Theoretical Analysis and Numerical Modeling of Heat Transfer and Fuel Migration in Underlying Soils and Constructive Elements of Nuclear Plants During an Accident Release from the Core

**R. V. Arutunjan, L. A. Bolshov, V. V. Vitukov, V. M. Goloviznin,
F. M. Dykhne, V. P. Kiselev, S. V. Klementova, I. E. Krayushkin,
A. V. Moskovchenko, V. D. Pismennii, A. G. Popkov, S. Y. Chernov,
V. V. Chudanov, O. V. Khoruzhii and A. I. Yudin**
FIAE, Moscow, USSR

ABSTRACT

Migration of fuel fragments and core fission products during severe accidents on nuclear plants is studied analytically and numerically. The problems of heat transfer and migration of volume heat sources in construction materials and underlying soils are considered.

INTRODUCTION

A study of probable consequences of severe accidents on nuclear plants with core meltdown and release of fission products into the environment is carried out in the framework of government nuclear safety program. A review of works made in this direction in the USA was elaborated by the special group of APS[1].

The problem of migration heat sources in the environment is very important because there always exists possibility spreading fuel fragments during the accident. Heating of significant amount of fuel resulted from residual radioactivity can be large enough to destroy surrounding materials by melting, evaporation, chemical reactions etc. Damage of containment constructions and underlying soils can lead to fuel migration upwards, downwards and in sides. The speed of migration and its appearance depend on initial fuel distribution, chemical composition of the environment, construction firmness, thermophysical properties of materials, correlation of fuel and environment densities, conditions for convection and radiation heat transfer etc. The main part of these data is unknown during accident destruction of the reactor. Lacking full information simulation of heat and fuel transfer in the unit is of a probabilistic nature. Investigation of low probability events and elaboration of reliable methods to cease the fuel migration is necessary because of catastrophic

consequences of accidents.

The problem of heat transfer and fuel migration in situations involved is essentially nonlinear and multidimensional, that's why an approximate solution can lead to wrong conclusions. So a complete numerical experiment is needed, including both analytical and computational efforts and based on mathematical models deduced from the basic physical principles and free from restrictive simplifications.

The present work includes a description of some mathematical models of radionuclide migration in soils, developed in the Kurchatov Institute of Atomic Energy in 1986, as well as some physical results, derived from these models.

INSTABILITY OF PLANE FUEL LAYER IN UNDERLYING GROUND.

1. The problem of migration of fuel fragments through underlying ground is an actual physical problem. Consider a model situation, where the fuel fragments form a plane layer. The layer pulling is a result of heating and melting of underlying ground with following filtration of lighter melted ground through the heavier fuel.

Assume that the fuel layer with thickness H and volume heat generation power q pulls down at a constant rate V_0 . The fuel, the underlying ground and the melt occupy regions $0 < Z < H$, $Z < 0$ and $Z > H$, correspondingly, in the coordinate system moving with the layer. Equations of heat conduction are as follows:

$$\begin{aligned} V_0 T_1' &= \chi_1 T_{11}', & Z > H, \\ c_1 V_0 T_2' &= \alpha_2 T_2' + q, & 0 < Z < H, \\ V_0 T_3' &= \chi_1 T_3', & Z < 0 \end{aligned} \quad (1)$$

where the prime denotes Z -derivative, χ_1 , c_1 - are thermal diffusivity; α_2 - the thermal conductivity of the fuel.

The temperature and heat-conduction fluxes are continuous through the layer boundaries $Z=0$ and $Z=H$. The bottom layer boundary coincides with melting isotherm $T=T_m$. The melting heat flux is neglected because of small parameter $\lambda_m/c_1 T_m$ (where λ_m - is the volume melting heat of the ground). System (1) have been easily integrated, and the rate V_0 is determined by

$$1 - \exp\left(-\frac{c_1 V_0 H}{\alpha_2}\right) = \frac{c_1^2 V_0^2 T_m}{\alpha_2 q} \quad (2)$$

Determine a simpler expressions for the pull down rate in two limit cases.

The first one corresponds to a sufficiently thin fuel layer pulling down at a small rate. In this case one can neglect convection heat transfer due to melt filtration in comparison with layer heat conduction. It follows then

$$V_0 = \frac{qH}{c_1 T_m}$$

The obtained expression is valid in approximation $H \ll$

$(\alpha_2 T_m / q)^{1/2}$. Note, that characteristic time of stabilization of the rate of layer pull down is larger than the heat-diffusion time for a scale of the order of the layer thickness H . The maximum temperature of the layer is very close to the ground melting temperature T_m .

In a realistic situation the temperature of fuel melt is higher than the temperature of ground melt, therefore the fuel is a solid in a sufficient thin lay.

In another limit case, the fuel layer is thick and has pull down rate.

If

$$H \gg \sqrt{\frac{\alpha_2 T_m}{q}},$$

then

$$V_o = \sqrt{\frac{\alpha_2 q}{c_1^2 T_m}}.$$

In this case the maximum layer temperature is higher, than the ground melt temperature. Thus the fuel can be believed considered as a solid, if

$$H \leq H_o = \sqrt{\frac{\alpha_2 T_m}{q}}.$$

2. Let's investigate the stability of lower boundary $z=\xi$ of the pulling down fuel layer with compactivity ε (in the undisturbed case $\xi=0$). Inhomogeneous disturbances are considered as large-scale in comparison with the layer thickness. The instability mechanism is connected with a modulation of the layer thickness caused by displacement of fuel filling relief depression of the underlaing ground. This result feeding back the inhomogeneous melting and futher modulation of ground relief. In this dynamic model we belive that at the initial stage of the instability a narrow layer of the fuel near the lower boundary, with a thickness of the order of the relief modulation amplitude takes part in the displacement. Such a case can be realized when the fuel layer adjascent to the underlying ground is less compact, so that fragments have higher mobility. Thus, the underlying ground relief is a slip surface. Fuel fragments in the depth of the layer are not displaced, because of sufficiently large internal friction. For this reason the upper boundary of the layer remains horizontal. Thus, the temperature perturbation is caused inhomogeneous melt filtration and does not depend of fuel displacement, staying near the melt isotherm. Heat-conduction equation for ingomogeneous temperature are as follows:

$$\begin{aligned}\delta T_1 + V_0 \frac{\partial}{\partial Z}(\delta T_1) &= \chi_1 \Delta(\delta T_1), & Z > H, \\ c_2 \delta T_2 + c_2 V_0 \frac{\partial}{\partial Z}(\delta T_2) - (I - \varepsilon) c_1 \xi T_1' &= \alpha_2 \Delta(\delta T_2), & 0 < Z < H, \\ \delta T_3 + V_0 \frac{\partial}{\partial Z}(\delta T_3) &= \chi_1 \Delta(\delta T_3), & Z < 0.\end{aligned}\quad (3)$$

At the lower boundary $Z = \xi$:

$$\begin{aligned}\delta T_2 + \xi T_2' &= 0, \\ \delta T_3 + \xi T_3' &= 0, \\ \alpha_2 (\delta T_2 + \xi T_2'') - \alpha_1 (\delta T_3 + \xi T_3'') &= -\lambda_{\text{III}} \xi.\end{aligned}$$

Where the two first expressions reflect the fact that the lower boundary of the layer coincides with the melt isotherm. The last expression describes continuity of heat-conduction fluxes with respect to the melt.

At the upper boundary $Z = H$ the perturbation of temperature and heat-conduction fluxes are continuous.

Solution to equation (3) is searched in the form $\delta T \sim f(Z)e^{\gamma t + i k x}$, where $f(Z)$ vanishes at infinity. In the general case this results a rather cumbersome dispersion expression. Consider two particular cases of practical interest.

$$1.) \quad \alpha_1 = \alpha_2 = \alpha, \quad \chi_1 = \chi_2 = \chi$$

If

$$\frac{q H^2}{\alpha T_m} \ll 1,$$

then

$$\gamma(0) = A \frac{\chi}{H^2},$$

where A is the solution of the following equation

$$\frac{\lambda_m}{q} \cdot \frac{\chi}{H^2} \cdot A^2 + (3 - \varepsilon)A + (I - \varepsilon)e^{-A} - 2 + \varepsilon = 0$$

Note, if $H < (\chi \lambda_m / q)^{1/2}$ (very thin layer), then $\gamma \rightarrow q / \lambda_m$.

If

$$\frac{q H^2}{\alpha T_m} \gg 1,$$

then

$$\gamma(0) = \frac{q}{(3-\varepsilon)cT_m} \cdot e^{-\frac{V_o H}{\chi}}$$

With an increase of parameter kH the increment γ decreases and if $kH=0.5$, then γ equals to zero.

2.) $c_1/c_2 \ll 1$. Volume heat capacity of the ground is essentially less than the volume heat-capacity of the fuel.

If $k = 0$, $H^2 \ll H_o^2$, then

$$\gamma(0) = \beta^2 \frac{\chi_2}{H^2}$$

where β is the solution of equation

$$\text{th}(\beta) + \sqrt{\frac{\chi_2}{\chi_1}} - \frac{1}{\beta} = 0$$

If $\chi_2 \gg \chi_1$, then

$$\gamma = \frac{\chi_1}{H^2} (1 - 3k^2 H^2).$$

3. Investigation of instability of the lower boundary of a pulling down fuel layer demonstrates that the perturbation with $k=0$ has the maximum increment at fixed thickness of the layer. The obtained dependence of the increment on the layer thickness H can be easily interpreted. At the region $H < (\chi \lambda_m / q)^{1/2}$ modulation of the lower boundary with amplitude ξ causes additional surface heat source with intensity ξq . This heat source gives rise to inhomogeneous melting $\xi \lambda_m$ and heat conduction flux

$$\propto \sqrt{\frac{\gamma}{\chi}} \nabla T \xi$$

If $H \rightarrow 0$, then $\nabla T = \frac{V_o}{\chi} T_m \rightarrow 0$, because $\gamma \rightarrow q/\lambda_m$. If $\chi \lambda_m < q H^2 \ll c T_m$, then the increment is determined from the balance equation.

$$q \xi = \propto \sqrt{\gamma/\chi} \cdot \nabla T \xi.$$

This gives

$$\gamma \propto \frac{\chi}{H^2}$$

Note, that in this range of H the perturbation growth rate $\gamma \xi$ does not depend on parameters q and $c T_m$ like the pull down velocity. This is because the characteristic time of instability is less, than the time of pull down velocity stabilization H/V_o . Another case corresponds to large $H > H_o$. Here the increment is exponentially small and determined by dependence of disturbance of homogeneous pull down velocity with disturbance of layer thickness.

NUMERICAL SIMULATION OF THE PLANE LAYER INSTABILITY AND FUEL CONFINEMENT IN THREE-DIMENSIONAL GEOMETRY.

The nonlinear phase of instability of ground melting by plane fuel layer and interaction of a single fuel fragment were

investigated numerically. For this special thermalphysical codes were written in which the following processes were taken into account:

1. Transient heat transfer in one, two and three dimensions caused by the dependences of the specific heat on temperature and spatial.

2. The motion of bodies pulling down through the melt, fuel intermixing in melt due to dissolving and convection, thermal convection, vaporization of active parts while heating the fuel, and subsequent condensation (absorption) while cooling the fuel.

In the framework of thermal model the motion of pouring bodies in a melt is simulated as fall of a thermal source on the melt bottom provided by a fuel volume and power density are constant values. Process of intermixing is simulated by distribution of volume thermal source in the melt.

Thermal convection caused by high temperatures (greater than the melt temperature) is described by effective heat transfer coefficient. The phenomena of vaporization and flux motion are described by introducing negative sources in the heat transfer equation. The influence of the negative source is pronounced when the temperature is greater than boiling point.

We used two techniques for numerical solution of two-dimensional heat transfer equation. These techniques are described in [2,3]. The results obtained with the help of these two techniques are close each to other. For three-dimensional problem the method [3] was used.

The results of calculations show that the instability process very quickly (for the time of the order of $0.1t^*$, where t^* is the characteristic time of layer displacement to the depth compared with its thickness) comes to the nonlinear phase. Nonlinear phase of melting dynamics is essentially depended on the initial temperature, amplitude, and disturbance scale and the directions of fuel fragment motion.

Based on numerical results consider some of the possible ways of fuel behavior in the nonlinear melting phase.

Cosine perturbation with amplitude $\delta=0.2$ cm and wave length $l=48$ cm is laid upon the lower boundary of the flat layer with thickness $h=1$ cm and energy release power $q=0.3$ wt/cm³. It is assumed that heavy fuel parts fall on the melt bottom. According to the results of linear analysis such a layer should be stable. But the linear theory considers perturbation of steady-state one-dimensional melting front. If the initial perturbation is not one-dimensional, the stabilization time can be equal or even greater than the evolution time of two-dimensional perturbations. In this case instability evolution is very sensitive to initial condition.

If initial conditions correspond to a stable phase of one dimensional melting the current perturbation decays with time. But if in the beginning the melting zone is absent then another picture is observed. Initial temperature of the fuel and the medium is 700°K. Melting begins in a zone of maximum thickness owing to the space heterogeneity of the layer. Fuel migration is possible only in the melting zone. Characteristic melting time is comparable with the time of heating the remaining fuel parts to the up melting point. Under these conditions a single drop is separated from the point of maximum layer thickness and its independent motion begins.

While heating the remaining "solid" fuel part, another drop

can be generated. This drop moves in a hotter medium compared with the first one and at eventually overtake the first drop. Thus initially immovable perturbed layer has a tendency to split into several drops which can later accumulate in more complex structures.

The size of the first separated drop practically does not depend on the perturbation wave length if the latter greater than 6 cm. If the wave length λ equals 6 cm the first drop "consumes" the main part of the fuel layer. And as a result of thermal interaction the neighbor drops accumulate together and a stationary layer is formed again. The time of drop tearing off is equal to 4 days 1 hour 30min. At the moment 4 days 10 hours 30min the whole layer is restored again.

The three-dimensional simulation of confluence of two drops was carried too. Initial form of the fuel drops is a cube with the side of 10.5 cm. The distance between them is 21 cm. Energy release power q equals 0.5 w/cm³, initial temperature is 321°K. The total confluence of two drops occurs in about 25 hours. Analogous calculations for two-dimensional case show that the confluence time is 16 hours.

RELIABLE STOPPING SYSTEM STOPPING AND SPREADING OF LARGE VOLUMES OF FUEL OVER COOLING PLATE.

The two-dimensional program for solving heat transfer equation with moving heat sources has been used to simulate fuel fall on a cooling trap plate. We show the results of numerical simulation of fuel fall on the system of parallel pipes for spacing 30 cm. In this case the break of safety system has taken place. If the pipe spacing equals 26 cm the front of the melting fuel is stopped at the distance 1 cm from the surface of cooling pipes. It is assumed that the pipes are placed in sand or concrete with heat transfer conduction 0.02 w/cm.grad.

The absence of fuel spreading through the closely placed pipes is related with effective cooling the fuel "tongue" after its displacement by a distance of the pipe radius.

Thus, the fuel confinement by a system of parallel pipes essentially depends on the spacing between them. Even if this structure cantake away the total heat flux from the falling uniform fuel layer, the fuel melt will spread down transforming into separate "tongues" provided that the spacing is greater then critical value, wich depends on the pipe diameter. For the diameter of 200 mm the spacing should be less than 26 cm.

Then dynamics of fuel falling on the pipe cooling safety system with required spacing or on a flat cooling surface was investigated. After fuel melt front stops at a distance of the order of several centimeters (it depends on the thermal characteristics of the medium: from 1 cm in sands to 4 - 5 cm in concretes) fuel spreads along the horizontal surface of the cooling plate due to concrete or sand melting at the side walls of the fuel.

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