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# INSTRUMENTING A PRESSURE SUPPRESSION EXPERIMENT FOR A MARK I BOILING WATER REACTOR - ANOTHER MEASUREMENTS ENGINEERING CHALLENGE

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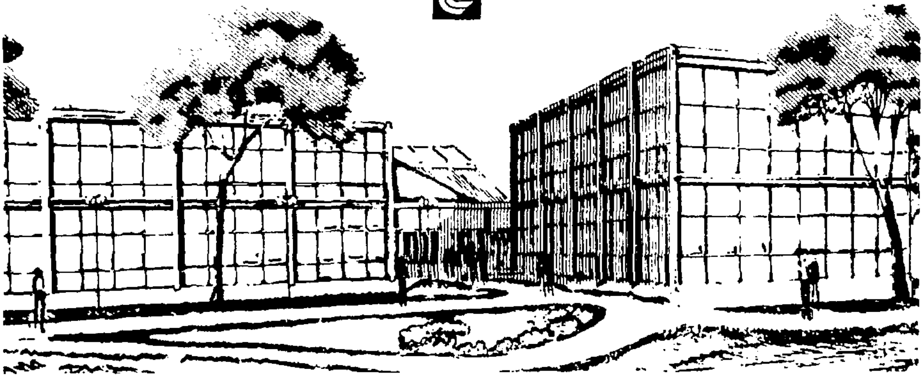

**MASTER**

# INSTRUMENTING A PRESSURE SUPPRESSION EXPERIMENT FOR A MARK I BOILING-WATER REACTOR — ANOTHER MEASUREMENTS ENGINEERING CHALLENGE*

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## ABSTRACT

A 1/5-scale test facility of a pressure-suppression system from a Mark I boiling water reactor was instrumented with seven types of transducers to obtain high-accuracy, dynamic loading data during a hypothetical loss-of-coolant accident. A total of 27 air tests have been completed with an average of 175 transducers recorded for each test. An end-to-end calibration of the total measurement system was run to establish accuracy of the data. The instrumentation verified the analysis of the dynamic loading of the pressure-suppression system.

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## PURPOSE OF EXPERIMENT

The primary purpose of the experiments was to determine the vertical forces that occur on the pressure suppression system during a hypothetical loss-of-coolant accident (LOCA), for a Mark I boiling water reactor (BWR).

The success of a pressure-suppression containment system design for a light water reactor is based on the capability of a large water sink to provide rapid and stable condensation of the primary coolant released during a LOCA. The pressure suppression system for the Mark I BWR design includes a drywell that surrounds the reactor (Fig. 1). The steam released from a break of a line in the drywell during a LOCA is discharged into the drywell resulting in the injection of air, followed by steam, to a toroidal wetwell via vent pipes that are connected to a smaller torus inside the wetwell. Downcomers are connected from this torus to direct the steam under the water sink. The steam condenses on contact with the water, releasing energy and keeping the pressures inside the drywell and wetwell below safe and containable limits.

At the Lawrence Livermore Laboratory (LLL) a 1/5-scale facility of the pressure-suppression system was designed and constructed as part of the Safety Research Program of the Mark I class of reactors for the Nuclear Regulatory Commission (NRC). Figure 2 shows a plan view of the test facility at LLL. In the actual reactor the wetwell completely surrounds the drywell, but for our tests only a 90° sector of the wetwell was

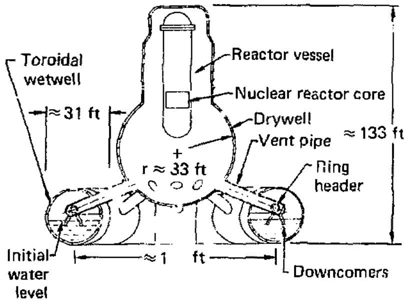

FIG. 1. Cross section of a Mark I boiling-water reactor.

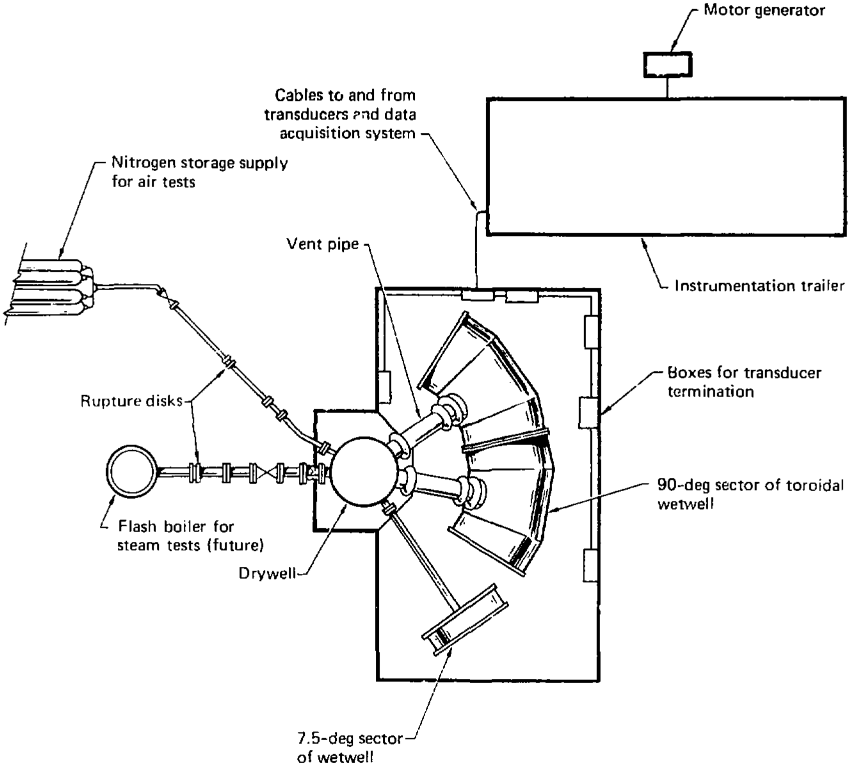

FIG. 2. Schematic diagram of the 1/5-scale experimental facility (plan view).

used.[1] A 7.5° sector was also built and tested concurrently, so that two- and three-dimensional results could be compared in a single test.

The experimental program was divided into two phases: air tests and steam tests. The air tests consisted of purging the drywell with air, as in a LOCA, by using high-pressure nitrogen gas to expel water from the downcomers into the toroidal wetwell. This "clearing" of the downcomer water resulted in vertical loads to the wetwell.

A typical LOCA would be simulated as follows: the storage bottles would be pressurized with a specified volume of nitrogen to a level that would produce the desired drywell pressure-time history; the drywell and toroidal wetwells would be evacuated to 1/5-atm; the data recording systems would be turned on and a rupture disk burst to initiate the air flow. The test is complete in approximately 20 s, with the vertical load occurring in the first few seconds. The steam tests[*] will consist of forcing saturated steam into the drywell to purge out all the air from the drywell. The steam would then continue to the wetwell to be condensed. This clearing also results in vertical loads to the wetwell.

The prime measurement for the pressure-suppression system was the vertical loads in the toroidal wetwell which were measured by load cells supporting the wetwell, and by integrating the pressure-time history for pressure transducers installed on the wetwell. Figure 3 shows a cross section of the scale pressure-suppression system experiment with the load cells supporting the wetwell. Figure 4 shows the 1/5-scale facility at LLL.

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[*] At this time the steam tests have not been conducted and are scheduled for fiscal year 1978.

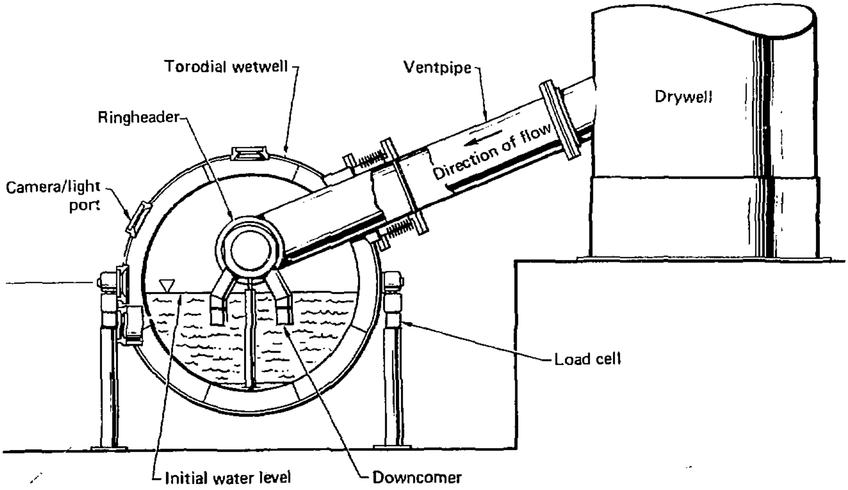

FIG. 3. Cross section of the 1/5-scale pressure suppression experimental system.

FIG. 4. Photograph of the 1/5-scale Mark I BWR test facility at LLL.

## PHILOSOPHY OF A MEASUREMENTS ENGINEER

When a measurements problem at LLL arises, we believe that the last thing we should do is to grab any transducer and recorder. With careful analysis of the problem and a good measurements system design, it is possible to fulfill the program requirement for valid, noise-free data, the first time around. To obtain this kind of data implies that the transducer and data acquisition system are selected for their applicability and not their availability. This is true whether the experiment is dynamic or static in nature. The responsibility of a measurements engineer is to select the proper instrumentation system to the best of his ability while under many outside pressures.

Our philosophy for selecting the instrumentation system for the pressure-suppression experiment, from the transducer to the data acquisition system, was based on the following guidelines:

- All transducers were designed and selected for the steam tests. Our requirements for most of the transducers were that they give valid data when exposed to a thermal transient of 300°F and 50 psig for 30 s. We were hoping for a maximum error of less than 1% as a result of the thermal transient.
- Each transducer was inspected and static-calibrated under laboratory conditions to insure that those fielded actually met the rigid performance requirements of this experiment.
- Because the noise level could not be defined before the testing started, a grounding and shielding technique with the most options was used.
- The total error, from the transducer to the final data plot, was kept as low as possible. Our target, and main concern, for this experiment was a maximum error of less than 2% of the full-scale range set on the data acquisition system for a specific transducer.

A common suggestion from the project personnel was: "To get more accurate data just purchase a more accurate transducer". While this is partially true, and a natural statement for someone not acquainted with the instrumentation and its limitations, it is not only the transducer but the complete instrumentation system, from the transducer, to the data acquisition system, to the final data plot that determines the accuracy. It is our job as measurements engineers to inform project personnel of these facts and then arrive at compromises that satisfy both project requirements and what is practically attainable. This goal then was the challenge for the experiment.

## TRANSDUCER - SELECTION AND CALIBRATION

To analyze the pressure-suppression system we had seven types of transducers: (1) pressure, (2) load, (3) temperature, (4) acceleration, (5) strain, (6) displacement, and (7) pool swell. There were 489 possible locations on the major components for transducers including 290 for pressure, 8 for load, 101 for temperature, 8 for acceleration, 21 for strain, 11 for displacement, and 50 for pool swell. The large number of locations gave us flexibility to meet the requirements of the project personnel. We did not have a transducer in each location, but we did record data from an average of 175 transducers on the 27 air tests.

Instead of describing each transducer in detail, we will concentrate mainly on the pressure transducers because we had over 100, and the pressure measurements (secondary measurements), comprised the majority of measurements that we performed.* The selection and calibration of the pressure transducers were the most difficult, and also the most frustrating. Figure 5 shows the 90° sector of the wetwell with all the possible locations specifically for pressure transducers.

The two major problems in selecting the transducers were protecting against a thermal transient and selecting one with a low static error band. Many transducers manufactured today will operate continuously at temperatures of 1000°F, but virtually all pressure transducers will give erroneous data when exposed to a thermal transient.

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*For a more detailed description of the remaining transducers see Reference 2.

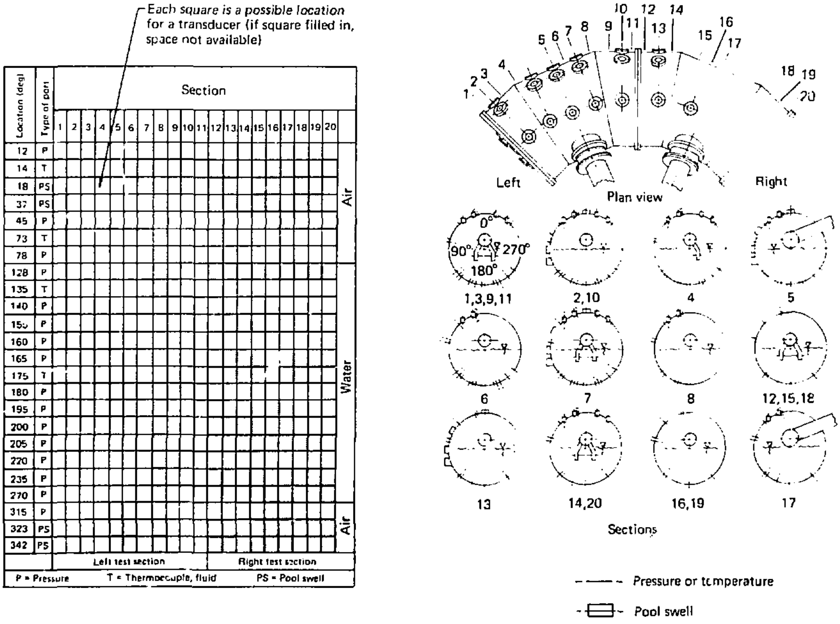


FIG. 5. Transducer locations for the 90° wetwell.

We grouped the pressure transducers for the thermal transient into two categories for our evaluation process: (1) diaphragms with thermal barriers, and (2) diaphragms without thermal barriers. The two methods we used for the evaluation were: exposing the test transducer to a thermal transient of steam with a temperature of approximately 300°F and 50 psig, and dipping the transducers in a container of boiling water. Data for each method was recorded for 30 s. We realized that these two methods would be somewhat nebulous because there are no standard industry methods to follow, but some form of testing was better than none at all.

Of approximately ten manufacturers of pressure transducers we contacted, only four responded with transducers for evaluation. Using the data collected from both test methods we selected two pressure transducers that would give the least error for 30 s. As expected, the transducers with the thermal barrier, a room temperature vulcanizing (RTV), over the diaphragms generally gave the least error. The RTV slowed the heat flow to the diaphragm for the 30 s we wished to record. There are many transducers manufactured with low error bands, but program requirements dictated that the static error band for the pressure transducers on the wetwell were to be less than 0.05%. This percentage excluded the affect of a thermal transient, because these transducers would be integrated for comparison with the load cells.

For these measurements we chose a transducer with a range of 0 to 100 psia manufactured by Senso-Metrics, Inc.[3] The manufacturer advertised it as having a static error band of ±0.03% best-straight-line (BSL) between 0 and 15 psia, excluding any thermal transients. This transducer would also measure pressures from 3 to 10 psia while surviving overpressures to 65 psia, and convert pressures to a high-level voltage using semiconductor strain gages. Figure 6 shows the Senso-Metrics pressure transducer with an RTV over the diaphragm. The transducer included a 30-ft integral cable that allowed us to place it in the many possible locations on the wetwell. Generally, most instrumentation engineers have reservations when using a semi-conductor, especially in the presence of thermal transients where high accuracy is required, but, after evaluating this transducer for thermal transient effects, we were pleasantly surprised with its performance.

The second transducer we used for the remaining pressure measurements was manufactured by Precise Sensors, Inc.,[3] with a range of 0 to 75 psia (Fig. 7). The manufacturer advertised this transducer as having a static error band of less than

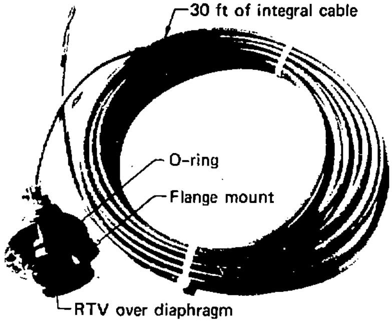


FIG. 6. Senso-Metrics, Inc., pressure transducer used on 90° wetwell.

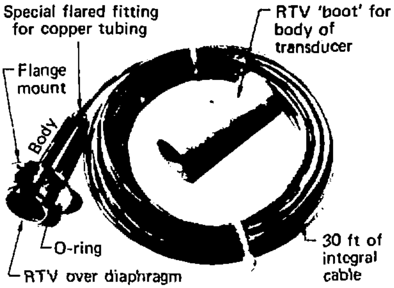


FIG. 7. Precise Sensor, Inc., pressure transducer used on 90° wetwell.

0.5% BSL between 0 and 75 psia, excluding affects of any thermal transients. This transducer used conventional metal foil strain gages to convert the pressure to a low-level voltage. Notice that both transducers have the same type of flange mount, which made them interchangeable and reduced any errors from torquing the transducer in place. The transducer from Precise Sensors also had a 30-ft integral cable. Because this transducer was primarily used inside the wetwell, hot water during the steam tests could be splashed on the body, affecting its output. To prevent this from happening we placed a protective 'boot' of RTV over the back of the transducer body. This boot functioned the same as the RTV did over the diaphragm. The results in Table 1, show the errors from both transducers after the boiling water tests. The RTV reduced the thermal transient affects and we slightly exceeded our less-than-1% error goal, but we felt this was acceptable. Although the two transducers used different types of strain gages, their errors are comparable, which was not expected.

The transducers were calibrated after the steam pipe and/or boiling water tests. A terminal-point error plot and a least-squares error plot were made for each pressure transducer calibrated. Figure 8 is a typical terminal point plot generated for a transducer. This plot contains 21 data points and is the first of three calibration runs. A considerable amount of transducer information, such as its linearity, hysteresis,

Table 1. The error results of the pressure transducers after the boiling-water test. An RTV surrounds the diaphragm.

| Transducer | Time (s) | Maximum and Minimum errors(a) (%) | Average error (%) |
|---|---|---|---|
| Senso-Metrics (55)[b] | 10 | +0.39 to -0.54 | ±0.2 |
| | 40 | +0.47 to -5.4 | +1.12 to -1.37 |
| Precise Sensors (24)[b] | 10 | +0.4 to -1.8 | +0.2 to -0.4 |
| | 40 | +3.5 to -2.0 | +1.14 to -0.75 |

[a] Compared to the rated range of the transducer.

[b] Total tranducers tested.

and sensitivity, is contained on this plot. This is a typical plot made at LLL, except that only one calibration run is normal for most projects. However, because more accuracy was required for this project, three runs were necessary to characterize the transducer and its error. A calibration run, or cycle, consisted of three runs from 0 psia to full range to 0 psia, and three runs from 0 psia to 15 psia to 0 psia. The lower calibration was necessary because most of the transducers would be scaled for the lower range on the data acquisition system and transducer accuracy is generally not as good in the lower range of the transducer.

Figure 9 shows a typical least-squares plot for the same transducer as in Fig. 8. From this figure the transducer sensitivity and the error band can be found. The former is the sensitivity we used for the data reduction for the air tests, and the latter is the error we report to the project personnel. From this plot the error band for the transducer is +0.16 and -0.24% of the full scale output.

The error band from all the least square plots was used to state a "general" accuracy for each transducer manufacturer. Errors, plus value, and minus value were summed algebraically. The sum was divided by the total number of transducers calibrated and these results divided by 2 to give an average error that approximated a best-straight-line. This error band was based on the calibrated ranges and not necessarily on the rated range of the transducer. The results for the two transducers are shown in Table 2. The static error bands for the two transducers were low when compared

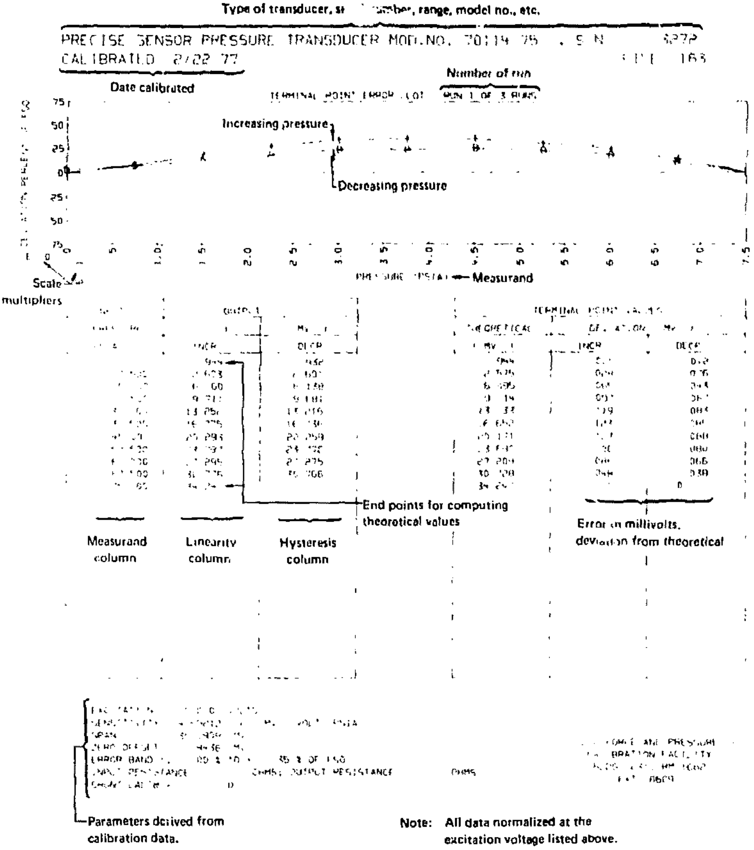
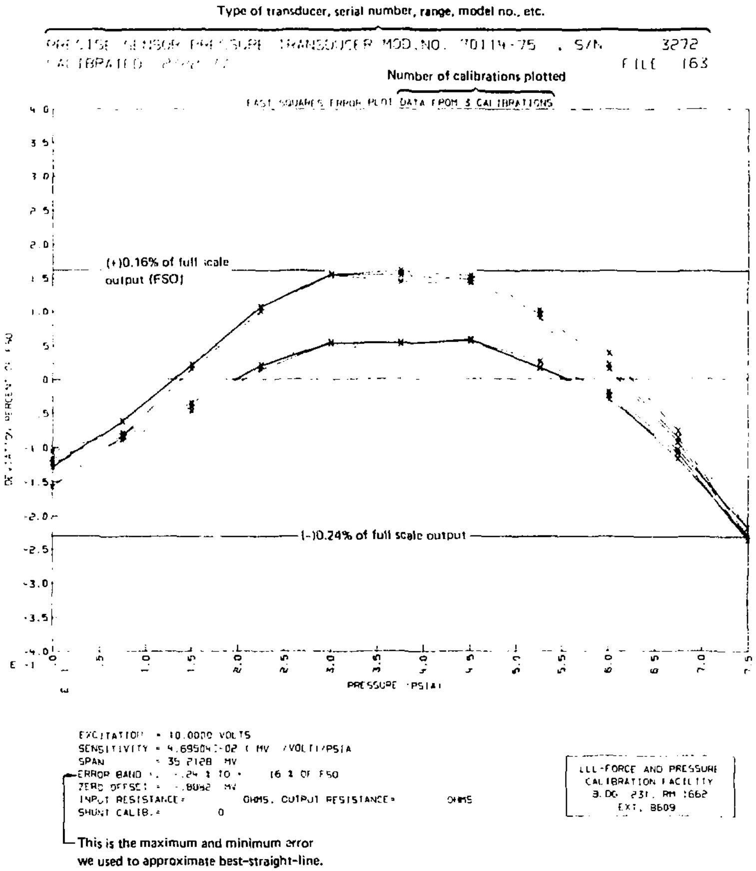


FIG. 8. A typical terminal point calibration plot for a pressure transducer.

to the ±2% total error we were seeking, which was a good start toward achieving this goal. We found that the static error for the Senso-Metrics transducer was not what the manufacturer had quoted initially, in fact the error was greater by a factor of approximately three!

While the error for these transducers is still small, and acceptable, the main point to remember in selecting a transducer is that one having a quoted lower static error band will not necessarily give a corresponding lower error in the final reduced data. Instead,



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EXCITATION   = 10.0000 VOLTS
SENSITIVITY = 4.69504E-02 ( MV  /VOLT)/PSIA
SPAN         = 35.2128  MV
ERROR BAND = (  -.24 % TO +   .16 % OF FSO
ZERO OFFSET =   -.8082  MV
INPUT RESISTANCE=          OHMS. OUTPUT RESISTANCE=          OHMS
SHUNT CALIB.=          0
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This is the maximum and minimum error
we used to approximate best-straight-line.

FIG. 9. A typical least squares calibration plot for a pressure transducer.

it is the accuracy of the complete instrumentation system that governs the final reduced data and not the assignment of a manufacturers stated accuracy for a transducer. This assigning is usually optimistic, almost always misleading, and <u>not</u> what is realized in field testing.

As previously noted, there were many transducers to select and calibrate, but to describe the selection and calibration of each one would be repetitious, therefore, the pressure transducers will be representative of the process we employed.

Table 2. Static errors for the two types of pressure transducers used on the wetwell.

| Transducer | Range (psia) | Average Error (%) |
|---|---|---|
| Senso-Metrics | 0-100 | ±0.22 |
| | 0-15 | ±0.10 |
| Precise Sensors | 0-75 | ±0.36 |
| | 0-15 | ±0.13 |

## DATA ACQUISITION SYSTEM

After selecting and calibrating the transducers the next step was to implement a data acquisition system to accurately measure and record the actual test signals in a format acceptable as computer input for data reduction. The required dynamic response of each channel (or transducer) was estimated to be either 400 or 1500 Hz. A high-gain instrumentation amplifier and filter were used for each channel to provide a high-level signal. Instead of making a continuous recording of each channel, which would not be feasible with the large amounts of data being generated during a test, a sampling scheme was used to format and record the data. Groups of 4 to 60 channels (the number depending on frequency response requirements) were multiplexed into an anlog-to-digital converter that converted the sampled analog signals into a digital word. The sampling rates were much higher than required to ensure accurate reproduction of the dynamic signals during data reduction. With the data now in a digital format, all essential parity bits, frame synchronization words, and other related digital words were combined and transmitted at a rate of 1.228 megabits/s, using pulse code modulation (PCM) techniques to a tape recorder. The 14 track, 2 MHz, analog tape recorder was used to record timing signals as well as the PCM data. Figure 10 is a block diagram of the data acquisition system; calibration circuits were included to determine the accuracy of each data channel.

A time consuming calibration procedure was followed before and after each series of tests to insure the accuracy of the data acquisition system. The first step of the procedure was to check and log the excitation voltage of each bridge transducer. The next step was to measure and log the calibration signal at the input of each amplifier. The

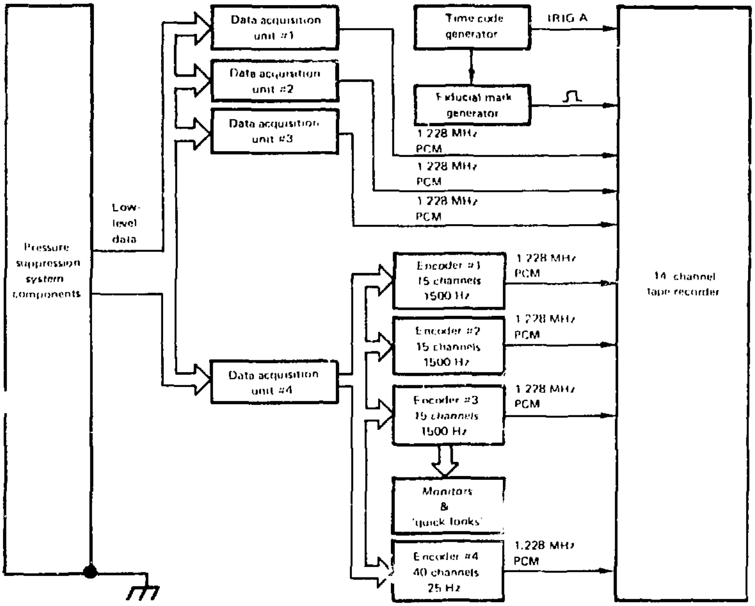

FIG. 10. Block diagram of the data acquisition system for the pressure suppression experiment.

high or low calibration signal was generated in one of three ways, depending on the type of transducer. For a thermocouple, a digital-to-analog convertor remotely controlled via the PCM command bus, was programmed with a low and high voltage. For transducers with conventional metal foil strain gages, a shunt resistor was switched across one arm of the bridge to generate a calibration-signal level. A voltage-insertion technique was used for transducers with semiconductor strain gages (Senso-Metrics). The difference between the high and low signals, including the sensitivity of each transducer, is the level that was used to scale the engineering plots. These calibrations provided only a relative accuracy, not an absolute. The method used to obtain absolute accuracies is discussed in the next sections.

Most of the known grounding and shielding techniques were used to reduce errors resulting from noise. Although a motor-generator provided power for the data acquisition system, its main purpose was to isolate the instrumentation power from the utility power to reduce spurious noise on the data. A single-point ground consisting of a large wire connected to the wetwell that terminated at an earth-dug pit filled with salt water was used to further reduce noise. Individual pair-shielded cables were used throughout the instrumentation system and for each transducer.

The PCM analog tape from a test was first taken to the LLL Analog-to-Digital Data Conversion Facility where digital tapes were generated. The tapes were then sent to the LLL Computer Facility for data reduction to produce the engineering plots that would be used to analyze the suppression system. The flow diagram shown in Figure 11 shows the data reduction procedure.

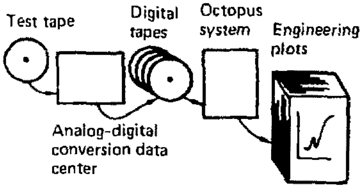

FIG. 11. Schematic of the data reduction steps for the pressure suppression experiment.

## END-TO-END PERFORMANCE

We were hoping the accuracy of the data from these experiments would be less than ±2% of the full-scale range for a transducer set on the data acquisition system. To achieve this kind of accuracy definitely required some type of calibration in the field. We were fortunate with this experiment because we could actually subject some of the installed transducers to a known input at the test site facility, and compare those readings to the transducer to determine the accuracy of the instrumentation system.

The pressure transducers, all of the accelerometers and displacement transducers could easily be subjected to a known input. For the pressure transducers, the complete suppression system void of water was pressurized at various levels and an LLL secondary standard pressure transducer was used to establish the known pressure. We rotated the accelerometer 180° at 2 g, using the earth's gravitational field as the known input. For the displacement transducers, accurate shims were placed between the transducer and wetwell. The remaining transducers were not subjected to the end-to-end (ETE) calibration because there was no convenient means of applying a known input without considerable difficulty.

The known inputs were applied to the transducers in discrete levels and the data recorded for 20 s and then processed as if it were an actual test. We computer-averaged each discrete level and determined the accuracy by subtracting the transducer reading from the standard known input and dividing this by the full-scale range set on the data acquisition system. We checked approximately 50% of the total number of transducers used on the suppression system and found that 88% of those checked achieved total errors of 2% or less. This was a pleasant surprise, and we can only infer that the remaining unchecked transducers would be the same.

How the ETE calibration data should be used is not clear, because it was collected at one specific time during the 27 air tests, and not before or after each test. To be meaningful for data analysis it probably should have been done before or after a series of tests, but that was not possible. After completing the air tests, and as a footnote to the ETE calibration data, we selected 11 Senso-Metrics transducers at random from two wetwells for a post-calibration run and found that five of the transducers had a sensitivity change of 1 to 9.5% from the original laboratory calibration. These five transducers also had errors greater than .% on the ETE calibration. We have not found the reason for the sensitivity change, but it is certainly reflected in the ETE calibration. Also interesting to note is that the quoted error bands of the pressure transducers from the two manufacturers differ by a factor of approximately 16, but the difference was not reflected in the results of the ETE calibration.

## SAMPLES OF DATA

This report would not be complete without some of the actual data traces we recorded for a test. Figures 12 and 13 show typical plots of the approximate 4400 engineering plots generated for the air tests. The ordinate of each plot is labeled with the particular transducer number, the engineering unit, and the location on the suppression

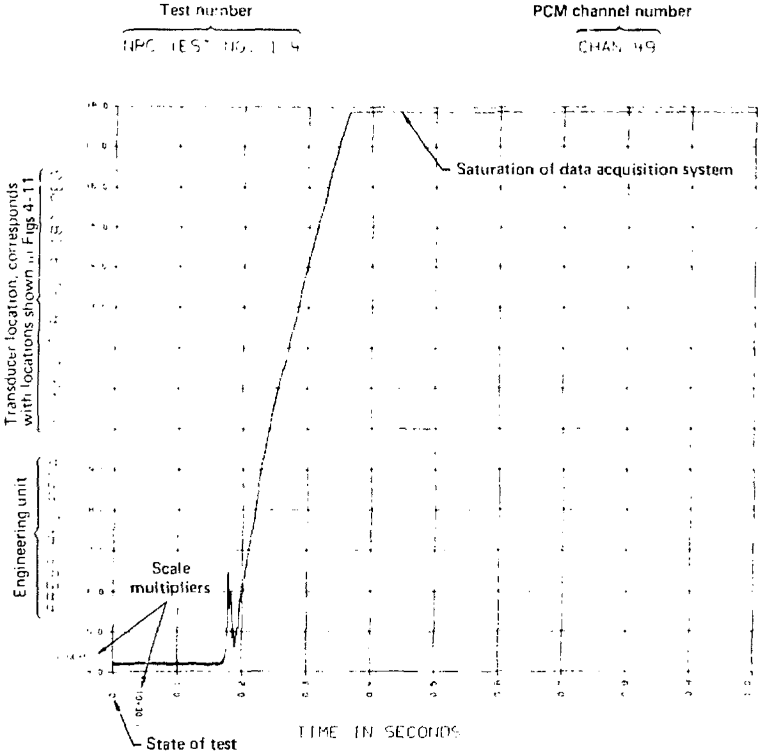

FIG. 12. A typical data trace from a Senso-Metrics pressure transducer for an air test.

system component, while the abscissa is time. Although these two figures are plotted for 10 s, the time can be changed as required. Figure 12 shows a data trace from a Senso-Metrics transducer. Notice the absence of noise on the trace; this is partly because of the high-level voltage output that a semiconductor normally gives. The data acquisition system went into saturation at a pressure of approximately 16 psia which is typical for all the Senso-Metrics pressure transducers and results from scaling the system to 10 psia. We were looking only for the pressure pulse generated by the vertical loads and not the final pressure in these transducers. Figure 13 shows a data trace from a

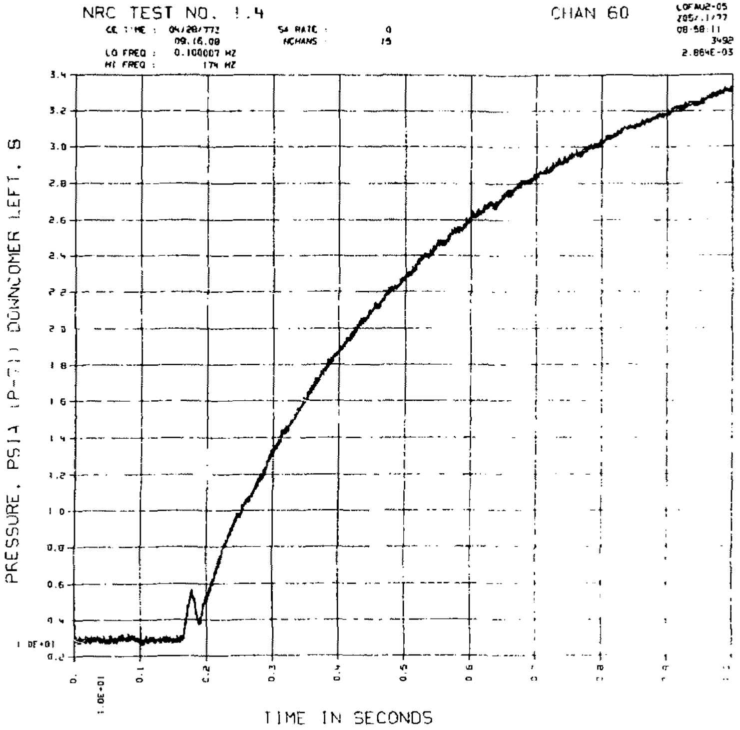

FIG. 13. A typical data trace from a Precise Sensor pressure transducer for an air test.

Precise Sensors transducer for the same test. A little more noise can be seen from this transducer, but then the voltage output was less than the Senso-Metrics. This transducer was scaled for 50 psia on the data acquisition system.

As previously noted the pressure-time history of the pressure transducers installed on the wetwell are integrated to obtain the vertical-load and should compare with the sum of the load cells supporting the wetwell. Figure 14 shows the variation of the vertical-load function for a typical test between the load cells supporting the wetwell, and the integration of the Senso-Metrics transducers over the surface area of the wetwell.[4] The dashed line represents the vertical load as determined from the sum of

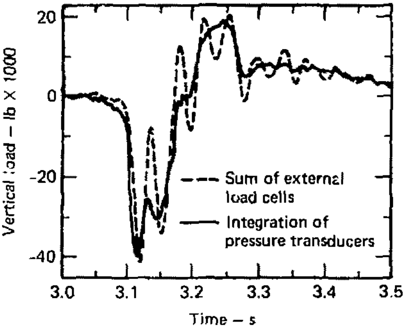

FIG. 14. Variation of the 90° toroidal wetwell vertical-load response as determined by load cells (dashed line) and by the integration of the pressure transducers (solid line) for a typical air test.

the load cells, and the solid line represents the vertical-load as determined from the integration. This agreement, in part, is because of the low error that we achieved with the data, since large errors in the transducer data would be magnified by the integration. This one figure alone makes all of our effort with the instrumentation system worthwhile, because it is seldom that two methods of measuring the same phenomenon will give the same results on the same test. We hope to have the same success with the steam tests.

## CONCLUSION

While there are several conclusions we could report from an experiment of this size, perhaps the most important is that specifying a total error determined by a manufacturer for a transducer or for a data acquisition system to a field test is not always the error realized in field testing; it is the ETE accuracy that determines the final accuracy of the data. We believe that this experiment has indeed been a challenge where our efforts were met with success, an event that is not always the experience of a measurements engineer.

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3. Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Department of Energy to the exclusion of others that may be suitable.
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