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FUEL COOLANT THERMAL INTERACTION PROJECT

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Reports and Papers Published Under
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<u>Progress Reports</u>(Available from National Technical Information Service, U.S. Department of Commerce, Springfield, Va. 22151)

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Mujid, S. Kazimi, "Theoretical Studies on Some Aspects of Molten Fuel-Coolant Thermal Interaction," 31-109-38-2831-1TR, MITNE-155, May 1973.

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Introduction

The objective of the continued work on this project at M.I.T. is to experimentally and analytically study the dominant mechanisms in fuel coolant thermal interactions which could lead to vapor explosions. Our exploration of mechanisms is focused in two areas:

a) Mechanisms responsible for fragmentation in molten metal droplet experiments (here we will include assessment of the validity of the proposed Spontaneous Nucleation Mechanism),

b) Thermal Stress Initiated Fracture as a fragmentation mechanism (this mechanism is not considered responsible for the fragmentation of molten metal drops - see Knapp's work).

Work is being performed in both these areas simultaneously and will be briefly described below.

I. Mechanisms Responsible for Fragmentation in Molten Metal Droplet Experiments

(Gautam Shiralker)

Evaluation of Gas Solubility Hypothesis

Pieces of tin were heated in a vacuum and then dropped into a coolant to observe the resulting interaction.

a) Coolant Vacuum Pump

Since oil has very low vapor pressure at ordinary temperatures, it is relatively easy to maintain a "vacuum" above it, and to drop the molten tin directly in.

The tin did not fragment in this experiment (neither does it when heated in air and dropped through air into the same oil), but was found to be pitted on its undersurface, which we thought was due to bubbles coming off the bottom of the tank when the tin contacts it.

b) Coolant-Oil, Water

An attempt was made to sustain a vacuum over a layer of oil nearly one foot in height over a depth of water, so as to prevent vaporization of water. Molten tin, heated in the vacuum, was then dropped in. The tin was still molten when it reached the water but did not fragment. It solidified on reaching the tank bottom and a few bubbles were seen coming off. The undersurface of the tin was again found to be severely pitted.

c) Coolant-Water.

The tin was heated and melted in a separate chamber at very low pressure (∿ 10 μ). This was separated from the water chamber by a trapdoor valve. Curves were plotted of the pressure in the chamber before and after heating and in this way it was insured, as far as possible, that the tin in the crucible had outgassed.

After heating the tin and bringing it to the desired temperatures the space above the water was slightly pressurized by nitrogen at a couple of psi above atmosphere. The trapdoor valve was then opened by equalizing the pressure above and below it. This was achieved by opening a solenoid valve connecting the space above the water which contained the nitrogen to the vacuum chamber. The crucible was then lowered and the tin dropped.

Fragmentation ocurred extensively and the pressure history was picked up by a pressure transducer placed some distance below it in the water. Successful runs taken to date indicate a signal very similar to those with tin heated in air - i.e. a big bang.

It seems fairly sure now that whatever is responsible for the tin fragmentation, it is not the presence of dissolved gases in the tin.

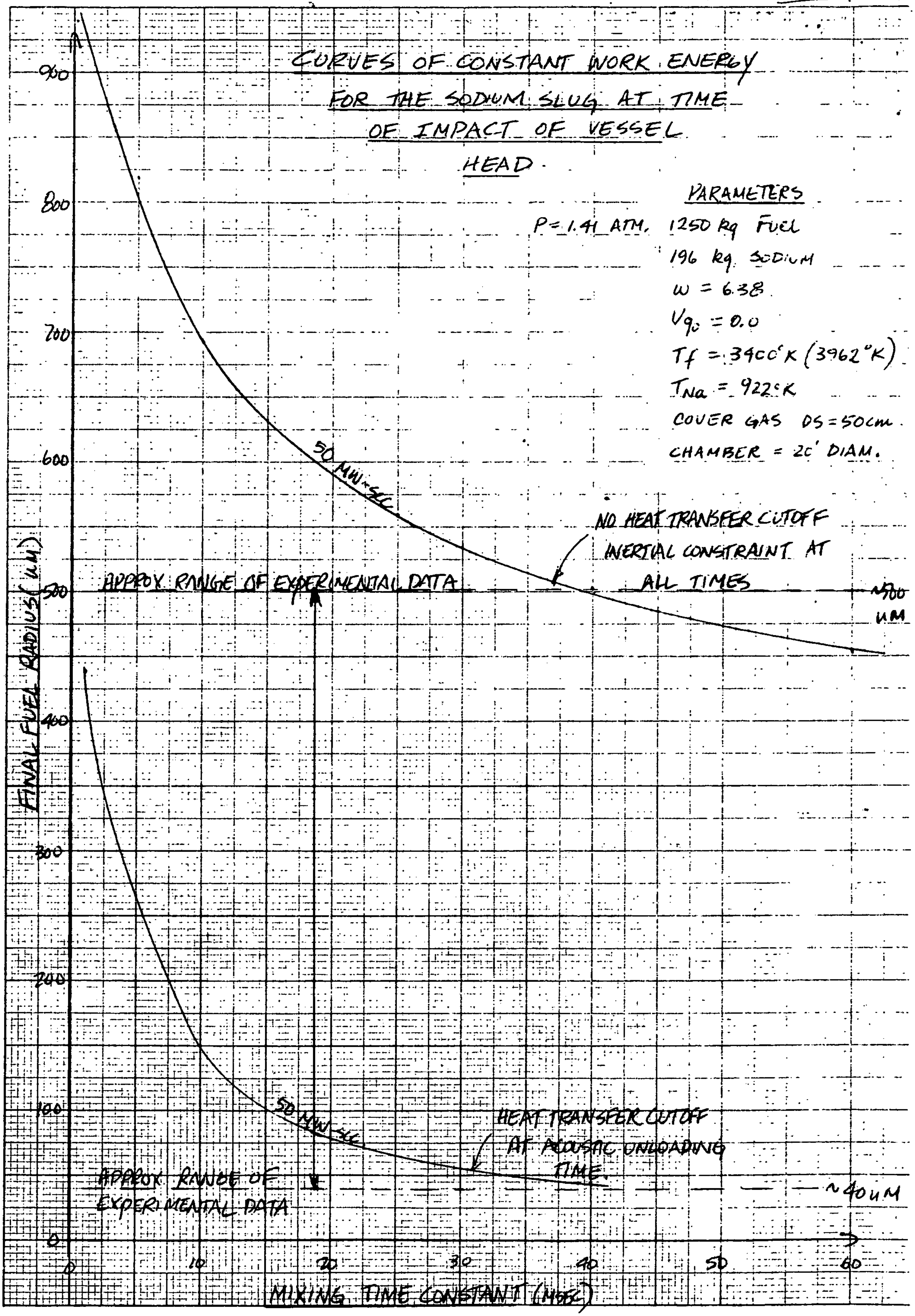
II. A. Thermal Stress Initiated Fracture

(W. Fred Lenz)

1. Introduction

The primary purpose of the research this report period has been two fold. The first goal set was to relate the maximum containable MFCI in the FFTF to two physical parameters that characterize the fuel coolant interaction. These two parameters were the final particle size of the fuel and the mixing time constant, an artificial means of dictating the rate at which the hot fuel contacts the coolant. The second goal set was to evaluate the solidification rate of a molten sphere of fuel assuming different boundary conditions. The rate of creation of solidified fuel was taken as an upper physical bound to the rate at which particles of final size could be created i.e. the mixing time constant. This analysis was performed such that given an initial fuel droplet size and an assumed boundary condition, mixing time constants could be approximated and subsequently used in defining areas of applicability in the result of the first portion of this period's work. (Figure 1).

FIGURE 1



CURVES OF CONSTANT WORK ENERGY FOR THE SODIUM SLUG AT TIME OF IMPACT OF VESSEL HEAD

PARAMETERS

P = 1.41 ATM, 1250 kg FUEL
196 kg SODIUM
$w = 6.38$
$V_{g_0} = 0.0$
$T_f = 3400°K\ (3962°K)$
$T_{Na} = 922°K$
COVER GAS DS = 50cm
CHAMBER = 20' DIAM.

2. ANL Parametric Model

To characterize the physical parameters of the maximum containable FCI, the structural limitations of the FFTF had to be understood. Based on several discussions with people at Argonne, it was decided the FFTF could probably withstand an overall vessel strain energy of 50 MW-sec. before a rapid deterioration of the vessel integrity would occur.

Calculating the vessel strain energy with time during a FCI is a difficult task. It requires, first, a model such as the ANL FCI parametric model to generate a pressure versus time curve for the interaction zone and second, a hydrodynamics code such as REXCO (also developed at ANL) to relate the pressure in the interaction zone to vessel strain. To avoid using such a large code as REXCO, it was decided that the upper limit to the vessel strain energy could be approximated by the sodium slug energy (as calculated by the ANL model) at the time of impact with the reactor vessel head.

With these assumptions, the ANL parametric model was run to provide values of the final particle size and mixing time constants that correspond to sodium slug impact energies of 50 MW-sec. The results are presented in Figure 1 for both an inertial constraint only and an acoustic-inertial constraint with a heat transfer cutoff at the acoustic unloading time of the FFTF.

3. Solidification Calculations

Two basic boundary conditions were assumed in calculating the solidification rate and subsequently, the mixing time constants for an initially molten sphere of UO_2. The first boundary condition used was a fixed surface temperature. Using the Adams' approximation, the solidification rate was calculated assuming first that the sphere remain intact and second that fuel particles of the final radius continuously broke off from the solidifying outer shell of the sphere. In the latter case, the solidification rate was faster due to the reestablishment of the fixed surface temperature on a continually shrinking sphere (Table 1). This scenario may be more representative of the actual situation due to the fact that the thermal stresses exceed the fracture strength of UO_2 in the solidifying shell.

The other boundary condition used a fixed heat transfer coefficient on the surface of the sphere. This problem was previously solved using the steady state solution of London and Seban in which the specific heat of the solid is considered zero. For the UO_2/Na system, this assumption is only good for very thin solid shells. Therefore, a numerical solution by TAO was employed to evaluate the solidification rate with a surface heat transfer coefficient. Unfortunately, if a heat transfer coefficient is chosen in the range of either nucleate or film boiling,

TABLE I

MIXING TIME CONSTANTS FOR FIXED SURFACE TEMPERATURE ASSUMPTION

Initial Radius (CM.)	Particle Breakoff	R_f	Time to Freeze Center (Msec.)	τ_M (Msec.)
0.09	No	0.005	235.3	36.2
0.09	Yes	0.005	25.5	8.0
0.07	No	0.005	142.3	21.9
0.07	Yes	0.005	19.2	6.2
0.05	No	0.005	72.6	11.2
0.05	Yes	0.005	13.7	4.4
0.03	No	0.005	26.1	4.0
0.03	Yes	0.005	7.6	2.6
0.015	No	0.005	6.5	1.0
0.015	Yes	0.005	3.3	---

TAO's method is undefined. Only when the number of grids used approaches approximately 14000 will this method provide a correct solution but at this point, the running time becomes prohibitive.

It is nonetheless evident that for the case of molten UO_2 in Na with, for instance, a nucleate boiling heat transfer coefficient, the fixed surface temperature solution is an adequate method due to the large mismatch in thermal resistances. Only when the surface heat transfer becomes quite small will TAO's solution become necessary. A criterion for stability has been established for TAO's method which is as follows:

$$U_i r_i \leq 0.011 \frac{\text{cal}}{\text{sec cm}^2\ {}^\circ\text{F}}$$

where U_i - overall heat transfer coefficient

r_i - surface radius

From this equation, a vapor film thickness can be calculated that will satisfy the criterion. However, this calculation has not yet been performed due to the lack of information for the thermal conductivity of sodium vapor at the temperatures and pressures characteristic of the interaction zone during a FCI.

IV. Future Work

Once the thermal conductivity of sodium vapor is known at the state properties characteristic of a FCI, the required vapor blanket thickness will be calculated. Beyond this calculation, the research work will continue in two directions.

The first direction will be towards the development of a computer code that will determine the values of the stress intensity factor across the solidifying shell given the assumed boundary conditions, initial sphere radius, etc.

The second direction will be a continuation of the search for mechanisms of particle generation that can be shown to bound the applicability of the ANL code results or to change the ANL model, itself, such as the inclusion of the energy dissipation effects at the interface between the interaction zone and the sodium slug.

II. B. Thermal Stress Initiated Fracture

(Michael Corradini)

The purpose of this investigation is to establish if a stress induced fragmentation mechanism can produce a particles size distribution as found from molten fuel coolant experimentation. The study treats both solid and liquid particles that could be produced during the fragmentation interaction. The constraints on the analysis will deal with two possible conditions; perfect wetting of sodium fuel interface at a fixed temperature and a variable heat transfer coefficient from fuel to sodium coolant due to possible vapor blanketing. At the present time the analytical models for the analysis have been determined and fut ure efforts will be aimed at integrating these components into a coded form. From preliminary analysis done on liquid fuel solidification interaction, the smallest particle size possible which does not fragment further is approximately of the same size as observed in experiments i.e. 50 microns. This expanded investigation will seek to verify the preliminary results and extend the analysis to solid fuel-coolant interactions.