

A major purpose of the Technical Information Center is to provide the broadest dissemination possible of information contained in DOE's Research and Development Reports to business, industry, the academic community, and federal, state and local governments.

Although a small portion of this report is not reproducible, it is being made available to expedite the availability of information on the research discussed herein.

1

LA-UR-89-1666

LA-UR--89-1666

CONF. 890815--7

DE89 013452

Los Alamos National Laboratory is operated by the University of California for the United States Department of Energy under contract W-7405-ENG-36

TITLE: AN ASSESSMENT OF HELIUM GAS BEHAVIOR IN SP-100 CLASS REACTORS

AUTHOR(S): John M. McGhee and Professor Mohamed S. El-Genk
Institute for Space Nuclear Power Studies
University of New Mexico, Albuquerque, NM 87131

Richard B. Rothrock
Los Alamos National Laboratory, Group N-12

SUBMITTED TO: Space Nuclear Reactor Systems Topical Session
24th Intersociety Energy Conversion Engineering Conference
6-11 August 1989, Washington, DC

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

By acceptance of this article, the publisher recognizes that the U.S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or to allow others to do so, for U.S. Government purposes.

The Los Alamos National Laboratory requests that the publisher identify this article as work performed under the auspices of the U.S. Department of Energy.

MASTER

Los Alamos Los Alamos National Laboratory
Los Alamos, New Mexico 87545

AN ASSESSMENT OF HELIUM GAS BEHAVIOR IN SP-100 CLASS REACTORS

J. McGhee¹ and M. El-Genk
 Institute for Space Nuclear Power Studies
 Department of Chemical and Nuclear Engineering
 University of New Mexico
 Albuquerque, New Mexico 87131

R. Rothrock²
 Reactor Design and Analysis Group (N-12)
 Los Alamos National Laboratory
 Los Alamos, New Mexico 87545

¹Currently at Los Alamos National Laboratory

²Currently at Oak Ridge National Laboratory

ABSTRACT

A theoretical investigation into the behavior of helium gas in the primary heat transport system (PHTS) of the SP-100 space nuclear power system was performed. Results indicate that helium gas dissolved in the primary coolant will most likely diffuse out of solution directly into existing bubbles in the system accumulators/gas separators before reaching a concentration sufficient to drive a nucleation process elsewhere in the loop. Differences in individual loop flow rates of only a few percent were demonstrated to have a significant impact on the relative gas diffusion rates in the loop accumulators. Small bubbles (<15 μm radius) which may escape the gas separators will not expand from temperature and pressure changes as they circulate in the PHTS. Bubbles smaller than $\approx 40 \mu\text{m}$ in radius will eventually collapse by mass diffusion.

NOMENCLATURE

<p>A_s - mass transfer surface area (m^2)</p> <p>\dot{W}_A - mass transfer rate (kg of He/sec)</p> <p>Nu_{AB} - dimensionless mass transfer Nusselt number (also known as the Sherwood Number)</p> <p>C_0 - analytic He concentration in bulk Li (kg/m^3)</p> <p>C_s - saturation concentration of He in bulk Li (kg/m^3)</p> <p>C_s^* - saturation concentration of He in Li at low flow accumulator (kg/m^3)</p> <p>ΔC_0 - $C_0 - C_s$ - supersaturation (kg/m^3)</p> <p>ΔC_0^* - $C_0 - C_s^*$ - supersaturation at low flow accumulator (kg/m^3)</p> <p>$\Delta C_0/C_s$ - relative supersaturation (dimensionless)</p> <p>D_{AB} - diffusion coefficient of He in Li (m^2/sec)</p> <p>D_h - channel hydraulic diameter (m)</p> <p>D_i - annulus inner diameter (m)</p>	<p>D_o - annulus outer diameter (m)</p> <p>K - Henry's Law Constant (m^3/s^2)</p> <p>L - length of annulus (m)</p> <p>n - amount of inert gas (moles)</p> <p>Pr - Prandtl Number (dimensionless)</p> <p>P_L - liquid pressure at operating conditions (Pa)</p> <p>P_v - liquid vapor pressure at temperature T (Pa)</p> <p>P_g - inert gas partial pressure inside bubble (Pa)</p> <p>R - Universal Gas Constant = 8.3144 (J/mole-K)</p> <p>r - bubble radius (m)</p> <p>r_c - vapor bubble radius at incipient nucleation (m)</p> <p>r_{eq} - bubble radius at mass and mechanical equilibrium (m)</p> <p>r' - radius of liquid meniscus in the equivalent cavity at surface pre-conditioning temperature and pressure (m)</p> <p>Re - Reynolds Number = $\rho D_h V / \mu$ (dimensionless)</p> <p>Sc - Schmidt Number = $\mu / \rho D_{AB}$ (dimensionless)</p> <p>T - liquid temperature (K)</p> <p>V - liquid velocity in the channel (m/s)</p> <p>V_b - gas bubble volume (m^3)</p> <p>\dot{W}_A - mass transfer rate (kg/s)</p> <p>α - r_c / r' (dimensionless)</p> <p>ζ - ratio of gas removal rate at low flow accumulator to gas removal rate at full flow accumulator = $(C_0^* / \Delta C_0)$ (dimensionless)</p> <p>μ - Li dynamic viscosity ($\text{kg}/\text{m}\cdot\text{s}$)</p> <p>$\rho$ - Li density (kg/m^3)</p> <p>σ - Li surface tension (N/m)</p> <p>ψ - a measure of inert gas concentration in the nucleation cavity, a function of cavity geometry, contact angle, and moles of gas in the cavity (m-N/K)</p>
---	---

1. INTRODUCTION

The SP-100 space nuclear power system, currently in the engineering design and development phase, employs a 2.5-MWt, uranium nitride fueled, fast spectrum reactor [1]. Heat is transported from the reactor core to a series

of thermoelectric power conversion assemblies by a multi-loop, liquid lithium primary heat transport system (PHTS) (Figure 1). Because of its high specific heat, high heat transfer coefficient, and low pumping power requirements, lithium is an extremely efficient coolant. However, it undergoes reactions with neutrons produced in the reactor core resulting in the generation of isotopes of hydrogen and helium. The hydrogen isotopes are expected to dissolve readily in the coolant at the proposed operating temperature of 1300 K, and then to diffuse rapidly through the niobium primary loop walls. Helium, in contrast, has both a low solubility in lithium and a low diffusion coefficient in almost any metal. Helium is therefore expected to accumulate in the primary coolant during normal system operation. This accumulation could adversely impact the system's operation by degrading TE-EM pump performance, heat transfer in the core, and heat transfer in the power conversion assemblies. As a result of these concerns, the current design of the SP-100 primary coolant loop includes six gas separator/accumulators to remove gases generated in the coolant during normal system operations (see Figure 2). However, these gas separators are designed to meet certain finite reliability and separation efficiency criteria. As a result, a quantity of gas may escape the separators either in solution or in the form of small bubbles. The possibility also exists that gases which appear in the PHTS external to the separators could adversely impact system operations in the time before they are removed from the coolant by normal separator function. Consequently, an analysis of the nucleation and subsequent behavior of gas bubbles in the PHTS is of interest.

The method of analysis consisted of a series of analytic and numerical computations combined with review of previous relevant work. No experimental work was performed. Additional details on both the method of analysis and the results presented below are provided in [2].

2. RESULTS AND DISCUSSION

Results are presented in two sections. The first discusses the removal of helium from the PHTS coolant by nucleation and mass diffusion processes. The second section discusses the behavior of small bubbles which may circulate in the PHTS prior to removal by the loop gas separators.

2.1 Gas Removal in the PHTS

An estimation of the amount of helium gas generated in the primary heat transport system (PHTS) of a SP-100 class reactor has been reported elsewhere [3]. The results of [3] indicate that radiologic gas production rates in the primary coolant of a typical SP-100 class system (coolant ^6Li content 0.1 atom %) are such that the primary coolant can be expected to become saturated with helium within 24 hours after the start of full power operation. Shortly after this time, helium will be removed from solution by a nucleation process forming new gas bubbles, or, the helium may diffuse directly out of solution into pre-existing bubbles such as those in the system accumulators/gas separators.

2.1.1 PHTS Hydraulic Parameters

A simplified computational model of a typical SP-100 system was developed and used to predict pressure, temperature, helium solubility, flow velocity, and other relevant hydraulic parameters throughout the PHTS. Data from this model was used throughout the study. The predicted PHTS helium solubility profile is presented in Fig 3.

2.1.2 Nucleation

Both homogeneous and heterogeneous nucleation were investigated. The primary mechanism for helium bubble nucleation in the PHTS was found to be heterogeneous nucleation at small surface cavities on PHTS wall surfaces. A liquid metal incipient boiling superheat model proposed by Dwyer [4] was adapted to predict the required helium supersaturation for nucleation in the PHTS.

The Dwyer correlation is based on the "equivalent cavity" nucleation model. In this model a force balance is made using the Laplace equation for a unwetted, oxide covered surface inside a small idealized cavity. This balance is used to produce an estimate for the radius of curvature of the liquid surface inside the cavity at preconditioning temperatures and pressures. Another force balance is used to determine the pressure required to form a vapor nucleus at incipient boiling, now assuming that the liquid interface has moved up the walls of the cavity to a well wetted, un-oxidized surface. Dwyer's correlation can be expressed as follows:

$$P_v + \psi T / (r')^2 - P_L - 2\sigma / ar' \quad (1)$$

The value of r' is obtained from the following relationship:

$$(r')^3 - (2.0\sigma' / (P_L' - P_v'))(r')^2 - \psi' T' / (P_L' - P_v') = 0 \quad (2)$$

The primed symbols refer to values taken at the surface pre-conditioning pressure and temperature. The ratio ψ/ψ' can be assumed to lie between 0 and 1 for the present purposes.

The material properties of lithium are available in the literature [5], [6], but ψ and α are not measurable and must be evaluated from experimental data. Excellent agreement with the experimental data of Chen [7] (potassium flowing inside a 0.5" diameter smooth tube, $Re = 5,000$) was obtained for $\psi = 6.1 \times 10^{-16}$ (m-N/K), and $\alpha = 0.72$.

This correlation may be extended to account for nucleation as a result of dissolved gas supersaturation by adding the term KC_0 to represent the ultimate pressure available inside the cavity from any gas dissolved in the liquid:

$$KC_0 + P_v + \psi T / (r')^2 - P_L - 2\sigma / ar' \quad (3)$$

Taking pressure and temperature as normal system operating setpoints, the above equation can be solved for C_0 . Table 1 presents calculated He supersaturations in lithium for various values of ψ , α , P_L' , and T' .

Of note are the effects of flow rate on nucleation in liquid metal systems. It is well known that increased flow rates result in a decrease in the incipient boiling superheat. The reasons for this phenomena are not clear, and they may or may not impact nucleation from dissolved gases. The Dwyer model presented here does not take flow rate into account. Also of concern is

the possibility that local flow conditions, such as pressure changes near an entrance or exit, could provide more favorable nucleation conditions than those used above. These concerns, together with the uncertainty in the values of ψ and α , and uncertainties in the effects of surface preconditioning, all suggest that the predictions of this model be used with caution, as there may be a significant margin of error.

2.1.3 Mass Diffusion

As previously mentioned, a helium gas bubble will be maintained in each of the six loop gas separators to serve a volume accumulator function, allowing room for coolant expansion and contraction as system temperature changes. Since these bubbles will exist from the start of system operation, no initial supersaturation is required to begin nucleation. The He will simply diffuse out of solution and into the bubble when the supersaturation is great enough to drive mass transfer from the Li/He solution to the bubble. The resistance to this diffusion process can be represented as a mass transfer coefficient.

The mass transfer rate at a surface in a flow channel may be expressed as:

$$W_A = Nu_{AB} \Delta C_0 D_{AB} A_s / D_h \quad (4)$$

Nu_{AB} can be estimated from Nusselt number correlations by replacing the heat transfer Prandtl number with the mass transfer Schmidt number in the Nusselt number correlations [8].

For lithium at 1300 K: $\mu = 1.66 \times 10^{-4}$ (kg/m-s), $\rho = 431.5$ (kg/m³), and $D_{AB} = 6.16 \times 10^{-8}$ (m²/s) (D_{AB} estimated from Stokes-Einstein relationship). Using these values, $Sc = 6.245$.

The construction of the PHTS gas separator is such that the helium bubble is contained in the center of the separator with Li flowing in an annulus around the bubble (See Figure 2). He that diffuses into the bubble will cross the inner wall of the Li annulus. Assuming that the helium bubble is maintained in a cylindrical shape by centrifugal forces, and ignoring the effects on lithium flow of the deflectors, filter, and swirl vanes, an estimate can be made for the mass transfer coefficient at the bubble surface. Listed below is a experimentally confirmed heat transfer correlation from the Heat Exchanger Design Handbook [9]:

$$Nu = (.85(D_1/D_0)^{-0.15}) (1.012(Re^{0.87} - 280)Pr^{0.4}) \cdot (1 + (D_h/L)^{0.87}) \quad (5)$$

In the PHTS accumulators at full power (1300 K): $D_1 = 0.11$ (m), $D_0 = 0.22$ (m), $Re = 4.24 \times 10^4$, $Sc = 6.245$, and $L = 0.60$ (m).

Substituting these values into (5) above and replacing the Prandtl number with the Schmidt number results in $Nu_{AB} = 327$.

Neglecting the cylinder end surfaces, the mass transfer surface area $A_s = 0.207$ (m²), and the hydraulic diameter ($D_0 - D_1$) is found to be 0.11 (m). Now substituting into (4) yields:

$$W_A = 327(\Delta C_0)(6.16 \times 10^{-8})(0.207)/0.11 \\ = 3.80 \times 10^{-5}(\Delta C_0) \quad (\text{kg/s}) \quad (6)$$

For an initial coolant Li⁰ content of 0.1 atom %, the total radiologic production of He over a seven year operational life is estimated to be 0.25 moles - 0.001 kg [3]. The production rate per second per accumulator (six accumulators in system) is therefore:

$$P_{He} = (0.001)/((7.0)(3.1567 \times 10^7)(6)) \\ = 7.54 \times 10^{-13} \quad (\text{kg/s}) \quad (7)$$

Now, combining (6) and (7) to set the mass transfer rate in the accumulator to equal the production rate results in an expression for ΔC_0 :

$$3.80 \times 10^{-5}(\Delta C_0) = 7.54 \times 10^{-13} \quad (8)$$

$$\Delta C_0 = 1.99 \times 10^{-8} \quad (\text{kg/m}^3) \quad (9)$$

At beginning of life (BOL) in the accumulator (1300 K, 35 kPa), $C_0 = 9.33 \times 10^{-7}$ kg/m³, therefore: $\Delta C_0/C_0 = 0.021 = 2\%$. At end of life (EOL) (1350 K, 128 kPa), $C_0 = 3.57 \times 10^{-7}$ kg/m³, other parameters remain essentially constant and $\Delta C_0/C_0 = 0.0056 = 0.6\%$.

Thus, at full power, He can be expected to diffuse out of the coolant into the accumulator bubbles with relative supersaturations in the range from 0.6 to 2%. These results should be considered to be somewhat tentative as the geometries of the gas separator and helium gas bubble have been idealized to simplify analysis. In addition, the correlation used for the diffusion coefficient of helium in lithium, an important physical property in the calculation of the mass diffusion rate, has not been confirmed experimentally.

2.1.4 PHTS Supersaturation Profile

Assuming that the mass diffusion process in the loop accumulators will limit the relative helium supersaturation at the accumulator exits to 2% or less as discussed above, the solubility data of Figure 3 can be used to create a supersaturation profile for the PHTS (see Figure 4). Examination of Figure 4 indicates that the maximum supersaturation to be expected in the PHTS is well below that calculated to be necessary for bubble nucleation on PHTS wall surfaces. Consequently, it is concluded that mass diffusion at the gas separators will dominate the gas removal process in the PHTS.

2.1.5 Preferential Diffusion at One Accumulator

The model SP-100 PHTS discussed above is composed of a series of identical, parallel flow loops. The mass flow rate, loop pressure profile, and loop gas solubility profile have all been assumed to be identical for each loop in the preceding analysis. However, in the actual manufacture, assembly and operation of a system such as the SP-100, it is impossible to make each flow loop hydraulically identical. The possibility therefore exists that each loop may have a slightly different mass flow rate and pressure profile, thereby resulting in a different helium solubility profile in each loop.

Solubility profiles were calculated at reduced mass flow rates and then used to estimate the gas removal rate at the low flow accumulator relative to the gas removal rate at one of the other "normal" accumulators. Assuming that Nu_{AB} is

unaffected by a small reduction in mass flow rate (8) can be modified to express the balance between system He production and removal in the case of a loop with a reduced flow:

$$(3.80 \times 10^{-6})(\Delta C_0^* + 5\Delta C_0) = (6)(7.54 \times 10^{-13}) \quad (10)$$

where ΔC_0^* is the helium supersaturation at the low flow accumulator.

Now the ratio of the two removal rates will be:

$$\xi = \Delta C_0^* / \Delta C_0 \quad (11)$$

Taking $C_0 = 9.33 \times 10^{-7}$ as before (BOL, Full Power), ξ can be determined as a function of the mass flow rate reduction. The results of this calculation indicate that an 8% reduction in mass flow rate is sufficient to eliminate gas removal at the low flow accumulator. This implies that separators should be sufficiently oversized to accept extra gas without saturating, as it is uncertain whether or not each separator will accumulate the same amount of gas over the life of the system.

2.2 Bubble Behavior in the PHTS

As discussed in the previous section, it appears most likely that helium will diffuse out of solution directly into the gas accumulator bubbles. However, the possibility of nucleation outside the gas separators cannot be eliminated entirely due to uncertainties in the nucleation models. If for some reason gas bubbles are formed outside the separators, or if helium in the separators manages to escape as a result of a less than 100% separator efficiency or some other unspecified means, the behavior of the gas bubbles released into the PHTS becomes of interest.

The scope of this investigation was limited to normal operations, which include a functional gas separator system. The gas separators are expected to retain all bubbles with radii greater than 15 μm , and the coolant void fraction leaving the separators is expected to be well below 0.10. The effects of temperature, pressure, and mass diffusion on bubbles of this size were investigated.

2.2.1 Temperature and Pressure

Bubbles leaving the gas separators or wall nucleation/growth sites will experience variations in pressure and temperature as they circulate in the PHTS. These variations will cause the bubbles to expand and contract as they flow through the loop. A detailed analysis of this process requires an accounting of inertial and diffusion terms which are significant mainly in cases of rapid transients. Assuming slow transient, steady state, or quasi-steady state conditions, a simplified analysis is appropriate [10]. This analysis, which ignores inertial and mass diffusion effects and assumes the bubbles to be spherical and in thermal equilibrium with the surrounding coolant, is described below.

The Laplace equation ($P_v + P_g + P_L = 2\sigma/r$), the perfect gas law ($P_g = nRT/V_b$), and, the formula for the volume of a sphere ($V_b = 4\pi r^3/3$) can be combined to determine the radius of a gas bubble for any given temperature, pressure and inert gas content:

$$(P_L - P_v)r^3 + 2\sigma r^2 - 3nRT/(4\pi) = 0 \quad (12)$$

Substituting pressures and temperatures from the PHTS computational model into the above equation, the changes in bubble size during a circuit of the PHTS can be calculated. Results of this calculation are presented in Figure 5 for full power. In both BOL and EOL cases, pressure changes dominate temperature effects. Bubbles leaving the gas separator are compressed as they pass through the pump, and gradually return to their original size as they continue through the loop. As a result of higher surface tension forces at small r , bubbles of small initial radius are affected less than those with a larger initial radius.

2.2.2 Mass Diffusion

Mass equilibrium for a spherical bubble occurs when the partial pressure from the inert gas dissolved in the bulk liquid is equal to the partial pressure of the inert gas inside the bubble. This requirement for mass equilibrium can be expressed mathematically as:

$$P_g = KC_0 \quad (13)$$

At mass equilibrium, the bubble must also meet the mechanical equilibrium requirements of Laplace's equation. Combining the requirements for mass and mechanical equilibrium and noting that $P_L = KC_0$ results in an expression for r for no growth conditions:

$$r_{eq} = 2\sigma / (P_L \Delta C_0 / C_0 + P_v) \quad (14)$$

Bubbles created in a liquid which have an initial radius larger than this equilibrium radius will grow, while bubbles with initial radii smaller will ultimately collapse.

The loop supersaturation profiles of Figure 4 can be used with equation (14) to estimate the minimum bubble size stable against collapse by mass diffusion at any point in the SP-100 PHTS. The results of this calculation are presented in Figure 6. At full power, a large portion of the loop is considerably subsaturated, and no bubble of any size is stable. The minimum stable bubble radius calculated for the remainder of the loop is seen to be $\approx 40 \mu\text{m}$. Assuming that the gas separators function as designed and limit bubble size to 15 μm radius or less, it would appear that all bubbles which escape the gas separators will ultimately collapse by mass diffusion.

ACKNOWLEDGMENTS

This work was performed at the University of New Mexico, Institute for Space Nuclear Power Studies, under funding provided by Los Alamos National Laboratory.

REFERENCES

- [1] General Electric Company, "Draft SP-100 Reference Flight System Design Description", DRD SE004, Astro Space Division, Philadelphia, PA, 19 July 88.
- [2] McGhee, J., "Gas Production and Behavior in the Coolant of the SP-100 Space Nuclear Power System", PhD Dissertation, University of New Mexico, Albuquerque, NM, May, 1989.

[3] McGhee, J., M. El-Genk, R. Rothrock, "Coolant Radiologic Gas Production in SP-100 Class Reactors", paper presented at the Sixth Symposium on Space Nuclear Power Systems, Albuquerque, NM, Jan 8-12, 1989.

[4] Dwyer, O.E., "On Incipient Boiling Wall Superheats in Liquid Metals", International Journal of Heat and Mass Transfer, Vol. 12, p 1403, 1969.

[5] Jappson, D.W., et al., Lithium Literature Review: Lithium's Properties and Interactions, HEDL-TME:78-13, Hanford Engineering Development Lab, Richland, Wa., April, 1978.

[6] Slotnick H.S., et al., The Solubility of Helium in Lithium and Potassium, FWAC-380, Pratt and Whitney Aircraft Co., Middletown, Conn., 24 February, 1965.

[7] Chen, J.C., "Incipient Boiling Superheats in Liquid Metals", Transactions of the ASME, Series C, Journal of Heat Transfer, Vol. 90:303, 1968.

[8] Bird, R.B., W.E. Stewart, and E.N. Lightfoot, Transport Phenomena, John Wiley and Sons, New York, 1960, p646.

[9] Schlunder, E.U., et al., Eds., Heat Exchanger Design Handbook, Hemisphere Publishing Corporation, 1983, Section 2.5.1.

[10] Singer, R.M., France, D.M., and Minkowycz, W.J., "A Simplified Model of Inert Gas Dynamics in Liquid Metal Circuits", International Journal of Heat and Mass Transfer, Vol 20, No. 1, pp 87-88, January 1977.

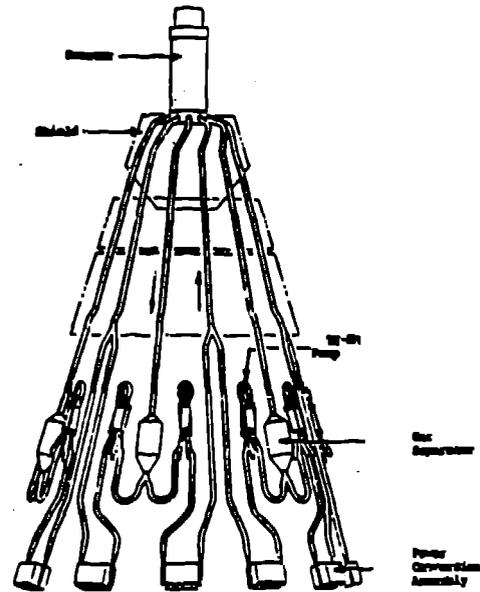


Figure 1 SP-100 PHTS Overview

Case	Relative Super Saturation (β)	ψ (N-m/K)	α	T (K)	P_L (kPa)	T' (K)	P'_L (kPa)
1	107.8	6.1×10^{-10}	0.72	1300	62.0	1300	62.0
2	1.4	"	"	"	"	680	8.0
3	30.8	6.1×10^{-14}	"	"	"	1300	62.0
4	111.0	0.0	"	"	"	"	"
5	74.0	6.1×10^{-16}	1.00	"	"	"	"
6	160.5	"	0.50	"	"	"	"
7	99.9	"	0.72	1350	152.0	1350	152.0
8	138.9	"	"	680	9.5	680	9.5
9	138.7	"	"	680	30.5	680	30.5

Case Descriptions:

Case #1 - Base Case. System assumed to be preconditioned to normal BOL, full power operating parameters. Recommended experimental values of ψ and α .

Case #2 - Surface preconditioned to BOL, standby power, temperature and pressure.

Cases #3 and #4 - Effects of change in ψ .

Cases #5 and #6 - Effects of change in α .

Case #7 - EOL operating parameters.

Case #8 - Standby Power, BOL

Case #9 - Standby Power, EOL

Table 1 Supersaturation for He Nucleation on PHTS Wall Surfaces

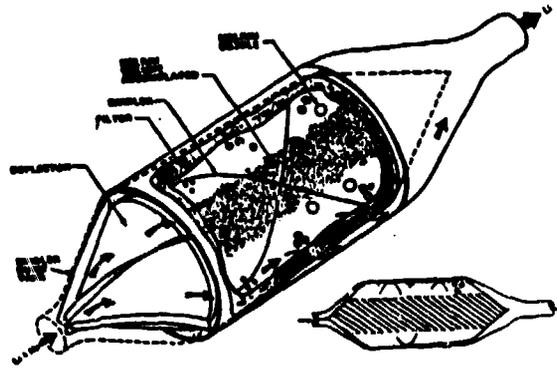


Figure 2 SP-100 Gas Separator/Accumulator

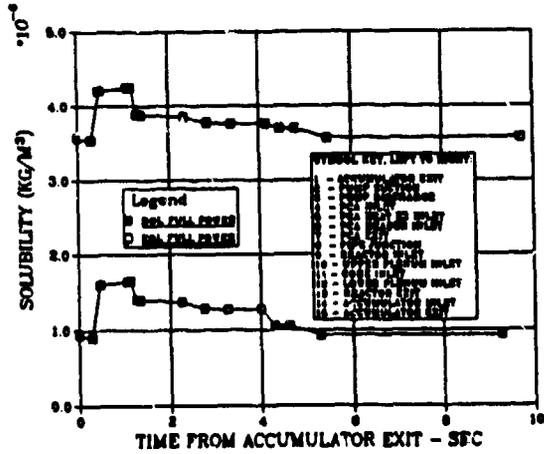


Figure 3 PHTS He Solubility, Full Power

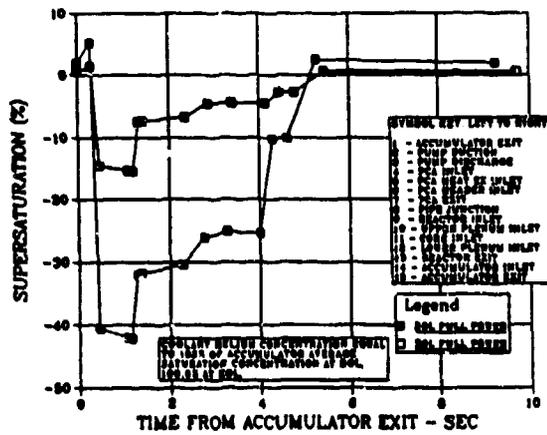


Figure 4 PHTS He Supersaturation, Full Power

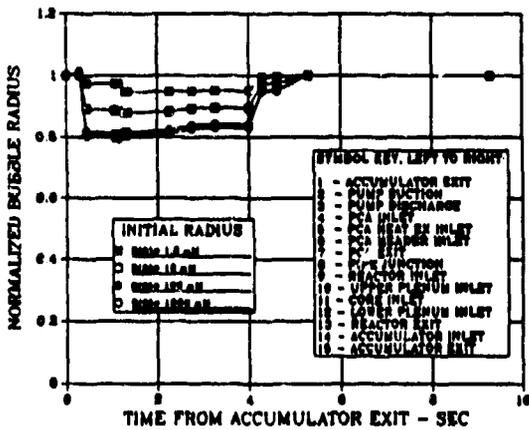


Figure 5 Effects of Pressure and Temperature on Bubble Radius.

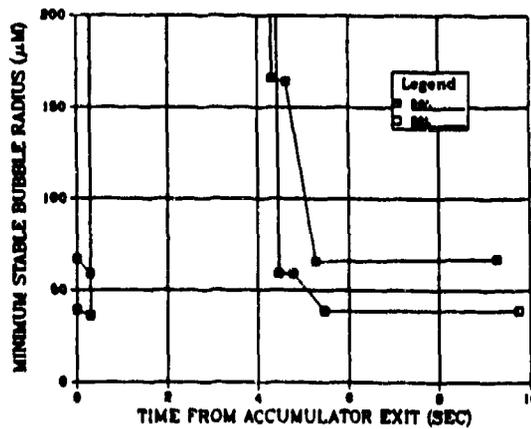


Figure 6 Minimum Bubble Size Stable Against Collapse by Mass Diffusion, Full Power.