UNCLASSIFIED **OAK RIDGE NATIONAL LABORATORY**

Operated By

UNION CARBIDE NUCLEAR COMPANY

POST OFFICE BOX P
OAK RIDGE, TENNESSEE**EXTERNAL DISTRIBUTION
AUTHORIZED****ORNL
CENTRAL FILES NUMBER**

CF-57-2-112

DATE: February 6, 1957

SUBJECT: Inert Atmospheres in Non-Vacuum
Chambers For Welding Applications

TO: G. M. Adamson

FROM: W. J. Leonard

COPY NO. 75

LEGAL NOTICE

This report has been released to the United States Atomic Energy Commission by the United Kingdom Atomic Energy Authority under an Agreement for Cooperation with the understanding that the position of the United Kingdom regarding legal responsibility is identical to that of the United States, which is stated as follows: Neither the United States, nor the Commission, nor any person acting on behalf of the Commission:

A. Makes any warranty or representation, expressed or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights; or

B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method, or process disclosed in this report.

As used in the above, "person acting on behalf of the Commission" includes any employee or contractor of the Commission, or employee of such contractor, to the extent that such employee or contractor of the Commission, or employee of such contractor prepares, disseminates, or provides access to, any information pursuant to his employment or contract with the Commission, or his employment with such contractor.

DISTRIBUTION

1. G. M. Adamson	27. K. A. Kraus	73. J. C. Thompson
2. S. E. Beall	28. J. A. Lane	54. D. S. Toomb
3. L. R. Bledsoe	29. W. J. Leonard	55. W. E. Unger
4. E. G. Bohlmann	30. R. E. Leuze	56. R. Van Winkle
5. F. R. Bruce	31. R. B. Lindauer	57. J. K. White
6. W. D. Burch	32. M. I. Lundin	58. C. E. Winters
7. W. R. Carver	33. R. N. Lyon	59. F. C. Zapp
8. R. D. Cheverton	34. J. P. McBride	60. ORNL Doc. Ref.
9. C. J. Claffey	35. H. F. McDuffie	Library, Y-12
10. E. L. Compere	36. R. A. McNeese	61. Central Research
11. J. S. Culver	37. E. C. Miller	Library
12. W. K. Eister	38. E. O. Nurmi	62-65. REED Library
13. D. E. Ferguson	39. L. F. Parsly	66. ORNL-RC
14. J. H. Frye, Jr.	40. P. Patriarca	67. F. C. Moesel, AEC
15. C. H. Gabbard	41. M. L. Picklesimer	Washington
16. W. R. Gall	42. R. C. Robertson	68-74. Westinghouse
17. J. C. Griess	43. A. M. Rom	PAR Project
18. J. P. Hammond	44. W. L. Ross	75-89. TISE, AEC
19. P. H. Harley	45. H. C. Savage	90-91. Lab. Records
20. P. N. Haubenreich	46. C. H. Secoy	
21. J. W. Hill	47. C. L. Segaser	
22. G. H. Jenks	48. I. Spiewak	
23. S. I. Kaplan	49. R. W. Stoughton	
24. P. R. Kasten	50. J. A. Swartout	
25. A. S. Kitzes	51. E. H. Taylor	
26. R. B. Korsmeyer	52. D. G. Thomas	

NOTICE

This document contains information of a preliminary nature and was prepared primarily for internal use at the Oak Ridge National Laboratory. It is subject to revision or correction and therefore does not represent a final report.

UNCLASSIFIED

133-1

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.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

LEGAL NOTICE

This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission:

- A. Makes any warranty or representation, express or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights; or
- B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method, or process disclosed in this report.

As used in the above, "person acting on behalf of the Commission" includes any employee or contractor of the Commission to the extent that such employee or contractor prepares, handles or distributes, or provides access to, any information pursuant to his employment or contract with the Commission.

**DO NOT
PHOTOSTAT**

INTRODUCTION

In the HRP welding program, a major part of the welding and fabrication, and some of the testing, is performed using an inert atmosphere. The use of the inert gas consumable arc welding process and dry box welding or other work in a dry box comes within this category. Since much of the work in the project makes use of, or requires, inert atmospheres, a general discussion follows of the methods used, description of equipment, processes, quality of atmospheres, purity requirements, kinetics of metal-gas reactions, and practical recommendations which should serve as a guide for shop setups and proper application of the equipment and methods used in obtaining the desired results.

The use of inert-gas in flushing out a space in order to provide an atmosphere relatively free of air is considered the most practical and feasible, other than vacuum methods. In welding various materials, this type of operation is encountered both in "dry box" operations, and pipe or other confining shapes which are capable of maintaining a gas internally.

Two types of dry boxes are used (1) a chamber of permanent shape in which the inert gas is purged through an inlet and expelled through an outlet, both of which are normally closed after completion of the purge. The total volume of air plus inert gas is constant. (2) A compressible chamber which is compressed to the minimum size, expanded to maximum volume with inert gas, then compressed to minimum volume, expelling the mixture of inert gas and air, and again expanded to maximum volume with inert gas. This cycle may be repeated the number of times necessary to lower the air content to the desired level.

Pipe, cylindrical shapes, spheres and other closed containers are special applications of (1) in which the desired atmosphere is obtained by flow of inert gas into the container and exit of the mixture of inert gas in air at the outlet, commonly referred to as purging.

PURGING FIXED VOLUME CHAMBERS

The concentration of air initially at 100% is reduced by purging with inert gas. The air and gas mixture is removed at the outlet by displacement, due to the incoming gas. The outlet and interior of the chamber remain at essentially atmospheric pressure. The incoming gas is at a pressure greater than atmospheric. The ratio of inert gas to air in the chamber is dependent

UNCLASSIFIED

on the amount of mixing of the two gases (air and inert gas). If the mixing is zero, the air will be displaced by the incoming gas, and one volume of gas will completely displace the air. If the mixing is the maximum obtainable, air will constantly mix with the incoming gas. The exit gas will also be a mixture, thus it can be seen that air will always comprise some percentage of the volume of the chamber. The extent of mixing depends on such variables as flow velocity, inert gas density, outlet and inlet location, chamber design and other variables. The least desirable condition for purging is perfect mixing, which is given by the simple rate equation:

$$R = 1 - e^{-Gt/V}$$

Where R is the volumetric ratio of inert gas to total gas in the chamber, G is inert gas flow rate CFH, t is time of flow in hours, V is volume of chamber in cubic feet.

When $Gt = V$, or purging one volume of gas through the chamber,

$$R = 1 - 1/e = .632.$$

It can be seen that the percentage of air is then 36.8% (approximately). For 2 volumes of gas purging

$$R = 1 - 1/e^2 = .858 \quad \text{Air percentage } 14.2\% \text{ (approx).}$$

From the graph in Fig. 1 of the simple rate curve for perfect mixing, the reduction of air after any amount of gas flow is given. The line marked $X = 4$ is that of a three (3) cubic foot chamber. The other plotted line to the left is one taken from actual experimental data¹ reduced to the same volume for comparison. The use of one volume of purge gas resulted in an atmosphere containing 5% air by volume as compared to 36.7% for perfect mixing. This indicates an occurrence of 14% of the potential mixing which could occur under perfect mixing conditions. This datum represented the optimum curve obtained experimentally, as the balance of curves lay between this and the perfect mixing curve, due to different variables used for these experiments. The perfect mixing curve gives the lowest efficiency purge expected in a dry box or pipe length.

* See appendix for mathematical derivation.

1. S. I. Cohen and J. M. Peele, Determination of the Optimum Procedure for Obtaining Inert Atmosphere in Non-Vacuum Dry Boxes (Nov. 26, 1955) ORNL CF-55-10-132.

PURGING VARIABLE VOLUME CHAMBERS

This type of dry box is compressible to some percentage of the total expanded volume. Rubber, plastic, or bellows type boxes are constructed to allow exhaust of the gas mixture by compressing to the minimum volume. The box is expanded to maximum volume to obtain maximum working space. As an example, take a cylindrical box of slightly less than 2 feet in diameter and 4 feet in height fully expanded, and compressible to 1 foot in height. The volume is approximately 12 cubic feet maximum and 3 cubic feet compressed, or an expansion ratio of 4. The ratio of inert gas to air in the box after n expansions from 3 to 12 cubic feet is given by the formula:

$$R = 1 - \frac{1}{X}^* \quad \text{Where } X = \frac{V_{\max.}}{V_{\min.}} = \text{expansion ratio} = 4$$

$$\text{Total gas consumption} = (X - 1) V_{\min} X^n$$

Fig. 1 contains a plot of the percentage air after five expansions at $X = 4$. A similar plot for X equal 2 and 3 is also made. It is apparent from comparing the curves at the higher expansion ratios that less gas and fewer number of operations are required to lower the air content to a desired level. For instance, to lower the air content of the box to 1.5% approximately, requires 3 expansions at $X = 4$, 4 at $X = 3$ and 6 at $X = 2$; gas consumption is 27, 32 and 36 cubic feet, respectively.

Note on the graph the line for straight purging at $X = 4$, which means compressing the box to 3 cubic feet and flowing inert gas through the inlet with the outlet open. Much more efficient reduction of air in the box is possible by purging in the compressed condition, and expanding up to working volume. In this example, flowing 8 cubic feet of inert gas reduces the air content to 7%-- closing the outlet and adding 9 cubic feet to expand the box to the normal volume of 12 cubic feet reduces the air content to approximately 1.5%, thus using a total of 17 cubic feet of inert gas compared to 27 cubic feet with the same dry box using an expanding and expelling technique. The ratios of inert gas to air resulting from combinations of these two methods is given by the expression:

$$R = 1 - \frac{e^{-Gt/V}}{X}^{**}$$

V = Min Volume
 G = Purge gas flow rate (CFH)
 t = Total time that purge gas flowed (hours)
 n = No. of inflations from $V_{\min}$ to $V_{\max}$
 X = expansion ratio

* Mathematical derivation in Appendix II.

** Derived in Appendix III.

G. M. Adamson

-5-

February 6, 1957

For use of this equation on the graph of Fig. 1, select the proper X of the dry box used, and follow the ideal mixing curve to intersection of a perpendicular from the abscissa drawn from a value equal to the total cubic feet of gas used in purging (Gt). This locates a point on the ideal mixing curve. From this point draw a line of the same slope (parallel) to the dry box expansion curve of the same X, until it intersects a perpendicular drawn from the total gas volume used viz. the sum of gas used in purging (Gt) plus the gas used in expanding the dry box $\frac{[(V_{\max} - V_{\min})^{1/X}]}{X}$. This point will give the percentage of air in the dry box read on the ordinate.

The graphs (Fig. 1) were constructed on the basis of using a variable chamber of 12 cubic feet maximum volume, and compressible to 6, 4 and 3 cubic feet of 1/2, 1/3, and 1/4 its original volume. To extend the use of these plots for any size chamber, the gas volume is plotted in terms of V_c --the maximum volume of any chamber--along the abscissa. It will be noted that value 1V, 2V etc. on the ideal mixing rate curves refers to the actual volume of the chamber at the time of purging, which is $V_{\min}$, and not the maximum volume of the chamber. Thus the graphs in Fig. 1 may be used for determining the purity of atmospheres in purging pipes, spheres, and other shapes, or fixed volume dry boxes as well as variable volume dry boxes.

GAS PURITY REQUIRED FOR WELDING

In welding, molten metal reacts with the gases of which air consists to form products or structures in the metal which are not desirable in the end product. For example:

These type reactions, oxidation or nitriding, are simply referred to as contamination in welding. By keeping the gas concentration on the left-hand side of the equations at a low enough value the reaction can be prevented from proceeding in the direction to form an oxide or nitride.

UNCLASSIFIED

UNCLASSIFIED

G. M. Adamson

-6-

February 6, 1957

The exact concentrations of gas that can be in contact with a molten metal before the chemical reaction proceeds, depend on the reaction rate equilibrium constant, the temperature, relative concentrations of the gas and metal, percentage of the metal under consideration in an alloy, crystallographic phase of the alloy at temperature, time-temperature, and numerous other physical phenomena which make an exact experimental calculation very difficult.

Other conditions, such as the solubility of the gases in the molten metal, may result in alloying of a gas and metal or promote the formation of crystallographic phases which change the physical and mechanical properties of the metal to an extent that renders it undesirable. Concentrations of oxygen, nitrogen, etc., below that required for chemical reaction, may not eliminate these latter conditions.

In inert-atmosphere chambers, the chemically or metallurgically active gases are displaced by inert gas to such an extent, that these undesirable reactions are eliminated or retarded to a tolerable level. This is usually determined by a cut-and-try method in welding. A weld is made of the particular alloy in or out of a dry box, and examined for evidence of "contamination" or "alloying." When the purity of the gas surrounding the weld is sufficiently high that no evidence of chemical or metallurgical changes are noted, this atmosphere is selected as adequate in inert gas content for the required welding.

In stainless steel welding, which is usually done in air, the face of the weld (top of molten puddle) is within a cone of inert gas (Heliarc Welding) while the root side (bottom of molten puddle) is covered by an inert gas flowing over the surface. The air content of the gas must be maintained under 1.5% to insure no undesirable effects. It has been found by experience that under these conditions (heat input, time at temperature, etc.), a gas such as nitrogen on the root side does not react with molten stainless steel. Experiments made under these conditions indicate that nitrogen could be considered an inert gas, as far as an alloy consisting of 8 to 20% nickel, 18 to 25% chromium, balance iron, is concerned.

In welding titanium, which has a much greater tendency for chemical reaction, and alloying properties with these gases, under approximately the same conditions, the critical air content of the gas in contact with the molten metal is different. It must be much lower, thus requiring "dry box" welding or much closer control of the atmosphere in contact with the metal. The air content of gases in contact with titanium should be maintained at less than 0.2%.

UNCLASSIFIED

Each type metal or alloy to be welded by the inert gas-shielded arc process must undergo an evaluation of the chemical affinity and the alloying ability of its constituents with the gases present in air. Those with relatively low tendencies such as steel, copper, stainless steel, aluminum, noble metals, may be welded in air, with coverage by inert gas from the torch on the face and purge gas on the root. Active metals, such as titanium, zirconium, thorium, uranium, molybdenum, must be surrounded by a larger and less air-contaminated inert gas envelope. This requires welding in high purity enclosed chambers, or special arrangements when welding in the open atmosphere, to insure a high purity inert gas envelope adjacent to the molten metal and heated adjacent area.

PRACTICAL APPLICATIONS

From the data and graphs presented in Fig. 1, it is apparent that in variable volume dry boxes, those permitting the largest possible expansion are the more efficient. Also, using a procedure which consists of purging the box while at its minimum volume prior to expanding to maximum working volume, results in the most efficient use of inert gas and time. Purging with argon entering at the bottom and exiting at the top appears to be the most efficient purging method.

In fixed volume chambers purging with argon at flow rates of 25 CFH from bottom to top, at least three volumes of gas must flow through the chambers prior to welding. The use of helium as a purge gas requires at least 6 volumes of purging gas.

In purging the inside volume of pipes and other shapes, the amount of purge gas used is dependent upon the material. Titanium requires a minimum of 6 volumes of purge gas, while stainless steel requires 5. There is some variation in efficiency using argon, which is dependent on the force of gravity as related to the purge inlet and outlet location, and the internal geometry of the shape being purged. For example, a pipe with its axis in a vertical position will require somewhat less gas when purging from bottom to top than a pipe in a horizontal position. Rather than carry out calculation in the field for each set-up, it seems more advisable to use the table recommendations as a general rule. Table 1 gives the time required to purge various pipe sizes per foot of length, at a flow rate of 30 CFH, using a total of 6 volumes of gas. Five-volume purging requires $5/6$ of the given time. Dividing any other flow rate used for purging by 30, and dividing the "table time" by the resulting quotient, gives the desired time to purge at any other flow rate used to obtain 6-volume displacement.

UNCLASSIFIED

G. M. Adamson

-8-

February 6, 1957

Table 1. Theoretical Time for 6-Volume Flushing of Various Diameter Pipe
Per Ft. Length At Gas Flow Rate of 30 CFH

ID	Time	ID	Time
1/2"	1 s	9"	5 m 20 s
1"	4 s	10"	6 m 30 s
2"	16 s	11"	8 m
3"	35 s	12"	9 m 20 s
4"	1 m 2 s	13"	11 m
5"	1 m 38 s	14"	13 m
6"	2 m 20 s	15"	14 m 45 s
7"	3 m 15 s	16"	16 m 40 s
8"	4 m 10 s		

UNCLASSIFIED

APPENDIX IIdeal Mixing of Gas In Fixed Volume ChamberUnder Positive Flow Conditions

The gas chamber of volume V opens at inlet and outlet, consists of air as initial gas at concentration C_0 and time t_0 , which is instant of starting gas flow of the second gas through the inlet at a given rate of flow G . After a finite interval of time t , the volume of gas introduced into the chamber equals Gt , which equals the volume of gas which has flowed through the outlet. The gas at t_0 flowing through the outlet is 100% air, but after a finite time, the gas flowing out is a mixture of the initial air occupying the space, and the incoming purging gas. At this time the flow of air out is equal to CG , where C is the concentration of air in cubic feet per cubic foot of exiting gas.

The change of concentration of the air in the exiting gas with time is expressed

$$\frac{d(c)}{dt} = \frac{CG}{V}$$

$$\begin{aligned} G &= \text{gas flow rate} \\ V &= \text{volume of chamber} \\ t - t_0 &= dt \\ C &= \text{concentration of air} \\ &\quad \text{ft}^3 \text{ air/ft}^3 \text{ gas} \\ C_0 &= \text{initial air concentration} \end{aligned}$$

which is the change of air content within the chamber, since ideal mixing is assumed in the chamber. Thus rearranging and integrating the above equation,

$$\int_{C_0}^C \frac{dc}{C} = - \frac{G}{V} \int_{t_0}^t dt$$

$$\ln \left(\frac{C}{C_0} \right) = - \frac{G}{V} t$$

which may be expressed

$$\frac{C}{C_0} = e^{-Gt/V} = R_a$$

C_0 equals 1, since the original chamber is 100% air, R_a is the fractional ratio of air by volume in the chamber after purging for a time t . The ratio of inert gas by volume in the chamber to the total volume is

$$R = 1 - R_a = 1 - e^{-\frac{Gt}{V}}$$

UNCLASSIFIED

APPENDIX IIGas Mixing in Compressible Chambers

In these type chambers, the chamber is compressed to a minimum volume containing air, the inert gas is introduced through the inlet with the outlet closed. The chamber expands, due to pressure increase within, until inside and outside pressures are equalized. The flow of gas into the chamber expands the chamber to the maximum volume. The chamber is then compressed to minimum volume with the gas outlet open and inlet closed. With the outlet closed and the inlet open, the chamber again is expanded to maximum volume. These cycles may be repeated any number of times.

For a specific calculation as an example, using a dry box of this type with 12 ft³ maximum capacity, and compressible to 3 ft³ minimum volume, the following will illustrate the inert gas purity obtainable.

n = number of expansions

Volume $V_{\max} = 12$; $V_{\min} = 3$

Expansion Ratio $X = \frac{V_{\max}}{V_{\min}} = 4$

$\frac{V_{\max}}{X} = V_{\min} = 3$

$V_{\max} - \frac{V_{\max}}{X} = 9$

Gas consumption = $(X-1)V_{\min}^n$

R = Ratio inert gas to air in chamber

The chamber contains 3 ft³ air initially compressed, inert gas consumption is 9 ft³ per cycle. The atmosphere within the chamber is now 75% inert gas after one expansion. Assuming intimate mixing, this mixture is exhaled during compression. During the next expansion 9 ft³ of inert gas is added to the 3 ft³ consisting of 75% inert gas. The resulting 12 ft³ of gas in the chamber is now 93.75% inert gas. If this is calculated arithmetically for further cycles, it is obvious that after expansions:

$$R_1 = 9/12; R_2 = \frac{9 + \frac{9}{12} \times 3}{12}; R_3 = \frac{9 + \frac{9}{12} \times 3 + (\frac{9}{12} \times 3)^2}{12}$$

it can be seen that R can be expressed by the following power series:

$$R_n = \sum_{n=1}^{n=\infty} \left/ \frac{9}{12} + \frac{9 \cdot 3}{12^2} + \frac{9 \cdot 3^2}{12^3} + \dots + \frac{9 \cdot 3^{n-1}}{12^n} \right/$$

Thus

$$R_n = \sum_{n=1}^{\infty} \left/ \frac{9}{12} \left(1 + \frac{3}{12} + \frac{3^2}{12^2} + \frac{3^3}{12^3} + \dots + \frac{3^{n-1}}{12^{n-1}} \right) \right/$$

Substituting equals:

$$R_n = \sum_{n=1}^{\infty} \left/ \frac{V - \frac{V}{X}}{V} \left(1 + \frac{V}{X} + \frac{\left(\frac{V}{X}\right)^2}{V^2} + \frac{\left(\frac{V}{X}\right)^{n-1}}{V^{n-1}} \right) \right/$$

Reduces to:

$$R_n = \sum_{n=1}^{\infty} \left/ 1 - \frac{1}{X} \left(1 + \frac{1}{X} + \frac{1}{X^2} + \frac{1}{X^3} + \dots + \frac{1}{X^{n-1}} \right) \right/$$

It is obvious that for any n terms in the parenthesis, all will cancel out except the first obtained by multiplying the parenthesis by 1 and the last obtained resulting from the multiplication by $1/X$. Thus

$$R_n = \sum_{n=1}^{\infty} \left/ 1 - \frac{1}{X^n} \right/$$

which is a convergent power series for all values of X greater than 1 converging on the value of 1. ($1 < X < \infty$).

Since R is ratio of inert gas to total volume of chamber, it follows that 1-R is ratio of air to total volume of chamber which is $\frac{1}{X^n}$. The latter ratio multiplied by 100 to give percentage is shown in Fig. 1 as the ordinates of the graph. The equation

$$R_n = \left. \begin{array}{l} n = \infty \\ n = 1 \end{array} \right| - \frac{1}{X^n} \left| \right.$$

is plotted for limited values of X and n.

CLASSIFIED

APPENDIX IIIPurging And Expanding In Compressible Gas Chambers

The dry box as compressed to a minimum volume of 3 ft³ and purged with 1 volume of inert gas results in an R of .633 before any expansion ($1 - \frac{1}{e}$). In expanding to full volume with 9 ft³ of inert gas the resultant R by arithmetical means is

$$R = \frac{9 + 3 \times .633}{12} = .90825$$

This is equivalent to the following formula:

$$R_{11} = 1 - \frac{1}{X} + \frac{1}{X} \left(1 - \frac{1}{e}\right)$$

Similarly, in compressing to 3 ft³ and purging this volume with 3 ft³ (1 volume) of inert gas, the resulting ratio of inert gas to total volume of gas in chamber is

$$R_2 = 1 - \frac{1}{X} + \frac{1}{X} \left(1 - \frac{1}{e^2}\right) = .967$$

where the value of X is 4.

On inflating to 12 ft³

$$R_{22} = 1 - \frac{1}{X} + \frac{1}{X} \left(1 - \frac{1}{4e^2}\right) = .992$$

R_{11} or R_{22} are the only ratios of practical interest, since R_2 is at the minimum volume of the chamber which would be expanded up to 12 ft³ before use.

The general formula that gives the desired ratio of inert gas to total volume of gas is

$$R = 1 - \frac{1}{X} + \frac{1}{X} \left(1 - \frac{e^{-\frac{Gt}{V}}}{X^{n-1}}\right)$$

This reduces to

$$R = \sum_{n=0}^{\infty} \left| 1 - \frac{e^{-Gt}}{X^n} \right|$$

G = Gas flow rate

X = Expansion ratio

t = time

n = No. of expansions

V = Volume being purged

which is seen to be a combination of the ideal mixing law equation and sum of the infinite power series developed in Appendix II. The second term of the expansion $\frac{e^{-Gt}}{X^n}$ is the ratio of air to total volume in the chamber after a given flow of inert gas and finite number of expansion cycles; subject to the limitation of purging at the minimum volume of the dry box.

From the slopes of the two lines for the equations $R_{\text{air}} = \frac{1}{e^{-Gt/V}}$ and $\frac{1}{X^n}$ which are $\frac{d}{dV} (\log R)$, where $\bar{V} = Gt$ or Kn ($K = V_{\text{max}} - V_{\text{min}}$) respectively, it can be seen the former is a larger number (negative), which indicates a greater purging efficiency; the values of $\frac{d}{dt} (\log R)$ are similarly related. For the plots of $R_{\text{air}} = \frac{1}{X^n}$ at different expansion ratios using no through flow purging, the greater slope (negative) results from the largest value of X ($\frac{d}{dV} (\log R) \propto X$); also $\frac{d}{dt} (\log R)$ and $\frac{d}{dn} (\log R)$ are directly related to X.

Fig. 1. Inert Gas Requirement versus Air Content for Various Methods of Atmosphere Purification.