SIMULATION OF FEED/BLEED OPERATION IN AGS*

DEW POINT MONITORING

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ABSTRACT

The dynamic operation of the AGS in a CANDU nuclear reactor has been modelled in terms of the gas chemistry and particularly dew point which is used to monitor a potential D_2O leak from the Primary Heat Transport (PHT) System. The computerized model, in an early stage of development, is being used to study the performance of the AGS in the feed/bleed mode of operation. Continuous feed and bleed operation refers to deliberately removing gas from the AGS downstream of dew point detection and adding fresh dry gas upstream. This mode is being examined as an automated means of reducing the system purge frequency while maintaining its sensitivity to detecting pressure tube (PT) leaks.

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1.0 INTRODUCTION

It has been decided to design and install oxygen addition systems to the Annulus Gas System (AGS) of all Ontario Hydro reactors. This is intended to better protect CANDU pressure tubes (PT) from deuterium ingress via the AGS. Oxygen addition helps to maintain the oxide layer on the PT's but converts any deuterium/hydrogen present to moisture vapour. This moisture is generated throughout the calandria section of the AGS and if allowed to accumulate tends to dampen the response of the dew point monitors to a real PT leak in its early stages. The progressive accumulation of moisture also causes the system dew point to rise to the present target alarm dew point at which the system is purged dry more frequently. This makes more demands on the station who require a less labour intensive monitoring arrangement.

An oxygen addition test has already been carried out on a Bruce B unit AGS to measure the amount of moisture generated. It was found that the dew point trending rate was three times that without oxygen addition. It has been suggested that a feed and bleed arrangement be adopted for AGS operation as an alternative to frequent system purges. A controlled bleed of moist gas from the system downstream of the dew point monitors would be balanced by a feed of dry gas into the system prior to the calandria section of the AGS. By adjusting the bleed rate the steady state dew point of the system in the absence of a PHT D_2O leak would be controlled. The introduction of a bleed stream simplifies system operation but introduces the potential disadvantage of desensitizing the AGS leak detection capability. There is also the added complication of ensuring that the "imposed" gas leak (bleed) fails safe in practice i.e. does not give rise to a greater gas leak than allowable.

The chemistry specification for the AGS has been revised with limits on dew point, oxygen and deuterium concentration. In order to co-ordinate the operation of the AGS to meet leak detection and chemistry requirements for the postulated feed/bleed scenario it was decided to model the system for both pre and post oxygen addition. It was intended to assess the suitability of the feed/bleed concept as well as alternatives and identify optimum operating parameters prior to any decision to use it for design purposes.

2.0 DEVELOPMENT OF FEED/BLEED AGS MODEL

2.1 Description of a Typical AGS

The AGS is a unique feature of the CANDU reactors. The fuel channel assembly has an annular gap between the PT and calandria tube. These annular gaps in conjunction with the external piping and equipment constitute the AGS. Its primary purpose originally was to minimize the heat transfer from the PTs to the moderator, to maintain a dry and non-corrosive environment for the fuel channel components and to provide drainage in the case of a PT leak. This has been extended to include the vital role of detecting moisture leaks, particularly from the Primary Heat Transport System. Recently a further requirement has been added to provide an oxidizing atmosphere for the outside diameter of the PTs to ensure an oxide layer giving PT integrity. The flow sheet for Bruce A, Units 3 and 4 AGS (see figure 1) is typical of that for Bruce B, Pickering B and Darlington.

It is basically a recirculating system employing 3 compressors (1 on standby) and carbon dioxide gas. Gas make up is from bottles or more often, a bulk gas system. There are typically 48 parallel flow paths (vary from 44 to 52) with 3 to 12 channels in series. Two hygrometers in parallel monitor dew point and system pressure; temperature is also measured. Liquid moisture in the AGS is detected by means of a moisture "beetle" at the inlet and outlet of the calandria section. The liquid collection rate can be monitored and a cold finger sample taken at an early stage in a D_2O leak scenario to determine the source (PHT, moderator or end shield cooling).

2.2 Development of Dew Point Model

To better understand the system operation and response to moisture ingress to the AGS an in-depth study was undertaken. The moisture transfer mechanism, hydraulics and equipment response were included in these studies. This was carried out originally for Bruce A because of the initial PT leaks there; the dew point model developed is reported in Reference 1. This model was developed as a generic code provided with Bruce A parameters. Provision for gas leaks was made for Pickering A where significant gas leaks occur in Units 3 and 4. Initially this was achieved using an analytical version of the model suitable only for Pickering A. See Reference 2. Subsequently the numerical version of the dew point model was developed to provide for gas leaks from both channel strings and the ancillary piping, headers and equipment.

Verification of the model has been carried out with actual station tests as follows:

(a) Injection of argon as a tracer gas at Bruce A, Unit 1 in 1982 showed the core flow distribution was adequately predicted from hydraulic analyses.

(b) Injection of carbon dioxide as a tracer gas in the nitrogen annulus of Pickering A, Unit 1 in 1983 confirmed the residence time in the AGS circuit.

(c) Injection of methane as a tracer gas in the carbon dioxide annulus of Bruce B, Unit 8 in 1984 for strings from 4 to 12 channels confirmed the moisture transfer pattern through the annuli.

(d) Actual moisture tests with D_2O injection in the carbon dioxide annulus of Pickering A, Unit 1 (after retubing) in 1987 verified the overall dew point model with modification for hygrometer calibration (see reference 3).

(e) Actual moisture tests with D_2O injection in the carbon dioxide annulus of Darlington, Unit 2 during commissioning in 1989 have further verified the dew point model.

2.3 Development of a Feed/Bleed Model for AGS Operation

The existing dew point model has been significantly upgraded to include the following features which are illustrated diagrammatically in Figure 2. The AGS is modelled generically as several "lumped" strings of nodes in parallel representing the internal or calandria section. The external circuit of pipework, headers and equipment has only 2 percent of total system volume and is represented by links which do not contain any volume. Ninety-eight percent of the system volume is in the internal circuit. Each channel is represented by a number of nodes, the total volume of which corresponds to the actual annulus volume of the channel.

2.3.1 Main Features

(a) Up to 10 different channel strings can be modelled. This node volume of each is "lumped" to include all channel strings of that length. The existing dew point model handles only 2 channel strings one of which is "lumped".

(b) There is provision for a gas leak upstream of each node so that bellows gas leaks can be modelled. This is in common with the existing dew point model.

(c) There is provision for gas leaks in the external circuit both upstream and downstream of the compressors. This is in common with the existing dew point model.

(d) The gas make up (nitrogen or carbon dioxide) for the AGS may be introduced downstream or upstream of the compressors. This is in common with the existing dew point model.

(e) Oxygen is introduced as make up downstream of the dew point monitors and upstream of the gas make up.

(f) The bleed stream is located downstream of the dew point monitors and upstream of the gas make up.

(g) The programme will accommodate both purge and recirculation modes of AGS operation. This is in common with the existing dew point model.

2.3.2 Source Terms

(a) Provision is made for ingress of D_2O at a specific rolled joint in the event of a PT leak.

(b) Provision is made for diffusion of D_2O from the PHT system into the AGS at each end fitting.

(c) Provision is made for diffusion of D_2 from the PHT system into the AGS at each end fitting.

2.3.3 Component Balances

Oxygen

(a) Oxygen is removed at each gas leak.

(b) Oxygen is removed by reaction with D_2 as follows:

$$D_2 + 1/2\ O_2 = D_2O \tag{1}$$

(c) Oxygen is removed by renewal of the zirconium oxide layer as follows:

$$2\ Zr + 3/2\ O_2 = Zr_2O_3 \tag{2}$$

Deuterium

(a) Deuterium is introduced at each end fitting node by diffusion.

(b) Deuterium is removed at each gas leak.

(c) Deuterium is removed by reaction with oxygen per equation (1) during oxygen addition.

(d) Deuterium is removed by reaction with carbon dioxide without oxygen addition as follows:

$$D_2 + CO_2 = CO + D_2O \tag{3}$$

Deuterium Oxide

(a) There is provision for D_2O to be added at the end fitting nodes.

(b) There is provision for a moisture leak at any rolled joint node.

(c) Moisture is removed at each gas leak.

(d) Moisture is generated at the end fitting nodes from D_2 oxidation according to Equation (1) during oxygen addition and from CO_2 oxidation according to equation (3) without oxygen addition.

The nodal component balance terms are shown in figure 3.

The rate equations for the oxygen, deuterium and deuterium oxide balances for a typical node, i, in a given string are as follows:

(a) Oxygen Rate Equation

$$d[O_2]_i/dt = [O_2]_{i-1}*M_{i-1}/m - [O_2]_i*M_i/m_i - 4*\ [D_2]_i * \eta_2/m - 4*\eta_2*d_i - C/m_i \quad (4)$$

(2) Deuterium Rate Equation

$$d[D_2]_i/dt = \{M_i*([D_2]_i*(1-\eta_2) - [D_2]_i) + (1-\eta_2)*d_i\}/m_i \quad (5)$$

(3) Deuterium Oxide Rate Equation

$$d[H_i]/dt = W_i/m_i + M_{i-1}*[D_2O]_{i-1}/m_{i-1} - M_i*[D_2O]_i/m_i + 5*\eta_2*M_{i-1}*[D_2O]_{i-1}/m_{i-1} + 5*\eta_2*d_i/m_i \quad (6)$$

If there is no oxygen present then equation (4) is removed and η in the remaining equations is that for reaction equation (3).

2.3.4 Inlet Distribution of Gas Flows

The gas flow distribution to each string is modelled in terms of the ratio of the node volume of that string to the total i.e.:

$$f_i = m_i/\Sigma_i^n m_i \quad (7)$$

This is the default value. If the hydraulic analysis shows a distinctly different distribution then individual values of f are input.

2.3.5 Mass and Component Balances for the External Circuit

The individual flows for each string are combined with the final node concentration for each component to obtain a combined concentration at the outlet of the internal circuit. The appropriate equations are given in the Appendix.

2.3.6 Mass and Component Balances for the Internal Circuit

With reference to the subroutine, DVERK, described in Appendix 7.2, the optimal values of DELT and TOL were found by first selecting very small values i.e. DELT = .001, TOL = .0001 involving significant run times. Reducing these parameters still further did not change the dew point output data even at the fourth decimal place. The above parameters were then increased until the dew point output data changed at the second decimal place. The largest values of DELT and TOL which did not alter the second decimal place were selected as optimal. These values are DELT = .01 and TOL = .005. These values were also the limiting ones for predicting oxygen and deuterium concentrations because dew point is more sensitive than concentration.

2.3.7 Conversion of Humidity to Dew Point

Low moisture concentration in a gas stream is commonly measured as dew point. Consequently the mass concentration of D_2O in the gas stream, namely humidity, is converted to dew point as follows:

The partial pressure of moisture in the gas stream is given by:

$$P_{D_2O} = H^*\pi^*M_{gas}/\{H^*M_{gas} + M_{D_2O}\} \tag{8}$$

from the law of partial pressures.

The Clausius-Clapeyron equation for D_2O is:

$$\ln P_{D_2O} = -5519.34/T + 17.597 \tag{9}$$

$$\text{or } P_{D_2O} = \exp \frac{-5579.34}{T} + 17.597 \tag{10}$$

$$T = -5579.34\{\ln [\frac{M_{gas} \times H * \pi}{M_{gas} \times H + M_{D_2O}}] - 17.597\} \tag{11}$$

There is a similar relation for frost point ($T \leq 273$ K)

3.0 DATA SETS

3.1 Input File

It is first decided whether purge or recirculation mode operation is required. The following input data is required for both modes as follows:

(a) Initial oxygen concentration at all nodes,

(b) Initial deuterium concentration at all nodes,

(c) Initial dew point at all nodes,

(d) Number of lumped strings,

(e) Flow weighting for each string,

(f) Nodal volume for each string,

(g) Nodal conversion efficiencies:

$CO_2 + D_2 = CO + D_2$ η_1
$1/2\ O_2 + D_2 = D_2O$ η_2

(h) Bleed Rate,

(i) Gas leak Scenario:

Distribution between internal and external circuits
Distribution within internal circuit

(j) Oxygen addition rate,

(k) Oxide renewal rate,

(l) Distribution matrix of source terms,

Deuterium ingress rate(s) at end fittings
Deuterium oxide ingress rate(s) at end fittings
Deuterium oxide leak rate(s) at end fittings

(m) System pressure, and

(n) System flow rate.

3.2 Output File

(a) Echo of input file.

(b) Predicted values of deuterium concentration (v/v), oxygen concentration (v/v) and dew point (°C) at three node locations and at the dew point monitor (external circuit). The selected node locations are the first, middle and final nodes of the longest string.

3.3 Establishment of Input Data

The geometric terms for input data are easily obtained from system drawings e.g., nodal volume etc. Operational process parameters e.g., pressure, flow rate, gas leakage and oxygen addition rate are also straight forward. However, certain terms were more difficult to quantify and these are as follows:

3.3.1 Oxide Layer Renewal

Data from a British source (Reference 4) indicates that an oxygen uptake rate of 1.05 * 10-3 g/h.channel should be used in the absence of other data sources.

3.3.2 Deuterium Diffusion Rate

A range of deuterium ingress rates is available from measurements at the stations. The range is 230-470 * 10-3 L/min.(STP).

3.3.3 Deuterium Oxide Diffusion Rate

Dew point data from successive purge cycles indicate a wide range of possible ingress rates depending on the station and the unit.

3.3.4 Conversion Efficiency

3.3.4.1 Deuterium Oxidation with Carbon Dioxide

Station AGS chemistry data show there is typically a 33 percent overall steady state conversion of deuterium in the presence of carbon dioxide for Bruce and Pickering B type AGS.

The nodal conversion efficiency, η_1, is calculated as follows:

The number of recirculation cycles by the gas before a gas molecule will escape from the AGS is:

Number of cycles = Recirculation rate/Leak rate = R/L

Total number of nodes traversed by a gas molecule before exiting from the system is given by:

Average number of nodes/string (N) * R/L

Therefore the overall conversion efficiency, E, is given by:

$$[1-\eta_1]^{N*\frac{R}{L}} = 1-E$$

A typical example is Pickering B AGS which is given in Appendix 7.3.

3.3.4.2 Deuterium Oxidation with Oxygen

At present there are no measured data for nodal conversion efficiency but it has been estimated that 95 percent conversion may be adopted for each flow cycle of the AGS. This figure is probably conservative based on oxygen addition tests at the stations. It corresponds to a typical nodal conversion efficiency of:

$$\eta_2 = 1 - (1 - 0.95)^{(1/17.2)} = 0.16$$

4.0 PRELIMINARY RESULTS

4.1 The feed/bleed programme has been checked for consistency by running it for a standard moisture leak case at a specific rolled joint with no oxygen addition or deuterium/moisture ingress. The dew point response to a single moisture leak was identical to that for the dew point programme which had been previously verified.

4.2 Station data for Pickering B AGS to date indicate that the presently adopted deuterium ingress rate and nodal conversion efficiency without oxygen addition predict dew point trending which matches measured dew point trends. See Figure 4. This suggests that moisture ingress is negligible in keeping with the fact that the larger D_2O molecules are less likely to diffuse into the AGS.

4.3 A feed/bleed analysis for Bruce B AGS shows the steady state dew point as a function of the feed/bleed rate. See Figure 6. This shows that a significant feed/bleed rate is required to ensure the steady state dew point is low enough for sensitive leak detection e.g., to achieve -20°C dew point the feed/bleed rate is 43 L/min. (STP).

4.4 Initial studies of the effect of oxygen addition on leak detection monitoring have been carried out for the Bruce B AGS arrangement. The dew point responses for PHT moisture leaks of 1 g/h and 10 g/h for no oxygen addition and no bleed compared with oxygen addition and a high bleed rate are shown in Figure 5. The results indicate that the initial dew point response is marginally increased by oxygen addition with no bleed compared with no oxygen addition and no bleed. Even a superimposed bleed rate as high as 161 L/min. (STP) does not significantly reduce the initial dew point rise as dry feed gas does not enter the AGS until the system recycles. Consequently the high bleed rate does not significantly affect the leak detection performance.

5.0 CONCLUSIONS

The previously established generic dew point model programme which predicts the dew point response of the AGS to a moisture leak has been significantly extended to include the dynamics of the full chemistry of the AGS. A preliminary study of the impact of feed/bleed operation on the chemistry of the AGS and in particular dew point shows the following main points:

5.1 Dew point trends during normal operation have been modelled allowing for deuterium diffusion at the end fittings and oxidation in the presence of carbon dioxide and show good agreement with measured station data.

5.2 Preliminary results show that operating with feed/bleed does not desensitize the dew point response during an actual moisture leak at a rolled joint. This is true for the first cycle but there is a reduction in response during successive cycles. However the dew point response during the first cycle is the most important and consequently feed/bleed operation appears to be satisfactory at this stage of the analysis.

6.0 REFERENCES

1. Kenchington, J.M., Ellis, P.J. and Meranda, D.G., "The Dew Point Response of the Annulus Gas System of Bruce NGS A - Derivation of a Model", CNS Conference, Montreal, June 1983.

2. Kenchington, J.M., "Analytical Developments in the Dew Point Model for Predicting Annulus Gas System Response", CNS Conference, Saskatoon, June 1984.

3. Kenchington, J.M., Ellis, P.J., and Meranda, D.G., "Annulus Gas System Response Tests for Pickering A, Unit 1 Commissioning", CNS Conference, Winnipeg, June 1988.

4. Asher, R.C. et al, "The Corrosion of Some Zirconium Alloys under Radiation in Moist CO_2 - Air Mixtures", Journal. of Nuclear Mat., 49, pp 189-196, 1973.

7.0 APPENDIX

7.1 Mass and Component Balances for the External Circuit

The individual flows for each string are combined with the final node concentrations for each component to obtain a combined concentration in each case at the outlet of the internal circuit as follows:

$$\Sigma(f_j * [D_2]_{j,\ i}) = W_0 * [D_2]_0 \quad (1)$$

$$\Sigma(f_j * [O_2]_{j,\ i}) = W_O * [O_2]_0 \quad (2)$$

$$\Sigma(f_j * H_{j,\ i}) = W_0 * H_0 \quad (3)$$

In the external circuit, flows and concentrations are modified successively by bleed stream, gas leaks and make up flow as follows:

$$W_1 = W_0 - W_B \quad (4)$$

$$W_1 * [D_2]_1 = W_0 * [D_2]_0 - W_B * [D_2]_0 \quad (5)$$

$$W_1 * [O_2]_1 = W_0 * [O_2]_0 - W_B * [O_2]_0 \quad (6)$$

$$W_1 * H_1 = (W_0 - W_B) * H_0 \quad (7)$$

$$W_2 = W_1 - W_{L1} \quad (8)$$

$$W_2 * [D_2]_2 = W_1 * [D_2]_1 - W_{L1} * [D_2]_{L1} \quad (9)$$

$$W_2 * [O_2]_2 = W_1 * [O_2]_1 - W_{L1} * [O_2]_{L1} \quad (10)$$

$$W_2 * H_2 = W_1 * H_1 - W_{L1} * H_{L1} \quad (11)$$

$$W_3 = W_2 + W_{M1} \quad (12)$$

$$W_3 * [D_2]_3 = W_2 * [D_2]_2 + W_{M1} * [D_2]_{M1} \quad (13)$$

$$W_3 * [O_2]_3 = W_2 * [O_2]_2 + W_{M1} * [O_2]_{M1} \quad (14)$$

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$$W_3 * H_3 = W_2 * H_2 + W_{M1} * H_{M1} \quad (15)$$

$$W_4 = W_3 + W_{M2} \quad (16)$$

$$W_4 * [D_2]_4 = W_3 * [D_2]_3 + W_{M2} * [D_2]_{M2} \quad (17)$$

$$W_4 * [O_2]_4 = W_3 * [O_2]_3 + W_{M2} * [O_2]_{M2} \quad (18)$$

$$W_4 * H_4 = W_3 * H_3 + W_{M2} * H_{M2} \quad (19)$$

$$W_5 = W_4 + W_{M3} \quad (20)$$

$$W_5 * [D_2]_5 = W_4 * [D_2]_4 - W_{M3} * [D_2]_{M3} \quad (21)$$

$$W_5 * [O_2]_5 = W_4 * [O_2]_4 + W_{M3} * [O_2]_{M3} \quad (22)$$

$$W_5 * H_5 = W_4 * H_4 + W_{M3} * H_{M3} \quad (23)$$

$$W_6 = W_5 - W_{L2} \quad (24)$$

$$W_6 * [D_2]_6 = W_5 * [D_2]_5 - W_{L2} * [D_2]_{L2} \quad (25)$$

$$W_6 * [O_2]_6 = W_5 * [O_2]_5 - W_{L2} * [O_2]_{L2} \quad (26)$$

$$W_6 * H_6 = W_5 * H_5 - W_{L2} * H_{L2} \quad (27)$$

7.2 Mass and Component Balances for the Interval Circuit

The rate equations for the nodes of the internal circuit and the component/mass balance equations of the external circuit form a solution matrix. This matrix is solved by a subroutine, DVERK, from the IMSL library. This is essentially a Runge-Kutta-Verner fifth or sixth order routine. The entire set of equations is solved simultaneously for successive time increments.

DVERK has four adjustable parameters to set the time steps and tune the final solution. There is a time step, DELT, which controls the frequency of solving the matrix of differential equations. The print time, PRTIME, is a multiple of DELT at which a record of the output data set is required. The total time frame, TEND, is also defined. The accuracy of prediction is controlled by the tolerance, TOL, which sets the limit of agreement between successive iterations.

7.3 Conversion Efficiency for Pickering B AGS (Without O_2 Addition)

R = 340 L/min.(STP)
L = 1 L/min.(STP)
N = 17.2 L/min.(STP)
E = 33%

$$\eta_1 = 1 - (1-E)^{L/N*R} = 1 - (1 - 0.33)^{1/17.2*340}$$

$$\eta_1 = 6.85 * 10-5$$

8.0 NOMENCLATURE

f	Fraction of total gas flow through an individual string
C	Oxidation rate
H	Humidity
H_0	Humidity outlet the calandria section
m	Mass of gas in each node
M	Mass flow rate of gas (internal circuit)
M_{gas}	Molecular weight of gas
W	Mass flow rate of gas (external circuit)
M_{D2O}	Molecular weight of D_2O
d_i	Mass rate of deuterium entering any node
W_i	Mass rate of moisture entering any node
t	Time
T	Absolute temperature
P_{D2O}	Partial pressure of D_2O in gas stream
η_1	Nodal conversion efficiency with CO_2
η_2	Nodal conversion efficiency with O_2
E	Overall steady state conversion
$[D_2]$	Deuterium concentration

$[O_2]$	Oxygen concentration
π	System pressure
i	Node i
j	String j
$W_0, W_B, W_1, W_{L1}, W_2, W_{M1}, W_3, W_{M2},$ $W_4, W_{M3}, W_5, W_{L2}, W_6$	Defined in Figure 2

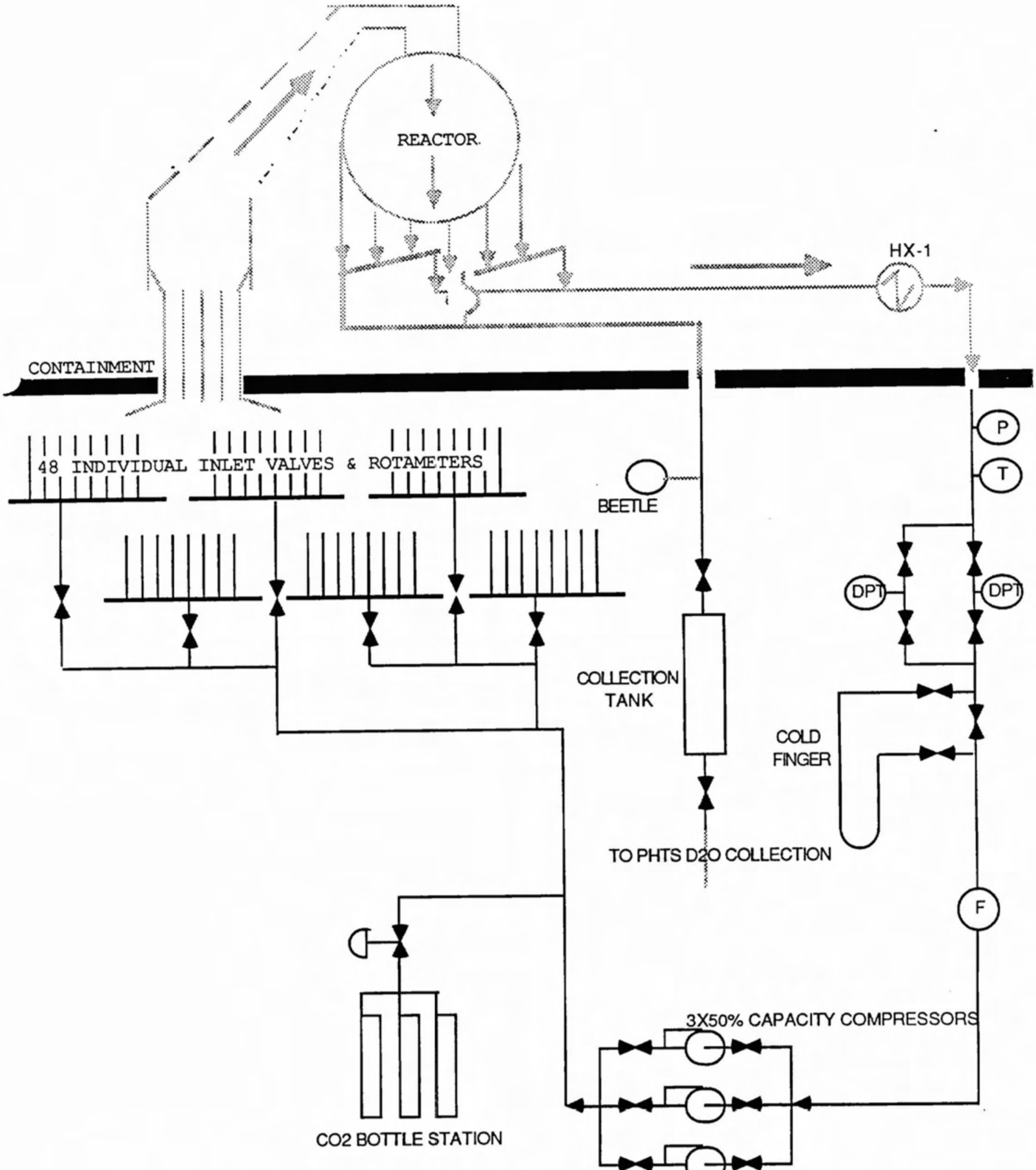

FIGURE - 1

BRUCE 'A' UNITS 3 and 4 - A.G.S. FLOW SCHEMATIC

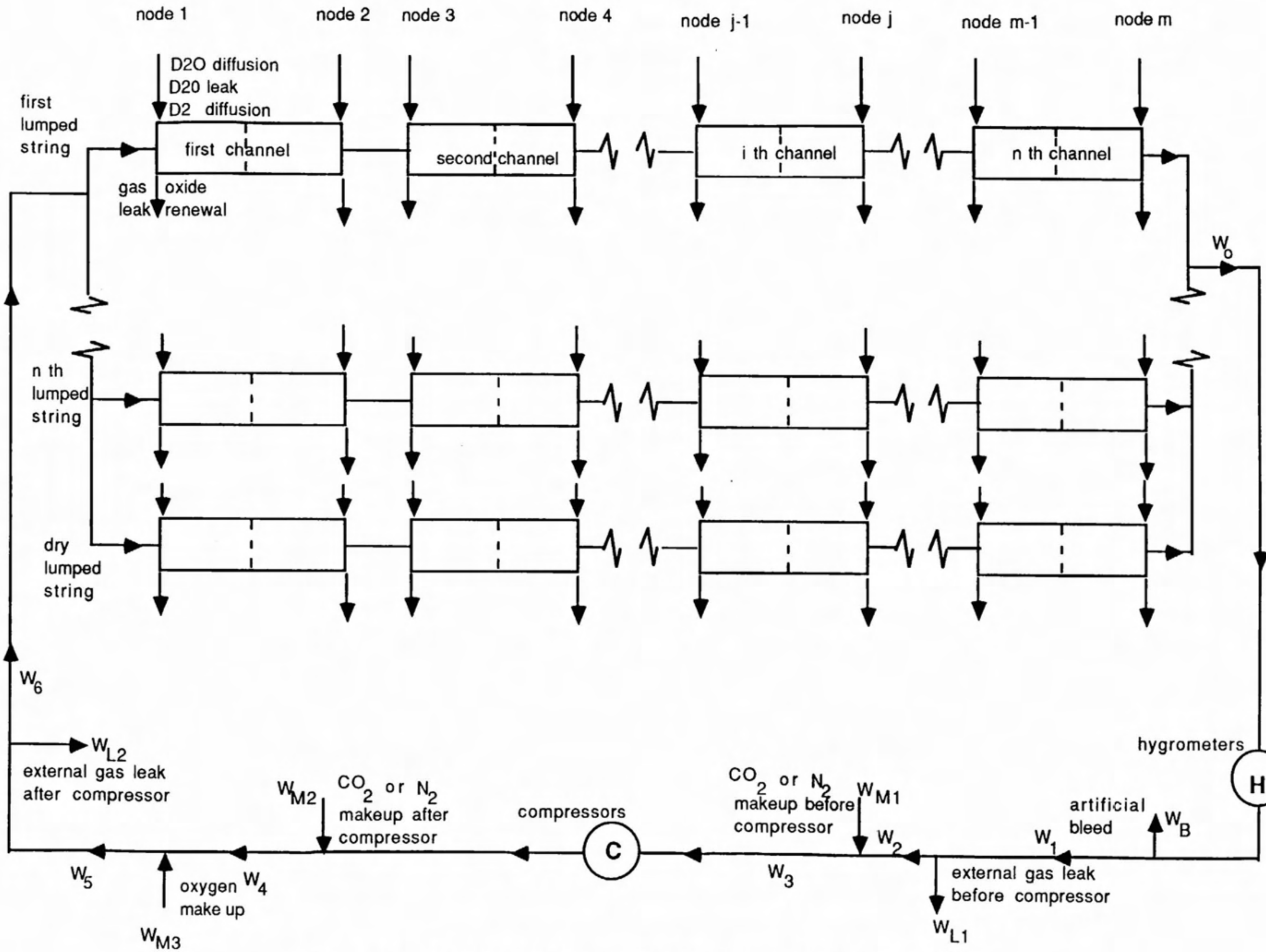

Figure 2: Feed and Bleed model in the recirculation mode

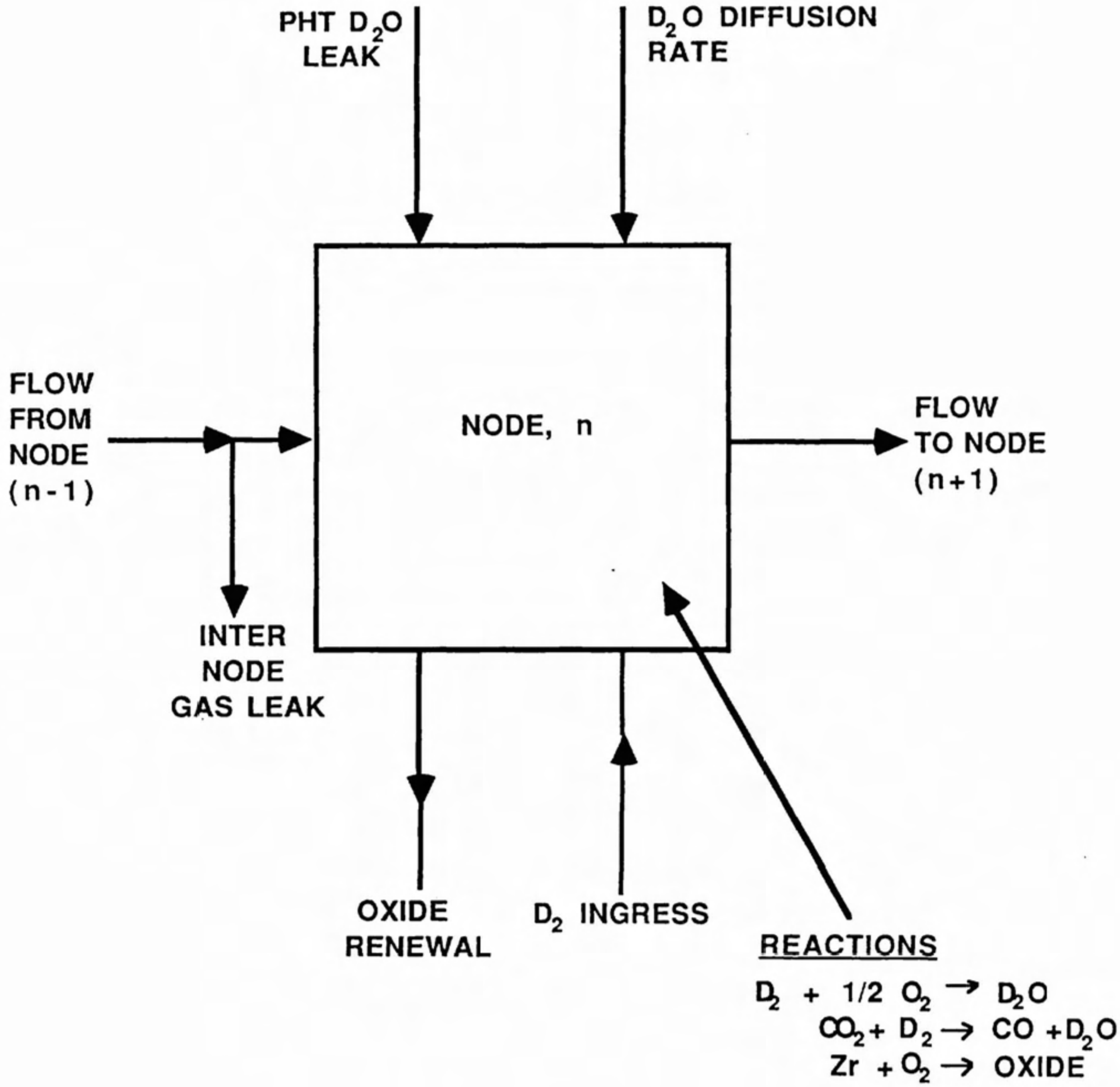

FIGURE 3

INPUT/OUTPUT TERMS FOR EACH NODE OF THE FEED/BLEED DEW POINT MODEL

FIGURE - 4

VARIATION OF ANNULUS GAS SYSTEM DEW POINT WITH TIME

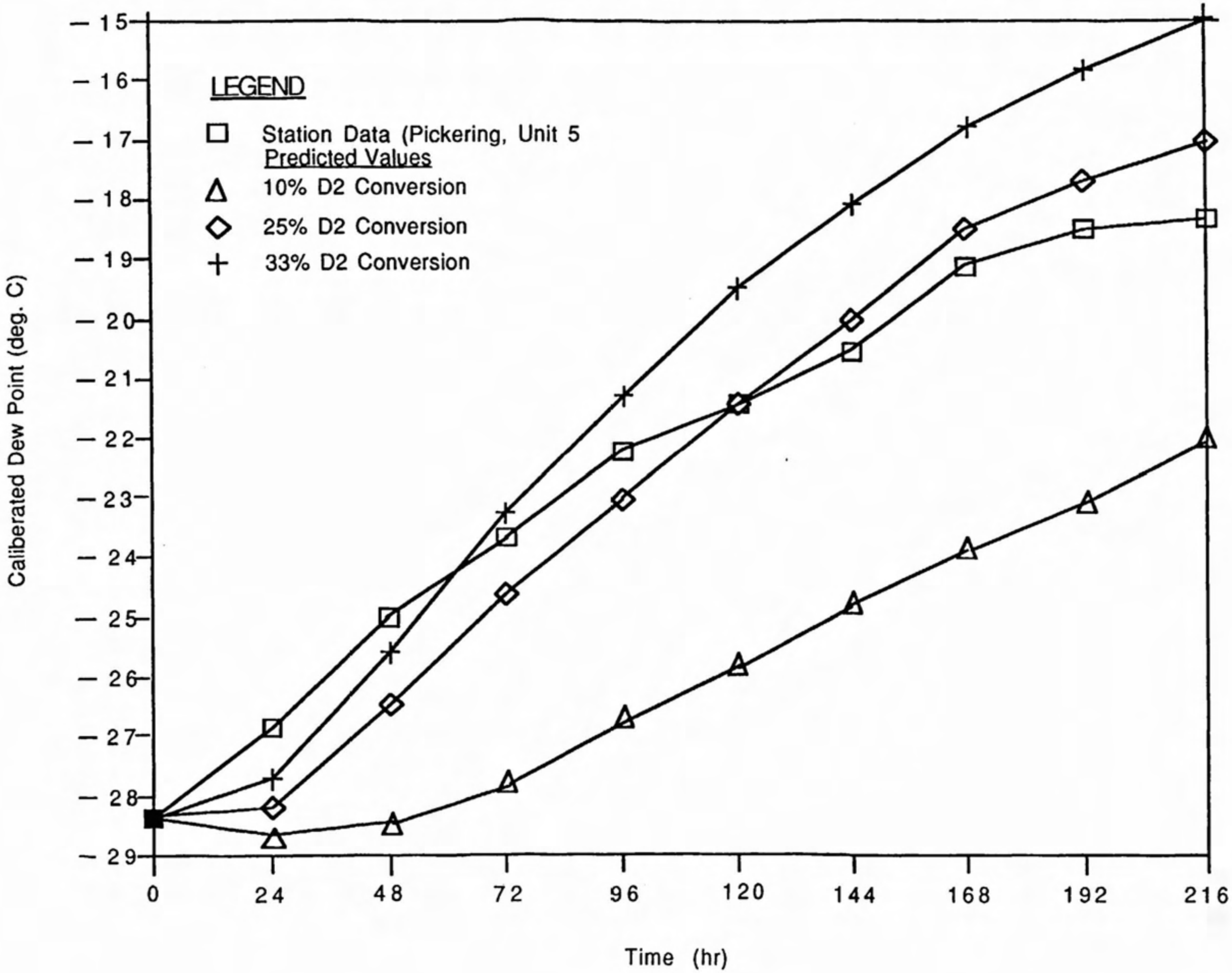

FIGURE - 5 PREDICTED RELATION BETWEEN STEADY STATE DEW POINT AND BLEED RATE
BRUCE B AGS

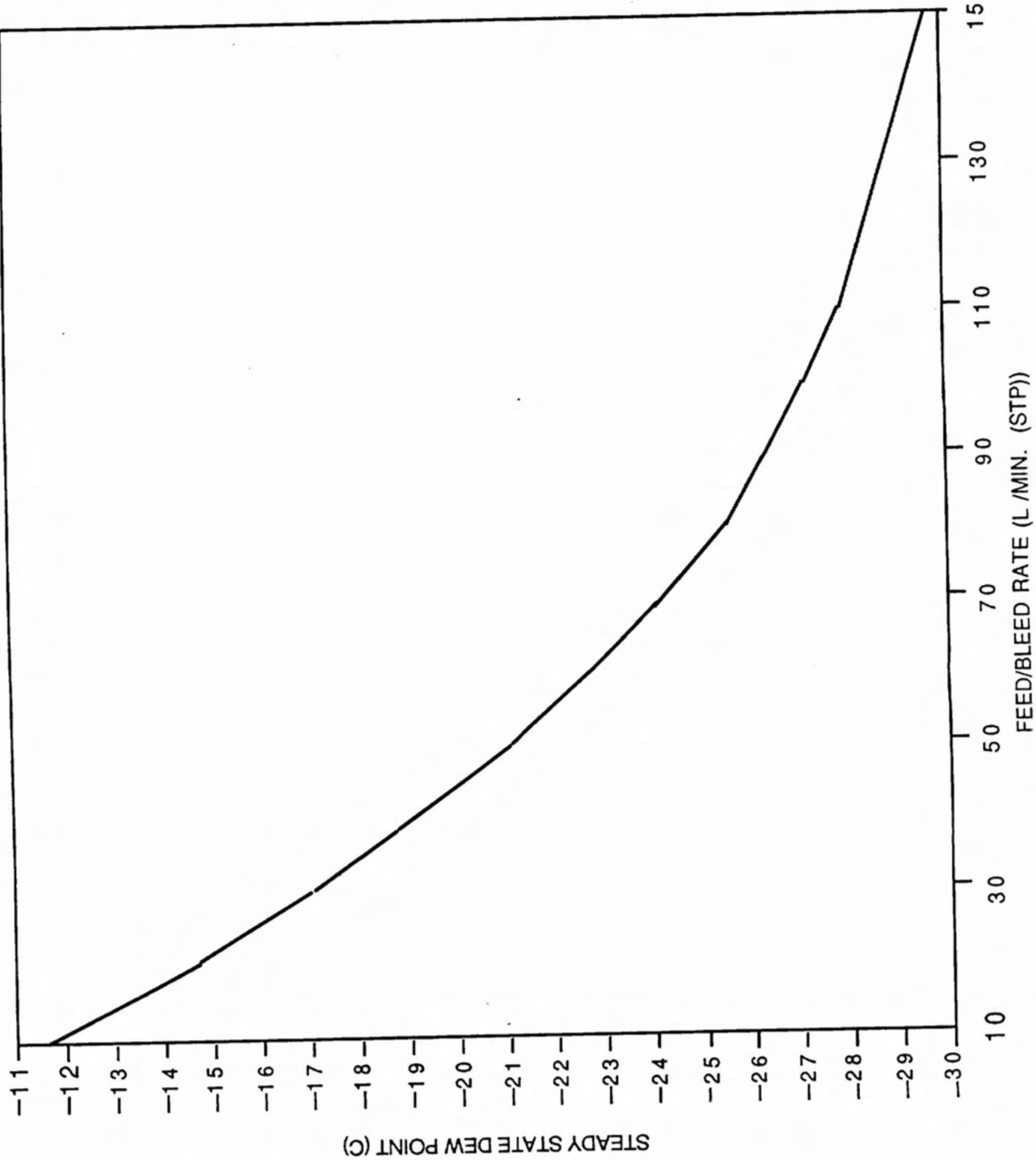

FIGURE 6 ANALYSIS OF DEW POINT VARIATION WITH TIME FOR DIFFERENT BRUCE B AGS SCENARIOS