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ABSTRACT

Several technical issues relating to expansion of the HFIR spent fuel pool storage capacity are discussed, including mechanical and thermal design analyses of the high-density storage arrays, potential for increased corrosion of spent fuel cladding due to longer pool residence times, and impacts on the pool water treatment and liquid low-level waste (LLLW) systems.

I. INTRODUCTION

The current hiatus in aluminum fuel reprocessing in the United States has forced many operating reactors to make new plans for extended storage or disposition of irradiated fuel. The HFIR at the Oak Ridge National Laboratory, managed by Martin Marietta Energy Systems, Inc., for the United States Department of Energy, provides several key national research functions. It provides transplutonium isotopes for research, medical and industrial use, as well as a variety of high-intensity neutron beam facilities and short-term high-flux irradiation capability for the production of special isotopes for medical research and other purposes. The HFIR facility was originally designed to store approximately 25 spent cores, sufficient to allow for operational contingencies and for cooling prior to off-site shipment for reprocessing. The original capacity has now been increased to 60 positions, of which 53 are currently filled (September 1994). Additional spent cores are produced at a rate of about 10 or 11 per year. Continued HFIR operation, therefore, depends on a significant near-term expansion of the pool storage capacity, as well as on a future capability of reprocessing or other storage alternatives once the practical capacity of the pool is reached. To store the much larger inventory of spent fuel that may remain on-site under various future scenarios, the pool capacity is being increased in a phased manner through installation of a new multi-tier spent fuel rack design for higher density storage (Figure 1). A total of 143 positions was used for this paper as the maximum practical pool capacity without impacting operations; however, greater ultimate capacities were addressed in the supporting analyses and approval documents.

This paper addresses issues related to the pool storage expansion including (1) seismic effects on the three-tier storage arrays, (2) thermal performance of the new arrays, (3) spent fuel cladding corrosion concerns related to the longer period of pool storage, and (4) impacts of increased spent fuel inventory on the pool water quality, water treatment systems, and LLLW volume.

II. HFIR SPENT FUEL POOL DESIGN FEATURES AND CURRENT CONDITIONS

HFIR spent fuel is stored in a steel-lined, 430,000 L (114,000 gal) rectangular pool about 6 m (20 ft) deep, separated from the adjacent reactor pool by a movable dam. The annular spent fuel assemblies, with an OD of about 0.435 m (17.134 in.) and an overall length of 0.79 m (31 1/8 in.), are currently stored in one high rectangular arrays of storage fixtures with cadmium-lined central posts and outer shrouds for criticality control. The pool water is continuously demineralized, maintaining a conductivity of 200 μS/m or less. The oldest fuel currently in storage was discharged in March 1986 prior to the extended HFIR shutdown in 1986 through 1989 for evaluation of reactor vessel embrittlement.

III. SEISMIC ANALYSIS OF SUBMERGED SPENT FUEL STORAGE STRUCTURE

A design calculation was made to provide a structural analysis for the new spent fuel arrays against possible seismic excitation.[1] Numerical analysis for the new arrays was based on the computer code ABAQUS 5.2. The analysis was made for the hourglass cluster array and the diamond cluster, as shown in Figure 1, with and without the effect of the surrounding water. Seismic excitation was based on the UCRL-15910 recommended 0.32 g peak ground acceleration and 5% damping anchored to Newmark and Hall spectrum. One of the horizontal seismic excitations was applied along the weakest direction of the structure. The 0.32 g peak ground acceleration with 5% damping was applied to the other two horizontal directions, and two-thirds of its magnitude was applied to the vertical direction of the structure. The square rooted sum of the squares (SRSS) procedure was used in response calculation. Seismic margin of safety or fragility analysis against peak-ground acceleration was based on the maximum allowable buckling stress and yield stress of the rack array. Fluid-structure interaction was modeled by using the added-mass correction.

The 0.32 g peak ground acceleration was based on UCRL 15910. It is more conservative than the Oak Ridge site-specific spectrum of 0.29 g recommended by the MMES Natural Phenomenon Engineering Center. The main difference of the two spectra occurs in the frequency range $f < 40$ Hz, with some minor differences up to 50 Hz. To choose UCRL 15910 spectrum for Oak Ridge area is on the conservative side. This is also more conservative than the current design basis seismic acceleration of 0.15 g for the HFIR.

The seismically-induced vibration of the storage rack is affected by the surrounding pool water. Water tends to increase the apparent mass (the "added-mass" effect) of the structure. It reduces the natural frequency of the structure and, therefore, induces additional response. The amount of increase can be calculated by considering the induced-fluid flow. A comprehensive review of the subject can be found in open literature.

A. Silo and Pedestal Dimensions

The silo assemblies are made of 304 stainless steel. Each unit of the redesigned spent fuel racks consists of a circular cylindrical silo and a pedestal seating for the silo. A maximum of three packages of jacketed spent fuel can be stored in the silo part of the rack. Six-hole openings are evenly distributed around the cylindrical wall of the pedestal to allow natural convection of pool water through the rack. A cluster of four or five silo assemblies is constructed as one unit.

The triple-tier silo has a height of 2.5 m (98 in.) with inner diam. of 0.52 m (20.5 in.) and the silo wall is 0.47 cm (3/16-in.) thick. The silo rests on a pedestal 0.93 m (36.5-in.) high. The assembly is seated on a bottom plate of 1.9 cm (3/4-in.) thickness.

The seismic analysis for the fuel-loaded silo in air uses the dry fuel and jacket weight of 272 kg (600 lbs). The added mass effect is substantial. The virtual mass must be considered in the frequency calculation.

B. Natural Frequencies for Hourglass and Diamond Arrays

The natural frequencies for the two different arrays are listed in the following table. The effects of the surrounding water are shown for both arrays.

Mode No.	Hourglass frequency, Hz		Diamond frequency, Hz	
	w/o water	w/ water	w/o water	w/ water
1	21.678	13.783	21.483	13.755
2	21.718	13.801	21.968	14.072
3	45.790	29.997	58.219	36.656
4	58.263	39.178	77.028	48.410
5	71.231	47.585	80.931	51.524

It is observed in the above table that, as expected, the presence of water tends to reduce the natural frequency and to increase the response of the seismic excitation. The effect of water is significant.

The eigenvectors that correspond to the first few eigenvalues are calculated from ABAQUS. These eigenvectors after multiplication by the corresponding magnitudes in the response spectrum and after SRSS give the estimated response.

C. Structure Response and Margin of Safety

The principal stresses for both of the arrays were plotted by using the contour option. The von Mises stresses were also plotted. The yield stress for stainless steel was assumed to be 276 MPa (40 ksi). If no yielding is allowed in a buckling calculation, then the factor of safety is 11.76. For the maximum displacement for the submerged hourglass array, u_x is 0.91 mm and u_y is 0.92 mm. For the submerged diamond array, u_x is 0.91 mm and u_y is 0.87 mm.

To confirm the computer solution, a simplified method was used to obtain the natural frequency of one silo attached to one pedestal. The simplified model is based on the assumption that the silo and pedestal assembly can be approximately represented by a cantilever beam with the equivalent mass and moment of inertia. By using this approach, the natural frequency for the dry silo and pedestal assembly is found to be equal to 23.59 Hz, which is only about 10% higher than the ABAQUS solution of approximately 21.6 Hz.

The seismic margin of safety, or fragility, was also calculated. Peak ground acceleration of 0.32 g for the safe shutdown earthquake was used in the finite element seismic calculation. The median ground acceleration capacity A_m for the structure is estimated as 4.52 g, which is based on the safety factor of 11.76 that was mentioned above. Then, with 95% confidence, the 5% probability of failure for the structure is 2.33 g, which is substantially larger than the design basis of 0.32 g. Therefore, the structure has sufficient margin against seismic excitation.

IV. THERMAL ANALYSIS AND DESIGN OF NEW STORAGE RACKS

The principal design criterion with respect to thermal issues requires that no boiling take place anywhere. Furthermore, a sufficiently large subcooled margin was imposed to eliminate any uncertainty associated with the supporting thermal calculations. The primary reason for not allowing boiling is the lack of a sufficient experimental data base for the HFIR fuel geometry and pool conditions to support a boiling heat transfer analysis. Hence, the HFIR SAR[2] does not currently take credit for pool boiling heat transfer from the fuel to the pool as a design basis. Secondarily, HFIR operations require a clear visual contact for material movements in the pool.

In all aspects of the design of the new system, sufficient flow paths are provided for natural convection heat transfer. However, in the thermal analysis of the design, the only flow path credited is the flow channel adjacent to a fuel plate. Therefore, this conservative analysis approach does not consider secondary flow paths including the annulus between the fuel elements and the jacket, the annulus between the jacket and silo, the annulus between the inner and outer fuel elements, the annulus between the inner fuel and cadmium-inlaid post, and the "target" flow area within the post. By not crediting these additional flow paths, it was not necessary to simulate all details of the flow patterns that might occur between these parallel paths. The drawback to this conservative approach (only crediting the primary flow path) is an overprediction of the fluid temperatures[3] unnecessarily imposing operational constraints from a thermal perspective.

Three methods of analysis were utilized to arrive at a best estimate of the thermal response of the new system. The first method utilized a "hand calculation" approach that essentially evaluated a momentum and energy balance on the flow channel. The approach iteratively balanced the friction forces with buoyancy forces. The iteration was necessary since the fluid velocity is induced via heat transfer and cannot be solved in closed form (nonlinear). This first approach is identical to that used in the original HFIR design of the present fuel rack system.[3] The drawback to this approach is that it does not accurately predict the fluid temperature peaks. However, it did serve as an adequate independent review calculation.

A second method of analysis utilized a modern computer code, HEATING7.2 (H7).[4] Since H7 is widely accepted by the nuclear community as a bona fide calculation tool for heat transfer analysis, the question of code validity would not arise during the short time frame allotted for the project. Three major sections of user-supplied subroutines were created to interface with H7. First, a section to read in and allocate an externally

generated relative power distribution of the fuel plates was incorporated. Secondly, a section to compute all water fluid properties needed was generated by utilizing an ASME steam tables subroutine package.[5] Finally, a section to formulate and iteratively solve the buoyancy-driven momentum and energy balance of the fluid was interfaced as a boundary condition to each individual node of the H7 fuel plate model. The result was a model of sufficient detail to capture peak fluid temperatures not achievable in the first method. Figure 2 depicts a representative H7 node showing the relationship between the H7 indexing and the user-supplied subroutine indexing. Figure 3 shows a representative mesh of a three-high stacked silo fuel plate boundary producing greater than 1600 nodes for each plate on the coarse grain (a fine grain produced essentially the same result). Figure 4 shows a representative fuel plate surface temperature distribution produced by the steady state result for a stacked silo configuration with fuels having 1-day, 61-days, and 365-days decay time. The overall results produced temperatures greater than or equal to that of the first method when independently compared. In general, regions with relatively little power production, shown as the top layer of Figure 4, were nearly identical via the two methods. This second method captured peak temperatures as high as 8.3°C (15°F) greater than that of the first method in regions of higher power production and hot channel geometry configurations.

One key assumption made in the second method is that the fluid velocity is constant throughout the flow channel. Two subsets of the analysis were performed using this assumption. The first assumed that each stacked fuel assembly did not allow for hydraulic coupling with an adjacent fuel assembly (i.e., no "chimney" effect was allowed as if all the flow could divert around an adjacent fuel assembly). A second subset allowed for complete hydraulic coupling, hence, maximizing the "chimney" effect as if the flow existed in the fuel plates only. The actual flow is expected to be somewhere between these two extremes. However, because a conservative safety analysis is desired, the results of the decoupled channels (i.e., no "chimney") were used for final results.

Because of all the simplifying assumptions necessary to produce the H7 results, a third method of analysis utilizing a modern computational fluid dynamics (CFD) code to analyze representative fuel channel heat transfer is underway. This last method is not complete at this writing, but benchmark simulations of a single plate have shown remarkably similar results with the second method. Results of the CFD analysis will be presented in a detailed paper at a later time.

The final results showed a representative hot channel to be in the worst condition if stacked as 14-days, 31-days, and 366-days three-high in a silo producing an 4.7°C (8.4°F) subcooled margin. Since each fuel assembly will be at least 31 days apart in age, this scenario is not possible. Further parametric studies were performed examining bounding values on uncertainties such as friction factor and heat transfer coefficient and found the results to be tolerable. In essence, as long as the top tier is at least one year old, no thermal limitations should exist in the stacked silo.

One accident scenario that was deemed credible considered a dropped jacketed fuel assembly on the pool floor. A second accident scenario, a blocked flow channel, was bounded by other more credible events in the HFIR SAR. A detailed calculation of the dropped fuel assembly is currently being investigated by a CFD code discussed in the third method above. Until credible results can be obtained using these detailed CFD methods, an adiabatic heat up calculation was utilized to analyze the dropped jacketed fuel assembly. The results from this adiabatic analysis yielded a maximum time to wait before uprighting a dropped jacketed fuel assembly without fuel damage.

V. CORROSION CONSIDERATIONS

One consequence of the inability to reprocess spent HFIR fuel elements is the increased time the fuel elements will remain in the HFIR pool. The fuel elements as fabricated have a nominal cladding thickness of 254 ±51 μm of 6061 aluminum over the U_3O_8—aluminum fuel matrix. During a reactor cycle, the cladding may be thinned as much as 50 μm at localized hot spots, leaving the possibility of a minimum cladding thickness of 152 μm at the time the fuel elements are transferred to the pool. Some fuel elements have now been in the pool for more than 8.5 years without evidence of cladding penetration, and the question is how much longer can these and other fuel elements remain free from cladding failures in the high purity pool water. In order to make a reasonable prediction about the long-term behavior of fuel elements in the HFIR

pool, experimental results obtained under controlled conditions as well as experience at other representative pools were examined.

A. Experimental Corrosion Results

Over the years, several investigations have been carried out at ORNL (as well as other laboratories) that show aluminum alloys undergo very little corrosion in water similar to that in the HFIR pool. Some examples of the results of such tests conducted at ORNL are given below.

Specimens of 1100, 3003, 5052, 5154, and 6061 aluminum were exposed for one year in the core of the Oak Ridge Research Reactor (ORR) and in the pool surrounding it.[6] In the core, water flowed past the specimens at 2.4 to 3.7 m/s (8 to 12 ft per second) and the temperature was 51 to 56°C (124 to 133°F); in the pool the water flow was very low and the temperature was 38°C (100°F) or less. Both systems underwent continuous bypass demineralization, and the conductivity of the water was 333 to 667 μS/m. In all cases observed, corrosion rates were 2.5 μm (0.1 mils) per year or less and pitting was absent. It should also be noted that the ORR pool liner is made of 6061 aluminum, and at least near the air-water interface the aluminum can be easily viewed. No evidence of damaging corrosion or obvious pitting has ever been reported in this area.

Numerous tests were conducted with 1100, 6061, and 8001 aluminum in support of the HFIR primary system[7,8] in which the pH of the deionized water was adjusted to 5.0 with nitric acid. The temperature was 100°C or less in all cases. Corrosion rates both in flowing and static systems were 5 μm (0.2 mils) per year or less. Occasional shallow pits were found in static systems but not in flowing water.

Fuel plates from three different HFIR cores were examined after a year's cooling period in the HFIR pool.[9] The results suggest that little if any corrosion occurred during the year in the pool.

A simple relevant experiment was recently reported.[10] A weighed specimen of 6061 aluminum with a machine finish was placed in a beaker of deionized water, which was covered with a polyethylene film. The beaker remained in an office at 16 to 19°C (61 to 66°F) and was only occasionally observed during the next five years. During that period, the shiny surface changed to dull gray and a small amount of white-gray powder collected in the bottom of the beaker. The author estimated that the average penetration was about 2.5 μm (0.1 mil) during the five years. Several small pits were noted but the deepest was only about 25 μm (1 mil).

B. Experiment Storage Pools

The operators of storage pools at the following sites were contacted to obtain their experience with aluminum clad fuel elements: Idaho National Engineering Laboratory (INEL), Brookhaven National Laboratory (BNL), University of Missouri (U of Mo), National Institute of Standards and Technology (NIST), Westinghouse Savannah River Plant (W-SRP) and, of course, the two pools at ORNL. While the quality of the water in the pools can be quantitatively measured, the condition of the fuel elements can be viewed only through deep water, and with most fuel elements, only the outermost fuel plates can be seen. With the HFIR fuel elements, no plates can be observed without destruction of the element. Consequently, the condition of fuel elements in a pool is usually inferred by the presence or absence of fission products in the pool water.

At INEL, W-SRP, and ORNL, two or more pools were discussed whereas at the other installation only a single pool was considered. At each of the first two installations, one pool is filled with high quality water and the second contains extremely impure water. At INEL, the pool built in 1950 reportedly contained water with about 50 ppm chloride (from sodium hypochlorite additions to control algae) as well as fission products and the conductivity is reported to have been as high as 0.18 S/m (560 ohm-cm). Fuel elements in this pool had random, whitish-gray nodules, which are or have been active pits, at least some of which have penetrated the aluminum cladding.

At W-SRP, the disassembly basins (pools) where the elements removed from the production reactors are stored until disassembled also contain low-grade water. Up to 20 ppm dissolved solids are allowed and a typical conductivity is 0.045 S/m (2.5×10^3 ohm-cm). In these basins, aluminum cladding has been penetrated in times as short as 60 to 90 days.

The other pools at INEL and W-SRP as well as all pools at the other referenced installations contain high-purity water, which is continuously deionized. The conductivity of the water is 200 μS/m or less in all cases, except in the NIST pool where it is 250 to 500 μS/m. So far as is known, no fuel elements stored in these pools have developed leaks with the possible exception of one pool at ORNL. The maximum times fuel elements have been in these pools are BNL—11 years; INEL—9 years; W-SRP—31 years (Hector reactor fuel elements); U of Mo—4 years; NIST—11 years; ORNL-HFIR—8.5 years; and ORNL-BSR—29 years.

The Bulk Shielding Reactor (BSR) pool contains fuel elements from the Pool Critical Assembly (PCA) and from the BSR and ORR. Fission gas leakage into the common confinement building (BSR and PCA) has occasionally been detected during high-power operation of the PCA (5 to 10 kW). The identity of the leaking PCA element and whether the leak developed in the pool have not been determined. Leakage has not been detected when the reactor was not operating at high power.

One interesting observation was reported by personnel at the U of Mo. A spent 6061 aluminum clad fuel element, after about 3 years in the pool was stored in a stainless steel lined shipping cask along with enough water to cover the fuel element, which was in electrical contact with the stainless steel liner. The cask was stored indoors and was totally undisturbed for 2.5 years. On removal, the element had a whitish gray coating and the water contained a suspension of aluminum oxide. There were no obvious pits in the aluminum, and there were no fission products in the water. This result agrees with the observation made in the beaker test previously described.[10] In both cases, even though the water quality undoubtedly deteriorated significantly during the prolonged exposure, there was no serious damage to the aluminum.

C. Conclusion

The experience at several storage pools, as well as experiments conducted in other systems, strongly suggest that corrosion failure of the HFIR fuel cladding is not probable in the foreseeable future, provided the present water quality is maintained. On the other hand, in very impure water, cladding penetration can be expected in short times. How bad the water quality must get before aluminum corrosion becomes significant has not been determined. As a general rule and to allow an adequate safety factor the conductivity of the pool water should not be allowed to exceed 200 μS/m, while 100 μS/m would be preferable. Even the lower value is achievable without undo strain on operating personnel.

VI. IMPACTS ON FUEL STORAGE POOL OPERATIONS AND WATER SYSTEMS

While water conditions (conductivity, clarity, and absence of fission product activity) in the HFIR pool have historically been very good, a substantial increase in quantity and age of spent fuel could impact pool operations through fission product contamination from leaking fuel elements and/or suspended fine aluminum oxide particles which could obstruct underwater vision. Continuous operation of the water purification system, which includes filters and demineralizers, should minimize the potential for serious interference with operations from either fission products or undissolved aluminum oxide by keeping the dissolved ion concentrations at a minimum.

Currently, the HFIR pool demineralizer resins are replaced at about two-year intervals and are regenerated one or two times between replacements, generating 42,000 L (11,000 gal) of regeneration solutions and rinse water each regeneration. These solutions are contaminated with long-lived activities (principally ^{152}Eu and ^{154}Eu from prior leakage from activated HFIR control plates and ^{60}Co from safety plate bearing alloys) and, therefore, are ordinarily discharged to the ORNL LLLW system. However, to meet evolving requirements for LLLW minimization in the future, the demineralizer resins in both the pool and primary water purification systems will be replaced without regeneration, and the depleted resins will be dewatered and discharged as solid waste. Filter rinses will still be required, but the rinse water will be cleaned in a small auxiliary demineralizer and recycled. The impact of an increased stored fuel inventory on these operations is expected to be more frequent resin replacement and increased solid waste disposal, and a possible increase in discharged resin activity if fission product leakage should occur. These effects are generally acceptable under current waste limitations and are preferable to the increased LLLW volume associated with demineralizer regeneration.

The HFIR pool water has been routinely monitored for gross activity and conductivity. With the future increase in spent fuel inventory, the pool surveillance activity will be expanded to include (1) identification of fission product isotopes, if present, through gamma spectrometry; (2) installation of aluminum corrosion specimens in the pool, to detect any changes in corrosion rate; and (3) design and fabrication of a "sniffer" to locate leaking fuel elements in the event fission products are detected in the pool water. The sniffer concept, currently under consideration, is similar to others used in the past by ORNL and involves pumping water from a fuel storage location through a small ion exchange column to concentrate fission product activity for comparison with water samples drawn from other locations.

If a leaking fuel element should be discovered, it can be placed in one of two special storage positions where direct cooling is provided without contamination of the bulk pool water. These are located near the bottom of the reactor pool, and water discharged from these positions flows directly into the purification and pool cooling system. Cans are also being designed to isolate individual fuel assemblies from the pool and will be available in the future for use with leaking fuel assemblies that do not require direct contact with pool water for cooling.

VII. CONCLUSIONS

Spent fuel storage capacity at the HFIR is being increased in stages to accommodate a much larger inventory of irradiated fuel. This increase is necessary to provide for continued operation of the reactor while allowing adequate time for the exploration of alternatives such as fuel reprocessing, dry storage, or other measures. The increased storage capacity is made possible by using a more dense, three-tier storage rack design.

The oldest fuel now in the pool was discharged 8 1/2 years ago, and there has been no sign of fission product leakage thus far. If the 20 oldest fuels (including 12 fuels discharged prior to the 1986 HFIR shutdown) are shipped to the Savannah River Site as currently planned, the oldest fuel remaining in pool storage when 143 positions are filled will have been stored for about 14 years. A survey of other storage pools with similar fuel and water conditions has shown consistently low risk of fission product leakage from fuel stored for equal or longer durations.

Methods and equipment for detecting and isolating leaking fuel, should this occur, are either currently available or planned for near term acquisition. Finally, the HFIR fuel design which uses an Al-U_3O_8 dispersion fuel is expected to limit the fission product transport from a leaker into the pool to a very small rate which can be handled by the pool demineralizers without seriously affecting normal operations.

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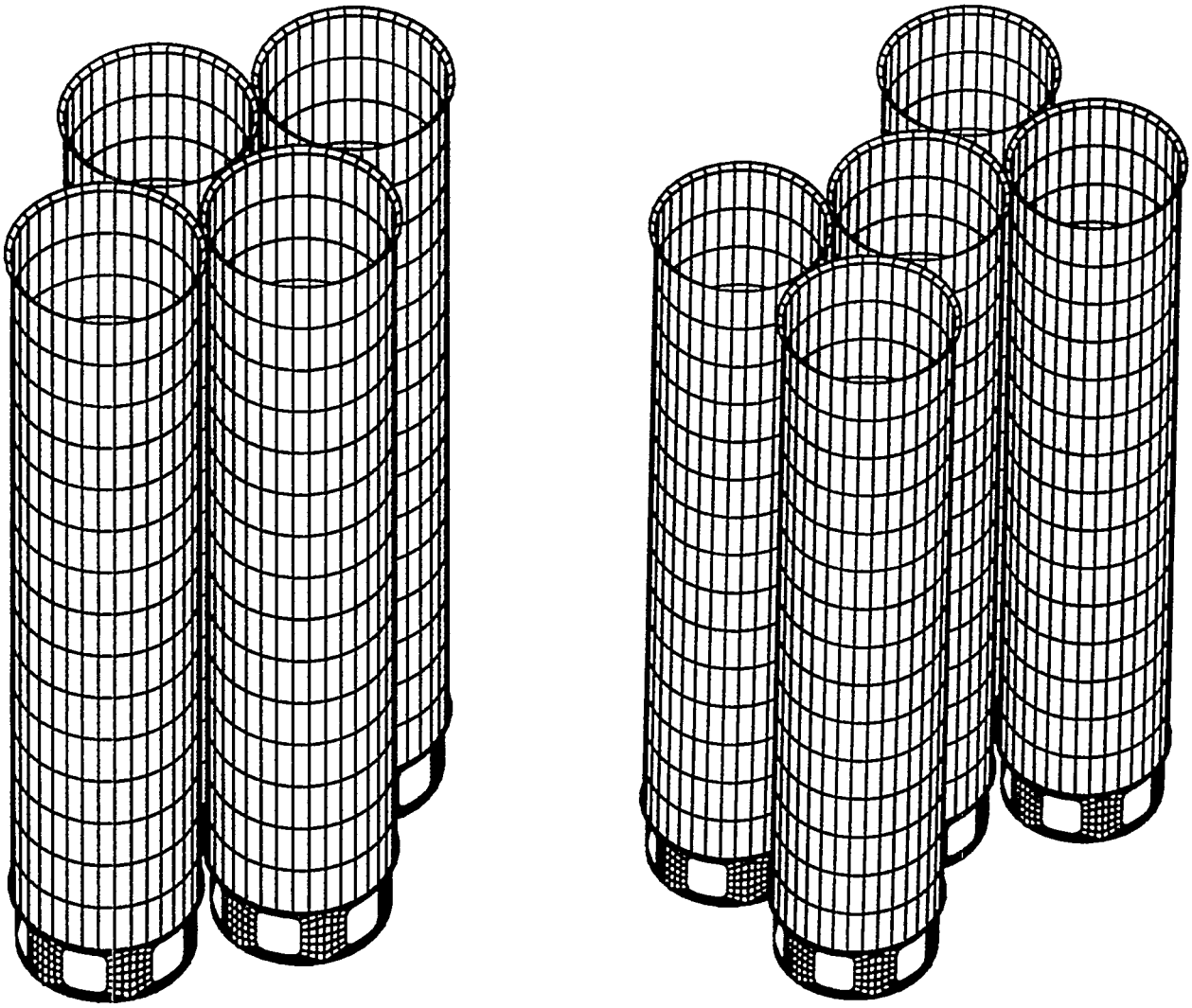

Figure 1. "Diamond and "Hourglass" Arrays

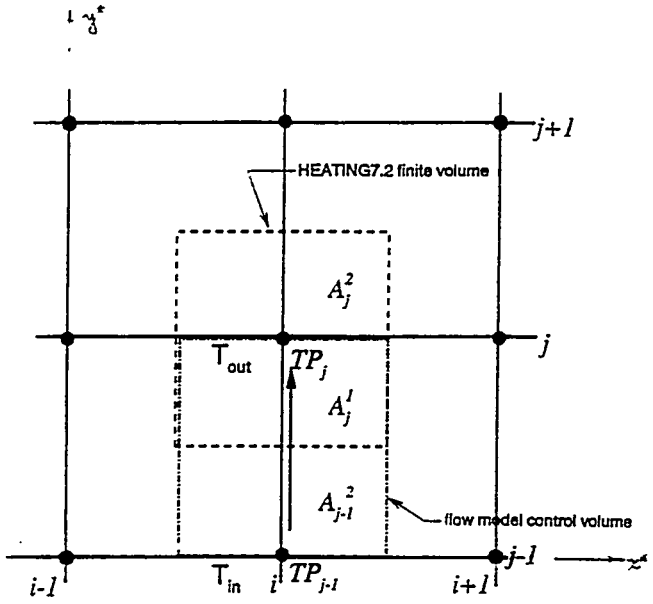

Figure 2. HEATING7 Node Structure

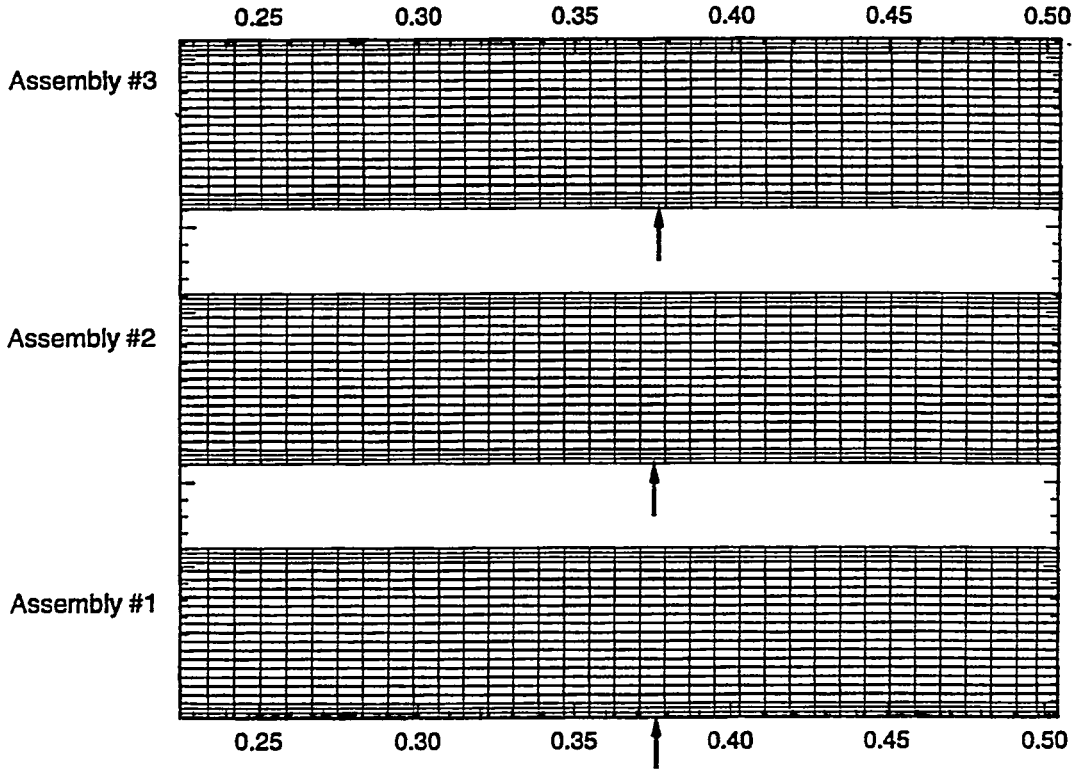

Figure 3. Three-Tier Array Calculational Mesh

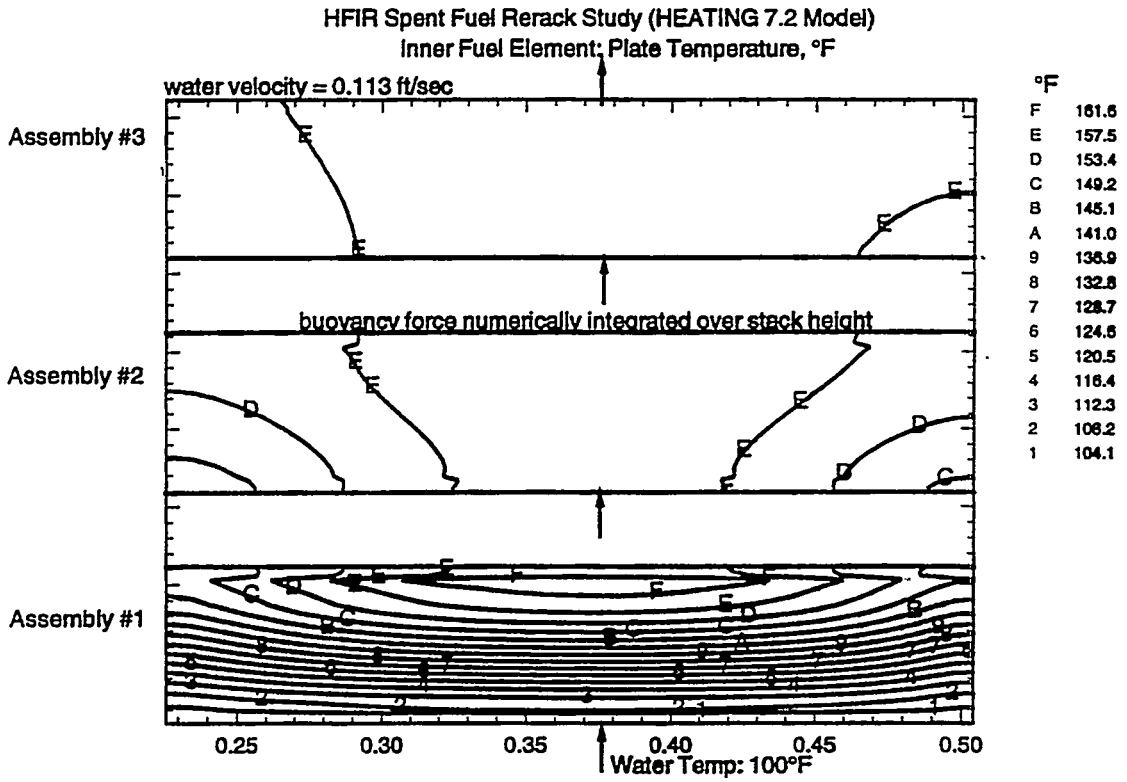

Figure 4. Inner Plate Calculated Surface Temperatures