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EXPERIENCES WITH THE FIDAP CODE IN ANALYSIS OF A NATURAL CONVECTION PROBLEM OF AN LMR PRIMARY HEAT TRANSPORT SYSTEM*

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DISCLAIMER

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ABSTRACT

The Experimental Breeder Reactor II (EBR-II) at Argonne National Laboratory (ANL) West in Idaho is currently undergoing a plant closing operation, and a number of technical issues need to be addressed. This paper is related to the heat transfer analysis support effort performed for the upcoming draining operation of the primary sodium from the primary system tank. The issue addressed was how much of heat input would be required to the sodium if it were to be maintained in the liquid state during the prolonged period of the draining operation. The fluid dynamics analysis package FIDAP Code of Fluent Incorporated was used to model the primary tank system.

It was possible to obtain solutions to the model in most of the cases considered, which provided the needed information for the project. However, certain appropriate choices of the solution algorithms were necessary in certain cases and in addition certain special measures had to be followed in order to successfully realize the solution. In certain other instances, only some entirely different algorithm was the only successful choice, while in some other limited instances none of the algorithms or the special measures that were satisfactory for the earlier cases proved successful. Several configurations of the model with varying sodium levels to represent the quasi-steady state draining operation are considered. The reference configuration of the model was first calculated and the results are compared with measurement data. The model thus benchmarked to the reference case then was calculated for other model configurations.

This paper discusses details of the experiences we gained, including successes, the difficulties we had to overcome, and in some instances the eventual failures. The results of the successful calculations are first presented. For each of the model configurations calculated, various computational aspects are then discussed in view of the numerical stability, convergence, and robustness of the solution algorithms in use. Finally, effects of certain model simplifications on the solutions and performance of the solution algorithms are discussed.

INTRODUCTION

The fuel assemblies in the reactor core and many of the major primary heat transport system components have been removed in preparation for draining of the sodium from the primary tank. The primary heat transport system EBR-II is shown in Fig. 1. The sodium is presently heated and maintained in the liquid state by six electrical heater assemblies that are immersed in the sodium. The draining of sodium will take place over an extended period of time and the concern is that the heater elements may overheat as they become bare and fail prematurely. The operational question then was what minimum heater power would be required to keep the sodium in the liquid state. Only a limited number of heater elements are available for replacement.

As can be seen from Fig. 1, the EBR-II primary tank system to be modeled is quite complicated. To include all of the details in the model would not only require an extensive modeling effort but also will not be necessary for the purposes of this work. Hence a simple model was developed to represent the overall heat transfer behavior of the system in such a way that the model is consistent with the instrument readings and other documented technical data in the present configuration. In the present configuration prior to the initiation of the draining process, the sodium is in its maximum depth and cover gas in its minimum height. The reference configuration of the FIDAP model representing the current system configuration was first calculated and the results compared with the instruments readings and necessary modifications were made. The model thus benchmarked then is used to calculate additional model configurations representing various stages of the draining.

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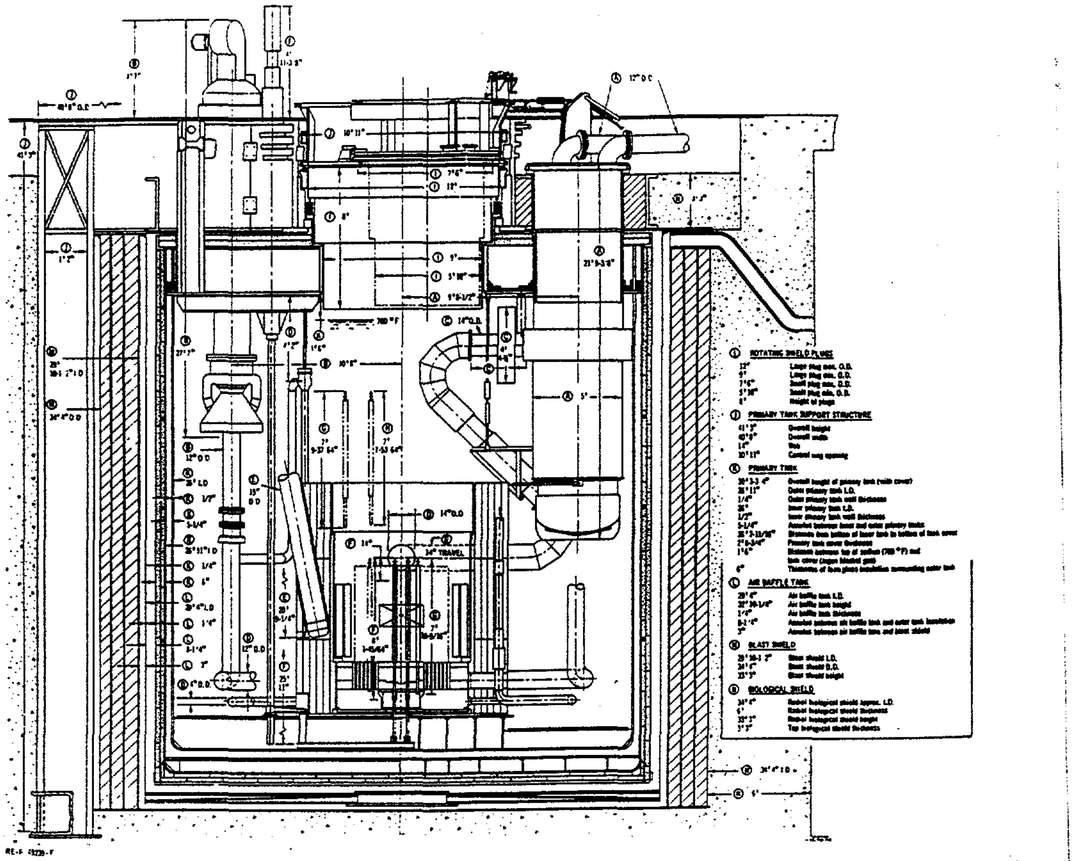

Fig. 1. EBR-II Primary Heat Transport System

In what follows, details of the basic FIDAP model and the various configurations representing the various draining operational stages are first described, followed by presentation of the calculation results for each of the three model configurations. Details of the solution algorithms and other choices of related options we selected for obtaining these results will then be discussed. There were a number of unsuccessful calculations we attempted in certain other model computations and of these unsuccessful attempts will next be discussed. FIDAP Code offers a number of alternative solution methods for any given problem. In the course of this work, various solution methods have been tried to obtain the valid solutions to the problem. Results of these efforts are discussed in detail in view of the stability, convergence, and robustness of the particular solution methods and also for the problem being solved.

EBR-II PRIMARY HEAT TRANSPORT SYSTEM

The EBR-II primary heat transport system consists of the reactor vessel, two sodium pumps, two intermediate heat exchangers (IHXs), fuel handling machineries, and other miscellaneous equipment all immersed in the pool of sodium in the double walled primary tank system (see Fig. 1). The reactor vessel sits centrally on the inner tank, while all other heat transport components and the fuel handling machine are inserted from top and supported by top cover structures. Currently all fuel assemblies and many of the heat transport components have been removed from the reactor core and the tank, respectively, for preparation of the sodium draining. With absence of heat from the reactor core, the sodium in the tank is heated by six electrical heater assemblies so that in remains in liquid state. In a normal reactor operation, the sodium in the tank is drawn into the reactor core, heated, pumped by the pumps into the primary side of the IHXs, and returned to the tank again. The tank inner diameter is 26 ft, the inner tank height about 26 ft, and the cover gas height about 1.5 ft.

During normal reactor operation, the hot sodium leaves the reactor core at about 900 F while the cold sodium returns to the pool from the IHXs at about 700 F. Since the shutdown of the reactor and during the various pre-sodium draining operation, the primary sodium has been heated to and maintained at 700 F. As the pre-draining operations are completed, including removal of major components from the tank, the pool sodium temperature has been lowered and maintained at about 350 F. This temperature will be maintained during the draining as well as the subsequent deactivation of the residual sodium in the tank. Pure sodium melts at about 250 F. With the impurities in the primary sodium the melting point will be slightly higher, and 350 F temperature is considered sufficiently high to ensure that all sodium in the tank will be kept molten.

In reference to Fig. 1, the double-walled primary tank is insulated material on the outside. A thick layer of biological shield concrete layers are installed and to keep the temperature of the concrete from reaching an unacceptable level an air circulation channel is introduced between the insulation and the concrete. This feature helped to simplify the FIDAP model a great deal, and this will be discussed again below where details of the model are described.

FIDAP MODELING

Theoretically speaking, the problem on hand is truly a three-dimensional time-dependent problem if more exact analysis were to be performed. But to perform such an analysis it would require quite an extensive effort. Hence it was decided to simplify the problem to the extend possible but retain all important aspects such that the model results appropriately address the key issues. The problem first was simplified as an axi-symmetric cylindrical model. The draining operation is to take place over a long period of time, as long as about a year, and we made an early observation that under these circumstances the system would behave in a quasi-steady state manner. It is hence possible to perform several selected steady-state analyses in place of the full transient problem. This greatly reduced the amount of work needed to complete the analysis.

The schematic drawing of the FIDAP model for the EBR-II primary heat transport system is shown in Fig. 2. This is the reference configuration where the sodium level is in the normal full height as in the present condition. The axi-symmetric model consists of the liquid sodium, Argon gas above the sodium, and the surrounding solid wall structures. The six heater assemblies are lumped into one cylindrical heat source and placed in the lower center location of the tank. In addition to the Reference Configuration, two additional configurations were calculated successfully and discussed. Configuration A is one in which the sodium level is at the top of the heat source representing about the mid point of the draining. Configuration B represents the configuration at the end of the draining operating where sodium is fully drained from the tank.

As can be seen from the system drawing of the EBR-II primary system shown in Fig. 1, the system is very complex. The FIDAP model constructed here and shown in Fig. 2 is a great simplification. However, the model includes essential features of the problem. The model includes natural circulation in the sodium pool and the cover gas region and the radiation heat transfer between the hot sodium surface and the surrounding wall surfaces. As the sodium level drops and the heat source region becomes uncovered as in Configurations A and B, the radiation heat exchange between the hot heat source surfaces and the cold surrounding wall surfaces would be important and included in the model.

The walls are made up of layers of different materials, and it was rather difficult to characterize the heat transfer properties for each of the layers. However, it was possible to deduce information on the total heat loss from the system and how it is divided between the three walls (top, side, and bottom) and the information was used to characterize the wall heat resistance properties. Design data, various test data, and instrument measurement readings during the reactor operation and since the reactor shutdown were used as basis for this purpose. These wall resistance characterstics were then used for next configurations, Configuration A and Configuration B, where the sodium level was lowered to about the half height (to the top of the heater area) and to the bottom of the tank, respectively.

It was mentioned earlier that there exists an air channel in the walls between the tank insulation and the biological shield concrete structure. This air is cooled by a heat exchanger and instruments are available and the air temperatures are recorded. This feature of the system is used to further simplify the model. Instead of including the biological shield concrete material and the air channel in the model, the air channel provides for a convenient convective boundary condition. The air channel runs through all walls and convective boundary conditions are used for all wall exterior surfaces.

Figure 3 shows the finite-element mesh structure of the model for the Reference Configuration given in Fig. 2. A total of approximately 10,000 elements are used in the model. As can be seen from the figure, finer mesh spacings are used in the cover gas region than in other regions in order to resolve the fine natural circulation flow cells expected in the region. Similar finer meshes are used in the vicinity of the heat source region for resolution of the anticipated high velocity and temperature gradients. FIDAP manual states that fully-coupled solution algorithms available in FIDAP may not perform well if the total elements exceed much over 10,000. Hence an effort was made stay within this limit.

CALCULATION RESULTS

Results of the FIDAP model Reference Configuration calculation are shown in Figs. 4 and 5, where the temperature contours and the velocity vectors are given, respectively. The results shown are for the sodium bulk temperature of 690 F. These are the final results that were obtained after the model wall resistance characteristics have been revised to agree with the available overall heat loss data discussed above. A heater power of 98 kW was necessary to attain the sodium bulk temperature of 690 F. Using a simple linear interpolation, a heater power of 42 kW was then estimated for the bulk sodium temperature of 350 kW.

In the Reference Configuration, the velocity vector field shows a number of recirculation cells in the cover gas region. In the sodium pool on the other hand, one large closed flow pattern sweeping the entire region is present and it is driven by the heat source in the center region. A small recirculation cell also is present in the upper outer corner region. The temperature contour plot indicates that the temperature is high near the heat source region and the bottom sodium pool region. The temperature in the sodium then gradually decreases toward the upper region. The large temperature gradient near the tank side wall and the relatively high sodium temperature near the side wall and top of the pool are consistent with the natural circulation flow pattern in the pool. Hot sodium heated by the heat source flows upward, turns toward the side wall, and flows down the side wall. The high sodium temperature is seen retained during much of the closed flow pattern.

The model for Configuration A next was successfully calculated using 42 kW of heat source and the same wall heat transfer characteristics as in the Reference Configuration. The results are as shown in Figs. 6 and 7. In Configuration A, the sodium level is lowered halfway to the top of the heat source region. It is seen that there is one large closed flow cell in the expanded cover gas region. This large closed flow pattern results in relatively high temperatures near the upper and outer part of the cover gas region. The large closed flow pattern in the sodium pool observed in the Reference Configuration is not as

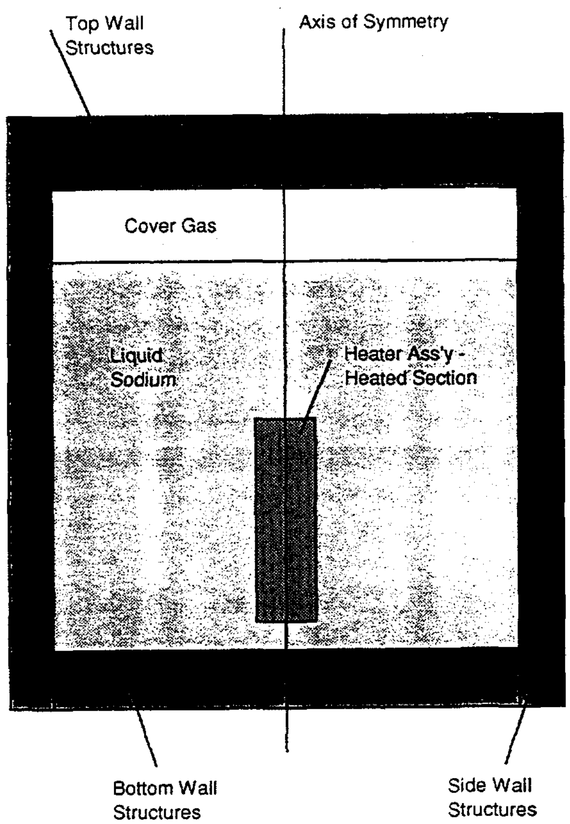

Fig. 2. EBR-II Primary System FIDAP Model-Reference Configuration

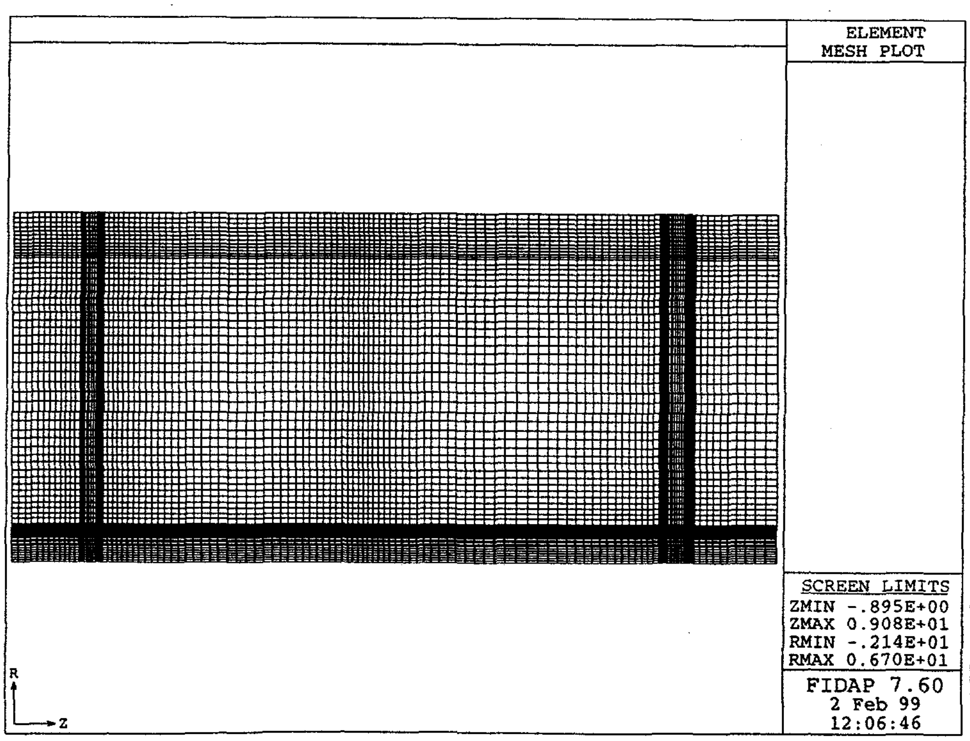

Fig. 3. FIDAP Model Finite-Element Mesh Structure – Reference Configuration

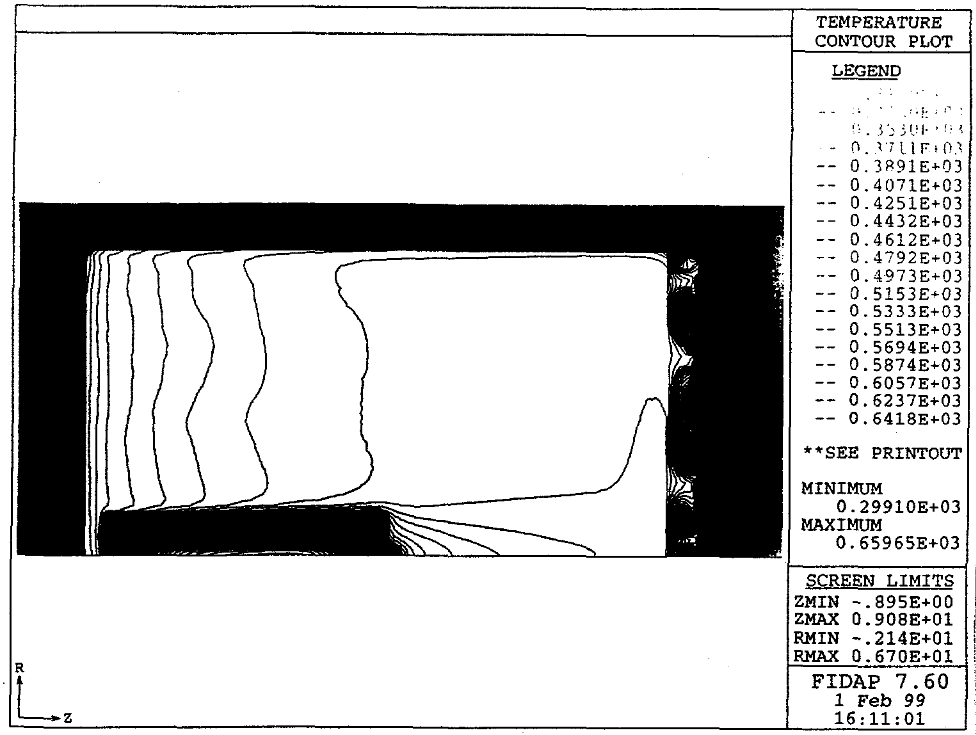

Fig. 4. FIDAP Result Temperature Contours - Reference Configuration

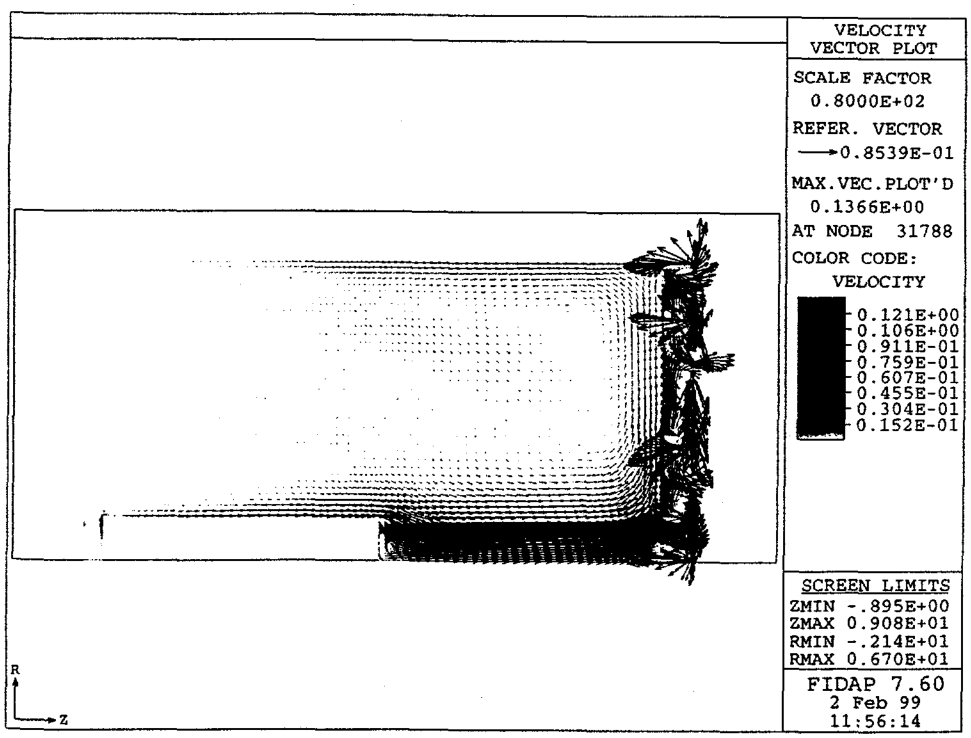

Fig. 5. FIDAP Result Velocity Vectors - Reference Configuration

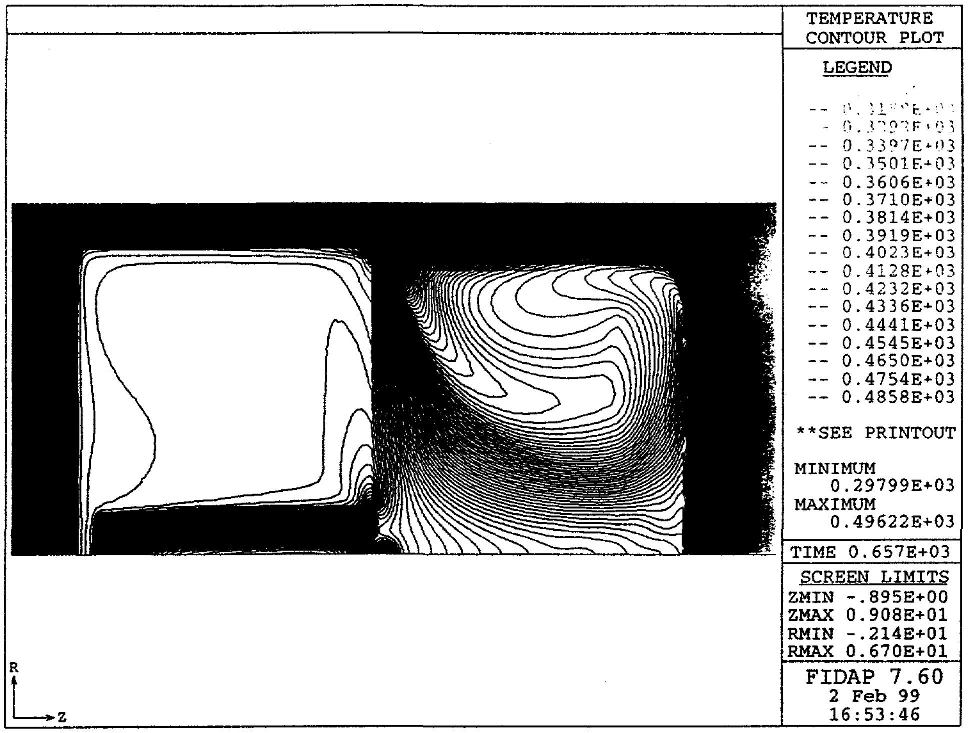

Fig. 6. FIDAP Result Temperature Contours - Configuration A: Sodium Level Lowered to Half Height

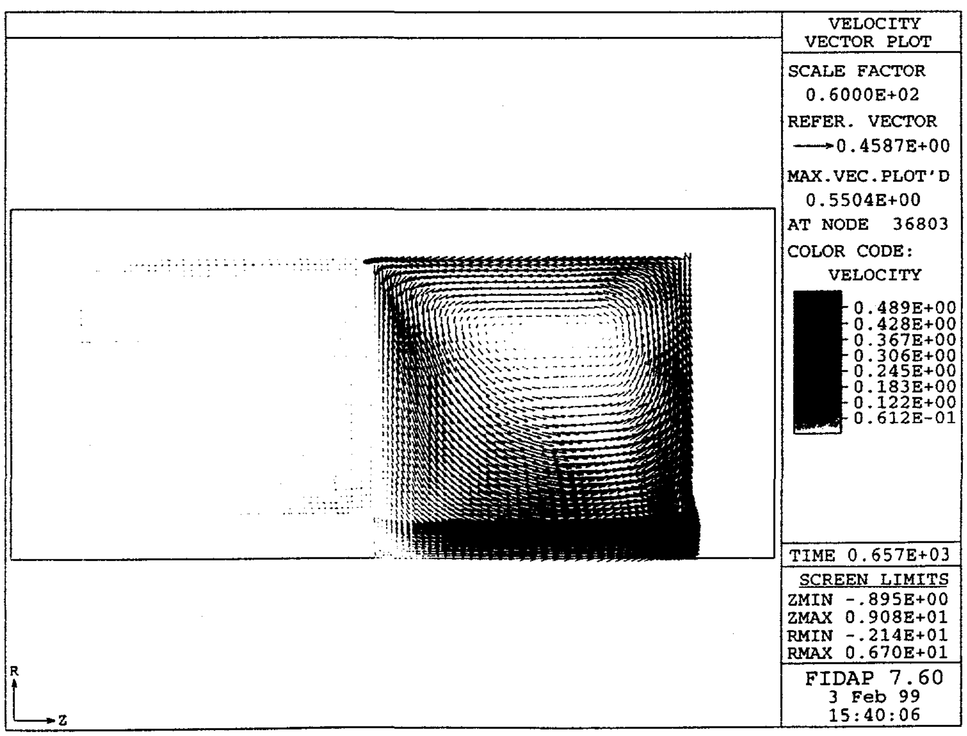

Fig. 7. FIDAP Result Velocity Vectors - Configuration A:

pronounced here. Similarly the high sodium temperatures near the side wall shown in Reference Configuration are not as evident.

The results for Configuration C are given in Figs. 8 and 9. The sodium is completely drained and the entire tank is occupied by the cover gas. The natural circulation flow pattern in the cover gas is similar to Configuration A and also to that in the sodium pool of the Reference Configuration. The effects of this large recirculation cell on the side wall temperatures are likewise similar. Here again a small recirculation cell is shown in the upper outer corner region. High temperature gradients are evident near the side wall and this again is consistent with the flow pattern. Here too the temperatures are high near the heat source and the bottom region and decrease toward the top region.

Review of the results of all three configurations in more detail, it was revealed that the tank wall surfaces in contact with sodium tend to be at temperatures higher that the surfaces not in contact. This is due to the fact that sodium has a much higher thermal conductivity than the cover gas and tends to transfer heat much more readily than the cover gas. It is therefore shown that somewhat higher heater power is required as the sodium level drops if the tank wall temperature is to be kept at about the same during the sodium draining process. The most heat input would therefore be required for Configuration C where no sodium exists in the tank.

DISCUSSION OF SOLUTION METHODS USED

Since only the steady-state solutions were of interest, steady-state solution algorithms were first sought. Both the fully-coupled and the segregated solvers are offered in FIDAP. In the fully-coupled scheme, all field equations are solved simultaneously. Whereas in the segregated scheme, the equations are solved sequentially one equation at a time. Without any exhaustive effort to explore both these algorithms in full, the segregated algorithm worked well for the Reference Configuration model calculation and was used. It was later discovered that, in the Configuration A and Configuration B calculations, the segregated solver was not successful. The fully-coupled algorithms also failed for these calculations. Various iteration methods are available in the fully-coupled algorithm: The successive substitution method, Newton-Raphson, modified Newton-Raphson, and Quasi-Newton method. All these methods were tried and the results were found to be unsuccessful.

As for the solution of pressure, there are basically two different methods available in FIDAP. In the first method, pressure is solved together with other independent variables in the method called mixed method. In the second method called the penalty method, the pressure is solved by a separate pressure equation. The pressure equation is obtained by combining the momentum equations and the continuity equation and eliminating the velocities. The mixed method was found to work satisfactorily and always chosen. The penalty method appeared not as satisfactory. Here again, we did not explore all of the possible combinations in full.

Since all available steady-state solvers failed for Configuration A and B, it was thought the time-dependent solver may be a more natural way to solve the steady-state problem. Indeed it was found that it was the case. Both Configurations A and B were successfully solved by a time-dependent solution algorithm. Among the implicit time integration schemes available in FIDAP, backward Eulerian, trapezoidal, and explicit forward integration scheme, the trapezoidal scheme worked well. Steady-state solutions were obtained by a long term solution of the time-dependent problem by continuing the calculation until no significant change is evident in the solution. The final check of the solution was made by examining the overall system energy balance: the total heat loss from the system to the surroundings must be equal to the total heat input by the heat source.

There was another model configuration that was attempted but the result was not very successful. This configuration is between Configuration A and Configuration B and the sodium level is at the bottom of the heat source. Hence, in this configuration, the cover gas region is expanded and shallow sodium pool still remains in the tank. The time integration process did not outright diverge at any time step calculation or showed any clear indication of not converging. The scheme appeared to be only marginally stable and not sufficiently robust to yield converging transient solution. It was clear, however, that the solution drifted and did not show any clear indication of approaching the steady-state as the integration progressed.

CONCLUDING REMARKS

FIDAP Code calculations have been performed for a relatively simple axi-symmetric cylindrical heat transfer model involving natural circulation, and the experiences gained with respect to performances of the various solution algorithms used in the calculations have been discussed. It was possible to obtain large part of the needed results. In the process, however, certain special efforts were necessary in terms of choosing the appropriate methods available and developing and following other helpful procedures. Among the steady-state solvers, only the segregated algorithm performed successfully. For some model configurations, none of the steady-state algorithms performed in any successful manner. The time-dependent solution algorithm, using the implicit trapezoidal time integration scheme, proved satisfactory. For some model configuration, it was discovered that the same time-dependent solution algorithm was unsuccessful, irrespective of the time integration scheme, either the implicit or the explicit scheme.

We also would like to note that certain simplifications we made in the model construction or the nature of the problem we have on hand may also adversely contribute to the performance of the numerical algorithms. For example, the recirculation flow cells in the cover gas region (see Fig. 5) are toroidal cells in the framework of our simplified axi-symmetric model. It is not likely that such toroidal cells will exist in the actual three-dimensional system. Another observation to make is that the small scale details in natural circulation will be inherently unstable or transient, and there may not be a true steady-state solution in reality. Nevertheless it was encouraging to be able to produce a number of valid solutions to the problem, which were all useful for the plant closing operation.

ACKNOWLEDGMENTS

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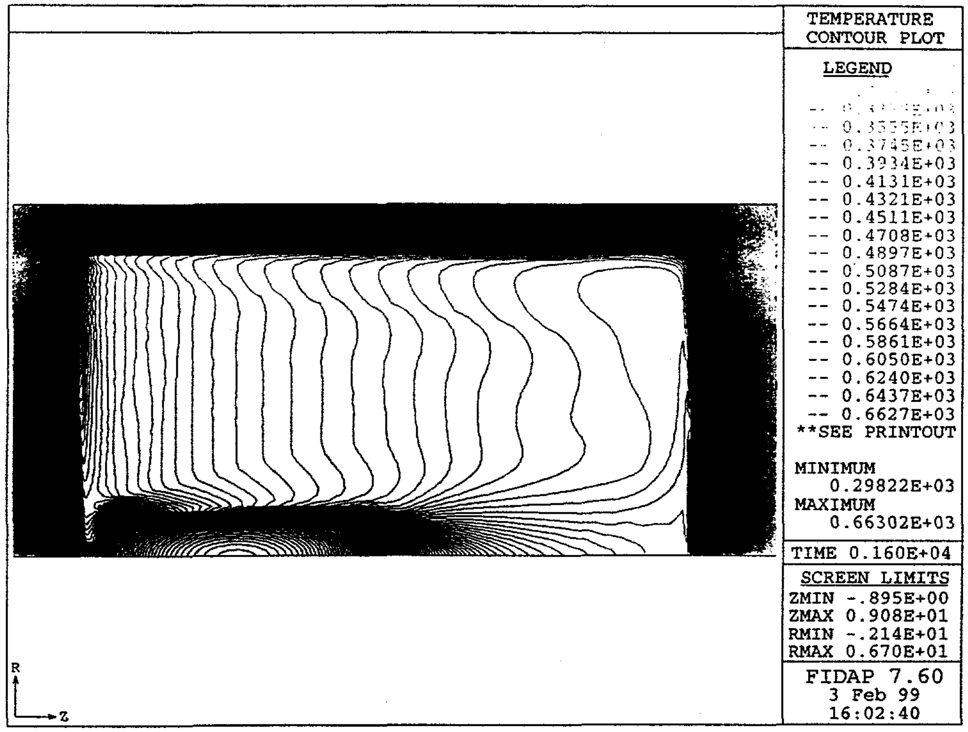

Fig. 8. FIDAP Result Temperature Contours – Configuration B: Sodium Completely Drained

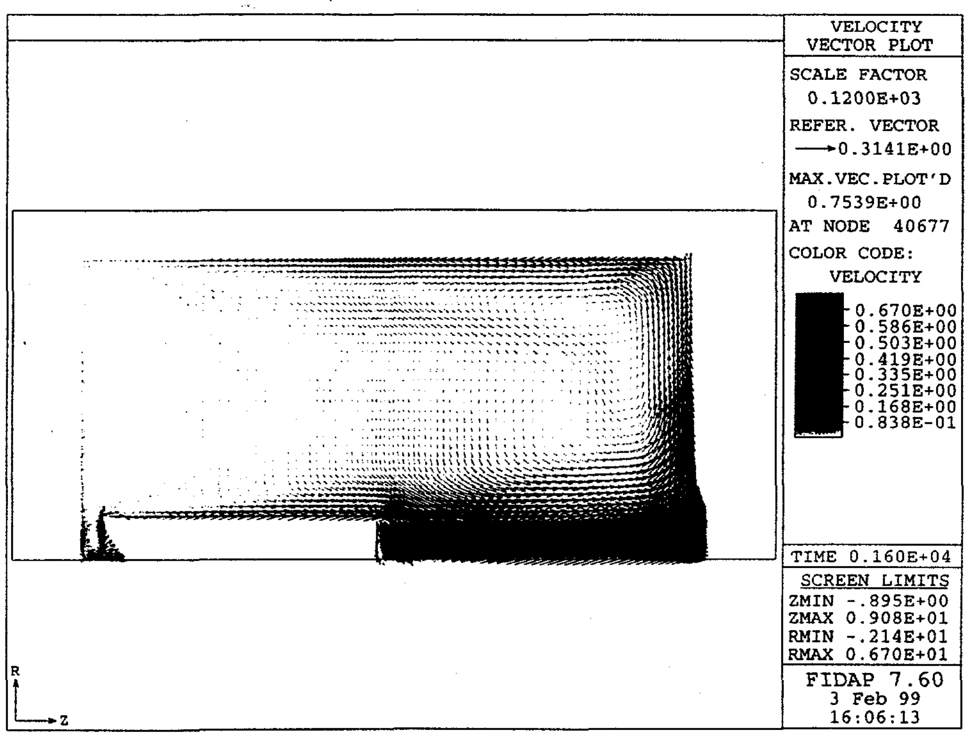

Fig. 9. FIDAP Result Velocity Vectors – Configuration B:

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FIDAP Users Manual, Fluid Dynamics Analysis Package, Rev. 7.0, 1st Ed., FLUENT Inc., Evanston, IL, April 1993.