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MEMORANDUM

(EPS-X-272)

KT-240

October 19, 1956

TO: D.S. Toomb

FROM: R. Gelman and C.S. Robertson, Jr.

SUBJECT: Frequency Response Analysis of HRT Mockup Pressurizer-Level Control Loop

INTRODUCTION

The HRT Mockup is a complete working model of the HRT designed to test various reactor components and controls under anticipated operating conditions with non-radioactive solution. The stability and response characteristics of the HRT Mockup Pressurizer-Level Control Loop as well as the effectiveness of pneumatic damping units have been investigated and are presented in this report.

In the HRT it is necessary to pressurize the fuel solution (uranyl sulfate in heavy water). This is accomplished by evaporating pure heavy water in a pressurizer vessel which is open to the fuel solution. If the fuel level were to rise above the barrier separating it from the pure heavy water, the pressurizer would become contaminated and uranyl sulfate would precipitate out of solution. Conversely, should the level of the fuel solution fall too low, the vapor would be entrained in the core fuel cycle. These conditions require that the level of the fuel solution be closely regulated.

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Figure 1 is the HRT Mockup. The 80 kw input heat exchanger supplies heat to the system and represents the HRT reactor core.

Figure 2 is a block diagram of the existing control system which regulates the fuel level. The let-down valve (always partially open) allows a slow continuous recirculation of fuel solution as well as partial separation of gaseous products (D_2 , O_2 , I^{131} , Ze , Kr) from the main loop. Opening the let-down valve allows more fuel solution to drain from the fuel cycle into a dump tank, thus causing a decrease in the liquid level. A continuously operating pulsafeed pump replenishes the loop fuel from the dump tank. A magnetically damped float level element signals variations of level and a pneumatic transmitter relays the signal through a pulsation damper (for suppression of pump "noise" and better response characteristics) to a level recorder and a controller which activates the let-down valve.

Although the control system has exhibited stable response during a sustained equilibrium operation, its behavior when subjected to extreme fluctuations (start-up, shut-down) has not been previously determined.

The work reported in this memorandum was performed during the period, Oct. 5 to 19, 1956, at the Oak Ridge National Laboratory in the Reactor Experimental Engineering Division (REED) with Messrs. D.S. Toomb and H.D. Wills as consultants.

PROCEDURE

The HRT Mockup Pressurizer-Level Control Loop is a closed loop with feedback, i.e., deviation from desired operation (too high or too low a liquid level) is signaled to the controller which then activates a mechanism (the valve) to counteract the deviation and bring the system back to normal. A convenient and standard method for determining the stability and response characteristics of such a loop is to operate the system as an open loop, i.e., eliminate the feedback into the controller and in its place insert a controlled sine wave. By studying the amplitude and phase lag of the output of the system as a function of the frequency of the input, the characteristics of the system may be determined. Results are usually presented as plots of a ratio of the magnitude of the output to the input amplitude (referred to as magnitude ratio or gain) against frequency and as a plot of the phase difference between the output and input wave forms against frequency. The combination of the two graphs on a single page is called a Bode Diagram.

Open and closed loops are composed of the same components and hence their mathematical formulation is the same, i.e., differential equations are equal. The discontinuity of the open loop is the boundary condition that differentiates them otherwise. By mapping the mathematical relationships of closed loop gain and phase angle on the "imaginary" plane, lines of constant loop gain (m) and constant phase angle (α) can be obtained. Since these relationships can be expressed in terms of the open loop characteristics, it has been found convenient to superimpose the open loop plot on the same graph. Thus, by plotting the open

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Level Element

Damping Unit

Level Recorder & Controller

Level Transmitter

Slide-Wire
Potentiometers

Let Down
Valve

SYSTEM

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Pressurizer Level Control Loop

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FIG.
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loop characteristics for a given frequency, it is possible to obtain the associated closed loop response (Figures 7, 10, and 13). The closed loop value (actual condition of operation) is then plotted on a Bode Diagram (Figures 6, 9, and 12) for simpler recognition of loop characteristics.

Both the frequency and step responses of the control loop were obtained when one, two, and three damping units in series were included in the circuit between the level transmitter and level controller. The test set-ups are diagrammed in Figures 3 and 4.

To obtain the open loop frequency response of the system the sine wave generator output was connected to the controller. This input signal and the output from the level transmitter were recorded simultaneously on a two pen recorder as shown in Figure 3. If the mean value of the sine wave is equal to the signal of the actual liquid level, the output of the level transmitter will oscillate about a constant value and its phase and amplitude relative to the input sine wave can be recorded. Since, with the system feed back loop broken, there is no correction afforded by the controller, the mean value of the sine wave must be manually adjusted. This adjustment is quite sensitive, and constitutes a major factor in obtaining (or not obtaining) concise data.

When extra dampers are used, they can be placed outside the actual control loop in the line to the output recorder (Figure 4). In this manner, should trouble develop, e.g., if the level of the fuel falls below the critical limit, the system can be switched back to the controller without having the extra dampers (and hence larger lag time) in the system.

The step response of the closed loop was obtained by using a setup similar to that of Figures 3 and 4 except that only one recorder and no generator are used, i.e., valves "a" and "b" are open and valve "c" is closed. The controller set point was rapidly shifted to simulate a step input (i.e., moving the set point from 40% to 50% corresponds to a 10% step increase in the liquid level). A change of 100% in level corresponds to 5" in the pressurizer. However, the set point was kept between 30% and 70% for safety. The results were recorded and plotted to give Figures 8, 11, and 14.

To obtain the frequency response of the Taylor pulsation damper units, the output of the sine wave generator was fed into the unit and both the input and output were recorded. These results were handled in the same way as the system response data, except that no closed loop frequency response was made since it is meaningless for this case. These tests were performed with 0.062 inch diameter wires in the damper units; with 0.0505 inch diameter wires; and without any wires in them. The units were tested singly, in series, and in parallel. A schematic representation of the test setups used is presented in Figure 5.

RESULTS

The frequency responses of the three separate systems are shown in Figures 6, 9, and 12 while step responses are plotted in Figures 8, 11, and 14. The

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Pressurizer Level Control Loop
Frequency Response Test Set Up
System With One (1) Damping Unit

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FIG.

3

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Pressurizer Level Control Loop
Frequency Response Test Set Up
System With Many Damping Units

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FIG.
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A) Test Set Up For Frequency Response Of One Damping Unit.

B) Test Set Up For Frequency Response Of Series Connection.

C) Test Set Up For Frequency Response Of Parallel Connection.

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Set Up For Frequency Response
Of Damping Units

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FIG. 5

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BLACK-NICHOLS PLOT OF SYSTEM WITH ONE (1) DAMPING UNIT

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Black-Nichols Plot System With 1 Damping Unit			
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Step Response Of System With 1 Damper

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FREQUENCY RESPONSE DIAGRAM

MASSACHUSETTS INSTITUTE OF TECHNOLOGY ENGINEERING PRACTICE SCHOOL UNION CARBIDE NUCLEAR COMPANY A DIVISION OF UNION CARBIDE CORPORATION		FIG. 9
FREQUENCY RESPONSE SYSTEM WITH 2 DAMPING UNITS		FILE NO.
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Step Response Of System With 2 Dampers

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FIG.
11

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FREQUENCY RESPONSE DIAGRAM

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Frequency Response System With 3 Damper Units	
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FIG. 12	

BLACK-NICHOLS PLOT OF SYSTEM WITH THREE (3) DAMPING UNITS

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Black-Nichols Plot System With 3 Damper Units			
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m - CLOSED LOOP GAIN
 α - CLOSED LOOP PHASE ANGLE

OPEN LOOP PHASE ANGLE

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Step Response Of System With 3 Dampers

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three systems investigated are compared to a resonant system by use of a stability criterion (phase and gain margin). A measure of the rate of response for the systems has been determined by utilizing the damped stability criterion.

The stability criterion used is that the phase margin should be greater than 30° and the gain margin greater than 0.6. Phase margin is defined as the distance, in degrees, between the angle at which the open loop gain is unity and 180° . Gain margin is the distance between the open loop gain of unity and the open loop gain at 180° . Measured values for the system are given below in Table I, as obtained directly from Figures 6, 9, and 12. If the phase margin is less than 30° or the gain margin less than 0.6, the system may oscillate. As both phase and gain margins approach zero, i.e., output signal exactly coincides in all respects with the input signal, the system will resonate, resulting in unstable operation.

TABLE I
STABILITY AND RESPONSE CRITERIA

No. of Dampers	1	2	3	Criteria	
				Value	Type
Phase Margin (open loop)	55°	70°	60°	Exceed 30°	Stability
Gain Margin (open loop)	0.3	0.52	0.62	Exceed 0.60	
Maximum Offset Ratio (closed loop step response)	2.15-	2.4-	1.9-	Approx. 1.5	Response
	1.23+	1.33+	1.45+		

(Signs in the maximum offset data denote displacement of the set point. Positive (+) displacement closes the let-down valve and, conversely, negative (-) opens the valve.)

The damped stability criterion states that a decay ratio of 0.25 should be obtained for optimum response. The decay ratio is a measure of the amount of damping in the system (rapidity of oscillation decay).

The maximum offset, taken from the closed loop step response curves, is defined as:

$$\text{Max. offset ratio} = 1 + \sqrt{\text{decay ratio}} = \text{max. deviation/offset (See Figures 8, 11, and 14)}$$

Corresponding to a decay ratio of 0.25, the maximum offset ratio is 1.50. The maximum offset ratio is presented here since this was readily determined from the step response curves and since the decay ratio was not calculated directly. Tabulated results are presented in Table I.

The damper units have linear lag characteristics, as may be seen in Figures 15 through 18. These plots were useful in predicting the response of the system when more than one damper is installed.

During the tests the let-down valve operated erratically. This is probably attributable to the large frictional resistance in its operation (evident from the hysteresis curves, Figures 19 through 25). Figures 24 and 25 are data obtained with operation at identical conditions (same system and frequency) and attest to the erratic operation of the valve. Frequency and step responses of the valve can be obtained from the original data recordings.

CONCLUSIONS

It can be seen that the system with three dampers is the optimum one of those tested as it is the one that most closely approaches the criteria for stability and response.

The system is working satisfactorily because it is within a stable region. Its performance would be improved by including additional dampers in the system to damp out the resonance peak now present. Controller settings need not be changed, since they seem to be able to handle both large step changes and small pulsations quite successfully.

LOCATION OF ORIGINAL DATA

The original data are in: 1) M.I.T. Practice School Data Book No. 21, pages 1-37; 2) M.I.T. Practice School data book No. 27, pages 5-27; and 3) on rolls of recorder tape stored at the Instrument Division of REED (H.D. Wills).

Ralph Gelman

Charles Robertson, Jr.

FREQUENCY RESPONSE DIAGRAM

FREQUENCY RESPONSE DIAGRAM

FREQUENCY RESPONSE DIAGRAM

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Let-Down Valve Hysteresis Curve

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FIG.
19

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25

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Let-Down Valve Hysteresis Curve

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FIG.
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Let-Down Valve Hysteresis Curve

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Let-Down Valve Hysteresis Curve

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98

$\omega = 4.23 \text{ CPM}$

Air Pressure (volts DC)

Valve Travel (volts DC)

-0.2

-0.1

0.1

0.2

0.3

-0.1

-0.2

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Let-Down Valve Hysteresis Curve

DATE	DRAWN BY	FILE NO.	FIG.
10-25-56	RG		23

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Let-Down Valve Hysteresis Curve

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10-25-56	RG		24

620-490

30

$\omega = 2.64 \text{ cpm}$

Air Pressure (volts DC)

Valve Travel (volts DC)

0.2

0.1

0

0.1

0.1

0.2

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Let-Down Valve Hysteresis Curve

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10-25-56	RG		25

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APPENDIX

A. System Data

Controller

Foxboro Model 58P5, Serial Number 349215, Settings used were: Proportional band, 250%; Reset, 0.5 per minute; Derivative, 0.1 minute.

Sine Wave Generator

This was a Taylor Pneumatic Sine Wave Generator Number 227. The unit produces sine waves of the frequencies shown in Table II. The amplitude and bias of the signal is variable and the unit has a two pen recorder geared to the motor that drives the generator proper, thus three inches of tape are always equal to one cycle at any frequency.

Pulsation Dampers

These are Taylor Pulsation Damper Units, Model Number 58S104 with removable center wires. Several different sized wires are available. They can be used for either gas or liquid applications.

Recorder

A Sanborn two Channel Recorder, Model 150, Serial Number 152-100B; Serial 15, is used to record the output of two slide wire potentiometers. One is a Bourns Pressure Potentiometer No. 2985 connected to the controller output. The other is a simple slide wire attached to the valve stem.

B. Bibliography

Notes on Frequency Response for Process Control, Taylor Instrument Companies, 1954, 1955.

TABLE II

FREQUENCY CALIBRATION OF SINE WAVE GENERATOR

<u>Generator Setting</u>	<u>Manufacturer's Calibration (cpm)</u>	<u>Experimental Calibration (cpm)</u>
A	44.34	42.4
B	27.72	21.8
C	17.34	20.0
D	10.80	10.0
E	6.78	5.46
F	4.23	4.00
G	2.64	2.50
H	1.66	1.58
I	1.032	0.822
J	0.642	0.625
K	0.4026	-
L	0.252	0.241
M	0.1572	-
N	0.0984	-
O	0.0612	-
P	0.0384	-
Q	0.02388	-
R	0.015	-
S	0.00936	-
T	0.005856	-

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