

EXPERIENCES WITH DYNAMIC TESTING METHODS AT THE MOLTEN-SALT REACTOR EXPERIMENT



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A series of reactivity-to-power frequency response measurements was made on the Molten-Salt Reactor Experiment. This was done for ²³³U and ²³⁵U fuels, for a range of operating power levels, at several points in the system operating history, and for several different test procedures. A comparison of experimental results with prior theoretical predictions confirmed the validity of the theoretical predictions. The test program included measurements using the pseudorandom binary sequence, pseudorandom ternary sequence, n-sequence, and the multifrequency binary sequence.



I. INTRODUCTION

An extensive dynamics testing program was carried out at the Molten-Salt Reactor Experiment (MSRE).¹ The tests consisted of reactivity to power frequency response measurements. The purpose of the test program was:

1. to demonstrate the safety and operability of the system
2. to check the validity of the theoretical analysis so that the safety of the plant could be

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reassessed if necessary and so that confirmed methods could be established for analyzing future, high-performance molten-salt reactors

3. to evaluate techniques for performing dynamics experiments and methods of data analysis.

Tests were performed at several different power levels, at several different times in the system's operating history, and for the reactor fueled with ²³⁵U and with ²³³U. Items 1 and 2 were the main objectives of the test program, but this paper emphasizes item 3 since it should be of general interest to those planning dynamics tests in other systems. Those interested only in the performance of the MSRE could skip Secs. II and III and proceed directly to the results in Sec. IV.

II. PLANNING THE TESTS

A. Objective

The primary test objective was to measure the reactivity-to-power frequency response over the range of frequencies where important system dynamic effects occurred. Inspection of the frequency response predictions (see Figs. 8 and 14 of Ref. 1) indicated that measurements down to ~0.005 rad/sec at the low frequency end were needed. It would have been desirable to carry the high frequency end of the measurements out to about 50 rad/sec if the zero-power reactor kinetics effects were to be observed. If the interest were in feedback effects, the upper frequency need not have been greater than ~0.5 rad/sec. The approach used here was to determine the high frequency (1.0 to 100.00 rad/sec) response by noise

measurements during zero-power operation. Subsequent at-power measurements concentrated on the 0.005- to 0.5-rad/sec range where feedback effects were important.

B. Equipment Used in Experimental Measurements

The selection of the experimental methods for the MSRE dynamics tests was based on the information required and on the capabilities of the available equipment. Fortunately, the emphasis on low frequency results (0.005 to 0.5 rad/sec) made it possible to obtain the important part of the system frequency response using the standard MSRE control rods to introduce the input reactivity perturbations.

The MSRE has three identical control rods, each with an active length of 59.4 in. One rod is normally designated as the regulating rod and is used for fine control. The other two rods are used as shim rods for coarse adjustments. The rods are actually flexible, stainless-steel hoses on which are strung gadolinium oxide poison cylinders. The rods are mounted in thimbles which have two 30-deg offsetting bends so that the rods can be centrally located even though there is no room for the control-rod drive assemblies above the central axis of the core. The maximum rod speed is ~ 0.5 in./sec. Typical rod travel in the experiments was ~ 0.5 in. for most of the ^{235}U tests and 0.3 in. for most of the ^{233}U tests. This gave a reactivity change of $\sim 0.025\%$ (7¢) in the ^{235}U tests and $\sim 0.02\%$ (12¢) in the ^{233}U tests.

Figure 1 shows the control-rod and drive assembly. The position indication for each rod was obtained from a synchro geared to the rod drive mechanism. A coarse synchro (5-deg rotation per inch of rod travel) was used in early tests and a fine synchro (60-deg rotation per inch of rod travel) was used in later tests. The signal from the position synchro was amplified and low-pass filtered (1-sec time constant) to eliminate high-frequency noise and the accompanying aliasing effect prior to input into the Bunker Ramo computer, BR-340, where the signal was digitized every 0.25 sec and recorded on magnetic tape.

The nuclear power level signal was furnished by the output of a compensated ion chamber located adjacent to the core. This signal was also amplified, low-pass filtered (1-sec time constant), digitized at 0.25-sec intervals, and recorded on magnetic tape.

The BR-340 computer was also used in conjunction with a portable analog computer for generation of the input signal for the test. A computer program was prepared for on-line generation of each test signal used in the tests (the signals are described in Sec. II.C.2).

C. Test Signals

1. *Introduction.* Test signal selection was influenced by considerations of accuracy requirements, frequency range over which information was needed, and hardware capabilities. The following input signals were used during the testing program:

- a. pulse
- b. step
- c. pseudorandom binary sequence
- d. pseudorandom ternary sequence
- e. n -sequence
- f. multifrequency binary sequence (flat input spectrum)
- g. multifrequency binary sequence (prewhitened output spectrum).

Pulse and step tests are easy to implement, but these signals give results with limited accuracy. This is because the signals are nonperiodic, and therefore have a continuous frequency spectrum and resulting low signal energy in the neighborhood of a frequency of interest.

The other five signals are more trouble to implement, but they permit more accurate results. This is because they are periodic, and therefore concentrate the signal energy in discrete harmonic frequencies. In all of the tests using periodic signals, the period is determined by the lowest desired frequency:

$$T = \frac{2\pi}{\omega_1}$$

where

T = period

ω_1 = lowest desired frequency.

For example, the required period for a test in which the lowest required frequency is 0.01 rad/sec in 628 sec. All other harmonics would be at integer multiples of 0.01 rad/sec. The accuracy of the results is improved by using input signals consisting of more than 1 cycle. In the MSRE measurements 2 to 10 cycles were used.

2. Properties of Input Signals.

a. *Pulse.* The energy density e of a pulse of duration T and amplitude A at frequency ω is given by:

$$e = \frac{A^2 T^2}{2\pi} \left[\frac{\sin(\omega T/2)}{\omega T/2} \right]^2$$

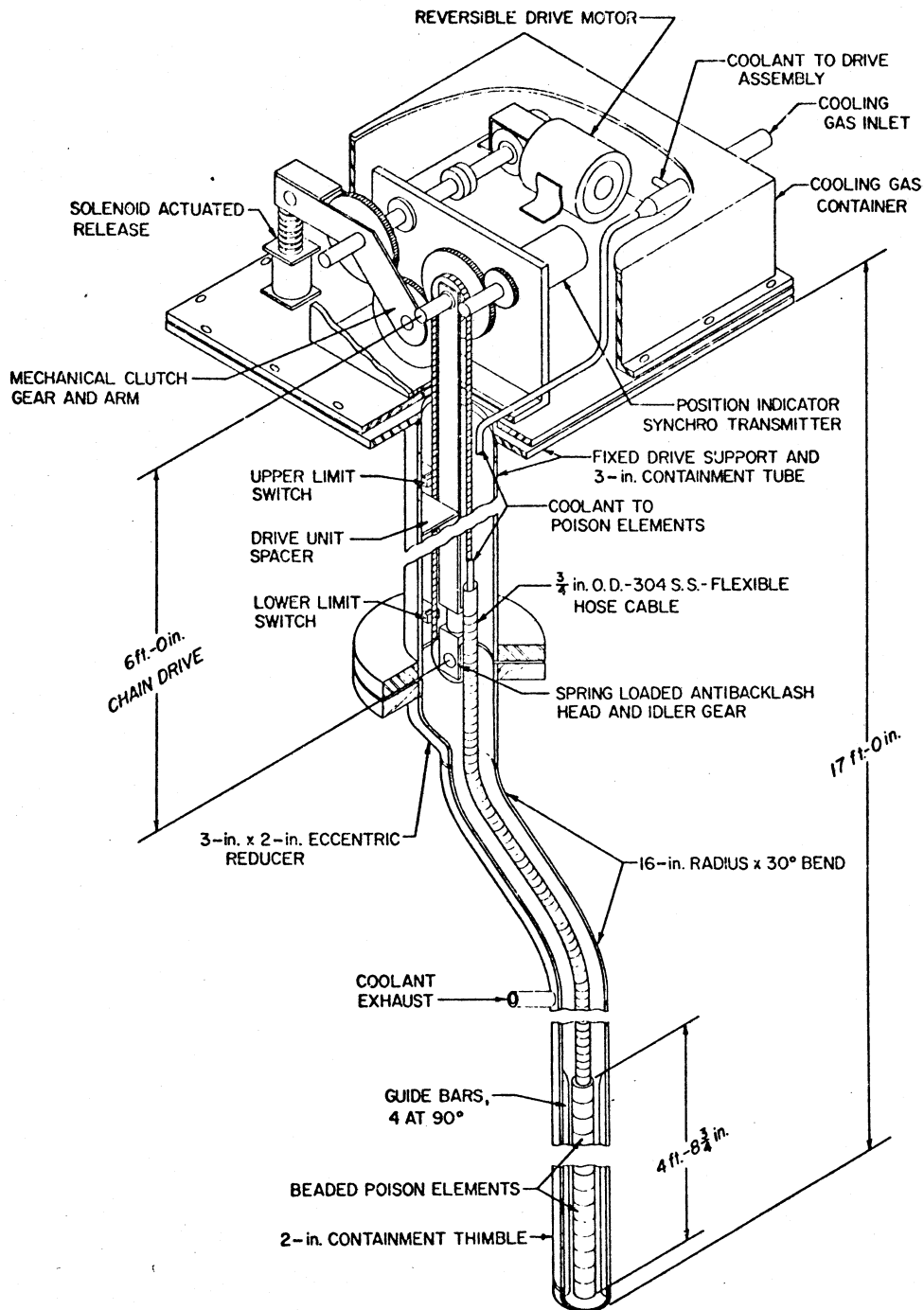


Fig. 1. Control-rod drive assembly.

This spectrum appears in Fig. 2. Note that the amplitude is expressed as energy spectral density (energy per unit frequency).

b. *Step.* A step input may be thought of as a pulse whose duration has gone to infinity. The step test is suitable only for systems whose response settles to some constant value after the

step input. This requires that the system's zero-frequency gain be a finite constant (including zero). In principle, the step input contains an infinite amount of energy, but this energy is concentrated in the low frequencies where it is of little use.

c. *Pseudorandom Binary Sequence.* The pseudorandom binary sequence (PRBS) is often used

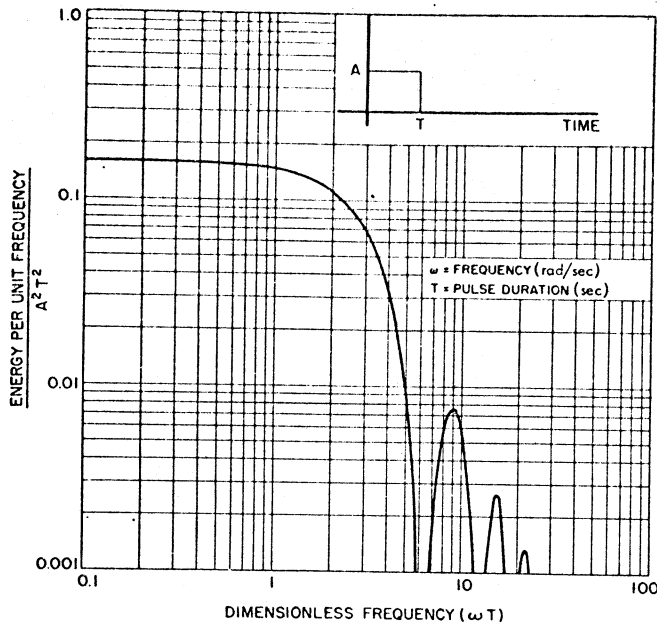


Fig. 2. Energy spectrum of a square pulse.

for frequency response measurements and for approximate impulse response measurements. The methods for generating the PRBS are well known.^{2,3} These methods give periodic sequences of +1's and -1's (each member of the sequence is called a bit). The total number of bits in the sequence N must be $2^Z - 1$ for any integer value of Z . The period of the signal is given by the product of the number of bits N and the bit time interval Δt .

The spectrum of the PRBS with pulse amplitude A and total test duration T is given by:

$$A_k = 2 \frac{(N + 1)A^2 T}{N^2} \left[\frac{\sin(k\pi/N)}{k\pi/N} \right]^2 \quad \text{for } k \neq 0$$

$$A_0 = \frac{A^2 T}{N^2} \quad \text{for } k = 0, \quad (1)$$

where A_k = amplitude of the energy spectrum at the k 'th harmonic frequency. The spectra for several sequences are shown in Fig. 3. Note that the short sequences concentrate most of the signal energy in the first few harmonics and the longer sequences spread the signal power among more harmonics.

In planning a test, one must select the period to give the required lowest frequency. The required upper frequency fixes the sequence length N or equivalently (since the period is fixed) the bit duration. The following relation specifies the harmonic number at which the signal power is half as large as the amplitude of the harmonic with the

greatest amplitude³ (thereby furnishing a measure of the bandwidth of the signal):

$$k_h = 0.44 N, \quad (2)$$

where k_h = harmonic number of the harmonic with half the power as the harmonic with the greatest power. Thus, if the lowest frequency is ω_1 rad/sec, and the required highest frequency is ω_h rad/sec, then the number of bits is given by:

$$N = 2.27 \frac{\omega_h}{\omega_1}. \quad (3)$$

The bit duration Δt is fixed by the highest frequency of interest. The relation is

$$\Delta t = \frac{2.77}{\omega_h}. \quad (4)$$

Of course, these are just rules of thumb. If the total signal energy is too small, the signal energy per harmonic may be too small even for the harmonic with the largest amplitude.

d. *Pseudorandom Ternary Sequence.* The pseudorandom ternary sequence⁴ (PRTS) is similar to the PRBS, but three levels of the input signal are

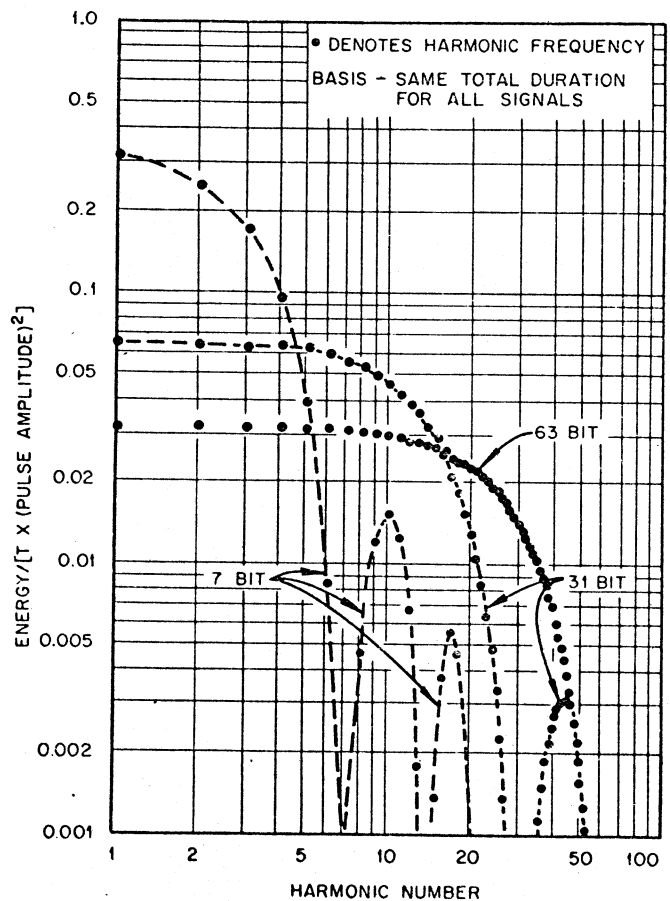


Fig. 3. Energy spectrum for several PRBS signals.