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MASTER

STATUS OF PRESSURIZED WATER REACTOR
REACTIVITY ACCIDENT ANALYSIS
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INTRODUCTION

The construction of pressurized water reactors with large excess reactivities has made possible accidents with fast power excursions. A knowledge of the fastest power transient that a pressurized water reactor is capable of withstanding without destructive effects is an important factor in its safety aspects. To obtain this information, a precise evaluation of the reactor thermal transient behavior is necessary.

The general problem indicated above may be broken into three well defined and more or less independent sub-problems, namely:

1. What constitutes a destructive effect in a pressurized water reactor?
2. By what mechanisms is the heat which is generated within a fuel plate during a transient transferred to the coolant?
3. What mechanisms are available for spontaneous reactivity reduction during a transient?

The purpose of the present study was to define possible methods of attack upon these three categories of problems. This has naturally led to a study of the literature available and, in the case of sub-problem (2), to a number of analytical and numerical evaluations. As the list of references is quite lengthy, time did not permit their complete review, but all have been included for subsequent detailed analysis.

DISCUSSION

I. What Constitutes a Destructive Effect from a Power Transient in a Pressurized Water Reactor?

This problem will probably have to be settled separately for each specific reactor. "Non-tolerable" damage will be taken here to mean such damage as would release substantial quantities of fission products to the coolant. It is quite likely that regardless of the make-up of the reactor, "non-tolerable" damage will result if certain of the following occur:

A. Physical

1. Vaporization within the fuel region.
2. Melting of the fuel or cladding.
3. Crystal structure phase transition within any of the fuel element components.

B. Mechanical

1. Fracture of fuel plate from excessive thermal stress.
2. Distortion and rupture of fuel plates due to high differential pressures developed.

C. Chemical

1. Reaction between components of fuel element.
2. Reaction between fuel element and coolant.

No extensive correlations have been made although a great deal of data are available for consideration in this area. That the most obvious cause of damage i.e., melting of the fuel plate may not always be the limiting effect is shown in a number of studies. For example, a number of oxide fuel pins have been investigated by WAPD (28,39), at Chalk River in which the central portions of the oxide regions have "cored". However, these experiments were undertaken to determine escape rates of fission products through small holes in fuel pin cladding, and consequently quantitative information on the coring was not taken. It was observed that coring and rupture of a fuel pin seemed to occur simultaneously. A series of very fast transients (approximately 2 ms period) in steel-clad copper plate type fuel element were performed at Columbia University (27). These experiments showed that an explosive type failure did occur, but the data taken did not establish whether it was due to vaporization. It was shown that any chemical reaction between the simulated fuel elements and the water played an insignificant part in the explosion. Again, an analytical study during a fast transient of the relative damage caused by melting and thermal stress has been made by R.C. Mack (40). Although a final conclusion is difficult to reach without a thorough review of the whole report, which was not available during this review, the abstract does indicate that under suitable conditions melting of the fuel plate is not the limiting criterion for failure. Excessive thermal stresses may very well cause a fuel plate failure even before melting has occurred. Similar work by J. Chernich (41) supports the above conclusion.

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Such reports together with available experimental data appear to be sufficient to determine the limit of non-tolerable damage in any given reactor.

II. How is the Heat Generated within a Fuel Element during a Transient Transferred to the Coolant?

It is well known from both in-pile and laboratory experiments that the method for heat removal during the initial power pulse depends upon the period of the transient. In general, there are three phases of heat removal: non-boiling, nucleate boiling, and film boiling. For very long periods (roughly greater than 100 ms) only the first two phases occur, with coolant flow having a significant effect. For very short periods (roughly less than 5 ms) all three phases occur, and coolant flow has a negligible effect. For intermediate periods, of primary interest in a reactor hazards analysis, all three phases also occur to an extent determined by the coolant flow and the specific period involved.

In order to conduct an analytical study of heat removal during a transient caused by a power excursion having an intermediate period, several models have been proposed. Among these the following may be mentioned:

- 1) Only a single phase is considered during which the fuel element is assumed fully insulated. The temperature distribution so calculated is then used to determine the heat flux into the coolant.
- 2) Only two phases are considered, non-boiling and film-boiling in a stagnant coolant. Suitable constant heat-transfer coefficients at the fuel element-coolant interface are used for each phase.
- 3) Only two phases are considered, non-boiling, and film-boiling, in a flowing coolant. Again suitable constant heat transfer coefficients are used for each phase.

It is evident that the first model will tend to give higher fuel element temperatures than actually occur and hence will overestimate the severity of any transient. The extent of conservatism of this model cannot be determined without referring to more elaborate studies and its only virtue is that it is amenable to a simple analytical treatment. Since it is desirable to have the least restrictive conditions on the period of reactor transients and since numerical studies can be carried out on the more correct models there is little advantage in the use of this assumption.

The second and third models differ from each other only in that the latter considers forced flow. In order to determine whether this leads to any significant difference in fuel element temperature a specific problem comparing the two has been solved. The fuel central temperature was calculated at various times for a reactor period of 40 msec as detailed in the appendix. A comparison of temperature rise for various models is shown in Figure I. At a point before inception of nucleate boiling the difference in calculated temperatures is about 20%. Consideration

FIGURE 1

TEMPERATURE OF FUEL
VS
TIME

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must therefore be given to coolant flow.

It is Vitro's opinion that even this third model is far from adequate to properly describe the transient behavior of a reactor during an incident. It does not, for example, consider the nucleate boiling phase during which time the reduction of the initial excess reactivity of the incident, though small, may be very important. Neither does it properly account for the variation in the film coefficient during the boiling period.

At the present time, there is a serious lack of knowledge of the relative importance of the various mechanisms causing reactor shutdown. This is not to say that the basic mechanisms causing shutdown are themselves unknown, but rather that they have never been adequately included in a comprehensive model of transient behavior. It therefore seems inadvisable to use any simple model to describe the heat transfer phenomena. Rather it would seem that the most comprehensive model should be employed and all problems solved by the use of a high-speed digital computer. As a result of such studies, augmented where necessary by experimental work it should be possible to define suitable heat transfer coefficients and bubble formation rates to be used in one of the simpler analytical models which may then be used with assurance. Such a method, of course, is common in engineering and is already well established in obtaining nuclear fluxes, where two group constants, for example, are derived by suitably averaging the results derived in a high order multi-group analysis. With a machine for calculations, it is no longer necessary to idealize a fuel element to a thin infinite slab having a constant axial temperature. It will be possible to introduce the usually important temperature variations along a channel including end effects. It will also be possible to adequately account for reactivity variation along a channel. Another important advantage would be that problem temperatures and stresses can be continuously monitored within the machine and a large number of non-tolerable damage criteria simultaneously tested.

Such a model should incorporate the following features:

A. Non-Boiling Phase

1. Changes in thermal conductivity of fuel element components with temperature.
2. Expansion of media considered.
3. Changes in film coefficients.

B. Nuclear Boiling Phase

1. Delay in formation of bubbles as function of overpressure, temperature overshoot, water conditions and fuel surface features.
2. Frequency and size of bubbles during this phase.
3. Transport of bubbles into main coolant stream.
4. Other changes similar to those considered during the non-boiling phase.

C. Film Boiling Phase

1. Transition time from coalescence of nucleate bubbles to establishment of stable film.
2. Film size and resonant frequency as functions of wall temperature.
3. Average temporal behavior of bubble radii.
4. Other changes similar to those considered during the non-boiling phase.

Most of the items mentioned for consideration above have been the subject of rather extensive individual studies, so that initially little new experimental data will be needed. Certain of these data have been obtained under conditions not readily transferable to an operating reactor and may therefore require additional laboratory work. For example, Rosenthals' (11) study of nucleate boiling in which thin ribbons of platinum and aluminum were brought to burnout in a large stagnant pool of water attempted to correlate delay times with the quantity of oxygen dissolved in the water. Since the rate of bubble formation is sensitive to gas molecules adsorbed on the ribbon surface and the roughness of this surface, as well as gas concentration in the bulk liquid, the fact that delay times as measured by Rosenthal appeared to be independent of volume gas concentration may be misleading when applied under reactor conditions. Bubble growth rates have been studied experimentally and analytically with encouraging results. Analytical solutions have been obtained which agree well with available experimental data (42). Experimental work may have to be done before the rate of bubble formation can be predicted. The work already done on critical bubble size may help in this regard.

III. What Causes Spontaneous Reactivity Reduction During a Transient?

This is probably the best understood of the sub-problems noted above. In addition to steam formation, some reactivity compensation is generally held to be due to simple expansion and radiolytic decomposition. The importance of these effects as well as the ones mentioned in the outline below, is sensitive to the temperature and especially the instantaneous pressure of the reactor. Among the factors which should be accounted for in the machine code previously suggested are the following:

A. Rapid Compensation

1. Voids due to radiolytic gas formation.
2. Expansion effects.
3. Doppler broadening and other effective cross-section changes.

B. Delayed Compensation

1. Voids due to steam formation.
2. Expansion effects.
3. External effects, e.g. control rods.

The comprehensive machine code suggested in the previous section considers the coolant behavior, within a single channel. Since reactivity depends upon the simultaneous effects within all channels some estimate has to be made for the local reactivity changes in all other channels and then these have to be combined to give the gross reactivity change. In determining the gross reactivity change, it will, of course, be necessary to weight the contribution from each channel with the flux-importance of that channel. The behavior of the importance function with time can be readily determined either from existing calculations or by running a number of preliminary calculations. The local reactivity changes in channels other than that of interest may be obtained by a slight elaboration of the machine code.

RECOMMENDATIONS

It is recommended that the most effective method for studying fast power excursions is to develop a comprehensive digital computer code which can be varied to allow for changes in experimental parameters. Such a treatment would make the most efficient use of presently available experimental and theoretical work and would provide a foundation for the eventual development of simpler, analytically tractable models. After such a machine code has been developed and used on a sufficient number of problems any need for new experimental data should become evident. An experimental program based on such a foundation should provide the most useful information in the shortest time, with a minimum of needless duplicated effort. A reasonable estimate of this experimental program cannot be developed until the review and calculation program are underway.

The proposed work can be broken down into two phases. The start of the 2nd phase depending upon successful completion of the first. The computer work can be performed simultaneously with both phases and is tabulated under Phase I since it would probably start during this period. A tabulation of the tasks are given below along with man-hour requirements for each task. The man-hour requirements stated are a preliminary estimate reflecting Vitro's present feeling of the complexity of the problems in each task. As is the case with most studies the program could be budgeted to nearly any number but in order to achieve a significant contribution it is our feeling that a thorough program is required. Further, compared to the man-hours expended in obtaining the original data, the effort is quite modest, and indeed should be required prior to the expenditure of substantial experimental dollars.

PHASE I - STUDIES AND CORRELATIONS

<u>TASK</u>	<u>MAN-MONTHS</u>
1. Studies on Mechanisms Controlling the Inception of Nucleate Boiling	4
2. Studies on Rate of Formation and Rate of Growth of Bubbles	6
3. Studies on Mechanism Effecting Transition from Nucleate to Film Boiling	3
4. Film Coefficient of Heat Transfer Correlations	2
5. Establishing the Criteria for "Non-tolerable" Damage	6
6. Programming and Coding, Checking, and Computing:	60
Mathematician - 1	
Programmer - 1	
Calculators - 3	

PHASE II - REACTOR TRANSIENT ANALYSIS

<u>TASK</u>	<u>MAN-MONTHS</u>
1. Check of Code with Experimental Transient Data	9
2. Compilation and Correlation of Resulting Data from Computer	2
3. Interpretation of Results in Light of Criteria Established for Incidents Terminating a Reactor Transient	3
4. Write-up and Final Report	3

APPENDIX I - CALCULATIONS

The aims in the computation was to show the relative importance of the methods of heat transfer and to give estimates of fuel plate surface temperature and heat flux changes with time. Two simple analytical models were considered. The first model considered the heat transfer as one of conduction only. The second model considered forced convection of the coolant. The initial conditions assumed steady state at full power. The results were compared (Figure 1) to the model proposed in letter, subject: Sub-contract 73(14-1025) Vitro Job #5, dtd Jan. 30, 1958, which considered the fuel plate insulated.

The plots shown in this report of temperature rises with time for the particular reactor transient chosen are not valid in the boiling region except for relative comparisons. If a shorter reactor period were chosen, in the order of 5 msec, the results probably would have showed that heat transfer by conduction would be controlling. This conclusion is based on reports of studies done by Westinghouse on PWR reactor transients (10). Further studies, as discussed previously, have to be made to verify this conclusion. An estimate of the time at which nucleate boiling occurred was made by use of the Jenns and Lottes (23) equation. From this relationship it was calculated that at 95 msec after start of transient, nucleate boiling would occur. The fuel plate surface temperature at this time is 10°F above water saturation temperature. Rosenthal's (11) experiments on temperature overshoot at atmospheric pressure resulted in a 14°F overshoot for a 40 msec power transient period. Although the Jenns and Lottes correlation takes into account high pressures, there is reasonable agreement between the two values. The heat flux at incidence of nucleate boiling is 1.68×10^6 BTU/hr ft². The time of transition from nucleate boiling to film boiling was calculated by use of Jenns and Lottes burn-out data (23). Their correlation gave a heat flux at incidence of film boiling of 2.96×10^6 BTU/hr ft². The time at which this heat flux occurs at the fuel plate surface is about 115 msec after the initial input of excess reactivity. This gives a nucleate boiling interval of approximately 20 msec. According to reports cited in the literature, on the growth rate of bubbles, the time for bubble formation varies from 80 to 120 micro seconds. The value of the film heat transfer coefficient during nucleate boiling is dependent upon the turbulent effect from bubble formation. The frequency of bubble formation is so great in comparison to the nucleate boiling time interval given above, that variation in the water film turbulence may be neglected. This indicates that the lifetime of a bubble is an insignificant factor in consideration of the film heat transfer coefficient during nucleate boiling.

In the above studies a change in the film heat transfer coefficient was not considered during the interval from time zero to the incidence of film boiling. If time allowed, present published correlations on nucleate boiling and film boiling heat transfer coefficients would have been used for both phases of heat transfer. If this was done, the results would probably show that the time interval between the inception of film boiling to melting of the fuel plate would be significant.

APPENDIX II - LITERATURE SURVEY RESUME

There are numerous papers published treating the reactor transient problem using both analytical and experimental approaches. Brief reviews of some of the available reports are given below:

MATHEMATICAL TREATMENTS

Mathematical treatments of the heat transfer problem for plate type elements are set forth by: Somers (1), LeTourneau, et al (2), Golian, et al (3), Gartner and Daane (4), and Alexander (5).

Somers (1)

discusses the thermal and hydraulic conditions that exist in the channels of a nuclear reactor when a transient flow condition exists. The governing equations are set up so that they could be programmed for a digital computer. Most of his analysis can be used for a reactor power transient. His formulation of the equations and boundary conditions indicate the heat transfer at the clad-coolant interface is by conduction only.

LeTourneau (2)

considers the transient heat conduction equation, subject to boundary conditions representing approximately a burn-out condition with heat generation constant in time.

Golian (3) & Gartner & Deane (4)

assume an exponential heat generation increase with time. They consider heat transfer by conduction only.

Alexander (5)

solves the problem of transient conduction in an unclad fuel plate with negligible surface resistance wherein simultaneous step changes are made in the volume distributed heat generation rate and the surface temperature.

INVESTIGATION OF THE MECHANISMS OF BOILING

Griffith (6)

considered the growth rate of a bubble on a surface and advances a mathematical model in light of his experimental investigation.

Zuber (8)

predicted heat transfer rates in the nucleate and the film-boiling regimes on a theoretical basis and they showed to be in good agreement with experimental data.

Rohsenow and Clark (12)

measured the heat quantity required to form a vapor bubble in a liquid, and found it to be a negligible part of the total convective heat transfer.

Faneuff, et al (19)

experimentally measured bubble growth rates and bubble sizes at various ambient water temperatures.

Green (24)

gives estimates for film-boiling coefficients using forced convection, single phase heat transfer correlations.

EXPERIMENTAL INVESTIGATIONS

Rosenthal, et al (11)

experimental investigation of heat transfer to water under transient conditions. Experiment was performed using electrically heated platinum and aluminum ribbons. The temperature attained by the surface before boiling commenced and the time delay between passage of the boiling point and the beginning of boiling were measured. Effect of exponential period on heat flux at incidence of film boiling is also tabulated.

Ulrich, A. J. (13)

discusses heat transfer information relating to the shutdown mechanism of the Borax II reactor.

Schroeder, et al (14)

the response of a heterogeneous, water-moderated and reflected reactor (Spart 1) to instantaneous reactivity additions has been studied experimentally. Plots of the typical behavior of reactor power, fuel plate temperatures and transient pressures for the tests are presented and discussed.

Egen, et al (15)

an experimental program was conducted to study the formation and distribution of vapor in a rectangular channel under boiling - heat flux conditions at 2000 psia. The void fraction is correlated with the quality and heat flux, in the vicinity of zero quality; the dependence upon heat-flux decreases with increasing quality in this region.

Dietrich, J. R. (20)

discusses the Borax I experiments, 1954.

Markels, M. et al (27)

results of exploratory experiments which were performed to determine by measurement and fast photography the observable effects of rapidly heating several types of clad metals under water.

INVESTIGATION OF BURNOUT HEAT FLUX

Investigations of burnout heat flux have been made by Jacket, et al (16), Dingee, et al (18), Debortoli, et al (25), Kezios and Lo (21), Gunther (22), and Jenns and Lottes (23). Each investigation was performed under various flow rates, pressures, coolant subcooled temperatures, and flow systems.

Griffith (7)

correlated nucleate boiling burnout data from various sources.

Bernath, L. (28)

presents a generalized correlation that predicts the burnout conditions over a wide range of conditions, but, is limited to local boiling regime for water.

Dobel, H.F. et al (29)

presents the results of in-pile heat transfer burnout tests conducted at M.T.R. Results indicate that in-pile heat transfer burnouts were about 50% higher than the values calculated by the use of an existing design correlation obtained from electrical burnout tests, but were only about 10 to 15% higher than many of the experimental points of the electrical burnout tests.

ADDITIONAL REVIEWS

Friedmann (9)

considers the influence of variation (with temperature) of thermal conductivity, density and heat capacity at constant pressure on the solutions of the heat-conduction equation.

Jones, D. H. et al (10)

results of investigation of reactivity accidents in the PWR reactor. Two accidents of consequence to the PWR are improper motion of control rods or sudden introduction into the core of cold water. Using the method of Colian, et al (3) fuel center-line temperature at shutdown vs reactor period was calculated and a plot of the

results is given in the report for both accidents.

Lipkis, et al (17)

the paper is concerned with the density response of boiling water, heated uniformly throughout the volume by dissipation of electrical energy when subjected to a sudden manyfold increase in the power input.

Redmond, R. F. et al (26)

gives approximate solutions for two start-up type accidents in a pressurized-water reactor. In both accidents, continuous withdrawal of the control rods is the method of reactivity addition.

Rohsenow, E. et al (30)

states a physical picture of the mechanism of transition to vapor binding and then postulates a "burnout" criterion.

Bankoff, S. G. (31)

extends the nucleation theory of Volmer and Fisher to the super-heating of liquids in contact with various solid boundaries.

Chang, Y. P. (32)

presents a theoretical analysis of natural convection and boiling heat transfer. Instead of approaching these problems according to a conventional concept, a short-cut method is introduced by the application of wave motion.

Hsu, Y. Y. et al (33)

results of an experimental investigation of film-boiling outside vertical tubes. The test liquids were methanol, benzene, carbon tetrachloride and nitrogen, each boiling at atmospheric pressure.

Clark, J. A. et al (34)

the paper considers the solution of the time response of the bulk temperature of the coolant at any point in a heterogeneous reactor following a transient consisting of a step-change in power level from any steady-state point of operation.

Bromley, L. A. (37)

derives equations to calculate coefficient of heat transfer to be expected in natural convection stable film-boiling. Equations are verified by experimental data.

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