727314

R. W. Thomas
R. L. Doan
J. P. Lyon
J. R. Huffman
B. F. Boardman
W. E. Nyer
S. O. Forbes
F. L. Bentzen
G. O. Bright
G. F. Brockett
J. C. Haire
F. H. Murray
J. A. Norberg
F. Schroeder
A. H. Spano
T. R. Wilson
J. B. Philipson (15)
Technical Library (15)

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SPERT Destructive Tests
FOLDER Program Preliminary Review PTR-458

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SPERT DESTRUCTIVE TESTING PROGRAM
PRELIMINARY REVIEW

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SPERT DESTRUCTIVE TESTING PROGRAM
PRELIMINARY REVIEW

I. INTRODUCTION

Core destructive testing was specifically included in the initial instructions issued by the Atomic Energy Commission to Phillips Petroleum Company at the inception of the Spert program in 1954. This aspect of the program was subsequently deferred, principally for two reasons: first, it was felt that a broader program of basic investigations of reactor kinetics should precede destructive tests; and second, it was undesirable to perform destructive tests in the only facility then available for transient testing of heterogeneous water reactors. The completion and analytical correlation of a substantial portion of the investigations which could be performed in Spert I[1], and the construction of the Spert II and Spert III reactors, removed both of these deterrents to destructive tests. Consequently, it was proposed in the 1959 review of the Spert program[2] that destructive testing in Spert I be included in the experiments to be conducted during the 1960 calendar year. Since destructive testing is necessarily more expensive than nondestructive testing, it is appropriate that the objectives and the expected returns from such tests be considered in detail before embarking on this phase of the program. This report has been prepared for this purpose at the request[3] of the Idaho Operations Office of the Atomic Energy Commission.

II. OUTLINE OF OBJECTIVES

A. General

In the 1957 review of the Spert program[4] reactor accidents were divided into three phases: initiation, response, and consequences. The major effort in the initial Spert work has been on the response phase,

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since this represents that aspect of reactor safety which is most strongly influenced by the inherent properties of the system. Some extension into the initiation phase has been provided by the ramp experiments, the stability studies, the dropped fuel assembly tests, and by the inclusion of the complete reactor control and instrumentation system in the BSR-II experiments currently in progress. The proposed destructive tests will provide additional information on the response phase in the region of short period transients, and will also constitute the first extension of the Spert experimental program into the consequences phase of reactor accidents. Very little experimental work has been performed in this latter field beyond the one Borax destructive test[5] in 1954, with the notable exceptions of the uncompleted but extensive investigations of metal-water reactions and containment.

B. Problem Areas in Destructive Tests

The following is a list of the major problem areas to be investigated by destructive testing. As noted above, these factors fall in both the response and consequences phases of an accident and will be so classified for discussion.

Response Phase:

(1) Nature of the shutdown process for violent transients.

(2) Extrapolability of data obtained under nondestructive conditions to destructive situations.

(3) Source of the high pressures observed in the Borax test--chemical reactions, steam explosion, metal expansion, etc.

(4) Non-nuclear sources of energy, such as metal-water reactions.

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Consequences Phase:

(5) Nature of the pressure pulse in the reactor vessel.

(6) Nature of the pressure pulse in the atmosphere surrounding the reactor.

(7) Extent of mechanical damage--missile sizes, velocities, etc.

(8) Extent of radiation exposure to personnel from primary burst.

(9) Extent of fission product release and spread to environs.

C. Specific Objectives of Destructive Tests

The nature of the problem and the data to be obtained in each of these areas will now be discussed in detail.

1. Shutdown Mechanisms

One of the unanswered questions in reactor self-shutdown is whether or not the shutdown mechanism at very short periods is basically the same as that at longer periods. It has been shown in the Spert experiments that, even though three different processes become successively dominant in self-shutdown as the reactor period is shortened, the overall behavior is well represented by a simple theoretical model[6] which assumes a constant shutdown coefficient. It is of fundamental importance to the basic program to determine the nature of the effective shutdown mechanism as far into the short period region as feasible and to determine whether prediction from simple theory can be extended reliably to destructive transients.

This portion of the investigation is clearly a logical extension of the basic program of mechanism studies. As such, it would begin with a series of capsule experiments designed to obtain thermodynamic information on subsections of typical plate-type cores. By control of flux peaking and fuel plate loading, these tests will be carried beyond plate melting conditions for a number of reactor periods extending to the limit of non-destructive transients in the remainder of the reactor. Some preliminary photographic and thermodynamic data have already been obtained from capsule experiments in the Spert I reactor. In the next series of capsule tests the program will be extended to provide data on self-shutdown behavior in the region of core meltdown.

2. Extrapolability of Nondestructive Data

One of the objectives of the experimental program on thermal reactor safety should be the investigation of maximum credible accidents. The practice of assuming a maximum credible accident is widespread in reactor hazards analyses, yet there is very little experimental evidence which can be used as a yardstick in evaluating the appropriateness of the assumptions. It would be extremely useful if it could be determined whether or not the nuclear energy release continues to increase with increases in the size of the reactivity disturbance, even after violent disassembly becomes the principal shutdown process. It is equally important to determine the maximum reactivity addition rates that can realistically be expected, since there is evidence from the Spert results that in many cases the maximum practical assembly rates will limit the maximum credible accident to an energy release of the same order of magnitude as that observed in the Borax destructive test.

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It has been shown[7] that the maximum reciprocal period during a severe ramp accident is given approximately by the expression

$$\alpha_m \cong \sqrt{30\dot{k}/\ell} \qquad (1)$$

For example, the ramp rate, $\dot{k}$, required to achieve a minimum period of 1 msec in a reactor having a prompt neutron lifetime, ℓ, of 3×10^{-5} sec is about 100% Δk per second. This ramp rate is about three times that available from the specially designed Spert transient rod used for initiation of step transients and about ten times the highest observed spontaneous rate produced by void collapse during Spert instability runs. Since the reciprocal period increases only as the square root of the ramp rate, very high rates will be required to produce periods much less than 1 msec. Furthermore, it has also been shown[7] that, for reactors of the Spert type which exhibit nonlinear shutdown processes, the energy release increases roughly as the square root of the maximum reciprocal period. Thus, the nuclear energy release will increase extremely slowly with increasing ramp rate in reactors of this type if the behavior observed in the nondestructive tests persists in the destructive region.

Destructive tests would provide information both on the extrapolability of nondestructive data and on the existence of a practical limit on energy release for reactors of the Spert type.

3. Source of High Pressure in Destructive Tests

Although no direct measurement of the maximum pressure was obtained in the 2.6 msec Borax destructive test, estimates based on mechanical damage ranged from six to ten thousand pounds per square inch. These estimated pressures are about an order of magnitude higher than would be predicted by extrapolation of the Spert data (which extend down

to 5 msec periods). If such pressures are to be reliably predicted in hazards analyses, the underlying causes must be understood. In the ANL report on the destructive tests[5] it was postulated that the explosive pressures were a result of either a chemical reaction or a simple steam explosion. The available evidence indicated that the latter was the more probable source of the pressure pulse in the reactor vessel. It has been suggested[8] that the rapid expansion of aluminum in changing from the solid to the liquid phase could generate pressures of the observed magnitude. This can be demonstrated by the following simple calculation.

The condition for the establishment of a shock wave in a reactor accident is roughly that the rate of pressure rise be rapid compared to the time required for a sound wave to return from the tank boundary. For the Borax reactor this time is approximately one millisecond. In an exponential power transient initiated from room temperature, the time required to produce the solid-to-liquid phase change in aluminum is about four tenths of a period, which for the 2.6 msec test is also about one millisecond. Thus, the shock wave condition was at least approached in this transient. If it is assumed that the acoustical equations may therefore be applied, the transient pressure in the water moderator can be found from the relationship.

$$\Delta P = \frac{-\Delta V}{V} K$$

where $\frac{\Delta V}{V}$ = the fractional change in fluid volume

K = the bulk modulus of elasticity for the fluid

= 2.04×10^9 Newtons/m^2 for water.

In the Borax core the metal volume increases 6% on melting and, because the water channel thickness is twice the plate thickness, the

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corresponding reduction in water volume is 3%. (The aluminum may be regarded as incompressible since it has bulk modulus of elasticity about thirty times that of water.) The resulting pressure peak is

$$\Delta P = (0.03)(2.04 \times 10^9 \text{ Newtons/m}^2) = 6.12 \times 10^7 \text{ Newtons/m}^2$$

or

$$\Delta P = 8{,}900 \text{ psig},$$

which is in good agreement with the Borax estimates of six to ten thousand psig.

It is clear that further investigations will be required to determine the origin of the observed pressure pulses. At present the destructive tests on subsections of typical plate-type cores appear to be the most promising approach to this problem. A full-scale destructive test can serve as a check on the conclusions drawn from the subsection work.

4. Metal-Water Reactions

Probably the most difficult question in core destruction by meltdown concerns the existence and extent of metal-water reactions. In capsule studies of subsection meltdowns, information on this point can be obtained by energy balance and chemical analysis. Extension to integral core destruction is more difficult because of the difficulty in containing either the released energy or the chemical products. If the destructive program is extended to include a containment vessel as part of the experiment, the situation would be greatly improved in this regard. However, it should be kept in mind in evaluating the results of such metal-water reaction studies that if the reaction proceeds only to such a small extent that it is difficult to detect, then it is of purely academic interest in hazards analyses. It is the massive reaction

contributing substantially to the total energy release that is of primary concern in safety, and this should be readily detectable in a contained destructive experiment.

The preceding items are those more specifically related to the understanding of the processes which take place in a violent transient. In a more pragmatic approach to safety philosophy it would be extremely helpful if a more quantitative evaluation could be put on the magnitude of the accident consequences with which we must cope. This objective can certainly be met in considerable degree by integral destructive testing. The existing data on the phenomenological consequences of reactor destruction, listed below, are extremely meager. With the benefit of hindsight and experience, improvements in their quantitative evaluation are virtually certain.

5. Nature of the Pressure Pulse in the Reactor Tank

The time history of the transient pressure pulse in reactor destruction is not only readily obtainable by existing techniques, but is also of vital importance in performing realistic explosive mockups for containment evaluation studies. High range pressure transducers and ball crusher gauges can be used to obtain, respectively, the pressure pulse profile and the maximum pressures at several points in the reactor vessel. This information alone would probably justify at least a few full-scale destructive tests.

6. Nature of the Pressure Pulse in the Atmosphere Surrounding the Reactor

Pressure measurements in the air surrounding the reactor can be made by standard techniques and will be useful in assessing the loads that

might be imposed on a reactor building during a reactor explosion. There is also a possibility that the total release of explosive energy can be approximately determined from air pressure measurements.

7. Extent of Mechanical Damage

A general assessment of the extent and nature of the mechanical damage to the reactor structure will be useful in evaluating the destructive effects of reactor explosions. Matters of particular importance to containment studies are the sizes and velocities of missiles ejected by the explosion. It is the opinion of the containment study group at Stanford Research Institute that valuable information of this type can be obtained by high-speed photography in the reactor building.

8. Extent of Radiation Exposure to Personnel

Measurements of the peak radiation dose rates during the burst and the total dose at various distances from the reactor can readily be made for evaluation of the health physics hazard.

9. Extent of Fission Product Release and Spread to Environs

An integral destructive test will provide data on the release of fission products and the extent of the spread of contamination. An estimate of the fraction of the fission products released to the atmosphere can probably be obtained by measurements on the recovered portions of the fuel. Contamination spread can be determined by fallout collectors and air samplers to detect air-borne activity.

III. PROPOSED SHORT RANGE PROGRAM

A. Subsection Work

The presently planned program of mechanism studies includes melting of fuel subsections in closed capsules under controlled conditions. For these experiments the reactor serves only as a driving source for the fuel subsection. The basic procedure in this work will be to obtain pressure, volume, temperature and photographic data on a series of fuel plates of varying composition. The principal independent variables will be the reactor period and the static pressure in the fuel-bearing capsule. By control of sample position and the fuel loading of the test plates, control of the maximum plate temperature can be made relatively independent of the reactor period. The basic objective will be to derive an equation of state for the transient formation of steam voids. These studies are essential to the investigation of the self-shutdown process and the response phase of a reactor accident.

B. Destructive Test

The analysis of the data from the first series of such tests will involve a considerable effort and probably will not lead immediately to the desired goal. It is, therefore, suggested that this initial work be followed by a core destructive test. The justification for an integral core destructive test at this time rests entirely on the data to be obtained on the extrapolability of nondestructive data and on the consequences phase of an accident. At the present time there are essentially no experimental results that can be used to relate a destructive accident to either nondestructive tests or explosive mockup studies. This gap can be closed to a very large extent by phenomenological

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measurements on destructive tests. Although some additional information on mechanisms may be obtained, this should be regarded as incidental rather than as a primary objective.

C. Containment

It is recommended that this first core destructive test be conducted in the Spert I facility without a containment shell. This recommendation is based principally on the fact that there is only very limited data from the only previous experiment of this type, and the proposed test will accordingly involve a considerable element of exploration. It is our expectation that subsequent destructive tests will profit appreciably from experience gained from the first test, and that any decision regarding a containment shell or other special facilities could then be made on a much sounder basis.

D. Predicted Behavior

1. Period

The first destructive test would be performed with the stainless steel "P" core (APPR critical assembly fuel elements). The maximum ramp rate available with the present transient rod is about 30% Δk/sec, and the prompt neutron lifetime of the P core is approximately 22 μsec. Because of the limited speed of the transient rod, the reactor power peak will occur with the rod at about 85% of its full travel and the transient will be a ramp rather than a step. Prediction of the minimum reactor period is uncertain because variations in the transient rod worth and in the rod speed result in a nonlinear ramp; however, it is unlikely that the minimum period will be less than the 1.5 msec value predicted from equation (1). To obtain shorter periods it would be necessary to employ

extraordinary measures to accelerate the transient rod. This is considered to be unnecessary and undesirable for the first test since the existing addition rate is greater than that which would be expected in normal practice. The predictions of reactor behavior are based on a reactor period of 1.5 msec; therefore, the severity of the reactor response is somewhat overestimated. It will be noted that the expected behavior differs significantly from that of the previous Borax destructive test, and thus the P core test will not be a repetition of Borax.

2. Power

The peak power extrapolated from the existing P core data is 9×10^9 watts at 1.5 msec.

3. Energy Release

The energy release can be found from the empirical observation that the total energy release is approximately equal to 2.25 times the product of the peak power and the reactor period. This is in essential agreement with the Spert I short period experimental results from five different cores. The total nuclear energy release thus predicted for a 1.5 msec transient is 30 Mw-sec. That this is less than 25% of energy release observed in Borax is due to the high ratio of the void coefficient to the prompt neutron lifetime in the P core[1].

4. Maximum Temperature

On the basis of the core heat capacity and the total energy release, the maximum predicted fuel plate temperature will be about 1400°C. Since stainless steel melts at 1260°C, and since the prediction may be in error by as much as ± 300°C, it is uncertain whether fuel plate melting will occur. In any event, core melting will be confined to the

hot spot region unless the behavior is more violent than would be predicted from the nondestructive tests.

5. Maximum Pressure

The maximum pressure extrapolated from the P core data is 1200 psig. This is the least certain of the predicted quantities since the peak pressure versus alpha curve is extremely steep. The highest measured pressure in the P core, 5 msec test was 37 psig. From the simple theory[6] the pressure should, and apparently does, increase as α^3 Pressures of the order predicted will certainly produce complete mechanical destruction of the core even if melting does not occur.

E. Cleanup and Hazards

The cleanup problem for the P core test should not be difficult from the contamination standpoint. The predicted energy release corresponds to about 10^{18} fissions. The total fission product activity will be about 3000 curies one hour after the burst and about 100 curies one day after the burst. Since both the total energy release and percentage of core melting are expected to be small compared to the Borax destructive test, it is reasonably safe to use the Borax experience as an upper bound for the contamination problem. The cleanup procedures will be planned in advance in cooperation with the Radiological Safety Division of IDO, and the experiment will be conducted under meteorological control.

Except for operations in the contaminated area after the test, the hazards to personnel will not be appreciably greater than for normal test conditions. The predicted energy release is no greater than that experienced in nondestructive tests on the aluminum "A" cores. In the Spert III hazards report[9] it was shown that under favorable

meteorological conditions the release of all the fission products from a 10^5 Mw-sec transient would not constitute a hazard for neighboring installations at the NRTS. The predicted energy release for the P core destructive test is a factor of 3000 lower than this hypothesized maximum possible accident. Even if a shift in wind direction should place the control building downwind from the reactor, the total dose to personnel would be only 300 mr for 100% release of the predicted fission products.

F. Recommended Program for Destructive Tests

The following briefly outlines the recommended program for the initiation of destructive testing at Spert.

(1) At the completion of the BSR-II core tests, the stainless steel P core will be reinstalled in the Spert I reactor.

(2) The P core will be used as a driving source for mechanism studies on fuel assembly subsections. These tests will include subsection meltdown.

(3) Following the subsection work, the P core will be prepared for a destructive test. This test will be conducted in the present Spert I facility without containment. The principal measurements will be of the power, energy, fuel temperature, transient pressures (both inside and outside the vessel), high-speed photography of fragments, radiation burst, and spread of contamination.

(4) Following this test the Spert I facility should be prepared for transient testing of the low-enrichment NS Savannah core.

(5) On the basis of the test results from the P core destructive tests, the advisability of continuing destructive tests and the need for separate or special facilities should be reviewed.

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IV. FUTURE PROGRAM

General recommendations for a long range program of destructive testing were set forth in both the recent review of the Spert program[2] and the ten year Spert program proposal[10]. Little can be added to these general comments without some experimental experience in obtaining data under destructive conditions; however, the formulation of the long range program will proceed simultaneously with the immediate work in order to take full advantage of the experimental results as they develop. Neither the prediction of the performance of reactors under extreme accident conditions nor the assessment of the efficacy of containment measures can be placed on a realistic basis without substantiating experimental evidence. This evidence is currently in very short supply.

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