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ASSESSMENT OF ENGINEERING PLANT ANALYZER WITH PEACH BOTTOM 2 STABILITY TESTS*

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ABSTRACT

Engineering Plant Analyzer (EPA) has been developed to simulate plant transients for Boiling Water Reactor (BWR). Recently, this code has been used to simulate LaSalle-2 instability event which was initiated by a failure in the feed water heater. The simulation was performed for the scram conditions and for the postulated failure in the scram. In order to assess the capability of the EPA to simulate oscillatory flows as observed in the LaSalle event, EPA has been benchmarked with the available data from the Peach Bottom 2 (PB2) Instability tests PT1, PT2 and PT4.

The PB2 stability tests were run by perturbing the pressure regulator set point with pseudo-random binary sequence signal of amplitude of 4 psi. The data from the tests were available in the form of power spectral density functions for the power and the core pressure, and gain and phase of the transfer function between the power and the pressure. EPA has been applied to simulate these PB2 tests. The time domain results from EPA simulations were analyzed by spectral analysis for predicting gain and phase, which were compared with their test values.

The EPA predicted for Peach Bottom Tests PT1, PT2 and PT4 the gain of the power to pressure transfer function with the biases and standard deviations of -10 ±28%, -1 ±40% and +28 ±52%, respectively. The respective frequencies at the peak gains were predicted with the errors of +6%, +3% and -28%. The phase shift for these three tests at the peak frequency was underpredicted by 93°, 35° and 42° respectively. These comparisons are for small amplitudes, but it compasses neutron kinetics, thermal fuel response, coolant thermohydraulics, and control systems. Considering the sensitivity of the frequency domain parameters to the inputs and the models in the code, the discrepancy in the code predictions are reasonably small. To our knowledge, this type of code validation for a time domain code has not been done in the recently published literature.

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I. BACKGROUND

On March 9, 1988 LaSalle County Plant, Unit 2 (GE BWR-5) suffered a power and flow instability event. The power and flow oscillations in this event were successfully terminated through a scram. This event renewed interest in the BWR stability analyses. The BWR instability of interest here is caused by density waves which generate power and flow oscillations. The density waves can develop in parallel heated channels with boiling and the wave can be enhanced by void reactivity feedback. The codes simulating the BWR instability must model nonhomogeneous, nonequilibrium two-phase flows, two phase multipliers for the wall friction and form losses, and the effects from void and temperature feedback to the fission power.

The Engineering Plant Analyzer (EPA)[1] is a time domain code which has been used to analyze the LaSalle event and to investigate transients which could arise from additional failures such as Anticipated Transient Without Scram (ATWS). This code has the four-equation drift flux formulation with constitutive relationships for the drift flux formulation[2], and nonequilibrium vapor generation rate[1]. The mixture momentum and mass balance equations are analytically integrated over the flow paths in the reactor vessel. The mixture energy and vapor mass balance equations are integrated over fifty-five computational cells in the reactor vessel. The resulting ordinary differential equations are explicitly integrated with respect to time. EPA also simulates the void and temperature feedback effects in the fission power predictions. Therefore, EPA has the capability to analyze instability events.

The United States Regulatory Commission (USNRC) requires that codes be validated with data which are relevant to the type of transient being analyzed. For the stability application, EPA's ability to predict oscillatory transients has been assessed with the Stability Tests at Peach Bottom Atomic Power Station Unit 2 at the End of Cycle 2[3]. The data are available in form of gain and phase shift between the system pressure and core power. The EPA results are in form of arrays of power and pressure as functions of time. The results have been processed by spectral analysis to obtain the gain and phase shifts for comparison with the data.

The EPA assessment, described in the following sections, covers the interactions of neutron kinetics, the fuel heat transfer, the thermohydraulics, as well as the balance of plant dynamics, including the pressure regulator and the feedwater control system.

II. PEACH BOTTOM STABILITY EXPERIMENTS

The objective of the Peach Bottom Core Stability Test was to show that small pressure perturbations can be used to demonstrate the BWR stability margin, to obtain data for the validation of stability analyses, and to demonstrate BWR stability at low core flow conditions. Here, we use the data for assessing the capability of the EPA to serve for stability analyses.

The Peach Bottom Stability tests were conducted by maneuvering the rector into the selected low-flow, steady initial conditions, as listed in Table I below, and then by introducing periodic step changes of 0.55 bar (8 psi) in the pressure regulator reference setpoint setting, starting with a down step. At first the steps were equally spaced at 10 second intervals. This method was then abandoned in favor of the more advanced pseudo-random binary stepping sequence with a 1 sec. sampling interval[4]. All the documented results were obtained by pseudo-random binary sequence stepping.

The system pressure and the fission power (APRM signal) were measured and the pressure to fission power transfer function was calculated from the measurements by nonlinear least-square fitting, in the frequency range between 0.02 and 1 Hz. From the calculated transfer function were then obtained the gain and the phase shift as functions of frequency[3] as well as the coherence between pressure and fission power. The coherence results indicate that the experimental results are valid only up 0.45 Hz and beyond this frequency the data are noisy.

Table I Initial Reactor Conditions Peach Bottom Stability Tests[3] (p. 3-6)

Test No.	Power MWt	Power %	Core Inlet Flow kg/s	Core Inlet Flow lb/hr 10^6	Core Inlet Flow %	Pressure bar	Pressure psia	Core Inl. Subcooling Temperature °C	Core Inl. Subcooling Temperature °F
PT1	1,995	60.6	6,627	52.6	51.3	68.9	1000	26.1	14.5
PT2	1,702	51.7	5,418	43.0	42.0	68.4	992	28.3	15.7
PT3	1,948	59.2	4,901	38.9	38.0	69.3	1005	11.5	6.4
PT4	1,434	43.5	4,901	38.9	38.0	68.9	999	27.4	15.2

It should be noted that Test PT3 is reported[3] to have a remarkably low Core Inlet Subcooling Temperature. A simple combination of global mass and energy balances with the mass and energy balances for the downcomer relates for steady state conditions the feedwater enthalpy h_{FW} to the specified total power P, the Core Inlet Mass Flow Rate W_{CI} and the specified Core Inlet Subcooling Enthalpy $(h_f - h_{CI})$ by

$$h_{FW} = h_f - \frac{h_{fg}}{\dfrac{P}{W_{CI}\,(h_f - h_{CI})} - 1}, \qquad (1)$$

where the liquid saturation enthalpy h_f and the evaporation enthalpy h_{fg} are evaluated at the vessel pressure. After evaluating Eq. (1) for Test PT3, subtracting from the result the feedwater enthalpy rise (9,141 J/kg) in the feedwater pump and looking up the corresponding feedwater temperature from the steam table, one finds that the feedwater exit temperature at the last feedwater heater would have had to be 59.3 K (106.8°F) higher than the steam inlet temperature of 469 K (196°C, 385°F) at the same heater. Since that is impossible (violation of Second Law of Thermodynamics), and since it was impossible to consult with the authors of the test documentation, it was decided to omit Test PT3 from the EPA assessment.

III. EPA SIMULATION OF PEACH BOTTOM STABILITY TESTS

A. Input Data and Initial Conditions

The EPA was set up for simulating the Peach Bottom Station Unit 2 for Cycle 2, with input data taken from the references listed in Table II. The Peach Bottom stability tests are documented in the EPRI report[3].

It was difficult to obtain consistent, plant-specific information from a single, reliable source. It was not available in the test reports[3]. The information was collected from different sources as shown in the last column of Table II, and inconsistencies had to be resolved, primarily in the information on core pressure drop and form loss coefficients.

The axial power shape was taken directly from documented tables[3] (pp. C-2,3 and 5). The radial peaking factor was computed by square power weighting of the data reported on the core cross-section[3] (pp. C-2,3 and 5).

Since it was impossible to obtain reactivity coefficients for Peach Bottom, we approximated the void, moderator and Doppler reactivity coefficients for Peach Bottom by those of the LaSalle-2 power plant, for the same fuel burn-up. This approximation is justified because LaSalle-2 has the same core size and the reactivities do not strongly depend on geometric fuel parameters.

Form losses at core entrance and exit affect the core stability strongly, but they had to be taken from two different publications since no complete source could be found.

As there was no information available for validating directly any of the important pressure regulator parameters, we matched the documented natural frequency of 0.25 Hz of the pressure regulator and the documented power spectral density of the pressure in the steam line[3] (p. 6-4).

Steady state conditions were achieved in the EPA at the same power and pressure levels as in the Peach Bottom tests. Table I shows the initial conditions for the three tests, Test Nos. PT1, PT2 and PT4 used in this assessment.

B. Transient Simulation

The pseudo-random binary sequence generator of J. March-Leuba[8] was used in the EPA, to superimpose a binary switching sequence on the pressure setpoint, at the output junction of the integrator to the right of the RPSP Block in the pressure regulator schematic shown in Fig. 1. The stepping was controlled to have the mean of zero and the amplitude of 0.276 bar (4 psi), that is the same peak to peak change as in the experiments, but without the steady-state drift caused in the experiment by the chosen off-on switching. Figures 2,3 and 4 show the pseudo-random binary sequence, core pressure and core power, respectively.

Table II List of Input Data References for Simulating Peach Bottom Stability Tests

Type of Data		Reference
Neutron Kinetics Parameters:		
Void Feedback	CVOID1, CVOID2	Reference 5, p.34[5]]
Axial Power Shape		Reference 3, pp. C-2,3 and 5
Radial Power Distribution (factor for spatial power square-weighting)		derived from Reference 3, pp. C-2,3 and 5
Fuel Specifications:		
Standard GE Fuel Design		75% 7x7 and 25% 8x8
Gap Conductance (constant)		5,678 W/(m^2 °K) 1,000 Btu/(hr ft^2 °F)
Thermohydraulic Parameters:		
Form Loss Coefficients:		
Core Inlet Channels	29	Reference 6, p. B-4
Core Exit Channels	1.35	Reference 7, Table II
Spacers, lower core	2.42	do.
middle core	3.63	do.
upper core	2.42	do.
Pressure Regulator (see Fig. 1):		
Lead/Lag Comp. Parameters τ_{p1}, τ_{p2}		Reference 1, (p. 3-140)
Actuator:		
Frequ. Coeff. k_{p1}	$= 4.15\ s^{-1}$	computed to match nat. frequ. of 0.25 Hz and PSD funct. for pressure Reference 3, p. 6-4. For symbols see Fig. 2, Reference 1, p. 3-140.
Damping Coeff. k_{p2}	$= 2.60\ s^{-1}$	normal HIPA value.

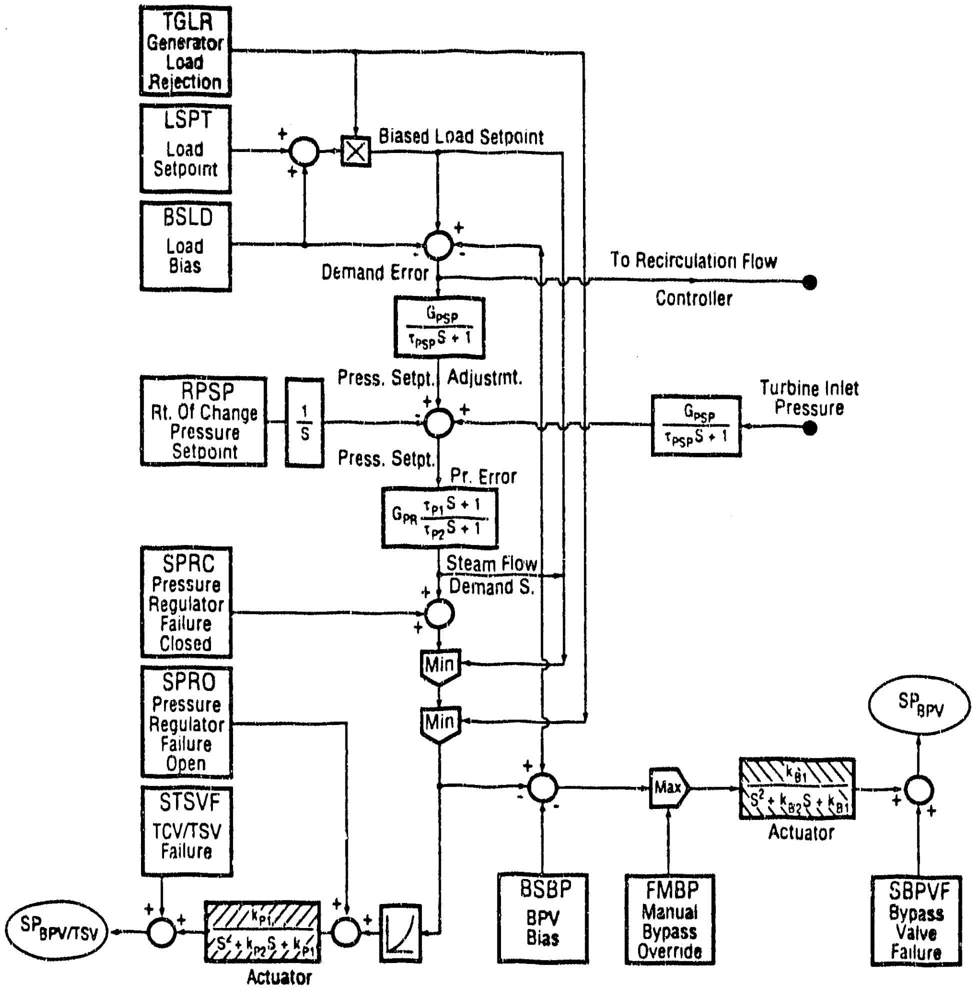

Figure 1 Pressure Control System Model
Engineering Plant Analyzer

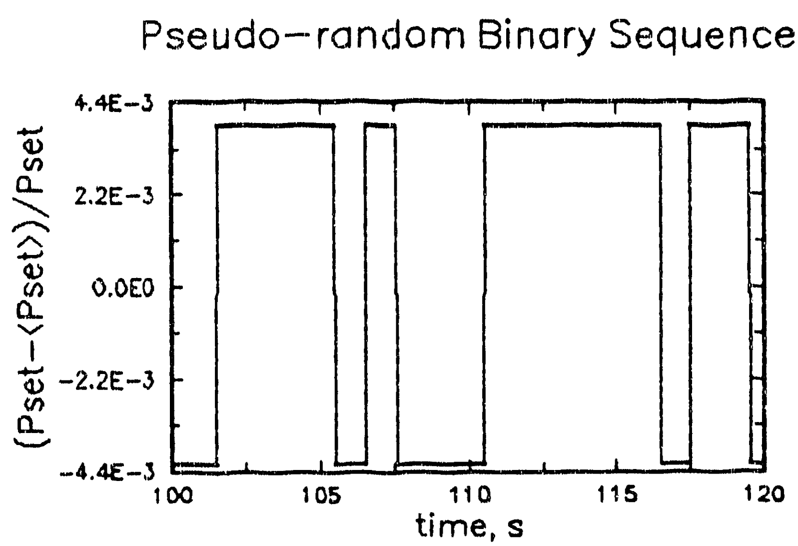

Figure 2 Pressure Regulator Set Point Perturbation
With Pseudo-random Binary Sequences

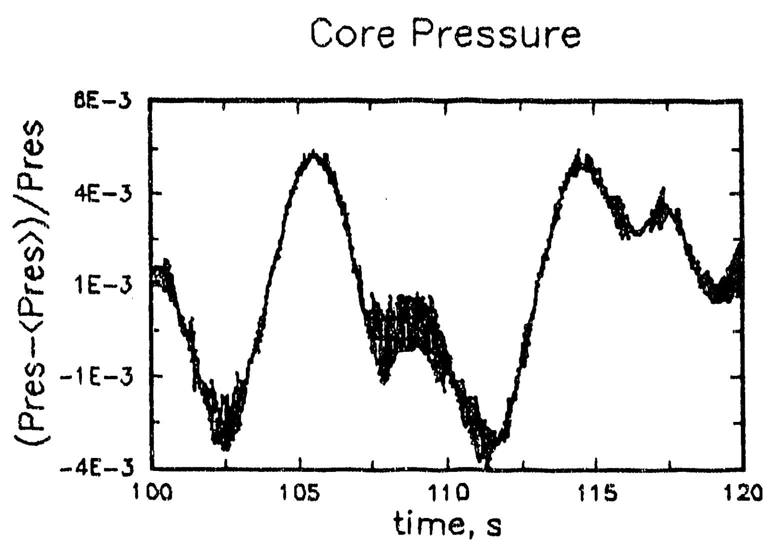

Figure 3 A Sample of Core Pressure Predicted by EPA For PRBS Perturbation in Pressure Regulator Set Point

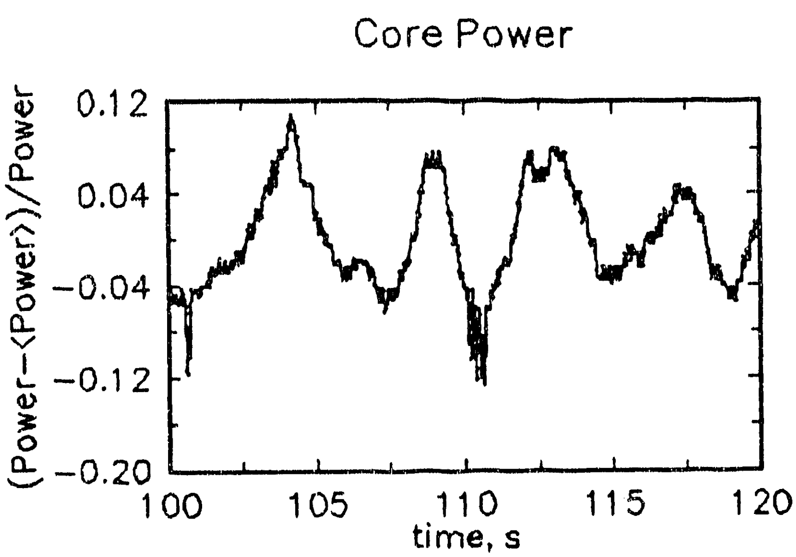

Figure 4 A Sample of Core Power Predicted by EPA For PRBS Perturbation in Pressure Regulator Set Point

C. Frequency Domain Results

Standard programs[8] for spectral analysis were used to calculate the complex transfer function, its gain and phase shift as functions of frequency. The details are given elsewhere[9] (Appendix E).

The spectral analysis introduces bias and random errors in the results due to the finite size (number of data points) and the finite number of blocks.

The bias error ϵ_b is estimated from the following expression[10], (page 76):

$$\epsilon_b = \frac{1}{3}\left[\frac{B_e}{B_r}\right]^2 = \frac{1}{3}\left[\frac{1}{N\cdot\delta t\cdot B_r}\right]^2 , \qquad (2)$$

where $B_e = 1/(N\bullet\delta t)$ denotes the frequency resolution, B_r is the frequency bandwidth associated with the gain equal to $1/\sqrt{2}$ times the maximum gain, δt is the sampling time interval, and N is the block size. The bias error decreases with the size N of the block, the sampling time interval and the half peak gain bandwidth[10] (page 21, Eq. (1.58)).

The transfer function also has a random error ϵ_r which is estimated from[10] (page 274):

$$\epsilon_r = [1 - \gamma^2_{PPr}]^{0.5} \;/\; \gamma_{PPr}\sqrt{n} \qquad (3)$$

where n is the number of blocks of size N and the coherence γ_{PPr} is defined by

$$\gamma_{PPr}(\omega_k) = \frac{CSD_{PPr}(\omega_k) * CSD_{PPr}(\omega_k)}{PSD_{PP}(\omega_k) * PSD_{PrPr}(\omega_k)} \qquad (4)$$

Furthermore, CSD and PSD are cross spectral density and power spectral density functions, respectively. Notice that the random error ϵ_r decreases as n, the number of blocks, increases.

For a fixed sample size $n\bullet N$, and without overlapping of data at the ends of data blocks, any attempt to decrease the bias error ϵ_b by increasing the block size N will lead to a reduction in n, the number of blocks, and thereby an increase in the random error ϵ_r. The choice of the block size N is governed by the need to control the bias error n_b within the limits between 0.5% and 2%. Experience showed[10], (page 268) that this bias error bracket is a reasonable compromise in balancing the two errors ϵ_b and ϵ_r with opposite trends.

1. Application of Spectral Analysis to Code Results

The EPA-computed pressure, fission power and time were transferred from the EPA to a Personal Computer. For each transient, 10,000 data triplets, consisting of pressure, fission power and time were transferred. The spectral analyses of all three EPA predictions were performed with the existing Personal Computer-based program[8]. This program utilized 8,192 of 10,000 supplied data points. The 8,192 data points were divided into four blocks of 2,048 points each. Three additional blocks were formed by combining one half of the points in the first four blocks with the adjacent half of the neighboring block. An eighth block contained the first half of the first and the last half of the fourth block. Thus, there were

n=8 blocks of N = 2,048 points.

Table III
Spectral Analysis Results and Error Estimates

Test Number	Block Size N	Number of Blocks n	Time Step, δt s	Peak Gain (Power/ Pressure) G_{max}	Frequency at Peak Gain ω Hz	Coherence at Peak Gain γ_{PP_r}	Bias Error, ϵ_b %	Random Error, ϵ_r %
PBT1	2048	8	0.0305	48	0.34	0.79	0.5	27.4
PBT2	2048	8	0.0305	69	0.37	0.82	1.06	24.4
PBT4	2048	8	0.0305	79	0.29	0.84	1.97	22.4

Table III summarizes the results of the calculations. In this table, columns 1 to 7 list the test numbers, the block sizes N and the numbers n of blocks used in the spectral analysis, the sampling time interval δt, the peak gain G_{max} the frequency ω at the peak gain, and the coherence γ at peak gain, respectively. The remaining two columns show the bias error ϵ_b and the random error ϵ_r, respectively. The bias errors are under 2.1%, so the block size is acceptable. The largest random error is 27.4%.

IV. COMPARISON BETWEEN EPA AND PEACH BOTTOM TEST RESULTS

The pressure regulator model in the EPA was tested by comparing the EPA-predicted power spectral density with the reported power spectral density of the pressure. The result is shown in Figure 5 and demonstrates that the pressure control system in the EPA does not filter out or unduly excite the system pressure.

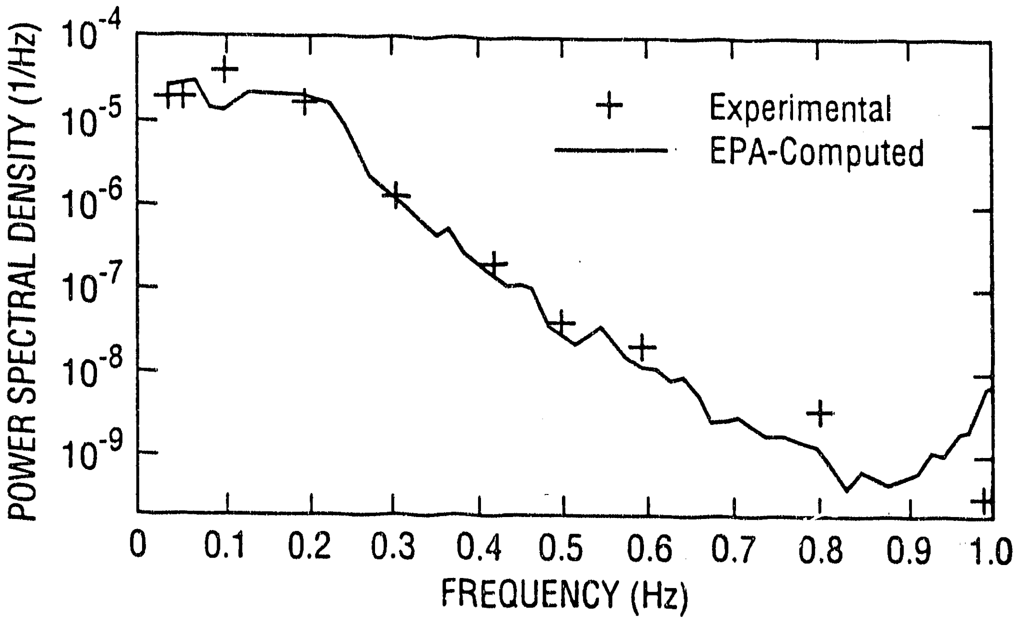

Figure 5 Power Spectral Density Functions. Comparison of EPA-Computed (solid line) and Experimental Results (dashed line) for Testing Pressure Regulator Model in EPA.

Table IV
Comparison of EPA Prediction of Gain With Experimental Data from Peach Bottom Stability Tests

	Test PT1			Test PT2			Test PT4		
	Exp.	EPA	Dif.	Exp.	EPA	Dif.	Exp.	EPA	Dif.
Hz	%	%	%	%	%	%	%	%	%
0.04	5.0	2.5	-50	4.8	3.3	-31	4.2	2.9	-31
0.06	5.0	3.9	-22	4.8	3.8	-21	4.2	4.5	7
0.08	5.0	5.6	6	5.0	5.4	8	5.7	6.0	5
0.10	8.0	7.2	-10	7.0	8.6	23	6.6	8.4	27
0.20	14.5	18.0	24	14.0	23.0	64	16.4	29.0	77
0.29							38.	79.	108
0.30	29.	38.	31	38.	46.	21	40.	76.	85
0.32	49.	44.	-10						
0.34	46.	48.	4						
0.37				53.	69.	30			
0.38				55.	61.	11			
0.40	37.	28.	-24	51.	34.	-33	55.	32.	-41
0.50	47.	23.	-51	93.	20	-78	36.	44.	22

While these two effects have in principle no impact on the pressure to power transfer function, they affect very strongly the signal to noise ratio and the coherence.

Table IV shows for selected frequencies the experimentally obtained and the EPA-predicted gains and phase shifts, along with the differences. The bold values are the peak values. Unlike the experimental data, the predicted pressure and fission power data were not fitted to "empirical models", but processed directly by Fast Fourier Transform. The coherence at the computed peak gain is 0.75, 0.70, and 0.82, respectively, for Tests PT1, PT2 and PT4.

The Table shows that the EPA underpredicted the gain vs. frequency curve by the means and standard deviations of -10 ±28% and of -1 ±40% for Tests PT1 and PT2, respectively, and overpredicted for Test PT4 by +29 ±52%. The test with the lowest power came out with the lowest signal to noise ratio and the largest difference between test data and prediction.

Figures 6 through 8 show the graphical comparison between experiment and prediction for the gain of the pressure to power transfer function, Figures 9 through 11 show the corresponding phase shift comparison. The bars with the open circles in these figures represent the uncertainty in the data.

V. CONCLUSIONS

The EPA predicted for Peach Bottom Tests PT1, PT2 and PT4 the gain of the power to pressure transfer function with the biases and standard deviations of -10 ±28%, -1 ±40% and +28 ±52%, respectively. These error estimates can be viewed with the perspective of 70% gain error reported by Yadigaroglu[11], (page 376). The respective frequencies at peak gain were predicted with errors of +6%, +3% and -28%. This comparison is for small amplitudes, but it encompasses neutron kinetics, thermal fuel response, coolant thermohydraulics, and control systems. We are not aware of a published comparison between test data and a time domain computer prediction, such as the one presented here.

Based on the assessment presented here, it is concluded that the EPA is reliable for analyzing small-amplitude oscillations.

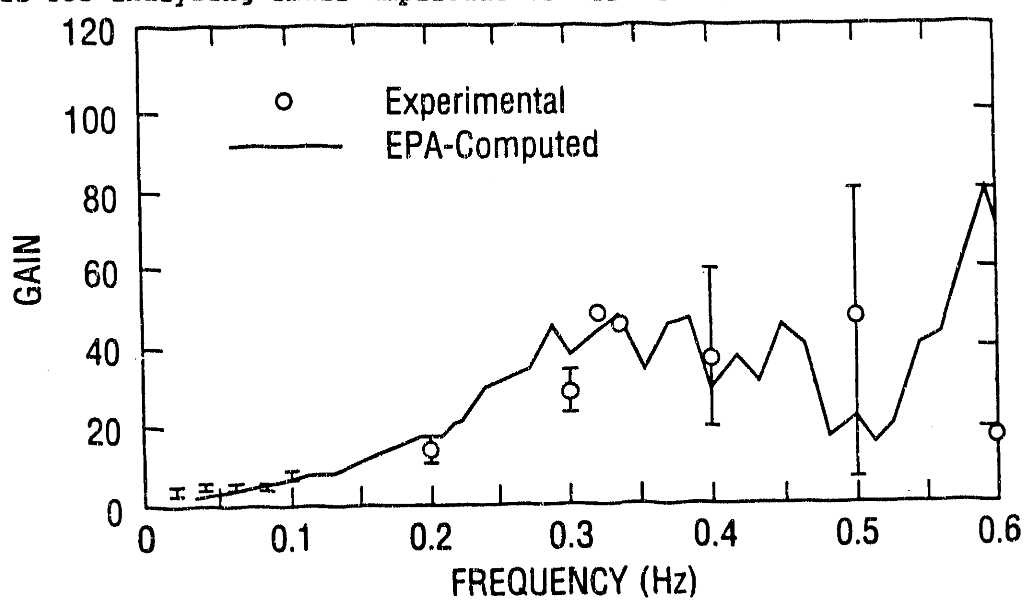

Figure 6 Gain of Power to Pressure Transfer Function for Peach Bottom Test PT1. Power and pressure are normalized by initial values.

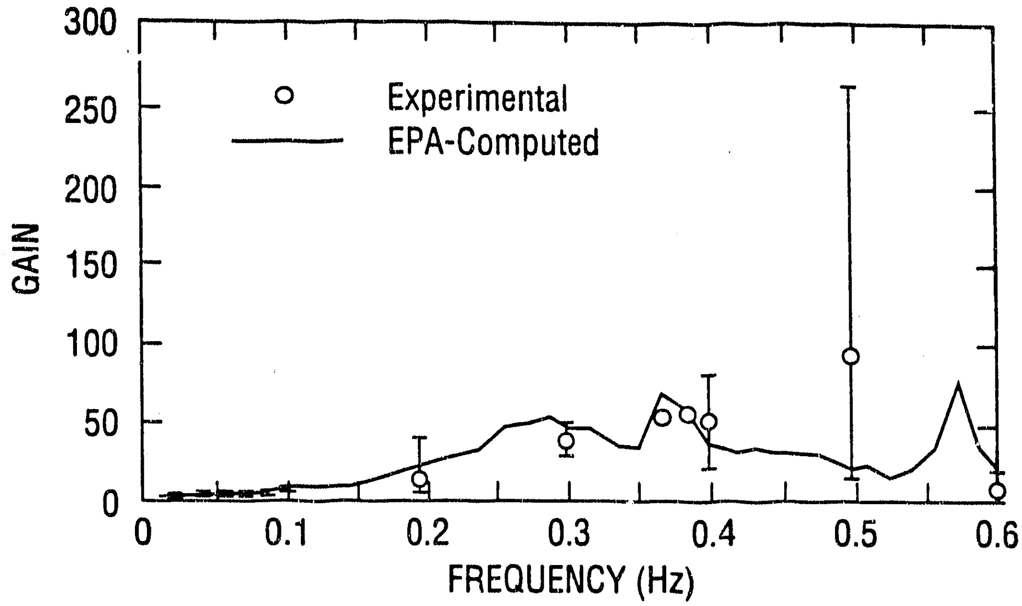

Figure 7 Gain of Power to Pressure Transfer Function for Peach Bottom Test PT2. Power and pressure are normalized by initial values.

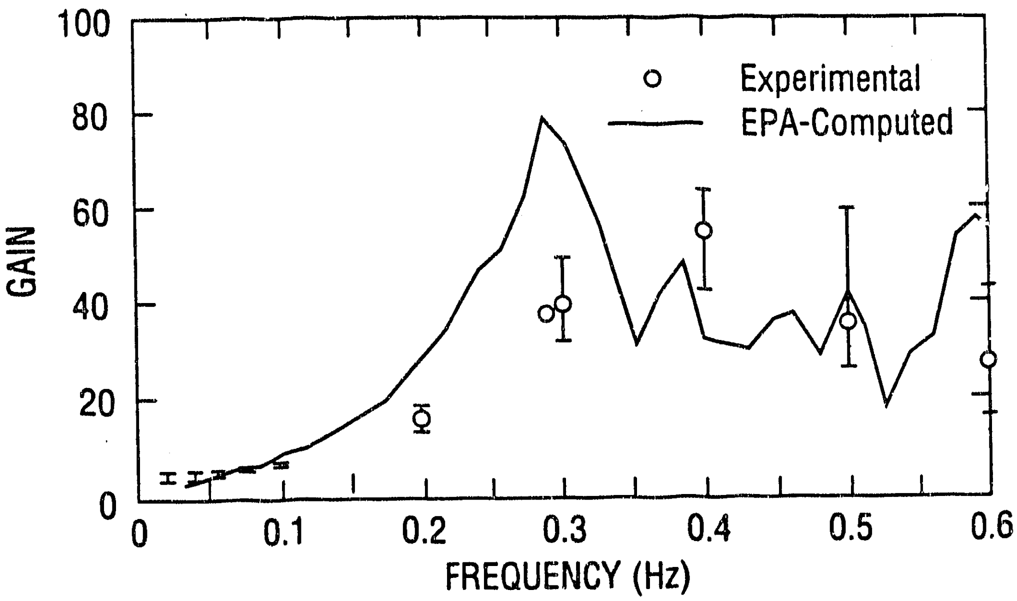

Figure 8 Gain of Power to Pressure Transfer Function for Peach Bottom Test PT4. Power and pressure are normalized by initial values.

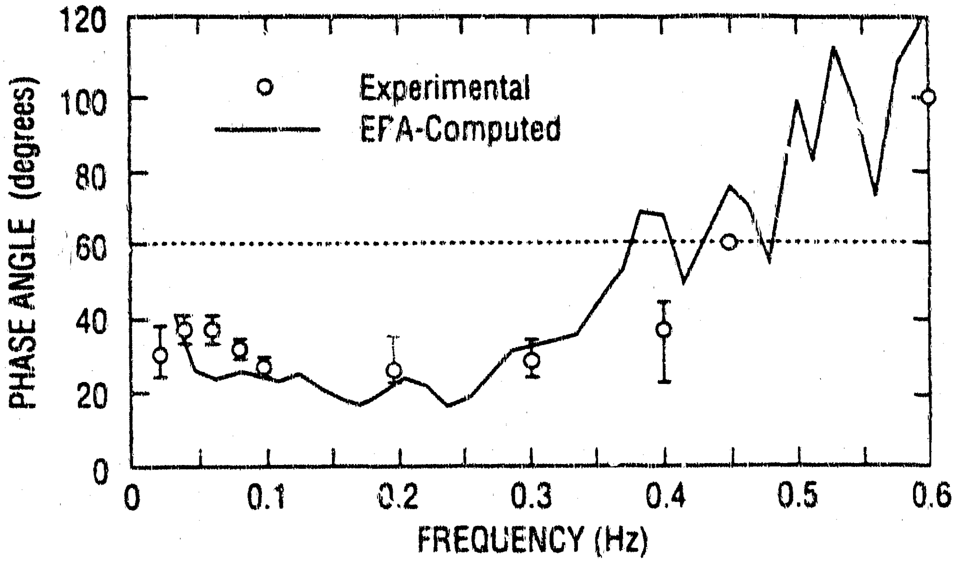

Figure 9 Phase Angle of Power to Pressure Transfer Function for Peach Bottom Test PT1. Power and pressure are normalized by initial values.

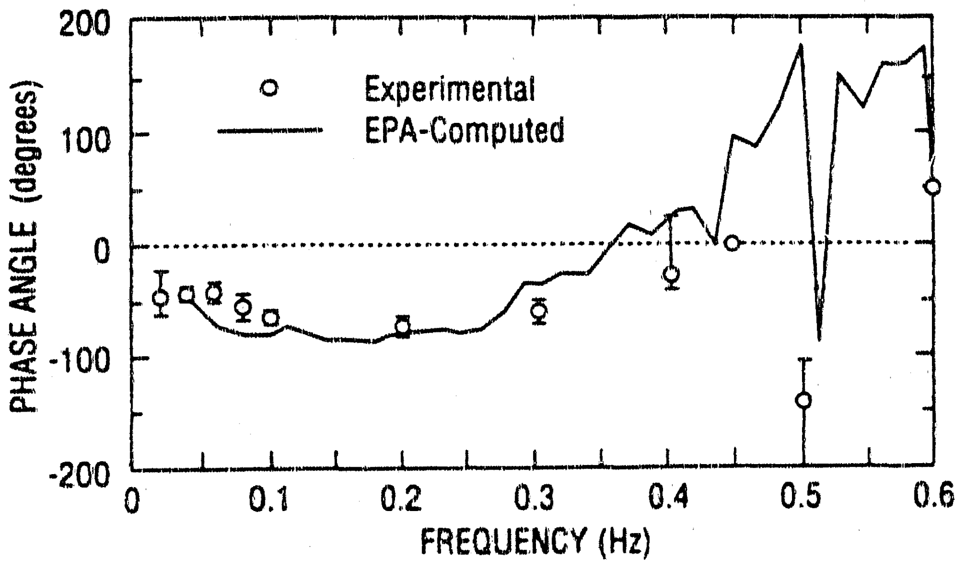

Figure 10 Phase Angle of Power to Pressure Transfer Function for Peach Bottom Test PT2. Power and pressure are normalized by initial values.

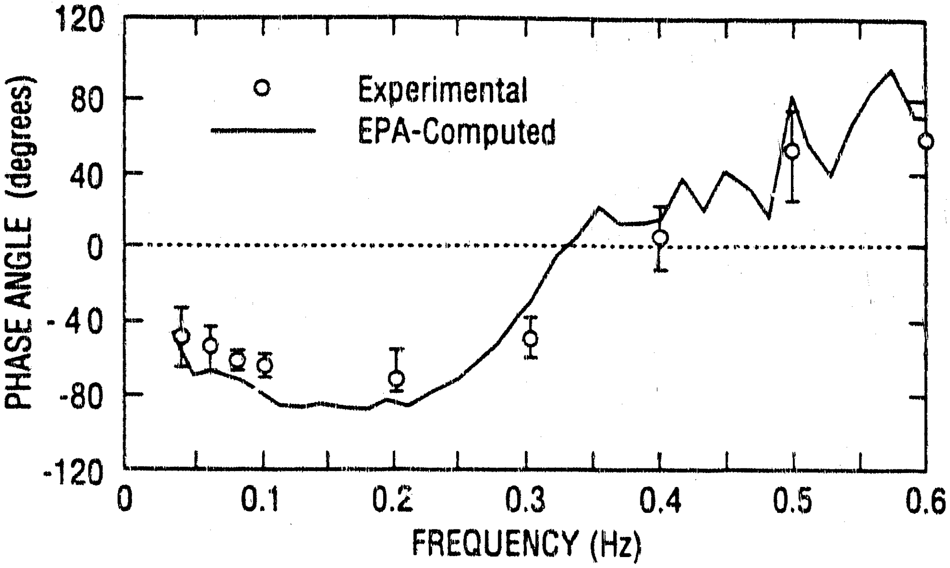

Figure 11 Phase Angle of Power to Pressure Transfer Function for Peach Bottom Test PT4. Power and pressure are normalized by initial values.

VI. NOMENCLATURE

B_e	frequency resolution
Br	half power point band width
CSD	Cross Spectral Density
n	number of blocks
N	block size
P	Power
Pr	Pressure
PSD	Power Spectral Density
T	duration of the transient for one block
δt	Sampling time internal t
γ_{PPr}	coherence between P and Pr
ϵ_b	bias error
ϵ_r	random error
θ	phase Angle
ω	frequency
*	complex multiplication

Subscripts

P	power
Pr	pressure

VII. REFERENCES

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