before entering the rod. Consequently, the resistance to flow is a function of the rod position. The driving force for flow into the rod is equal to the difference in D_2O height inside the rods and outside the guide tubes because both surfaces are exposed to the gas space in the top of the reactor.

Calculations indicated that the flow of D_2O into the rods was not sufficient for some rod configurations to maintain the level of the D_2O above the holes in the bottom of the rod housings. Under these conditions gas would be aspirated through these holes and forced into the moderator. This condition was calculated to exist for the six central rods when they were fully inserted and possibly for the ring control rods when they were partially withdrawn. The likelihood of aspiration would be greater when the D_2O level in the reactor is lower than normal because the imbalance of pressures would be greater.

Entrainment

The inlet nozzles on the reactor for the main coolant streams are located four feet above the top shield. A perforated cylindrical baffle provides mixing of the influent D_2O and prevents channeling of cool D_2O through the fuel elements nearest to the inlet nozzles. This arrangement causes considerable turbulence in the region just above the top shield. The free surface of the D_2O is normally 10 feet above the top shield to minimize the possibility of gas being trapped in the turbulent D_2O and carried into the moderator. The chance of entrainment, however,

increases as the D_2O level is lowered, and with the level five feet below normal, which is about at the elevation of the top of the cylindrical baffle, entrainment was probable.

Gas Evolution

The evolution of helium gas from solution in the core region was a possibility because under certain combinations of reactor operating conditions the saturated concentration of helium in the D_2O was less in the core region than in the neck region of the vessel. With maximum D_2O circulation, the moderator at the elevation of the exit nozzles is at a pressure 27 psi lower than the pressure at the D_2O surface because of the pressure loss across the fuel elements. If the D_2O in the neck section of the reactor is very nearly saturated with dissolved helium, then the pressure gradient can cause helium to evolve from solution and form voids in the moderator. The degree of saturation in the neck region required to produce voids is defined by:

$$\frac{C}{C^*} = \frac{(P_g)_2}{(P_g)_1}$$

where $(P_g)_1$ and $(P_g)_2$ are the helium pressures in the neck section and the moderator space, respectively, and C/C^* is the fraction of saturation. For example, at a helium pressure of 1000 psig and at constant temperature,

$$\frac{C}{C^*} = \frac{1000 - 27}{1000} = 0.973$$

Temperature differences between the two regions can also contribute to helium evolution under certain conditions. The data available for ordinary water indicate that the solubility of helium increases with temperature above 50°C (references 4, 5, 6, and 7). At a constant partial pressure of helium, the solubility of helium increases with temperature. At a constant total pressure, however, the solubility of helium first increases with temperature, reaches a peak, and then decreases until the solubility reaches zero at the boiling temperature of the water. Solubility curves for helium at constant total pressure are shown in Figure 9, and a plot of the constant in Henry's Law is shown in Figure 10.[8]

The data of Figure 9 show that if the D_2O is saturated with dissolved helium at the temperature of maximum solubility, an additional temperature increase will cause helium to evolve from solution. This condition is possible in the HWCTR because the power that is generated in the fuel heats the D_2O as it passes through the fuel channels and into the moderator space. The temperature rise across the fuel, the

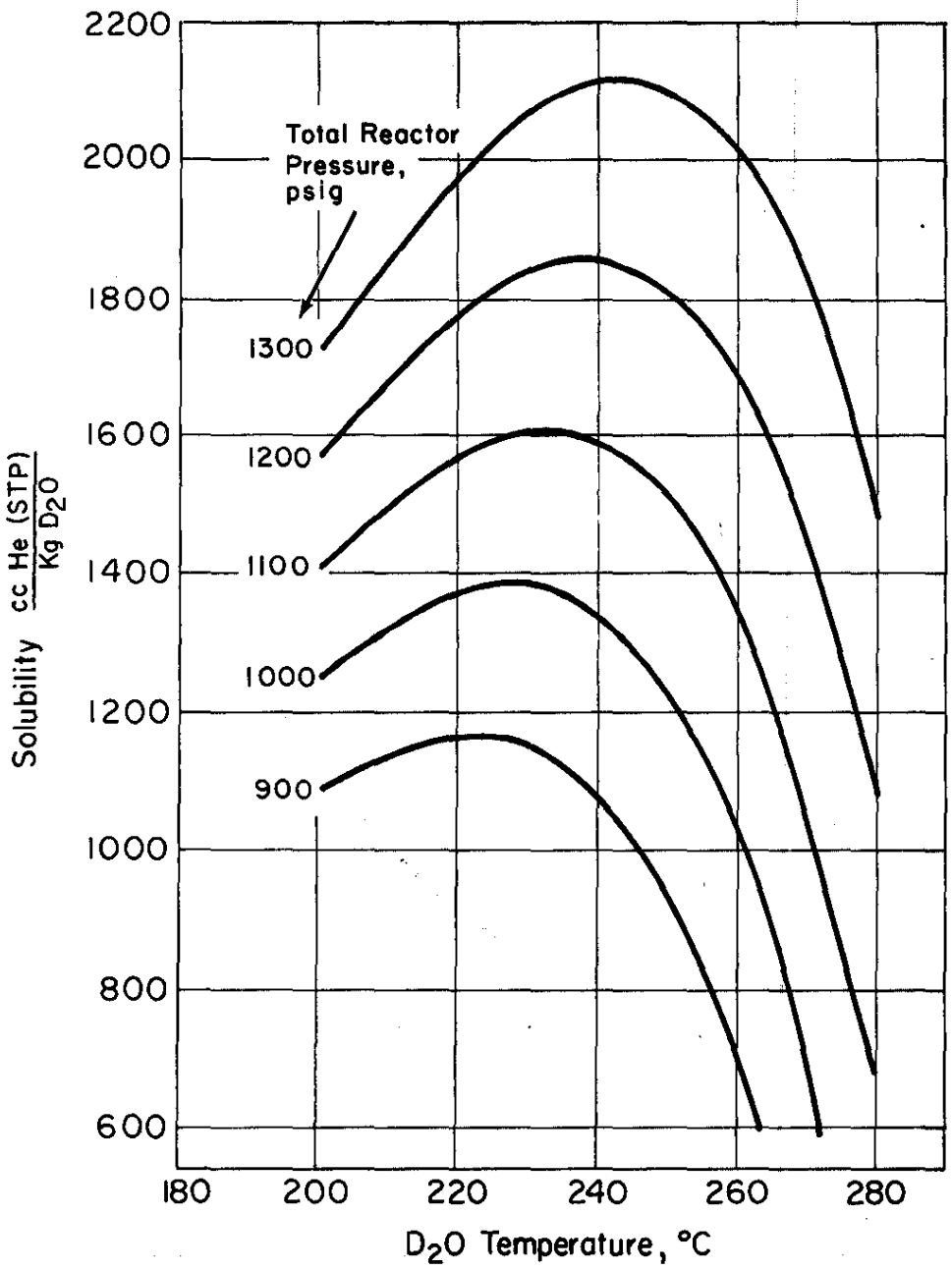


FIG. 9 SATURATED SOLUBILITY OF HELIUM IN D_2O

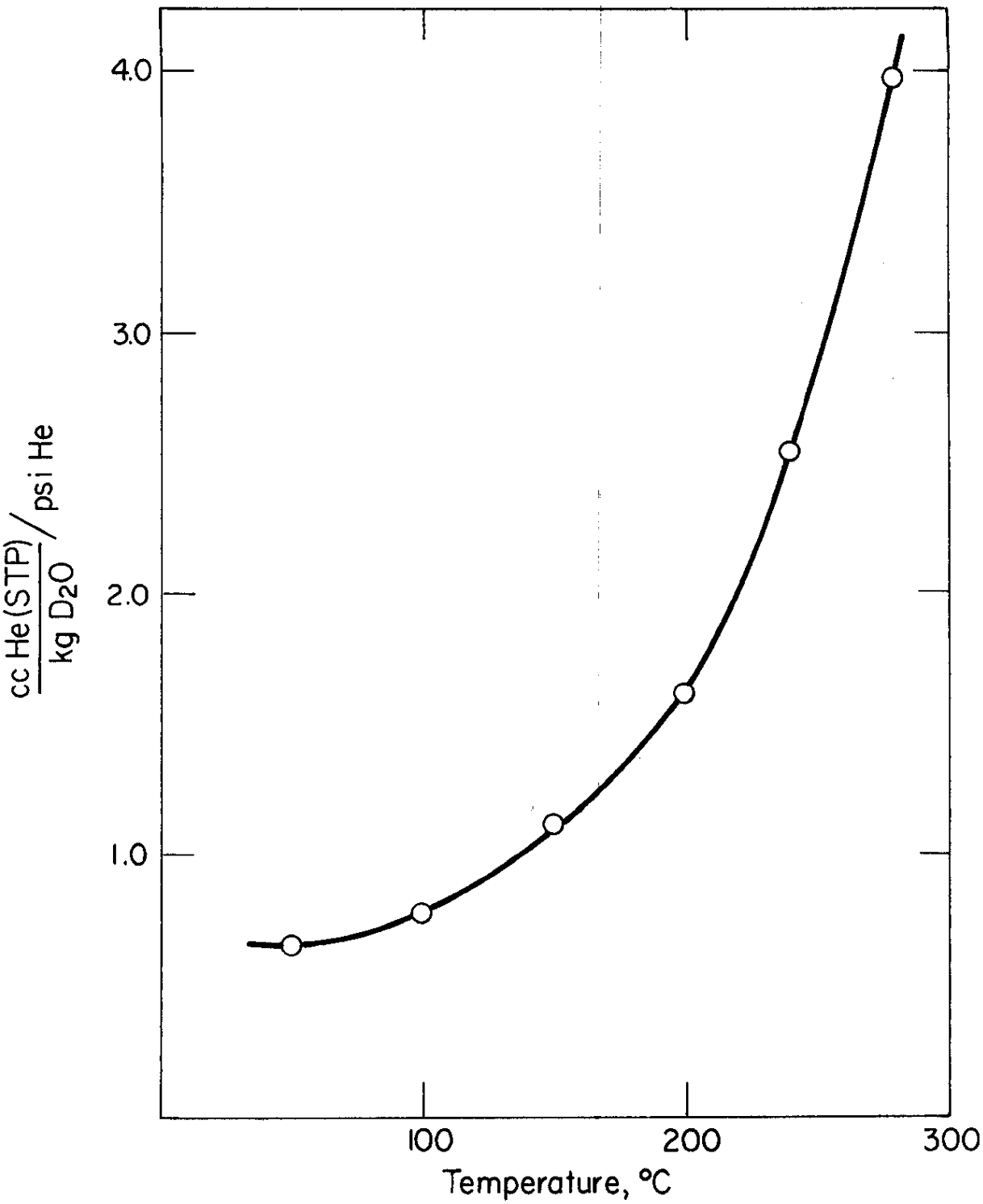


FIG. 10 SOLUBILITY OF HELIUM IN D_2O
(Data of BMI - 1587)

inlet D_2O temperature, and the concentration of helium dissolved in the inlet D_2O determine whether or not helium will evolve from solution. The peaks in helium solubility are at conditions nearly coincident with the D_2O inlet condition expected in the HWCTR, e.g., 215°C at 1000 psig, or about 235°C at 1300 psig. As seen from Figure 9, if the inlet temperature is constant an increase in pressure permits a larger temperature rise to be taken before voids occur.

The relations that control the concentration of helium in the D_2O are expressed quantitatively in the following equations:

$$\text{Solution rate at interface} = kA\,(C^* - C)$$

$$\text{Removal rate through purge} = PC$$

$$\text{Fractional saturation at steady state} = \frac{C}{C^*} = \frac{kA}{kA + P}$$

where

C^* = dissolved helium concentration at saturation, lb-moles/ft^3

C = actual dissolved helium concentration, lb-moles/ft^3

k = mass transfer coefficient for dissolving helium, lb-moles/(hr)(ft^2)(lb-moles/ft^3)

A = area of gas - D_2O contact, ft^2

P = liquid purge rate, ft^3/hr

The helium balance, and a plot of C/C^* vs kA, are shown in Figure 11.

Neither the contact area nor the mass transfer coefficient for the HWCTR system could be calculated or estimated with any accuracy.

On the basis of data[9,10] on the hydrogen-water system, the kA product for the HWCTR system at 240°C was estimated to be about 200 lb-moles/(hr)(lb-moles/ft^3). During the low power physics tests the purge rate was about 2 gpm, or 16 ft^3/hr, and the expected fractional saturation was about 200/(200 + 16) = 0.93. During operation at power with a purge rate of 10 gpm, or 80 ft^3/hr, the fractional saturation would be 200/(200 + 80) = 0.715. With all of the uncertainties involved, the estimates of mass transfer rate and fractional saturation served only to point out that gas evolution was definitely a possible void mechanism, and that additional analyses based on experimentally determined mass transfer rates were necessary.

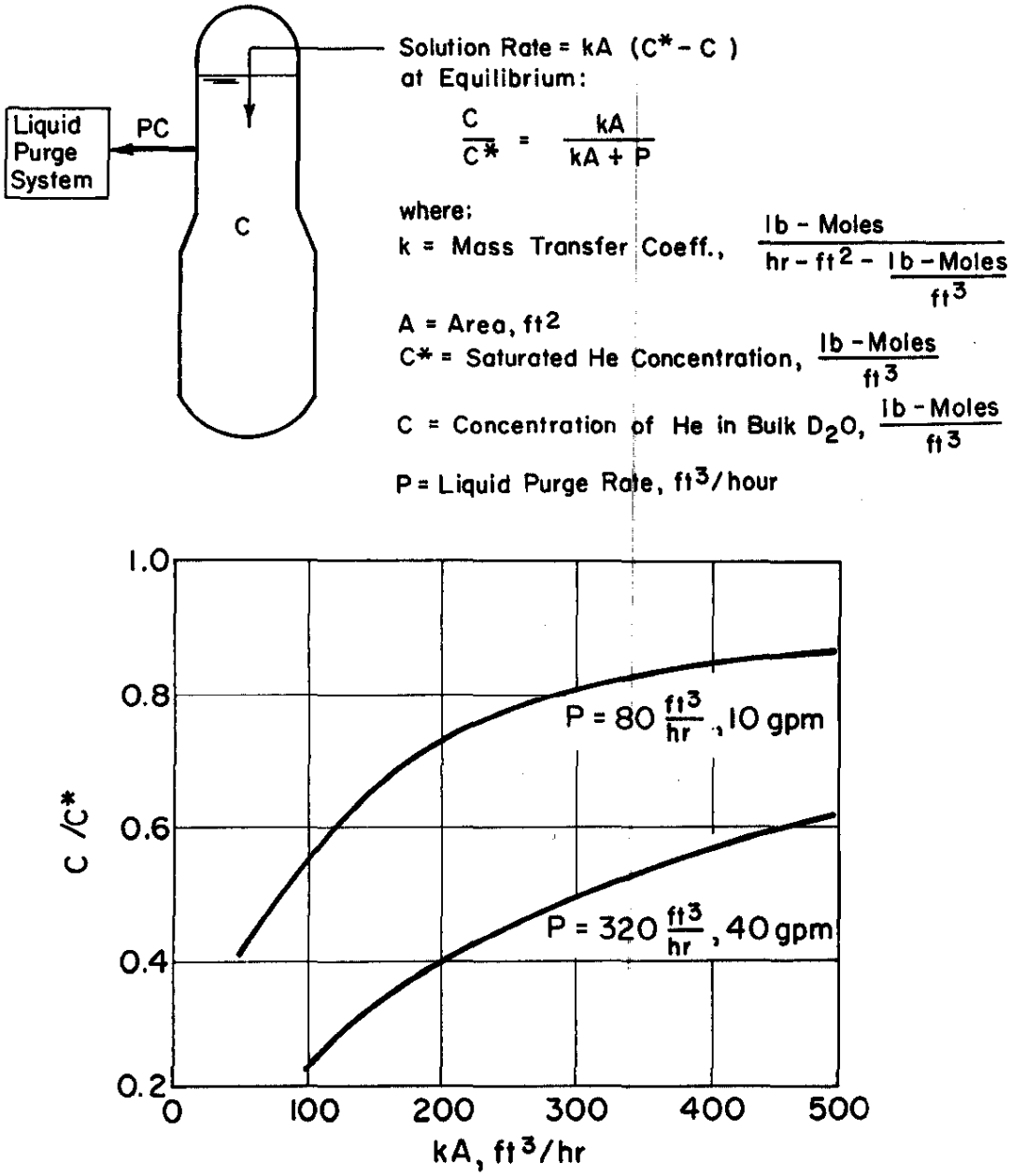


FIG. 11 HELIUM BALANCE IN REACTOR SYSTEM

MODIFICATIONS TO ELIMINATE VOID FORMATION

Aspiration

The elimination of the aspiration through the safety and control rods appeared to be a matter of modifying the rod and guide tubes to eliminate the excessive resistance to flow of D_2O through the assemblies. A simple mockup of the rod and guide tube arrangement was made in a test facility where flows and levels could be measured and various modifications could be tested.

The initial tests confirmed that gas did aspirate through the rod assemblies at reactor operating conditions. Subsequent tests demonstrated that the proposed modifications would eliminate the aspiration. The modifications consisted of cutting extra entrance slots in the upper guide tube and entrance holes in the rods. These changes eliminated the excessive resistance to coolant flow regardless of the rod position. Tests of the final-design rod assemblies in the reactor showed that there was no aspiration under the following operating conditions:

D_2O Level	normal to -36 inches
D_2O Temperature	30 to 220°C
D_2O Flow	3400 and 10,000 gpm
Rod Positions	All positions

Entrainment

Tests in the reactor showed that entrainment of gas in the D_2O occurred only when the D_2O level was lower than 42 inches below normal. This margin is more than ample for normal operation. Operating procedures were written to require normal D_2O level during reactor operation; safety circuits were installed to annunciate when the level dropped six inches below normal, and to shut down the reactor whenever the pressure dropped 10%.

Gas Evolution

Two changes to the system piping were made to prevent introduction of helium directly into the liquid D_2O. The return line from the process gas recompressor was connected to a nozzle above the normal water level, rather than to a nozzle on a 10" D_2O inlet line as originally intended. An extra line and a control valve were added to the main seal system to return the excess D_2O from the seal pump to a main

pump suction line rather than allowing the excess D_2O to overflow from the seal head tank. The overflow line from the seal head tank enters the reactor above the normal D_2O level.

The gas solution rate was determined in HWCTR tests at conditions of temperature and pressure expected during operation. The general test procedure was to heat the D_2O with pump energy to an equilibrium condition at about 240°C and 650 psig with a purge rate of about 2.5 gpm. The seal pump was operated intermittently to maintain the D_2O level in the seal head tank below the overflow. The gas space pressure was then rapidly increased to about 1100 psig. This change increased the helium partial pressure from about 175 to about 625 psig, and forced more helium into solution. The rate of increase of dissolved helium concentration was measured, by analysis of high pressure D_2O samples, to determine the effective kA product for mass transfer of helium into solution.

The high pressure D_2O samples were taken by connecting the two ends of a sample bomb to sample lines from the inlet and outlet pipes of one of the main system steam generators. The pressure loss across the tubes of the steam generator caused D_2O to flow through the sample bomb at the rate of about 0.3 gpm until the bomb was valved off and removed. The D_2O samples were analyzed for dissolved gas content by standard laboratory techniques.

The concentration data obtained in the tests were plotted and compared with theoretical curves of concentration increase. The theoretical curves were generated from the equation

$$\frac{\frac{C}{C^*} - \frac{kA}{kA+P}}{\frac{Co}{C^*} - \frac{kA}{kA+P}} = e^{-\left(\frac{kA+P}{V}\right)t}$$

where:

$\frac{Co}{C^*}$ = initial fraction of saturation

$\frac{C}{C^*}$ = fraction of saturation after time t

t = time after steady state conditions were interrupted, hours

V = volume of D_2O in system, 790 ft^3

kA = mass transfer coefficient X area, $\frac{\text{lb - moles}}{\text{hr}\left(\frac{\text{lb - moles}}{ft^3}\right)}$

P = purge rate, ft^3/hr

This equation was derived by integrating the differential form of the steady state gas balance equation,

$$\frac{C}{C^*} = \frac{kA}{kA + P}$$

The results of the first test showed that the kA product was higher than the estimated value of 200 lb-moles/(hr)(lb-moles/ft^3). As shown in Figure 12, the kA product was initially about 800 - 1100 but leveled off at 380 after the first two hours. The high initial value is believed to result from a disturbance of the gas space when fresh helium was introduced to increase the pressure and start the concentration increase. The kA product for the system was higher than desired.

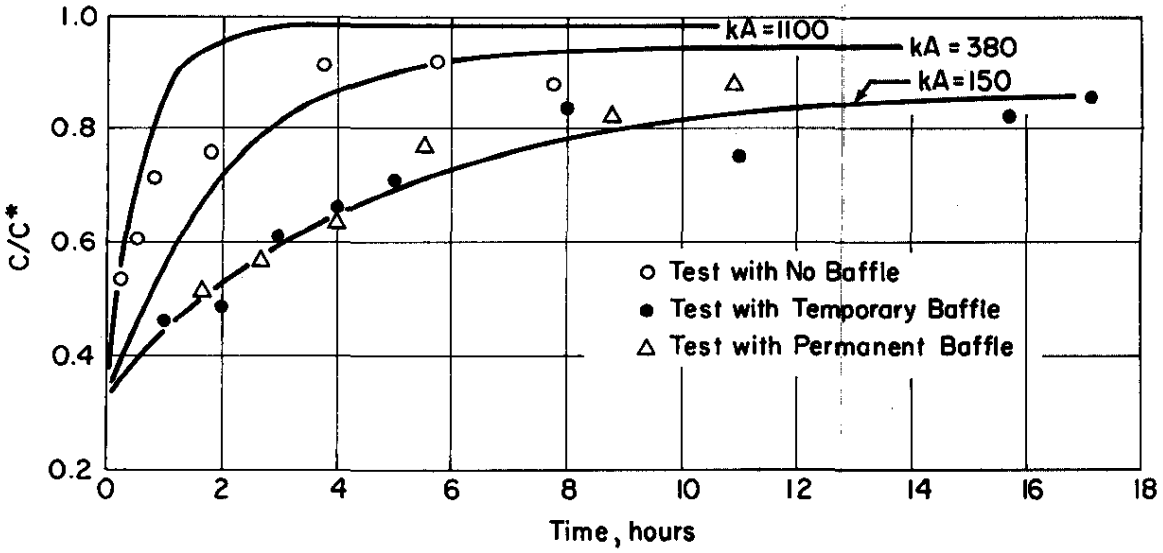


FIG. 12 THEORETICAL AND MEASURED INCREASE IN HELIUM CONCENTRATION
AC Flow, D_2O Temperature 240°C, Liquid Purge Flow 2.5 gpm

A stilling baffle was designed to fit in the reactor about 30 inches below the normal D_2O level. Such a baffle would reduce the flow between the D_2O in contact with the gas and the large bulk of D_2O below the baffle. The baffle was designed to fit around all of the guide tubes with a minimum of clearance, or free area, and required extensive machining and field fitting. To save time and to obtain a preliminary result, a simple prototype baffle was made to be used with no guide tubes installed. Holes were placed in the temporary baffle to simulate the free area expected with the permanent baffle.

The kA product determined with the temporary baffle installed and maximum D_2O flow was about 150, compared to 385 without the baffle (see Figure 12). The significant reduction in the kA product indicated that the baffle would lower the gas concentration in the circulating D_2O and thus eliminate the gas evolution. The permanent baffle was fabricated and installed.

Two solution rate tests were also performed with DC flow, which is about 1700 gpm or one-third the maximum flow rate. The kA product was about 100 with no baffle, and approximately the same with the temporary baffle installed (see Figure 13). The turbulence in the D_2O was considerably less with DC flow; therefore, these results indicated that the lower limit of the kA product that could be achieved by calming the D_2O turbulence is probably about 100 lb-moles/(hr)(lb-mole/ft^3). The test results obtained with DC flow conditions were difficult to analyze because the lower pump energy input caused the D_2O temperature to decrease throughout the test; thus the purge rate, the saturated solubility, and the mass transfer coefficient (affected by temperature and viscosity) were not constant.

After the permanent stilling baffle was installed, another solution rate test was conducted. The kA product was about 150, essentially the same as with the temporary baffle, as shown in Figure 12.

Each of the solution rate tests was concluded by reducing the pressure in the reactor until helium was evolved in the moderator, as evidenced by an abrupt increase in the indicated D_2O level. The dissolved helium concentration was calculated from the pressure at which voids occurred. This calculated value agreed well with the concentration determined by sample analysis.

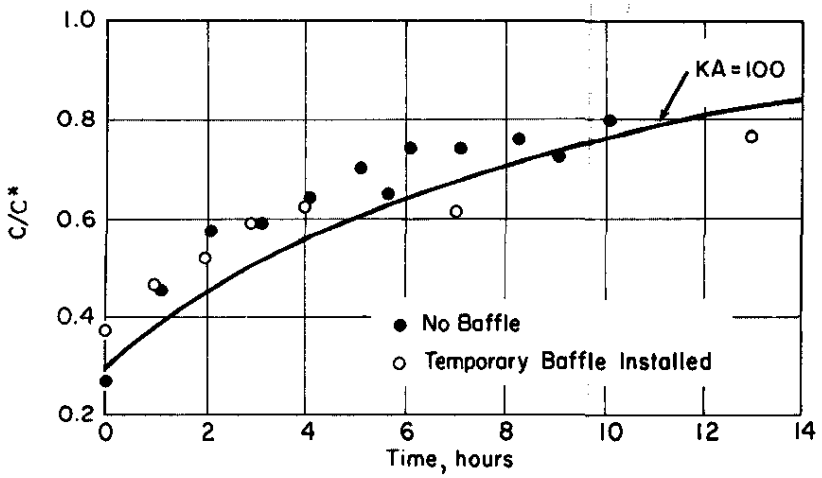


FIG. 13 HELIUM CONCENTRATION DURING DC FLOW
D_2O Temperature; Initial 240°C, Final 200°C
Liquid Purge Flow, 1 gpm

Control of the Dissolved Gas Concentration

The measured value of kA product of 150 is equivalent to a fractional saturation of 65% when the purge rate is normal at 10 gpm. This is sufficiently low to eliminate the void formation from supersaturation in the moderator space. Appropriate Technical Standards and Operating Procedures were prepared and the necessary gas measuring instruments were installed to provide adequate operating margins on gas concentration during nuclear operation.

An integral orifice consisting of a combined orifice and transmitter was installed to measure the flow rate of gas evolved from the liquid purge stream. This purge stream from the reactor is cooled and depressurized and then flows into the holdup tank. Essentially all of the gas, dissolved at the higher temperature and pressure conditions of the reactor, is evolved. The evolved gas flows through the orifice and into the storage tank. The ratio of evolved gas flow to the liquid purge flow is proportional to the dissolved gas concentration, as follows:

$$\frac{\text{cc He at STP}}{\text{kg } D_2O} = \frac{\text{evolved gas flow, SCFM}}{\text{liquid purge flow, gpm}} \times 6800$$

The evolved gas flow and purge flow are both recorded in the Control Room.

A Technical Standard on dissolved gas concentration was prepared to prevent gas voids during normal operation of the reactor, and to provide enough margin so that transients of temperature or pressure cannot produce voids without also causing a fast nuclear shutdown. The Standard places an upper and lower limit on the temperature of the circulating D_2O as a function of the dissolved gas concentration and the pressure in the gas space of the reactor. The temperature limits are shown in Figure 14. The Standard applies to all phases of nuclear operation, including startups.

The Standard treats the possibility of void appearance in a transient conservatively by placing adequate margins in the normal operating limits. The two transients that can produce voids under normal operating conditions are (1) a temperature increase or (2) a pressure decrease. The pressure decrease is considered to be the more likely. The margins provided in the Technical Standard are sufficient so that a temperature or pressure transient that can produce voids must also produce a reactor scram. Additional voids will be produced by the scram, but conditions cannot be restored to collapse the voids.

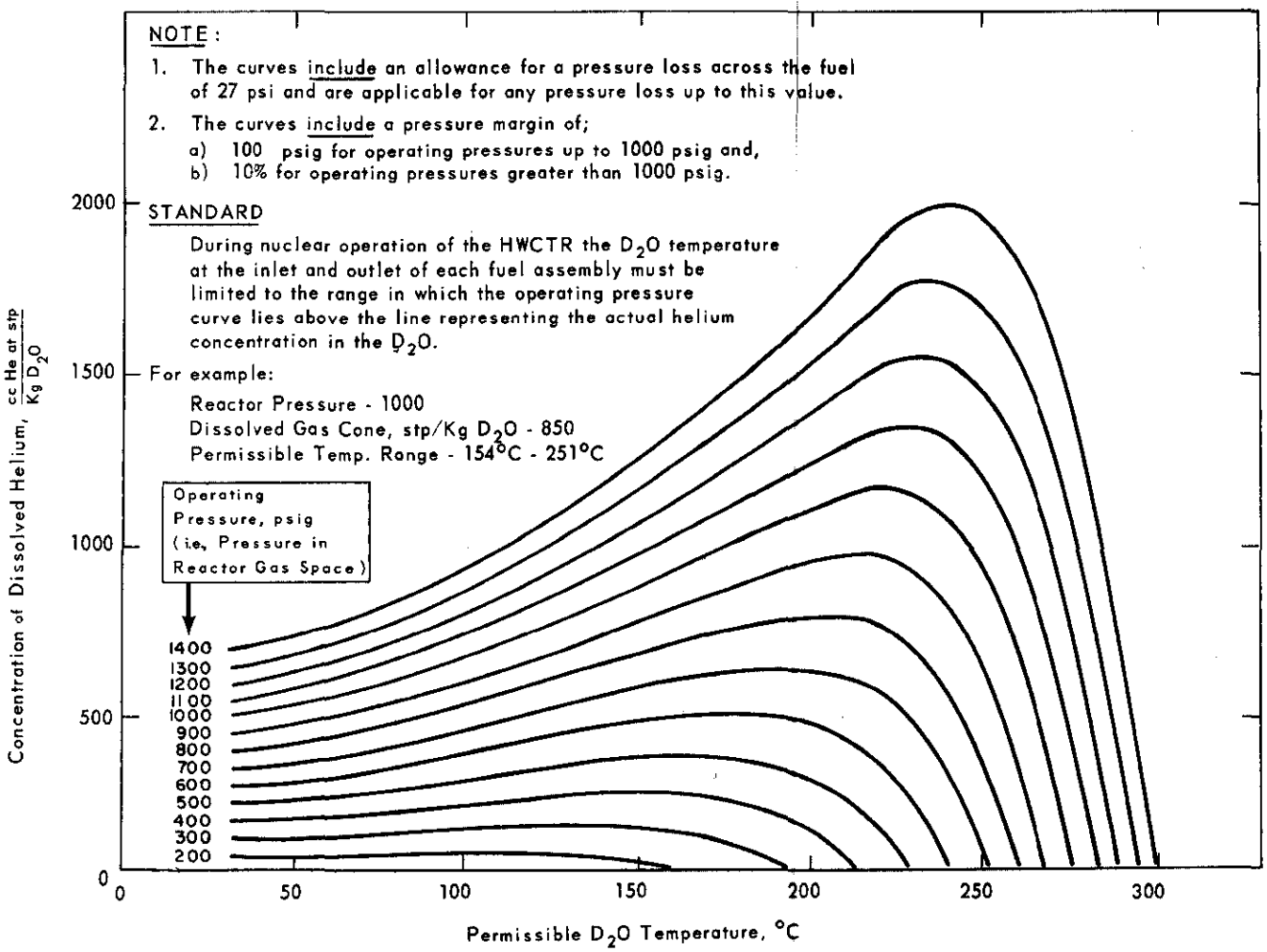


FIG. 14 PERMISSIBLE RANGE OF D_2O TEMPERATURE AS A FUNCTION OF OPERATING PRESSURE AND DISSOLVED HELIUM CONCENTRATION

The margin provided by the limits in the Standard for normal operation is based on a 10% pressure decrease; i.e., the pressure can decrease 10% before voids will appear. The scram setting for a pressure decrease will be maintained at 10%. The temperature margin associated with the 10% pressure margin varies from 8° to more than 23°C. All the following safety circuits prevent a general temperature increase of more than 8°C: (1) neutron flux up 10%, (2) reactor period 15 sec, (3) loss of reactor pump power, (4) reactor flow down 8%, (5) fuel element ΔT up 25%, and (6) reactor effluent temperature up 5°C (rod reversal).

The temperature limit curves in Figure 14 were calculated from the equation

$$C = (P_T - P_R - P_{D_2O} - 27)\ K$$

where:

C = dissolved gas concentration, cc/kg

P_T = total pressure in gas space, psia

P_R = pressure reduction that will cause voids to occur, psi

P_{D_2O} = vapor pressure of D_2O, psia

K = Henry's Law constant

This equation has a unique solution for each particular D_2O temperature and total pressure (i.e., P_{D_2O} and K both vary with temperature). To generate the curves in Figure 14, a value of P_R was chosen, a temperature and total pressure were assumed, and the equation was solved for C. For total pressures up to 1000 psig the value of P_R was taken as 100 psi, and for total pressures of more than 1000 psig the value of P_R was taken as 10% of the total pressure. The value of 27 in the equation is the pressure loss across the fuel with maximum flow.

Reactivity Effects of Gas Voids

The maximum amount of reactivity known to have ever been held in gas voids was the 0.00824 $\Delta k/k$ observed during the early critical experiment when the existence of gas voids was first detected. Under these conditions, all three mechanisms for introducing voids into the moderator are believed to have been operative. From this point on during the investigation of the problem, the mode of hydraulic operation

was never altered in such a direction to collapse existing voids while the reactor was critical. Reactivity differences associated with voids were measured by establishing the hydraulic condition, withdrawing rods to the critical configuration, inserting rods to the full-in position, and repeating the operation for the new hydraulic conditions.

Following the modifications to eliminate aspiration and entrainment but before the installation of the stilling baffle, the reactivity difference between conditions of full flow of 10,000 gpm and no flow was measured at a moderator temperature of 240°C and a reactor pressure of 1000 psig. The difference between control rod positions at critical for these two conditions corresponded to a reactivity of 0.0014 $\Delta k/k$. The product of the estimated void fraction under these conditions and the calculated reactivity effect of voids[1] is 0.36% x 0.0038 $\frac{\Delta k/k}{\% \text{ void}}$ = 0.0014 $\Delta k/k$, in excellent agreement with observation.

The estimated void fraction at the above conditions is estimated in the following manner. The saturated concentration of helium in the D_2O at 240°C and a total pressure of 1000 psig is 1338 cc (STP)/kg D_2O from Figure 9. The partial pressure of the helium is 520 psi and the pressure drop across the core at full flow is 27 psi. Thus, the saturated concentration in the core or moderator is

$$1338 \times \frac{520-27}{520} = 1268 \text{ cc (STP)/kg } D_2O.$$

Therefore, 70 cc He (STP)/kg D_2O is evolved as gas in the core. At 240°C and a helium pressure of 493 psi, the volume of helium is

$$70 \times \frac{15}{493} \times \frac{513}{273} = 4.0 \text{ cc He/kg } D_2O.$$

Because the density of D_2O at 240°C is 0.9 g/cc, the void fraction is 0.36%.

BIBLIOGRAPHY

1. L. M. Arnett, et al. Final Hazards Evaluation of the Heavy Water Components Test Reactor. USAEC Report DP-600, E. I. du Pont de Nemours & Co., Savannah River Laboratory, Aiken, S. C. (1961).

2. T. C. Gorrell. The Initial Critical and Zero Power Testing of the HWCTR. USAEC Report DP-967, E. I. du Pont de Nemours & Co., Savannah River Laboratory, Aiken, S. C. (1965).

3. E. O. Kiger. Operational Summary of the HWCTR 1962-1964. USAEC Report DP-991, E. I. du Pont de Nemours & Co., Savannah River Laboratory, Aiken, S. C. (1965).

4. Handbook of Chemistry and Physics, 44th Ed., 1708. Chemical Rubber Publishing Co., Cleveland, Ohio.

5. H. A. Pray, et al. "Solubility of Hydrogen, Oxygen, Nitrogen, and Helium in Water." Ind. & Eng. Chem. 44, 1146 (1952) and USAEC Report BMI-T-25, Battelle Memorial Institute, Columbus, Ohio (1950).

6. E. F. Stephan, et al. Solubility of Gases in Water and in Aqueous Uranyl Salt Solutions at Elevated Temperatures and Pressures. USAEC Report BMI-1067, Battelle Memorial Institute, Columbus, Ohio (1956).

7. D. M. Himmelblow. "Solubilities of Inert Gases in Water." Jour. Chem. and Eng. Data 5, 10 (1960).

8. E. F. Stephan, et al. Helium Solubility in D_2O at Elevated Temperatures and Pressures. USAEC Report BMI-1587, Battelle Memorial Institute, Columbus, Ohio (1962).

9. T. K. Sherwood and R. L. Pigford. Absorption and Extraction, 2nd Ed. McGraw Hill Book Co., Inc., New York (1952).

10. W. H. Linton, Jr. and T. K. Sherwood. "Mass Transfer from Solid Shapes to Water in Streamline and Turbulent Flow." Chem. Eng. Prog. 46, 258 (1950).