Rec'd 2/1/73

CONF-730304--2

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Atomic Energy Commission, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

LOCA MODELING ON THE HYBRID COMPUTER

R. S. Stone *

Oak Ridge National Laboratory
Oak Ridge, Tennessee

MASTER

ABSTRACT

The hybrid computer is a working, symbiotic combination of an analog and a digital computer. The combination offers unique advantages in speed and stability when used for the analysis of large space-time dependent systems. Application to the fuel pin heatup problem addressed by the digital code THETA has produced a fast running, flexible alternative for looking at LOCA-related problems.

DISCUSSION

As we all know, LOCA computer programs for water reactors have been highly visible for the last several years. They have been written, run, criticized, duplicated, discussed, and corrected to the point where this rather specialized discipline is now indecently familiar to the nuclear community. This is not to say that the ultimate programs have been realized, but efficiency and credibility have been, and continue to be, steadily improved. I feel the hybrid computer has a logical place as an element in this process, and this I shall attempt to demonstrate.

*Work sponsored by the U. S. Atomic Energy Commission under contract with the Union Carbide Corporation.

MASTER

The hybrid computer represents more than an excuse to smuggle a digital computer into the laboratory of a die-hard analogist, or to sanitize the presence of an analog computer within the sacred walls of a digital computation center. Digital and analog machines do have things to say to one another, and I would like to tell what these things are in the context of blowdown heat transfer. The advantages of the hybrid over the all-analog calculation can be crucial. The simulated system can be far larger, the accuracy greater, and data from the early part of a run can be remembered and applied later on. What then are the advantages over the all-digital calculation? The analog or hybrid program is almost always faster running, and for equivalent capability the hybrid machine will be considerably cheaper. Depending on circumstances, these may or may not be important considerations. Interaction of the engineer with the program is easier where an analog machine is involved, and can lead to expanded insight into the system under study. Alterations tend to be more easily accomplished in a hybrid than in a digital program. This is mainly because the analog compartmentalizes the component parts of the system, and one can go into such a compartment and make changes without affecting the rest of the program.

This then explains why we went to a hybrid model of LOCA heat transfer. We basically wanted a fast-running program, a flexible program, and one which permitted hands-on manipulation. With these objectives we adapted the digital code THETA-1B to the hybrid computer.

Adaptation of an existing program has advantages and drawbacks, both fairly obvious. The advantages are that one has an existing computational framework to start from, and a built-in means for checking final results. The latter is particularly important for a new program. Moreover, a hybrid program is sufficiently diverse that it represents a useful independent check of the digital coding. The main drawback is that one is in a sense duplicating an existing capability. In our case, the consideration which overrode this objection was the many hour

running time with which the THETA of two years ago was afflicted. It was felt that the hybrid's anticipated reduction in running time was sufficient justification for some repetition of coding.

The THETA code is a two-dimensional representation of a fuel-pin, azimuthal symmetry being assumed. In the hybrid model, individual analog hardware is provided to simulate behavior at various nodes in a single axial slice of the fuel pin. Figure 1 shows circuitry for 3 nodes of thermal diffusion in the fuel. Non-linearities in the equations involved are handled by frequent resetting of the analog coefficient devices. Heat transfer coefficients and thermal capacities are functions of temperature, and so must change as the transient progresses. This is done by sampling the nodal temperatures at frequent intervals ranging from a few milliseconds to a few hundred milliseconds, and feeding these temperatures to the digital computer for calculation of heat transfer coefficients, and other temperature dependent terms. Note that each of these nodes is constantly seeking equilibrium with each of the others. As input power drops following the break-induced scram, it drops simultaneously at each node, and differential temperatures are taken between temperatures which are simultaneously dropping. There are no problems of time skews, and no iterations to develop a consistent set of temperatures. The only iterations required are encountered in the steady state, where a few resettings may be required to find a set of temperature dependent parameters and temperatures which are mutually consistent.

Continuing radially through the axial slice of fuel pin, analog hardware is supplied to simulate heat transfer through a gas gap, the same through the clad, and into the coolant. Differential expansion of the fuel and clad are provided for in calculating the gas gap conditions. In the clad, provisions are made for heat storage and property alterations due to change-of-phase. In the coolant, heat balances are made for fluid transport, conduction from the clad, and for change of phase. In this part of the circuit, coefficients representing heat transfer from the clad are changed by the digital computer as change in phase or heat rate indicate change in correlations, or as dictated by change in flow rate, pressure, quality, or other process variable. None of these features is unique to the hybrid program; all come directly from the digital formulation. What is unique to the hybrid is the simultaneous display of and interactive equilibrium among all of the heat transfer nodes making up one axial slice of fuel, clad, and coolant. Such a computational arrangement is extremely important in gaining on-line familiarity with the behavior of the system, and in making the stability of the computation more nearly approach the stability of the prototype. Figure 2 provides a simplified illustration of this. Suppose we have a small element of coolant, assumed to be well-mixed so that the mean temperature is the same as the outlet temperature. Heat is being added at such a rate Q as to be exactly in balance with the heat removal represented by the mass flow $\dot{m}$ and the ΔT between inlet and outlet temperatures. Suppose now that our calculation creates a ΔQ increase in the heat input. In the reactor itself, such an increase in Q initiates an immediate upward ramp in ^{cell} temperature T_i , and

through the inverse feedback effect of T_i in Eq. (1), the rate of increase is reduced. In the analog circuit, the same condition holds. In integrating Eq. (1) to obtain T_i , the T_i used in the integrand is a continually changing dynamic quantity, helping to generate its own rate of rise. [In the same context, Q is also a continuous function of T_i , since in general $Q = hA(T_{\text{clad}} - T_i)$. Hence, from this relation as well, a rise in T_i tends to reduce its own rate of rise.]

Now consider the case of where Q rises in the digital code. By the nature of things, in calculating $\dot{T}_i$ with Eq. (1), T_i must remain constant at its last previous value. Since this is smaller than the now increasing T_i , the heat swept out by the fluid flow is underestimated, and $\dot{T}_i$ comes out too large. This effect is added to that which reduces Q as T_i increases. At the end of the time step, T_i is calculated as $\dot{T}_i \Delta t$, and comes out too large. This too large T_i is plugged into Eq. (1), and the equation for Q , and of course leads to underestimating $\dot{T}_i$ in the next time step, so that this time T_i comes out too small. There are various ways of handling this: one tries to keep the time steps small; one has schemes which set T_i equal to the average of some number of recently calculated values; or perhaps other schemes. The fact remains, control systems with built-in delay in response tend to be unstable, and what we have here is essentially a control system. This of course is just one small part of a large system which is loaded with feedback loops of this kind. An ideal analog system would provide continuously varying coefficients for all parameters. Unfortunately, this ideal is precluded by the complexity of some of the formulations, but in general the coefficients do not change as abruptly as do state variables like temperatures and enthalpies. In some cases, of course, coefficients can change abruptly in the middle of a time step. An example is where the heat flux reaches CHF, and hence should drop to a clad-to-water heat transfer coefficient which is representative of film

* As another example,
boiling. ^r Rates of change of specific volume are drastically altered when the coolant node starts boiling, or when it reaches 100% quality. If these events take place during the middle of a time step, and the relevant coefficient devices are left set at their suddenly obsolete values, the sets of variables involved can achieve inconsistent values, even for a short time step. This can introduce a sudden glitch in the output when the time step ends and the machine is faced with the results of its fragmented vision. In order to avoid this phenomenon, we continually monitor the state of such critical parameters, and when they cross a point of inflection in the middle of a time step, we stop the music. The digital processes are interrupted, the analog goes into HOLD, and the time step is not allowed to proceed until those coefficients which have experienced an abrupt change have been suitably reflected in hardware settings.

What I have been saying is that the long computing times sometimes required by an all-digital code, and the instabilities that such a code sometimes exhibits, are usually due to the unavoidable use of noncurrent values for all variables, including the one you are currently in the process of changing. Most of the time a few iterations converge these discrepancies to insignificance, but sometimes they do not, and a machine which calculates everything in parallel, with all variables continuously updated on the basis of the latest values of all other variables is going to have a great advantage in speed and stability.

Of course, eventually you run out of hardware from which to create all these simultaneities. In the case of our THETA program, it takes over half the hardware complement to create one complete axial slice of the simulation. Our procedure is therefore to multiplex this hardware slice, stepping it along the length of the pin, using digital programming. During the course of a blowdown event, the coolant runs first one way, and then the other, through the core. Under the present ground rules, it is only presumed to run in one direction at a time, however, and this simplifies programming. We run the axial slice which is nearest to the inlet end until our

input data tells us that the flow is about to reverse. During this run we have been storing each node's ~~constant~~ outlet enthalpies in the digital memory, ^{enthalpy, for storage} ^{At the end of the run} and now we move on to the next axial slice downstream, using the stored outlet enthalpies from the preceding slice as input data. This goes on until we get to the outlet end, which when finished now becomes the inlet end as flow reverses. This is a straightforward procedure, and results in efficient use of the analog hardware.

It was our intention to make our program equationally identical to digital THETA, at least to begin with. This approach would exploit the existing program formulation, and would provide the optimum arrangement for checking results. The staff at Idaho Nuclear were most cooperative in supplying us with their equations and physical constants as a starting point for the hybrid program. Our version did not turn out to be a completely paint-by-the-numbers copy, however. In a few areas, we did not have the complete model, and wrote in our own approach; in a few more we added what we felt were minor improvements; and in a few places the differences between digital and analog capabilities dictated some changes in procedure. The proportion of such alterations to the whole was quite small, however, and what we have is indeed THETA, with some minor and identifiable variations.

Because of this situation, the results of our first runs were quite interesting. The input data were taken from a 100 percent inlet break blowdown case, run on RELAP by Idaho Nuclear. This is in effect a benchmark problem. When we got Idaho's results for comparison, we found that the hybrid was reproducing the qualitative shape of the curves very well, but that our peak temperatures were several hundred degrees lower. There followed several interesting weeks of tracking down the causes, which all turned out to be in the formulation of the program. Once our input errors were taken care of, and differences which turned out not to be different were resolved, there still remained a discrepancy of about 100° in peak clad temperatures. Figure 3 shows a comparison of outputs. The solid curve is taken from the digital output, the dashed

curve from the hybrid. I emphasize that these differences are due to the models, not to the machines.

Figure 4 shows a comparison where we reprogrammed the hybrid to get rid of the differences between the two programs. Here the fit is quite good. The source of the discrepancy in Fig. 1 lies in two areas: the treatment of fuel expansion, and the pool boiling heat transfer correlation.

Figure 5 shows identical programs except for the fuel expansion. Our model leads to a narrower gas gap, and consequent lower initial fuel temperature. Figure 6 shows identical programs except for the treatment of the pool boiling correlation. The difference between the formulations makes one version higher for one pressure range and the other higher elsewhere. In the interim, the decision has been made to go to a different correlation entirely, so this is a moot issue. The fig. does point up the fact that the choice and treatment of a heat transfer correlation can be very important. ✕

We feel that the develop-

ment of this parallel computational

method, making full use of an al-

ready developed program formula-

tion, ^{provided a valuable trial} has been ~~well worthwhile~~ as ^{of the hybrid approach, and an interesting} ~~a verification~~ and check of an

existing program. The original

incentive was, however, to speed

up operations. At the time we

began our program, THETA was reportedly taking 7 to 9 hours to run. This was obviously a great impediment to its frequent and effective use. On the hybrid, actual program time is about 2 minutes, though tape shuffling adds another 7 minutes to this. So our objective of a fast-running THETA was realized. I must hasten to add that the last I heard, reprogramming of the digital code has reduced running time to an hour and a half on the 360/75, and recent results on the ORNL 360/91 indicate running times of 12 or 13 minutes, about the same as on the hybrid machine. Advantages remaining to the hybrid are its much lower cost, immediate turn-around, and hands-on operation.

At this time, the THETA code is in the process of being phased out. As I understand it, the people at Idaho Nuclear are absorbing THETA into an expanded, more detailed blowdown code, which will run blowdown and heatup as concurrent instead of consecutive processes. In our operation we are expanding the program in the other direction, keeping the dedication to heatup, but creating a multipin heatup model, so as to permit an investigation of the effects of such things as flow blockage. This is the history of most computer programs, which tend to have finite lifetimes. The approaches learned, however, should continue to be applicable, particularly

as space-dependent programs become larger and more detailed. The hybrid approach has been demonstrated to be an effective means for important and involved investigations.

The contribution of Francis H. Clark of ORNL, who wrote the digital portion of the hybrid program, and was an equal partner in its running, must be acknowledged, as well as the invaluable assistance of a number of individuals at Idaho Nuclear Corporation, principally Carl Hovevar and Jay Larson, who were most cooperative in supplying details of their digital program THETA1-B.