USE OF COMPUTATIONAL FLUID DYNAMICS (CFD) TOOLS FOR FUEL ASSEMBLY ANALYSIS

P. L. Garner and T. Sofu
Nuclear Engineering Division
Argonne National Laboratory, 9700 South Cass Avenue, Argonne, Illinois, 60439 - USA

ABSTRACT

The STAR-CD computer program for Computational Fuel Dynamics (CFD) has been applied to the Russian pin-type fuel assemblies proposed as low enriched uranium (LEU) replacements for the high enriched uranium (HEU) (36%) IRT-3M fuel assemblies currently used in the WWR-SM reactor in Uzbekistan. For fuel assemblies containing twisted, finned pin-type fuel, STAR-CD was first used to model the single pin having the highest power density along with its associated coolant as an isolated unit cell. Velocity, pressure, temperature, heat flux, etc. were calculated on a detailed spatial basis in the coolant, cladding, and fuel. The model was then expanded to include multiple fuel pins; the computed motion of coolant from one portion of the assembly to another can reduce the peak temperatures below what one would compute using a single-pin model and, thus, change conclusions regarding the margin to onset of nucleate boiling. STAR-CD has also been applied to the IRT-3M tube-type fuel assemblies in the current HEU core.

1. Introduction

Computational Fluid Dynamics (CFD) refers to the numerical solution, by computational means, of the governing equations for fluid flow, including the equations for the conservation of mass, momentum, and energy plus other subsidiary equations (e.g., state). The solutions are used to investigate complicated or extensive physical situations for which experiment measurements are difficult. The solution techniques and the situations analyzed have become more complex as digital computers have continued their advancement in memory and speed. There are many commercial computer programs applicable to CFD, for example, FLUENT, CFX, FLOW-3D, and STAR-CD.

The present paper uses one such CFD computer program, STAR-CD, to analyze the fluid flow and heat transfer aspects of several fuel assembly designs being considered as low enriched uranium (LEU) replacements for the high enriched uranium (HEU) (36%) IRT-3M fuel assemblies currently used in the WWR-SM reactor in Uzbekistan. There is also a preliminary application of the code to the tube-type fuel assemblies currently in the reactor. A goal of this type of analysis is a reliable estimate of the margin to onset of nucleate boiling.

2. STAR-CD Computer Program

The STAR-CD computer program [1] has been developed by CD adapco Group of Computational Dynamics Limited. The name of the computer program is an acronym for simulation of turbulent flow in arbitrary regions developed by Computational Dynamics Limited. Rather than being specific to one reactor type or one fuel design, the geometry is general and multidimensional. There are capabilities for semiautomatic meshing and interfacing with computer-aided drawing programs.

Phenomena included in the computer program are incompressible and compressible fluids, turbulence (multiple models), heat transfer (e.g., conduction, convection, and radiation), mass transfer, and chemical reactions. Arbitrary shape solids may be embedded in the flow field, interacting via both heat and momentum transfer mechanisms. The solids can move, including reciprocating and rotational components.

The primary interaction between the user and the computer program is in the form of a graphical user interface (GUI). The same GUI is used for both input preparation and for results review.

The computer program will run serially on a single computer and in parallel on a cluster of computers. The parallel aspects of the computer program allow larger problems to be solved in a shorter time than would be possible using only a single computer.

3. Application to IRT-MR Fuel Assemblies

An LEU fuel assembly (FA) design being considered for conversion of the WWR-SM research reactor in Uzbekistan consists of 176 fuel elements (or "pins"), placed in a 15 by 15 pin matrix with the central 7 by 7 pins removed, as illustrated on the left side of Figure 1 [2]; the pins in the four outer corners do not contain fuel; there are both outer and inner shroud tubes for the fuel assembly. An individual fuel element is square, has a fin on each corner, and is twisted, as shown on the right side of Figure 1. The combination of the fins and the fuel element twisting provides pin to pin separation. Others (e.g., Reference [2]) have provided studies of number of fuel assemblies, size of fuel meat, thickness of cladding, etc. versus power level and various safety criteria.

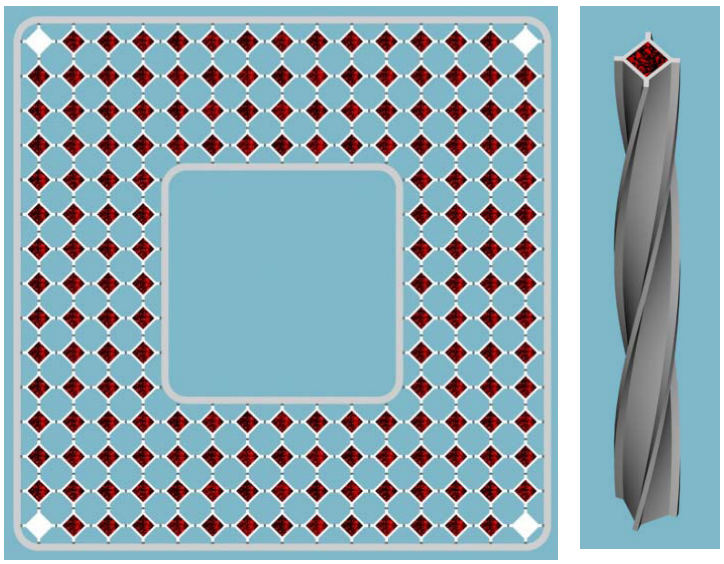

Figure 1. IRT-MR Pin-Type Fuel Assembly and Fuel Element Detail (In top row, the pins are numbered FE-184 through FE-198 from left to right.)

A particular design of this fuel element has been chosen for study using STAR-CD. The U-9%Mo dispersion fuel meat has a square cross section, 1.75 mm by 1.75 mm, and an active length of 600 mm. The Al cladding is 0.4 mm thick and the fins are 0.4 mm thick. The fin tip to fin tip distance is 4.5 mm. The fuel element pitch is 4.547 mm. The fuel element twists 90 degrees for every 100 mm of height.

The power generation distribution was obtained from MCNP calculations [3] for cores containing 18 and 20 fuel assemblies generating a power of 9.4 MW in the fuel meat; there is another 0.6 MW assumed to be generated in the reflector and structure, for a total nominal power of 10 MW. The peak power density is 3.63 GW/m^3 in the 18 FA core and 3.11 GW/m^3 in the 20 FA core; for both cores, the peak power density occurs in pin FE-185, which is adjacent to the outer fuel assembly wall and adjacent to the corner pin position (where there is no fuel); it occurs at a height of 220 mm above the bottom of the fuel meat. The pins along this wall (i.e., the top row of Figure 1) have the highest power levels in the fuel assembly (ranging from 5.12 kW to 4.46 kW in the 18 FA core and from 4.47 to 4.00 kW in the 20 FA core), due to there being a beryllium reflector just outside of this fuel assembly wall.

Several calculations have been performed using STAR-CD for this fuel assembly, both for isolated fuel elements and for collections of fuel elements.

The nodings at several axial levels are shown in Figure 2. The fuel meat is divided into 8 cells in each direction, or 64 cells per axial level. The cladding is divided into 8 by 2 cells per flat side plus 3 cells in the corner, or 76 cells per axial level. Each fin is divided into 4 by 2 cells, or 32 cells per axial level. The inner coolant between adjacent fins is divided into 8 by 4 cells, or 128 cells per axial level. The outer coolant between the circle scribed by the fin tips and the edges of the unit cell is divided into 20 by 3 cells per quadrant, or 240 cells per axial level. The vertices of the inner and outer coolant are allowed to be noncoincidental across the circle scribed by the fin tips. The total number of cells per axial level is 540. The fuel, cladding, and inner coolant cells twist 90 degrees for every 100 mm of axial distance; the outer coolant cells remain fixed; this is illustrated in Figure 2. The mesh spacing in the axial direction is 1 mm in order to accommodate the twisting of the inner cells.

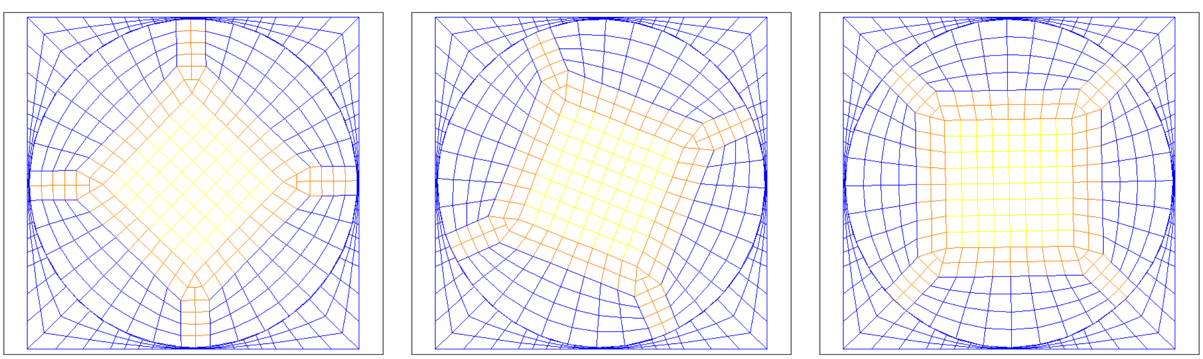

Figure 2. STAR-CD Noding for Pin-Type Fuel Element and Associated Coolant at 0 (left), 25 mm (center), and 50 mm (right) Above Bottom of Fuel Meat

The coolant velocity (3.31 m/s, corresponding to 27.9 m^3/h per fuel assembly), temperature (318 K), and pressure (0.128 MPa) are specified at the inlet, which is the top of the fuel meat in these calculations. If the fuel element is adjacent to the fuel assembly shroud, then that part of the unit cell boundary is treated as a zero-slip wall; otherwise, the sides of the unit cell are symmetry boundary conditions. The interface between the coolant and the cladding is also a zero-slip wall. Calculations were performed using the k-ε turbulence model for high Reynolds number.

An item of interest from these calculations is the margin to the onset of nucleate boiling (ONB). This condition is sometimes viewed as the "safety coefficient", SC, defined as

$$SC = (T_{ONB} - T_{in}) / (T_{FE,surf} - T_{in})$$

where T_{ONB} is the temperature for the onset of nucleate boiling, $T_{FE,surf}$ is the surface temperature of the fuel element, and T_{in} is the temperature at the fuel assembly inlet. There are several correlations for T_{ONB}. The present work uses one attributed to Forster-Greif [4], given by

$$T_{ONB} = T_{sat} + 2.04\, q^{0.35} / P^{0.25}$$

where T_{sat} is the saturation temperature [K] at the local pressure, q is the local heat flux [kW/m^2], and P is the local coolant pressure [bar]. The constants in the Forster-Greif correlation are partially connected with the units being used for the variables in the correlation. Temperature may be either [K] or [°C] if used consistently in all equations. A design constraint currently requires SC greater than 1.4.

STAR-CD does not have the capability to compute internally the margin to the onset of nucleate boiling. Instead, after a case is complete, the pressure, cladding surface temperature, and the heat flux distributions are exported from STAR-CD to an external program, which then calculates SC as a function of position.

4. Results for Single Pin Analysis

Calculations were initially performed for the highest power pin on an isolated basis. Figures 3 and 4 show the values for SC as a function of axial position for the 18 and 20 FA cores, respectively, where 0 is the bottom of the fuel meat. Since the value of SC varies around the circumference of the fuel element at each axial level, two values for each axial level are shown in these figures corresponding to the maximum and minimum. An example of this variation at one axial level is shown in Figure 5; the value of SC is a minimum at the center of the flat portion of the cladding (i.e., where the heat flux is maximum) and increases as you move toward the ends of the fins (i.e., where the heat flux is minimum). On an axial basis, the value of SC is a maximum at the top of the fuel meat; decreases as one moves down the fuel meat, has a minimum at about 28% of the meat height (i.e., somewhat below the peak power density location), and then increases slightly as you move toward the bottom of the meat. The minimum

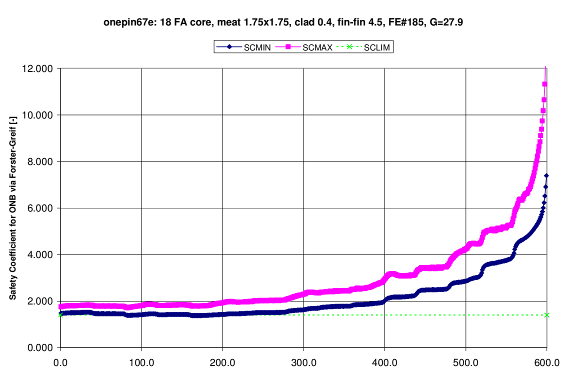

Figure 3. Minimum and Maximum ONB Margin versus Axial Position for Isolated Peak Power Pin in 18 FA Core

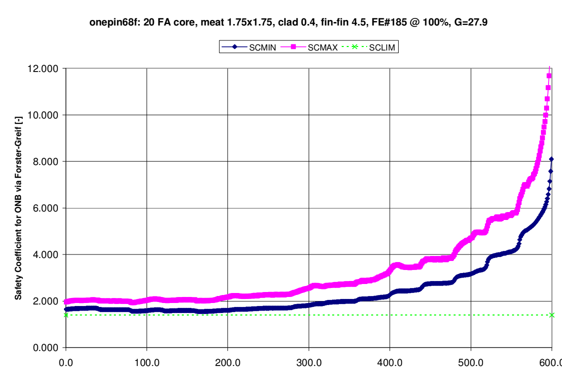

Figure 4. Minimum and Maximum ONB Margin versus Axial Position for Isolated Peak Power Pin in 20 FA Core

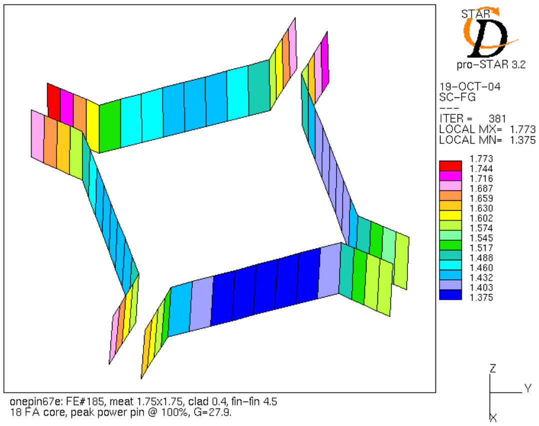

Figure 5. ONB Margin Variation Around Pin Circumference 170 mm Above Bottom of Fuel Meat for Peak Power Pin in 18 FA Core

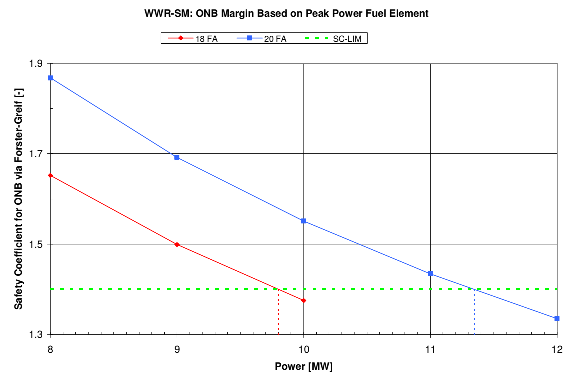

Figure 6. Minimum ONB Margin versus Power for 18 and 20 FA Cores Based on Isolated Peak Power Pin Model

value of SC based on the isolated peak power pin analysis is 1.375 for the 18 FA core and is 1.551 for the 20 FA core at nominal power.

Calculations were performed for a range of powers about these nominal powers. The results for SC_{min} are shown in Figure 6. These calculations indicate that the maximum power level in the 18 FA core needs to be reduced to 9.8 MW in order to satisfy the SC>1.4 criterion. On the other hand, the 20 FA core satisfies the SC>1.4 criterion for a power level up to 11.3 MW.

5. Results for Multiple Pin Analysis

In most respects, performing the ONB studies using the pin with the peak power density should provide a conservative result, since ignoring the coolant mixing that does occur in the fuel assembly leads to higher temperatures. The CFD tools and computer clusters allow the analysis to be expanded to consider more than just a single fuel pin. Such multiple pin calculations have been performed for the pins with a fuel meat cross section of 1.75x1.75 mm^2. In particular, an additional calculation has been performed considering the upper two complete rows of fuel pins in the left side of Figure 1 (i.e. 15x2 pins); this region includes the 28 highest power pins in the fuel assembly plus two non-fueled corner pins. The temperature distribution calculated at the bottom of the fuel meat for the 18 FA core is shown in Figure 7. The pins in the row closest to the outer shroud are hotter than the pins in the next row inward. Within each row, the pins on the left are hotter than the pins on the right. Both of these two patterns match the expectations from the power distribution. Figure 8 shows a close-up view of the three highest power pins from the multiple pin calculation. For comparison, Figure 9 shows the temperature distribution calculated at the bottom of the fuel meat when each of these pins is analyzed as a single isolated pin.

There are several interesting results. When analyzed as isolated pins, the highest temperatures are associated with the highest power pin, which is the expected result. When analyzed as a group, the peak power pin (i.e., FE-185) is not the hottest; it is receiving additional cooling due to its location next to the corner pin which has no fuel. The second highest power pin (i.e., FE-186) is now the hottest, and the third highest power pin (i.e., FE-187) is the second hottest; these

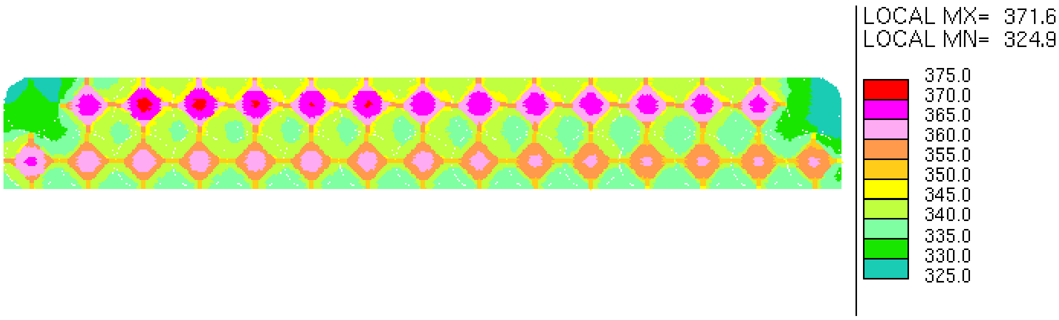

Figure 7. Exit Temperature Distribution Calculated using STAR-CD for 15x2 Pin Sector

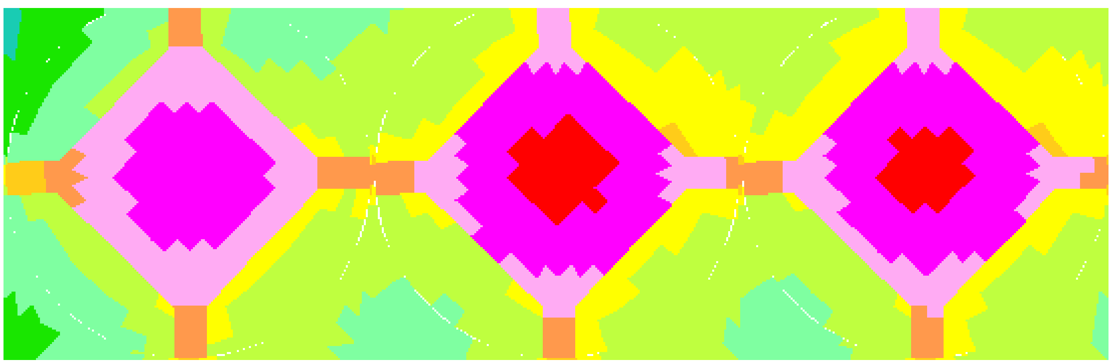

Figure 8. Enlarged Section of Figure 7 to Show Pins FE-185, FE-186, and FE-187 (Same color scale as in Figure 7.)

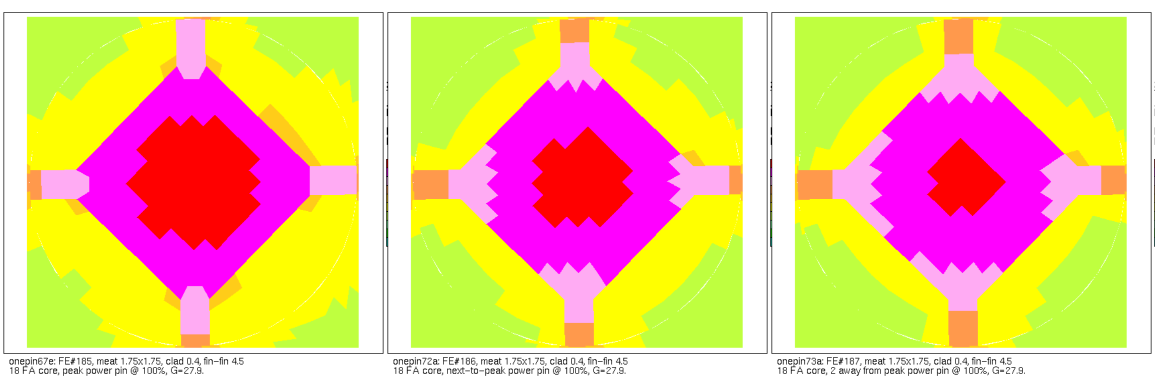

Figure 9. Exit Temperature Distribution Calculated using STAR-CD for Pins FE-185 (left), FE-186 (center), and FE-187 (right) as Isolated 1-Pin Models (Same color scale as in Figure 7.)

pins do not experience the extra cooling from the corner like the peak power pin. An additional cause for the shift in results is that the coolant flow associated with the pins near the wall in the multiple pin case is less than the coolant flow in the isolated pin cases; even though both cases have the same uniform inlet velocity distribution, the additional resistance provided by the shroud causes coolant to be diverted toward the interior of the fuel assembly, leading to higher temperatures at the exterior.

The shift in results can also be seen in the values for ONB margin in Table 1. The isolated pin results are shown under the heading "1 pin". For the 18 FA core, the calculations indicate that the peak power fuel element, when analyzed on an isolated basis, has SC_{min} equal to 1.375, which is somewhat below the 1.4 design limit; SC_{min} for the next two highest power fuel elements are above the 1.4 design limit. The multiple pin results are shown under the heading "15x2 pins". For the 18 FA core, the calculations indicate that the peak power fuel element (i.e., FE-185), when analyzed on an multiple pin basis, has SC_{min} equal to 1.406, which is slightly larger than 1.4. The next two highest power fuel elements are shifted downward in ONB margin due to the coolant diversion. The second highest power pin (i.e., FE-186) now has SC_{min} equal to 1.389, which is somewhat below the 1.4 design limit, whereas the third highest power pin (i.e., FE-187) remains slightly above the 1.4 design limit. Table 1 shows similar relative shifts between isolated pin and multiple pin analyses for the 20 FA core; a key difference is that ONB margin is substantially above the 1.4 design limit.

Table 1. ONB Margin for Peak Power Pins

FE	18 FA Core			20 FA Core		
	Power (kW)	SC_{min} 1 pin	SC_{min} 15x2 pins	Power (kW)	SC_{min} 1 pin	SC_{min} 15x2 pins
185	5.12	1.375	1.406	4.47	1.551	1.575
186	4.92	1.417	1.389	4.34	1.591	1.553
187	4.82	1.434	1.402	4.27	1.607	1.555

In summary, the safety margin to ONB is determined by the fuel pin with the smallest value of SC. For the 18 FA core, the smallest value of SC is 1.375 in single-pin analysis and 1.389 in the multi-pin analysis; thus only a small benefit is predicted due to the coolant mixing which is included in the multi-pin calculation. For the core with 20 FA, the single-pin and multi-pin analyses provide nearly identical values of 1.55 for SC_{min}, and, more significantly, the values from both analyses are greater than the 1.4 minimum limit.

6. Application to IRT-3M Fuel Assemblies

Another fuel assembly being considered for the WWR-SM research reactor in Uzbekistan consists of 6 concentric tube-type fuel elements with flat sides and rounded corners. The core in the currently operating reactor has 18 fuel assemblies having high enriched (36%) uranium fuel (UO_2-Al). In each plate, the fuel meat is 0.5 mm thick with 0.45 mm cladding on each side. The fuel meat is 600 mm in height. There is a 2.05 mm water gap between tubes. Others (e.g., Reference [5]) have provided studies of number of fuel assemblies, size of fuel meat, thickness of cladding, etc. versus power level and various safety criteria.

A detailed power generation distribution was obtained from MCNP calculations [6]. Values used here are for a core generating a power of 9.4 MW in the fuel meat; there is another 0.6 MW assumed to be generated in the reflector and structure, for a total nominal power of 10 MW. The peak power density is 3.07 GW/m^3 and occurs in the outer tube in the flat portion which is adjacent to the beryllium reflector; it occurs at a height of 200 to 240 mm above the bottom of the fuel meat.

The noding for a 90 degree sector of the bundle is shown in Figure 10. The fuel meat is 2 cells thick; there are 20 cells along each flat and 10 cells in each corner, or 240 cells per axial level per tube. The cladding is 2 cells thick with the same azimuthal noding as in the fuel meat, or 480 cells per axial level per tube. The coolant between adjacent solid surfaces is 6 cells thick; on the +y face of the outer tube, the nodes extend across the full gap to the outer edge of the reflector; in the other three directions, the nodes only extend to the middle of the gap; there are 720 cells between adjacent fuel tubes and 660 cells outside of the outer tube. The total number of cells per axial level is 9300. The mesh spacing in the axial direction is 1 mm.

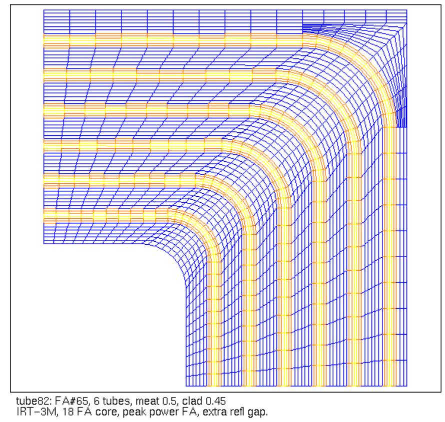

Figure 10. STAR-CD Noding for IRT-3M 6-Tube Fuel Assembly

The coolant velocity (average of 3.21 m/s, with -7 to +18% gap to gap variations, corresponding to 33.7 m^3/h per fuel assembly, of which 1 m^3/h is due to including the extra half gap on +y side), temperature (318 K), and pressure (0.128 MPa) are specified at the inlet, which is the top of the fuel meat in these calculations. The tube surfaces are treated as a zero-slip walls. Calculations were performed using the k-ε turbulence model for high Reynolds number.

Figure 11 shows the temperature distribution at the bottom of the heated zone; the fuel temperature distribution is similar to the power distribution; the coolant temperature is hottest along the flats and coolest in the corners. Figure 12 shows the velocity distribution at the bottom of the fuel meat illustrating low values adjacent to the tube surfaces, higher values in the middle of the gap between tubes, and the highest values in the corners. The minimum margin to ONB is 1.53, which is substantially above the SC>1.4 design limit. The distribution of SC values at the axial level where the minimum occurs is shown in Figure 13; the minimum value occurs on the inner side of the +y flat portion of the outermost tube, which corresponds to the peak power sector; the increase in value for other locations is due to the decreased power density and the relative overcooling of the corners relative to the flats.

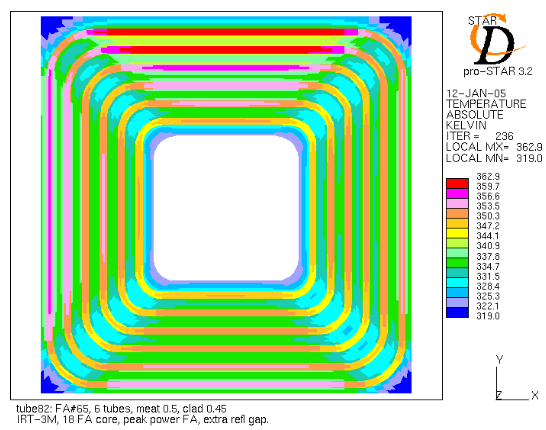

Figure 11. Temperature Distribution at Bottom of Fuel Meat

This calculation merely illustrates the capabilities of STAR-CD with respect to the tube-type fuel assembly designs. Additional calculations would need to be performed to examine newer tube-type designs for the LEU fuel.

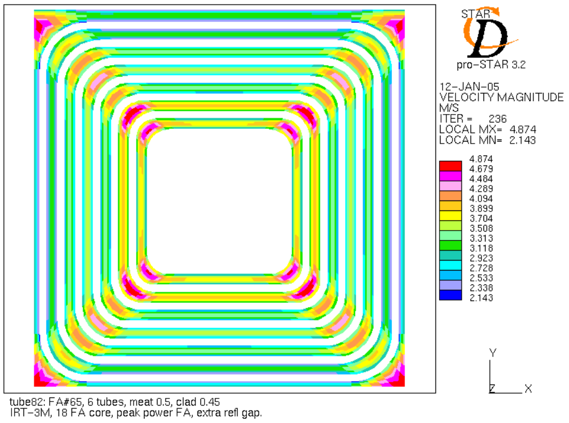

Figure 12. Velocity Distribution at Bottom of Fuel Meat

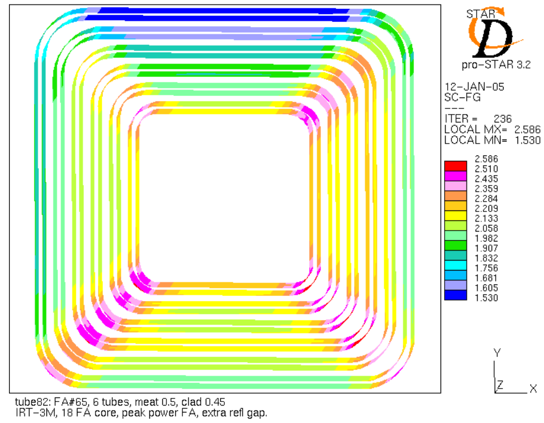

Figure 13. ONB Margin Distribution 160 to 170 mm Above Bottom of Fuel Meat

7. Conclusions

The STAR-CD computer program has been used to perform analyses of a Russian fuel assembly design containing pin-type fuel elements that is being considered for LEU conversion of the WWR-SM reactor in Uzbekistan. The detailed coolant flow, pressure, and temperature distributions computed have been used to evaluate the design with respect to ONB margin. By either single or multiple pin analysis, the 18 FA core seems to be very close to, and likely below, the 1.4 design limit. On the other hand, the 20 FA core has an acceptable ONB margin of 1.55, which is above the 1.4 design limit and corresponds to a power level of 11.3 MW.

STAR-CD has also been applied to the HEU (36%) IRT-3M tube-type fuel assemblies currently used in the WWR-SM reactor. These calculations are illustrative of the velocity and temperature distributions which are encountered in such designs. The work has not yet addressed the LEU IRT-3M tube-type fuel designs being proposed.

References

[1] "STAR-CD Methodology", "STAR-CD User Guide", and other related reports, version 3.20, CD adapco Group, Melville, New York (2004).

[2] A. Vatulin, A. Morozov, V. Suprun, I. Dobrikova, V. Mishunin, G. Kulakov, A. Alexandrov, A. Enin, and A. Tkachev, "Development of IRT-Type Fuel Assembly with Pin-Type Fuel Elements for LEU Conversion of WWR-SM Research Reactor in Uzbekistan", *Proceedings of the 2003 International Meeting on Reduced Enrichment for Research and Test Reactors*, *ANL/NE/TM03-05*, Argonne National Laboratory, Argonne, Illinois, 327-337 (2003).

[3] N. A. Hanan, personal communication, Argonne National Laboratory, Argonne, Illinois, (August 24, 2004).

[4] Roger Ricque and Roger Siboul, "Ebullition Locale De L'eau En Convection Forcee", Report CEA-R-3894, Centre d'Etudes Nucleaires de Grenoble, Grenoble, France (May 1970).

[5] N. A. Hanan, M. M. Bretscher, A. P. Olson, and J. E. Matos, "Feasibility Studies for LEU Conversion of the WWR-SM Reactor in Uzbekistan Using Pin-Type and Tubular Fuels", *Proceedings of the 2003 International Meeting on Reduced Enrichment for Research and Test Reactors*, *ANL/NE/TM03-05*, Argonne National Laboratory, Argonne, Illinois, 316-326 (2003).

[6] N. A. Hanan, personal communication, Argonne National Laboratory, Argonne, Illinois, (March 3, 2004).