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FINAL REPORT ON MIT CONTRACT
ON
FUEL-COOLANT INTERACTIONS

By

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TABLE OF CONTENTS

	<u>Page</u>
ABSTRACT.	ii
ACKNOWLEDGMENTS	iii
BACKGROUND.	iv
RESEARCH GOAL	iv
ACCOMPLISHMENTS	iv
a) The Mechanism of Molten Metal/Water Interactions (Free Drop Contact Mode)	1
b) Thermal Stress Initiated Fracture as a Fragmentation Mechanism for Ceramic Fuels in Sodium	4
c) Thermal Interaction Between Fuel Vapor and the Sodium Slug in the Upper Plenum.	7
CONCLUSIONS	9
REFERENCES.	10

FINAL REPORT ON MIT CONTRACT ON
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ABSTRACT

The work of this contract has yielded results in three areas which can be summarized as follows. The existing body of molten metal/water interaction data appears consistent with the criteria of the spontaneous nucleation theory. The observed fragmentation of UO_2 can be satisfactorily predicted using the proposed thermal stress initiated fracture model. The work potential of a hypothetical fuel vapor source acting on a sodium slug can be reduced by about a factor of two by considering entrainment due to Taylor instabilities at the vapor-liquid interface.

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BACKGROUND

The MIT Fuel-Coolant Interaction Project was initiated on October 1, 1971 and continued until June 30, 1975 under funding provided by the now Department of Energy through Argonne National Laboratory. Effective July 1, 1975 through January 15, 1978, the program was technically administered directly by the Department of Energy. Finally, from January 16, 1978 to program completion on September 30, 1978, funding was provided by the Department of Energy through the Los Alamos Scientific Laboratory. Since the goals and accomplishments of our research from all these programs form a consistent theme, this final report will cover the entire research program.

RESEARCH GOAL

The goal of this work was to contribute to the understanding of the mechanisms of fuel-coolant interactions particularly as related to the liquid metal fast breeder reactor.

ACCOMPLISHMENTS

Work was accomplished in three areas, each of which is discussed separately in the remainder of this report.

- a) The Mechanism of Molten Metal/Water Interactions (Free Drop Contact Mode)
- b) Thermal Stress Initiated Fracture as a Fragmentation Mechanism for Ceramic Fuels in Sodium
- c) Thermal Interaction Between Fuel Vapor and the Sodium Slug in the Upper Plenum

a) THE MECHANISM OF MOLTEN METAL/WATER INTERACTIONS
(Free Drop Contact Mode)

Initial efforts were directed at surveying the available studies of thermal interactions of hot molten materials and coolants - both experimental and theoretical. A central observation was the existence of a large body of molten metal/water data which underwent extensive fragmentation in the free contact mode, but was not seemingly consistent with the spontaneous nucleation theory (1). It seemed necessary to identify the mechanism responsible for this behavior to preclude the existence of an undiscovered mechanism which might be applicable to the mixed oxide-sodium system. Successful study of this fragmentation behavior appeared to be related to the dynamic behavior of the vapor film growing at the surface of the hot molten sphere when it was suddenly immersed in a coolant. Consequently, a model was developed to predict this vapor film behavior *(Report 31-109-38-2831-1TR, May, 1973). Using these results, this report further proposed that fragmentation was caused by acoustic cavitation resulting from the magnification internally of the pressure fluctuations created at the surface of the molten drop. Sub-

* This was the first published study of this problem which is of general interest to other technologies. Subsequent papers by M. Rooney and L. Burmeister, "Pressure Excursions In Transient Film Boiling From A Sphere", IJHMT, Vol. 8, pp. 671-675, (1975)., and Louis Burmeister et al, "Influence of Liquid Heat Conduction on Maximum Pressure During Transient Film Boiling From A Sphere to a Saturated Liquid", IJHMT, Vol. 20, pp. 1069-1075 (1977) have provided analytic, dimensionless solutions for this problem for the case of a saturated quenching pool.

sequent work was directed at solving the acoustic wave equation for a compressible, viscous fluid to calculate these negative interior drop pressures. This work yielded evidence of good correlation between the negative internal drop pressure trends and the known fragmentation behavior (Report 31-109-38-2831-2TR, August, 1973). To further investigate this hypothesis and determine the full character of the fragmentation behavior with the key independent variables of pool temperature, drop temperature and drop mass, a series of free contact experiments with tin and bismuth drops in water were performed (Reports 31-109-38-2831-31TR, May, 1974; and 31-109-38-2831-4TR, June, 1975; and COO-2781-7TR, November, 1976). These experiments showed that the geometry of the drop-coolant arrangement was often far from the ideal spherical geometry considered in the formulation of the theory. Also, the observed pressure fluctuations in the vapor film were less than those predicted, also inferring less than assumed pressure fluctuations in the molten drop. In view of these factors and the necessity to interpret the interaction process as a series of fragmentation steps to insure that the energy input required by the cavitation theory was consistent with that which could be reasonably transmitted from the vapor film into the drop, it was concluded that a modified theory, although it could be formulated, would appear very complex. A

report was written (COO-2781-6TR, November, 1976) to document the existing theory and the steps by which the acoustic cavitation concept could be preserved and made consistent with the available evidence. Although further immediate work was stopped on this theory, M. Kazimi renewed investigation of this theory independently in 1978, which is presently continuing. Additionally, it should be noted that a result of our experimental efforts (Report COO-2781-7TR, November, 1976) was to present a set of evidence which disproved another proposed mechanism, that of sudden gas release from the molten metal.

Immediate subsequent efforts focused on the mixed oxide-sodium system as described in the next section. With the availability of new, extensive molten tin/water data from Culham (2) and stroboscopic pictures of the interaction phenomena from UCLA (3), our interest in the fragmentation mechanism of this system was renewed and the data was extensively surveyed (Report COO-2781-11TR, January, 1977). A model was proposed for the observed upper boundary above which no self triggered fragmentation occurs on a plot of pool temperature and initial hot drop temperature. Additionally and very significantly, explanations were also advanced for the observed behavior which had for so long seemingly contradicted the spontaneous nucleation hypothesis. Here, use was made of the UCLA

photographs which showed that interaction was initiated on a region of the drop which protruded from the bulk of the droplet. Using available data on both molten drop cooling history and geometry at interaction, it was determined that the local molten fuel conditions at the interaction location were consistent with the spontaneous nucleation theory, ($T_{sn} < T_I < T_{crit}$) although it appears that once triggered, the fragmentation propagates even though $T_I > T_{crit}$. The observed trend of peak interaction pressures with drop size and coolant temperature seemed to be due to incoherency effects in the interaction and hence, did not refute the applicability of the spontaneous theory. (Report COO-2781-12TR, September, 1978).

b) THERMAL STRESS INITIATED FRACTURE AS A FRAGMENTATION MECHANISM FOR CERAMIC FUELS IN SODIUM

Analytic studies were initiated to determine the applicability of the concept of thermal stress fragmentation to the UO_2 /sodium fuel-coolant interaction. Major emphasis was put on the fracture mechanics approach to assess whether or not the solidifying UO_2 would fracture under the thermally induced stresses. It was found that the stress levels were sufficient to generate K_I values substantially in excess of the UO_2 fracture toughness, K_{IC} . Thus, rapid instantaneous propagation of inherent flaws was anticipated. Parametric studies in which the surface heat transfer boundary condition was varied did not alter this conclusion.

Extension of the thermal stress fracture concept to Al_2O_3 resulted in similar behavior. Subsequently, this material was selected as a good stimulant for use in experimental studies if the mechanism were to be experimentally tested. Additional studies led to the conclusion that thermal stress fracture was not an applicable mode of fragmentation inducement in ductile metal/water interactions. (Report 31-109-38-2831-5TR, May 1975).

With the thermal stress mode of fragmentation established as a feasible mechanism, attention was next directed at predicting the minimum fuel particle size that could survive a UO_2 -sodium and a UC-sodium interaction. The brittle fracture mechanics approach above was adopted as the basis of the study whereby stress intensity factors K_I were compared to the fracture toughness K_{IC} to determine if the particle could fracture. Solid and liquid UO_2 droplets were considered each with two possible interface contact conditions; perfect wetting by the sodium or a finite heat transfer coefficient. This analysis indicated that particles below the range of 50 microns in radius could survive a UO_2 -Na fuel coolant interaction under the most severe temperature conditions without thermal stress fragmentation. For UC with its higher conductivity, particles below the range of 5 microns in radius were predicted to survive an interaction.

It should be noted that consistent with these predicts are results from experimental fragmentation studies of UO_2 which show that sizes below 50 microns account for less than 5% of the fragmented debris. No fragmentation studies for UC have been conducted to our knowledge.

It was concluded that this analytic study seemed to verify the experimental observations as to the range of the minimum particle size due to thermal stress fragmentation by FCI. (Report COO-2781-4TR, August 1976, and (4)). However, in the light of the basic assumptions of the method, the analysis is crude at best, and can be viewed as only a rough order of magnitude analysis.

The basic complexities in fracture mechanics made further investigation in this area interesting, but not necessarily fruitful for the immediate future. Therefore, the next study was aimed at utilizing these results on minimum final particle size and time for fracture with calculations from the Argonne Cho-Wright Parametric FCI Model (5). Requirements on the minimum initial particle sizes (which are to be subsequently fragmented at a rate set by the thermal stress hypothesis) necessary to provide work potential sufficient to lift the reactor head (supplied to us as 40MW-sec for FFTF/70MW-sec for CRBR) were determined. For the CRBR UO_2 particle, sizes of 4500 μ or smaller were determined as required, indicating that the coarse mixing process before fragmentation must produce particles of this size or less to cause head lifting. Further, it was shown that then postulated incoherencies in fuel release in transient overpower accidents coupled with particle breakup times from the thermal stress mechanism led to effective mixing times far greater than those which would lead to damaging work potentials (Report COO-2781-8TR, November 1976).

Additionally, this effort introduced us to the models being used to calculate the interaction of the gaseous core on the sodium slug in the upper plenum between the core and the head. At that time, no credit was being taken for energy dissipation in the fuel vapor bubble due to hydrodynamic interactions with the sodium slug which it was accelerating. Consequently, our final studies concentrated on this area as described next.

c) THERMAL INTERACTION BETWEEN FUEL VAPOR AND THE SODIUM SLUG IN THE UPPER PLENUM

From initial work (Report COO-2781-9TR, December 1976), a model was proposed relating the mechanism of heat transfer between the liquid and the high temperature gas to liquid drops entrained by Taylor Instabilities at the moving gas-liquid interface. The key to the accurate numerical application of the model was the determination of the wavelength and growth rate of the Taylor Instabilities, since these parameters establish the characteristic size of the entrained coolant drops and the entrainment rates, respectively. Consequently, an experiment was performed to extend the Taylor Instability data available in the literature over the range of accelerations of our interest. These results indicated that the relative penetration velocity of the instability was proportional to the square root of the acceleration times λ_c , where λ_c is the critical wavelength. It was noted, however, that an additional test at an order of magnitude larger scale (i.e. approximately 4 ft characteristic length of gas/liquid

interface) was necessary to confirm the use of λ_c as the length scale. This information was then incorporated into a coolant entrainment model ($\dot{V}_e \sim A_p \sqrt{a \lambda_c}$) and applied to past small scale experiments at SRI, Purdue, and MIT.

Using this result with phenomenological heat transfer models, satisfactory predictions of the results of available small heated noncondensable and condensable tests were obtained. From the analysis of these tests, it was empirically determined that the characteristic entrained droplet size (D_d) fell within the range $\lambda_c < D_d < \lambda_m = \sqrt{3} \lambda_c$. This seems to fairly agree with recent low pressure entrainment rate measurements at MIT, but high results suggest that an additional entrainment mechanism (for example, Kelvin-Helmholtz instabilities) could be operative (i.e. at high relative velocity between the gas and the liquid [9]).

Analysis of full scale reactor conditions was then made which included consideration of radiation, coolant entrainment and coolant vaporization. The net effect of these phenomena was to reduce the expansion work of the fuel vapor by approximately a factor of 2. The interrelation between these phenomena was fully explored. While Taylor Instabilities are responsible for creating entrained droplets of a characteristic size, the fuel vapor is cooled predominantly by radiation heat exchange with these drops. Coolant vaporization effects are small due to vapor diffusion effects. It was noted that small scale simulant experiments utilizing refrigerants could confirm the postulated vaporization behavior, while reactor materials tests were necessary to investigate the radiation heat transfer behavior. (Report COO-2781-12TR, September 1978.)

CONCLUSIONS

The following comments, based on our research, are relevant with regard to current knowledge and other ongoing programs in each of the above three areas.

1. The existing body of molten metal/water interaction data appears consistent with the criteria of the spontaneous nucleation theory. However, the detailed description of the energetics of this theory (6) have not been completely resolved (7).
2. Observed fragmentation of UO_2 , when contacted with sodium, seems due to induced thermal stresses. This mechanism does not proceed fast enough, nor necessarily lead to sufficient intermixing of the particles with the coolant to lead to energetic fuel coolant interactions. However, for those situations where the fragmentation of the UO_2 needs to be modeled, this stress initiated fracture mechanism should be pursued. In such efforts, the more mechanistic views advanced in (8) of the solidification process should be considered.
3. Significant total reduction in the work potential of the hypothetical fuel vapor source can be realized by detailed consideration of entrainment, radiation, and solid structure effects. This has been recognized and is being pursued by the SIMMER code development. The physical modeling done and reported in COO-2781-12TR represents a significant source of concepts regarding liquid droplet entrainment which could be considered and tested for incorporation into the governing algorithms of SIMMER.

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