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STEP PROJECT

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SUMMARY

The feedback energy reactivity coefficient for the coupled-drum impulse transient tests was evaluated as part of the SNAPTRAN-1 test program. Results of the evaluation indicate that within the range from zero to 5.5 MW-sec energy release, the feedback coefficient is equal to 0.139 ± 0.022 \$/MW-sec.

The SNAPTRAN-2 scram and coupling clutch systems were tested to evaluate the scram capability and to determine the effectiveness of the coupling clutch clamp in synchronizing impulse drum motion. The total reactivity swing was 9.25 ± 0.05 dollars with an excess reactivity of 5.05 ± 0.05 dollars. Coupled-drum step transient tests were made to calibrate the nuclear instrumentation, to confirm predictions made from SNAPTRAN-1 testing, and to calibrate the Edgerton, Germeshausen, and Grier (EG&G) gamma chamber. Electromagnetic interference tests were performed to determine if the discharge of xenon flash-lamps used in obtaining photographs of the reactor during the destructive test would produce spurious signals within experimental measurement systems. The experimental and radiological measurement programs for the destructive test were established, and all instrumentation was installed and evaluated. The experimental measurements consists primarily of measurements to determine the behavior of nuclear energy generation and reactor disassembly, and the radiological measurements consist primarily of measurements of direct radiation, airborne radioactivity, and the quantity of beryllium released during the destructive test.

The methods and data used to obtain diffusion theory constants for LOFT nuclear design studies were revised to improve the accuracy of reactor physics calculations. The effective multiplication factor was calculated for three critical experiments to evaluate the accuracy of the reactor physics calculational techniques and parameters. The use of revised group constants resulted in significantly improved criticality predictions.

A two-dimensional depletion calculation was made to determine the excess reactivity required at the beginning-of-life for the reactor to operate at full power for 1600 hours. The excess reactivity calculated was 0.072.

The BURST digital computer program for calculating acoustic wave behavior during blowdown was extended to treat a subcooled system with variable cross-sectional areas in one dimension and with zero initial fluid velocity. Comparison of the results of a sample calculation based on a variable-area system with those predicted by acoustic theory indicates that the relative transmission and reflection of the initial decompression wave after it reaches the adapter is treated correctly by the BURST code. The results obtained indicate that the technique of treating variable-area piping systems during blowdown by utilizing adapter sections produces reasonable results.

Numerical results from three mathematical models for nuclear reactor core meltdown analysis following a loss-of-coolant accident were obtained. Results from the explicit pin model show the significance of conductive and radiative heat transfer on the angular and radial temperature distribution. For the particular studies made, comparisons of the results from the explicit pin model with the results from the "lumped" X-Y model show good agreement.

Results from the annular ring model demonstrate the feasibility of using a lumped annular ring concept to describe axial and radial radiative and conductive heat transfer. The effect of the zirconium-steam chemical reaction on temperature distribution is shown to be important in meltdown analysis.

The temperature decay of the inside surface of the LOFT containment for the first 26.6 hours following blowdown was calculated using the digital computer code, CONTEMPT. A maximum inside containment atmospheric temperature of 216.1°F occurs during blowdown. Pressure in the containment decreases to zero after 26.6 hours.

Laboratory data on joint sealants and coatings were obtained. Although the data relating to joint sealants indicates that silicone elastomer is better suited for LOFT than polyurethane, they do not indicate whether the silicone elastomer is satisfactory for LOFT construction joints. Data relating to coatings indicate that zinc silicate primer can cause coating failures under LOFT conditions.

The semiscale blowdown program was established to investigate the thermal, hydraulic, and mechanical behavior of a pressurized water reactor system subjected to a loss-of-coolant test. The blowdown tests during this period were preliminary and were aimed at obtaining information regarding the most effective method of producing ruptures resulting in coolant blowdown. Ruptures were produced by overpressurization and underpressurization of two rupture discs and by the rupture of a single disc by pyrotechnic means. Results were obtained for several Phase I blowdown tests at subcooled conditions with test pressures ranging from 600 to 1600 psi and test temperatures at room temperature.

Tests were conducted in which measurement of the residual strain of the SNAPTRAN 2/10A fuel pin cladding was made at room temperature to furnish information to aid in interpreting the strain data obtained during SNAPTRAN-1 transient tests. Residual strain values were obtained at several pin locations for maximum strains up to 3000 $\mu\text{in./in.}$

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I. SNAPTRAN-1 TEST PROGRAM

An evaluation of the feedback energy reactivity coefficient for the coupled-drum impulse transient tests was made as part of the SNAPTRAN-1 test program. The errors involved in the data processing were evaluated to establish upper and lower bounds on the values obtained from each test. Results of the evaluation indicate that within the range from zero to 5.5 MW-sec energy release, the feedback reactivity coefficient is nearly constant and equal to 0.139 ± 0.022 \$/MW-sec. The plot of feedback reactivity versus energy release at peak power approximates a straight line with a slope of approximately 0.138 ± 0.041 \$/MW-sec.

1. DATA ANALYSIS -- FEEDBACK ENERGY REACTIVITY COEFFICIENT

The energy reactivity coefficient was obtained by taking the ratio of the incremental change in reactivity, based on drum calibrations, to the associated incremental amount of energy release for each test. This ratio was then taken to be an average value over the energy increment ∂E and plotted at $\partial E/2$. The drum position reactivity associated with the tests of zero energy release was the relative value asymptotically approached for tests of successively decreasing energy. The relative reactivity associated with the drum position at peak power, as determined from the drum calibration curves versus energy release at peak power, is shown in Figures 1 and 2. The value of this relative reactivity for zero energy release was determined to be 1.73 dollars and was used as the reference

Fig. 1 Relative reactivity at peak power versus energy release for coupled-drum impulse transient tests.

Fig. 2 Relative reactivity at peak power versus energy release for coupled-drum impulse transient tests.

point for the reactivity associated with the drum positions at peak power for tests of greater energy release. The time of peak power obtained from the REACTIVITY [1] program outputs, referenced to the time of peak power indicated by nuclear channel N-10, was used in the determination of the individual peak-power drum positions from the raw data. Plots of drum position data versus time were made to permit a smoothing of the drum position data which exhibited fluctuations due to variations in the contact resistance of the drum position wiper arm while the drums were in motion. The individual drum reactivity data were combined to obtain the relative core reactivity level at the time of peak power. The values of energy release at peak power were also taken from computer outputs of the REACTIVITY program. These values were corrected using a correction factor obtained by averaging the weighted detector outputs used during a particular test referenced to nuclear channel N-16.

2. ERROR ANALYSIS -- FEEDBACK ENERGY REACTIVITY COEFFICIENT

The indeterminate errors in $\partial \rho / \partial E$ were estimated assuming differential deviations in the data; that is, letting ΔE and $\Delta \rho$ equal the indeterminate error in E and ρ , respectively, and thereby obtaining the error equation:

$$\frac{\Delta \frac{\partial \rho}{\partial E}}{\frac{\partial \rho}{\partial E}} = \frac{\Delta(\partial \rho)}{(\partial \rho)} + \frac{\Delta(\partial E)}{(\partial E)} \quad (1)$$

For this evaluation $\Delta(\partial E)$ was estimated to be less than ± 20 percent based on analyses of the errors in measurement of the absolute power level and the capability of estimating the time of peak power. The error in reactivity $\Delta(\partial \rho)$ took into account the error in drum position determination at a given time, the error in estimating the time of peak power, and the error in the integral drum worth calibration curves. Assuming the worst possible combination of these errors, $\Delta(\partial \rho)$ was found to be less than ± 7 cents, total.

3. DISCUSSION -- FEEDBACK ENERGY REACTIVITY COEFFICIENT

Results of the feedback coefficient evaluation indicate that $\Delta \rho / \Delta E$ is approximately a constant for energy release pulses up to 5.5 MW-sec. The uncertainty in the determination of each value of $\partial \rho / \Delta E$ is quite large for tests of small energy release; that is, the uncertainty is of the order of ± 100 percent for energy releases of 0.25 MW-sec; whereas, the uncertainty is approximately ± 27 percent for energy releases greater than 1 MW-sec. A statistical comparison of the ten values presented in Figure 3 reveal an arithmetic-averaged value

Fig. 3 Energy feedback coefficient versus energy for coupled-drum impulse transient tests.

of 0.139 \$/MW-sec with a standard deviation of 0.030. For a Gaussian error distribution, the probable error is $\pm (0.6745) (0.030)$, or ± 0.020 \$/MW-sec. Assuming that $\partial \rho / \partial E$ is a constant, its value is determined to be 0.139 ± 0.030 \$/MW-sec. Up to 5.5 MW-sec energy release, the results compare favorably with the results of the single-drum impulse transient tests; that is, 0.139 for the

coupled-drum tests versus 0.142 for the single drum tests where 0.142 is an arithmetic average of the seven values reported for the tests of energy release less than 5.0 MW-sec. The slight decreasing trend in reactivity feedback with tests of increasing energy feedback, however, is not observed for the coupled-drum tests over a range of energy release up to 5.5 MW-sec.

II. SNAPTRAN-2 TEST PROGRAM

The performance of the SNAPTRAN-2 reactor was evaluated to determine scram capability and to determine the effectiveness of the coupling clutch clamp in synchronizing the impulse drum motion during destructive testing. Following the mechanical performance evaluation, the SNAPTRAN-2 reactor was loaded with fuel, and a four-drum banked critical was performed. A power calibration was conducted at 760 watts for an equivalent time of 23.2 minutes, and the drums were shimmed and calibrated to determine the reactivity state of the reactor in this configuration. The total reactivity swing was 9.25 ± 0.05 dollars with an excess reactivity of 5.05 ± 0.05 dollars.

Coupled-drum step transient tests were performed to aid in calibration of the nuclear instrumentation, to confirm predictions made from SNAPTRAN-1 testing, and to calibrate the Edgerton, Germeshausen, and Grier (EG&G) gamma chamber which triggers the high-speed cameras during the destructive test.

Electromagnetic interference tests were performed to determine if the discharge of the xenon flashlamps used by EG&G in obtaining photographic measurements would impose spurious voltage and current signals within experimental measurement detectors and data recording equipment. The interference tests established the existence of photoflash interference and corrective measures were employed to reduce the interference to acceptable levels.

The experimental and radiological measurement programs for the destructive test were established, and all instrumentation was installed and evaluated. The experimental measurements consist primarily of measurements to determine the behavior of nuclear energy generation and reactor disassembly, and the radiological measurements consist primarily of measurements of direct radiation, airborne radioactivity, and the quantity of beryllium released during the destructive transient. The experimental measurements and experimental instrumentation are discussed in Sections II-4 and II-5, respectively; the radiological measurements and instrumentation are discussed in Section II-6.

1. MECHANICAL PERFORMANCE EVALUATION

Evaluation of the drum drive units was performed to determine scram capability, average scram time, and scram repeatability. Drum rotation times were checked to determine the capability of transient nuclear operation. To ensure impulse drum synchronization during the destructive test, tests were conducted to determine the effectiveness of the coupling clutch clamp.

1.1 Drive Unit Evaluation

Scram tests from 0 deg were made with each drive unit and reflector drum to determine scram action, average scram times, and scram repeatability. The results of these tests are shown in Table I.

As can be seen from Table I, the stepper drum (Drums B and C) scram times are approximately the same as for SNAPTRAN-1 [2] and well within the 300-msec,

TABLE I

SNAPTRAN-2 SCRAM CAPABILITY

<u>Drum</u>	<u>Time from Scram to Drum Movement (msec)</u>	<u>Time from Drum Movement to 135 deg (msec)</u>	<u>Time from Scram to 135 deg (msec)</u>
A	140	650	790
B	85	140	225
C	115	115	230
D	145	450	595

maximum allowable scram time. The impulse drum (Drums A and D) scrams, however, are approximately 700 msec, which is substantially longer than for SNAPTRAN-1 and exceeds the maximum allowable time of 300 msec. These longer scram times are due to the shallow slope of the scram cams. On the SNAPTRAN-1 reactor, the cams were machined to a slope which resulted in 300-msec scram times, thus allowing nuclear operation with the drum positioned in the negative sector.

Nuclear operation of the SNAPTRAN-2 reactor was not performed under conditions requiring the 300-msec scram time capability; therefore, the 700-msec scram time was adequate for safe operation.

Tests were also conducted on the stepper and impulse drum drive units to ensure adequate transient operation and drum rotation times. The drives were checked at reduced pressures and at gradually increasing pressures until normal operating pressures of 350 psi for the stepper drives and 1000 psi for the impulse drives were reached. All drive units performed satisfactorily.

In conjunction with the checkout of the drive units, electromagnetic interference tests and vibration tests were conducted. These tests were conducted to ensure that interference problems did not occur when the EG&G flash lamps were fired and that there were no vibrational effects on the EG&G mirrors and pin detectors when all four drums were inserted simultaneously.

1.2 Drum Synchronization Evaluation

The destructive test will be initiated by firing the stepper drums to 0 deg and 0.5 seconds later firing the impulse drums to 0 deg. For the destructive test results to be meaningful, synchronized impulse drum motion during the test is essential. During the coupled-drum impulse transient tests, attempts were made to synchronize impulse drum motion. These attempts included using delay circuits, lubricating the tooth clutch, and boosting the effectiveness of the coupling clutch. Fairly good transient test results were achieved with these methods, but none gave the synchronization and reliability required for the destructive test. To obtain the required synchronization, the impulse-drum tooth clutches must "drop-out" together, and the impulse coupling clutch must be clamped so no clutch slippage occurs during drum rotation.

To achieve synchronization, a relay testing program was conducted to find two relays which would give the desired drop-out times and the necessary repeatability. The two relays found were then used as the impulse tooth clutch drop-out relays. A coupling clutch clamp, as shown in Figure 4, was also devised which could readily be installed on the coupling clutch and which would prevent clutch slippage during impulse drum rotation. Tests were conducted to check the effectiveness of the coupling clutch clamp. The results of these tests are shown in Table II.

Fig. 4 Coupling clutch clamp.

TABLE II

COUPLING CLUTCH TORQUE BEFORE SLIPPING OCCURS

<u>Test</u>	<u>Conditions</u>	<u>Torque (lb-ft)</u>
1	Coupling clutch not energized	15
2	Coupling clutch energized	150
3	Coupling clutch energized and clamp installed	> 600

2. NUCLEAR OPERATIONS

Nuclear operation of the SNAPTRAN-2 reactor before destructive testing consisted of fuel loading, power calibration, drum calibration, and coupled-drum step transient testing. Dry runs were conducted in preparation for the destructive test.

2.1 Fuel Loading

Loading of the SNAPTRAN-2 reactor took place on October 20, 1965, and was accomplished by initially loading the vessel with nineteen hollow aluminum dummy fuel pins in Positions 1 through 19 and eighteen solid lucite dummy fuel pins in Positions 20 through 37. Figure 5 is a cross-sectional view of the reactor core showing core positions. A Po-Be neutron source was positioned directly below the lower grid plate on the center line of the core; and four neutron pulse chambers, located as shown in Table III, were used to obtain counting data for 1/M plots.

Fig. 5 Core showing fuel rod locations.

The fuel rods were loaded one at a time in a center-out circular configuration according to the loading order and core locations outlined in Table IV. Two one-minute neutron counts were taken between successive fuel rod loadings. Figure 6 gives the counts on a $1/M$ plot where $1/M$ is the ratio of the initial counts before any fuel installation to the respective counts after each fuel pin installation.

Following full core loading, a four-drum banked critical was run. The critical drum positions observed were 61 deg 10 min for Drums B and C and 289 deg 50 min (equivalent to 61 deg 10 min in the negative sector of drum travel) for Drums A and D.

TABLE III

DETECTOR LOCATIONS FOR SNAPTRAN-2 FUEL LOADING

Detector Channel	Detector Location	Detector Moderator
1	Vertical center of core adjacent to fixed beryllium reflector -- north side	None
2	Vertical center of core adjacent to fixed beryllium reflector -- south side	None
3	Vertical center of core 3 feet from core -- west side	1 inch of polyethylene
4	Vertical center of core 3 feet from core -- east side	1 inch of polyethylene

2.2 Power Calibration

A power calibration was conducted for which nine flux monitors were inserted in various core interstices. Each monitor contained five 1/4-in. U-235 flux wires spaced at 3-in. vertical intervals. From an analysis of the data, the power level of the reactor was determined to be 760 watts for an equivalent time of 23.2 minutes, with an uncertainty in the absolute magnitude of 9 percent.

The results of the power calibration were used to

- (1) Provide a calibration of the nuclear detectors used for reactor operational instrumentation
- (2) Provide a constant power level for calibration of the nuclear detectors to be used for SNAPTRAN-2 destructive test measurements
- (3) Provide a constant power level for the conduct of sample irradiation experiments; the results of which will be used in the development of destructive test instrumentation for measurement of flux density, energy spectra, and energy release.

2.3 Drum Calibration

The beryllium control drums were shimmed to the configuration which would yield the reactivity desired for the destructive test, and the drum worths were determined for the full range of drum travel (180 to 0 deg) to determine the reactivity state of the reactor with shimming. A standard "drum-bump-period" technique was used for the reactivity measurements. The differential and integral worths of Drums B and C coupled and Drums A and D coupled were determined and are plotted in Figures 7, 8, 9, and 10.

The total reactivity swing was determined to be 9.25 ± 0.05 dollars, with an excess reactivity of 5.05 ± 0.05 dollars. With Drums B and C full-in and with Drums A and D full-out, the reactor was supercritical by 43 cents. This reactivity

TABLE IV

SNAPTRAN-2 LOADING SCHEDULE

Loading Order	Core Location	Fuel Rod Number	U-235 Loading (kg)[a]	
			Pin	Accumulation
1	1	E-104	0.1283	0.128
2	4	E-64	0.1268	0.255
3	2	E-101	0.1280	0.383
4	6	E-45	0.1265	0.510
5	3	E-283	0.1283	0.638
6	7	E-121	0.1286	0.767
7	5	E-117	0.1286	0.895
8	11	E-10	0.1274	1.023
9	17	E-102	0.1280	1.151
10	9	E-17	0.1266	1.277
11	15	E-32	0.1282	1.405
12	19	E-50	0.1271	1.532
13	13	E-100	0.1284	1.661
14	12	E-263	0.1291	1.790
15	18	E-31	0.1273	1.917
16	10	E-42	0.1263	2.043
17	16	E-97	0.1282	2.172
18	8	E-38	0.1280	2.300
19	14	E-54	0.1283	2.428
20	25	E-95	0.1302	2.558
21	34	E-13	0.1285	2.678
22	21	E-105	0.1273	2.814
23	30	E-96	0.1314	2.945
24	22	E-79	0.1270	3.072
25	31	E-93	0.1274	3.200
26	26	E-119	0.1286	3.329
27	27	E-48	0.1257	3.454
28	36	E-43	0.1266	3.581
29	35	E-34	0.1280	3.709
30	24	E-8	0.1275	3.836
31	33	E-98	0.1270	3.963
32	37	E-44	0.1266	4.089
33	28	E-99	0.1313	4.221
34	23	E-61	0.1273	4.348
35	32	E-103	0.1284	4.477
36	20	E-49	0.1264	4.603
37	29	E-94	0.1267	4.730

[a] U-235 loading information provided by Atomics International is based on destructive analysis of fuel machined from the fuel rod ends.

Fig. 6 Inverse multiplication for SNAPTRAN-2 loading.

(43 cents) plus the integral worth of Drums A and D (4.62 dollars) gives the excess reactivity of 5.05 dollars.

2.4 Transient Tests

Coupled-drum step transient tests were performed to aid in the calibration of SNAPTRAN-2 nuclear instrumentation, to confirm predictions made from SNAPTRAN-1 testing, and to calibrate the EG&G gamma chamber which will be used to trigger the high-speed cameras. A reactivity insertion of approximately 1.05 dollars was chosen for these tests to give adequate peak power values to calibrate nuclear instrumentation while keeping the energy release and attendant temperature rise small. The results of these tests are given in Table V.

For the destruction test, to obtain low shutdown reactivity states and low transient starting powers, the stepper drums were fired from 60 degrees instead of 45 degrees, thus increasing the shutdown reactivity by 65 cents and decreasing the starting powers.

Dry runs were conducted in conjunction with the step tests to simulate the planned destructive test conditions and preparations. All groups intending to participate in the destructive test (Health and Safety, LASL, EG&G, and Photography) participated in the dry runs. The runs followed the destructive test countdown check lists as closely as possible, both as to time and sequence of events, and were used to make the destructive test procedures effective and complete.

Fig. 7 Differential worth of the coupled B and C step drums.

Fig. 8 Integral worth of the coupled B and C step drums.

Fig. 9 Differential worth of the coupled A and D impulse drums.

Fig. 10 Integral worth of the coupled A and D impulse drums.

TABLE V

SNAPTRAN-2 STEP TRANSIENT TEST RESULTS

Test	Period (msec)	Reactivity (\$)	Energy to Peak Power (MW-sec)	Total Energy (MW-sec)	Peak Power (MW)	Temperature Rise to Peak Power (°F)	Maximum Hot Spot Temperature Rise (°F)
329	23.0	1.03	0.09	0.18	3	45	110
330	19.5	1.04	0.55	1.1	12	45	130
332	22.4	1.03	0.45	1.1	11	56	165
334	18.9	1.04	0.49	1.7	13	75	195
340	13.4	1.06	0.63	1.6	26	95	350

3. PHOTOFLASH INTERFERENCE TESTS

Xenon flashlamps are to be used by Edgerton, Germeshausen, and Grier (EG&G) as light sources for photographic measurements of reactor disassembly during the SNAPTRAN-2 destructive test. Large electrical currents are required to discharge these flashlamps; and since these currents imposed spurious voltage and current signals within the experimental measurement detectors and data recording equipment during the SNAPTRAN-3 photoflash interference tests, similar interference is expected during the SNAPTRAN-2 test. Therefore, a series of tests was performed to determine the extent of interference and to determine corrective measures to eliminate the interference if it existed.

The experimental instrumentation system for the SNAPTRAN-2 destructive test is capable of measuring, conditioning, and recording reactor phenomena with rise times up to 17.5 microseconds (20-kc bandwidth) and is capable of covering a dynamic range of electrical signals of 30 microvolts to 1 volt. The broad bandwidth and wide dynamic range capability of this instrumentation system makes the system sensitive to spurious current and voltage signals; therefore, existing electromagnetic, electrostatic, or ground loop interference from any electrical system operating during the test could be recorded.

The tests established the existence of photoflash interference on the SNAPTRAN-2 experimental instrumentation system. The corrective measures developed during the tests proved effective in permitting use of the photographic system without intolerable levels of interference.

3.1 Test Description

Three photoflash units are used by EG&G in the photographic measurement system. Each of these photoflash units consists of a four-turn xenon (FX-4) flashlamp housed in an aluminum shielded enclosure, a capacitor discharge power supply, and a pulse-forming network. Gamma detector trigger circuits are used to discharge the flashlamps at a given reactor power level. The arrangement of the photographic system is illustrated in Figure 11. Two flashlamps are mounted above the reactor, and the third

Fig. 11 Photographic and experimental instrumentation systems.

flashlamp is mounted below the reactor. High voltage and signal cables are routed approximately 200 feet to an area adjacent to the reactor control room for connection to the photographic control equipment, power supplies, and pulse forming networks.

For the photoflash interference tests, more than 90 percent of all detectors were placed at their destructive test positions and connected to the signal conditioning equipment in a manner to minimize nuclear radiation interference and other spurious interference signals. Analog magnetic tape systems were used as the major recording media for recording and processing data from sensors and signal conditioning equipment. Oscillographs were used as back-up recording devices for measurements not requiring broad bandwidths and for use during data processing to facilitate analyzing the recorded data for spurious interference signals.

For time correlation purposes, the trigger signal from the photographic control console and the signal from a photocell mounted on the SNAPTRAN-2 reactor were routed to the data acquisition system to record the initiation and discharge of the photoflash event.

The test series was performed in three phases. The first phase was performed to determine the existence of any interference and to define the character of the interference problem; the second phase was performed to determine corrective measures; and the third phase was performed to establish that the corrections were effective and adequate when all systems were restored to normal conditions.

In determining the existence of photographic interference, the entirety of the photographic system (three flashlamps, two gamma detectors, two pulse-forming networks, and one trigger circuit) was used. However, to define the problem and bring about corrective measures, the use of all three units of the photographic system was not considered necessary after a reference test had established that one unit would provide a predictable correlation to all three units. Therefore, during the latter portion of the first phase and during the entire second phase, the tests were made using only one of the three photographic flashlamp systems. However, during the final series of tests, the complete photographic system was employed.

3.2 Test Results

The first phase of the test showed that interference caused by the photoflash system existed in magnitudes considerably in excess of the predetermined tolerable level of ± 5 percent of full scale and in time durations greater than the allowable 150 microseconds. Time histories of typical photoflash interference on data is shown in Figure 12. This interference is representative of the noise that appeared on nuclear detector, thermocouple, and energy probe data.

Early in the test series, electromagnetic coupling to detector and detector leads was determined to be an insignificant contributor to the interference phenomena associated with the discharge of the xenon lamps. To verify that the coupling interference was insignificant, a detector system which had consistently shown photoflash interference was selected. This detector and cable were installed within a copper enclosure to eliminate coupling interference. Subsequent tests showed no significant reduction in the photoflash interference for this particular detector.

Tests were initiated to determine the existence of ground loops between the signal conditioning equipment and the photographic system. These tests positively verified that a ground loop did exist. To measure the magnitude of this phenomena, a differential amplifier was connected to the reactor ground point on the dolly and the signal conditioning ground bus to measure the capacitive-coupled IR drop in the facility ground bus. The result of this measurement established that the photoflash unit was causing enough current flow within the facility ground bus to raise the voltage of the reactor ground point to approximately 1 volt above the signal conditioning ground point on the ground bus.

The current used to discharge the xenon flashlamp was 250 amperes with the initial rise time of 1 millisecond. As a consequence of the distributed capacitance C_D between the photoflash cable and the facility ground, the return current from the flashlamp flowed through the shield of the photoflash cable and the facility ground bus producing the currents, I_2 and I_3 , shown in Figure 13. The current flow within the ground bus proved significant in raising the reactor-dolly ground voltage to 1 volt.

With the high common mode rejection designed into the signal conditioning amplifiers, and with the capability of receiving common mode voltages five times greater than the 1 volt imposed on the amplifiers, common mode signals of the amplitude and rise time displayed by the photoflash ground loop were not expected to cause significant data interference. However, significant interference was observed.

The greatest magnitude of interference appeared on channels having detectors grounded to the reactor dolly. A study revealed that the detector cables had low distributed capacitive reactance to the signal conditioning ground bus, thereby creating a capacitive-coupled ground loop for each detector grounded to the reactor dolly. An example of a thermocouple installation is shown in Figure 13 where R_4 and R_5 represent the unbalanced lead wire resistances of the thermocouple. The thermocouple reference junction is omitted from the circuit schematic for simplicity. As the photoflash ground loop raised the voltage of the reactor dolly above the signal conditioning ground voltage, the capacitive reactances of the

Fig. 12 Initial representative interference on typical data channels.

Fig. 13 Ground loop paths encountered.

cables, C_4 and C_5 , caused currents, I_4 and I_5 . The currents were unequal, due to the electrical unbalance of R_4 and R_5 ; and as a consequence, a normal mode signal appeared at the input of the amplifier. Investigation revealed that the common mode currents degenerated the effective common mode rejection of the input circuitry of the amplifiers in varying degrees, depending on the electrical unbalance of R_4 and R_5 .

To reduce the photoflash current returning through the reactor ground system, the photographic system was regrounded to the facility ground bus at Point A, shown in Figure 11. By this grounding configuration, the photographic system ground currents would enter the ground bus downstream of the signal conditioning and dolly ground points, thereby significantly reducing the ground loop current between the dolly and signal conditioning grounds.

3.3 Conclusion

The entirety of the photographic system and data acquisition system was employed to determine that the correction measures were adequate. Final tests demonstrated that the photoflash interference was well below the predetermined tolerable levels of interference as indicated by typical examples shown in Figure 14. Additional tests will be conducted just prior to the SNAPTRAN-2 destructive test to verify that with the final configuration of the instrumentation and photographic equipment, no interference problem exists.

Fig. 14 Representative interference after corrective measures.

4. EXPERIMENTAL MEASUREMENTS

The measurements for the SNAPTRAN-2 destructive test are those which provide information regarding energy generation and reactor disassembly. The types of information necessary for understanding the nuclear energy generation and the reactor disassembly are discussed, and the measurements to provide this information are presented in the following sections.

4.1 Nuclear Energy Generation Measurements

Specifically, the following information is needed for interpreting and understanding the generation of nuclear energy:

- (1) The rate and magnitude of nuclear energy generation
- (2) The space-time distribution of nuclear energy density within the core
- (3) The major contributors to reactivity compensation and the time dependence of reactivity compensation.

Measurements to provide this information are reactivity insertion rate measurements, fission-rate time-history measurements, neutron flux distribution measurements, and nuclear energy measurements.

4.11 Reactivity Insertion Rate Measurements. In conjunction with determining whether a stable asymptotic period is reached, measurements of drum rotation time-history are obtained to determine if the total reactivity insertion is complete before the onset of negative reactivity feedback. Drum rotation time-history information is also used to correlate predicted test results with actual test results for verifying or revising theoretical calculations.

4.12 Fission-Rate Measurements. Measurements of fission rate provide information on reactor period, power, burst shape, reactivity, and energy release. These measurements are obtained at several locations outside the reactor core by recording the amplitude and rate of change of the gamma flux and the neutron flux above 0.5 eV. Fission-rate measurements are also made at several locations inside the reactor core. These measurements provide information on the reactor period and on any spatial period effects.

4.13 Neutron Flux Distribution Measurements. Three methods are used to obtain information on the neutron flux distribution. The first method is to measure the magnitude and rate of change of the thermal neutron flux at several locations interior to the reactor core using nuclear ionization detection techniques. The second method is to measure the magnitude and rate of change of the fuel and reflector temperature at several locations interior to the reactor core and reflector using energy probe thermometry techniques. The third method is to measure the total time-integrated thermal neutron flux at several locations interior to the reactor core using activation techniques.

4.14 Nuclear Energy Measurements. Nuclear energy information is obtained by measuring the amplitude and rate of change of the fuel temperature in the reactor core. These measurements, in addition to providing information on energy density and deposition rate, also provide information concerning thermal expansion effects, change in fuel heat capacity, and rate dependence of energy deposition on hydrogen evolution. All of this information is necessary for determining the reactivity compensation process. Data on nuclear energy generation as a function of time are obtained from integration of the data obtained from measurements of the fission-rate history. Total nuclear energy release data also are obtained in this manner. In addition, total nuclear energy release data are obtained from the total time-integrated thermal neutron flux measurements presented in the previous section.

4.2 Reactor Disassembly Measurements

Specifically, the following information is needed concerning reactor disassembly:

- (1) The space-time behavior of fuel disintegration and reactor component disassembly
- (2) The mechanical energy generated from hydrogen release or resulting chemical reactions
- (3) The fission product release, transport, and deposition.

This information is provided by measurements of fuel element deformation, core and reflector displacement, environmental effects, and radiological phenomena.

4.21 Fuel Element Deformation Measurements. Measurements of fuel element deformation provide information concerning thermal expansion effects resulting in fuel element elongation and bowing, hydrogen pressure buildup resulting in fuel can elongation and bulging, and propagation behavior of disturbances ultimately resulting in core disassembly.

The measurements will consist of axial and circumferential expansion measurements of the fuel cladding of several fuel elements situated in a radial array, a diametrical array of fuel element axial displacement measurements, and several arrays of interstice closure measurements. These measurements consist of measurements of phenomena variations in time and measurements of the time of occurrence of events.

4.22 Core and Reflector Displacement Measurements. Measurements of the top and bottom grid displacements and of the vessel and fixed beryllium displacements are made to provide information on the later stages of reactor disassembly. Specifically, these measurements consist of measurements of grid plate vertical displacement and fixed beryllium radial displacement; measurements of vessel expansion; and measurements of the velocity, acceleration, and sequence of events of the reactor component disassembly. These measurements also consist of measurements of phenomena variation in time and measurements of the time of occurrence of events.

4.23 Environmental Effects Measurements. Measurements of environmental temperature and pressure provide information concerning the total mechanical energy generation from hydrogen evolution and from exothermic chemical reactions. Pressure measurements are made at approximately 10, 30, 100, 300, and 1000 feet from the reactor. Temperature measurements are made at several locations close to the reactor. Measurements also are made of the displacement of the reactor support structure and railroad dolly to further describe the mechanical energy generation and deposition.

Measurements of the production of airborne beryllium are made to assess the potential personnel hazard in the vicinity of the test area.

4.24 Radiological Phenomena Measurements. Active and passive measurements are made to determine dose and dose rate from the power burst and

radioactive cloud. In addition, measurements are made to determine the composition of the cloud in terms of isotopic, particulate, and gaseous fission product distribution and total fission product release or release fraction. These measurements provide information necessary to assess the radiological hazard and to determine a source release factor. The dose from fallout downwind of the test, the direct dose from the cloud, the relative concentrations of the radioactive noble gases in the cloud, and the particle size of the radioactive materials in the cloud are measured. These measurements are discussed in greater detail in Section 6.

5. EXPERIMENTAL INSTRUMENTATION

The instrumentation for use in making the measurements discussed in the previous section can best be presented by dividing the instrumentation into experimental instrumentation and radiological instrumentation. The experimental instrumentation consists of all instrumentation used for measurements providing data concerning nuclear energy generation and reactor disassembly. Radiological instrumentation consists of all instrumentation used for measurements providing data concerning the radiological effects of the reactor power burst and disassembly. The experimental instrumentation is presented in this section, and the radiological instrumentation is presented in the following section.

The experimental instrumentation can be further divided into phenomena detection instrumentation, signal conditioning instrumentation, and signal recording instrumentation. The signal conditioning and recording instrumentation used for the SNAPTRAN-2 destructive test is the same as that used for the SNAPTRAN-3 destructive test and the SNAPTRAN-1 transient tests^[3].

The detection instrumentation consists of the detectors or transducing elements used to convert phenomena into electrical signals. The criteria for selecting detectors are amplitude accuracy, dynamic range, and frequency response.

5.1 Reactivity Insertion Rate Instrumentation

One angular position potentiometer is placed on the top of each control drum and drive assembly. The potentiometers are 360-deg angular position potentiometers.

Reactivity as a function of control drum angular position has been determined for each step and impulse drum and also for coupled step and impulse drums. The output of the potentiometers is a voltage related to angular position which, in turn, is related to reactivity. Reactivity insertion rate measurements then consist of correlating time-history output voltage data of the potentiometers to the control drum position-reactivity calibration data.

5.2 Fission-Rate Instrumentation

Fission-rate instrumentation consists of scintillation and ionization detectors for the neutron flux above 0.5 eV and ionization detectors for the gamma flux. Cadmium is used to absorb neutrons having energies below 0.5 eV.

The ionization and scintillation detectors are located at different distances from the reactor and are either bare or enclosed by neutron and gamma moderating and absorbing materials to vary the sensitivities of the detectors (amperes/watt) over a dynamic range of approximately twelve decades to provide three types of power measurements. The detector enclosures are presented in Table VI.

TABLE VI

NUCLEAR DETECTOR ENCLOSURES AND ENCLOSURE LOCATIONS^[a]

-
- (1) Enclosure 1 is a 2-inch lead enclosure placed on the flatcar on 0.02 inch of cadmium. R and Z are approximately 9 and -8 feet, respectively.
 - (2) Enclosure 2 is built of 2 inches of lead, 0.02 inch of cadmium, and 4 inches of wax, in that order, looking out of the enclosure. The enclosure is placed on the north end of the flatcar at R and Z approximately 11 and -8 feet, respectively. The enclosure is placed on 0.02 inch of cadmium.
 - (3) Enclosure 3 is built of 4 inches of lead, 0.02 inch of cadmium, and 8 inches of wax, in that order, looking out of the enclosure. The enclosure is placed on the ground immediately outside the test cell. The base of the enclosure is 0.02 inch of cadmium and 2 inches of lead. R and Z are approximately 40 feet and -14 feet, respectively.
 - (4) Enclosure 4 is an 8-inch lead enclosure placed next to Enclosure 3. The base is the same as that for Enclosure 3.
 - (5) Enclosure 5 is a 2-inch lead enclosure on the test cell floor directly under the reactor. R and Z are approximately -14 feet.
 - (6) Enclosure 6 is located in the coupling station. R and Z are approximately 20 and -15 feet, respectively. The enclosure is made from polyethylene-borated-lead brick covered with 0.02 inch of cadmium. The enclosure is placed on 0.02 inch of cadmium. The concrete wall of the coupling station is 5 feet thick.
 - (7) Enclosure 7 is a 2-inch lead enclosure with a 0.02-inch cadmium cover. The enclosure is on the test cell floor at Z = -14 feet and at a distance of R = 20 feet. The enclosure is placed on 0.02 inch of cadmium.
-

[a] R and Z are measured from the center of the reactor core. Z is positive upward and R is the radial distance from the enclosure to the center of the core.

The ionization detectors for gamma and epithermal neutron measurements are General Electric, Westinghouse, Reuter-Stokes, and 20th Century detectors. The scintillation detectors are Phillips Petroleum Company detectors. Two types of scintillation detectors are used. The first, shown in Figure 15, consists of a

Fig. 15 Neutron scintillation detector components for reactor power coverage of 10^6 to 10^{12} watts.

Pilot B crystal and ITT FW-114 photodiode. These detectors are designed to cover the reactor power from 10^6 watts to 10^{12} watts. The second type of scintillation detector, shown in Figure 16, consists of a Pilot crystal and an RCA 6342A photomultiplier tube. These detectors are designed to cover the reactor power from 10^1 watts to 10^6 watts. A summary of the nuclear detectors, the code designations, and the detector locations is contained in Table VII.

The reactor power coverages of the gamma ionization detectors, the neutron scintillation detectors, and the neutron ionization detectors are shown in Figures 17, 18, and 19, respectively. In each case, the detectors were ranged to provide recorder channel overlap for matching of data (reactor period, peak power, and burst shape coverage) from several channels and protective power coverage of approximately two decades in excess of the predicted peak power.

One miniature thermal neutron ionization detector is placed in each of the core Interstices 6-5, 6-6, 6-7, and 9-5, as shown in Figure 20. The detector in Interstice 6-5 is located 3.8 inches above the core center. The other three detectors are located at the core center. All of the detectors are ranged to cover the reactor power between 1×10^8 watts and 3×10^9 watts. These measurements provide information on the reactor period and on any spatial period effects.

A summary of all the fission-rate measurements is presented in Table VIII. In addition to the detectors and the associated electronics, the table lists the specific tape recorder channel allocations, the channel sensitivity (units/volt), and the CEC oscillograph channel sensitivity (units/mm) for the reproduction of the tape recorder channel information.

5.3 Neutron Flux Distribution Instrumentation

Information regarding the magnitude and rate of change of the thermal neutron flux is obtained from the miniature ionization detector measurements discussed in the previous section. The detectors are calibrated to give the power as a function of time over the power range of 1×10^8 watts to 3×10^9 watts. Since the power is directly related to the thermal neutron flux, and since the detector sensitivities (amperes/thermal nv) are known, the proper conversion factors provide data concerning thermal neutron flux as a function of time for each of the four detector positions.

Fig. 16 Neutron scintillation detector components for reactor power coverage of 10^1 to 10^6 watts.

Energy probes, which consist of Chromel-Alumel thermocouples attached to small pieces of fuel, have been built by Atomics International for use in obtaining data concerning the magnitude and rate of change of the fuel and reflector temperature at several core and reflector locations. The fuel pieces in the probes vary in wt% of U-235 and degree of hydriding. Similar energy probes were used during the SNAPTRAN-3 destructive test and during the SNAPTRAN-1 transient test program [3,4]. The locations of the energy probes are shown in Figure 20, and a summary of the measurements by energy probes is presented in Table IX.

Five small gold samples of known mass, enclosed in aluminum containers, are placed in each of two interstices, 11-3 and 11-5, as shown in Figure 20. The axial locations of the gold samples are listed in Table X. Measurements of the neutron-induced activation of the samples provide information regarding the axial flux profile at these two interstices.

5.4 Nuclear Energy Instrumentation

Information regarding the nuclear energy generation is obtained from the energy probe measurements discussed in the previous section. The time constant of the probes is approximately $100 \mu\text{sec}$, and the thermal leak-off time constant is approximately 2 sec. Thus, the probes behave as thermal integrating devices for periods of one second or less.

As previously discussed in Section 4, information regarding the nuclear energy generation as a function of time is obtained from integration of the fission-rate time-history data. Information concerning the total energy release is obtained from total time-integrated thermal neutron flux measurements using gold samples. In this case, similar gold samples were placed in identical core positions for the low-power transient tests performed

TABLE VII

NUCLEAR DETECTORS

Code Designation	Detector	Type	Location
N-1	Westinghouse WL-8105 643002	Neutron Ionization	Enclosure 2
N-2	Reuter-Stokes RSN-76A F1252	Neutron Ionization	Z = -0.5 ft R = 1 ft
N-3	Reuter-Stokes RSN-76A F1253	Neutron Ionization	Enclosure 3
N-6	20th Century VF 1259	Neutron Ionization	Enclosure 3
N-8	20th Century VF 1258	Neutron Ionization	Enclosure 2
N-9	General Electric GE-22 5477539	Gamma Ionization	Z = -3.5 ft R = 7 ft
N-10	General Electric GE-22 5452797	Gamma Ionization	Enclosure 1
N-11	General Electric GE-12 5451839	Gamma Ionization	Z = 0.5 ft R = 1 ft
N-12	General Electric GE 8NA01 5477599	Neutron Ionization	Enclosure 6
N-16	Phillips Petroleum Company SC-1478	Neutron Scintillation	Enclosure 5
N-18	Phillips Petroleum Company SCPM-3	Neutron Scintillation	Enclosure 7
N-20	Phillips Petroleum Company SCPM-1	Neutron Scintillation	Enclosure 2
N-22	Phillips Petroleum Company SCPM-2	Neutron Scintillation	Enclosure 7
N-23	Phillips Petroleum Company SC-2031	Neutron Scintillation	Enclosure 1
N-25	Phillips Petroleum Company SC-2059A	Neutron Scintillation	Enclosure 4
N-26	General Electric 8NA05 5477677	Gamma Ionization	Z = 40 ft; between Enclosures 3 and 4
N-27	General Electric 8NA05 5477678	Gamma Ionization	Enclosure 4
N-30	Phillips Petroleum Company SC-2056	Neutron Scintillation	Enclosure 7
N-32	General Electric Miniature 5477725	Neutron Ionization	Interstice 6-7 Z = 0
N-33	General Electric Miniature 5477726	Neutron Ionization	Interstice 6-5 Z = 3.8 in.
N-34	General Electric Miniature 5477727	Neutron Ionization	Interstice 6-6 Z = 0
N-35	General Electric Miniature 5477728	Neutron Ionization	Interstice 9-5 Z = 0
N-43	Phillips Petroleum Company SC-2022	Neutron Scintillation	Enclosure 5

for instrumentation evaluation. Information obtained from the activation of these samples was used to calibrate the core positions. These calibrations are used with succeeding gold sample activations to obtain the total energy release.

5.5 Fuel Element Deformation Instrumentation

Axial and circumferential expansion measurements of the fuel element cladding are made using Baldwin Lima Hamilton, Type HT-812-4B-59 strain gages installed by flame spraying. Details of the installation of the strain gages has been reported^[4]. Also, one strain gage is sensitive only to radiation effects, so measurements of these effects can be separated from the actual strain measurements.

Fuel element axial displacement measurements are made using Bourns linear motion transducers, Model 10820-17-4,00-502. These detectors are placed on top of the fuel pins.

Interstice closure measurements are made using interstice closure devices constructed by Phillips Petroleum Company. These devices consist of a magnetostrictive gage and a strain gage. The magnetostrictive gage consists of a small coil of tubing containing an 0.5-mil Chromel wire. The strain gage is a Baldwin Lima Hamilton, Type Fa06-12-S9 gage installed with Armstrong A-2 epoxy.

High-speed photographic measurements of the closure of the interstice are made by Edgerton, Germeshausen, and Grier (EG&G). The measurements consist of streak-type and frame-type photographs of overhead views of the core. The EG&G photographic measurements are summarized in Table XI, and the fields of view are shown in Figure 21. A summary of the other fuel element deformation measurements is continued in Tables XII, XIII, and XIV.

5.6 Core and Reflector Displacement Instrumentation

Grid plate vertical displacement and fixed beryllium radial displacement are measured using Bourns linear motion transducers, Models 10820-17-400502 and 1411621-.44-103. Four transducers are placed on the top grid. Two transducers are placed on the outside of the fixed beryllium at the core center at 90 and 180 deg -- one at each position. Two transducers, having different sensitivities, are placed on the outside of the fixed beryllium at the core center at 0 and 270 deg -- one at each position.

Vessel expansion measurements are made using hoop strain gages located -0.5 inches below the core center (the strain gages are not located at the core center because of other instrumentation at that location). The strain gages are constructed of Nichrome flat-band, 1/32 inch in width by 1 mil in thickness, and attached with flame spray. These measurements are supplemented by time-of-arrival measurements using magnetostrictive gages of the same type used in the interstice closure devices. Magnetostrictive gages are installed between the vessel and fixed beryllium at 0, 90, 160, and 270 deg -- one at each position.

Fuel element and fixed beryllium acceleration and velocity measurements are made using accelerometers developed by Phillips Petroleum Company. The accelerometers utilize four-arm strain gages. The output of the accelerometers is sent directly to the FM magnetic tape recorder channels and also to

Fig. 18 SNAPTRAN-2 destructive test -- power coverage of neutron scintillation detectors.

Fig. 19 SNAPTRAN-2 destructive test -- power coverage of neutron ionization detectors.

Fig. 20 In-core, vessel, and reflector instrumentation.

LEGEND

- (1) ● Five 2.5 wt% nonhydrided energy probes, four units each, two inches apart, bottom unit at core center plane.
- (2) ▲ Two 5 wt% nonhydrided energy probes, four units each, two inches apart. Bottom unit of outermost probe 1/4 inch above core center plane. Bottom unit of other probe 1/8 inch above core center plane. One energy probe (on vessel wall) consists of two 5 wt% and two 2.5 wt% units. Bottom unit is at core center plane.

- (3) Three 10 wt% hydrided energy probes, one unit each at core center plane.
- (4) Three zirconium hydrided energy probes, one unit each at core center plane.
- (5) Three miniature ionization chambers at core center plane, one miniature ionization chamber (interstice 6-5) 3.5 inches above core center plane.
- (6) Nine interstice closure devices at core center plane.
- (7) Five axial fuel cladding strain gages on lower 1/3 of fuel rod.
- (8) Two circumferential fuel cladding strain gages on lower 1/3 of fuel rod.
- (9) Eight pin clusters; four on top of fuel rods and four on bottom of fuel rods.
- (10) Three 4-inch travel linear motion potentiometers on top of fuel rods and one 7/16-inch travel linear motion potentiometer on top of grid.
- (11) Three 4-inch travel linear motion potentiometers on the top grid.
- (12) Two circumferential strain gages on vessel at core center plane.
- (13) Four magnetostrictive devices at core center plane.
- (14) Two 180-degree hoop strain gages 0.5 inches below core center plane.
- (15) Two pin arrays; seven horizontal pins per vertical array at 0 and 270 degrees with center pin of each array at core center plane.
- (16) Four pin clusters; one horizontal cluster at 90 degrees on core center plane, and three vertical clusters at 180 degrees with center cluster at core center plane.
- (17) Four 4-inch travel and two 7/16-inch travel, horizontal linear motion potentiometers at core center plane.
- (18) Four accelerometers; two at core center plane and two on top of fuel rods.
- (19) Two Chromel-Alumel thermocouples spot welded to top grid.
- (20) Two Chromel-Alumel thermocouples located 2 inches below core center plane.
- (21) Ten gold, passive measurement samples (five per interstice) symmetrical about core center plane.

TABLE VIII

MEASUREMENTS BY NUCLEAR DETECTORS

Detector		Detector Location	Assigned Amplifier or Electrometer	Amplifier Gain or Electrometer Range	Amplifier or Electrometer Output (Percent Full Scale)	Isolation Amplifier		Channel Assignment		Magnetic Tape Channel Calibration (units/volt)	Oscillograph Channel Calibration (units/mm)
Code	Type					Offset	Gain	Magnetic Tape	Oscillograph		
N-1	Westinghouse WL-8105 (neutron)	Enclosure 2	Keithley	20×10^{-5}	2 100	---	---	2-4 4-7	---	3.2×10^7 W 6.3×10^5 W	9.2×10^5 W 1.8×10^4 W
N-2	Reuter-Stokes RSN-76A (neutron)	Z = 0.5 ft R = 1 ft	Keithley	20×10^{-6}	2 100	---	---	6-2 4-9	---	3.7×10^4 W 7.4×10^2 W	1.1×10^3 W 2.1×10^1 W
N-3	Reuter-Stokes RSN-76A (neutron)	Enclosure 3	Low Level (offset-1V)	R = 10Ω G = 200	10 100	---	---	4-2 4-3	---	1.1×10^{11} W 1.1×10^{10} W	3.1×10^9 W 3.1×10^8 W
N-6	20th Century (neutron)	Enclosure 3	Low Level (offset-1V)	R = 10Ω G = 100	10 100	---	---	8-2 8-3	---	6.4×10^{11} W 6.4×10^{10} W	1.8×10^{10} W 1.8×10^9 W
N-8	20th Century (neutron)	Enclosure 2	Low Level (offset-1V)	R = 10Ω G = 200	10 100 100	---	---	4-4 4-5 ---	---	3.3×10^9 W 3.3×10^8 W Log	9.5×10^7 W 9.5×10^6 W
N-9	General Electric (gamma)	Z = -3.5 ft R = 7 ft	Keithley	20×10^{-7}	2 100	---	---	2-5 4-8	---	2.4×10^7 W 4.7×10^5 W	6.9×10^5 W 1.4×10^4 W
N-10	General Electric (gamma)	Enclosure 1	Keithley	20×10^{-5}	2 100	---	---	6-3 4-6	---	7.0×10^9 W 1.4×10^8 W	2.0×10^8 W 4.0×10^6 W
N-11	General Electric (gamma)	Z = 0.5 ft R = 1 ft	Keithley	20×10^{-7}	2 100	---	---	2-3 4-11	---	9.7×10^4 W 1.9×10^3 W	2.8×10^3 W 5.4×10^1 W
N-12	General Electric (neutron)	Enclosure 6	Low Level (offset-1V)	R = 10Ω G = 100	10 100	---	---	7-2 7-3	---	5.7×10^{11} W 5.7×10^{10} W	1.6×10^{10} W 1.6×10^9 W
N-16	Scintillator (neutron)	Enclosure 5	Low Level (offset-1V)	R = 10Ω G = 25	10 100	---	---	3-4 3-5	---	6.2×10^{11} W 6.2×10^{10} W	1.8×10^{10} W 1.8×10^9 W
N-18	Scintillator (neutron)	Enclosure 7	Keithley	20×10^{-5}	2	---	---	5-2	---	3.1×10^5 W	8.9×10^3 W
N-20	Scintillator (neutron)	Enclosure 2	Keithley	20×10^{-7}	2 100	---	---	5-3 4-10	---	1.2×10^4 W 2.4×10^2 W	3.4×10^2 W 6.9×10^0 W
N-22	Scintillator (neutron)	Enclosure 7	Keithley	20×10^{-5}	2	---	---	2-14	---	1.9×10^6 W	5.4×10^4 W
N-23	Scintillator (neutron)	Enclosure 1	Low Level (offset-1V)	R = $1k\Omega$ G = 50	10 100	---	---	1-6 3-13	---	2.1×10^8 W 2.1×10^7 W	6.0×10^6 W 6.0×10^5 W

TABLE VIII (Contd.)

MEASUREMENTS BY NUCLEAR DETECTORS

Detector		Detector Location	Assigned Amplifier or Electrometer	Amplifier Gain or Electrometer Range	Amplifier or Electrometer Output (Percent Full Scale)	Isolation Amplifier		Channel Assignment		Magnetic Tape Channel Calibration (units/volt)	Oscillograph Channel Calibration (units/mm)
Code	Type					Offset	Gain	Magnetic Tape	Oscillograph		
N-25	Scintillator (neutron)	Enclosure 4	Low Level (offset-1V)	R = 10 Ω G = 25	10 100	---	---	11-2 11-3	A-14 A-15	1.5 x 10 ¹² W 1.5 x 10 ¹¹ W	4.3 x 10 ¹⁰ W 4.3 x 10 ⁹ W
N-26	General Electric (gamma)	Z = 40 ft; between Enclo- sures 3 and 4	Keithley	20 x 10 ⁻⁴	2 100	---	---	2-2 4-14	---	3.4 x 10 ¹² W 6.8 x 10 ¹⁰ W	9.7 x 10 ¹⁰ W 1.9 x 10 ⁹ W
N-27	General Electric (gamma)	Enclosure 4	Low Level (offset-1V)	R = 10 Ω G = 100	10 100	---	---	---	A-17	1.6 x 10 ¹³ W 1.6 x 10 ¹² W	4.6 x 10 ¹¹ W 4.6 x 10 ¹⁰ W
			Low Level (offset-1V)	R = 1k Ω G = 100	10 100	---	---	10-3 5-6	---	1.6 x 10 ¹¹ W 1.6 x 10 ¹⁰ W	4.6 x 10 ⁹ W 4.6 x 10 ⁸ W
N-30	Scintillator (neutron)	Enclosure 7	Low Level (offset-1V)	R = 10 Ω G = 100	10 100	---	---	3-6 3-7	---	5.1 x 10 ¹⁰ W 5.1 x 10 ⁹ W	1.4 x 10 ⁹ W 1.4 x 10 ⁸ W
N-32	General Electric Miniature (neutron)	Interstice 6-7; Z = 0	Low Level (offset-1V)	R = 10 Ω G = 200	10 100	---	---	9-2 ---	---	2.0 x 10 ⁹ W 2.0 x 10 ⁸ W	5.9 x 10 ⁷ W 5.9 x 10 ⁶ W
N-33	General Electric Miniature (neutron)	Interstice 6-5; Z = 3.8 in.	Low Level (offset-1V)	R = 10 Ω G = 200	10 100	---	---	9-3 ---	---	1.1 x 10 ⁹ W 1.1 x 10 ⁸ W	3.2 x 10 ⁷ W 3.2 x 10 ⁶ W
N-34	General Electric Miniature (neutron)	Interstice 6-6; Z = 0	Low Level (offset-1V)	R = 10 Ω G = 200	10 100	---	---	9-4 ---	---	2.7 x 10 ⁹ W 2.7 x 10 ⁸ W	7.7 x 10 ⁷ W 7.7 x 10 ⁶ W
N-35	General Electric Miniature (neutron)	Interstice 9-5; Z = 0	Low Level (offset-1V)	R = 10 Ω G = 200	10 100	---	---	9-5 ---	---	3.0 x 10 ⁹ W 3.0 x 10 ⁸ W	8.6 x 10 ⁷ W 8.6 x 10 ⁶ W
N-43	Scintillator (neutron)	Enclosure 5	Keithley	20 x 10 ⁻⁴	2 100	---	---	1-4 1-5	---	1.3 x 10 ¹⁰ W 2.6 x 10 ⁸ W	3.7 x 10 ⁸ W 7.4 x 10 ⁶ W

TABLE IX

MEASUREMENTS BY ENERGY PROBES

Detector		Assigned Amplifier or Electrometer		Amplifier Gain or Electrometer Range	Amplifier or Electrometer Output (Percent Full Scale)	Isolation Amplifier		Channel Assignment		Magnetic Tape Channel Calibration (units/volt)	Oscillograph Channel Calibration (units/mm)
Code	Type					Offset	Gain	Magnetic Tape	Oscillograph		
EP-147	0 wt% Hydrided	Interstice Z = 0	10-4;	Low Level (offset-1V)	100	100	---	---	9-7	---	441°F 13°F
EP-149	0 wt% Hydrided	Interstice Z = 0	8-4;	Low Level (offset-1V)	100	100	---	---	11-4	---	441°F 13°F
EP-150	0 wt% Hydrided	Interstice Z = 0	12-4;	Low Level (offset-1V)	100	100	---	---	11-5	---	441°F 13°F
EP-153	10 wt% Hydrided	Interstice Z = 0	8-4;	Low Level (offset-1V)	200	10	---	---	1-7 1-8	B-26 ---	2200°F 220°F 63°F 6.3°F
EP-154	10 wt% Hydrided	Interstice Z = 0	10-4;	Low Level (offset-1V)	200	10	---	---	3-8 3-9	---	2200°F 220°F 63°F 6.3°F
EP-155	10 wt% Hydrided	Interstice Z = 0	12-4;	Low Level (offset-1V)	200	10	---	---	1-9 1-10	---	2200°F 220°F 63°F 6.3°F
EP-M6-1	2.5 wt% Non- hydrided	Interstice Z = 6 in.	9-4;	Low Level (offset-1V)	100	100	---	---	1-13	---	441°F 13°F
EP-M6-2	2.5 wt% Non- hydrided	Interstice Z = 4 in.	9-4;	Low Level (offset-1V)	50	100	---	---	1-14	---	877°F 25°F
EP-M6-3	2.5 wt% Non- hydrided	Interstice Z = 2 in.	9-4;	Low Level (offset-1V)	25	100	---	---	10-7	---	1761°F 50°F
EP-M6-4	2.5 wt% Non- hydrided	Interstice Z = 0	9-4;	Low Level (offset-1V)	200	10	---	---	10-8 ---	---	2200°F 220°F 63°F 6.3°F
EP-M8-1	2.5 wt% Non- hydrided	Interstice Z = 6 in.	11-4;	Low Level (offset-1V)	100	100	---	---	11-6	---	441°F 13°F
EP-M8-2	2.5 wt% Non- hydrided	Interstice Z = 4 in.	11-4;	Low Level (offset-1V)	50	100	---	---	11-7	---	877°F 25°F
EP-M8-3	2.5 wt% Non- hydrided	Interstice Z = 2 in.	11-4;	Low Level (offset-1V)	25	100	---	---	11-8	---	1761°F 50°F
EP-M8-4	2.5 wt% Non- hydrided	Interstice Z = 0	11-4;	Low Level (offset-1V)	200	10	---	---	11-9 ---	---	2200°F 220°F 63°F 6.3°F
EP-M9-1	2.5 wt% Non- hydrided	Interstice Z = 6 in.	13-4;	Low Level (offset-1V)	100	100	---	---	7-8	---	441°F 13°F

TABLE IX (Contd.)

MEASUREMENTS BY ENERGY PROBES

Detector		Detector Location	Assigned Amplifier or Electrometer	Amplifier Gain or Electrometer Range	Amplifier or Electrometer Output (Percent Full Scale)	Isolation Amplifier		Channel Assignment		Magnetic Tape Channel Calibration (units/volt)	Oscillograph Channel Calibration (units/mm)
Code	Type					Offset	Gain	Magnetic Tape	Oscillograph		
EP-M9-2	2.5 wt% Non-hydrated	Interstice 13-4; Z = 4 in.	Low Level (offset-1V)	50	100	---	---	7-9	---	877°F	25°F
EP-M9-3	2.5 wt% Non-hydrated	Interstice 13-4; Z = 2 in.	Low Level (offset-1V)	25	100	---	---	4-12	---	1761°F	50°F
EP-M9-4	2.5 wt% Non-hydrated	Interstice 13-4; Z = 0	Low Level (offset-1V)	200	10 100	---	---	4-13 ---	---	2200°F 220°F	63°F 6.3°F
EP-M10-1	2.5 wt% Non-hydrated	Interstice 14-3; Z = 6 in.	Low Level (offset-1V)	100	100	---	---	2-8	---	441°F	13°F
EP-M10-2	2.5 wt% Non-hydrated	Interstice 14-3; Z = 4 in.	Low Level (offset-1V)	50	100	---	---	2-9	---	877°F	25°F
EP-M10-3	2.5 wt% Non-hydrated	Interstice 14-3; Z = 2 in.	Low Level (offset-1V)	25	100	---	---	2-10	---	1761°F	50°F
EP-M10-4	2.5 wt% Non-hydrated	Interstice 14-3; Z = 0	Low Level (offset-1V)	200	10 100	---	---	2-11 ---	---	2200°F 220°F	63°F 6.3°F
EP-M11-1	2.5 wt% Non-hydrated	Interstice 13-3; Z = 6 in.	Low Level (offset-1V)	100	100	---	---	12-10	---	441°F	13°F
EP-M11-2	2.5 wt% Non-hydrated	Interstice 13-3; Z = 4 in.	Low Level (offset-1V)	50	100	---	---	8-4	---	877°F	25°F
EP-M11-3	2.5 wt% Non-hydrated	Interstice 13-3; Z = 2 in.	Low Level (offset-1V)	25	100	---	---	8-5	---	1761°F	50°F
EP-M11-4	2.5 wt% Non-hydrated	Interstice 13-3; Z = 0	Low Level (offset-1V)	200	10 100	---	---	8-6 ---	---	2200°F 220°F	63°F 6.3°F
EP-M14-1	5 wt% Non-hydrated	1 in. in Beryl- lium Reflector; θ = 60 deg; Z = 6-1/4 in.	Low Level (offset-1V)	100	100	---	---	8-7	---	441°F	13°F
EP-M14-2	5 wt% Non-hydrated	1 in. in Beryl- lium Reflector; θ = 60 deg; Z = 4-1/4 in.	Low Level (offset-1V)	100	100	---	---	8-8	---	441°F	13°F

TABLE IX (Contd.)

MEASUREMENTS BY ENERGY PROBES

Detector			Assigned Amplifier or Electrometer	Amplifier Gain or Electrometer Range	Amplifier or Electrometer Output (Percent Full Scale)	Isolation Amplifier		Channel Assignment		Magnetic Tape Channel Calibration (units/volt)	Oscillograp- Channel Calibration (units/mm)
Code	Type	Detector Location				Offset	Gain	Magnetic Tape	Oscillograph		
EP-M14-3	5 wt% Non- hydrided	1 in. in Beryl- lium Reflector; $\theta = 60$ deg; $Z = 2-1/4$ in.	Low Level (offset-1V)	50	100	---	---	8-9	---	877°F	25°F
EP-M14-4	5 wt% Non- hydrided	1 in. in Beryl- lium Reflector; $\theta = 60$ deg; $Z = 1/4$ in.	Low Level (offset-1V)	50	100	---	---	8-10	---	877°F	25°F
EP-M15-1	5 wt% Non- hydrided	Vessel Wall; $\theta = 60$ deg; $Z = 6$ in.	Low Level (offset-1V)	50	100	---	---	7-4	---	877°F	25°F
EP-M15-2	5 wt% Non- hydrided	Vessel Wall; $\theta = 60$ deg; $Z = 4$ in.	Low Level (offset-1V)	50	100	---	---	7-5	---	877°F	25°F
EP-M15-3	2.5 wt% Non- hydrided	Vessel Wall; $\theta = 60$ deg; $Z = 2$ in.	Low Level (offset-1V)	50	100	---	---	7-6	---	877°F	25°F
EP-M15-4	2.5 wt% Non- hydrided	Vessel Wall; $\theta = 60$ deg; $Z = 0$	Low Level (offset-1V)	400	10 100	---	---	7-7 ---	---	1100°F 110°F	31°F 3.1°F
EP-M16-1	5 wt% Non- hydrided	1/2 in. in Beryl- lium Reflector; $\theta = 0$ deg; $Z = 6-1/8$ in.	Low Level (offset-1V)	50	100	---	---	12-11	---	877°F	25°F
EP-M16-2	5 wt% Non- hydrided	1/2 in. in Beryl- lium Reflector; $\theta = 60$ deg; $Z = 4-1/8$ in.	Low Level (offset-1V)	50	100	---	---	12-12	---	877°F	25°F
EP-M16-3	5 wt% Non- hydrided	1/2 in. in Beryl- lium Reflector; $\theta = 60$ deg; $Z = 2-1/8$ in.	Low Level (offset-1V)	50	100	---	---	12-13	---	877°F	25°F
EP-M16-4	5 wt% Non- hydrided	1/2 in. in Beryl- lium Reflector; $\theta = 60$ deg; $Z = 1/8$ in.	Low Level (offset-1V)	50	100	---	---	12-14	---	877°F	25°F

TABLE X

GOLD SAMPLE LOCATIONS

Gold Sample	Aluminum Container Code [a]	Interstice 11-3 [b]	Interstice 11-5
1	X1	Z = 2.25 in.	
2	X11	Z = 1.1 in.	
3	X111	Z = 0	
4	X1111	Z = -1.1 in.	
5	X11111	Z = -2.25 in.	
6	//1		Z = 2.25 in.
7	//11		Z = 1.1 in.
8	//111		Z = 0
9	//1111		Z = -1.1 in.
10	//11111		Z = 2.25 in.

[a] Each aluminum container was inscribed with the code listed for location identification.

[b] Z is the axial distance measured from the center of the reactor.

TABLE XI

EDGERTON, GERMESHAUSEN, AND GRIER
SNAPTRAN-2 PHOTOGRAPHIC MEASUREMENTS

Camera Type	Camera Location[a]	Distance from Reactor (ft)	Field of View at the Reactor (in.)	Effective Distance (ft)	Recording Time (msec)	Operating Speed	Remarks
(1) Beckman & Whitley DynaFax -- Model 350	EG&G Dolly	110	10 x 14	120	5.5	34,770 frames/sec	-----
(2) Beckman & Whitley DynaFax -- Model 350	EG&G Dolly	110	4 x 5.5	120	5.5	33,100 frames/sec	-----
(3) Beckman & Whitley DynaFax -- EG&G Modified	EG&G Dolly	110	1 x 9.5	120	5.5	1.25 x 10 ⁴ cm/sec	Streak-type photograph; 3.5 usec time resolution
(4) Beckman & Whitley DynaFax -- EG&G Modified	EG&G Dolly	110	1 x 8.5	120	5.5	1.38 x 10 ⁴ cm/sec	Streak-type photograph; 3.5 usec time resolution

[a] All cameras use 35 mm film.

Fig. 21 Fields of view of Edgerton, Germeshausen, and Grier photographic measurements.

electronic integrators. The output of the integrator represents the velocity of the reactor components whose acceleration is measured. The output of each integrator is recorded on FM magnetic tape.

Photographic measurements of reactor disassembly are made by Phillips Petroleum Company. The photographic measurements are performed for large and small fields of view of the reactor and its environment. These measurements are made using slow and fast camera operating speeds so photographic measurements can be made of the control drum rotation, the initial reactor disassembly, and the later stages of the disassembly.

A summary of the core and reflector displacement measurements is contained in Tables XII, XIII, XIV, XV and XVI.

TABLE XII

MEASUREMENTS BY STRAIN DETECTORS

Detector			Assigned Amplifier or Electrometer	Amplifier Gain or Electrometer Range	Amplifier or Electrometer Output (Percent Full Scale)	Isolation Amplifier		Channel Assignment		Magnetic Tape Channel Calibration (units/volt)	Oscillograph Channel Calibration (units/mm)
Code	Type	Detector Location				Offset	Gain	Magnetic Tape	Oscillograph		
SG-1	Axial Flame Spray	Interstice 7-4; Z = -2 in.; Pin Position 1	Low Level	100	10 100	---	---	3-10 ---	---	3.5×10^4 μ in./in. 3.5×10^3 μ in./in.	1.0×10^3 μ in./in. 1.0×10^2 μ in./in.
SG-2	Axial Flame Spray	Interstice 7-5; Z = -2 in.; Pin Position 5	Low Level	100	10	---	---	---	B-19	3.5×10^4 μ in./in.	1.0×10^3 μ in./in.
SG-4	Axial Flame Spray	Interstice 8-5; Z = -2 in.; Pin Position 14	Low Level	100	10 100	---	---	10-6 ---	---	3.5×10^4 μ in./in. 3.5×10^3 μ in./in.	1.0×10^3 μ in./in. 1.0×10^2 μ in./in.
SG-7	Axial Flame Spray	Interstice 13-3; Z = -2 in.; Pin Position 11	Low Level	100	10	---	---	9-6	---	3.5×10^4 μ in./in.	1.0×10^3 μ in./in.
SG-8	Axial Flame Spray	Interstice 14-2; Z = -2 in.; Pin Position 24	Low Level	100	10 100	---	---	9-8 ---	---	3.5×10^4 μ in./in. 3.5×10^3 μ in./in.	1.0×10^3 μ in./in. 1.0×10^2 μ in./in.
SG-11	Circumferential Flame Spray	Interstice 7-6; Z = -2 in.; Pin Position 14	Low Level	100	10 100	---	---	10-5 ---	---	3.5×10^4 μ in./in. 3.5×10^3 μ in./in.	1.0×10^3 μ in./in. 1.0×10^2 μ in./in.
SG-13	Circumferential Flame Spray	Interstice 13-3; Z = -2 in.; Pin Position 11	Low Level	100	10 100	---	---	5-4 ---	---	3.5×10^4 μ in./in. 3.5×10^3 μ in./in.	1.0×10^3 μ in./in. 1.0×10^2 μ in./in.
SG-14	Circumferential Flame Spray	Vessel Wall; Z = 0; θ = 0 deg	Low Level	100	10	---	---	3-11	---	3.5×10^4 μ in./in.	1.0×10^3 μ in./in.
SG-15	Circumferential Flame Spray	Vessel Wall; Z = 0; θ = 180 deg	Low Level	100	10 100	---	---	---	C-5 C-4	3.5×10^4 μ in./in. 3.5×10^3 μ in./in.	1.0×10^3 μ in./in. 1.0×10^2 μ in./in.
SG-16	180-deg Hoop	Vessel Wall; Z = -0.5 in.; 0 to 180 deg	Low Level	50	10	---	---	9-10	---	8.0×10^4 μ in./in.	2.3×10^3 μ in./in.
SG-17	180-deg Hoop	Vessel Wall; Z = -0.5 in.; 180 to 360 deg	Low Level	50	10	---	---	3-12	---	8.0×10^4 μ in./in.	2.3×10^3 μ in./in.
SG-18	Flame Spray (dummy)	Next to Reactor	Low Level	100	10	---	---	9-9	---	3.5×10^4 μ in./in.	1.0×10^3 μ in./in.

TABLE XII (Contd.)

MEASUREMENTS BY STRAIN DETECTORS

Detector		Detector Location	Assigned Amplifier or Electrometer	Amplifier Gain or Electrometer Range	Amplifier or Electrometer Output (Percent Full Scale)	Isolation Amplifier		Channel Assignment		Magnetic Tape Channel Calibration (units/volt)	Oscillograph Channel Calibration (units/mm)
Code	Type					Offset	Gain	Magnetic Tape	Oscillograph		
ICD- 1S	Compression Gage	Interstice Z = 0	7-4; Low Level	200	10	---	---	11-10	---	1.9×10^4 μ in./in.	5.4×10^2 μ in./in.
ICD- 2S	Compression Gage	Interstice Z = 1 in.	6-5; Low Level	200	10	---	---	11-11	---	1.9×10^4 μ in./in.	5.4×10^2 μ in./in.
ICD- 3S	Compression Gage	Interstice Z = 0	7-5; Low Level	200	10	---	---	11-12	---	1.9×10^4 μ in./in.	5.4×10^2 μ in./in.
ICD- 4S	Compression Gage	Interstice Z = 0	7-6; Low Level	200	10	---	---	11-13	---	1.9×10^4 μ in./in.	5.4×10^2 μ in./in.
ICD- 5S	Compression Gage	Interstice Z = 0	5-5; Low Level	200	10	---	---	11-14	---	1.9×10^4 μ in./in.	5.4×10^2 μ in./in.
ICD- 7S	Compression Gage	Interstice Z = 0	9-3; Low Level	200	10	---	---	3-14	---	1.9×10^4 μ in./in.	5.4×10^2 μ in./in.
ICD- 8S	Compression Gage	Interstice Z = 0	10-1; Low Level	200	10	---	---	2-12	---	1.9×10^4 μ in./in.	5.4×10^2 μ in./in.
ICD- 9S	Compression Gage	Interstice Z = 0	7-1; Low Level	100	10	---	---	2-13	---	3.8×10^4 μ in./in.	1.1×10^3 μ in./in.
ICD- 10S	Compression Gage	Outside Fixed Beryllium; Z = 0; $\theta = 0$ deg	Low Level	200	10	---	---	---	C-2	1.9×10^4 μ in./in.	5.4×10^2 μ in./in.

TABLE XIII

MEASUREMENTS BY DISPLACEMENT DETECTORS

Detector			Assigned Amplifier or Electrometer	Amplifier Gain or Electrometer Range	Amplifier or Electrometer Output (Percent Full Scale)	Isolation Amplifier		Channel Assignment		Magnetic Tape Channel Calibration (units/volt)	Oscillograph Channel Calibration (units/mm)
Code	Type	Detector Location				Offset	Gain	Magnetic Tape	Oscillograph		
DT-1	Linear Motion Potentiometer	Top of Fuel Pin Position 5	---	---	---	[a]	1	1-12	---	1.6 in.	0.046 in.
DT-2	Linear Motion Potentiometer	Top of Fuel Pin Position 14	---	---	---	[a]	1	6-4	---	1.6 in.	0.046 in.
DT-3	Linear Motion Potentiometer	Top of Fuel Pin Position 29	---	---	---	[a]	1	6-5	---	1.6 in.	0.046 in.
DT-4	Linear Motion Potentiometer	On Top Grid by Interstice 7-4	---	---	---	[a]	1	6-6	---	1.6 in.	0.046 in.
DT-5	Linear Motion Potentiometer	On Top Grid by Interstice 7-5	---	---	---	[a]	1	5-7	---	1.6 in.	0.046 in.
DT-6	Linear Motion Potentiometer	On Top Grid by Interstice 7-6	---	---	---	[a]	1	5-8	---	1.6 in.	0.046 in.
DT-7	Linear Motion Potentiometer	Outside of Beryl- lium; Z = 0; $\theta = 0$ deg	---	---	---	[a]	1	5-9	---	1.6 in.	0.046 in.
DT-8	Linear Motion Potentiometer	Outside of Beryl- lium; Z = 0; $\theta = 90$ deg	---	---	---	[a]	1	5-10	---	1.6 in.	0.046 in.
DT-9	Linear Motion Potentiometer	Outside of Beryl- lium; Z = 0; $\theta = 180$ deg	---	---	---	[a]	1	5-11	---	1.6 in.	0.046 in.
DT-10	Linear Motion Potentiometer	Outside of Beryl- lium; Z = 0; $\theta = 270$ deg	---	---	---	[a]	1	5-12	---	1.6 in.	0.046 in.
DT-11	Linear Motion Potentiometer	Below the reac- tor on the underside of the dolly	---	---	---	[a]	1	6-7	---	4.0 in.	1.1 in.

TABLE XIII (Contd.)

MEASUREMENTS BY DISPLACEMENT DETECTORS

Detector			Assigned Amplifier or Electrometer	Amplifier Gain or Electrometer Range	Amplifier or Electrometer Output (Percent Full Scale)	Isolation Amplifier		Channel Assignment		Magnetic Tape Channel Calibration (units/volt)	Oscillograph Channel Calibration (units/mm)
Code	Type	Detector Location				Offset	Gain	Magnetic Tape	Oscillograph		
DT-12	Linear Motion Potentiometer	On Top Grid by Interstice 6-3	---	---	---	[a]	1	1-11	---	0.18 in.	0.005 in.
DT-13	Linear Motion Potentiometer	Outside of Beryl- lium; Z = 0; $\theta = 0$ deg	---	---	---	[a]	1	5-13	---	0.18 in.	0.005 in.
DT-14	Linear Motion Potentiometer	Outside of Beryl- lium; Z = 0; $\theta = 270$ deg	---	---	---	[a]	1	5-14	---	0.18 in.	0.005 in.

[a] Offset of isolation amplifier cancels zero displacement voltage from potentiometer.

TABLE XIV

TIME-OF-ARRIVAL MEASUREMENTS

Detector		Detector Location		Assigned Amplifier or Electrometer	Amplifier Gain or Electrometer Range	Amplifier or Electrometer Output (Percent Full Scale)	Isolation Amplifier		Channel Assignment		Magnetic Tape Channel Calibration (units/volt)	Oscillograph Channel Calibration (units/mm)
Code	Type						Offset	Gain	Magnetic Tape	Oscillograph		
ICD-1M	Magnetostrictive	Interstice Z = 0	7-4;	Low Level	200	100	---	---	10-9	---	---	---
ICD-3M	Magnetostrictive	Interstice Z = 0	7-5;	Low Level	200	100	---	---	10-10	---	---	---
ICD-4M	Magnetostrictive	Interstice Z = 0	7-6;	Low Level	200	100	---	---	10-12	---	---	---
ICD-9M	Magnetostrictive	Interstice Z = 0	7-1;	Low Level	200	100	---	---	10-11	---	---	---
ICD-10M	Magnetostrictive	Vessel Wall; Z = 0		Low Level	200	100	---	---	---	C-3	---	---
MA-1	Magnetostrictive	Between Vessel and Fixed Beryllium; Z = 0; $\theta = 0$ deg		Low Level	200	100	---	---	8-11	---	---	---
MA-2	Magnetostrictive	Between Vessel and Fixed Beryllium; Z = 0; $\theta = 90$ deg		Low Level	200	100	---	---	8-12	---	---	---
MA-3	Magnetostrictive	Between Vessel and Fixed Beryllium; Z = 0; $\theta = 160$ deg		Low Level	200	100	---	---	8-13	---	---	---
MA-4	Magnetostrictive	Between Vessel and Fixed Beryllium Z = 0 $\theta = 270$ deg		Keithley	100	100	---	---	8-14	---	---	---
TA-3	2 Crystal Pressure Transducers 3 in. Apart	On Radiological Tower		Kistler	1.0	100	---	---	7-12	---	---	---

TABLE XV

MEASUREMENTS BY ACCELERATION AND VELOCITY DETECTORS

Detector		Detector Location	Assigned Amplifier or Electrometer	Amplifier Gain or Electrometer Range	Amplifier or Electrometer Output (Percent Full Scale)	Isolation Amplifier		Channel Assignment		Magnetic Tape Channel Calibration (units/volt)	Oscillograph Channel Calibration (units/mm)
Code	Type					Offset	Gain	Magnetic Tape	Oscillograph		
AC-1	4-Arm Strain Gage	Pin Position 1	Low Level	50	100	0	1	2-6	---	12,600 G	360 G
AC-2	4-Arm Strain Gage	Pin Position 20	Low Level	50	100	0	1	2-7	---	11,300 G	320 G
AC-3	4-Arm Strain Gage	Outside Fixed Beryllium; $\theta = 0$ deg	Low Level	50	100	0	1	6-8	---	12,800 G	270 G
AC-4	4-Arm Strain Gage	Outside Fixed Beryllium; $\theta = 270$ deg	Low Level	50	100	0	1	6-9	---	11,760 G	340 G
AC-1V	Integration of AC-1	Pin Position 1	Low Level	50	100	---	---	12-3	---	119 ft/sec	3.4 ft/sec
AC-2V	Integration of AC-2	Pin Position 20	Low Level	50	100	---	---	12-4	---	107 ft/sec	3.1 ft/sec
AC-3V	Integration of AC-3	Outside Fixed Beryllium; $\theta = 0$ deg	Low Level	50	100	---	---	12-5	---	123 ft/sec	3.5 ft/sec
AC-4V	Integration of AC-4	Outside Fixed Beryllium; $\theta = 270$ deg	Low Level	50	100	---	---	12-6	---	110 ft/sec	3.1 ft/sec

TABLE XVI

SNAPTRAN-2 PHOTOGRAPHIC MEASUREMENTS

Orientation of Station with Reactor (distance-angle)	Camera Type	Field of View at the Reactor (ft)	Effective Distance (ft)	Mirror Size (in.)	Operating Speed (frames/sec)	Film Type	Primary Purpose
(A) 95 ft -- 250 deg ^[a]	Photosonics	6.8 x 5.0	130	30 x 40	762	16 mm -- color	High-Speed Data
(A) 95 ft -- 250 deg ^[a]	Waddell	4.5 x 3.3	130	30 x 40	2800	16 mm -- XR ^[b]	High-Speed Data
(C) 97 ft -- 236 deg ^[c]	Photosonics	7.5 x 5.5	110	36 x 48	1000	16 mm -- color	High-Speed Data
(C) 97 ft -- 236 deg ^[c]	Photosonics	11.0 x 8.0	110	36 x 48	846	16 mm -- infrared	High-Speed Data
(C) 97 ft -- 236 deg ^[c]	Waddell	7.5 x 5.5	110	36 x 48	1950	16 mm -- XR	High-Speed Data
(C) 97 ft -- 236 deg ^[c]	Bell & Howell	22.0 x 16.0	110	36 x 48	64	16 mm -- color	Medium-Speed Documentary
(D) 100 ft -- 121 deg	Photosonics	12.5 x 9.0	125	20 x 30	974	16 mm -- color	High-Speed Data
(D) 100 ft -- 121 deg	Photosonics	25.0 x 18.0	125	36 x 36	1143	16 mm -- color	High-Speed Data
(D) 100 ft -- 121 deg	Waddell	6.3 x 4.6	125	20 x 30	1500	16 mm -- BW ^[b]	High-Speed Data
(D) 100 ft -- 121 deg	Hulcher Press	21.0 x 18.8	125	36 x 36	20	70 mm -- color	High-Resolution Documentary
(E) 500 ft -- 215 deg	Photosonics	10.0 x 7.2	500	None	943	16 mm -- BW	High-Speed Documentary
(E) 500 ft -- 215 deg	Photosonics	17 x 12	500	None	889	16 mm -- color	High-Speed Documentary
(E) 500 ft -- 215 deg	Bell & Howell	100 x 72	500	None	64	16 mm -- color	Medium-Speed Documentary
(E) 500 ft -- 215 deg	Bell & Howell	200 x 144	500	None	48	16 mm -- color	Medium-Speed Documentary
(E) 500 ft -- 215 deg	Hulcher Press	200 x 200	500	None	20	70 mm -- color	High-Resolution Documentary
(E) 500 ft -- 215 deg	Photosonics	50 x 36	500	None	1000	16 mm -- color	High-Speed Documentary

[a] All directional angles are expressed in degrees clockwise rotation from 0 deg which represents north.

[b] XR and BW indicate extended range and black and white, respectively.

[c] Camera Station B, located on the northwest periscope, was omitted because of excessive radiation exposure to the film.

5.7 Environmental Effects Instrumentation

Environmental pressure is measured using Kaman Model K-1200 pressure transducers and Bruel and Kjaer Model 4135 acoustic microphones. Two pressure transducers; one positioned side-on and one positioned face-on, are located at each distance of approximately 10, 30, and 100 feet from the reactor. Two acoustic microphones are located at 300 and at 1000 feet from the core.

Environmental temperature measurements are made using four Nanmac Model G copper-constantan thermocouples located approximately 16, 24, 32, and 40 inches from the center of the core. These thermocouples record the temperature of the hydrogen gas and also provide time-of-arrival information.

Two Chromel-Alumel thermocouples are attached to the top grid and two additional Chromel-Alumel thermocouples are attached to the cladding of two fuel elements. These thermocouples record the gamma heating effects on these reactor components.

A Bourns linear motion transducer, Model 200-128-9002, is installed on the underside of the reactor dolly and below the reactor to record the displacement of the reactor dolly. This measurement is intended to provide information regarding the mechanical energy deposition in the dolly.

Two Atlantic Research crystal pressure transducers, Model DB-15, are installed 100 feet from the reactor and 3 inches apart on the radiological tower to provide information on the time-of-arrival and velocity of the pressure wave. Both transducers comprise one measurement and are designated as TA-3.

The measurements of the environmental effects are contained in Tables XIII, XIV, XVII and XVIII.

TABLE XVII

MEASUREMENTS BY THERMOCOUPLES

Detector		Assigned Amplifier or Electrometer	Amplifier Gain or Electrometer Range	Amplifier or Electrometer Output (Percent Full Scale)	Isolation Amplifier		Channel Assignment		Magnetic Tape Channel Calibration (units/volt)	Oscillograph Channel Calibration (units/mm)
Code	Type	Detector Location			Offset	Gain	Magnetic Tape	Oscillograph		
TC-1	Nanmac Model G, Copper Constantan	Edge of Core; Z = 15-7/8 in.; θ = 0 deg	Low Level (offset-1V)	200	10 100	--- ---	--- 6-10	B-13 ---	2400°F 240°F	69°F 6.9°F
TC-2	Nanmac Model G, Copper Constantan	Edge of Core; Z = 23-7/8 in.; θ = 0 deg	Low Level (offset-1V)	200	10 100	--- ---	6-11 ---	--- B-2	2400°F 240°F	69°F 6.9°F
TC-3	Nanmac Model G, Copper Constantan	Edge of Core; Z = 31-7/8 in.; θ = 0 deg	Low Level (offset-1V)	200	10 100	--- ---	--- 6-12	B-4 ---	2400°F 240°F	69°F 6.9°F
TC-4	Nanmac Model G, Copper Constantan	Edge of Core; Z = 39-7/8 in.; θ = 0 deg	Low Level (offset-1V)	200	10 100	--- ---	6-13 ---	--- B-16	2400°F 240°F	69°F 6.9°F
TC-5	Chromel-Alumel	Spot Welded to Top Grid be- tween Inter- stices 7-5 and 8-5	Low Level (offset-1V)	200	10 100	--- ---	--- 6-14	B-17 ---	2200°F 220°F	63°F 6.3°F
TC-6	Chromel-Alumel	Spot Welded to Top Grid be- tween Inter- stices 7-6 and 8-6	Low Level (offset-1V)	200	10 100	--- ---	--- 5-5	B-25 ---	2200°F 220°F	63°F 6.3°F
TC-7	Chromel-Alumel	Interstice 7-4; Z = -2 in.; Pin Position 1	Low Level (offset-1V)	50	100	---	---	B-14	880°F	25°F
TC-8	Chromel-Alumel	Interstice 7-5; Z = -2 in.; Pin Position 5	Low Level (offset-1V)	50	100	---	---	B-15	880°F	25°F

TABLE XVIII

MEASUREMENTS BY PRESSURE DETECTORS

Detector			Assigned Amplifier or Electrometer	Amplifier Gain or Electrometer Range	Amplifier or Electrometer Output (Percent Full Scale)	Isolation Amplifier		Channel Assignment		Magnetic Tape Channel Calibration (units/volt)	Oscillograph Channel Calibration (units/mm)
Code	Type	Detector Location				Offset	Gain	Magnetic Tape	Oscillograph		
P-1	Kaman ac Bridge	R = 10 Core Diameters; Detector Side-On	Low Level	25	10	---	---	7-10	---	3.1×10^3 psi	8.9×10^1 psi
					100	---	---	10-9	---	3.1×10^2 psi	8.9×10^0 psi
P-2	Kaman ac Bridge	R = 10 Core Diameters; Detector Side-On	Low Level	25	10	---	---	7-11	---	6.8×10^3 psi	1.9×10^2 psi
					100	---	---	---	C-7	6.8×10^2 psi	1.9×10^1 psi
P-3	Kaman ac Bridge	R = 30 Core Diameters; Detector Side-On	Low Level	50	10	---	---	10-10	---	2.6×10^2 psi	7.4×10^0 psi
					100	---	---	9-12	---	2.6×10^1 psi	7.4×10^{-1} psi
P-4	Kaman ac Bridge	R = 30 Core Diameters; Detector Side-On	Low Level	25	10	---	---	9-11	---	3.8×10^2 psi	1.1×10^1 psi
					100	---	---	10-11	---	3.8×10^1 psi	1.1×10^0 psi
P-5	Kaman ac Bridge	30 ft up on Radio- logical Tower; Detector Side-On	Low Level	50	10	---	---	10-12	---	6.0×10^1 psi	1.7×10^0 psi
					100	---	---	7-13	---	6.0×10^0 psi	1.7×10^{-1} psi
P-6	Kaman ac Bridge	30 ft up on Radio- logical Tower; Detector Side-On	Low Level	25	10	---	---	7-14	---	4.2×10^1 psi	1.2×10^0 psi
					100	---	---	---	C-11	4.2×10^0 psi	1.2×10^{-1} psi
P-7	Bruel and Kjaer Microphone	R = 100 M	Keithley (ac)	0.1	100	---	---	9-13	---	4.7×10^{-2} bar	1.3×10^{-3} bar
P-8	Bruel and Kjaer Microphone	R = 300 M	Keithley (ac)	1.0	100	---	---	---	B-5	4.9×10^{-3} bar	1.4×10^{-4} bar
P-9	Bruel and Kjaer Microphone	R = 100 M	Keithley (ac)	1.0	100	---	---	9-14	---	4.8×10^{-3} bar	1.4×10^{-4} bar
P-10	Bruel and Kjaer Microphone	R = 300 M	Keithley (ac)	10	100	---	---	10-14	---	4.5×10^{-4} bar	1.3×10^{-5} bar

5.8 Special Instrumentation

The summary of the reactor control and operation measurements is continued in Table XIX. This summary includes the drum rotation measurements previously discussed, the drum clutch release signals, the reactor fire signal, a light cell measurement of the time the camera lights turn on, and the Edgerton, Germeshausen, and Grier reference signal of the initiation of the photographic measurements.

Optical pyrometry techniques are used to determine the temperature of the dispersed fuel. A Huggins Laboratory, Inc., Mark IX infrared radiometer is installed in a radiation shield 200 feet from the reactor. A front-surfaced, aluminized mirror is placed to one side of the shielding and oriented such that the infrared radiation emitted from fuel ejected from the top of the core is reflected to the sensing area of the pyrometer.

Three difference measurements involving amplifier voltage outputs of neutron scintillation, neutron ionization, and gamma ionization power measurements are made to determine if a measurable neutron spectrum shift occurs during the power burst. The signal amplitude of the neutron scintillation detector varies directly with neutron energy; whereas, the signal amplitude of the neutron ionization detector varies inversely with neutron energy. Thus, by comparing the measurements from the neutron detectors with the measurements from the gamma ionization detectors which do not experience any spectrum shift, any measurable neutron spectrum shift is determined. The three measurements consist of comparing the output of a neutron scintillation detector with the output of a gamma ionization detector, the output of a neutron ionization detector with the output of a gamma ionization detector, and the output of a neutron scintillation detector with the output of a neutron ionization detector. A summary of these measurements and the infrared measurement is contained in Table XX.

Displacement and velocity data as a function of time for the fuel pins, reactor vessel, and fixed beryllium from pin technique measurements are obtained by EG&G. These measurements, although completely separate from the experimental measurements and instrumentation presented, provide backup data on the velocity and displacement of the reactor components.

The pin technique consists of the sequential closure of a series of electrical switches whose locations are known. The electrical switch is an open-ended coaxial cable having conductors which are charged. A conducting moving body bridges the pin wire conductors, causing a current spike to be generated. A summary of the pin detector measurements is contained in Table XXI, and locations of the pin detectors are shown in Figure 20.

The tape recorder and oscillograph channel allocation of the detectors for all of the measurements is summarized in Table XXII and XXIII. The channel allocation is based on (a) separation of the same type of measurements on several tape transports to prevent loss of all data of a given type in the event of tape transport failure; (b) selection of specific detectors for recording on specific transports to provide a general overall description of the destructive test for first analysis; and (c) provision for intertransport timing correlation from noise analysis of similar measurements.

TABLE XIX

MEASUREMENTS OF REACTOR CONTROL AND OPERATION

Detector		Detector Location	Assigned Amplifier or Electrometer	Amplifier Gain or Electrometer Range	Amplifier or Electrometer Output (Percent Full Scale)	Isolation Amplifier		Channel Assignment		Magnetic Tape Channel Calibration (units/volt)	Oscillograph Channel Calibration (units/mm)
Code	Type					Offset	Gain	Magnetic Tape	Oscillograph		
DP-A	Angular 360 deg Position Potenti- ometer	Drum A Tower	---	---	---	-1V	1	1-2	A-2	180 deg	5.15 deg
DP-B	Angular 360 deg Position Potenti- ometer	Drum B Tower	---	---	---	-1V	1	1-3	A-3	180 deg	5.15 deg
DP-C	Angular 360 deg Position Potenti- ometer	Drum C Tower	---	---	---	-1V	1	3-2	A-4	180 deg	5.15 deg
DP-D	Angular 360 deg Position Potenti- ometer	Drum D Tower	---	---	---	-1V	1	3-3	A-5	180 deg	5.15 deg
DCR-A	Drum A Clutch Release Signal	---	---	---	---	---	---	---	A-6	---	---
DCR-B	Drum B Clutch Release Signal	---	---	---	---	---	---	---	A-7	---	---
DCR-C	Drum C Clutch Release Signal	---	---	---	---	---	---	---	A-12	---	---
DCR-D	Drum D Clutch Release Signal	---	---	---	---	---	---	---	A-13	---	---
FS	Fire Signal	---	---	---	---	---	---	---	A-18	---	---
LC-1	Light Cell	$\theta = 0$ deg on Edge of Cubical Support Struc- ture	---	---	---	---	---	10-13	B-3	---	---
EG&G	Reference Signal	---	---	---	---	---	---	10-4	A-16 B-21 C-12	---	---

TABLE XX

NUCLEAR-DETECTOR POWER-DIFFERENCE
MEASUREMENT AND INFRARED-DETECTOR MEASUREMENT

Detector		Detector Location	Assigned Amplifier or Electrometer	Amplifier Gain or Electrometer Range	Amplifier or Electrometer Output (Percent Full Scale)	Isolation Amplifier		Channel Assignment		Magnetic Tape Channel Calibration (units/volt)	Oscillograph Channel Calibration (units/mm)
Code	Type					Offset	Gain	Magnetic Tape	Oscillograph		
IR-1	Infrared Optical Pyrometer	200 ft from reactor	Kistler	0.1	100	---	---	12-2	---	1710 to 3744°F for 1V; $\approx 2040^\circ\text{F}/\text{V}$	58°F (Starting temperature of 1710°F)
DIF-1	Gamma-Neutron Scintillator Difference; 1k Ω 0.1 N-27; 10 Ω 1.0 N-25	---	Differential	10	100	---	---	12-7	---	0.1 V	2.9×10^{-3} V
DIF-2	Neutron Ioniza- tion Scintil- lator Differ- ence; 0.1 N-6; 0.1 N-16	---	Differential	5	100	---	---	12-8	---	0.2 V	5.8×10^{-3} V
DIF-3	Gamma-Neutron Ionization Difference; 0.1 N-12; 1k Ω 0.1 N-27	---	Differential	1.0	100	---	---	12-9	---	1 V	2.9×10^{-2} V

TABLE XXI

MEASUREMENTS BY EDGERTON, GERMESHAUSEN, AND GRIER PIN DETECTORS

Detector	Code	Location	Source Range Coverage
EG&G Pin Cluster (7 pins per cluster in circular array)	PC-1	Top of Fuel Pin; Position 1	0 to 1 cm; 7 Equal Increments
	PC-2	Top of Fuel Pin; Position 1	0 to 6 cm; 7 Equal Increments
	PC-3	Top of Fuel Pin; Position 4	0 to 3 mm; 7 Equal Increments
	PC-4	Top of Fuel Pin; Position 12	0 to 1 cm; 7 Equal Increments
	PC-5	Top of Fuel Pin; Position 1	0 to 1 cm; 7 Equal Increments
	PC-6	Bottom of Fuel Pin; Position 1	0 to 6 cm; 7 Equal Increments
	PC-7	Bottom of Fuel Pin; Position 4	0 to 3 mm; 7 Equal Increments
	PC-8	Bottom of Fuel Pin; Position 12	0 to 1 cm; 7 Equal Increments
EG&G Pin Cluster (7 pins per cluster in circular array)	PC-9	$\theta = 90$ deg; $Z = 0$; Fixed Beryllium	0 to 2 cm; 7 Equal Increments
	PC-10	$\theta = 180$ deg; $Z = 4.5$ in.; Fixed Beryllium	0 to 2 cm; 7 Equal Increments
	PC-11	$\theta = 180$ deg; $Z = 0$; Fixed Beryllium	0 to 2 cm; 7 Equal Increments
	PC-12	$\theta = 180$ deg; $Z = -4.5$ in.; Fixed Beryllium	0 to 2 cm; 7 Equal Increments
EG&G Pin Cluster (7 pins per cluster in straight line array, 2 in. be- tween pins)	PC-13	$\theta = 0$ deg; Center Pin at $Z = 0$; Midway between Vessel and Fixed Beryl- lium	Displacement Event Time
	PC-14	Same as PC-13 except $\theta =$ 180 deg	Displacement Event Time

TABLE XXII

MAGNETIC TAPE CHANNEL ALLOCATION

Transport												
Channel	1	2	3	4	5	6	7	8	9	10	11	12
1	TIMING	TIMING	TIMING	TIMING	TIMING	TIMING	TIMING	TIMING	TIMING	TIMING	TIMING	TIMING
2	DP-A	N-26	DP-C	N-3	N-18	N-2	N-12	N-6	N-32	N-27	N-25	IR-1
3	DP-B	N-11	DP-D	N-3	N-20	N-10	N-12	N-6	N-33	N-27	N-25	AC-1V
4	N-43	N-1	N-16	N-8	SG-13	DT-2	EP-M15-1	EP-M11-2	N-34	EG&G FIDU	EP-149	AC-2V
5	N-43	N-9	N-16	N-8	TC-6	DT-3	EP-M15-2	EP-M11-3	N-35	SG-11	EP-150	AC-3V
6	N-23	AC-1	N-30	N-10	N-27	DT-4	EP-M15-3	EP-M11-4	SG-7	SG-4	EP-M8-1	AC-4V
7	EP-153	AC-2	N-30	N-1	DT-5	DT-11	EP-M15-4	EP-M14-1	EP-147	EP-M6-3	EP-M8-2	DIF-1
8	EP-153	EP-M10-1	EP-154	N-9	DT-6	AC-3	EP-M9-1	EP-M14-2	SG-8	EP-M6-4	EP-M8-3	DIF-2
9	EP-155	EP-M10-2	EP-154	N-2	DT-7	AC-4	EP-M9-2	EP-M14-3	SG-18	P-1	EP-M8-4	DIF-3
10	EP-155	EP-M10-3	SG-1	N-20	DT-8	TC-1	P-1	EP-M14-4	SG-16	P-3	ICD-1S	EP-M11-1
11	DT-12	EP-M10-4	SG-14	N-11	DT-9	TC-2	P-2	MA-1	P-4	P-4	ICD-2S	EP-M16-1
12	DT-1	ICD-8S	SG-17	EP-M9-3	DT-10	TC-3	TA-3	MA-2	P-3	P-5	ICD-3S	EP-M16-2
13	EP-M16-1	ICD-9S	N-23	EP-M9-4	DT-13	TC-4	P-5	MA-3	P-7	LC-1	ICD-4S	EP-M16-3
14	EP-M6-2	N-22	ICD-7S	N-26	DT-14	TC-5	P-6	MA-4	P-9	P-10	ICD-5S	EP-M16-4

TABLE XXIII

OSCILLOGRAPH CHANNEL ALLOCATION

Oscillograph				Oscillograph		
Channel	A	B	C	Channel	A	B
1	TIMING	TIMING	TIMING	14	N-25	TC-7
2	DP-A	TC-2	ICD-10S	15	N-25	TC-8
3	DP-B	LC-1	ICD-10M	16	EG&G FIDU	TC-4
4	DP-C	TC-3	SG-15	17	N-27	TC-5
5	DP-D	P-8	SG-15	18	Fire Signal	SG-1
6	Drum A Clutch	SG-8	ICD-1M	19	---	SG-1
7	Drum B Clutch	EP-M6-4	P-2	20	---	N-8 LOG
8	N-32	EP-M8-4	ICD-3M	21	---	EG&G FIDU
9	N-33	EP-M9-4	ICD-9M	22	---	SG-4
10	N-34	EP-M10-4	ICD-4M	23	---	SG-11
11	N-35	EP-M11-4	P-6	24	---	SG-13
12	Drum C Clutch	EP-M15-4	EG&G FIDU	25	---	TC-6
13	Drum D Clutch	TC-1	---	26	---	EP-153

6. RADIOLOGICAL MONITORING PROGRAM FOR THE SNAPTRAN-2 DESTRUCTIVE TEST

The radiological monitoring program is oriented to obtain data for the evaluation of the radiological hazards of the SNAPTRAN-2 reactor destructive test. The monitoring program includes the measurement of fission product release, direct gamma and neutron doses, the spread of airborne contamination, and the spread of beryllium.

The information obtained from the SNAPTRAN-3 destructive test led to modifications to the radiological monitoring grid. The modified grid, shown in Figures 22, 23, 24, and 25, is a series of concentric arcs with the reactor test pad at the center. A heavy concentration of sampling equipment is placed in a 60-deg sector, oriented along the center line of the expected cloud trajectory, 30 deg east of true north.

Each of the grid stations along each arc are marked with 5-foot steel posts. The sampling equipment is fastened near the top of these posts to simulate the breathing height of a man and to reduce interference from the ground dust and vegetation.

The information obtained from downwind samplers positioned on the SNAPTRAN-3 destructive test monitoring grid indicated that the samplers were spaced too far apart to obtain sufficient information about the radioactive cloud. To correct this deficiency, the number of samplers on each arc on the 60-deg

Fig. 22 SNAPTRAN radiological grid, 2- and 10-meter arcs.

Fig. 23 SNAPTRAN radiological grid, 25- and 50-meter arcs.

downwind sector was increased. In particular, fallout plates and film dosimeters are used extensively within 50 meters of the reactor. On the 25- and 50-meter arcs, the film dosimeters and fallout plates are approximately 3 feet apart, allowing a measurement of the definite boundary of the radioactive cloud. Major stations, with their samplers, fission gas detectors, and ionization chambers were increased to ensure adequate sampling and to reduce the possibility of the cloud passing undetected between two adjacent stations.

6.1 Source Term Measurements

Instrumentation positioned around the reactor and on the radiological monitoring grid measures most aspects of the radiological consequences of the destructive test. Particular emphasis is given to measuring parameters necessary to calculate the quantity of fission products released from the reactor. The most commonly used and acceptable method for determining the release fraction is the application of a Sutton-type diffusion equation to the data obtained from the downwind samplers and the calculation of the source term which would give the measured fission product distribution. In addition to meteorological measurements of wind speed, wind direction, wind fluctuations, and vertical temperature profile, measurements of the radial, vertical, and lateral cloud diffusion are required for use of Sutton's basic diffusion equation.

The radial spread (length) of the radioactive cloud is measured at the 25- and 50-meter arcs by using anthracene crystals. These beta sensitive crystals detect only the beta particles; and because of the relatively short

Fig. 24 SNAPTRAN radiological grid, 100-, 200-, and 300-meter arcs.

Fig. 25 SNAPTRAN radiological grid, 500-, 900-, and 1500-meter arcs.

range of this radiation, the cloud arrival and departure times can be determined. The cloud arrival and departure times and the wind velocity are then used to determine the length of the cloud at the two arcs.

The vertical distribution of the radionuclides carried by the cloud is monitored by sampling devices mounted on lines connected to three 60-foot poles on the 50-meter arc. A vertical grid is established by securing a line between the top of the three poles with sample lines spaced across this top line and secured to the ground. Film badges and fallout plates are spaced on this vertical grid. Because of the relatively short range of beta particles, the beta activity recorded on film badges describes the vertical profile of the cloud. In addition to this grid, the radiological tower on the 20-meter arc, with samplers spaced to the 150-foot height, provides a second vertical measurement. Since this tower is close to the reactor, the recorded information on the samplers can be used to estimate the release height of the cloud.

The width of the cloud is determined on all downwind arcs by observing beta dose measurements on grid film badges and the activity deposited on high-volume air sampler filters. A highly sensitive counting technique is used to determine a gross count on all grid air sampler filters. This technique, which utilizes two scintillation crystals mounted opposite each other, provides a means of detecting activity on the filters for radiation levels as low as background level. The technique provides an accurate determination of whether or not the cloud passes over a particular sampler. In addition to this counting technique, autoradiography is performed on high-volume air sampler filters and fallout plates. The sensitive autoradiographic technique provides positive verification of any activity which exists on the fringe of the cloud at the given grid position.

Information from meteorological measurements and information from the measurements described in the preceding paragraphs are used to establish the meteorological diffusion and stability parameters C_x , C_y , C_z , and n for Sutton's diffusion equation. The remaining data needed for the diffusion calculation is obtained from analysis of the high-volume air samplers.

6.2 Fission Gas Sampling

Some of the fission gases have half-lives sufficiently long to be carried beyond the sampling grid before the gas decays to particulate daughters. Filtering media will not collect noble gases as they do the particulate daughters; therefore, a fission gas detector located three feet above the ground is used to sample the radioactive noble gases. The gases are collected by drawing a sample of the cloud through a high-efficiency, Microsorban filter and into an airtight balloon. The trapped noble fission gases are then allowed to decay to their particulate daughters for a prescribed time after which the balloon is deflated through a second high-efficiency filter. The daughter products trapped on the second filter and the activity plated on the inner surface of the balloon are measured by using a multichannel gamma-ray spectrometer.

Analytical techniques, which make use of the known half-lives and decay chains of the noble fission gases and their daughter products, are employed to calculate the amount of noble gases sampled. Since the fission gas detectors are on the 50-meter arc (for which data are available to calculate cloud size), the cloud volume and quantity of gas sampled are used to calculate the total quantity

of noble gases released with the cloud. The results of determining fission product release by this method are compared with the results of the diffusion-type calculations based on particulate measurements. The comparison provides a check on the validity of the diffusion model.

6.3 Particulate Activity

Particulate activity is collected by approximately one hundred high-volume air samplers positioned on the monitoring grid. Some of these samplers are modified to obtain greater flow rates by enlarging the inlet side of the sampler and allowing the air to be drawn through two 4-inch-diameter filters. These modified air samplers are used on distant arcs where the increased flow rates are desirable because of the specific activity reduction in the cloud caused by radioactive decay and cloud dispersion. All of the filters from the high-volume air samplers in the path of the cloud are counted for gross activity using scintillation counters and are also analyzed isotopically on a multichannel spectrometer.

6.4 Fallout Activity

Fallout plates made from a sticky paper are used to obtain fallout distribution and isotopic identification of the fission products deposited on the monitoring grid. These fallout plates are mounted on a metal frame fastened on a flat platform at the top of five-foot posts marking the grid stations. Isotopic isopleths are drawn to represent the distribution of radioactive fallout materials by using the analysis data obtained from the fallout plates.

6.5 Iodine Monitoring

The most effective method of collecting molecular iodine is by the use of charcoal traps; thus, the high-volume air samplers are modified to allow a standard one-inch-deep activated charcoal cartridge to fit behind the particulate filters.

6.6 Direct Radiation Measurements

The direct radiation measurements consist of measurements to determine the prompt gamma dose and dose rate from the excursion, the gamma radiation dose rate and dose from the radioactive cloud, the dose rate and dose from residual fission product decay, the neutron radiation dose, and the total radiation dose. Measurements of residual contamination are made during recovery of the test samples.

6.61 Radiation Dose Rate and Dose from the Reactor Excursion. The prompt gamma dose rate from the reactor excursion is monitored by gamma-sensitive miniature ionization chambers in and around the reactor core. The signals from these detectors are recorded on high-speed magnetic tapes. This information is used to calculate the dose rate from the destructive excursion and the calculated dose rate as a function of time for different chamber positions.

The dose contribution to the dose from the prompt radiation is calculated by graphically integrating the area under the dose rate curve.

Film badge drop stations are also used to measure the prompt radiation dose. The drop stations consist of two identical film badge dosimeters, one permanently attached to the station, the second held in place by an energized

solenoid which releases the dosimeter following the power excursion. The released dosimeter drops into a shielded receptacle, thereby measuring only the prompt radiation dose; the duplicate dosimeter measures the total integrated dose due to the excursion and fission product decay. The dose from the excursion is then obtained by a difference method. To determine the variation of the radiation dose with respect to distance, these film dosimeter stations are spaced in a straight line at a number of distances from the reactor.

6.62 Gamma Radiation Dose Rate and Dose from the Radioactive Cloud. The gamma radiation dose rate from the radioactive cloud is determined by 15 gamma-sensitive ionization chambers located at several downwind positions. The signal from each of these ionization chambers is sent to continuous pen recorders located at the control center where visual inspection of the recorder graphs gives immediate indication of the relative magnitude of the radioactive release. A few of these ionization chambers are elevated on the radiological surveillance tower and other poles to obtain the radiation intensity of the cloud as a function of vertical distance.

An estimate of the gamma radiation dose from the cloud is made by integrating the area under the dose rate curves.

A second method of determining the gamma dose utilizes the results of the analysis of the film dosimeters. The film dosimeters are placed in a small well at each major grid station of the 60-degree sector. The wells are fitted with a metal can about 4 inches deep, and film dosimeters are placed in the cans where they are shielded from the direct radiation of the reactor and fallout. Thus, the well dosimeters monitor only the radioactive cloud to give an integrated gamma exposure for the radiation received from airborne radiation.

6.63 Dose Rate and Dose from Residual Fission Product Decay. Fission product gamma radiation decay is monitored by three ionization chambers located at the 25-, 50-, and 100-meter upwind locations, three chambers located inside the test cell, and fifteen ionization chambers spaced on the downwind monitoring grid.

The upwind ionization chambers are positioned in direct line of sight of the reactor. By assuring minimum shielding, a curve representing dose rate versus distance can be obtained by plotting the recorder traces. An additional ionization chamber is attached to the remote-controlled, telescoping camera boom which can be positioned to give gamma dose rates between 8 and 15 feet from the reactor. The gamma dose rates monitored by all of the ionization chambers are recorded by strip chart recorders.

The radiation dose from fission product decay is made by film dosimeters at the film badge drop stations. The dose recorded on the released film dosimeter is subtracted from the total dose recorded on the film dosimeter which was held stationary. The dosimeters are recovered when field checks indicate radiation levels are approaching tolerable limits.

The gamma decay radiation dose can also be obtained by integrating the area under the dose rate curve from the upwind ionization chamber.

6.64 Neutron Radiation Dose. Several neutron activation systems are used to measure the neutron spectrum and the neutron dose resulting from the reactor excursion. The principle neutron dosimeter used is the ORNL Hurst-type, nuclear accident dosimeter (NAD). These dosimeters are positioned where they can be recovered as soon as possible after the destructive test.

6.65 Total Radiation Dose. The total radiation dose as contributed by the excursion, the residual fission product decay, and the radioactive cloud are recorded by film dosimeters, chemical dosimeters, glass dosimeters, and thermoluminescent dosimeters. The type of dosimeter used at a particular station is determined by comparing its sensitivity range with the expected dose range at that station. All film dosimeters are NRTS personnel, plastic film packets with enclosed sensitive and insensitive film for measuring low- and high-range exposures, respectively.

6.66 Residual Contamination. Recovery of test samples from distant points on the radiological grid is accomplished by vehicles equipped with two-way radios and radiological monitoring equipment including scintillation-type, dose rate meters and conventional air monitors. The scintillation detectors aid in the detection of radioactive contamination due to fallout, and the air monitors provide a warning to vehicle operators of any unsafe airborne radioactive contamination.

6.7 Beryllium Monitoring

At the time of the reactor destruction, the beryllium in the reactor assembly may be fragmented to the extent that a toxic hazard may develop. To evaluate this hazard, beryllium samplers are positioned for early recovery. Special air-intake lines are used for monitoring the atmosphere just above the reactor. Filters are placed in these lines at the coupling station where the shielding allows early recovery of these samples. The filters, after recovery, are sent as soon as possible for emission spectra analysis. The beryllium hazard assessment is made from these analyses. In addition, beryllium analyses are also made on high-volume-air-sampler filters and fallout plates to determine the degree of fragmentation and spread of the beryllium.

III. LOFT NUCLEAR DESIGN

In an effort to improve the accuracy of reactor physics calculations, some improvements have been made in the methods and data used to obtain diffusion theory constants for LOFT nuclear design studies. The GAM-I [5] code has been revised to allow resonance integral calculations for additional isotopes. Dancoff factors used in the resonance integral calculations are more accurately obtained using Sauer's method [6]. New cross-section data has been added to both the revised GAM and TEMPEST [7] code libraries.

1. REACTOR PHYSICS PARAMETERS AND CALCULATIONAL METHODS

Improvements were made in the basic nuclear data and in the reactor physics calculational methods used in the LOFT nuclear design studies. The effective multiplication factor, K_{eff} , was calculated for three critical experiments to evaluate the accuracy of the reactor physics calculational techniques and parameters.

1.1 Fast Group Constants

Diffusion theory constants for fast neutron energy groups were formerly computed with the GAM-I code. PHROG, a revised version of GAM, is complete and is used for LOFT nuclear design. The PHROG code retains basically all the GAM methods of solution. However, some revisions and extensions have been made in the calculation of resonance integrals. In addition, sub-routines have been added to allow "cell" and "blackness theory" constants to be computed.

One extension of the GAM code which appears in the PHROG code and which is of importance to LOFT is the capability to compute resonance integrals for U-235 and five isotopes of zirconium. As originally written, GAM computed resonance integrals for only U-238 and Th-232. The extension allows resonance self shielding of these isotopes to be conveniently accounted for within PHROG without resorting to auxiliary resonance integral programs. Resolved resonance integrals are computed for U-235 and U-238 using parameters of the RBU [8] code library. For the zirconium isotopes, the parameters of R. C. Block [9] are used.

Cross sections of the materials in the PHROG library were taken partly from a GAM-I library and partly from a Hanford revised GAM (HRG) library. GAM cross sections for hydrogen and oxygen are used since they agreed well with BNL-325 [10] data and give good agreement of calculated neutron age in water with measured values. Cross sections for uranium and zirconium were taken from HRG although modifications have been made in the tabulated smooth capture cross sections of both materials.

Dancoff factors which account for the pin shadowing effect used in the resonance integral calculations are now computed using Sauer's method with the Dancoff Jr code [11]. Previous methods used in design studies had underestimated the pin shadowing effect.

1.2 Thermal Group Constants

Diffusion theory constants for the thermal group are calculated with TOTEM [12], a code which links together the TOPIC [13] and TEMPEST programs. The TEMPEST library has been updated to agree with a recent cross-section description for U-235, U-233, Pu-239, and Pu-241 [14].

1.3 Criticality Calculations

Variations of the calculational model have been applied to critical experiments with varying degrees of success. Compared to the GAM-I code without revisions, the PHROG code with the revised group constants results in significantly improved criticality predictions. For low-enriched, pin-type cores, critical eigenvalues calculated to date appear to be about 0.5 percent high. For example, criticality calculations were done using FOG 3 [15] for some TRX critical experiments [16]. Three of these calculations have been rerun using the revised physics parameters and calculational methods. The experiments were composed of aluminum-clad UO₂ pins moderated and reflected by light water. Some characteristics of the clean cylindrical cores and the calculated eigenvalues are given in Table XXIV.

TABLE XXIV
CHARACTERISTICS AND CALCULATED K_{eff}
FOR TRX CRITICAL EXPERIMENTS

Lattice	Fuel Density (g-UO ₂ /cc)	Enrichment of U-235 in U (wt%)	Pin Pitch of Hexagonal Lattice (cm)	Pin Radius (cm)	Metal-Water Ratio	Calculated K_{eff}
1	10.53	1.311	1.558	0.575	0.928	1.006
2	10.53	1.311	1.652	0.575	0.744	1.005
3	10.53	1.311	1.806	0.575	0.552	1.005

2. REACTOR PHYSICS CALCULATIONS

Depletion calculations which predict the depletion of fuel, B-10 poisoning, and the buildup of fission product poisons as a function of operating time are necessary to predict the core lifetime at full power. To calculate reactivity loss rates, the two-dimensional TURBO [17] code was employed as well as a one-dimensional radial code.

The one-dimensional radial model is also used in the calculations for λ (the effective lifetime) and β (the effective delayed neutron fraction). In order to calculate λ and β , the radial model forms the basis of a two-dimensional model in R-Z geometry.

All depletion calculations were made for a hot reactor with the zirconium followers located in the control rod positions. The uranium in the UO₂ fuel had an enrichment of 2.44 percent atoms of U-235 in the low-enriched region and an enrichment of 5.33 percent atoms of U-235 in the high-enriched region.

2.1 Two-Dimensional Depletion Calculation

A two-dimensional, X-Y, TURBO depletion calculation was begun to determine the excess reactivity required at the beginning of life for the reactor to operate for over 1600 hours at full power. This calculation was carried through time Step 0 (10 hours of operation) and time Step 1 (90 hours of operation), and the time steps will continue for a total reactor operation time of 2800 hours. The available reactivity, ρ , calculated for the beginning of reactor life is 0.072.

2.2 One-Dimensional Depletion Calculation

A one-dimensional depletion calculation for the same time steps as the TURBO problem is needed to determine a reasonably accurate radial model.

As the first step in doing this one-dimensional depletion calculation, a synthesized radial model in which the X-Y geometry of the LOFT core is approximated by a number of regions composed of concentric circles was prepared. The flux-weighted cross sections from TURBO (X-Y geometry) were used in this one-dimensional model to account for the presence of the boron dummy pins. The regional areas inside the 3/8-inch flow skirt were conserved. The IMP code^[18] was used to calculate the reactivity of this model. After manipulation of the position of the two annular rings which represented the zirconium followers, a reactivity of 0.072 was obtained for beginning of reactor life. Thus, the reactivity of the synthesized LOFT slab radial model was made to agree with that of the LOFT slab X-Y geometry model at beginning of life.

IV. LOFT BLOWDOWN ANALYSIS

The BURST (Blowdown Under a Rapid Sonic Transient) digital computer program for calculating acoustic wave phenomena during blowdown [19] has been extended to treat a subcooled system with variable cross-section areas in one dimension with zero initial fluid velocity. An example of a variable-area system is a combination of pressure vessels and connecting piping. In the one-dimensional calculation, the primary flow direction (usually parallel to the pipe or vessel axis) within each system component is considered.

1. DIFFERENTIAL EQUATIONS FOR THE BURST CODE

The differential equations which form the basis for the variable-area version of the BURST code are

$$\frac{\partial G}{\partial t} = - \frac{\partial}{\partial z} \left(\frac{G^2}{\rho} \right) - \left(\frac{G^2}{\rho A} \right) \frac{dA}{dz} - \frac{\partial p}{\partial z} - \frac{(f/\rho) |G| G}{2 D_h} - \rho g \quad (1)$$

$$\frac{\partial p}{\partial t} = \left(\frac{a^2}{\rho} \right) \left\{ - R_h \left[+ \frac{G}{\rho} \frac{\partial p}{\partial z} - G \frac{\partial H}{\partial z} + \phi/\ell + q + \frac{(f/\rho) |G| G^2}{2 \rho D_h} \right] - \rho \left[\frac{\partial G}{\partial z} + \frac{G}{A} \frac{dA}{dz} \right] \right\} \quad (2)$$

$$\frac{\partial H}{\partial t} = \left(\frac{a^2}{\rho} \right) \left\{ + R_p \left[+ \frac{G}{\rho} \frac{\partial p}{\partial z} - G \frac{\partial H}{\partial z} + \phi/\ell + q + \frac{(f/\rho) |G| G^2}{2 \rho D_h} \right] - \left[\frac{\partial G}{\partial z} + \frac{G}{A} \frac{dA}{dz} \right] \right\}. \quad (3)$$

Symbols in these equations are defined in Section IV-3. Portions of the derivation of these equations employ methods described by J. E. Meyer [20,21]. For a uniform-area region, the spatial derivative of the area is zero, and Equations (1) through (3) reduce to the one-dimensional, uniform-area differential equations [19].

The method employed in developing the difference-equation representation of Equations (1) through (3) considers mass velocities (G) at integral mesh points; whereas, pressures (p) and enthalpies (H) are considered at the half-integral mesh points. The digital computer solution of these difference equations and the fluid state properties used in this solution have been discussed [19].

The technique which was initially incorporated in BURST for treating changes in flow area consisted of a series of discrete discontinuities (sudden enlargements or contractions) linking uniform-area pipe segments. Because pressures and enthalpies in the BURST code are normally determined only at half-integral mesh points, a method was incorporated to obtain the boundary condition values for these quantities at interfaces linking pipe segments. Techniques such as extrapolation or definition of special mesh points proved unsatisfactory in determining the boundary conditions, however, due to the

magnitude of the numerical error introduced at the interface. Consequently, an alternate method was developed in which the flow area change is considered to occur over a finite distance in the flow direction.

The area transition region in the version of the BURST code discussed is termed an "adapter." The dependence of flow area on the distance coordinate, z , within the adapter is described by a continuous analytical function consisting of a half-cycle of a cosine curve as follows:

$$A(z) = \left\{ A_2 + [A_1 - A_2] \left[\frac{1 + \cos \frac{\pi (z - z_1)}{(z_2 - z_1)}}{2} \right] \right\}; \quad z_1 \leq z \leq z_2 \quad (4)$$

The areas, A_1 and A_2 , are the cross-sectional areas of the pressure tube segments joined by the adapter; z_1 and z_2 are the coordinate values for each end of the adapter. The length of the adapter ($z_2 - z_1$) can be made relatively short compared to the length of adjacent tube segments although shorter adapter lengths generally require closer mesh-point spacing and longer digital computation time. Actually, a distance approximating that of a pipe diameter is required for the true three-dimensional transition in propagating an acoustic disturbance from one pipe section to another, even if the transition is a sudden enlargement. Hence, the finite length adapter employed in BURST is considered a reasonable one-dimensional representation of area changes.

The decompression pressure-time history at the exit plane is assumed to be described by an analytical expression which also consists of a half-cycle cosine function. The half-cycle cosine function is considered to be a reasonable approximation to the behavior at the exit plane when the rupture is initiated by a rupture disc. Moreover, incorporation of a continuous analytical function describing the shape of the decompression wave makes interpretation of the calculated results more straightforward. The half-cycle cosine function employed at the exit plane in BURST is

$$p(z_3, t) = \left\{ p_2 + [p_1 - p_2] \left[\frac{1 + \cos \frac{\pi t}{\tau}}{2} \right] \right\}; \quad 0 \leq t \leq \tau \quad (5)$$

where p_1 is the initial pressure of the system and p_2 is the ambient pressure. Once the pressure at the rupture disc has fallen to ambient pressure in calculations for ambient-temperature blowdowns, the pressure there is assumed to remain at ambient pressure throughout the remainder of the transient. The time, τ , is the decompression time at the rupture disc.

2. SAMPLE BLOWDOWN CALCULATION

The sample calculation is based on the calculational model shown in Figure 26. The axis of the system is horizontal. The smaller diameter pipe

Fig. 26 Variable-area system for sample blowdown calculation.

segment is located on the right, with the hypothetical rupture disc located at the far right end. The large tube segment is located on the left, and its left extremity is closed. Both tube segments are 2 feet 3 inches long; the diameters were arbitrarily chosen to be 6 and 3 inches, respectively, making their area ratio 4:1. An adapter length equal to one diameter of the larger pipe segment (or 6 inches) was used.

The initial and ambient pressures are 2500 and 1500 psig, respectively. The ambient pressure was chosen as 1500 psig to preclude calculation of negative pressures. The decompression time at the rupture disc was 50 μ sec, which is approximately one tenth of the travel time from the rupture disc to the adapter.

Six pressure profiles, presented in Figure 27, demonstrate the capability of the BURST code to show the propagation and reflection of an acoustic wave in a variable-area system. As shown by the 0.24-msec curve, the decompression wave travels down the smaller tube, reducing the pressure from 2500 to the ambient pressure of 1500 psig. The wave approaches the adapter 0.47 msec following the failure of the rupture disc. The wave traveling in the smaller tube views the adapter as a partially open-ended tube. Conversely, a wave traveling in the larger tube views the adapter as a partially closed-ended tube.

Fig. 27 Blowdown pressure profiles -- subcooled water; area ratio 4:1.

the partially reflected wave is approaching the open end. The resulting reflected waves are shown in the 1.17-msec curves. At the open end, the compression wave is reflected as a decompression wave which reduces the pressure in the small tube from 2100 psig to the ambient pressure, 1500 psig. At the closed end of the system, the 2500-to-2100-psig decompression wave is reflected as another decompression wave, that is, by doubling the incident wave. The pressure in the larger tube is reduced by another 400-psi increment, from 2100 to 1700 psig. The phenomena associated with the reflection of an acoustic wave from a fully open or fully closed end of a tube have been discussed [19]. The 1.41-msec curves show the two decompression waves approaching the adapter.

Comparison of the relative transmission and reflection of the initial decompression wave after it reaches the adapter with that predicted by acoustic theory shows that this process is treated correctly by the BURST code. Reflection of the wave at the adapter is affected by the lower acoustic impedance of the larger tube where the ratio of impedances is inversely proportional to the area ratio. Hence, $Z_2/Z_1 = A_1/A_2$ [22] where $A_1/A_2 = 4$ for this sample calculation. The reflection ratio is the same as that for electrical transmission line theory [22] and is given by [23]

$$\text{Reflection ratio} = \frac{(Z_2/Z_1) - 1}{(Z_2/Z_1) + 1} \quad (6)$$

For the acoustic impedances involved here,

$$\text{Reflection ratio} = \frac{A_1/A_2 - 1}{A_1/A_2 + 1} = 3/5 \quad (7)$$

The pressure oscillations following the wave front are due to computational limitations. The use of shorter space and time intervals in the solutions of the difference equations is expected to remove this limitation.

The 0.7-msec curve shows the pressure profile following the encounter of the incident decompression wave with the adapter. The partially transmitted decompression wave reduces the pressure in the larger tube from 2500 to 2100 psig. The partially reflected wave from the adapter is a compression wave which pressurizes the small tube from 1500 to 2100 psig. The depressurization in the large tube is 400 psi from 2500 to 2100 psig.

After 0.94 msec, the partially transmitted decompression wave is approaching the closed end of the system, and

Hence, the amplitude of the reflected wave (2100 - 1500 = 600 psi) to the incident wave (2500 - 1500 = 1000 psi) bears the correct relationship given by acoustic theory. The results presented indicate that the technique of treating variable-area piping systems during blowdown by utilizing adapter sections produces reasonable results. Further evaluation of the variable-area BURST code is planned utilizing experimental blowdown data.

3. NOMENCLATURE FOR HYDRODYNAMIC EQUATIONS

Equations in the text are written in terms of a consistent set of units as follows: Dimensions are denoted by M = mass, L = length, θ = time, $F = ML/\theta^2$ = force, and $H = FL = ML^2/\theta^2$ = energy.

<u>Symbol</u>	<u>Description</u>	<u>Dimensions</u>
a	Acoustic velocity	L/θ
A	Area normal to the flow direction	L^2
f	Friction factor	None
G	Mass velocity	$M/L^2\theta$
g	Component of acceleration of gravity in negative z direction	$F/M = L/\theta^2$
H	Enthalpy	H/M
l	(flow area) / (heated perimeter)	L
p	Static pressure	F/L^2
q	Volumetric internal heat generation rate	$H/L^3\theta$
R_h	Derivative of density with respect to enthalpy at constant pressure	$\frac{M^2}{HL^3} = \frac{M\theta^2}{L^5}$
R_p	Derivative of density with respect to pressure at constant enthalpy	$\frac{M}{FL} = \frac{\theta^2}{L^2}$
t	Time after the start of a transient	θ
u	Fluid velocity	L/θ
z	Position measured from closed end of tube	L
Z	Acoustic independence	$M/L^4\theta = \frac{F\theta}{L^5}$
Δt	Time increment for finite difference solution	θ
Δz	Mesh spacing for finite difference solution	L
ρ	Fluid density	M/L^3
ϕ	Heat flux to fluid from bounding surface	$H/L^2\theta$

Subscripts and Superscripts

i	Time-step index
j	Mesh-point index

V. LOFT MELTDOWN ANALYSIS

Three mathematical models for the initial phase of core meltdown analysis in a reactor system following a loss-of-coolant accident have been reported [24]. These models provide methods for describing reactor heat transfer with varying degrees of detail in the physical system. The explicit pin model provides a detailed description of the heat conduction within the fuel and cladding of a cluster of four pins and the radiation heat transfer between the four pins and between the pins and a heat sink. The annular ring model and the X-Y model provide for conduction and radiation heat transfer but with "lumping" of the fuel and structural material so larger portions of a reactor system can feasibly be represented. Fission product decay afterheat and zirconium-steam-reaction heat sources are included in each of the models. Programming of these models within the scope of the initial phase of meltdown analysis development is complete.

The scope of the initial phase of these models does not include changes in core geometry or radiation and convection heat losses to the steam. Further experimental information may be required to include these effects in the second phase effort.

1. EXPLICIT PIN MODEL

The initial version of the explicit pin model provides a mathematical description of a four-pin region within the core. This model forms a valuable link for use in conjunction with the less detailed "lumped" models to assure the adequacy of these models. Expansion of the model to an eight-by-eight array of pins is being considered as the ultimate size for application of an explicit pin representation for the LOFT analysis effort. Solution of equations in the model is accomplished in the IBM-7040 computer code, CONRAD [25].

A geometric representation of the explicit pin model is shown in Figure 28. Each fuel pin in the array is subdivided into interior and surface nodal volumes. The transient heat conduction equation in cylindrical geometry,

$$c\rho \frac{\partial T}{\partial t} = \frac{\partial}{\partial r} \left(k \frac{\partial T}{\partial r} \right) + \frac{k}{r} \left(\frac{\partial T}{\partial r} \right) + \frac{1}{r^2} \frac{\partial}{\partial \theta} \left(k \frac{\partial T}{\partial \theta} \right) + \frac{\partial}{\partial z} \left(k \frac{\partial T}{\partial z} \right) + q'''$$

(8)

Fig. 28 Geometric configuration for the explicit pin model.

is solved for each of the interior nodal volumes to establish the temperature distribution within the pins. The nomenclature employed in the meltdown analysis is defined in Section V-4.

Uniform axial temperature distribution is assumed; therefore, the z terms of Equation (8) are neglected. A radiation boundary condition,

$$q_j = W_j S_j - \sum_{i=1}^n B_{ij} W_i S_i \quad (9)$$

is imposed at the surface of the pins such that conduction at the surface is set equal to the radiation heat loss for a nodal volume.

Diffuse radiation is assumed and the surfaces are treated as gray bodies. The model is geometrically flexible in that the pin radius, r , the pin spacing, D , and the heat sink width, L , can be arbitrarily specified. The sink temperature is assumed to be a function of time only.

Due to the complexity of the calculation, a separate computer code was employed to establish the absorption factors, B_{ij} , in Equation (9) for radiant interchange phenomena [26]. Solution of the necessary equations, which have been reported, is accomplished with the IBM-7040 computer code, ABFACT [27].

The explicit pin model employs fission product afterheat and zirconium-steam-reaction heat source terms. No allowance for cladding composition change at the fuel pin surface is made, and the zirconium-steam-reaction heat is simply added as an additional heat source to the node nearest the chemical reaction interface. The explicit pin model zirconium-steam-reaction heat is determined from the parabolic oxidation law postulated by Baker and Just [28] for a specified time-dependent amount of steam available to the surface.

The initial programming in CONRAD utilized the Runge-Kutta [29] solution technique for formulating difference equations. The Runge-Kutta method, however, required excessively long IBM-7040 operating time, and an alternating-direction explicit method [29] was introduced as the solution technique. The alternating-direction explicit method reduced the operating time by a factor of five. CONRAD still has the major disadvantage of relatively long computation time. The use of faster computers such as the CDC-6600 is the simplest immediate solution to the problem of operating time. The alternating-direction implicit method [29] will be considered in the future development of CONRAD to provide potentially faster numerical techniques.

Test problems were selected that allow evaluation of the principal characteristics of the explicit pin model, that is, the ability to show the r and θ dependence of temperature. The input parameters used in the test problems are given in Table XXV, and the most significant results of a test problem based on these input parameters are shown in Figures 29, 30, and 31.

Figure 29 shows the significance of the zirconium-steam reaction on the temperature of the cladding hot spot and fuel center line. Figure 30 also shows a notable effect of the zirconium-steam reaction; and, in addition, it indicates that some variation in the temperature can occur around the surface of a fuel pin. For the test conditions of this problem, the zirconium-steam reaction does not reinforce the peripheral temperature peaking. Figure 31 shows that for a diametrical cross section from the cladding surface hot spot to the cladding surface cold spot, fuel temperature peaking may occur off the fuel center line. The r - θ temperature dependence is important for comparison

TABLE XXV

TEST PROBLEM INPUT PARAMETERS

Initial Fuel Temperature (fuel and cladding)	1750°F and uniform
Initial Sink Temperature	1250°F and constant
Pin Diameter	0.411 in.
Pin Spacing	0.58 in.
Cladding Thickness	0.0255 in.
Sink Dimension	11.0 in.
Heat Generation Rate	0.3 Btu/sec-in. ³
Fraction of Heat Generated in Fuel	1.0
Fraction of Heat Generated in Cladding	0
Number of Radial Nodes	8
Number of Surface Nodes	16
Stefan-Boltzman Constant	0.33×10^{-14} Btu/sec-°R ⁴
Emissivity of Cladding	0.35
Emissivity of Sink	0.50
Fuel-Cladding Gap	0

with the "lumped" models to ensure their adequacy. Additional test problems are planned for the explicit pin model to extend these studies to transients of longer duration.

2. X-Y MODEL

The X-Y model is one of two "lumped" model, analytical techniques [24]. The X-Y model describes fuel pin temperatures by an average interior node temperature, $\bar{T}$, and one surface temperature, T_s . Lumping of core fuel elements allows the model to include an explicit mathematical representation of control rods, fuel element canisters, support barrels, and major vessel components. These structural components are described by an average interior node temperature, $\bar{T}$, and two surface temperatures. The node locations are described in rectangular coordinates. The radiation and conduction heat transfer effects of these components on core meltdown is highly important because the components represent heat sinks in close proximity to the fuel. Comparisons of the results from the X-Y model with the results from the explicit pin model will aid in determining the effect of the loss of detailed physical descriptions in the "lumped" fuel pin approach.

The X-Y model is programmed for digital solution in the MOXY computer code^[30]. The initial version of MOXY is exploratory in nature and is comprised

Fig. 29 Temperature-time history, explicit pin model.

Fig. 30 Circumferential temperature distribution for explicit pin model.

Fig. 31 Diametrical temperature distribution for explicit pin model -- no metal-water reaction.

of four fuel pins surrounded by a heat sink. An expanded version of the code to provide a complete quarter-core geometric representation is currently under development. The configuration for the four-pin version of MOXY is shown in Figure 32. The four-pin version of MOXY was developed to permit detailed comparison of the X-Y model with the explicit pin model and to verify the numerical procedures for the expanded version of MOXY.

In MOXY the fuel material and cladding are combined to give volume-weighted thermal properties. The temperature within a fuel pin is determined by the transient heat conduction equation, Equation (8), except that the θ and z dependence is neglected. The steady-state solution of Equation (8) provides the shape of the temperature profile in the fuel pin for transient conditions. The surface temperatures are determined by a radiation heat balance equation with coupling between the pins and heat sink by overall view factors. The X-Y model incorporates fission product decay and zirconium-steam-reaction heat sources. The zirconium-steam-reaction heat is computed and added to the surface node heat balance equation based on the surface temperature.

Fig. 32 Four-pin, X-Y model geometry.

The four-pin version of the MOXY computer code uses an explicit solution technique. The large time constants derived from component lumping permit relatively long problems to be solved without excessive computation time. Shorter computation time is a significant advantage of the X-Y model over the explicit pin model.

A comparison of temperatures calculated by the four-pin, X-Y model and the detailed explicit pin model has been made to evaluate the differences between the results of the two models. Figures 33 and 34 present comparisons without the zirconium-steam reaction, and Figures 35 and 36 show comparisons with the zirconium-steam reaction. These figures show good agreement in the calculated temperatures between the X-Y and explicit pin models for the problem duration and temperature range involved.

For the case presented in Figures 35 and 36, the initial temperature distributions for the fuel, cladding, and heat sink were selected over a range which ensured that the effects of heat transfer and zirconium-steam-reaction energy would be significant. The initial jump in the X-Y model temperature in Figure 35 is a combined result of the conditions of high initial cladding temperature and clean (unoxidized) zirconium assumed at the start of the calculation. These conditions produced a rapid zirconium-steam reaction.

Fig 33 Surface temperatures for explicit pin and X-Y models -- without zirconium-steam reaction.

Fig. 34 Circumferential surface temperatures for explicit pin and X-Y models -- without zirconium-steam reaction.

Fig. 35 Average surface temperatures for explicit pin and X-Y models -- with zirconium-steam reaction.

Fig. 36 Average fuel temperature for explicit pin and X-Y models -- with zirconium-steam reaction.

Some of the differences in calculated temperatures observed in the figures are attributable to the view factors employed in each model for radiation boundary conditions. The X-Y model uses overall view factors as opposed to the explicit pin model in which detailed view factors [26] are employed. Adjustment of view factors for the X-Y model is expected to improve agreement with the explicit pin model. Additional comparisons between the X-Y and explicit pin models are planned for transients of longer duration.

3. ANNULAR RING MODEL

The second of the "lumped" models is the annular ring model. This model and its associated computer code, ARC, have been previously described [24]. The annular ring model is two dimensional in r and z coordinates. The exploratory version of the ARC code has the capability of handling five axial nodes and eight radial nodes.

In common with the previous two models, the annular ring model uses fission product decay afterheat and zirconium-steam-reaction energy as heat source terms. ARC, however, has the additional feature of determining the steam available to successive axial levels of the core for the zirconium-steam reaction. The steam determination is accomplished by a simple flow balance based on a specified time-dependent steam flow rate available at the bottom of the core, and the quantity of steam that is consumed at each axial level by the zirconium-steam reaction.

After initial operation of the ARC code, the modified Runge-Kutta technique of solution of the transient heat conduction equations used in ARC was changed to an explicit solution technique. Truncation error overrode the advantages of the stability for longer time steps made possible by the Runge-Kutta method. The revised numerical technique incorporates an explicit solution procedure and a major cycle for updating the heat sources, radiation heat transfer, and thermal properties. For each major cycle, a series of minor cycles are performed in which only the nodal temperatures are updated for advancement of the difference equations. The major and minor cycles permit a compromise between computer time and solution accuracy.

Typical results from test problems [31] using ARC are presented in Figures 37, 38, and 39. These results show the effect upon the surface temperature

Fig. 37 Annular ring model -- calculations without zirconium-steam reaction.

of assuming no steam, unlimited steam, and limited steam in calculating the zirconium-steam-reaction energy. (These results are intended to demonstrate the features of ARC and are not intended to represent a current "best" estimate of LOFT meltdown behavior.) Figure 37 shows results with no zirconium-steam-reaction energy. The calculated temperatures exhibit an initial rise which is approximately adiabatic until the temperature range is reached at

Fig. 38 Annular ring model -- calculations with zirconium-steam reaction and with unlimited steam flow.

which radiation becomes important. The center region of the inner ring becomes the hot spot with decreasing temperatures toward the top and bottom and toward the outer radius where the effects of the cooler boundaries are significant. Figure 38 exhibits the effect of incorporating zirconium-steam-reaction heat in the calculation. Until the zirconium-steam reaction becomes dominant, the initial temperature rise is similar to that shown in Figure 37. In the case of the zirconium-steam reaction, unlimited steam was assumed to be available to support the reaction. The zirconium-steam-reaction energy overrides

Fig. 39 Annular ring model -- calculations with zirconium-steam reaction and with limited steam flow.

the radiation heat loss and the temperatures increase according to the dominant chemical reaction heat. In Figure 39, the specified steam available to the bottom of the core region is continuously reduced to force the reaction to be steam limited. The effect of steam limiting is most evident at higher temperatures. Only the center-to-top and center-to-bottom temperature gradient is evident before the region of steam limiting is reached. As steam limiting is reached, the temperature of the bottom axial level maintains an exponential time behavior.

Eventually the condition is obtained at which the axial temperature gradient depends predominantly upon the steam available.

Results from the exploratory version of the annular ring model and the associated code, ARC, have demonstrated the feasibility of using this approach to the loss-of-coolant accident meltdown analysis. The annular ring model gives transient temperature information, which is necessary for complete reactor core description, in r and z coordinates. The model provides for the effects of radiative and conductive heat transfer and demonstrates the relative effects of each on axial and radial temperature distribution. The effect of zirconium-steam-reaction heat is readily seen from the results. Whereas the exploratory version of the annular ring model demonstrates principles and techniques, the final version is intended to predict actual reactor core behavior. The final version will include an extended geometric description of the reactor system, equations for convective and radiative heat transfer to the steam, and changes of core geometry (slumping).

4. NOMENCLATURE FOR MELTDOWN EQUATIONS

Equations used in the meltdown analysis are written in terms of a consistent set of units. Dimensions are denoted by M = mass, L = length, θ = time, $F = ML/\theta^2$ = force, and $H = FL = ML^2/\theta^2$ = energy.

<u>Symbol</u>	<u>Description</u>	<u>Dimensions</u>
B_{ij}	Absorption factor between surfaces i and j	
D	Pin spacing	L
S	Surface area	L^2
T	Absolute temperature	T
W	Total hemispherical emissive power per unit area	$H/\theta L^2$
c	Specific heat	H/MT
k	Thermal conductivity	$H/\theta LT$
q_j	Net rate of radiant energy loss from surface j	H/θ
q'''	Energy generation rate per unit volume	$H/L^3\theta$
r	Radius	L
t	Time	θ
z	Axial distance	L
L	Length of the side of the sink	L
ρ	Density	M/L^3
θ	Angular displacement	

Subscripts

i	i th surface
j	j th surface

VI. LOFT CONTAINMENT INSIDE SURFACE TEMPERATURE DECAY

The temperature decay of the inside surface of the LOFT containment and of the equipment inside the containment has been calculated to aid in the study of the fission product plateout during the LOFT experiment. The temperature decay predictions will also help determine the type and amount of condensation that can be expected on each surface, which, in turn, may affect the amount of plateout that will be washed off the surface.

The temperatures of the containment atmosphere and inside surfaces were calculated using the digital computer code, CONTEMPT [32]. Data on which these calculations were based are from the preliminary design of the LOFT facilities [33].

The surface areas of specific parts of the containment building and contents are presented in Table XXVI. This table also shows the percentage each

TABLE XXVI

INSIDE SURFACE AREAS FOR LOFT CONTAINMENT BUILDING

<u>Surface</u>	<u>Area (ft²)</u>	<u>Percent of Total</u>
Dome	7,600	19.0
Side Wall Exposed to Outside Atmosphere	7,250	18.1
Side Wall Not Exposed to Outside Atmosphere	6,250	15.6
Floor	3,750	9.4
Dolly		
6-inch Steel	1,470	3.7
3-inch Steel	530	1.3
Equipment Support		
3-inch Steel	1,100	2.7
2-inch Steel	700	1.8
Circular Crane		
2-inch Steel	530	1.3
1-1/2-inch Steel	1,470	3.7
Miscellaneous		
1-1/2-inch Steel	1,800	4.5
3/4-inch Steel	1,650	4.1

TABLE XXVI (Contd.)

INSIDE SURFACE AREAS
FOR LOFT CONTAINMENT BUILDING

Electrical Equipment		
1/4-inch Steel	1,000	2.5
Vessel Insulation Covers		
1/32-inch Steel	1,900	4.8
Piping Insulation Covers		
1/32-inch Steel	1,800	4.5
Lead-Water Shield Tank	<u>1,200</u>	<u>3.0</u>
Total	40,000	100.0

area represents of the total surface area exposed to the atmosphere inside the containment building.

Temperature decay curves are shown in Figures 40 through 48. Figures 41, 43, 45 and 46, and 48 are continuations of Figures 40, 42, 44, and 47, respectively. The maximum inside-containment atmospheric temperature during blow-down is 216.1° F. The pressure in the containment decreases to zero after 26.6 hr. All concrete temperatures given are for the inside surface. All concrete surfaces are coated with Amercoat 66 white coating. Figures 40 and 41 show the temperature decay for the inside atmosphere and concrete surfaces. Figures 42 and 43 show the temperature decay for steel of 3/4-, 1-1/2-, 2-, 3-, and 6-inch thicknesses. Figures 44, 45, and 46 show temperature decay for steel of 1/4- and 1/32-inch thicknesses. The 1/32-inch steel represents the metal covering over the insulation for the vessels and piping. Figures 47 and 48 show the temperature decay for the inside and outside surfaces for the lead-water primary shield tank. All tank temperatures are on the surface, and all surfaces are coated with Amercoat 66 white coating.

About 37 percent of the total inside surface has the other side exposed to the outside atmosphere. These surfaces are always colder than the inside atmosphere. Temperatures of surfaces not exposed to the outside atmosphere increase more and then remain hotter than the temperature of the inside atmosphere. Condensation will occur on surfaces with temperatures below the containment atmospheric temperature and will not occur on surfaces with temperatures above atmospheric temperature.

Fig. 40 Predicted LOFT temperature decay in concrete -- 0 to 2 hr.

Fig. 41 Predicted LOFT temperature decay in concrete -- 2 to 26 hr.

Fig. 42 Predicted LOFT temperature decay in thick steel -- 0 to 2 hr.

Fig. 43 Predicted LOFT temperature decay in thick steel -- 2 to 26 hr.

Fig. 44 Predicted LOFT temperature decay in thin steel -- 0 to 0.5 hr.

Fig. 45 Predicted LOFT temperature decay in thin steel -- 0.5 to 1.5 hr.

Fig. 46 Predicted LOFT temperature decay in thin steel -- 1.5 to 5.5 hr.

Fig. 47 Predicted LOFT temperature decay in lead-water shield tank -- 0 to 13 hr.

Fig. 48 Predicted LOFT temperature decay in lead-water shield tank -- 13 to 26 hr.

VII. LOFT RADIOLOGICAL STUDIES

A small mass spectrometer will be used as the design basis of a system to determine the oxygen, hydrogen, and nitrogen content of the reactor vessel as a function of time following blowdown.

Data on silicone rubber and polyurethane joint sealants were obtained. These data indicate that silicone rubber is better than polyurethane for sealing construction joints, but neither has been shown satisfactory for LOFT.

Zinc silicate primers were tested in a steam autoclave at 133°C and 30 psig for 24 hours. The tests show that zinc silicate primers can cause coating failures in pressurized steam. Other coating materials were evaluated in gamma radiation tests as well as in steam autoclave tests.

1. FISSION PRODUCT ANALYSIS

To understand the behavior of fission products prior to release from a reactor and primary system, the nature of the atmosphere inside this system must be known. The LOFT reactor atmosphere will be characterized by sampling for oxygen, hydrogen, and nitrogen as a function of time. The hydrogen measurements will also be used to follow any metal-water reactions in the reactor core.

The only practical instrument for the analysis of the atmosphere appears to be a mass spectrometer. Several different types of small mass spectrometers are available commercially which offer a wide variety of instrument characteristics. All instruments considered will give analyses covering wide ranges of concentration of unexpected components which might appear after blowdown. Regardless of the type of instrument used for analysis, water present in the sample as steam will be encountered as a problem. Possibly the sample, including the steam, can be taken directly into a mass spectrometer through a capillary sample inlet. The best analysis for hydrogen, nitrogen, and oxygen might then be by the partial pressure of these components derived from the mass spectrometer data, relative to the total pressure of the sample. A small mass spectrometer will be evaluated for this application.

2. DECONTAMINATION STUDIES

Laboratory data on joint sealants and coatings were obtained. These data indicate that silicone rubber is better than polyurethane for LOFT construction joints, and that zinc silicate primer can cause coating failures.

2.1 Joint Sealant Tests

A preliminary laboratory evaluation was completed on the two joint sealants (silicone rubber and polyurethane) considered for LOFT. A summary of the results obtained is presented in Table XXVII. Although these results indicate that the silicone elastomer is better suited for LOFT application than the urethane,

TABLE XXVII

EVALUATION OF ELASTOMERIC SEALANTS FOR LOFT

	Silicone Elastomer		Urethane Elastomer	
	Uncoated	Coated (epoxy system)	Uncoated	Coated (epoxy system)
<u>Dry Heat Tests:</u>				
80°C	No apparent detrimental effects in 48 hours of exposure			
100°C	No apparent attack in 24 hours	Coating over mastic cracked in 4 hours	No apparent attack in 24 hours	Coating over mastic cracked in 24 hours
130°C	No apparent attack; elastomer firm and well adhered to the concrete	Coating over mastic cracked in 2 hours	Sealant very soft and flexible after 96 hours -- adhesion lost at 168 hours	Coating over mastic cracked in 3.25 hours
<u>Autoclave Test:</u>				
133°C at ≈ 30 lb	Mastic-to-concrete bond failed progressively after 24 hours exposure	Coating over mastic cracked in 24 hours	Bond lost between mastic and concrete -- mastic very soft and sticky	Bond lost between elastomer and concrete -- mastic very soft and sticky
<u>Radiation Exposure Test:</u>				
100°C steam; 8 days exposure; 1.05 x 10 ⁹ R total	Mastic brittle, and easily cracked -- mastic is deeply checked and discolored	Coating over mastic apparently unaffected except for small cracks	Mastic swelled and lost bond with the concrete -- mastic crumbles easily	Coating over mastic failed due to the excessive swelling of the elastomer and loss of bond between elastomer and concrete
<u>Chemical Resistance Tests (80°C)</u>				
Turco 4502 (alkaline permanganate)	Lost bond between mastic and concrete	Lost bond between mastic and concrete	Partial loss of bond -- mastic soft and tacky	Specimen unaffected
10 Percent Sodium Hydroxide; 2.5 Percent Tartaric Acid	Mastic-to-concrete bond lost in 24 hours	Coating cracked over mastic -- coating to mastic bond lost -- coating slightly blistered	Mastic-to-concrete bond good, however, the mastic decomposed to a depth of 1/16 to 3/32 inches	Bond failed between coating and mastic -- mastic attacked chemically
Complex Decontamination Solution[a]	Mastic unaffected	Coating blistered slightly	Mastic unaffected	Coating slightly blistered
Nitric Acid (3M)	Mastic-to-concrete bond failed -- concrete suffered attack	Coating failed -- mastic-to-concrete bond good -- concrete suffered attack	Mastic soft and tacky -- mastic eaten away by chemical attack	Mastic soft and tacky -- mastic eaten away by chemical attack -- coating failed
[a] 0.4 M Oxalic Acid 0.16 M Ammonium Citrate 0.34 M Hydrogen Peroxide pH 4 with Ammonium Hydroxide.				

they do not indicate whether the silicone elastomer is satisfactory for use in LOFT. Additional tests are needed to determine if the bonding of the silicone elastomer to concrete can be improved and to determine the effect of a lesser amount of radiation exposure (10⁶ to 10⁷R) on the silicone. Joint sealant samples after exposure to 100°C steam for eight days in a radiation field which gave a total dose of 10⁹R are shown in Figures 49 through 53. The samples were as follows:

- (1) Uncoated urethane elastomer
- (2) Amercoat 66 coated silicone elastomer
- (3) Amercoat 66 coated urethane elastomer
- (4) Uncoated silicone elastomer

2.2 Zinc Silicate Primer Tests

Coupons primed with two brands of zinc silicate were autoclaved in steam 133°C and 30 psig for 24 hours. All coatings showed blister formation to

Fig. 49 Joint sealant test assembly.

Fig. 50 Uncoated urethane elastomer

Fig. 51 Coated silicone elastomer.

some degree. Figure 54 is a photograph of these coupons after testing. A description of each coupon is listed in Table XXVIII. The results of these tests indicated that zinc silicate primed carbon steel components, as commonly furnished by vendors, may not be suitable for use in LOFT, and a search for an alternate primer material was undertaken.

Fig. 52 Coated urethane elastomer.

Fig. 53 Uncoated silicone elastomer.

Fig. 54 Zinc silicate primed test coupons.

2.3 Coating Tests

As part of the overall coating evaluation studies being made for LOFT, specimens of several coatings were exposed to gamma radiation and to steam in an autoclave. The results of these tests are presented in Table XXIX.

TABLE XXVIII

STEAM AUTOCLAVE TESTS
ON ZINC SILICATE COUPONS

Sample	Prime Coat	Prime Coat (aging)	Top Coat
1	Dimetcote-3	1 week	Devoe Chemfast OX-1055
2	Dimetcote-3	1 week	Amercoat 66
3	Dimetcote-3	1 week	Carboline Phenoline 300
4	Dimetcote-3	1 week	Devoe Devran 600
5	Dimetcote-3	1 week	Carboline Epoxy 150
6	Dimetcote-3	1 week	Amercoat 33 HB
7	Dimetcote-3	1 week	Uncoated
8	Carbo-Zinc-11	1 month	Carboline Phenoline 302
9	Carbo-Zinc-11	1 month	Amercoat 66
10	Carbo-Zinc-11	1 month	Amercoat 33 HB
11	Carbo-Zinc-11	1 month	Devoe Chemfast OX-1055

TABLE XXIX

RESULTS OF COATING TESTS

Coating Tested	Gamma Radiation Test (100°C steam)	Autoclave Test (133°C steam and 30 psig)
Amercoat 66 (4 coat epoxy system)	8.4 and 8.9 x 10 ⁸ R No appreciable damage other than discolora- tion.	Small blisters developed along edges during first 24 hours of exposure. No further damage.
Amercoat 66 (Epoxy system reinforced with glass fabric)	8.4 x 10 ⁸ R No appreciable damage other than discolora- tion.	Apparently unaffected other than for the development of one small blister after 144 hours of expo- sure.
Carboline B-15 (A urethane topcoat over Phenoline 315 orange primer)	8.9 x 10 ⁸ R No appreciable damage other than discolora- tion.	Developed a large number of small blisters during the first 24 hours of expo- sure.
Carboglas (A polyester)	8.9 x 10 ⁸ R No appreciable damage other than discolora- tion.	Suffered checking (fine cracks in the coating) after 120 hours of expo- sure.

VIII. SEMISCALE BLOWDOWN TEST PROGRAM -- PHASE I

The semiscale blowdown program was established as a support task for the LOFT program to investigate the thermal, hydraulic, and mechanical behavior of a pressurized water reactor system subjected to a loss-of-coolant accident. The tests in this program are intended to yield information concerning the effect that the rupture size and location and the rate at which rupture occurs have on the dissipation of stored enthalpy and fluid efflux from a PWR system which is subjected to blowdown conditions. This information will be used in predicting the factors controlling heat removal and fission product release from the LOFT core and in predicting the extent of the metal-water reaction in the core. The blowdown tests are also intended to permit the evaluation of reduced-scale LOFT components such as the thrust cancellation device, core internals, and steam generator under conditions representative of those expected during the LOFT loss-of-coolant test.

The blowdown program has three primary objectives which are intimately related to the adequacy of the structural design and to the prediction analysis for the LOFT test. The first objective is to provide data which will assist in the evaluation and improvement of analytical models used in predicting the LOFT blowdown phenomena. This data will include (a) information regarding the overall thermal hydraulic behavior of the coolant in the subcooled region where acoustic effects predominate, through the saturation region, and into the post-blowdown convection region; (b) information regarding the transient and semi-steady-state hydraulic loading applied to system components and structures; (c) information regarding the significance of system configuration and initial conditions; (d) information regarding shock pressure loads on the containment; and (e) information regarding the water remaining in the system following blowdown. The second objective is to develop and establish proof of performance under blowdown conditions of measurement devices which will be used to measure pressure, temperature, mass flow, density, displacement, strain, and convection current velocity during the LOFT loss-of-coolant test. And the third objective is to test and evaluate the design of LOFT components under blowdown conditions. These primary objectives imply the additional objective of determining, from the blowdown tests, the LOFT test conditions which will provide results depicting the most representative loss-of-coolant accident in a PWR system.

The blowdown program consists of three phases: Phase I includes tests using an unscaled empty vessel; Phase II includes tests using a quarter-scale model of the LOFT vessel having a simulated reactor core and internal components; and Phase III includes tests using a quarter-scale model of the integral LOFT reactor and coolant system.

Phase I, which is preliminary in nature, was initiated during this period through the use of an available high-pressure flask which is only moderately different in dimensional configuration from the quarter-scale vessel being fabricated for Phases II and III. This flask has provisions for simulation of a top or bottom break at any desired initial conditions of temperature and pressure up to the LOFT conditions of 2400 psig and 540°F. The initial conditions are provided by an available primary system which can establish static liquid at the necessary enthalpy conditions but without flow. This vessel does not permit the installation of simulated reactor internals, but sufficient access

is available for accommodation of measurement devices. Of particular interest in Phase I of the blowdown program are the following:

- (1) Determination of rupture disc behavior and importance of rupture rate on the subcooled and saturated portions of blowdown
- (2) Determination of predictability and interpretability of the subcooled portion of blowdown as a function of top or bottom break, break size, and exit pipe length
- (3) Determination of thermal-hydrodynamic behavior of coolant in a vessel void of internals for various initial conditions of temperature, pressure, break location, break duration, and break size with emphasis on the determination of the quantity of water remaining in the system following blowdown
- (4) Determination of the performance of a model of the LOFT thrust cancellation device (jet deflector) and rupture simulating valve
- (5) Determination of the performance of fast response measurement devices for measurement of coolant pressure, temperature, mass velocity, density, and structural response.

The following discussion pertains to the facility experimental equipment and to the experimental instrumentation used in all phases -- with particular emphasis being given to Phase I. The blowdown tests during this period were preliminary, and were primarily concerned with determining effective methods of producing ruptures. Results obtained during the blowdown tests of Phase I are given for blowdowns conducted at fully subcooled conditions.

1. FACILITY AND EQUIPMENT DESCRIPTION

The facility housing the blowdown test equipment consists of a test cell, control room, and an equipment room as shown in Figure 55. The test cell, which measures approximately 16 by 35 feet, is separated from the control and equipment areas by a two-foot-thick concrete wall for personnel protection during blowdown tests. Both ends of the test cell are equipped with motor-driven, roll-up doors which may be remotely opened before a blowdown test to vent the steam and water vapor to the atmosphere and to relieve the building of any sudden pressures at the initiation of the coolant blowdown. Two heavy glass windows, which afford visual observation of the experimental equipment during operation, are in the concrete wall separating the test cell from the control room.

The control room houses a control console and all signal conditioning and experimental data recording and processing instrumentation.

The equipment room houses the supporting facilities and instrumentation for the control of process equipment on the experimental package. Motor control centers for the control of the various heaters and motors associated with the blowdown experiment are located in the equipment area. A process

Fig. 55 Semiscale blowdown facility.

instrument panel with the recorders, indicators, and alarms used to establish temperature, pressure, and flow conditions in the vessel before a blowdown test is also located in the equipment area. Both the experimental console and the process instrument panel are monitored during the test.

1.1 Experimental Equipment

Surplus equipment was used to fabricate the Phase I blowdown system. This equipment included a pressure vessel which was modified for blowdown use in Phase I and a primary system which was capable of supplying pressure and temperature conditions for both Phase I and Phase II portions of the semiscale blowdown program.

1.11 Blowdown Vessel. The blowdown vessel shown in Figure 56 is fabricated from Type 304 stainless steel. The shell has a 12-inch ID, a 118-inch length and a 1.9-inch wall thickness. The vessel heads are hemispherical with

Fig. 56 Phase I blowdown facility.

an inside radius of 6 inches and a thickness of 0.845 inch. Design pressure for the vessel is 3400 psi at 700°F. Two 5-inch nozzles in the vessel shell are used for the blowdowns, either top or bottom, as dictated by test requirements. A 5-inch nozzle in the head is used for instrumentation access to the vessel. Instrumented washers, sandwiched between the flanges on the 5-inch nozzles, are used for mounting temperature and pressure transducers. A 2-inch nozzle located 21 inches above the center of the lower 5-inch nozzle is used for instrumentation access to the vessel. An extension spool is inserted between the instrumented washer and rupture disc assembly in the blowdown line.

1.12 Support Structure. The vessel support structure shown in Figure 57 consists of two main parts, a fixed main frame and a movable triangular frame

Fig. 57 Vessel support structure.

which supports the blowdown vessel. The frames are constructed of 8-inch I-beams. The main frame consists of a rectangular assembly approximately 12 feet in height, reinforced by triangular members from the top of the assembly to the floor. The main frame is welded to I-beams embedded in the test cell floor. The triangular support frame is attached to the main frame through two thrust load cells directly in line with the blowdown nozzle on the vessel and by two weight-loss cells suspended from the main frame. The triangular support frame can be inverted to accommodate either a top or a bottom blowdown test.

1.13 Rupture Device and Control. The rupture device, shown in Figure 58, consists of a series of pipe spools and rupture disc flanges which can be bolted to either the top or bottom nozzle, and ruptures can be initiated by two techniques using this device. One technique is overpressurizing the volume between the rupture discs with nitrogen gas. The nitrogen gas is released into the volume between the rupture discs from pressure accumulation supplied by five nitrogen

Fig. 58 Rupture device.

gas bottles manifolded together. The second rupture technique involves depressurizing or underpressuring the volume between the rupture discs. In both rupture techniques, solenoid valves are used to control pressure.

For safety reasons, the system is designed such that a minimum of pressurized equipment is in an occupied area. This area is occupied only during adjustment of the regulators to establish the proper pressures required for the tests.

1.2 Primary System

The purpose of the primary system shown in Figure 59 is to heat, pressurize, and circulate the demineralized water to the temperature and pressure required for the blowdown tests. These tests range in temperature from ambient temperature to saturation temperature at pressures from 600 psi to 2300 psi.

1.21 Operating Limits. A description of the operating characteristics of the primary system loop is given below:

Flow	11 gpm	
Pressure		
Minimum	200 psi	
Operating	2330 psi	
Relief	2500 psi	
Temperature		
Maximum	650°F	
Heater Capacity	62 kW (total)	
	Clamp type	12 kW
	Flow type	50 kW
Heatup Rate	Approximately 2°F/minute

Fig. 59 Blowdown test flow schematic.

Makeup Water System	
Pump Capacity	6 gal/hr water at 100°F at 2100 psi
Water	Deionized or deionized and deaerated
Vacuum System	Two vacuum pumps Pressure: 10 mm Hg absolute
Degas System	Discharge pumped to pressurizer Flow: 3 gpm

1.22 Mechanical Components. Major components of the primary system equipment used are enumerated. Additional information concerning other primary system equipment has been reported [34].

(1) Pressurizer. The purpose of the pressurizer is to maintain the system pressure and to absorb fluid volume changes due to temperature variations. To maintain pressure and to account for pressurizer heat losses, 32 tubular immersion heaters with a total rating of 8 kW are used. The heaters are located in 1/2-inch-diameter wells and are replaceable from the top of the pressurizer.

The degas line entering the pressurizer serves two functions. The first function is to deliver the loop fluid from the pump discharge to the vapor space in the pressurizer during startup. Dissolved gases are removed from the loop fluid by the scrubbing action of the hot steam in the vapor space. The second function is to help depressurize the loop by circulating fluid through the degas line at the top of the pressurizer and back into the primary piping, thereby utilizing cooler loop water to help cool the pressurizer.

The heat input to the pressurizer is regulated by controlling the voltage to the heaters through the use of a saturable core reactor.

(2) Primary Pumps. Two Westinghouse, hermetically sealed, A-11, B-2 pumps that are installed in parallel provide the necessary flow. Under normal operation, both pumps are operated to deliver 11 gpm.

A pump interlock is provided to shut down the pump in case of low pump cooling water flow, high pump cooling water temperature or low loop pressure.

(3) Heaters. Two heaters are supplied in series to heat the loop water to a maximum of 650°F. The first heater (12 kW) consists of 12 clamshell heaters clamped on the 3/4-inch primary piping. The second heater is a flow-through-type (50 kW) heater designed for 2500 psi at 669°F. The heaters are wired for "on-off" operation and are protected by a low-flow cut off.

(4) Three-Way Control Valve. A Kieley and Muller Company, pneumatically operated diaphragm valve (TCV-1) controls the flow to the heat exchanger tubes. The valve receives the total primary loop flow and proportions this flow between the heat exchanger tubes and the heat exchanger bypass.

(5) Piping, Tubing, Fittings, and Valves. To assure minimum leakage, the entire primary portion of the loop system is of welded construction. All

primary system manual valves are Hancock globe boiler valves with bolted packing glands. All instrument valves are barstock-body, Autoclave Engineering, "Speedline" valves with copper foil and graphite packing rings.

(6) Loop Instrumentation Panel. The loop instrumentation panel serves to provide monitoring, recording, and controlling of the various parameters of loop operation such as flow, temperature, pressure and liquid level.

Loop flow is indicated and recorded by a dual pen recorder(FRC-1).

Pump cooling water flow, degassing flow, and heat exchanger flow have indicators located on the loop package in the test cell. These can be observed through one of the viewing windows.

Temperatures in the loop and in the supporting systems are monitored by three temperature recorders and a temperature indicator with a multi-position selector switch. Loop temperature is controlled by the loop heaters and by the temperature recorder controller (TRC-1) which positions the three-way, air-controlled valve to control loop water flow through the heat exchanger.

Loop pressure is controlled and recorded by a recorder controller (PRC-1). The recorder controller controls a saturable core reactor which, in turn, controls the electrical power to the pressurizer heaters. Loop pressure is also indicated by a gauge on the loop package.

The liquid level in the loop pressurizer is recorded and controlled by LCR-1. This system detects the water level by comparing the pressurizer level to that of a cold reference leg. Controls are provided for makeup pump operation and pressurizer heater cut off from the liquid level.

2. EXPERIMENTAL INSTRUMENTATION

A flexible instrumentation system was assembled to acquire transient and steady-state information regarding the hydrodynamic, mechanical, thermal, and acoustic blowdown phenomena during the semiscale blowdown tests. Requirements of the system were: (a) signal patching flexibility to accommodate rapid changes in measurement emphasis because of channel or detector reassignments or equipment failures; (b) signal conditioning equipment to provide signal amplification, isolation, strain gage bridge completion and balancing, and impedance matching functions; and (c) a method of rapidly monitoring each measurement channel to verify proper operation, adjustment, and noise level. The instrumentation system presently consists of 40 wide-bandwidth instrumentation channels and will be expanded to approximately 100 channels. The experimental instrumentation system layout is illustrated in Figure 60.

2.1 Detector Patch Facilities

To provide maximum flexibility in accommodating the blowdown test requirements, a termination point for frequently changed signal cabling was installed in the test cell. This termination station, referred to as the detector

Fig. 60 Instrumentation system.

patch panel, also serves as an interface between the detector wiring from the test cell and the signal cabling from the signal conditioning equipment. All instrumentation cabling, with the exception of the thermocouple cabling, terminates at the detector patch panel. The detector patch panel is designed to facilitate continuity of cable shields through the patch and to maintain the

electrical isolation in order to keep hum and noise to a minimum. Thermocouple patch panels are installed at varied locations on the test equipment to keep the length of moveable thermocouple cabling to a minimum.

2.2 Signal Conditioning Equipment

The signal conditioning equipment consists of low-level amplifiers, strain gage bridge completion networks and power supplies, attenuation networks, thermocouple reference junctions, and the equipment necessary to route, monitor, and calibrate the data channels. A block diagram of the blowdown facility instrumentation is given in Figure 61.

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Fig. 61 Blowdown conditioning instrumentation block diagram.

Signal cables from the detector patch panel are terminated at the appropriate conditioning equipment. Thermocouple and strain gage signal cabling terminates at the respective conditioning equipment. Piezoelectric crystal transducer signal cables are routed directly to the charge amplifiers. High-voltage signal cabling is terminated at attenuator networks. Cabling from the signal conditioning equipment, with the exception of that from the charge amplifiers and attenuator networks, and all remaining signal cabling from the detector patch panel are terminated at the low-level input patch panel. The low-level input patch panel allows channel changes and provides system flexibility by providing convenient detector-amplifier pairing to form the various instrumentation channels.

The thermocouple reference station consists of a 50-junction, Chromel-Alumel reference unit. This unit has an adjustable reference temperature of 125° to 250°F with a stability of 0.2°F. The adjustment range of the reference temperature is not sufficient for all test conditions, however, and amplifier off-set capability is relied on to suppress the "zero level" of the signal to permit use of the full dynamic range of the amplifiers.

High-performance, strain gage power supplies with self-contained bridge completion circuits are used with a companion monitoring unit to accommodate grounded and ungrounded strain gages having resistances from 60 to 1000 ohms. These power supplies have continuously adjustable output voltages from < 1 to 30V and current capability of 100mA with a resolution of adjustment of ± 10 μ V. The power supplies have regulations of better than 0.1 percent with ripple less than 0.5mV peak-to-peak and dc isolation of 10,000 megohms.

Requirements for amplifiers to accommodate accelerometers and pressure transducers of the piezoelectric crystal type are fulfilled by electrostatic charge amplifiers. These amplifiers have a frequency response of dc to 150 kHz with linearity better than 0.1 percent, an input impedance of 10^{14} ohms, and an output impedance of 100 ohms or less over the bandwidth capability of the amplifier. The charge amplifiers provide charge-to-voltage conversion as well as voltage gain which is adjustable in discrete steps in order to avoid the uncertainties associated with continuously adjustable gains. The outputs of the charge amplifiers are routed to attenuator networks to increase the number of gain ranges.

Low-noise-level amplifiers were required to use the maximum dynamic range of signals from the various detectors. Several types of amplifiers, as indicated in Figure 61, are used.

Three modes of signal conditioning are accommodated: (a) voltage gains at bandwidths from dc to 20 kHz with high-common-mode rejection, (b) voltage gains at bandwidths from 5Hz to 250 kHz, and (c) signals not requiring gain.

Low-level amplifiers fulfill the requirements of (a). These amplifiers have a frequency response of dc to 20 kHz, common mode rejection ratio of greater than 100 dB, and the capability of internal zero offset. The requirements of (b) are fulfilled by ac amplifiers. These amplifiers have a frequency response from 2 to 200 Hz and an input impedance of 400 megohms. The requirement of (c) is fulfilled by a patch panel and attenuator network referred to as the "jump patch panel" because it provides signal paths between the low-level input patch and low-level output patch panels without signal amplification. Attenuation in the jump patch panel is accomplished by appropriate resistors to form voltage dividers. The overall accuracy of the signal amplification components, including gain stability, linearity, and drift, is to within ± 1 percent of full scale.

A patching facility was also required between the data recording equipment and the signal conditioning equipment to conveniently route and channel the conditioned data signals. This patch facility is termed the low-level output patch panel. All signal outputs and all data recording inputs terminate at the low-level input patch panel for convenient pairing.

2.3 Data Recording Equipment

Recording equipment used in the blowdown tests consists of two 14-channel, high-performance, magnetic tape recorders and one 18-channel oscillographic recorder. For data recording, the magnetic tape recorders are operated in the frequency modulation mode at 60 ips, producing a dc to 20 kHz frequency response with an overall record, store, and reproduce accuracy of ± 1 percent of full scale. The tape recorders can also be operated in the direct mode to produce a 0.3 to 250 kHz frequency response with reduced amplitude accuracy of approximately ± 15 percent of full scale. The detailed performance evaluation for these recorders has been reported [35]. The bandwidth of the oscillograph-driver-amplifier combination with the fluid-damped galvanometers and constant current drive is dc to 3 kHz with nonlinearity and readability of ± 5 percent of full scale.

The oscillographic recorder is used as a diagnostic tool during system assembly and is used to provide a readily available record of pertinent data immediately after a test. Data obtained from the oscillograph is considered of secondary accuracy.

The full-scale value for all recorded signals is ± 1.414 V, which is consistent with the overload voltage of the magnetic tape recorders. The oscillograph driver amplifiers are adjusted for the same full-scale voltage to allow recording of data interchangeably on the magnetic tape or the oscillograph or both.

2.4 Timing, Grounding, and Calibration Equipment

Timing information for data correlation and event occurrence is provided by simultaneously recording a 100-kHz sine wave on one channel of each tape recorder. Timing signals are recorded in the direct mode, which provides a frequency response of 0.3 to 250 kHz, as needed to record 100 kHz signals. The accuracy of the timing signal is one count in 10^6 or ± 10 μ sec whichever is greater. Timing for the oscillograph is provided by an internal generator.

A grounding system for the instrumentation is needed to provide a grounding point for each channel, maintain cable shield continuity and isolation from detector to recording device, and eliminate common grounding of conditioning equipment chassis in order to reduce hum and noise levels to values consistent with published amplifier minimum noise levels. To provide these features, the grounding system was designed with the following features: (a) each instrument rack is electrically isolated from ground and from all other racks; (b) the ac power receptacles which are installed in approximately half of the racks are electrically isolated from the racks, and provisions are made to enable isolation of the ac power ground at the ac power receptacle; (c) a ground bus is installed in each rack and is also electrically isolated from each rack; (d) the test vessel is considered as the system ground point, and a large-diameter, low-resistance, insulated cable is brought from the metal frame of the test equipment into the control room where it may be connected to any combination of instrument rack ground buses; (e) connections from the individual rack ground buses to individual rack-mounted instruments can be made as required; and (f) each instrument is individually isolated electrically from the metal rack at points of mechanical attachment. In this way, complete flexibility in grounding is accomplished, and the best configuration is easily obtained. All cable shields are carried through each piece of instrumentation and, eventually, are terminated at either the

magnetic tape recorders or oscillographic strip-chart recorder enclosures which are electrically isolated.

Calibration of the signal conditioning and recording equipment is accomplished by applying a step-ramp signal of known value at points in the system as indicated in Figure 61. By the use of a calibration and monitoring system low-level amplifiers in groups of ten may be calibrated or monitored individually at either input or output. By using this system, data channels containing low-level amplifiers may be calibrated from input to readout exclusive of detectors. Data channels not containing low-level amplifiers are individually calibrated in a similar manner. Use of the step-ramp calibration signal allows determination of the transient response characteristics as well as determination of the linearity and gain accuracy.

2.5 System Performance

Results of test performed in the semiscale blowdown facility have shown the instrumentation system to perform well. Data acquired have been of good quality and repeatability. Sixty-cycle hum levels are 10 μ V rms or less with random noise of 20 to 60 μ V rms referred to the detector outputs. The accuracy and linearity of the complete instrumentation system is within ± 1 percent of full scale.

3. PHASE I BLOWDOWN TEST RESULTS

Preliminary blowdown tests were performed at subcooled conditions with test pressures ranging from 600 to 1600 psi and test temperatures at room temperatures to investigate the behavior characteristics of metal rupture discs and the behavior of the subcooled fluid in the semiscale vessel when subjected to rapid decompression. Two methods were used for conducting the blowdowns. The first method entailed providing the vessel pressure by pressurizing a gas dome in the vessel with nitrogen and using a double-rupture-disc rupture technique. The second method provided vessel pressure by compressing the fluid in the vessel with a positive displacement pump. The simulated pipe ruptures for this method were provided by single rupture discs.

3.1 Rupture Disc Studies

Metal rupture discs were chosen for initiating the decompression studies because of their simplicity and reliability of operation and their potential capability of effecting rupture in a time duration short compared to the acoustic propagation time within the system fluid. The discs were ruptured by three distinct methods to produce rapid ruptures simulating fractures in the primary piping of a pressurized system. The three methods were: (a) overpressuring the volume between two metal discs with nitrogen gas until the disc in contact with the atmosphere (downstream disc) ruptures, following which the test pressure in the semiscale vessel causes the remaining disc (upstream disc) to rupture, (b) underpressuring or depressurizing the volume between two metal rupture discs until the upstream disc which is subjected to test pressure in the semiscale vessel ruptures and allows the test pressure to be imparted to the downstream disc which subsequently ruptures, and (c) shearing a single rupture disc at the periphery with a pyrotechnic material.

3.11 Ruptures by Overpressurization. The ruptures produced by the overpressurization method resulted in decompressions in the blowdown nozzle that were different for each rupture. Typical decompression behaviors in the blowdown nozzle are displayed in Figure 62 where A, B, and C designate the times at which the onset of rupture occurred at the rupture disc nearest the pressure vessel. The initial drop in pressure for each test indicates that the rupture disc in contact with the atmosphere has ruptured and that the pressure between the two rupture discs is decreasing and is allowing the vessel pressure to work against the disc remaining in the blowdown nozzle. As evidenced by the traces for each test, an oscillatory pressure exists in the nozzle before the rupture event occurs. This oscillatory pressure was concluded to be the result of pressure waves being generated as the remaining rupture disc in the blowdown nozzle yielded but did not fail. The frequency of the pressure oscillation occurring before the rupture event was characteristic of the half-wave configuration of an organ pipe open at both ends. The half-wave behavior occurred because the pressure waves traversing the blowdown nozzle recognized the opening into the pressure vessel and the rupture disc as acoustic impedances that were considerably lower than the impedance represented by the fluid in the nozzle.

Oscillations in nozzle pressure due to the yielding of the rupture disc before the rupture event are undesirable in that a complex pressure disturbance is propagated through the system leading to results which are difficult to interpret. Therefore, methods of eliminating or reducing the extended deformation of the discs were studied. Factors which were found to affect deformation of the discs were (a) the extent to which the disc was prestressed, (b) the overpressure to which the disc was subjected, and (c) the material from which the discs were made. The percentages to which the discs were prestressed and the overpressure ratios, ratio of pressure subjected to the rupture disc to the pressure rating of the rupture disc, are given in Table XXX for tests in which stainless steel discs were used.

Examination of the results of Tests 504 and 505 in Figure 62 and the values for rupture disc deformations listed for these tests in Table XXX shows that the increase in the percentage deformation of rupture disc resulted in a reduction in the pressure oscillation before the rupture event. Also, a comparison of the results of Tests 505 and 506 and the values for overpressure ratios listed for these tests in Table XXX shows that the increase in overpressure ratio in Test 506 to 4.0 from 1.7 in Test 505 resulted in reduced pressure oscillations before the rupture event.

Thus, to reduce the deformation of the rupture discs before rupture, the disc should be prestressed to the highest feasible value and subjected to the highest overpressure ratio possible within the pressure limitations of the actuation system. Also, to reduce pressure oscillations due to rupture disc deformation, materials with a high degree of brittleness should be used.

3.12 Ruptures by Underpressurization. The underpressure method of providing ruptures was employed as part of the investigation to eliminate the yielding of rupture discs before rupture. In this method, the nitrogen gas pressure between the two rupture discs was decreased slowly to allow the differential pressure across the rupture disc nearest the pressure vessel to increase slowly, thereby causing this disc to yield at a rate prohibiting any development of oscillations in blowdown pressure before rupture.

Fig. 62 Blowdown nozzle pressure -- overpressure rupture: Tests 504, 505, and 506.

TABLE XXX

RUPTURE CONTROL PARAMETERS

Test	Rupture Disc Prestress[a] (percent)	Overpressure Ratio	Rupture Disc Material
504	70	1.4	SS-304
505	90	1.7	SS-304
506	90	4.0	SS-304

[a] Percentage of ultimate strength.

The underpressure rupture method eliminated the oscillations evidenced in the nozzle pressure prior to rupture of the upstream disc when the overpressure rupture method was employed. The oscillations were eliminated because the nozzle pressure equilibrated with the initial vessel pressure during each cycle of the disc expansion because of the long time constant involved in "bleeding-off" the pressure between the rupture discs. The time for disc expansion to the point of rupture represents a time which is long in comparison to the time for pressure pulses to propagate from the upstream disc to the vessel. Figures 63 and 64 show the nozzle pressure during decompression when the underpressure rupture method is used. Rupture of the upstream

Fig. 63 Blowdown nozzle pressure -- underpressure rupture: Test 508.

Fig. 64 Blowdown nozzle pressure -- underpressure rupture; gas dome: Test 507.

discs occurs at D and F, and rupture of the downstream disc occurs at E and G. Thus, blowdown initially starts at Points D and F but is impeded until the downstream disc ruptures at E and G.

The pressure drops rapidly once the upstream disc ruptures; and, as a result, fluid motion begins. However, the nozzle pressure again builds up as the fluid piles against the downstream disc until sufficient energy is absorbed by the downstream disc to cause rupture; at which time, the acoustically controlled portion of decompression takes place.

Essentially, rupture initiation is controlled by the impedance of the downstream disc to the fluid momentum when the underpressure rupture method is used. By lowering the impedance of the downstream disc or by increasing the separation between the discs, the decompression phenomena associated with the underpressure rupture method shows good agreement with the decompression phenomena associated with the overpressure rupture method once rupture has occurred. This can be seen by comparing Figures 62, 63, and 64 where Figure 62 represents the nozzle pressure for overpressure ruptures and Figures 63 and 64 represent the nozzle pressures for underpressure-type ruptures in which the downstream discs had overpressure ratios of 1.44 and 4.0, respectively. The nozzle pressure information in Figure 64 is different from the information for a similar test shown in Figure 63 because the downstream disc which ruptures at Point G of Figure 64 offers little resistance to the fluid momentum as compared to the resistance offered by the downstream disc which ruptures at Point E of Figure 63.

3.13 Pyrotechnic Ruptures. The pyrotechnic rupture method utilized a single metal rupture disc and a pyrotechnic material to explosively shear the periphery of the rupture disc. The burning rate for the pyrotechnic material

was 21,000 ft/sec and, as such, produced a complete shear at the periphery of the rupture disc in approximately 80 microseconds. Figures 65 and 66 show the

Fig. 65 Blowdown nozzle pressure -- pyrotechnic rupture; gas dome: Test 515.

blowdown nozzle pressure behavior for blowdowns in which ruptures were initiated with pyrotechnic explosive loads of 40 grains and 25 grains, respectively. The sharp rise in pressure shown in both figures resulted from a pressure pulse generated at the time the pyrotechnic material was ignited. This pressure pulse also excited the pressure transducer measuring the blowdown nozzle pressure and caused the pressure information shown in Figures 65 and 66 to exhibit spurious pressure spikes.

3.14 Comparison of Rupture Methods. The overpressure rupture method can produce ruptures that are satisfactory if judicious selections of rupture disc material, percentage deformation of rupture disc, and overpressure ratios are made. The underpressure rupture method does not offer any advantages over the overpressure method; in fact, the determination of rupture time was made difficult by this method because of the requirement that system fluid must flow to the downstream disc to effect rupture at that disc. The pyrotechnic rupture method eliminated the problems associated with the overpressure and underpressure rupture methods and produced fast ruptures with rupture times which were easily determined. The pyrotechnic method, however, did produce a pressure pulse at rupture that was transmitted within the blowdown nozzle and spuriously excited transducing mechanisms. The pressure pulse may be reduced considerably if pyrotechnic materials with reduced mechanical energy release times are used.

Fig. 66 Blowdown nozzle pressure -- overpressure rupture; gas dome; Test 516.

3.2 Subcooled Blowdown Behavior

The initial semiscale blowdowns were conducted at subcooled conditions with the temperature of the fluid at approximately room temperature and with the pressures ranging from 600 to 1600 psi. These blowdowns were performed by pressurizing a volume of approximately one cubic foot at the top of the vessel with nitrogen to the desired vessel test pressure and by initiating rupture by the overpressure- or underpressure-rupture method. Pressure data for measurements made in the blowdown nozzle and in the top nozzle, respectively, for subcooled gas-driven blowdowns are shown in Figures 67 and 68. Figure 67 shows the pressure behavior in the nozzle before and after the last disc in the blowdown nozzle ruptures at Point H. The frequency of the oscillations of the pressure in the blowdown nozzle is of the half-wave nature of a pipe open at both ends and changes slightly because an additional length from the final rupture disc to the end of the blowdown nozzle is presented to the fluid in the blowdown nozzle when the final disc is ruptured. About 4 milliseconds after the final disc ruptures, the pressure waves that have traversed the vessel begin to interact with the pressure waves in the blowdown nozzle and, consequently, complicate the pressure behavior in the blowdown nozzle.

The pressure in the top nozzle resulting from the rupture of the discs in the blowdown nozzle is shown in Figure 68. The amplitude of the pressure waves in the top nozzle is less than the amplitude of the pressure waves generated in the blowdown nozzle because the pressure waves generated in the blowdown nozzle travel through a transition in area at the entrance into the vessel, thus reducing the pressure waves introduced into the vessel by the ratio of some effective vessel area to blowdown nozzle area. The frequency of the pressure

Fig. 67 Blowdown nozzle pressure -- overpressure rupture; gas dome; Test 503.

Fig. 68 Top nozzle pressure -- underpressure rupture; gas dome; Test 508.

waves generated in the top nozzle is of the quarter-wave nature of an open-closed pipe since the top nozzle is open to the vessel and closed at one end by a blind flange. Modulation of the pressure oscillations occurs about every 4 milliseconds when pressure waves that have traversed the vessel interact with the pressure waves at the top nozzle.

The LOFT test conditions of 2330 psi and 520°F are representative of 30 percent subcooling and, as such, require the pressure to drop to about 812 psi from 2330 psi during the subcooled portion of decompression of the LOFT blowdown. Several blowdown tests were performed using a liquid-full vessel to obtain experimental information which should be similar to the subcooled portion of decompression during LOFT blowdowns. Figure 69 is indicative of the

Fig. 69 Top nozzle pressure -- overpressure rupture; single-disc, liquid-full system: Test 519.

pressure behavior at the top nozzle for a liquid-full semiscale blowdown in which the pressure was supplied by compressing the fluid within the semiscale vessel with a positive displacement pump until a single rupture disc in the blowdown nozzle ruptured. The pressure in the semiscale vessel was supported by the compressibility of fluid; consequently, at blowdown, small incremental volume changes in the fluid resulted in large pressure drops and a resultant decompression of the fluid to atmospheric pressure. The rapid decompression behavior exhibited during the liquid full blowdown should be indicative of the LOFT blowdown behavior during subcooled fluid decompression from 2330 psi to the saturation pressure of 812 psi.

IX. INSTRUMENTATION -- SNAPTRAN 2/10A FUEL PIN CLADDING RESIDUAL STRAIN MEASUREMENTS

Tests were performed in which measurement of the residual strain of the SNAPTRAN 2/10A fuel pin cladding was made at room temperature. The purpose of the tests was to furnish information for interpreting the strain data obtained from strain gages mounted on the cladding of the fuel pins during the SNAPTRAN-1 transient tests.

The objective of this measurement was to determine the residual strain in the fuel cladding for a given peak strain by using both Microdot weldable strain gages and foil strain gages located adjacent to each other at several locations on the pin.

1. EXPERIMENTAL EQUIPMENT

A hollow, Hastelloy-N clad, dummy SNAPTRAN 2/10A fuel pin was used in the test. The cladding was cycled between incrementally increasing peak strains and zero strain with a hydraulic-actuated internal piston to simulate fuel thermal elongation and the resulting axial strain. Peak elongation was measured with a dial gage system. The pin was instrumented with three Microdot Type SG-100-1A, Hastelloy-N, weldable strain gages; five Budd Type HE-121, post-yield strain gages; and one Baldwin-Lima-Hamilton (BLH) Type FABR-25-12-S9, rectangular rosette strain gage. A list of the strain gages giving their characteristics, orientation, and the angular location on the fuel pin is given in Table XXXI, and a drawing of the dummy fuel pin giving the locations of

TABLE XXXI

STRAIN GAGE IDENTIFICATION -- RESIDUAL STRAIN TESTS

Gage	Manufacturer	Type	Resistance (ohms)	Gage Factor (percent)	Lot	Orientation	Angular Location (degrees)
1	Microdot	SG-100-1A	60.3 ± 0.5	1.53 ± 3.0	5037+6	Axial	0
2	Budd	HE-121	120.0 ± 0.2	2.00 ± 0.5	A7-K11-1	Axial	10
3	Microdot	SG-100-1A	60.3 ± 0.5	1.53 ± 3.0	5037+6	Axial	120
4	Budd	HE-121	120.0 ± 0.2	2.00 ± 0.5	A7-K11-1	Axial	130
5	Microdot	SG-100-1A	60.3 ± 0.5	1.53 ± 3.0	5037+6	Axial	240
6	Budd	HE-121	120.0 ± 0.2	2.00 ± 0.5	A7-K11-1	Axial	250
7	Budd	HE-121	120.0 ± 0.2	2.00 ± 0.5	A7-K11-1	Circumferential	180
8	Budd	HE-121	120.0 ± 0.2	2.00 ± 0.5	A7-K11-1	Circumferential	0
9	BLH	FABR-25-12-S9	120.5 ± 0.5	2.10 ± 1.0	---	Axial	300
10	BLH	FABR-25-12-S9	120.5 ± 0.5	2.10 ± 1.0	---	Circumferential	300
11	BLH	FABR-25-12-S9	120.5 ± 0.5	2.10 ± 1.0	---	45 deg	300

the gages is shown in Figure 70. The first six gages are those of principal interest. As seen in Figure 70, the three Microdot gages (1, 3, 5) were spaced 120 degrees apart around the pin in different longitudinal locations, and Budd gages (2, 4, 6) were installed as close as possible to each Microdot gage. All six gages were installed in an axial direction. Two Budd gages (7, 8) were used to measure circumferential strain at two locations on the pin. A BLH rectangular rosette gage (9, 10, 11) was installed at the center of that part of the pin above the threaded collar. The circumferential and the rosette gages were installed for analytical purposes only since the thermal circumferential strain of the SNAPTRAN-1 fuel pin would not be simulated by this type of test. A test device was constructed to apply an internal longitudinal force to the dummy fuel pin. An exploded view of the device including the instrumented fuel pin is shown in Figure 71, and the assembled test device is shown in Figure 72. The dial gage shown at the right of Figure 71 was replaced by a lever-type dial gage in the final assembly. At the bottom of the test device is a lever-type, Standard Gage Company gage with 0.1-mil increments used to detect any movement of the pin subassembly relative to the housing. The top dial gage, used to measure the pin elongation, is a Scherr Tumico gage with 0.1-mil increments.

Fig. 70 Dummy fuel pin.

Fig. 71 Disassembled test device.

Fig. 72 Assembled test device.

2. EXPERIMENTAL PROCEDURE AND TEST RESULTS

The residual strain of the cladding was measured for maximum strains of multiples of 500 $\mu\text{in./in.}$ The hydraulic pressure was increased to produce a strain of 500 $\mu\text{in./in.}$, and the peak strain of all gages was measured. The pressure was reduced to zero; the piston was pulled down; and the residual strain was measured; after which the strain gage bridges were re-zeroed; and the procedure was continued in 500- $\mu\text{in./in.}$ increments.

The standard for determining the increments of strain was an elongation measurement using the combination of the two dial gages.

To check the operation of the test device, a low-strain test (Test 1) was run. An average strain of 160 $\mu\text{in./in.}$ for the three axial Microdot and the three axial Budd gages (Gages 1 through 6) was obtained with a pressure of 360 psi. The top dial gage reading was 1.0 mil and the bottom dial gage reading was 0.42 mil, giving a net elongation of the pin of 0.58 mil or about 47.5 $\mu\text{in./in.}$ From calculations using the stress due to the pressure on the hydraulic actuated slug, the strain should have been 198 $\mu\text{in./in.}$ which compares much more favorably to average strain derived from the axial gages than to the strain derived from the net dial gage measurement.

On the succeeding low-strain test (Test 2), at the same pressure, the average strain for Gages 1 through 6 was 218 $\mu\text{in./in.}$, but the net dial gage reading was the same as in the previous test. Several additional tests (Tests 3 through 8) at low strain gave similar results. To improve accuracy of the measurement, the top dial gage stem was repositioned toward the edge of the top of the pin cap rather than directly in the middle of the cap. Since the pressure measurement was apparently more accurate than the dial gage measurement, at least at lower strains, pressure was used as a reference. For the first increment test of 500 $\mu\text{in./in.}$, the average strain of Gages 1 through 6 was 488 $\mu\text{in./in.}$ The dial gage readings gave a net elongation of 4.7 mils or about 383 $\mu\text{in./in.}$ At 1000 $\mu\text{in./in.}$, the net reading of the dial gages was 10.8 mils, which corresponds to about 883 $\mu\text{in./in.}$ The average strain of Gages 1 through 6 was 947 $\mu\text{in./in.}$ The test was continued to 3000 $\mu\text{in./in.}$ During the attempt to increase the strain to 3500 $\mu\text{in./in.}$, the elongation increased very rapidly, but the strain was slightly less than that for the 3000 $\mu\text{in./in.}$ test. With increased pressure, the pin cladding broke loose at the weld on the threaded collar. Apparently, yielding in the weld had occurred during the previous test.

A summary of the test results is given in Table XXXII. A plot of the net maximum dial gage equivalent strain and the average measured maximum strain of Gages 1 through 6 versus measured pressure is given in Figure 73. The cause of the discrepancy between the maximum strains obtained from the net dial gage elongation measurement and the average measured maximum strains of Gages 1 through 6 up to Test 14 is unknown; the large difference in the two measurements for Test 15 was due to failure of the weld. A plot of maximum circumferential strain versus measured pressure for Gage 7 is shown in Figure 74. The circumferential gages all indicate compression. Plots of residual strain versus maximum strain for all of the strain gages used in the tests are given in Figures 75 through 85. Residual strain was not measured for Tests 1 and 5. For Tests 11 and 12, the decrease in residual strain for maximum strains on several gages may have been due to localized yielding

TABLE XXXII

RESULTS OF RESIDUAL STRAIN MEASUREMENTS

Test	Desired Maximum Strain ($\mu\text{in./in.}$)	Net Maximum Dial Gage Reading (mils)	Net Dial Gage Equivalent Maximum Strain ($\mu\text{in./in.}$)	Gages 1,3,5[a] Maximum Strain ($\mu\text{in./in.}$)	Gages 2,4,6[b] Maximum Strain ($\mu\text{in./in.}$)	Gages 1 through 6[c] Maximum Strain ($\mu\text{in./in.}$)	Gage 9[d] Maximum Strain ($\mu\text{in./in.}$)
1	(see text)	0.58	47.5	187	133	160	----
2	(see text)	0.58	47.5	239	197	218	190
3	(see text)	0.6	49	246	196	222	190
4	(see text)	0.6	49	236	200	218	194
5	(see text)	0.6	49	253	205	229	198
6	(see text)	1.05	86	340	305	322	290
7	(see text)	2.35	196	336	294	310	286
8	(see text)	2.8	228	337	310	324	293
9	500	4.7	383	490	486	488	450
10	1000	10.8	883	931	964	947	968
11	1500	17.2	1400	1372	1409	1390	1448
12	2000	24.62	2010	1848	1957	1902	2038
13	2500	33.35	2722	2456	2658	2557	2705
14	3000	44.3	3620	2887	3202	3044	3200
15	3500	50.7	4230	2923	3059	2991	3219

[a] Average measured values (Microdot).

[b] Average measured values (Budd).

[c] Average measured values.

[d] Rosette axial gage.

of the metal. The residual strain at different locations on the pin varied over a fairly wide range for each given pressure. The total strain for a given maximum strain can be obtained by adding the maximum strain to the summation of the preceding residual strains.

Fig. 73 Maximum strain with respect to measured pressure.

Fig. 74 Maximum circumferential strain versus measured pressure (Strain Gage 7).

Fig. 75 Residual strain versus maximum axial strain (Strain Gage 1).

Fig. 76 Residual strain versus maximum axial strain (Strain Gage 2).

Fig. 77 Residual strain versus maximum axial strain (Strain Gage 3).

Fig. 78 Residual strain versus maximum axial strain (Strain Gage 4).

Fig. 79 Residual strain versus maximum axial strain (Strain Gage 5).

Fig. 80 Residual strain versus maximum axial strain (Strain Gage 6).

Fig. 81 Residual strain versus maximum circumferential strain (Strain Gage 7).

Fig. 82 Residual strain versus maximum circumferential strain (Strain Gage 8).

Fig. 83 Residual strain versus maximum axial strain (Strain Gage 9).

Fig. 84 Residual strain versus maximum circumferential strain (Strain Gage 10).

Fig. 85 Residual strain versus maximum strain at 45 deg (Strain Gage 11).

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