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TRANSDUCER DEVICE EVALUATION
USING HIGH EXPLOSIVES

RELEASED FOR ANNOUNCEMENT
IN NUCLEAR SCIENCE ABSTRACTS

R. H. Meseryey

PHILLIPS
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ATOMIC ENERGY DIVISION

NATIONAL REACTOR TESTING STATION
US ATOMIC ENERGY COMMISSION

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ABSTRACT

This report contains a description of the performance of various transducer devices as they were subjected to the transient forces produced by chemical explosives. Devices were tested for use in measuring dynamic overpressures and shock wave propagation velocities. Transducers of this type were used to obtain mechanical energy release data for the January 11, 1966 SNAPTRAN-2 destructive test [1]. Reactor disassembly detecting instrumentation in the form of accelerometers, linear displacement transducers, strain gages, event recording devices, optical trackers, and thermocouples were also tested. Dispersed fuel temperature measuring techniques were investigated by means of thermocouples and an optical pyrometer. The series of tests was conducted on behalf of the STEP program to determine appropriate instrumentation and instrumentation techniques for the SNAPTRAN-2 destructive test.

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THE USE OF HIGH EXPLOSIVES IN THE DYNAMIC TESTING OF REACTOR INSTRUMENTATION

I. INTRODUCTION

A thorough check-out of all instruments and instrumentation techniques which were used in the January 11, 1966 SNAPTRAN-2 nuclear destructive test [1] was required prior to final reactor installation. In order to be meaningful, these instrumentation tests had to be conducted under conditions which closely approximated those expected to be produced by the reactor itself. Since the destruction of the reactor in the SNAPTRAN-2 destructive test will be accompanied by air-propagated shock waves, violent component displacement, etc, it was believed that small charges of high explosives, detonated in air, could be used to simulate certain parts of the destructive test. In particular, the explosives could be used to produce shock waves and overpressures in air, to cause very high strain rates of simulated reactor components, and to cause rapid displacement of other components.

Because air pressure measurements are required as part of the overall instrumentation for the destructive test, it was necessary to determine the most useful transducer, mounting technique, orientation, etc, for this purpose. A suitable means of detecting and recording shock wave propagation velocity was also required.

Since the reactor vessel will undergo very high strain rates and then break and impact the beryllium reflector in which it is enclosed, it was necessary to measure or detect each of these events. The most reliable strain gage and gage installation technique had to be found as well as a means of determining when the vessel would break and when it would strike the reflector. Appropriate recording techniques for the above devices also had to be determined.

A means of measuring the rapid displacement and high acceleration which the reflector and fuel pins are expected to undergo also had to be tested. Other devices such as thermocouple hot-gas probes to measure the propagation velocity of the expanding hot gas, and an optical pyrometer to measure its temperature were tested.

II. DESCRIPTION OF THE FACILITY

The high explosives were detonated at a distance of approximately 600 feet behind the rear entrance of a building located in the Central Facilities Area of the National Reactor Testing Station. To avoid the possibility of a fire, an area about 100 feet in diameter was cleared of all vegetation. An aluminum rod was then stuck in the earth at the center of this area. The charges were taped to the top of this rod approximately five feet above the earth. Instrumentation such as pressure transducers were mounted in the same manner and in the same horizontal plane as the charge. Signals from various detectors which were being tested were transmitted by cables to an instrument box located at the edge of the cleared area. Here the signals were amplified and fed into an eight-channel line driver. The line driver made it possible to drive the signals through 600 feet of 50-ohm coaxial cable to the recording console located in the CF-688 building. Reference 2 contains a more detailed description of this instrumentation. After arriving at the recording and control room, the signals were recorded on an Ampex CP-100 magnetic tape recorder and a CEC Model 5-124 oscillographic recorder. This produced a permanent record on magnetic tape and an original oscillographic record of each test. Later, the data were taken from the tape (by slowing the tape speed down by a factor of 32) and replayed on the oscillograph. This produced records of the data having greater time-scale resolution than the original oscillographic record. Figure 1 is a block diagram of the test instrumentation system for detecting and recording only, and does not include the playback electronics.

Fig. 1 Block diagram of test instrumentation system.

The signal from each sensor was recorded on both the FM and direct modes of the tape system. The purpose of this was to determine which mode was the more advantageous method of obtaining information from a particular type of sensor. Since the FM mode is incapable of indicating rise times faster than about 16 μ sec (20 kHz), the direct mode was used to obtain information for rise times less than this. The FM mode was used to obtain low frequency (dc to 20 kHz) information such as pressure pulse shape and duration. Unless otherwise noted, all data traces shown in this report were taken from FM magnetic tape recordings.

III. AIR PRESSURE MEASUREMENTS

1. DESCRIPTION OF AIR-PROPAGATED SHOCK WAVES AND OVERPRESSURES PRODUCED BY HIGH EXPLOSIVES

The air-propagated shock wave, created by detonating 1/4-pound charges of high explosive Cyclonite with electric blasting caps, produced a useful range of pressures for testing of air pressure monitoring devices. By varying the distance between the sensors and the charge, a wide range of pressures were encountered. These ranged from true shock conditions which existed near the charge to low-magnitude air overpressures at greater distances.

Information about the properties of these shock waves was derived using data obtained from a number of pressure sensors used in various orientations and positions with respect to the source. Mounting technique was accomplished by taping the sensors to one end of 3/8-inch-diameter aluminum rods five to six feet long. The other end of the rod was then placed in the earth at the appropriate distance from the charge, and the sensor lead wires run down the rod and along the surface of the earth to the instrument box. Mounting in this manner allowed the sensors to be easily repositioned. Also, this made it easy to change the incidence angle between the sensor face and the shock wave by rotating the rod.

Pressure sensors, which were designed for shock wave measurements in the 0-to-1000-psi range, were used at distances ranging from 3 to 20 feet from the charge. Microphones, which are normally used in the much lower magnitude air overpressure region, were tested at distances of 40, 50, 60, and approximately 600 feet from the pressure source. At most of the above distances, the transducers were orientated at both zero degrees (head on) and 90 degrees (side on) to the source. In this manner, the extent of a pressure increase or reflected pressure at the sensor face was determined. It has been shown [3] that for small dynamic pressures (weak shocks), the reflected pressure at a reflecting surface may be as large as $2p$, where p is the incident pressure. This effect was described as pressure doubling. Weak shocks have been defined [4] as those in which $\rho_1 < 6\rho_0$, where ρ_0 and ρ_1 are the ambient and shock densities, respectively. For strong shocks ($\rho_1 > 6\rho_0$), the reflected pressure approaches $8p$. At even greater shock strengths, the reflected pressure may be even greater because of the change in the properties of air. That is, the ratio of specific heat at constant pressure to that at constant volume ($\gamma=1.4$ for air under normal conditions) changes, thus permitting the reflected pressure to increase. The reflected pressure arises from the change of momentum when the moving air changes direction as a result of striking the surface. When this occurs at the face of a transducer, the device will indicate the peak reflected pressure. As was noted above, this is greater than the incident pressure. The factor by which the indicated pressure exceeds the actual incident pressure is called the reflection factor. Positioning the sensor so that its sensitive area is orientated at 90° (side on) to the pressure source will prevent pressure reflections, but may alter the indicated rise time of the pressure. Thus, by making measurements at both 0 and 90°, a more complete understanding of the measured pressure may be obtained.

By employing the above mentioned pressure measuring techniques, a reference pressure was established for the size and type of explosive used in these tests. This pressure may be described as follows: a fast rise time front of which peak pressure decays exponentially with distance and of which magnitude and duration are strong functions of the distance from the source. Figure 2 is a plot of peak incident overpressure versus distance from the source for the charges used in these tests. This reference pressure was obtained by averaging the pressure indicated by a number of different 90° orientated sensors, located at various distances from the charge. As can be seen, the slope of this plot changes at a charge-to-sensor distance of approximately five feet. Hoffman and Mills [5] have shown similar effects in pressure measurements made near high explosives, but the point at which the slope changes is less pronounced. Rise times (0 to 100 percent, taken from direct recordings) range from about 10 μ sec in the shock region to 20 μ sec for the overpressures.

A log-log plot of pressure duration versus distance from the source may be seen in Figure 3. The top curve was obtained from a Kaman Nuclear, Model K-1200, pressure transducer orientated at 0° to the source. The duration shown by this curve is the time between the initial pressure rise and when it again returns to zero. Duration at points of one-half peak pressure change in a similar manner but are much shorter. The lower trace shown in this figure was obtained by averaging the half-peak durations of all detectors. By measuring the durations at one-half peak pressure, the task of reducing the data is made easier by eliminating the need to take into account changes in resolution at different pressure levels. When the sensors are orientated at 90° to the source, the indicated total duration remains practically unchanged but the duration at half-peak pressure is increased somewhat.

The above discussion of the pressures generated by the high explosives used in these tests is given to acquaint the reader with the properties of these

Fig. 2 Reference pressure, obtained by averaging the response of all sensors when used in 90° orientations. Source: 1/4-pound charge of Cyclonite detonated in air.

Fig. 3 Pressure pulse duration. Upper curve, showing total duration, was obtained with a Kaman pressure transducer and microphones used in 0° orientations. Lower curve was obtained by averaging durations at one-half peak pressure from all sensors.

dynamic pressures. Following is a detailed discussion of the behavior of each sensor when subjected to the dynamic pressures described above. The discussion of the behavior of these sensors will be divided into two parts based on the extent to which the sensor was tested.

1.1 Kaman Nuclear

A Kaman Nuclear, Model K-1200, variable impedance pressure transducer [6] was tested extensively at the blast facility. In this model, the pressure is admitted to the diaphragm through eight, small, double-angle inlet ports. Although it is possible to obtain these sensors with a direct path to the diaphragm, these ports prevent a direct line-of-sight path for thermal radiation and offer protection from flying debris. The presence of the ports does not appear to degrade the response of the transducer as the unit tested was capable of indicating pressure rise times as short as 10 μ sec.

The unit used in these tests had previously been used in transient nuclear radiation effects tests [7] in a TRIGA Mark F reactor. Exposure to the thermal neutron flux had induced a small amount of radioactivity in the transducer, and at the time of the blast tests it still retained a residual activity of about 1.5 mr. It is believed that this radioactivity had no effect on the operation of this unit during these tests.

Electronics used with this unit included a Kaman Model 1101 oscillator-demodulator and a Keithley Instruments, Model 102B, decade isolation amplifier. The oscillator-demodulator is matched to the transducer by the factory and is not interchangeable (unless the sensor is recalibrated) with other units. The transducer output was amplified by a Keithley amplifier, fed to the line driver and transmitted via the coaxial cable to the recording console.

The response of the Kaman sensor at 0 and 90° orientations is shown in Figure 4. Line (A) is for 0° orientations, (B) is 90°, and (C) is the reference pressure described above. The pressure difference between lines (A) and (B) is an indication of the magnitude of the reflected pressure which is produced at the face of this transducer. It should be noted that the pressures shown are average values taken from a number of tests. Since there are variations in the high explosive charges and since changes in atmospheric conditions affect the propagation of the shock wave, a spread in data taken from day to day is expected.

In general, reasonable agreement was obtained between reflection factors indicated by the sensor tested and those predicted by theory [8]. In Figure 5 the reflection factors obtained with the unit are plotted with those furnished in a letter from Kaman Nuclear. As can be seen, the empirical values

Fig. 4 Effect of orientation on Kaman pressure transducer.

run slightly below those predicted by theory. Data were obtained only in the low-pressure region of this graph. As noted earlier, in addition to the reduction in indicated peak pressure at a transducer orientation of 90° , the duration at points of half maximum is increased. The change in transducer output with change in orientation is shown in Figure 6. Trace (A) is the output from sensor when it is in a 0° orientation, (B) is 45° , and (C) is in a 90° orientation. Peak pressures for these three orientations were 140, 90, and 60 psi, respectively.

The Model K-1200 was used in over 50 tests but it started to undergo what appeared to be a sensitivity change after about 35 tests. This change in calibration was in the form of a slowly decreasing sensitivity which, after an additional 20 tests, had reduced the apparent sensitivity to about one-half of its original value. It then more closely agreed with the other pressure sensors which were tested. Using the original calibration (performed in the laboratory using a dead-weight tester), the Kaman indicated a much higher pressure than other sensors located at corresponding positions. A post calibration of the sensor indicated that some type of damage had occurred. The unit appeared to undergo sensitivity changes during the post calibration. Although the extent or type of damage has not been determined, it is not believed to be a serious problem for the SNAPTRAN-2 application.

By consulting with personnel from Kaman Nuclear it was determined that this transducer indicated higher pressures than others at corresponding positions because of the mismatch between the detector and its electronics. As this system was not matched at the factory, an overshoot was present in its output which effectively caused a higher indicated peak pressure. This overshoot can be seen in trace (A) of both Figure 4 and Figure 8. A problem such as this would not exist with systems which were not interchanged.

Based on observations of the response of the Kaman Nuclear pressure transducer during the tests discussed above, it is believed that this is a reliable sensor, well suited for the air blast measurements associated with the SNAPTRAN-2 destructive test. It has been shown that even units having the

Fig. 5 Theoretical and empirical reflection factors for the Kaman pressure transducer.

Fig. 6 Response of the Kaman variable impedance pressure transducer at selected orientations. Traces (A), (B), and (C) represent 0, 45, and 90° orientations, respectively. Charge-to-sensor distance was four feet.

small double-angle pressure ports leading to the diaphragm are capable of indicating rise times as short as 10 μ sec. As long as the user realizes that they are occurring, effects such as reflected pressure increases may be accounted for and a reliable dynamic pressure measurement may be made with this sensor.

1.2 Atlantic Research Corporation

An Atlantic Research Corporation, Model LC-33, blast pressure gage was also used in these tests. This is a piezoelectric (zirconate) gage having the shape of a pencil. It has a diameter of 0.63 inch and a length of 10 inches. A usable pressure range of 1000 psi and a rise time less than 10 μ sec are other properties of this sensor. The aerodynamic nose, high sensitivity, and fast response of these transducers make them useful in determining free field blast parameters.

Electronics used with this sensor included an United Aero Products, Model 301, cathode follower and a Keithley Instruments, Model 102B, decade isolation amplifier. From the Keithley amplifier, the signal was fed to the line drivers and, hence, to the recording console.

In general, the response of the blast pressure gage to these dynamic pressures was quite similar to that of the Kaman transducer. Although this sensor was not tested as extensively as the Kaman, data obtained from it did indicate the same type of pressure-distance behavior for this high explosive source. This can be seen in Figure 7 where (A) was obtained with the sensor at 0° incidence to the source, (B) at 90°, and (C) is the reference pressure discussed earlier.

The response of this transducer at a charge-to-sensor distance of 10 feet can be seen in trace (D) of Figure 8. Trace (A) is the output of the Kaman transducer and is included for comparison. Rise time (0 to 100 percent) of this sensor is about 10 μ sec. With the possible exception of nuclear radiation damage to the sensor crystal, this sensor is very well suited for shock wave measurements.

Fig. 7 Effect of orientation on Atlantic Research blast pressure gage.

Fig. 8 Response of four types of pressure sensors. All were orientated at 0° to the source and a distance of 10 feet from it.

1.3 Kistler Instrument Corporation

Two Kistler Instrument Corporation, Type 601A, miniature quartz pressure transducers and one Type 701A, high sensitivity sensor were tested at the high explosive facility. The 601A sensors are high pressure units having a range of 5000 psi. They were used before the 701A was obtained and were selected because of their small size and fast response. Factory specifications list a three- μ sec rise time for these sensors. Much better suited to low level blast pressure measurement, the 701A has a maximum pressure range of 30 psi. A larger size, higher sensitivity, and 6- μ sec rise time differentiate this model from the 601A.

Behavior of the three Kistler transducers was similar to that of the other sensors, although the change in slope of the pressure-versus-distance curve, which occurs in the five to seven foot region, was not as pronounced. The small (0.25-inch diameter x 0.6-inch length) Type 601A did not produce reflection factors as large as those of the Kaman, the values being only slightly greater than one. The larger (0.43-inch diameter x 1-inch length) Type 701A indicated reflection factors whose magnitudes approximated those of the Kaman. The pressure magnitudes indicated by these sensors were slightly lower than that of the Atlantic Research blast gage and, hence, much lower than those indicated by the Kaman. Outputs of the two types of Kistler sensors were very similar and that of the 601A can be seen in trace (a) of Figure 8. This was obtained at an orientation of 0° and a charge-to-sensor distance of 10 feet.

These appeared to be very capable transducers with the ability to follow closely the fast rise time pressures created in these tests. Again, being a crystal device, its use in high nuclear radiation fields is not recommended.

1.4 Consolidated Electrodynamics Corporation

A CEC, Type 4-317-0100, unbonded strain gage pressure transducer was exposed to high-explosive-driven dynamic pressures. It had previously been shown that these sensors are unable to withstand the high accelerations associated with shock wave measurements [9]. Therefore, the device was placed in a region in which the air pressure was approximately 4 psi.

The output from the sensor was fed into a Keithley Instruments, Model 103, low noise amplifier. From this amplifier, the signal was transmitted to the line drivers and then to the recording console.

As can be seen in trace (c) of Figure 8, upon arrival of the pressure, a natural frequency mode of the sensor is excited and no reliable pressure information is obtained. The ringing seen in the output of this transducer has a frequency of 15.6 kHz, the magnitude of which decreased to one-half amplitude in about 16 cycles. This ringing persisted for approximately 5600 μ sec.

The ease with which the natural mode of this sensor is excited and the extent to which it affects its output makes this model totally unsuitable for dynamic pressure measurements of this type.

1.5 Kulite-Bytrex Corporation

A Schaevitz-Bytrex, HF Series, pressure transducer was also tested at the facility. This sensor consists of a silicone semiconductor strain-gage-type transducing element mounted in a stainless steel case. Forces applied to this

element through a pressure responsive diaphragm produce strains and, hence, resistance changes in the semiconductor members. When supplied with a constant excitation voltage, the sensor produces an output voltage which varies directly with pressure. The unit tested (HF-100) has a diameter of approximately 1/2 inch and a thickness of 0.29 inch.

Circuitry used with this transducer consisted of a Keithley Instruments, Model 103, low noise amplifier, a line driver, and a recording console. These were arranged in the same order as previously described for other sensors. A sensor excitation voltage of five volts was used on all tests.

As the model tested had a pressure range of 0 to 100 psi, tests were conducted at dynamic pressures less than 100 psi. The behavior of this sensor was quite similar to that of the Kistler Model 701. Peak indicated pressures and reflection factors show a close similarity.

An anomaly was noted in the output of this sensor and can be seen in trace (B) of Figure 9. The data shown were obtained with transducer orientations of 0° and a charge-to-sensor distance of 10 feet. As can be seen, approximately 1100 μ sec after the arrival of the pressure, a large negative deflection occurred. As noted above, the initial part of the pressure trace produces reliable data but the noise spike which occurs later makes the unit unsuitable for recording multiple events. This anomaly was noted on all tests and a possible explanation is microphonics produced in the calibration module which is located a short distance behind the sensor. For comparison, the response of the Kaman transducer (which was located beside the HF-100) is shown in trace (A) of this figure.

Fig. 9 Anomaly in the output of the Schaevitz-Bytrex pressure transducer. Trace (A) is the response of the Kaman sensor which is included for comparison. Both sensors were oriented at 0° with respect to the source and were at a distance of 10 feet from it.

Because of the behavior described above and the possibility of either a pressure of longer duration, or multiple pressure events, it is not recommended that this sensor be used in the SNAPTRAN-2 destructive test.

2. MISCELLANEOUS PRESSURE SENSORS

In addition to the above sensors, which were used in many tests, other devices were used at selected positions in a limited number of tests. Unlike the first group of pressure transducers, these were tested at only one charge-to-sensor distance. Usually only two tests per sensor were conducted: one at 0° and one at 90° incidence. Following is a brief description of the response of these detectors to the dynamic pressures created by the high explosives.

2.1 Susquehanna Instruments

A Model ST-4 pressure transducer, which is manufactured by Susquehanna Instruments, was tested at a distance of five feet from the charge. This is a crystal device (tourmaline) having a dynamic pressure range of 10 to 2000 psi. It was selected because of its known fast response to dynamic pressures. In previously conducted tests utilizing water-propagated, exploding wire-driven shock waves, these transducers had indicated rise times less than one μsec .

Output from the Model ST-4 went to a United Aero Products, Model 301, cathode follower and then to a Keithley Model 102B decade isolation amplifier. The rest of the electronics were as described previously for the other sensors.

Rise times as fast as 5 μsec were indicated by this sensor. This indicates that the 10- μsec risetimes shown by other sensors were the limitation of the transducer response rather than the shock wave rise time. The 5- μsec risetime was obtained with a 0° detector orientation while that at 90° was about 12 μsec . A reflection factor of approximately three was obtained five feet from the charge. Peak pressures obtained at 90° orientations were very close to those of the reference pressure discussed earlier. The response of this sensor at a 0° orientation and at a distance of five feet from the charge may be seen in Figure 10, trace (B). Trace (A) of this figure is the output of the Kaman which was in the same orientation and position as the Susquehanna transducer.

Fig. 10 Response of miscellaneous pressure sensors. Traces (A), (B), and (C) were obtained at a charge-to-sensor distance of five feet and 0° orientations. Trace (D) was obtained with the same orientation but at a distance of one foot from the charge.

2.2 Crystal Research, Inc.

The output from a Crystal Research, Inc., Model CR-63 (3/4-inch diameter), piezoelectric gauge^[10] may be seen in trace (C) of Figure 10. Position of this sensor was the same as that of the above detectors. Although reflection factors were not large (1.3 at five feet), changes in the indicated rise time of the pressure were a strong function of sensor orientation. An end-on orientation produced 30- μsec rise times while a side on (flat side of sensor toward source) position produced 8- to 10- μsec rise times.

As this is a piezoelectric device of which the working material is tourmaline, the same kind of electronics were used with this sensor as were used with the Susquehanna sensor.

2.3 Norwood

A Norwood, Model 114 (60,000 psi), bonded strain gage pressure transducer was placed very close to the charge in an effort to induce oscillations such

as those observed in the SNAPTRAN-3 destructive test. The detector was mounted in a STEP housing [11] and was unchanged from its condition upon removal from the STEP facility after the above test. A stand pipe which was attached to the housing was placed in the earth and used as a support for the transducer and housing. At a distance of 12 inches from the charge, an output from the unit was obtained. The FM recording of this output may be seen in trace (o) of Figure 10. The initial peak on this trace corresponds to a pressure of 2100 psi and, by extrapolation of data taken at greater distances, is in the vicinity of the pressure expected at 12 inches from these charges. The frequency of this ringing was about 50 kHz.

In addition to the standard line driver-recording console instrumentation, a Keithley Instruments, Model 103 amplifier was used in conditioning the output signal from this sensor. Sensor excitation voltage was five volts.

3. MICROPHONES

Two kinds of microphones were used to investigate pressure measuring techniques in the overpressure region at large distances from the source. Tests were conducted with various microphone orientations at 40, 50, 60, and approximately 600 feet from the source. The microphones were mounted in the same manner as were the pressure transducers.

Two Massa-Cohu, Model M-213, crystal microphones were tested. Because an accurate calibration was not available for these devices, they were used only to obtain pressure wave shape, duration, and approximate magnitude. It was found that both the indicated rise time and pressure magnitude obtained from these sensors was dependent upon transducer orientation. Indicated peak pressure obtained at an orientation of 45° was 65 percent of that from a 0° orientated sensor. Changing the orientation to 90° reduced the output to 45 percent of that at 0°. At the same time, the indicated rise time became twice as long in changing from 0° to 90° orientation. The output of one of these microphones which was orientated at 0° and at a distance of 40 feet from the source may be seen in trace (A) of Figure 11.

Electronics used with these detectors included two types of amplifying techniques. First, Kistler Instrument Corporation, Model 566, electrostatic charge amplifiers were used. The output signal obtained by the use of these was then compared to that obtained by using a United Aero Products cathode follower and a Keithley Model 102B decade amplifier. No great difference was observed in the magnitude of the signals but the cathode follower-decade amplifier combination is preferred because it does not produce an electronic drift.

Fig. 11 Microphone response to dynamic overpressures. Both sensors were 40 feet from the source and 0° orientations.

A Bruel and Kjaer (B & K), Type 4135, condenser microphone (with protecting grid) was subjected to the same tests as were the Massas. This unit appears to be much more suitable for small air overpressure measurements. This instrument did not show a change in output with a change in its orientation with respect to the source. Repeatability of the device was also good. The response of the B & K microphone may also be seen in Figure 11, trace (s). Position and orientation were the same as that of the Massa whose output is also shown in this figure. Overpressure duration indicated by these microphones may be seen in Figure 3. The magnitude of the overpressure at approximately 600 feet (outside the rear entrance of CF-688) was about 130 dB (referenced to $0.0002 \frac{\text{dyne}}{\text{cm}^2}$). This represents an overpressure of about 0.009 psi.

It was noted during the testing of this sensor that approximately 4500 μsec after the arrival of the pressure, a random noise signal appeared in the output of the microphone. The noise signal has a duration of about 250 milliseconds. It is believed that this is caused by microphonics in the power supply electronics which is located a few feet behind the detector head. The time lapse between the arrival of the pressure and the beginning of the noise also agrees with this.

In addition to the power supply/pre-amp furnished with the microphone, a Keithley Instruments, Model 102B, decade amplifier was used with this sensor. After being amplified by this unit, the microphone signals were handled in the same manner as those of the other detectors.

Although a noise signal does appear in the output of this microphone, it occurs at such a time so as not to interfere with the pressure signal. As long as the electronics associated with this sensor are placed a few feet behind it, a reliable measurement can be made.

4. PRESSURE INSTRUMENTATION CONCLUSIONS

As a result of the above tests, some conclusions can be drawn concerning pressure measuring and recording techniques suitable for the SNAPTRAN-2 destructive test. A pressure transducer having good mechanical reliability such that it is able to withstand the blast environment near the reactor and yet is capable of responding to the fast rise-time shock waves which occur in this region is required. This sensor must also possess desirable nuclear radiation resistant properties. Among the detectors tested, the Kaman Nuclear variable impedance pressure transducer fulfilled these requirements.

Care must be exercised in the use of any dynamic pressure-measuring device. If the approximate magnitude of the pressure is unknown, then the magnitude of any reflected pressure effects must be determined. This requires that two sensors be used in the determination of a dynamic pressure at any given position. One sensor should be orientated with its sensitive area at 0° to the source and the other at 90° to the source. Still more information may be obtained by measuring the shock wave propagation velocity at the site of the pressure measurements. A better understanding of the structure and behavior of the dynamic pressure will be obtained if these measurements are made at

various distances from the source. Pressure transducers, such as the one mentioned above, may be used in the high pressure region near the source and microphones may be used at the greater distances where air overpressures exist.

Recording techniques are also an important part of making reliable dynamic pressure measurements. Not only is the proper choice of amplifiers, line drivers, etc, necessary, but the recording mode (FM or direct) affects the reliability of the data. When sensors having very fast rise times are subjected to fast rise-time shock waves, the resultant response requirements are such that FM recording techniques used in these tests will not accurately follow the pressure. The result is that the indicated pressure is less than the actual peak pressure. In this case, both direct and FM recordings should be made to ensure that both high- and low-frequency pressure information is obtained. Slower rise-time pressures ($>20 \mu\text{sec}$) may be adequately obtained by FM recording techniques.

It should be noted that both FM and direct recordings were made for all sensors used in each of the tests discussed in this section. In general, transducers such as the Kistlers and Susquehanna gave more reliable peak pressure data when their signals were recorded in the direct mode. The exception to this occurred when they were used at distances greater than 10 feet from the source where the rise time of the pressure was longer. A direct mode recording is necessary only if rise time information less than about $20 \mu\text{sec}$ is desired.

It is believed that by observing the techniques discussed above, the dynamic pressure instrumentation proposed for the SNAPTRAN-2 destructive test will provide reliable data.

IV. SHOCK WAVE PROPAGATION VELOCITY

Shock wave propagation velocity measurement techniques were investigated as an alternate means of determining overpressures created by the destructive test. The relationship between an air overpressure and its propagation velocity is furnished in the theory of acoustics. Thus, a suitable type of backup pressure instrumentation may be derived from the measurement of propagation velocity. Larson and Olson [12] used pressures calculated from shock wave velocities to dynamically calibrate pressure transducers.

Detectors used in measuring air-blast velocity were Model BD-15 time-of-arrival pickups manufactured by the Atlantic Research Corporation. These small, crystal devices may be positioned a given distance apart (usually three to six inches). From the known distance and the time difference at which the two detectors sense the arrival of the pressure wave, the average propagation velocity over this distance may be determined. In addition to the regular transmitting and recording instrumentation, Kistler Model 566 charge amplifiers were used with these devices. As a means of conserving recorder channels, the outputs of both time-of-arrival gages were recorded on the same channel.

Tests were conducted at various distances from the same kind of high explosive charges that were used in the pressure sensor tests. Average propagation velocities were measured over distances of 3, 6, and 9 inches. Both direct and FM recordings were made and, although the FM recording lags the direct recording by a small amount, the accuracy is not impaired since the response of both sensors is affected equally.

Figure 12 is a reproduction of some of the data obtained from these tests. Traces (A) and (B) are the direct and FM recordings, respectively, of the combined outputs of two detectors which are three inches apart. Sensors were located approximately four feet from the charge. Traces (C) and (D) are the FM recordings of these sensors when the distance between them is six and nine inches, respectively. The distance between the transducers was increased by moving the front sensor nearer to the pressure source. The effect of this can be detected in the increased amplitudes of the first peak in traces (C) and (D), and also in an increased average propagation velocity over the increment. From the data presented in this figure it can be seen that a sensor separation of only three inches gives adequate time resolution when the outputs of both sensors are recorded on the same channel.

Fig. 12 Output of propagation velocity detectors. Traces (A) and (B) are direct and FM recordings obtained with sensors three inches apart. FM recordings obtained at six- and nine-inch increments are shown in traces (C) and (D), respectively.

Tests were conducted at charge-to-sensor distances ranging from 4 to 20 feet. This encompassed a pressure range of 25 to about 1 psi. The range of shock wave propagation velocities encountered may be seen in Figure 13. This is a semi-log plot of both the measured and calculated propagation velocity versus distance from source. The measured values were obtained in the manner described above, and the calculated values were determined in the following way. As shown by Bradley[13], a gas shock velocity may be expressed in terms of gas pressure and density increases, so that

Fig. 13 Shock wave propagation velocity. The over-pressure level at the above distances may be obtained by referring to Figure 2.

$$U = \tau_1 \sqrt{\frac{P_2 - P_1}{\tau_1 - \tau_2}} \quad (1)$$

where

U is the shock velocity in cm/sec

τ_1 is the reciprocal of the ambient density in cm^3/g

τ_2 is the reciprocal of the instantaneous shock wave density in cm^3/g

P_1 is the ambient pressure in dynes/cm²

P_2 is the total pressure within the shock wave (ambient plus excess) in dynes/cm².

Shock wave densities must be determined from the thermodynamic properties of rapidly compressed gases. The changes in pressure and density are so rapid that practically no heat energy has time to flow away from the compressed part of the gas before this part is no longer compressed. Thus, in the case of an adiabatic process,

$$\frac{P_2}{P_1} = \left(\frac{\rho_2}{\rho_1} \right)^\gamma \quad (2)$$

where

P_1 and P_2 are pressures as noted above

ρ_1 is the ambient air density in g/cm^3

ρ_2 is the instantaneous density in g/cm^3

γ is the ratio of specific heat at constant pressure to that at constant volume and has a value of 1.4 for air under standard conditions or weak shocks.

P_1 and ρ_1 and, hence, γ_1 are determined from ambient conditions. When these and the given pressure, P_2 , are applied to Equation (2), the instantaneous shock wave density, ρ_2 , may be determined. The reciprocal of this, when applied with the other parameters in Equation (1), results in the shock velocity for the given pressure.

The close agreement between calculated and measured values attests not only to the accuracy of the propagation velocity measurement, but also to that of the pressure instrumentation. Pressure levels used in these calculations were taken from the empirically determined pressure-distance relationship shown in Figure 2 of this report. It is believed that the major source of difference between the measured and calculated values is inaccurate charge-to-sensor distance measurements.

It should be noted that, like the pressure-versus-distance curves, this plot undergoes a major change-of-slope in the region between 4.5 and 5 feet from the charge. At this distance the overpressure level is 12 to 15 psi.

Because crystal transducers have a high sensitivity to nuclear radiation, these time-of-arrival devices should not be used in the high flux region near the reactor core. Since the nuclear radiation-induced signals observed in these sensors during nuclear transient tests of the SNAPTRAN reactor had rise times in the order of milliseconds, and since they are to be used to detect pressures having microsecond rise times, it should be possible to electrically filter out the low frequency, radiation-induced signal. In this manner, the devices could be used in a region of high nuclear flux. It is believed that more work should be directed toward the area of filtering undesirable radiation-induced signals. Because of the little work that has been done to date, other approaches to the problem of making this measurement near the reactor were investigated.

One of these was to use a drag-disk flowmeter to detect the arrival of the pressure pulse. Velocity information could be obtained by using two of them in the same way that the crystal gages were used. These flowmeters use metallic (rather than semiconductor) strain gages as sensing elements and hence have a low sensitivity to nuclear radiation. A flowmeter of this type (see Figure 14) was designed for use in the 10-to-100-psi range. Two units were built and tests were conducted to determine their usefulness in measuring shock wave velocities at distances between three and five feet from the source. It was discovered that these devices, as designed, were incapable of responding in a manner which permitted them to accurately measure propagation velocities over small distances. The flowmeters were then placed closer

Fig. 14 Drag disk flowmeter.

to the charge in a region in which the pressure was in excess of 100 psi. A better response was obtained, but as may be seen in trace (A) of Figure 15, it is of such a nature that the recording of the outputs of two of these devices on the same data channel would be impossible. The behavior of the particular drag-disk flowmeters which were tested suggests that a design change incorporating a higher sensitivity would allow better response at lower pressures.

The magnetostrictive property of alumel wire was proposed as a means of building a self-generating time-of-arrival device. It was planned to use the shock-induced vibrations in a small grid of this wire to detect the arrival of the shock wave. A self-generating device such as this would have a very low sensitivity to nuclear radiation.

Fig. 15 Response of two devices used to detect the arrival of a shock wave.

Two of these devices were fabricated by tightly winding 0.010-inch diameter, fiber glass-insulated alumel wire on a metal frame to form a square wire grid having sides approximately two inches in length. Results obtained from the use of these devices are also shown in Figure 15.

Trace (B) of this figure is the output of a single alumel wire grid and, as is readily seen, the restriction on recording technique that would be required with the flowmeters applies to these also. In testing these devices, it was found that a much better response was obtained if a small amount of tension was applied to the alumel wire as it was being wound onto the grid.

Several techniques are available which may be used to accurately measure shock wave propagation velocity. They can be roughly divided into types suitable for use in nuclear and nonnuclear environments. Among the types tested, the flowmeters and alumel grids are somewhat restricted to use at high pressures. Design changes could be incorporated in each device to increase their sensitivity and, hence, remove this restriction. An electronic filtering arrangement could be used with radiation sensitive crystal devices to permit them to be used in low-intensity nuclear radiation fields.

Another method of measuring shock wave propagation velocity has been suggested by Horinchi^[14]. The heat-induced resistance change in an evaporated gold foil was used to detect the arrival of the shock wave. Although the effect of intense nuclear radiation fields on such a system has not been determined, such a technique may hold some promise for a reactor installation.

Shock wave propagation velocity measurements may be used to obtain shock wave pressure magnitude and to furnish additional information on the

nature and behavior of the wave. It is believed that the careful selection and use of a combination of the devices discussed on the preceding page would result in the acquisition of valuable shock wave information from the SNAPTRAN-2 destructive test.

V. REACTOR VESSEL INSTRUMENTATION

As a means of determining the usefulness and reliability of proposed in-core instrumentation, a number of "dummy" reactor vessels were constructed. These vessels were fabricated by seam welding 0.032-inch-thick sheets of Type 304 stainless steel to produce open-ended cylinders having 9.5-inch diameters and lengths of 18 inches. This is approximately the same size as the SNAPTRAN vessel. For tests of the in-core instrumentation, the vessels were filled with dummy fuel pins which were similar to the SNAPTRAN fuel pins except they were filled with sand. A charge of the military high explosive, Composition-C4, was detonated at the center of the vessel, thus simulating the destruction of the SNAPTRAN-2 core. Tests which included only instrumentation on or immediately external to the vessel were conducted in the same manner, except that the dummy fuel pins were omitted. The amount of explosive used ranged from 25 to 50 grams of Composition-C4. The vessel was supported above the earth by three metal legs. A photograph of one of these vessels, complete with instrumentation, is shown in Figure 16. Following is a discussion of the devices and techniques investigated in these tests.

The feasibility of making extremely fast rise-time strain measurements on the vessel wall was investigated in the following manner. Dynamic loading of the vessel wall was produced in varying degrees ranging from that which caused the vessel to vibrate in its natural mode to those in which it was completely blown apart. Most of the tests were conducted in a manner such that only a slight bulge around the center of the vessel was produced. It was determined that 25 to 30 grams of Composition C-4 were required to produce this effect. A photograph showing the degrees to which the vessels were damaged is shown in Figure 17. It was also found that, in general, the effects of small amounts of this explosive were non-uniform. The careful placement of the moldable explosive around the cap was required to ensure detonation of the charge. Tests in which the charge was distributed in a thin layer around the cap or in which it was placed too near the top of the cap (instead of the bottom) produced "misfires" in which only the cap exploded and the charge did not detonate.

Fig. 16 Dummy vessel, instrumented and awaiting test.

Fig. 17 Degrees of deformation produced by the explosives. The vessel on the left contained 25 grams of Composition C-4, that on the right contained 50 grams. The small dents immediately above the bulge in the first vessel are caused by bits of metal which are blown from the cap as it detonates.

The rate of strain produced in the vessel walls by these explosives was too high to be accurately detected and recorded by the electronics available for these tests. Strain gages were intended to be used to record the first few thousand microinches of strain in the vessel walls at which time it was assumed that the gages would either break or become detached from the metal. In order to effectively accomplish this, the time at which they become defective must be clearly indicated on the oscillograph recording of their output. In the event the strain and ultimate destruction of the gage occurs in a time comparable to the response of the recording system, a reliable strain measurement would not be made.

In an attempt to determine strain gage behavior under dynamic loadings, several types of gages were installed on the vessels. Three distinct types were used and are distinguished by the method of attachment to the vessel. These are classified as adhesive, weldable, and flame-spray installations. In particular, the following strain gages were tested: types HT 812-4A-S9, HT 812-4A-S6, and HT 1220-2A-FP. All were attached to the vessel by flame spraying a ceramic (Al_2O_3) over the gage. These gages are manufactured by the Baldwin-Lima-Hamilton Corporation. Gages attached by cementing to the vessel included Allegany Instrument Company (Alinco), Type EP-NC-500BA-120, epoxy backed, foil strain gages attached with Armstrong C-2 cement. Iso-elastic gages manufactured by Baldwin-Lima-Hamilton (Type CB-7, Bakelite backed) and attached with Budd B-3 cement were also used. The only gages which were welded to the vessel were Microdot Inc., Type SG-110-1B, which are attached by spot welding.

A photograph of two strain gage installations can be seen in Figure 18. The white rectangle of ceramic with two lead wires extending on the left is the BLH, Type HT 812-4A-S9, flame-sprayed installation. To the right of this is the Allegany Instrument Co., Type EP-NC-500BA-120 gage. The wetted area surrounding this gage is the cement used to attach it to the vessel. The light-colored band on which these gages are installed is a thin coating of ceramic which was prepared for the flame-sprayed strain gage installations. On other tests the glue-down gages were cemented directly to the metal rather than over this layer of ceramic. The narrow metallic ribbon which may be seen immediately above these gages is a "hoop gage" which will be discussed below.

Fig. 18 Vessel strain gage installation.

In addition to conventional strain gages, another means of determining vessel strain was investigated. Hoop gages were installed to measure strain in 180° segments of the vessel wall. A thin layer of aluminum oxide was flame-sprayed around the center of the vessel. This provided an insulating base on which to place a 0.005-inch-thick, 0.031-inch-wide Nichrome ribbon. Two of these ribbons were used, each covering opposite 180° segments of the vessel.

The ends of these two ribbons were then fastened to the vessel and lead wires attached. The Nichrome ribbons were then placed in a bridge and operated as strain gages.

Two methods of attaching the ends of the hoop gages to the vessel were tested. One was simply to tack the ends to the vessel with flame-sprayed ceramic. A photograph of this type of installation is shown in Figure 19. Ceramic hold-downs for the ends of two hoop gages are located on either side of a flame-sprayed strain gage installation. The twisted wires are leads for the hoop gages.

Fig. 19 Strain and hoop gage installation.

The other method of attachment was to loop the ends of the ribbons through small nylon washers, double the ends back, and spot weld them to themselves. Lead wires were then attached at these points. This in effect produced two "belt buckles" 180° apart. The ribbons were held tightly against the vessel walls by tightening them against each other during installation.

Certain advantages are inherent in both methods. An important consideration is the space-limitation in the reactor installation. The flame-sprayed installation had the advantage in this respect as it required less space than the "belt buckle" arrangement. One disadvantage of the hoop gages which are flame-sprayed in place is that the ceramic has poor mechanical shock resistance and, hence, may be the weak point of this kind of installation. If the insulating washers, or "belt buckles", could themselves be attached to the vessel so that the breakage of one ribbon would not mean the loss of the other, and if they could be made very thin and yet retain adequate mechanical strength, then this type of installation would be preferred. When both space and time are considered, it appears that the hoop gages which are held down with a flame-sprayed ceramic hold more promise for reactor installation.

Tests were performed in the laboratory to verify the Nichrome gage factor. It was determined that considerable tension must be applied to extended lengths of the Nichrome ribbon before correct gage-factor values were obtained. A gage factor of 2.0 was approached only after all slack had been removed from the 36-inch length of ribbon which was being tested. Since the hoop gages are not installed under enough tension to remove this slack, it is felt that significant errors will be introduced at low strain levels. Because of this, careful attention must be paid to the installation and the interpretation of data resulting from any hoop gages used in the reactor destructive test.

A number of tests were conducted with strain indicating devices (conventional and hoop gages) in an attempt to extract some knowledge of the behavior of the vessel walls during their first few thousand microinches of strain. In general, the results of these tests were not encouraging. The rate of strain produced in the vessel walls by Composition C-4 was greater than the response of the recording system. Data traces on the oscillograph record were seen to deflect

and go into saturation without visual indication of the failure of the strain gage. The gains of amplifiers used with the gages were selected to range the gages for approximately 1000, 50,000, and 100,000 $\mu\text{in./in.}$ full scale in an attempt to detect the failure of the gages and, hence, determine the initial strain rate in the vessel walls. Occasionally the output from a gage which was ranged for approximately 1000 $\mu\text{in./in.}$ full scale would contain one spike before it saturated. An example of this may be seen in traces (c) and (d) of Figure 20. These are direct and FM recordings, respectively, of the output of a strain gage which had been flame sprayed to the vessel wall. This particular gage was ranged for about 1000 $\mu\text{in./in.}$ full scale. Results obtained from ranging a gage for approximately 100,000 $\mu\text{in./in.}$ full scale may be seen in traces (A) and (B) of this figure.

Again these are direct and FM recordings, respectively, of the sensor output. As a means of checking the recording system's response to a signal having a very fast rise time, square waves having durations of 220 μsec and rise times in the nanosecond region were fed into the amplifying and recording system at the same point as the strain gage signals. The direct and FM recordings, traces (E) and (F), of this may also be seen in Figure 20.

Although the data shown above were obtained from gages which had been attached to the vessel with flame-sprayed ceramic, all gages tested displayed a very similar behavior. No detectable difference was noted in the performance of the various gages under conditions in which they were destroyed.

Results similar to those discussed above were obtained with the hoop gages. Again, a spike would often be seen in the output of this device before it was destroyed and the electronics saturated. The signals obtained from these gages could not be distinguished from those of conventional strain gages.

During the course of the strain gage tests it was noticed that often the gage lead wires failed leaving the gage itself intact. After a thorough review of all tests and the data obtained, it was concluded that installation technique is a major factor in the success or failure of very fast rise-time strain measurements.

More strain gages were installed on dummy vessels. Lead wires were attached in various ways in an attempt to prevent the lead wires from being torn from the gages before they could respond to the dynamic strain. To observe the extremely fast rise times expected, strain gage signals were displayed and photographed on a Tektronix Model 565 oscilloscope. In this

Fig. 20 Strain gage and recording system response. Both direct and FM recordings are shown for two strain gages and a square wave.

manner, rise times (from start to saturation) somewhat less than two micro-seconds were observed. It is believed that the lead wires were being torn from the vessel before a measurable strain was achieved. The weldable strain gages remained intact but the lead wires were torn from them. A 10 to 12 percent increase in vessel diameter occurred during each of these tests.

Detonating a single blasting cap inside the vessel produced no visible deformation of the walls. Strain gages used in these tests indicated vibration of the vessel walls. Examples of the outputs of some of these gages may be seen in Figure 21. Traces (A) and (B) are the outputs of flame-sprayed Type HT 812-4A-S6 and HT 812-4A-S9, respectively. The response of a cemented gage (BLH, Type CB-7 with Budd B-3 cement) is shown in trace (C). Hoop gage response to this test is shown in trace (D). Note that this device, not being bonded to the vessel, indicates only positive strain. The difference in deflection magnitude noted among the traces in this figure is a result of ranging each gage for a different full-scale strain. These data indicate that a vibration rate of 7 to 10 kHz and a peak strain level of about 1000 $\mu\text{in./in.}$ were attained.

Fig. 21 Strain and hoop gage response to vessel vibrations. The result of detonating a single electric blasting cap inside the vessel.

Electromagnetic pickup tests were conducted to determine the amount, if any, of a noise signal which might be induced in the strain gages. Gages which were not subjected to vessel strain were located near "active" gages on the vessel. An analysis of the results of this test and other electrical noise pickup tests led to the conclusion that a problem did not exist in this area.

The above tests clearly show that strain gage installation technique must be perfected before further accomplishments may be made in the field of dynamic strain measurements. The violent expansion of the vessel wall destroyed the lead wires before a strain measurement could be made. As was demonstrated with in-core strain instrumentation (which will be discussed in another part of this report), this problem is not as prevalent when lower strain rates are encountered.

Although success was not attained in measuring strain at the very high strain rates occurring in the vessel walls, it is felt that, had time permitted, a successful installation could have been achieved. Although high explosives may be used to simulate certain phases of a reactor destructive test, the rate of energy release and, hence, the loading rate on simulated reactor components is much greater than that produced by the reactor itself. Thus, demands made on the instrumentation used in the high explosive tests were more severe in some respects than those under which the SNAPTRAN-2 reactor instrumentation will be placed. It is believed that, because of the expected slower strain rates during the nuclear test, present techniques may produce reliable information during the reactor destructive test.

VI. FUEL PIN AND REACTOR COMPONENT ACCELERATION AND DISPLACEMENT

1. ACCELERATION

Acceleration measurements on reactor components were planned as part of the SNAPTRAN-2 destructive test instrumentation program. These measurements were to provide information on reactor disassembly. Accelerometers were to be placed on top of fuel pins and on the outside surfaces of the beryllium reflector which surrounds the core. The location of these sensors required that they be very near the core and, hence, would be subjected to extremely high nuclear radiation fields. Therefore, piezoelectric sensing element accelerometers cannot be used because of undesirable nuclear radiation effects of the crystal. Since the nuclear effects are not accurately predicted, the data obtained from such a device may not be considered reliable. An accelerometer using a seismic mass to create strain in a member, which would be detected by strain gages as the sensing elements, is much less subject to spurious radiation-induced signals. Not only must the device have a low radiation sensitivity, but it must be capable of indicating acceleration levels in excess of 1000 g's. It is advantageous to use accelerometers in addition to linear displacement transducers in the nuclear destructive test because an accelerometer does not need to have its position referenced as do the linear displacement transducers. During the final nuclear transient, a fixed position reference may be difficult to maintain.

At the time these tests were started, an accelerometer having these properties was not commercially available. Strain gage accelerometers were, at that time, limited to acceleration levels of approximately 500 g's. Their limited use at high acceleration levels was usually due to a design incorporating unbonded strain gages. Since high acceleration levels were expected, a lower sensitivity could be tolerated if a rugged unit was obtained. A bonded strain gage accelerometer was therefore designed [15] and fabricated for this application.

The operation of this sensor is based on the measurement of the strain created in a thin-walled cylinder by a seismic mass. In essence, a seismic mass is supported by the cylinder; when the device is accelerated the mass exerts an axial force on it. Strain gages mounted on the cylinder detect the strain caused by this force.

The derivation of the sensitivity of these accelerometers is accomplished in the following manner:

$$\sigma = \epsilon E = \frac{F}{A} \quad (3)$$

and, for a thin-walled cylinder, the cross-sectional area A can be approximated by

$$A \approx 2\pi r t \quad (4)$$

so that,

$$\epsilon = \frac{F}{E 2\pi r t} \quad (5)$$

Solving for F and equating this to the force caused by the acceleration of the seismic mass,

$$F = \epsilon E 2\pi r t = ma = \rho V a \quad (6)$$

or

$$a = \frac{2\pi r t E \epsilon}{\rho V} \quad (7)$$

where

- σ is the stress in the cylinder in dynes/cm²
- A is the cross-sectional area of the cylinder in cm²
- F is the axially applied force on the cylinder in dynes
- m is the weight of the seismic mass in g
- a is the acceleration which it undergoes in cm/sec²
- ρ is the density of the seismic mass material in g/cm³
- V is the volume of the seismic mass in cm³
- ϵ is the axial strain in the cylinder (dimensionless)
- E is the modulus of elasticity of the cylinder material in dynes/cm²
- r is the radius of the cylinder in cm
- t is the cylinder wall thickness in cm.

The above equation is used to calculate the sensitivity of the accelerometer in terms of material constants. This sensitivity is expressed in g/dyne (cgs system), which may be converted to $\frac{\text{in./in.}}{g}$ or $\frac{-\text{in./in.}}{g}$, where g is the gravitational constant.

Four strain gages were installed on the cylinder so that two of them measured circumferential strain while the other two measured axial strain. The combined output of the four gages then became the accelerometer output. The magnitude of the strain indicated by a gage is determined with the following expression:

$$\epsilon = \frac{4e_o}{G_f V} \quad (8)$$

From this and the relationship between axial and circumferential strain, the output voltage of the accelerometer may be written as:

$$e = 2 \left[\frac{G_f V \epsilon}{4} + \frac{G_f V (0.3\epsilon)}{4} \right] \quad (9)$$

The output voltage, e , can be measured and hence the wall strain, ϵ , determined. When used in Equation (7), this strain gives the acceleration level experienced by the accelerometer. The factor 0.3 is Poisson's ratio.

The notation used in the above equations is defined as follows:

e_o is strain gage output voltage in volts

G_f is the "gage factor" for the strain gages (dimensionless)

V is the strain gage power supply voltage in volts

e is the accelerometer output voltage in volts.

A cross section of this accelerometer may be seen in Figure 22. As can be seen, the seismic mass not only lies above the top of the cylinder but extends down into its interior. This permits a greater seismic mass and resulting higher accelerometer sensitivity to be built into a smaller housing. Both the housing and the cylinder are made from aluminum. Although the dimensions may be selected to best suit a particular application, the accelerometers built to date have had cylinders having diameters of 0.395 inch. Wall thickness is 0.008 inch. The seismic mass was machined from lead and had a weight of approximately 11 grams. Overall dimensions of the accelerometers are given in the cross section shown in Figure 22. These sensors have a sensitivity of approximately 2 mV per 1000 g's.

Fig. 22 Cross section of bonded strain gage accelerometer.

The sensitivity of these devices can be optimized by using a more dense material for the seismic mass. Kennertium, which is a lead-tungsten alloy produced by Kennametal, Inc., is well suited for this purpose. This alloy is produced in two grades having densities of 17.0 and 18.5 g/cm³. This represents an increase of 50 and 62 percent, respectively, over pure lead. Not only does the higher density offer an increased sensitivity while maintaining a small accelerometer size, but the alloy is very hard and, therefore, less likely to deform under high accelerations.

After fabrication with lead seismic mass was complete, the accelerometers were calibrated by plotting their output voltage versus the acceleration level indicated by a commercially available, crystal-type accelerometer with both devices subjected to the same forces. The calibration obtained with one of these accelerometers is shown in Figure 23. As can be seen, the output voltage is a linear function of acceleration. Some tests were repeated at the same acceleration levels, and in this manner the repeatability of the device was determined. This also was found to be quite acceptable. The sensitivity which was calculated from design parameters proved to be approximately 20 percent lower than that obtained by comparison to a commercial crystal accelerometer.

The ultimate test of these devices was to determine their behavior when subjected to very fast rise-time accelerations such as those expected in the SNAPTRAN-2 destructive test. This was accomplished by mounting them on a thick metal plate and taping this to the side of the vessel. The bulge produced around the center of the vessel by the detonation of 25 grams of Composition C-4 was used to drive the accelerometer and its mount. Tests were conducted in which this accelerometer and a commercially available crystal accelerometer were both mounted on the metal plate. The crystal accelerometer represented a reference device with

which to compare the strain gage model. Acceleration levels produced in these tests were approximately 5000 g's. Experience with accelerometers used in shock-excited systems has shown that high frequency vibrations often mask low frequency acceleration components which are of greatest interest. For this reason, it was decided to operate on the "live" acceleration data with high-gain operational amplifiers to obtain velocity. Since velocity is the time integral of acceleration, this may be done by electronically integrating the accelerometer signals and applying the information in the following manner:

Fig. 23 Accelerometer calibration. Output of bonded strain gage accelerometer versus the acceleration level indicated by a crystal accelerometer.

$$v = \int_0^t a \, dt \quad (10)$$

and

$$a = \frac{S}{G} e \quad (11)$$

$$v = \int_0^t \frac{S}{G} e \, dt = \frac{S}{G} \int_0^t e \, dt \quad (12)$$

Also,

$$E_v = \frac{1}{RC} \int_0^t e \, dt \quad (13)$$

or

$$\int_0^t e \, dt = RC E_v \quad (14)$$

so that

$$v = \frac{S}{G} \int_0^t e \, dt = \frac{S}{G} (RCE_v) = \frac{SRCE_v}{G} \quad (15)$$

where

v is the velocity in ft/sec

a is the acceleration in ft/sec²

t is the time in sec

S is the sensitivity of the accelerometer in g/volt or $\frac{\text{ft/sec}^2}{\text{volt}}$

R is the value of the integrator resistor in ohms

C is the value of the integrator capacitance in farads

e is the output of the accelerometer in volts

E_v is the output of the integrator in volts

G is the gain of the amplifier which is used with the accelerometer.

From the above relationships, and the velocity trace deflection, the time history of the velocity of the plate on which the accelerometers were mounted can be obtained. Acceleration and velocity data obtained from one of the tests may be seen in Figure 24. Traces (A) and (B) are the acceleration and its time integral (velocity), respectively. These represent 5500 g's and 19 ft/sec, respectively. A reference crystal accelerometer (Kistler Model 808 K5) was mounted to the block in the same manner (not in same test). Its response is also shown in this figure. Traces (C) and (D) represent peak acceleration and velocity levels of 5300 g's and 20 ft/sec, respectively. The accelerometer outputs were electronically integrated by Tektronix Type O integrator ($R = 10^4 \Omega$, $C = 10^{-7} \text{ F}$).

Fig. 24 Acceleration and velocity data obtained during vessel tests.

Obviously, the two accelerometers are not in agreement. As a result, the two velocity traces are in poor agreement. As will be seen in the next section, the correlation with velocity derived from displacement transducers is also poor. Time and equipment obligations made it necessary to record the accelerometer data before it was integrated. As was mentioned above, this is not the preferred technique for obtaining velocity information in the presence of shock fields. After the high explosive tests were concluded and the acceleration

and velocity data analyzed, it was determined that more tests would be needed to determine the cause of the inconsistencies which appear in these data.

2. LINEAR DISPLACEMENT

As shown above, the electronic integration of the accelerometer output results in the time history of velocity. As a means of checking the accuracy of the integrated acceleration trace, a linear displacement transducer may be used. This furnished a time history of component displacement and from this the velocity may also be obtained.

A Bourns, Model 108 (four-inch maximum displacement), linear motion potentiometer was mounted in such a position that it would measure the displacement of a metal block to which the accelerometers were attached. In addition to the linear displacement transducer, an optical tracker was used to measure the motion of this block. This device, which is manufactured by the Optron Corporation, is designed to optically follow the movement of an object on which it is focused. The particular model used in this test is designed to cover a five-inch peak-to-peak displacement with 0.010-inch resolution. Working distance (ie, distance from end of lens to work) is 15 feet. A rise time of 50 μ sec then makes this instrument capable of following objects having a maximum velocity of about 4000 ft/sec. Initial tests indicated that the device failed to remain "locked on" the object which it was tracking, thus failing to provide the required information. Time did not permit further investigation of the cause of this trouble.

In addition to the above devices, a Bourns LINIPOT, miniature, linear motion potentiometer having a travel range of 0.47 inch was tested. This device was investigated as a means of obtaining high resolution of the initial movement of reactor components.

The two (non-optical) displacement measuring devices described above were tested to determine the best range and mounting technique for these tests. Linear displacement transducer response may be seen in Figure 25. Traces (A) and (B) are the outputs of the large (4-inch travel) and small (0.47-inch travel) displacement transducers, respectively. The negative polarity noise spikes which occur during the initial travel of the large displacement transducer were attributed to the device's inability to respond correctly to very fast transients. It is believed that the wiper loses contact during part of its travel in very fast transients. The point of maximum displacement (indicated by arrow) represents approximately

Fig. 25 Linear displacement transducer response. Trace (A) represents the movement of the metal plate to which the accelerometers were attached. Trace (B) represents the movement of the vessel wall.

two inches of travel. Average velocity over the two inches was about 25 ft/sec. This represents the velocity of the metal block to which the accelerometers were attached. The small linear displacement transducer, trace (B), was attached to the wall of the vessel and it indicated an average velocity over its range of about 55 ft/sec.

VII. FUEL PIN STRAIN AND INTERSTICE CLOSURE

In-core instrumentation, designed to furnish information on fuel pin behavior during the destructive test, was subjected to conditions which approached those of the destructive test as closely as possible. The fuel pins are expected to experience at least two distinct forces during the final nuclear destructive transient. One is the force from a shock wave propagating from the center of the core which will tend to displace the fuel elements in a radial direction. This shock wave is created at the center of the core by internally generated gas pressures which rupture the fuel pins. The other arises from the expansion of these elements as their temperature increases during the transient. The radial component of this latter effect will close the interstice between the circular pins. These elements have a diameter of 1.25 inches and are arranged on a triangular 1.25-inch pitch. As the pins expand from the internally generated heat, this opening will diminish in size. As it is necessary to know the rate at which this occurs, a device was designed and fabricated by STEP (Safety Test Engineering Program) personnel for this purpose.

The interstice closure device consists of three small, thin strips of metal spot welded together along their edges to form an open-ended, three-sided enclosure which closely fits the openings between the fuel pins. A photograph showing complete and sectioned interstice closure devices is shown in Figure 26. A strain gage is installed on the inner face of one side of the device. As may be seen in the sectioned view of Figure 26, in addition to the strain gage, the device contains a coiled metal tube. A 0.005-inch-diameter, Teflon insulated, alumel wire is threaded through this tube and lead wires attached. The magnetostrictive property of alumel is used to detect the movement of the device as the interstice closes and the pins move under the action of the shock wave. In addition to the instrumentation within the interstice closure device, strain gages are to be installed on the fuel pins themselves.

Fig. 26 Fuel pin interstice closure device. A completed device is shown as well as one which has been sectioned to show internal construction.

A test was conducted to determine the response of strain gages located on the fuel pins and within the interstice closure device to conditions expected in the nuclear destructive test. Not only was it necessary to create a shock wave which would be allowed to propagate through an array of dummy fuel pins, but the radial expansion of the pins themselves must be simulated. This was accomplished by placing a charge of explosive in each of three dummy fuel pins surrounding the interstice closure device and detonating the three simultaneously. The expansion of the three pins provided an excellent means of testing these devices. Another interstitial device was located in an interstice at the other side of the array of dummy pins. The pins surrounding this device did not contain explosives; therefore, it was used only to determine sensitivity to shock waves

propagated through the fuel pin array. Figure 27 is a diagram of the dummy fuel pin array showing the location of both interstice closure devices and the strain gages installed on the pins.

Because of a shortage of Hastelloy N, which is the cladding material for the fuel used in the SNAP reactors, dummy fuel pins were constructed from 12-inch lengths of Type 321 stainless steel having a 1.25-inch outside diameter and a 0.016-inch wall thickness. These were filled with sand and the ends sealed. Also because Type 321 stainless steel tubing of this size was not in abundant supply, part of the dummy fuel pins were made from open-ended, thick-walled steel pipes. The task of determining the correct type and amount of explosive required to bulge the stainless steel pins and yet not break them was solved by using black powder which is ignited rather than detonated. It was determined that 120 cm³ of Type FFFg produced a 10 percent increase in the diameter of these pins. This amount of powder nearly filled the pins; therefore, sand was not placed in the pins which contained a charge. Styrofoam plugs were placed in each end of the pins to hold the powder within them until it was ignited. As evidenced by the strain gage response, the strain rate produced in this test was much slower than that experienced in the previous tests. Following is a discussion of the results obtained in this test of fuel pin strain and interstice closure measurement techniques.

Four strain gages were flame-sprayed to the dummy fuel pins in the same manner as those which were attached to the vessels. Each of two pins contained an axial and circumferential gage located near the center of the pin. One of these pins was placed in the three-pin cluster which contained charges of black powder. The other was part of a cluster that was located across the fuel pin array.

The circumferential gage on the charge-containing pin was damaged at the beginning of the test and no reliable information was obtained. Although the cause of this damage was not definitely determined, it is possible that a break in the strain gage lead wires resulted in the loss of this data. The axial gage on this pin indicated a maximum strain of approximately 14,000 $\mu\text{in./in.}$ The strain history experienced by this gage may be seen in trace (A) of Figure 28.

Fig. 27 Dummy fuel pin array showing location of instrumentation. Except as noted above, dummy fuel pins were of heavy-walled iron pipe.

Fig. 28 Response of in-core instrumentation to forces created by igniting charges within the dummy fuel pins.

An anomaly appeared in the output of a strain gage located inside one of the interstice closure devices. This particular device was surrounded by three pins filled with explosive. The strain gage was located on the side of the device which was adjacent to the gages discussed above. The output of this gage was recorded separately on two data channels. The purpose of this was to cover a very wide range of strain values. One range was selected to cover very low strains up to about 10^3 $\mu\text{in./in.}$, and the other covered strains up to 5×10^5 $\mu\text{in./in.}$ Trace (B) of the above figure represents the data obtained from the low range. As may be seen, the recording system saturated, indicating that the gage experienced a strain level of at least 1000 $\mu\text{in./in.}$ It should be noted that although the maximum strain level cannot be obtained from this recording, very good resolution of the initial strain rise is obtained. The anomaly appears in the other recording of the response of this gage. A peak strain of 109,000 $\mu\text{in./in.}$ was indicated and may be seen in trace (C) of Figure 28. This does not appear to be consistent with the expected behavior of these gages. Previous tests in which the maximum range of various strain gages was determined showed that gages of this type (foil gage attached with cement) were incapable of withstanding static strains as high as this. Other tests [16] indicate that dynamic conditions produce an even lower useful range with about 2000 $\mu\text{in./in.}$ as the expected maximum. Post-test examination of the device disclosed no damage to the gage although it was apparent that the device had undergone large forces as a result of being surrounded by the rapidly expanding pins. Note the similarity in shape between this and trace (A) although the magnitudes differ greatly. It has not been determined if this indicated strain is correct or if some other problem caused an erroneous signal.

As a means of conserving data channels, the signals from the two alumel wires, which are contained within the two interstice closure devices, were recorded on the same channel. It was planned to use the propagation velocity of the shock wave transversing the array of pins as a means of separating the respective signals. As may be seen from trace (D) of Figure 28, the two signals are not distinctly separated although the point indicated by the arrow may be the time at which the signal from the second alumel wire is generated. Due to the nature of the signal generated by these devices, the precise time at which the shock arrives is not well defined and the usefulness of such a measurement in the SNAPTRAN-2 destructive test may be somewhat in doubt.

Instrumentation located across the fuel pin array from that discussed above was expected to experience relatively low strain levels and was ranged accordingly. Both the circumferential and axial gages indicated low magnitude strains such as might be expected from the manner in which the pins were disarranged. Traces (A) and (B) of Figure 29 are the outputs of the circumferential and axial gages, respectively. Peak strain indicated by the former is 566 $\mu\text{in./in.}$ The axial gage indicated 270 $\mu\text{in./in.}$ It should be noted that the explosive caused the metal bands which contained the dummy fuel pin array to break and as a result the pins were free to move in a random manner under the action of the shock wave. For this reason an exact correlation between the response of various gages used in the test is not possible.

Response of the interstice closure device to the shock wave and pin disarrangement is shown in trace (C) of this figure. This strain gage was ranged for a low strain level and, as may be seen, the electronics saturated indicating that

a level of at least 1000 $\mu\text{in./in.}$ was attained. Trace (D) of this figure is the signal from the strain gage inside the other interstice closure device and is included as a reference.

It is concluded from the results of this test that, at least for strain rates similar to those produced by the black powder, strain gages on the fuel pins themselves are capable of providing the required fuel expansion information. The strain gage within the interstice closure device appears to afford a means of detecting the arrival of a shock wave and in certain cases may provide information about the rate at which the area between the fuel elements diminishes. Although the alumel wire contained within this device is sensitive to the forces created in the process of reactor core destruction, more tests would be required to fully determine the potential of this technique.

Fig. 29 Response of in-core instrumentation to shock wave propagated through fuel pin array. Trace (D) was included as a time reference.

VIII. VESSEL MOVEMENT

The time at which the reactor vessel impacts the beryllium reflector is another event which must be detected by the destructive test instrumentation. A very small space exists between these two reactor components; hence, a detector whose thickness does not exceed 0.01 inch was required. Such a device was constructed in the form of a small coil of 0.005-inch diameter, Teflon insulated, alumel wire. Alumel is magnetostrictive and, hence, generates a magnetic field when subjected to shock and vibration fields. If the wire is held in such a way that it interacts with this field, then an electrical voltage will be generated which can be used to detect the movement of the wire. These conditions are produced when the coil of wire is placed between the vessel and reflector and is impacted as the vessel expands against the reflector.

The device was tested by placing a coil of alumel wire between an aluminum-faced lead brick and the wall of a dummy vessel. An explosive (same as used in other vessel tests) was then used to drive the vessel wall into the face of the brick. The wire was held in position by winding it between small terminal posts placed in the brick. A coil of the wire could also be cemented to the face of the brick. Copper extension wires were attached to these posts and the output signal was fed to a Keithley Model 102B amplifier. From this point the signal was handled in the conventional manner.

In order to verify that the output of this device was generated at the time the vessel wall contacted the face of the lead brick, a reference detector was fabricated. This consisted of two insulated electrical contacts installed in the aluminum face of the brick. They were adjusted to protrude from the face a distance equal to the thickness of the alumel wire. As the vessel impacted the face of the brick, the coil of alumel wire would be hit at the same time the vessel wall completed the circuit between the two contacts. Thus, an electrical reference signal was generated at the time at which the vessel arrived at the plane of the alumel wire.

The possibility of erroneous information caused by electrostatically or electromagnetically induced signals in the alumel coil was also investigated. This was done by placing a similar coil made of copper wire beside the alumel coil. Being non-magnetostrictive, the copper wire would be insensitive to shock and vibrations but would be susceptible to induced noise signals. A photograph of the lead brick with coils and contact closure device installed is shown in Figure 30.

The results obtained with the alumel wire technique were very encouraging. The device was used in several tests and found to be

Fig. 30 Arrangement for testing the magnetostrictive property of alumel wire. Signal was generated when vessel wall impacted the curved face of the brick.

both accurate and dependable. Figure 31 is a reproduction of the data obtained from one of these tests. As may be seen, the signal generated by the alumel wire [trace (A)] occurs at the correct time [trace (B)] and is a result of its magnetostrictive property since a signal is not produced by the copper wire [trace (C)]. The alumel wire broke during the test causing its amplifier to go into saturation. The time at which this occurred is shown by an arrow in trace (A). The voltage generated by these wires ranged from 10 to 30 mV.

Fig. 31 Data obtained as vessel wall impacted face of the brick. Correct time shown by initial rise of trace (a).

IX. PROOF TEST OF REACTOR DISASSEMBLY INSTRUMENTATION

A final test of this series was planned in which a mock-up of the reactor destructive test was to be conducted. A vessel was filled with dummy fuel pins with the exception of the center pin which was replaced by 25 grams of the high explosive Composition C-4. This vessel was then instrumented with a representative of each of the devices previously tested. An interstice closure device was placed in the core approximately midway between the charge and the vessel wall. Strain and hoop gages were installed on the vessel. Two accelerometers and a linear displacement transducer were mounted on a metal plate in contact with the vessel. Another, smaller linear displacement transducer was installed to measure vessel wall displacement adjacent to the strain gage. The magnetostrictive alumel wire was arranged to indicate contact between the vessel wall and a lead brick exterior to the wall. This in effect was a final proof test of the majority of the reactor disassembly instrumentation. Photographs of the top and side of this vessel may be seen in Figures 32 and 33, respectively. The top view shows the dummy fuel pin array and location of the charge. That of the side shows accelerometer and displacement transducer installations. A view of the above vessel after the test was conducted is shown in Figure 34.

The results of this test were encouraging in that all devices performed correctly and in the proper time sequence. The output characteristics of all devices have previously been discussed and will not be repeated here.

The measurement of component velocities during reactor disassembly may be accomplished in two ways. One is to measure the acceleration of the components. The time integral of this is then the desired velocity. This may also be determined directly by means of linear displacement transducers. In this manner velocity is obtained from the time history of component displacement. The use of accelerometers has the advantage of not requiring a position reference as do the linear displacement transducers. Because of the limitations noted above, it is believed that a combination of the two methods

Fig. 32 Photograph of the top of vessel used in final test. Roll of white paper at center of vessel contained the charge of explosive.

Fig. 33 Photograph of the side of vessel used in final test. Vessel impact, acceleration, and displacement instrumentation may be seen.

should be used for the SNAPTRAN-2 destructive test. This permits one system to be used as a check on the other or to act as backup instrumentation in the event one system is over-ranged or otherwise fails to work properly.

Fig. 34 Vessel immediately after test. Note vessel deformation which was caused by radial movement of the dummy fuel pins.

X. DISPERSED FUEL TEMPERATURE AND PROPAGATION VELOCITY

1. TEMPERATURE

The incandescent detonation product gas produced during the explosion of the 1/4-pound charge of Cyclonite was used as a source in determining optical pyrometry techniques suitable for the reactor destructive test. A Huggins Laboratories Mark IX Infrared Radiometer was obtained for the test. This instrument has a temperature range of 0 to 4000°C and a transient response of one microsecond.

One problem which immediately arises in the measurement of a temperature by infrared radiation techniques is that of unknown specimen emissivity. That is, the emissivity of the specimen whose temperature is being measured must be known before an accurate measurement can be made. Since expected detonation product emissivities range from 0.10 to 0.20, tests were planned to determine the magnitude of an error introduced by a given error in emissivity. At the same time the transient response of the instrument and its ability to measure temperatures over distances of several hundred feet were to be checked.

The optical head and power/control unit were placed outside the rear entrance of the building and the optical head focused on the charge of high explosive which was about 600 feet away. At that distance the instrument's field of view is 17 inches; hence, the average temperature within a circle having a diameter of 17 inches was measured. The diameter of the incandescent gas produced by these explosives appears to the eye to be somewhat in excess of two feet.

Tests were conducted at emissivity values of 0.05, 0.10, and 0.20. A malfunction within the optical pyrometer caused its electronics to saturate at the 0.05 and 0.10 values. Thus, it failed to provide useable data on these tests. The test which was conducted at an emissivity of 0.02 resulted in the data which may be seen in Figure 35. A peak temperature of 3500°C was indicated. The indicated rise time (direct recording) of this transient temperature was 35 μ sec. The electronic saturation problem has been corrected in preparation for the nuclear destructive test.

Fig. 35 Optical pyrometer response to transient-high-explosive-detonation-product-gas temperature.

In addition to the above tests, an electrical noise pickup check was performed. This was accomplished by selecting an emissivity of 0.05 and placing the end cap over the front of the optical head. A charge was detonated as in the previous tests and the output of the pyrometer recorded. Any noise signal induced in the instrument or cables would thus be detected. The results showed that a noise signal was not being induced into the system.

The above tests were conducted in a nonnuclear environment whereas the instrument will be subjected to very high nuclear radiation fields during the reactor destructive test. Special precautions must be exercised if reliable infrared radiation measurements are to be made in the presence of these fields. Since the radiation field at the optical pyrometer location (200 feet from reactor)

consists primarily of fast neutrons and gamma rays, adequate shielding must be constructed around the instrument to prevent radiation-induced signals from saturating the output and thus destroying the temperature measurement. This shielding eliminates a direct-line-of-sight path from the pyrometer to the reactor. The problem was solved by the use of front-surfaced aluminized mirrors. Laboratory tests show that these mirrors have somewhat less than a 100 percent reflectance in the infrared region. Thus when used with a single mirror of this type the optical pyrometer will indicate a temperature which is 96.5 percent of the actual temperature.

It is planned to use a hydrogen-containing material to thermalize the fast neutrons. Thermal neutrons produced by interactions with the hydrogen will then be absorbed by cadmium foil. These interactions within the cadmium will produce β and γ fields which will be absorbed, along with the primary γ 's from the reactor, by several inches of lead. The optical pyrometer will be placed behind this shielding and a single front-surfaced mirror will be positioned in front of it. Infrared radiation from the cloud of dispersed fuel produced during the destructive test will be transmitted via this mirror to the pyrometer.

The results of the above tests indicate that an optical pyrometer is well suited for this type of measurement. It is believed that by observing the above installation techniques, a very reliable temperature measurement may be made during the SNAPTRAN-2 destructive test.

2. PROPAGATION VELOCITY

Thermocouples which are presently available are not capable of responding to the peak dispersed fuel temperature, but some are suited to detecting the arrival of this cloud of hot fuel. Two commercially available, fast response thermocouples were tested to determine their suitability as fire ball propagation velocity devices for use near the reactor core. These were a Baldwin-Lima-Hamilton (BLH) Micro-Miniature thermocouple and a NANMAC Corporation, fast response, air temperature probe. Both were of ISA Type K calibration. The same explosive was used as a transient heat source for the thermocouples as was used for the optical pyrometer. Charge-to-sensor distances were varied from 1.5 to 4.0 feet.

During the course of the tests it was noticed that special care had to be exercised in the preparation of the NANMAC thermocouple in order for it to function properly. If the exposed junction had been contaminated by oil or dust, it was cleaned by wiping with a fine grade of sandpaper. This was done in a direction perpendicular to the line which could be seen across the face of the sensor. The effect this cleaning had on the response of the device is dramatically shown in traces (a) and (c) of Figure 36. Trace (a) is the output of this sensor when located 1.5 feet from the charge and before the sensing area was cleaned. Trace (c) was obtained under the same conditions except that the face of the sensor was cleaned as described above. Subsequent tests indicated that once the face was properly prepared, reliable results were obtained until it was again coated by oil or dirt. Direct recordings of the output of this thermocouple indicated rise times of 10 to 15 μ sec. Trace (b) is the response of the BLH thermocouple which was located alongside the above device. Maximum temperatures indicated by the above devices were near 200°C,

which is much below the temperature of the detonation product gases.

The NANMAC thermocouple is of a much sturdier construction and is, therefore, better suited for the reactor installation. On the basis of this and its fast response characteristics it is suggested that this thermocouple be used at intervals directly above the core in the SNAPTRAN-2 test. A calibration such as copper-constantan (ISA Type T) should be used rather than chromel-alumel (Type K) for reasons (magnetostrictive effects) which will be discussed later.

Fig. 36 Thermocouple response to transient-high-explosive-detonation-product-gas temperature. Maximum indicated temperatures were about 200°C.

XI. MISCELLANEOUS MEASUREMENTS

1. VESSEL TEMPERATURE

If a metal is dynamically strained, and the time in which this occurs is short enough so that the process may be considered adiabatic, the temperature of the metal will increase. The strain produced in the vessel wall by the dynamic loading of the high explosive should meet these requirements. It should, therefore, be possible to measure the temperature change in the vessel wall and from this arrive at the strain level experienced by the vessel.

A 0.005-inch diameter, chromel-alumel thermocouple was spot welded (electric discharge) in a spread junction to the outside of the vessel. A charge was placed inside the vessel and strain gage and thermocouple outputs recorded. Results from this were somewhat inconclusive as strain gage recording response problems discussed in an earlier part of this report prevented the determination of true vessel strain. Also, the output of the thermocouple contained electrical noise similar to that observed with the magnetostrictive device discussed earlier. A temperature increase of about ten Celsius degrees was indicated, however. This led to a question of the validity of using chromel-alumel thermocouples in a shock field. Because of the known magnetostrictive properties of the high-nickel-content alumel wire, an effect such as this might be suspected.

Another test was conducted to further investigate this phenomenon. For this test, a chromel-alumel thermocouple similar to the first one was installed on a vessel. Two other "thermocouples" were installed beside this one. These consisted of chromel-chromel and alumel-alumel "thermocouples" fabricated from two chromel and two alumel wires, respectively. The results of this test may be seen in Figure 37. The chromel-alumel thermocouple [trace (A)] contains noise, and yet a temperature increase of about ten Celsius degrees is indicated. Trace (B) of this figure is the output of the spread junction formed with the two alumel wires. Notice that this trace does not have an offset in its deflection indicating that, unlike the real thermocouple, it did not sense a temperature change. The chromel-chromel arrangement's output is shown in trace (C). The low output obtained with this combination is typical of what would be expected from non-magnetostrictive wires.

Fig. 37 Strain induced vessel temperature. Vessel wall temperature increased 10 to 15°C.

The data obtained from these tests imply that the magnetostrictive property of alumel wire can cause serious electrical noise problems when chromel-alumel thermocouples are used in strong shock or vibration fields. This then

dictates a different type of thermocouple for use in these fields. As a further means of isolating the source of this problem, a copper-constantan (ISA Type T) thermocouple was installed on a vessel in the same manner as the others. A test was conducted in which this thermocouple was subjected to the same conditions as were the others. The results may be seen in trace (D) of Figure 37. This thermocouple indicated a total vessel wall temperature increase of about 15 Celsius degrees and, as will be noticed, the noise problem was eliminated. A 10 to 15°C increase in wall temperature can be shown to be reasonably expected from a strain which produces a 10 to 12 percent increase in vessel diameter.

Although more work would be required to determine the relationship between dynamic vessel strain and the resulting temperature increase, it is believed that this technique would prove very useful. As demonstrated here, even the empirical approach to this problem would require careful planning, such as the correct selection of thermocouples.

2. BUILDING VIBRATION AND DISPLACEMENT

During the initial stages of the high explosive test program, concern was expressed over the possibility of creating large vibrations in the Technical Services Center (CF-688 and -689). It was decided to measure the building vibrations caused by detonating 1/4-pound charges of Cyclonite in air, and at a distance of approximately 600 feet from the rear of the structure. A Vibramite Model 11 vibration pickup manufactured by MB Electronics was installed a few inches inside the rear entrance of the building. Installation was accomplished by cementing the device to the floor with a quick-curing epoxy. This pickup is a seismic instrument which generates a voltage proportional to velocity.

The output from this transducer was recorded on magnetic tape. This produced a permanent record of the vibrations transmitted to the floor of the building by the high explosive. By replaying this recording and electronically integrating the Vibramite output, a signal proportional to the floor displacement can be obtained.

The procedure previously applied to accelerometer outputs in obtaining velocity may be applied to the Vibramite (velocity) output to obtain displacement. Displacement, which is the time integral of velocity, was thus determined. The maximum floor displacement experienced during these tests was 0.003 inch. It should be noted that this applies only to 1/4-pound charges of Cyclonite, detonated in air, and at a distance of approximately 600 feet from the building.

A reproduction of an oscillograph recording of floor velocity and its time integral (displacement) is shown in Figure 38. The velocity, shown in trace (A), indicates

Fig. 38 Building displacement. Velocity of building floor [trace (A)] and its time integral displacement [trace (B)].

that a vibration having a frequency of approximately 2 kc was transmitted to the building. Trace (B) is the time integral of trace (A) and represents the time history of the floor displacement. Although published information^[17] about explosive-induced vibrations in buildings did not contain data in the frequency range encountered here, it was apparent that these vibrations were well within a safe level for this building.

XII. BIBLIOGRAPHY

1. MANUFACTURERS

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2. Allegany Instrument Company, 1091 Wills Mountain, Cumberland, Maryland.
3. Ampex Corporation, Redwood City, California.
4. Atlantic Research Corporation, Shirley Highway and Edsall Road, Alexandria, Virginia.
5. Baldwin-Lima-Hamilton Corporation, Waltham 54, Massachusetts.
6. Bourns Instrument Division, 6135 Magnolia Avenue, Riverside, California.
7. Bruel and Kjaer Precision Instruments, 3044 West 106th St., Cleveland, Ohio.
8. Budd Company, P. O. Box 245, Phoenixville, Pennsylvania.
9. Consolidated Electrodynamics Corporation, Monrovia, California.
10. Crystal Research, Inc., 42 Concord Lane, Cambridge 38, Massachusetts.
11. E. I. duPont deNemours and Company, Inc., (Cyclonite, Composition C-4, Type FFFg) 922 Midland Savings Building, Denver 2, Colorado.
12. Huggins Laboratories, Inc., Sunnyvale, California.
13. Kaman Nuclear, Garden of the Gods Road, Colorado Springs, Colorado.
14. Keithley Instruments, Inc., 12415 Euclid Ave., Cleveland 6, Ohio.
15. Kennametal, Inc., Latrobe, Pennsylvania.
16. Kistler Instrument Corporation, 8989 Sheridan Drive, Clarency, New York.
17. Kulite-Bytrex Corporation, 50 Hunt Street, Newton 58, Massachusetts.
18. Massa Division, Cohu Electronic, Inc., 280 Lincoln Street, Hingham, Massachusetts.
19. MB Electronics, New Haven 8, Connecticut.
20. Microdot, Inc., 220 Pasadena Avenue, South Pasadena, California.
21. NANMAC Corporation, 140 Crescent Road, Needham Heights 94, Massachusetts.
22. Optron Corporation, 335 South Salinas Street, Santa Barbara, California.

23. Susquehanna Instruments Corporation, Box 299, R. D. 1, Bel Air, Maryland.
24. United Aero Products Corporation, Columbus Road, Burlington, New Jersey.

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