CONF - 790519--5

MASTER

EUROPEAN NUCLEAR CONFERENCE

May 6-11, 1979, Hamburg

USE OF A MOVING HEAT CONDUCTOR MESH TO PERFORM REFLOOD CALCULATIONS WITH RELAP4/MOD6

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RELAP4 is a computer code which can be used for the transient thermal hydraulic analysis of light water reactors and related systems. Various versions of the RELAP4 code are widely used throughout the world for experimental system analysis, reactor design, and nuclear system safety studies. RELAP4/MOD6[1] is the current version of the code which is available to the public through the National Energy Software Center at Argonne, Illinois and from the OECD/NEA Computer Program Library in Paris. RELAP4/MOD6 includes many new analytical models which were developed primarily for the analysis of the reflood phase of a PWR loss-of-coolant accident (LOCA) transient. The key feature forming the basis for the MOD6 reflood calculation is a unique moving finite differenced heat conductor. This paper will describe the development and application of the moving heat conductor mesh for use in reflood analysis.

The moving mesh provides for detailed heat transfer calculations in the vicinity of a moving reflood quench front. User-defined coarse heat conductors (heat slabs) that are used to represent core fuel pins or hot vessel walls in a LOCA simulation, are partitioned or sectioned into fine heat conductors during the quenching process. This refinement is desirable in view of the extensive variation in local fluid conditions that occur over the narrow quench region. The quench front detail obtainable in previous versions of RELAP4 was fixed by input through an upper limit of 50 heat conductors available for an entire problem. With the moving mesh, the degree of heat conductor refinements is a user option limited only by the memory capacity of the computer.

Typical instantaneous partitioning of a stack of coarse heat conductors and corresponding typical surface temperature profile are illustrated in Figure 1. Note that the actual mesh consists of a lower medium or intermediate mesh group, a fine mesh group, and an upper medium mesh group. The overall length of each region and the length of the intermediate and fine mesh conductors are specified by the user. The moving mesh model is quite general in application in that several moving meshes can be active simultaneously in various core channels.

The fine mesh partitioning shifts so as to follow or track the movement of the reflood quench front. The mesh will advance up or down a heat conductor as required to track the quench region. At each time step during a transient simulation the finite difference mesh is repositioned such that a fixed point within the fine mesh grid coincides with the point of critical heat flux (ΔT = 33K). When the quench front advances to a point exceeding one half of a fine slab height (DZF) beyond the tracking point, the mesh shifts up a distance of one fine slab height by slicing a fine slab from the lowest slab of the upper medium group. Simultaneously, the bottom slab of the fine mesh group will be absorbed by the lower medium slab group. As this process continues additional fine slabs are created from the upper medium slab group and the lower medium slab group grows in length by absorbing the bottom slabs from the fine group. If at any point, the length of the upper medium group is less than the user-specified minimum (SMINUP), the upper medium mesh will be extended through the next nonpartitioned coarse slab. Similarly when the length of the lower medium mesh extends beyond the minimum user-specified length (SMINLO) by the height of a coarse heat conductor, the medium mesh slabs will be recombined to form a coarse slab. Whenever a coarse slab is newly partitioned or a new fine slab is created from a medium slab, values of the thermal properties and temperatures are determined through interpolation. This movement of the mesh and the storage of associated data arrays is accomplished efficiently through the use of dynamic storage allocation and chaining techniques. Computer graphics can be used to display the mesh position or quench location as a function of time.

RELAP4/MOD6 performs, during each time step advancement, a one-dimensional transient radial heat conduction calculation for each coarse and moving mesh heat conductor. The actual model is based on the HEAT-1 code[2]. The general one-dimensional transient radial conduction equation

$$\rho C \frac{\partial T}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(Kr \frac{\partial T}{\partial r}\right) + q'''$$

where

ρC = volumetric heat capacity

T = temperature

t = time

r = radial co-ordinate

q''' = heat generation per unit volume

K = thermal conductivity,

is differenced and the resulting tridiagonal matrix is solved by elimination and back substitution. The fluid side boundary condition or heat flux expressed as

$$KA \left.\frac{\partial T}{\partial r}\right|_{r=R_o} = hA\,(T_N - T_{FLUID})$$

where

A = surface area

R_o = radius of heat conductor

h = surface heat transfer coefficient

T_N = node temperature at conductor surface

T_{FLUID} = fluid temperature adjacent to rod is resolved through iteration with a set of heat transfer correlations[3] applicable for reflood. If nuclear fuel rods are being simulated, simple fuel models[1] are available to the user to model fuel rod thermal and pressure response including gap conductance, metal water reaction, and fuel rod swelling.

To take full advantage of the fine mesh partitioning for calculating heat conductor thermal response, local fluid conditions must be used to compute the local heat transfer coefficient h. This has been accomplished by defining pseudo fluid control volumes in the core channel adjacent to each fine, intermediate,and coarse mesh conductor. This pseudo fluid control volume mesh moves with the moving heat conductor mesh to yield additional hydraulic detail in the vicinity of the quench region. For the purpose of computing local fluid conditions, the core is broken into a liquid region and a two-phase dispersed region. Entrainment of liquid is determined by computing the net vapor generation within the liquid region. Within the two-phase region steady state liquid and vapor heat and mass balances are performed over each pseudo volume beginning at the point of entrainment initiation and proceeding to the core outlet. This calculation results in a local quality, local mass flux, and local superheated vapor temperature which are then used in the heat transfer correlations for determination of the heat conductor boundary conditions.

The RELAP4/MOD6 moving heat conductor mesh model has been used to calculate quench phenomena for forced and gravity feed reflood experiments as well as PWR reactor systems. Comparisons of code calculated clad temperature with test data from FLECHT, Semiscale, and PKL have been presented elsewhere[4,5,6]. A detailed discussion of the code calculated moving mesh quench transient has not previously been presented. Figure 2 compares the moving mesh calculated quench point and collapsed core liquid level with experimental quench data for a RELAP4/MOD6 simulation of the German PKL gravity feed Test K5A. A brief portion of the complete reflood transient is shown for clarity. The curves indicate several important points. First, as is typical of most simulations of gravity feed reflood experiments, core mixture level manometer type oscillations were calculated to occur. Second, the RELAP4/MOD6 moving mesh model tracks both the advancing and the receding quench fronts that occur during the oscillatory reflood process. Third, the moving mesh calculated quench front agrees well with the smoothed experimental quench data. Experience to date with the RELAP4/MOD6 reflood model has indicated that although reflood turnaround time and quench time may not be as well predicted, the code generally provides a good estimate of the peak clad temperature over the length of the core.

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2. R. J. Wagner, HEAT 1 - A One-Dimensional Time-Dependent or Steady State Heat Conduction Code for the IBM-650, IDO-16867 (April 1963).

3. R. A. Nelson, L. H. Sullivan, "RELAP4/MOD6 Reflood Heat Transfer and Data Comparison," paper presented at the CSNI-Specialists Meeting on Transient Two-Phase Flow, Paris France, June 12-14, 1978.

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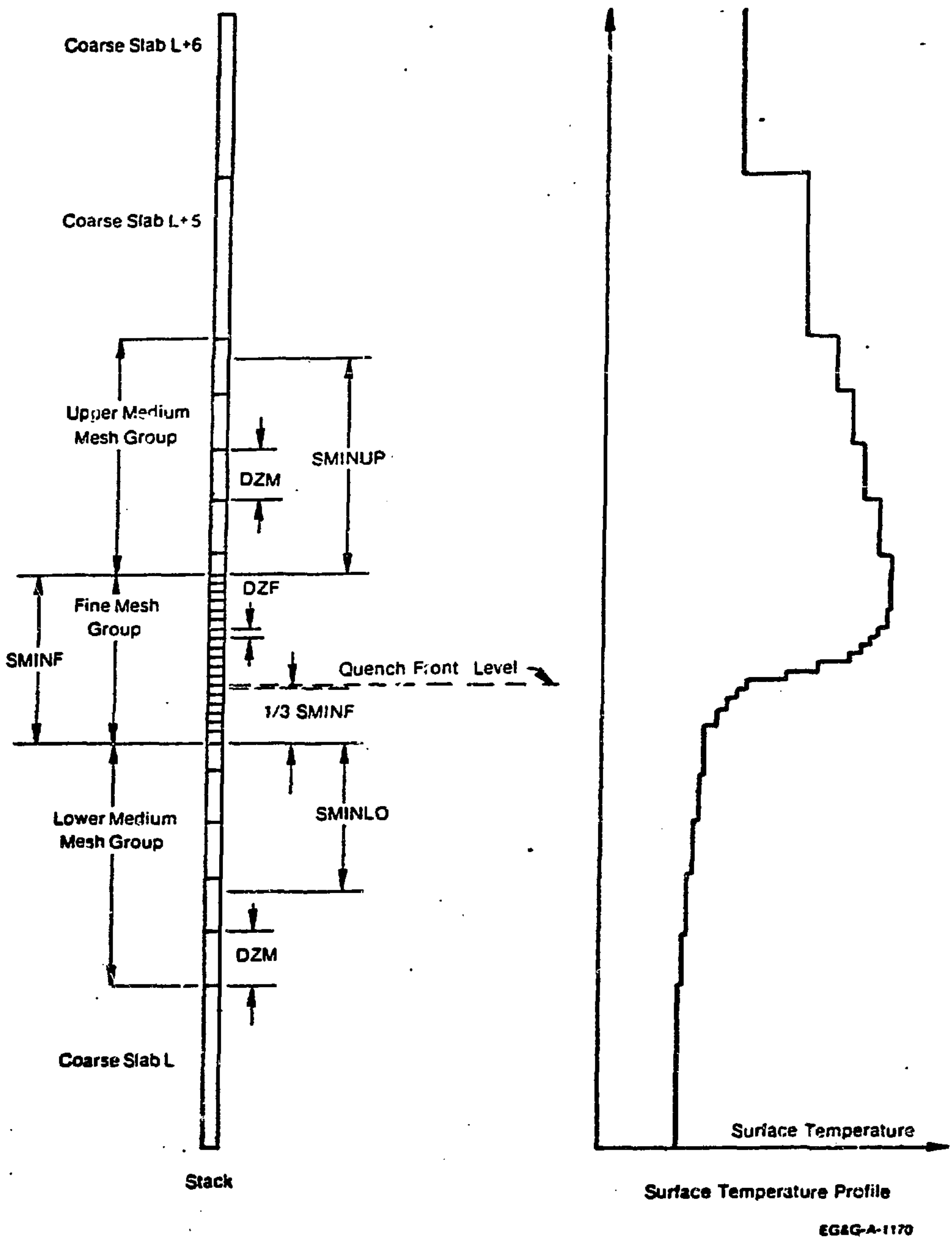

Fig. 1 Model stack of core heat slabs with moving mesh sectioning.

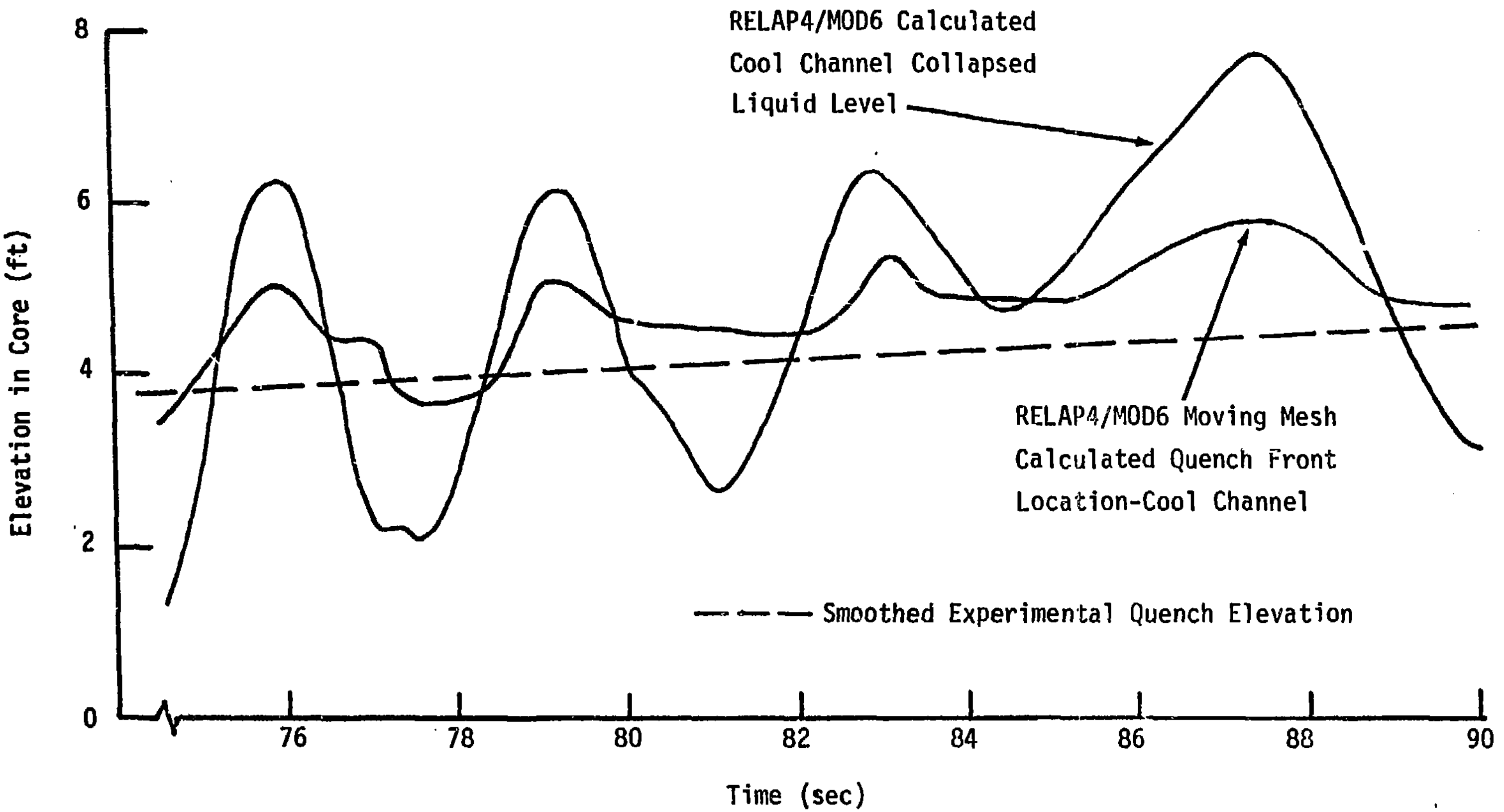

Fig. 2 Quench front propagation during reflood for PKL test K5A