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Tank 241-AZ-101 Criticality Assessment Resulting from Pump Jet Mixing: Sludge Mixing Simulations

Y. Onishi
K. Recknagle

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Pacific Northwest National Laboratory
Richland, Washington 99352

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Executive Summary

Tank 241-AZ-101 (AZ-101) is one of 28 double-shell tanks located in the AZ farm in the Hanford Site's 200 East Area. The tank contains a significant quantity of fissile materials, including an estimated 9.782 kg of plutonium. Before beginning jet pump mixing for mitigative purposes, the operations must be evaluated to demonstrate that they will be subcritical under both normal and credible abnormal conditions.

The main objective of this study was to address a concern about whether two 300-hp pumps with four rotating 18.3-m/s (60-ft/s) jets can concentrate plutonium in their pump housings during mixer pump operation and cause a criticality. The three-dimensional simulation was performed with the time-varying TEMPEST code to determine how much the pump jet mixing of Tank AZ-101 will concentrate plutonium in the pump housing.

Tank AZ-101 has 22 air lift circulators that have been operated continuously for years to mix the sludge during and after the period of plutonium-bearing waste additions. However, in these tests we neglected the mixing effects of the air lift circulators to obtain the conservative initial plutonium distribution within the sludge. Heterogeneous distributions of plutonium within the sludge might have been caused by two factors: the 262 sequential discharges of the plutonium-bearing wastes into AZ-101 and the preferential settling of heavier, larger solids affected by the three-dimensional, dynamic, interactive, flow/solid transport/rheological processes. Even though the dynamic slurry flow movements will not maintain the segregation caused by the sequential waste discharges totally intact, we added these two segregation factors together. This addition resulted in the initial maximum plutonium concentration of 1.88 g/L, which is 30 times greater than the actual average plutonium concentration in the AZ-101 sludge. The segregation factor of 30 is very conservative in light of the fact that even in the mining industry, the 10 to 20 μm size range is below the normal particle range for either gravity or flotation segregation processes without special chemical additives and very specialized equipment that would provide rhythmic shaking, thin liquid films, or high centrifugal forces coupled with selective collection and concentration to achieve the segregation. Furthermore, the total plutonium mass in the model is nine times higher than the actual amount stored in the tank, 9.782 kg.

The AZ-101 model, with these very conservative initial plutonium conditions, predicted that the total amount of plutonium within the pump housing peaks at 75 g at 10 simulation seconds and decreases to less than 10 g at four minutes. The plutonium concentration in the entire pump housing peaks at 0.60 g/L at 10 simulation seconds and is reduced to below 0.1 g/L after four minutes. Since the minimum critical concentration of plutonium is 2.6 g/L, and the minimum critical plutonium mass under idealized plutonium-water conditions is 520 g, these predicted maximums in the pump housing are much lower than the minimum plutonium conditions needed to reach a criticality level.

The initial plutonium maximum of 1.88 g/L still results in safety factor of 4.3 in the pump housing during the pump jet mixing operation. Even with the plutonium segregation factor of 130 (30 times 4.3), the total amount of plutonium in the pump will be 323 g, less than the minimum plutonium critical mass of 520 g. Thus the pump jet mixing operation in AZ-101 will not produce sufficiently large plutonium concentrations and mass within the pump housing to cause a criticality.

Contents

Figures

Table

1.0 Introduction

Hanford Tank 241-AZ-101 (AZ-101) contains a significant quantity of fissile materials, including an estimated 9.782 kg of plutonium (Vail 1997). Thus, before the planned jet pump mixing operation begins, the operation must be evaluated to demonstrate that mixing will be subcritical under both normal and credible abnormal conditions, as required by DOE Order 420.1, paragraph 4.3.2.

The objective of this study was to determine whether two 300-hp pumps with four rotating 18.3-m/s (60-ft/s) jets located 43 cm (17 in.) above the tank bottom could concentrate the heterogeneously distributed plutonium in their pump housings during mixer pump operation and cause a criticality. The three-dimensional computer code,TEMPEST (Trent and Eyler 1993; Onishi et al. 1995) was applied to the entire AZ-101 tank waste area, including its pump housing, to obtain time- and spatially varying plutonium amounts and concentrations. Results of an earlier study were reported by Onishi and Recknagle in Vail (1997).

Tank AZ-101 is one of 28 double-shell tanks located in the AZ farm in the Hanford Site's 200 East Area. Its diameter and height are 23 m (75 ft) and 10.6 m (35 ft), respectively. It began its service by receiving evaporator waste in 1976 (Vail 1997). Subsequently, the tank received more evaporator waste, complexed and noncomplexed waste, double-shell slurry feed, water, evaporator waste residual liquor, complexant concentrate, and transfers (primarily supernatant liquid) from other waste tanks. In 1981 and 1982, some of the waste in AZ-101 was transferred into several other tanks.

Between 1983 and 1986 the tank received PUREX aging waste containing an estimated 9.733 kg of plutonium. The tank currently receives only condensate from other aging waste tanks, so the plutonium-bearing waste stored in the tank results from the most recent, 1983–1989, PUREX separations operations.

This report describes the results of time-varying, three-dimensional simulations, including predicting the highest concentration and the largest amount of plutonium within the pump housing. Section 2 summarizes the main tank waste characteristics and the waste retrieval system. Section 3 discusses the TEMPEST code and the model input data and parameters, including boundary/initial conditions. Section 4 presents simulation results and evaluations, while Section 5 summarizes the study and states the conclusions drawn from the work.

2.0 AZ-101 Tank Wastes and Retrieval

Tank AZ-101 contains both sludge (a combination of solids and interstitial solution) and overlying supernatant liquid (Peterson et al. 1989). It currently contains 15 in. of sludge and 321 in. of supernatant liquid, totaling 336 in. of the tank waste; the volume ratio of sludge to supernatant liquid is 21.7. Tank AZ-101 has a sludge layer with a bulk density of 1.56 g/mL, while the supernatant liquid has a density of 1.22 g/mL.[a] The particle density of the average bulk sludge is 1.84 g/mL, and the volume fraction of the solids within the sludge is measured to be approximately 44%. The solid particles vary in size from 0.5 to 13 μm, with the average size about 4 μm based on the volume.[a]

The basic concept of tank waste retrieval for a double-shell tank is to 1) mix the sludge and supernatant liquid and 2) withdraw the resulting slurry mixture from the tank. This requires two sets of pumps, one for mixing the waste and the other for removing the waste from the tank. Waste mixing will be achieved by suctioning out the sludge near the tank bottom and injecting it back into the same tank. Injecting sludge with high speed will not only mix the sludge within the tank but also entrain the supernatant liquid as the injected sludge penetrates and spreads into the tank waste. With this entrainment, the sludge and supernatant liquid will be mixed together to form a nearly homogeneous slurry in the tank. Plans for AZ-101 are to use two 300-hp mixer pumps located off the tank center. Some other tanks may use one mixer pump located at the tank center, depending on the waste conditions and amounts. The mixer pump jets will rotate continuously to enhance waste mixing. The resulting slurry mixture, which is expected to have a very small settling velocity, will then be removed from the tank with another pump located at the tank center. These two pumps (mixer pump and removal pump) may or may not operate simultaneously, depending on the waste and operational conditions. Tank AZ-101 will be the first double-shell tank to actually test how effective these mixer pumps would be to homogenize the sludge and supernatant liquid.

The two mixer pumps in Tank AZ-101 have two jet nozzles each. The four outlets have 6-in.-diameter nozzles and are placed 17 in. above the tank bottom, while the pump suction line has a 13.5-in. diameter and is positioned 7 in. above the tank bottom. The volume of the pump housing was assigned to be approximately 122 L, excluding the nozzle volume. The jet nozzles inject recirculating slurry into the tank at a velocity of 60 ft/s. These two mixer pumps are located 22 ft from the tank center on opposite ends of an imaginary diagonal line through the tank center. Each jet rotates over a half-circle area at a speed of 0.05 rpm.

(a) Gray WJ, ME Peterson, RD Scheele, and JM Tingey. 1993. *Characterization of the Second Core Sample of Neutralized Current Acid Waste from Double-Shell Tank AZ-101* (draft). Pacific Northwest Laboratory, Richland, Washington.

3.0 Tank AZ-101 Model Setup with the TEMPEST Code

3.1 TEMPEST Code

The TEMPEST computer code can simulate flow and mass/heat transport coupled with chemical reactions (equilibrium and kinetic reactions) (Onishi et al. 1996a). For this study we used the T.2.10 version of TEMPEST to solve three-dimensional, time-dependent equations of flow, momentum, heat, and mass transport, based on conservation of

- fluid mass (the equation of continuity)
- momentum (the Navier-Stokes equations)
- turbulent kinetic energy and its dissipation
- thermal energy
- mass of dissolved constituents
- mass of solid constituents
- mass of gaseous constituents.

Complete equations for conservation of mass, momentum, energy, and treatment of turbulence energy are documented in Trent and Eyler (1993). TEMPEST uses integral forms of the fundamental conservation laws applied in the finite volume formulation. It uses the k-ε turbulence model (Rodi 1984) to solve the turbulence kinetic energy and its dissipation. TEMPEST can accommodate non-Newtonian power law fluids as well as fluids whose rheology depends upon solid concentrations (Mahoney and Trent 1995; Onishi et al. 1995). Transport of multiple liquid, gas, and solid constituent species also can be performed.

3.2 AZ-101 Model Conditions and Parameters

A Tank AZ-101 conceptual model used in TEMPEST simulates the operation of two mixer pumps each with two rotating jet nozzles. TEMPEST predicted the movements of supernatant liquid and nine different solid size fractions. Tank AZ-101 TEMPEST runs were three-dimensional but covered one-half of the tank domain through symmetry of the pump jet operation.

Main parameters for the AZ-101 modeling are particle sizes and densities, solid volume fraction in the sludge, and those values needed to calculate solid settling velocities, viscosity, and yield stress. The assumed initial plutonium distribution is discussed below.

3.2.1 Solid Physical Properties

The solid particles of AZ-101 sludge vary in size from 0.5 to 13 μm, with the average size about 4 μm based on the volume.[a] The particle density of the average bulk sludge is 1.84 g/mL. All TEMPEST calculations assumed that the non-plutonium-bearing solid particles have densities of 1.84 g/L. These particle size distributions actually represent heterogeneous agglomerates. As reported in Serne et al. (1996) and Whyatt et al. (1996), solid plutonium is aggregated with other precipitates. Because of the strong bonding of the agglomerate, the plutonium does not separate from the agglomerate.

(a) Gray WJ, ME Peterson, RD Scheele, and JM Tingey. 1993. *Characterization of the Second Core Sample of Neutralized Current Acid Waste from Double-Shell Tank AZ-101* (draft). Pacific Northwest Laboratory, Richland, Washington.

Whyatt et al. (1996) also reported that if pure plutonium solids exist in the tank, they are most likely $PuO_2 \cdot x\ H_2O$. The density of pure PuO_2 is 11.4 g/L. When initially precipitated, plutonium particles are x-ray amorphous, from which the size can be deduced to be <0.004 µm. Over time these crystallites can dissolve and reprecipitate to form larger particles. The upper bound of plutonium particulates was estimated to be approximately 8 µm, with 60% of the material finer than 2 µm.

Onishi et al. (1996b) examined the crystallinity, chemical composition, and crystalline phase of Hanford Tank 241-SY-102 sludge using transmission electron microscopy, electron energy dispersive spectroscopy, and electron diffraction. These measurements indicated sub-micron primary particle sizes, while light scattering and sludge settling tests showed larger particle size distributions of 10-175 µm, because those latter tests actually measure agglomerate properties. These measurements indicate that the solids behave as aggregates when they are transported and deposited. Agglomeration of particles prevents any significant segregation of plutonium, because the agglomerates settle based on their own size and density and thus mask the potential segregation of plutonium based on the size or density of a few (0.002 wt%) plutonium particulates.

However, to cover the possible conditions, the following four types of plutonium solids were considered in this modeling: Solid 1, with the smallest particle diameter (0.5 µm) and the density of the aggregate (1.84 g/L); Solid 2, of the smallest size (0.5 µm) and largest density (11.4 g/L); Solid 8, with the largest size (13 µm) and the density of an aggregate (1.84 g/L); and Solid 9, with the largest particle size (13 µm) and the largest density (11.4 g/L). The particle distribution and calculated unhindered settling (fall) velocity, with 2 cP viscosity, are shown in Table 3.1 for Solids 1 through 9 and are discussed in Section 3.2.3. The rest of the solids in the

Table 3.1. Particle Size Distributions of Tank AZ-101 Sludge

Size Fractions	Particle Sizes (µm)	Particle Density (g/L)	Weight Percent	Fall Velocity* (mm/s)
1	0. 5	1.84	< 0.002	4.2×10^{-5}
2	0. 5	11.4	< 0.002	6.9×10^{-4}
3	0.5 - 2.0	1.84	19.4	1.7×10^{-4}
4	2.0 - 5.0	1.84	40.9	1.7×10^{-3}
5	5.0 - 8.0	1.84	20.8	6.7×10^{-3}
6	8.0 - 11.0	1.84	14.7	1.5×10^{-2}
7	11.0 - 13.0	1.84	4.2	2.4×10^{-2}
8	13.0	1.84	< 0.002	2.9×10^{-2}
9	13.0	11.4	< 0.002	4.7×10^{-1}
Total			100	

* An unhindered fall velocity is input to the model. TEMPEST internally calculates hindered fall velocity for each particle size for the appropriate slurry conditions calculated at each computational node and time step.

sludge were divided into five size fractions (Solids 3 through 7). Concentrations of Solids 3 through 7 are distributed uniformly within the entire sludge layer at 157, 331, 169, 119, and 34 g/L, respectively.

The simulation was performed with nine solids instead of six (Solids 3–7 and one of the plutonium solids 1, 2, 8, or 9) to eliminate the need for four separate simulation runs, because the plutonium-bearing solids make up a very small fraction (less than 0.002 wt%), and their effects on flow and other solid movement are expected to be negligible.

The sludge layers in the AZ-101 model have a solid weight fraction of 0.54.[a] The corresponding volume fraction, C_{vmax}, was estimated to be 0.44.

3.2.2 Initial Distribution of Plutonium-Bearing Solids

There were 262 separate campaigns between November 15, 1983, and March 23, 1986, that injected 2.388 million liters of PUREX aging waste containing an estimated 9.733 kg of plutonium into AZ-101 (Vail 1997). The waste was discharged through a 3-in. process pipeline at a rate of approximately 70 gpm. The average discharge velocity at the pipe exit was 0.9 m/s, lasting about 30 minutes. These effluents were estimated to have on the average about 3 wt% of the solid with the density of 1.24 kg/L, compared with a supernatant liquid density of 1.22 kg/L.

AZ-101 has 22 air lift circulators (ALCs) to mix the sludge. The ALCs consist of two pipes (a 3-in. pipe inside a 20-ft long, 30-in. diameter pipe) placed 30 in. above the tank bottom. Compressed air was forced down through the inner pipe and escaped from the bottom, where it produced bubbles and entrained liquid and fine solids that rose with the bubbles within the outer pipe. The buoyancy produced by the rising bubbles moved the entrained slurry, creating convection cell flows in the tank to pull surrounding sludge/slurry into the ALCs[b] and mix nearby sludge to homogenize it (Whyatt et al. 1996). These ALCs had been operating continuously for years, during and after the plutonium-bearing waste was added. Eyler conducted three-dimensional modeling for waste movements in a double-shell tank with the ALC operation showing one-seventh of the tank area (See Figure 3.1).[b] Examples of predicted velocity distributions are presented in Figures 3.2 through 3.4, showing upward flows in ALCs and convection cell flows predominately moving down toward the tank bottom outside of ALCs. When the slurry was discharged to AZ-101 with the ALCs operating, the newly released slurry with its solids was entrained in the induced convection cell flows, which already contained some tank sludge, and moved with the flows. Although the downward velocity of the convective cell flows differs at the various locations, as shown in Figures 3.2 and 3.3, the average downward velocity is much greater than the free settling velocities of these solids (see Table 3.1). Under this type of slurry flow condition, these solids will not settle to the tank bottom as free settling separate particles. Eyler[b] and Whyatt et al. (1996) determined that much of AZ-101 sludge is well-mixed by the ALCs.

The more heterogeneous the plutonium distribution in the sludge, the greater the chance of higher plutonium concentrations within the pump housing at some point in time. We neglected the mixing effects of the ALCs to obtain conservative initial plutonium distribution in the sludge.

(a) Gray WJ, ME Peterson, RD Scheele, and JM Tingey. 1993. *Characterization of the Second Core Sample of Neutralized Current Acid Waste from Double-Shell Tank AZ-101* (draft). Pacific Northwest Laboratory, Richland, Washington.

(b) Eyler LL. 1983. *Sediment Settling and Resuspension in Waste Storage Tanks with Air Injection Circulators*. Letter report FATE-83-109, Pacific Northwest Laboratory, Richland, Washington.

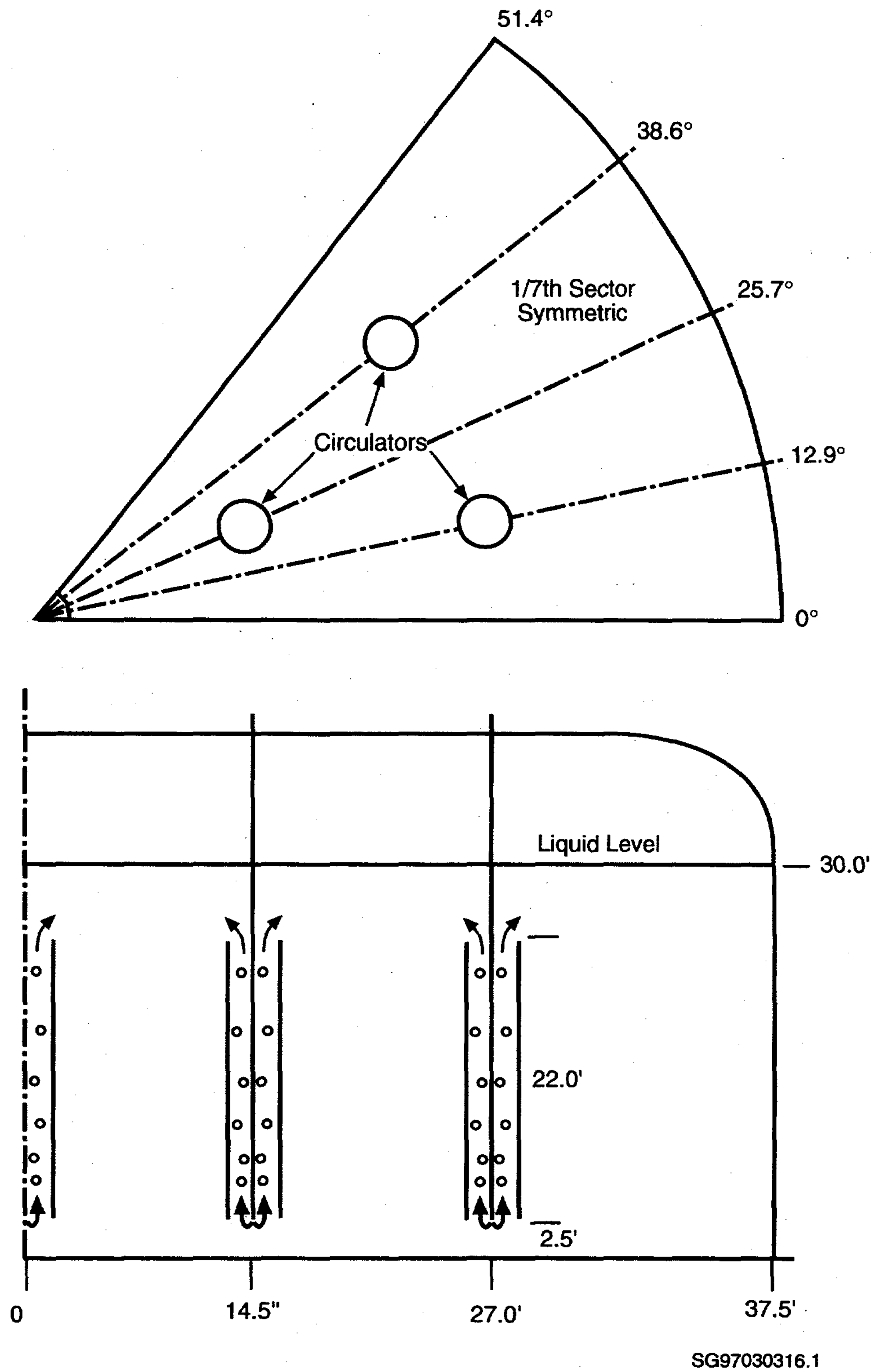

Figure 3.1. Air Lift Circulators

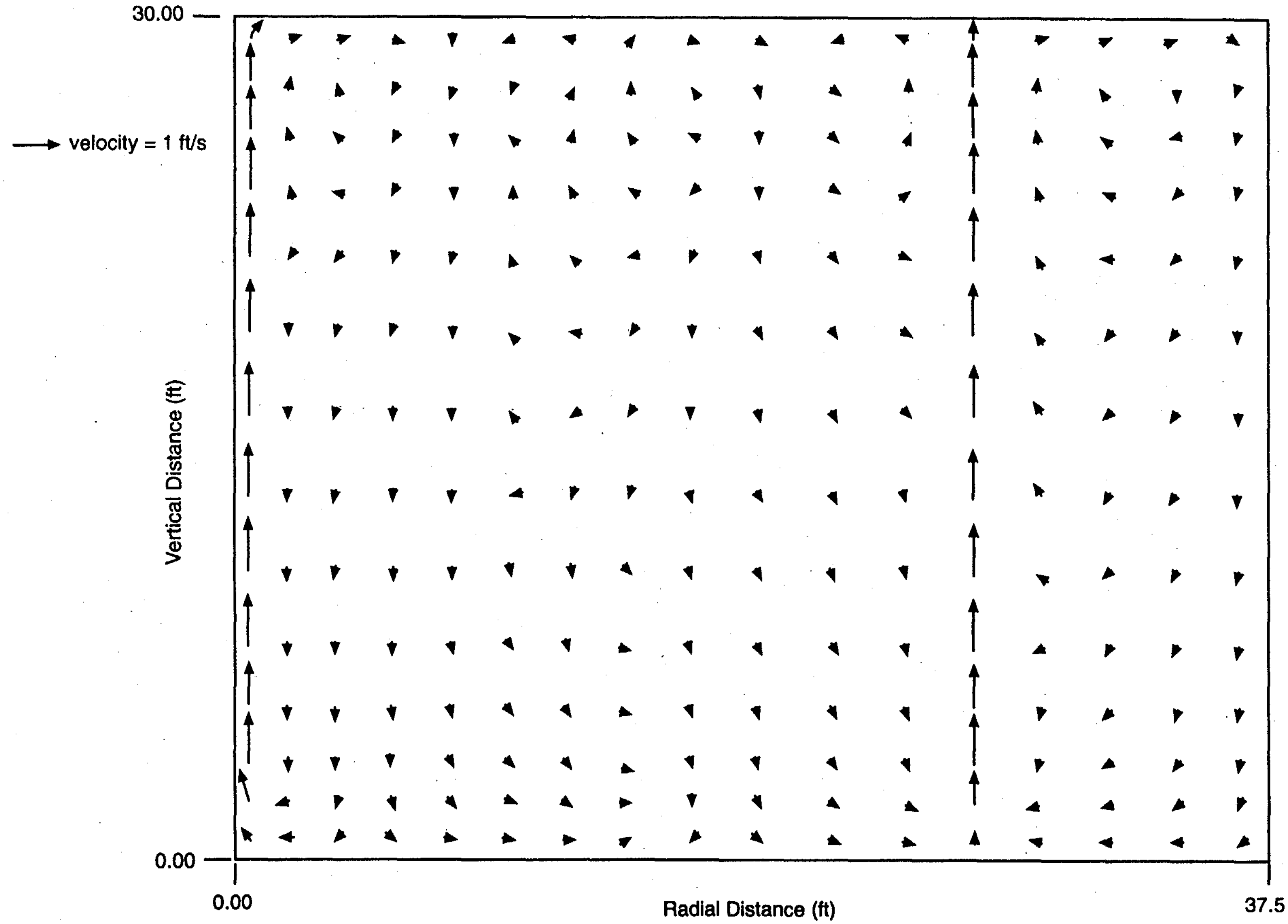

Figure 3.2. Predicted Velocity Distribution in a Vertical Plane along 12.9°[(a)]

(a) Eyler LL. 1983. *Sediment Settling and Resuspension in Waste Storage Tanks with Air Injection Circulators*. Letter Report FATE-83-109, Pacific Northwest Laboratory, Richland, Washington.

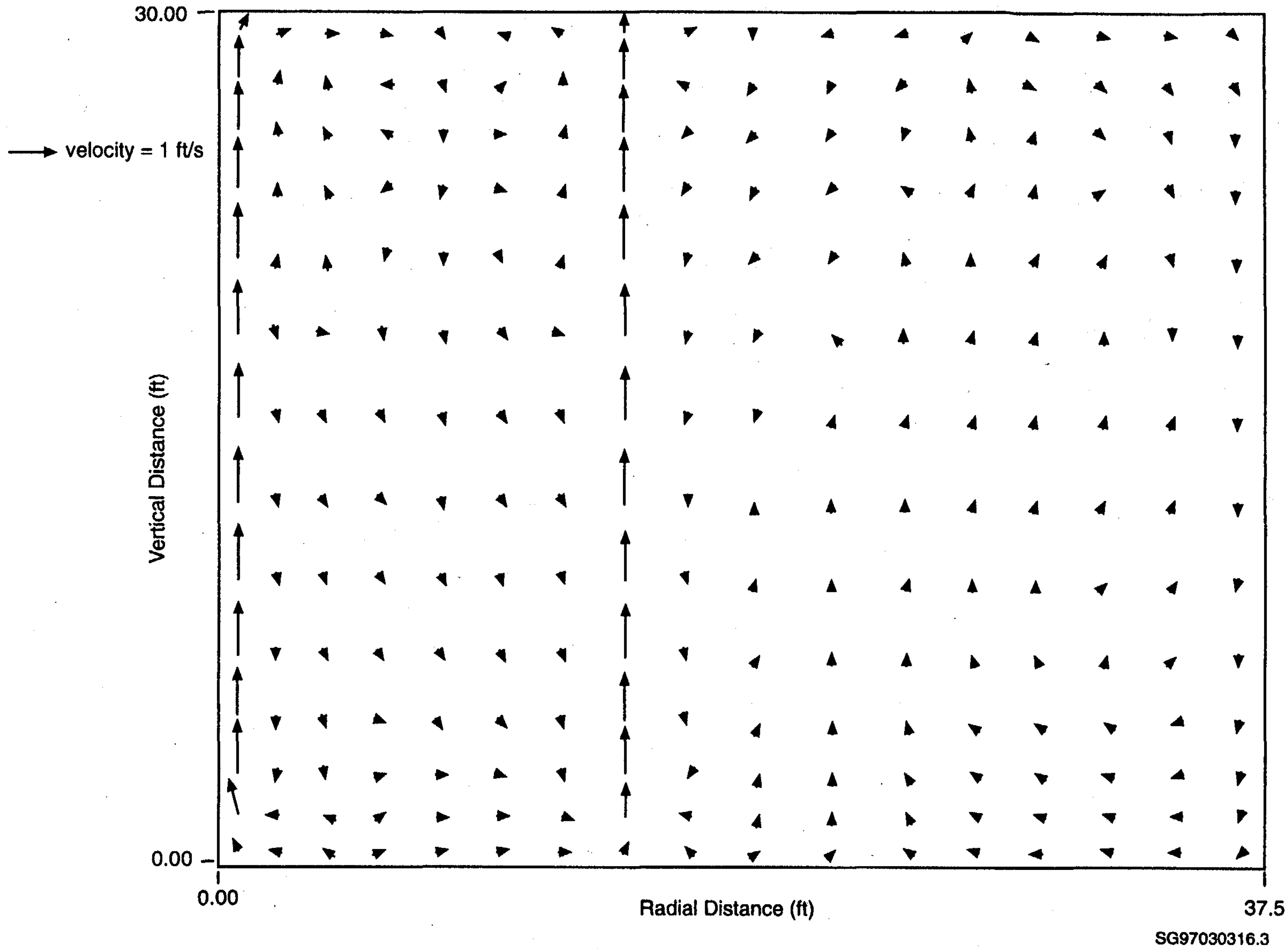

Figure 3.3. Predicted Velocity Distribution in a Vertical Plane along 25.7°[(a)]

(a) Eyler LL. 1983. *Sediment Settling and Resuspension in Waste Storage Tanks with Air Injection Circulators*. Letter Report FATE-83-109, Pacific Northwest Laboratory, Richland, Washington.

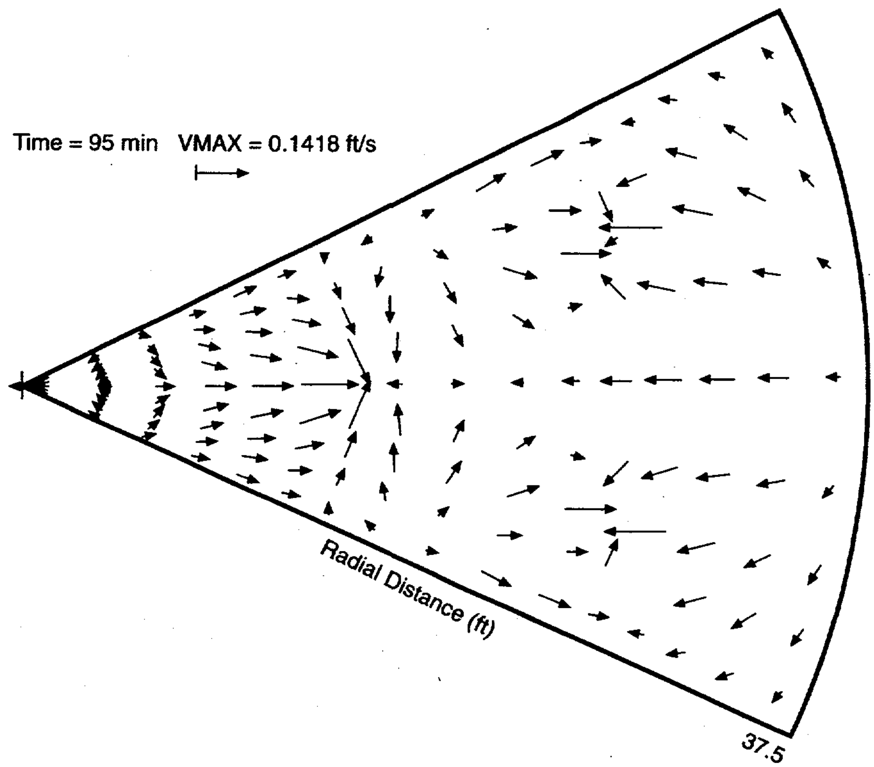

Figure 3.4. Predicted Horizontal Velocity Distribution near the Tank Bottom[(a)]

Two main factors can cause heterogeneous distributions of plutonium within the sludge. One is the sequential discharges of the plutonium-bearing wastes into AZ-101 between 1983 and 1986; the other is the dynamic interactive flow/solid transport/rheological processes that control solid/supernatant liquid mixing, slurry movements, and solid deposition and resuspension within AZ-101. With the three-dimensional slurry flow moving much faster than free-settling velocities of the solids within AZ-101, the concept of one-dimensional free settling through a quiescent supernatant liquid does not adequately describe the AZ-101 plutonium deposition pattern.

Tank AZ-101 received plutonium-bearing PUREX aging wastes 262 times between 1983 and 1986 (Vail 1997). The average sludge thickness was 6 in. before this slurry was received (Vail 1997). Since the current sludge thickness is 14.8 in., the 262 campaigns produced 8.8 in. of the sludge layer. Although each campaign discharged a different amount, each produced an average of 0.85 mm of the sludge layer. Assuming no mixing of the sludge within the tank by ALC operation during these campaigns, there could be 262 discrete sludge layers. Using the historical waste transfer records of the PUREX Material Balance Area log sheets and the Double-Shell Tank Plutonium Inventory Tracking System, a plutonium distribution was obtained without sludge mixing, as shown in Figure 3.5 (Vail 1997). It indicates significant variations in plutonium concentrations within the 8.8-in. layer, which has a maximum plutonium concentration of 0.625 g/L.

(a) Eyler LL. 1983. *Sediment Settling and Resuspension in Waste Storage Tanks with Air Injection Circulators*. Letter Report FATE-83-109, Pacific Northwest Laboratory, Richland, Washington.

We now consider the second factor. We expect that some solid segregation occurred to increase plutonium concentrations in some portions of the tank, because ALC-induced convection cell flows carry the slurry and eventually deposit the solids. Since sludge and plutonium distributions are the result of dynamic interactions between the slurry and the moving supernatant liquid, reflecting their vertical and lateral movements and sludge deposition, we must obtain plutonium distributions by accounting for these dynamic interactions.

As indicated above, the slurry was discharged into AZ-101 through a 3-in. process pipeline with an approximately 0.9 m/s exit velocity for these 262 waste transfers. The density difference between the waste effluent (1.24 kg/L) and the receiving supernatant liquid (1.22 kg/L) is 0.02 kg/L. If we neglect the ALC operation, the densimetric Froud number for this discharge to AZ-101 is 8.8. This case is equivalent to a case in which a colder, 10°C fresh water jet was discharged into warmer, 60°C receiving fresh water from the water surface. As many thermal plume (Schetz 1974; Gebhart et al. 1988), dredged material ocean disposal (Brandsma and Divoky 1976; Johnson and Fong 1990), municipal wastewater ocean disposal (Jirka et al. 1983; Onishi et al. 1985), and aerosol setting analyses and measurements (Hinds 1982) indicate, the mixture of the various solids and liquid released to AZ-101 through a 3-in. pipe without ALC operation will descend toward the tank bottom as a continuous negative plume rather than individual solid particles settling independently.

This convective descent and subsequent dynamic collapse of the negative buoyancy plume were previously predicted by TEMPEST for Tank AY-102 when the tank received C-106 slurry injected through four 1-in. nozzles (Whyatt et al. 1996). The AY-102 modeling and pump jet mixing modeling for Hanford double-shell tanks indicate that there is potential segregation of solids as the result of dynamic interactions between the sludge/slurry and supernatant liquid with ever changing rheology. These TEMPEST modeling studies revealed coarse solids (100–175 μm diameters) increase their concentrations by up to three times within some parts of tanks due to jet-induced slurry flow movements and preferential settling of coarse particles over fine particles (Whyatt et al. 1996; Onishi et al. 1996b).

Agglomeration of particles prevents any significant segregation of plutonium, because the agglomerates settle based on their own size and density and thus mask the potential segregation of plutonium based on size or density of a few plutonium particulates. Because of agglomerate formation, plutonium segregation is expected to occur to increase plutonium concentrations several times in some parts of the tanks, as predicted by these previous three-dimensional tank modeling efforts. Two AZ-101 core samples show that their plutonium concentrations are 2.0 and 2.8 times higher, respectively, than the average concentration over the sludge layer (Vail 1997), validating our conservative choice of a factor of 3 solids segregation occurring in the lateral direction.

Three measurements of gross alpha activity levels exist over the entire sludge depths in single-shell tanks B-203, B-204, and U-105. Tanks B-203 and B-204 contain metal waste from B-plant received through the 242-B concentrator. These two tanks exhibit relatively uniform vertical distributions of alpha activity, indicating that 1) alpha particles are in aggregates; 2) free-fall settling does not occur with an individual solid; and 3) segregation, if it occurs, would be more in a lateral direction due to the dynamic solid/liquid interaction. Tank U-105 originally received high-level coating waste from Redox, then evaporator bottoms from the 242-T concentrator, and finally more Redox high-level waste. Measured alpha activity in U-105 decreases from the top to the mid-point, then increases almost linearly from the mid-point to the bottom, reflecting the sequential waste transfers. Thus these three measurements also support the notion that the solid segregation is the combined result of the sequential waste transfers and three-dimensional dynamic flow/solid interactions.

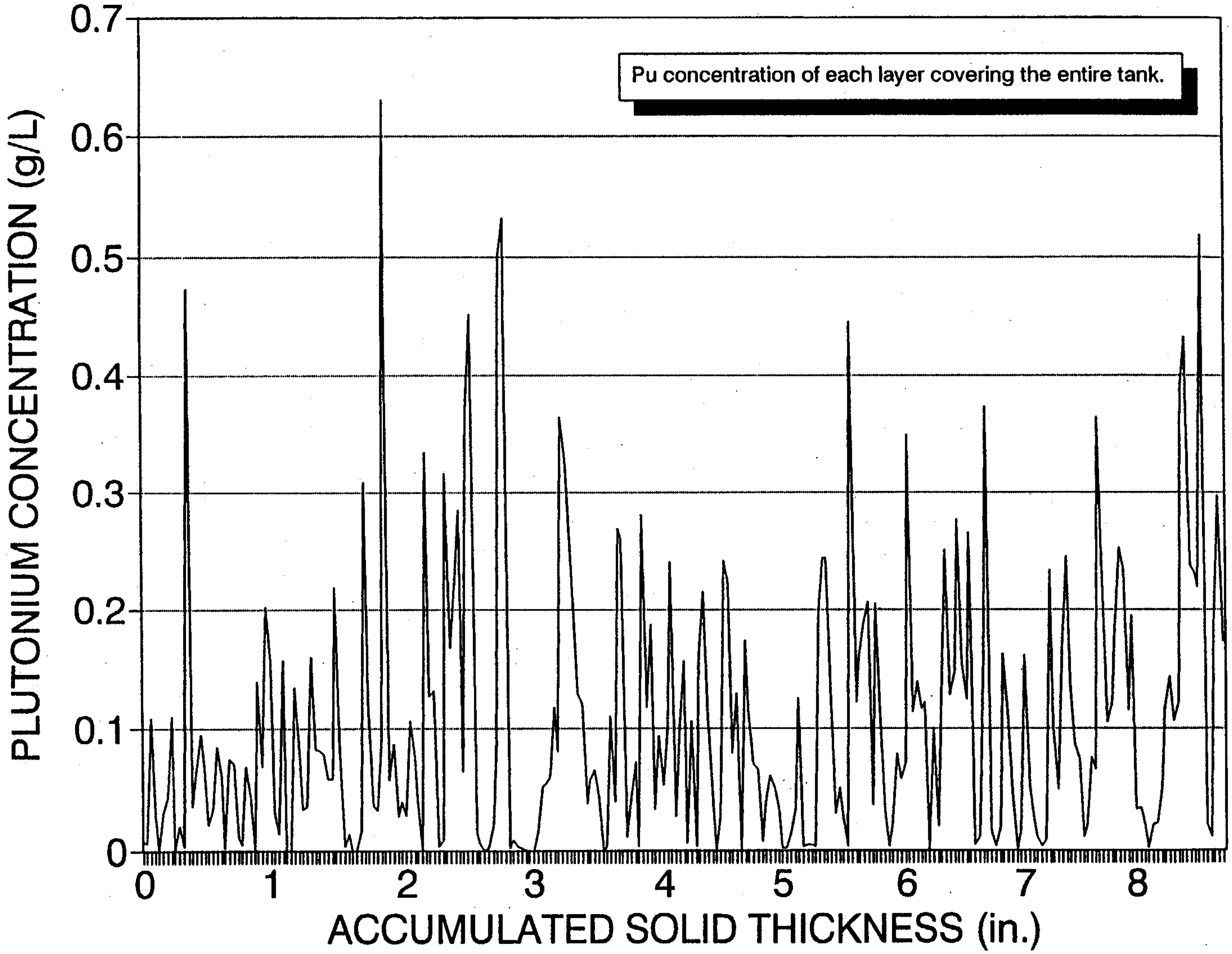

Figure 3.5. Plutonium Distribution Generated by 262 Waste Transfers (Vail 1997)

Because the dynamic slurry flow movements will not completely maintain the segregation due to the sequential waste discharges, the effects of the two factors (sequential discharges and segregation due to the dynamic slurry flow movements) to increase plutonium concentrations are not totally additive. Nonetheless, we combined them to increase plutonium concentrations within the sludge and produce a conservative condition. Thus, to account for these dynamic solid segregation effects in addition to the 262 sequential discharges, the plutonium concentrations were further increased by a factor of 3 for each of the 262 layers shown in Figure 3.4, resulting in the maximum plutonium concentration of 1.88 g/L.

As discussed above, with or without the ALC operation the sludge deposition is the result of three-dimensional dynamic interactions between the solids and supernatant liquid movements, not of one-dimensional free settling through a quiescent supernatant liquid. Since one-dimensional, free settling modeling with no solid aggregation (Whyatt et al. 1996) is not applicable to the AZ-101 sludge setting case, the value of up to 94 segregation factor produced by the one-dimensional modeling was not used for this study. For the sludge deposited through the 262 small transfers, as was assumed in this AZ-101 modeling study, the vertical variation within each of the 262 layers (with an average thickness of 0.85 mm) is not meaningful when the 300-hp pumps draw the sludge through their 13.5 -in. openings, as the current AZ-101 three-dimensional modeling reveals in the rapid mixing of much thicker modeled layers. As will be discussed at the end of Section 4, the current model study indicates that the plutonium segregation factor of up to 130 over the actual plutonium concentration averaged over the 15-in. sludge will still result in a subcritical condition in the pump housing.

Since modeling the 262 plutonium-bearing layers would result in excessive run time, the number of layers was reduced to 33 in the model; several layers were combined to form each modeled layer, with an average thickness of 0.33 in. When the plutonium-containing layers were combined to form the modeled layer, the maximum plutonium concentration occurring within the original layers was assigned to the combined layer. The sum of the plutonium contained in all of the modeled layers was thus about three times the sum of plutonium in the 262 layers, resulting in nine times more plutonium in the model than the actual total quantity (9.782 kg) in the tank.

As stated in Vail (1997), there are 6 in. of the sludge layer in the tank bottom that contain no plutonium solids. The layer containing the maximum plutonium concentration (1.88 g/L) is located 8 in. above the tank bottom. To make the sludge condition even more conservative, we reduced the thickness of this clean sludge bottom layer from 6 to 5 inches, so that the sludge layer containing the maximum plutonium concentration will be sitting right at the pump inlet height of 7 in. instead of 1 in. above the pump inlet.

The resulting initial distribution of the plutonium concentrations used in the modeling is shown in Figure 3.6. The average plutonium concentration over the entire group of sludge layers is 0.55 g/L in the model, 8.9 times higher than the actual average plutonium concentration of 0.062 g/L. Moreover, the maximum plutonium concentration of 1.88 g/L assigned to the model is 30 times more than the average actual plutonium concentration of 0.062 g/L in the tank. Thus the current AZ-101 modeling study imposed 30 times more plutonium segregation. The plutonium concentration level of 1 g/L shown in Figure 3.4 is 16 times greater than the average actual plutonium concentration and occupies 23% of the total sludge layer.

A review of mineral segregation literature from the mining industry revealed that the 10 to 20 μm size range is below the normal particle size range for either gravity or flotation segregation processes (Kim et al. 1966). Segregation in this size range would require special chemical additives and very specialized equipment that would provide rhythmic shaking, thin liquid films, or high centrifugal forces coupled with selective collection and concentration.

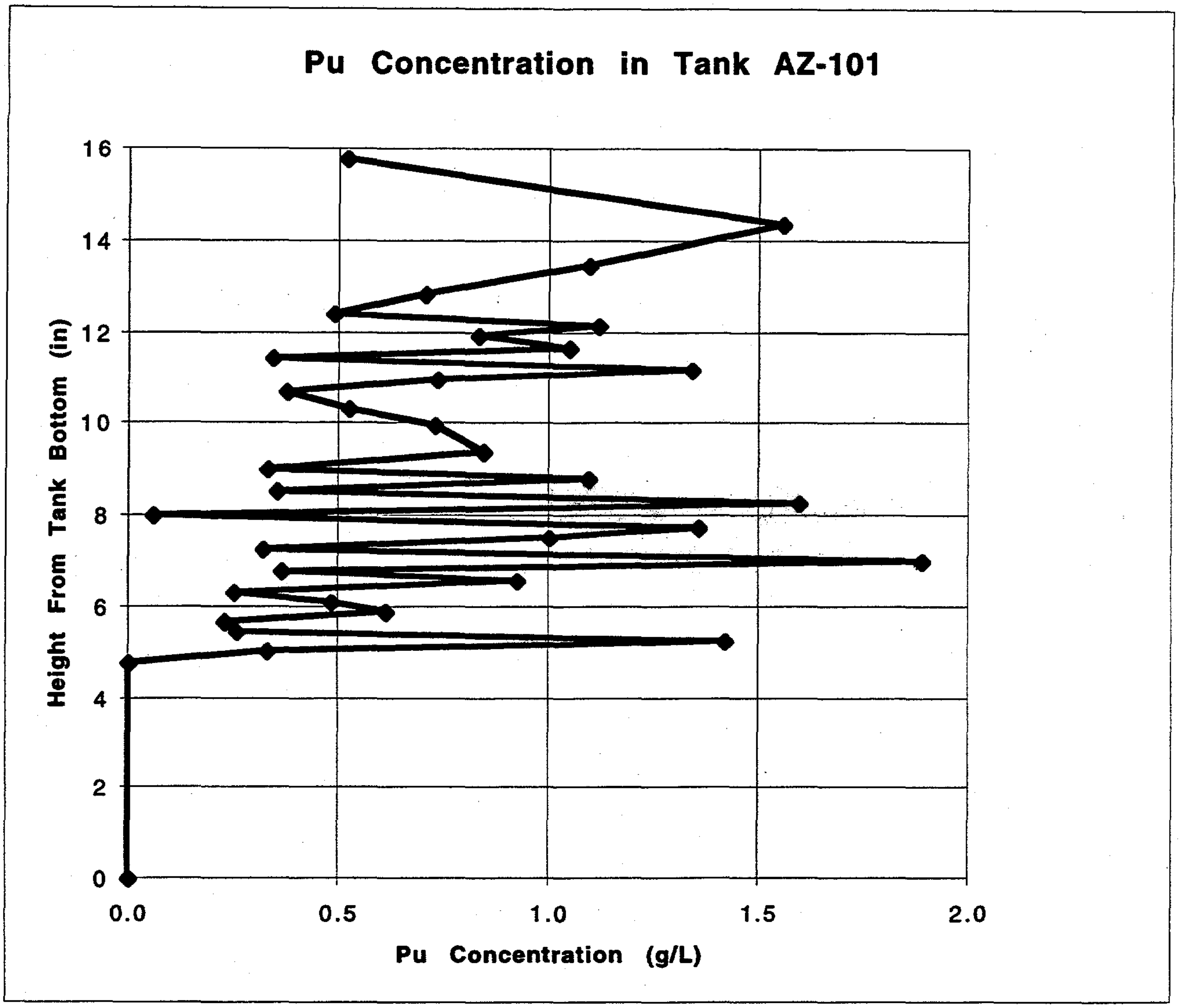

Figure 3.6. Initial Plutonium Distribution Within AZ-101 Sludge Model Layers

Based on the evidence of agglomeration, the estimated bounding $PuO_2 \cdot x\ H_2O$ particle size, previous three-dimensional tank model segregation predictions, and the mining literature, the 30-fold increase in maximum plutonium concentration over the average plutonium concentration used in the AZ-101 model was judged to be a very conservative selection.

3.2.3 Hindered and Unhindered Solid Settling Velocities

The unhindered settling velocities occurring under small solid concentrations for nine particle sizes were provided to TEMPEST by the Stokes Law (Vanoni 1975) by assuming that all particulates are spherical (see Table 3.1). These input settling velocities do not include the effects of particle interaction such as particle flocculation or agglomeration. The TEMPEST model does include the effect of hindered settling, which occurs in high solids concentrations. The unhindered settling velocity of each particle was internally adjusted by the model to account for effects of hindered settling by the following equation:

$$v_s = V_{so}(1-\beta)^a \quad (3.1)$$

where

V_s = hindered settling velocity
V_{so} = input settling velocity (unhindered settling velocity)
ß = C_v/C_{vmax}
C_v = solid volume fraction in slurry
C_{vmax} = maximum solid volume fraction (= 0.44 in this study)
a = 4.7 (based on the Stokes Law).

3.2.4 Rheology

Turbulent Reynolds stresses are modeled through an effective viscosity. The Prandtl-Kolmogrov hypothesis is used to relate the effective viscosity to a velocity and a length scale. In this approach, transport equations for the turbulent kinetic energy (k) and the dissipation of turbulent kinetic energy (e) are solved by the k-e model to determine the effective turbulent (eddy) viscosity, μ_T, as

$$\mu_T = C_\mu \rho k^2 / \varepsilon \quad (3.2)$$

where

C_μ = constant equal to 0.09
p = fluid density
k = turbulent kinetic energy
e = dissipation of turbulent kinetic energy.

For the Tank AZ-101 modeling, a measured value for the supernatant liquid density (1.22 g/mL) and the molecular viscosity of the supernatant liquid, 2 cP, were used for the supernatant liquid.

The slurry molecular viscosity is calculated by multiplying the molecular viscosity of the base fluid by a factor of "b" raised to the power "ß," as shown in Equation 3.3:

$$\mu = \mu_T b^\beta \quad (3.3)$$

where

μ_T = base fluid viscosity (= 2.0 cP in this study)
b = ratio of the sludge viscosity to supernatant liquid viscosity
ß = C_v/C_{vmax}.

This equation, which does not explicitly include the strain rate, was used in modeling jet pump mixing in Tank 241-SY-102 (Onishi et al. 1996b), slurry injection into Tank AY-102 (Whyatt et al. 1996; Serne et al. 1996), pumping sluiced sludge from C-106 (Whyatt et al. 1996; Serne et al. 1996), and periodic rollover and gas release processes in Tank 241- SY-101 (Trent and Michener 1993). Measured viscosities of diluted AZ-101 sludge were 10 to 40 cP for 10 wt% slurry and 40 to 150 cP for 30 wt% slurry.(a) Thus we selected the viscosity of the sludge

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(a) Gray WJ, ME Peterson, RD Scheele, and JM Tingey. 1993. *Characterization of the Second Core Sample of Neutralized Current Acid Waste from Double-Shell Tank AZ-101* (draft). Pacific Northwest Laboratory, Richland, Washington.

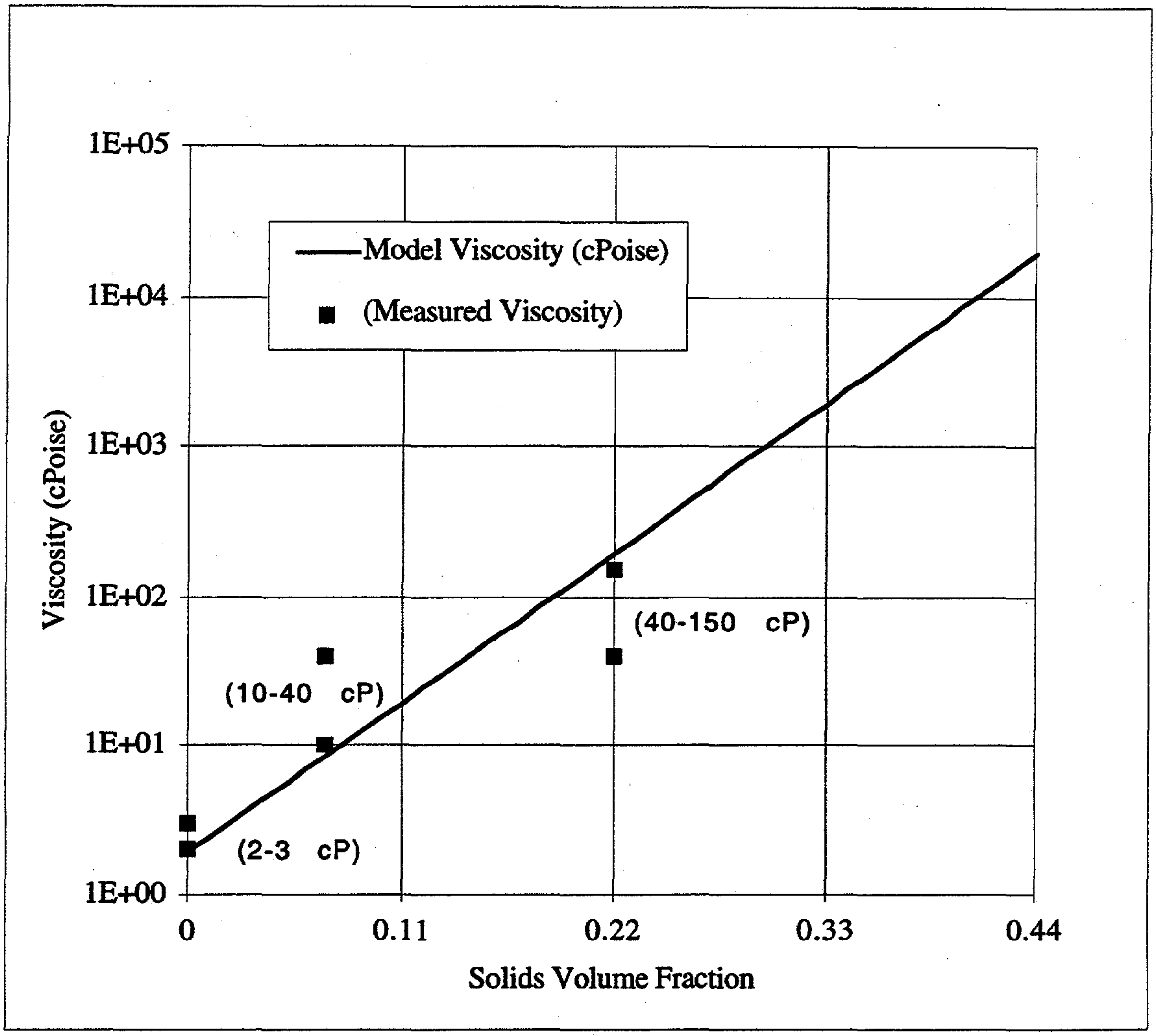

Figure 3.7. Variation of Viscosity with Solid Concentrations for Sludge Viscosity of 20 Pa-s and C_{vmax} of 0.44

($C_v = C_{vmax} = 0.44$) to be 20 Pa-s. The variation of viscosity with the solid fraction used in the AZ-101 model is shown in Figure 3.7 with these measured values. The molecular viscosity of the slurry is added to the turbulent viscosity, and the sum is used in fluid dynamic calculations.

The shear stress of AZ-101 sludge/slurry is measured to be

$$\tau = 1.28 + 0.0040\,\gamma^{0.827} \qquad \text{for 30 wt\% slurry} \qquad (3.5)$$

$$\tau = 0 + 0.0054\,\gamma^{0.643} \qquad \text{for 10 wt\% slurry} \qquad (3.6)$$

where

t = shear stress in Pascal
g = shear rate per second.

Since the sludge in Tank AZ-101 has only a small yield stress,[a] and the current study is mostly concerned with the sludge movements in and around the pump (high velocity areas), we did not include the yield stress in the simulations.

While TEMPEST has the capability to model diffusive effects on solutes and particles, the input was intentionally selected to eliminate diffusive effects to compensate for potential numerical diffusion effects on the tank waste transport.

(a) Gray WJ, ME Peterson, RD Scheele, and JM Tingey. 1993. *Characterization of the Second Core Sample of Neutralized Current Acid Waste from Double-Shell Tank AZ-101* (draft). Pacific Northwest Laboratory, Richland, Washington.

4.0 Model Applications and Results Evaluations

We simulated the movements, settling, and mixing of nine solids (see Table 3.1) and supernatant liquid in Tank AZ-101 for four simulation minutes with TEMPEST with an average time step of approximately 1 millisecond. The modeling objective was to evaluate whether two pumps with four rotating 18.3-m/s (60-ft/s) jets could concentrate enough plutonium within the pump housing to cause a criticality problem. Jets rotating at 0.05 rpm were assigned to be placed 22 ft off the tank center.

Previous jet mixing simulations for Tanks AZ-101[a] and SY-101 (Onishi et al. 1996b) indicated that 6-in. diameter, 60-ft/s jets are very effective at mixing the sludge and supernatant liquid to form a mostly homogeneous mixture. These studies also indicated that it takes 10 minutes to two hours to mix most of the wastes in these tanks, depending on the jet and sludge conditions.

Since the maximum plutonium concentration in the pump housing is expected to occur at an early stage of the jet mixing operation, before much of the sludge and supernatant liquid are being mixed within the tank, we set up two cases with identical conditions except for the starting directions of the jets. In Case 1, the jets initially point approximately in the 11 o'clock position (the longest distance to the tank wall) and the 5 o'clock position (180° from the 11 o'clock position). In Case 2, the jet is initially directed at the 3 o'clock position (the shortest distance to the tank wall) and 9 o'clock (toward the tank center). As stated above, all these jets are rotating at 0.05 rpm (or 10 minutes to sweep 180°). The pump was assumed to have an initial ramp-up time of 20 seconds to reach the full 60 ft/s.

The previous modeling studies for tanks, including AZ-101 (Whyatt et al. 1996)[a] reveal that when they are not operated, the ALCs do not change flow patterns near the bottom of the tank, since the bottoms of the ALCs are 30 in. above the bottom of the tank. Jet-induced flows move around the circulators and show minor wakes behind the ALCs, but these effects on the overall flow patterns are minimal. Because the sludge thickness is about 15 in. and the pump inlet is 7 in. above the tank bottom, the ALCs have very little effect on the movement of the sludge.[a] Thus the current model did not include ALCs.

4.1 Velocity Distributions

The predicted vertical distribution of jet-induced velocity in the 10:30 o'clock position at 1.5 simulation minutes for Case 1 is shown in Figure 4.1 (see p. 4.5) for the simulation area, from the pump to the tank wall and from the tank bottom to the surface of the supernatant liquid. Figure 4.2 shows the part of Figure 4.1 in the proximity of the pump. Figure 4.3 shows the predicted velocity in the 2:30 o'clock position in the area from the pump to the tank wall but just within 0.9 m of the tank bottom for Case 2. As stated previously, the center of the 6-in. jet nozzle is 17 in. above the tank bottom, and the surface of the sludge in the model is more than 1 in. below the nozzle centerline. At 1.5 simulation minutes, the jets already have rotated 27° away from the original directions. Figures 4.1 and 4.3 indicate that the slurry jets are reaching the tank wall, while the pump is withdrawing the sludge around the pump inlet.

(a) Antoniak ZI and KP Recknagle. 1996. *Simulation of Tank 101-AZ Mobilization Tests and TEMPEST Code Performance Evaluation*. Letter Report, Pacific Northwest National Laboratory, Richland, Washington.

At four simulation minutes, the jets were 72° away from the starting positions. The two jets in Case 1 are pointing at the 3 o'clock (the nearest to the tank wall) and 9 o'clock (toward the tank center) positions at that time. The vertical distributions of velocities in these two directions are very similar to one another, as shown in Figures 4.4 and 4.5. Moreover, velocities near the pump (see Figure 4.6) are almost identical to the velocity distribution shown in Figure 4.2 at 1.5 simulation minutes, with very minor differences right at the pump inlet edge. Predicted velocity distributions for Case 2 at this same time are shown in Figures 4.7 through 4.9, depicting two jets directed at 1 and 7 o'clock (farthest to the tank wall) positions. The significant difference in the distance from the pump to the tank wall between these two cases' starting jet directions initially makes the velocity distributions somewhat different around the tank wall in Cases 1 and 2, but as the jets rotate away from the initial directions, these flow differences become smaller. The flows around the pump are quite similar in these two cases, even at the early times.

4.2 Solid Distributions

Predicted plutonium concentrations in the pump housing are reduced overall during the first four minutes with several peaks along the way, as shown in Figure 4.10 for Solid 1 (lightest and smallest plutonium-bearing solid), Figure 4.11 for Solid 9 (the heaviest and largest plutonium-bearing solid) of Case 1, Figure 4.12 for Solid 1, and Figure 4.13 for Solid 9 of Case 2. Numbers 1 and 2 in these figures indicate predicted plutonium concentrations in each of the two hemispheres just inside the pump inlet (the bottom of the pump housing). Numbers 27 and 28 are two hemispheres at the top of the pump housing. Plutonium concentrations of Solids 1, 2, 8, and 9 are very similar within the pump housing, as shown for Solids 1 and 9 in these four figures. Because of the large flow velocity inside and around the pump, the different densities and sizes of these solids do not make a significant difference in their movements. As indicated in previous tank jet mixing (Onishi et al. 1996b), these differences become more apparent in the areas away from the pump, such as near the tank wall, due to preferential settling of some heavier, larger particles.

There are several plutonium-concentration peaks over four-minute simulations, as seen in these four figures. The first plutonium concentration peak of 0.9 g/L occurs at the bottom of the pump at approximately 0.3 second; the second peak of approximately 0.6 g/L appears at around 10 seconds. The third peak of approximately 0.25 to 0.4 g/L occurs at about 40–50 seconds and reflects the differences between Cases 1 and 2 in reverse flows around the tank wall at this time. Each succeeding peak is smaller than the previous one for both cases. After one minute, the plutonium very gradually decreases in concentration within the pump housing over time, and at four minutes all plutonium concentrations within the pump are less than 0.1 g/L.

Figure 4.14 shows predicted concentrations of Solid 9 (heaviest and largest plutonium solid) at four locations within the pump housing over the first 10 seconds for Case 1. Numbers 2, 16, 26, and 28 in this figure represent plutonium concentrations at the bottom, one-third of the way up, two-thirds of the way up, and at the top of the pump housing, respectively. As clearly shown, the highest plutonium concentration of 0.9 g/L occurs only at the pump bottom at 0.3 second, as plutonium from the 0.25-in.-thick sludge layer (with the highest concentration of 1.88 g/L) just below the pump inlet is initially drawn into the pump without much dilution. Still, there is a two-fold reduction in the plutonium concentration at the bottom of the pump housing compared with that immediately below the pump inlet, indicating that the pump does not differentiate between various plutonium concentrations within a 0.25-in. thickness.

As this initial pulse of the high plutonium concentration moves up within the pump housing, the concentration is reduced significantly, such that at the top of the pump housing (see plutonium concentration with Number 28) there is no increase in the plutonium concentration. This is also clearly indicated by Figure 4.15, showing the distribution of Solid 9 plutonium concentrations at 0.3 simulation second for Case 1. This figure depicts that there is an originally high-plutonium, 0.25-in.-thick sludge layer at the pump intake level, but plutonium concentrations there are already diluted from the original 1.88 g/L at 0.3 second. The pump is also withdrawing the sludge from layers of less or no plutonium concentration. This figure also confirms that any plutonium concentration variations within 0.25 in. are not meaningful when one is concerned about a potential increase in plutonium concentrations within the pump housing during the pump jet mixing operation. Within the pump near the pump inlet, this high plutonium concentration of approximately 0.9 g/L is rapidly being reduced (see Figure 4.15).

As indicated in Figures 4.10 through 4.13, plutonium also peaks in the pump housing at around 10 seconds. At that time, predicted concentrations in the pump housing are fairly uniform for all plutonium solids (Solids 1, 2, 8, and 9). Figures 4.16 and 4.24 show predicted concentrations of all nine solids including those of Solid 1 (the lightest and smallest), 2 (heaviest and smallest), Solid 8 (lightest and largest), and 9 (heaviest and largest) in and around the pump in the vertical plane along the 11 clock position for Case 1. The predicted Solid 9 plutonium distributions along the 3 o'clock position for Cases 1 and 2 are also shown in Figures 4.25 and 4.26. The jets are injecting the sludge at the 11 o'clock position for Case 1 and 3 o'clock for Case 2 (Figures 4.16 and 4.26). Predicted concentrations of non-plutonium Solids 3 through 7 (Figures 4.16 through 4.20) are all within 95% of their original uniform concentration values in the sludge layer. Thus, at 10 seconds the supernatant liquid contributes less than 5% of the slurry within the pump housing. Figures 4.21 through 4.26 (except for Figure 4.25) show the jets penetrating into and mixing with the sludge layers. These figures for plutonium distribution also show that the pump is withdrawing the sludge not only from the layer with the highest plutonium concentration (1.88 g/L) but also from layers that contain little or no plutonium. As a result of this suction flow pattern, the high plutonium-containing layers and low and non-plutonium-containing layers are mixing and lowering the highest concentration in the sludge layer. This mixing also pushes plutonium into the layers near the tank bottom, where there was none originally. These figures show relatively uniform plutonium concentrations of 0.42 to 0.64 g/L throughout the pump in both Cases 1 and 2.

Predicted distributions of the solids at 40 seconds show similar patterns at 10 seconds, but there is more mixing and dilution, as shown in Figures 4.27 and 4.28 for Solids 1 and 9 in Case 1. At 1.5 simulation minutes the mixing and dilution are progressing, as evidenced by the predicted distributions of Solid 4 concentrations in the vicinity of the pump (see Figure 4.29). Solid 4 has a particle diameter of 2 to 5 μm and makes up 40.9 vol% of the total solids in the AZ-101 sludge (see Table 3.1). The concentration of Solid 4 within the pump at 1.5 minutes is approximately 110 to 160 g/L. Since this solid was originally distributed uniformly within the sludge at a concentration of 331 g/L, the Solid 4 concentration in the pump housing indicates that the sludge was diluted approximately two to three times by the supernatant liquid by this time. Predicted plutonium concentrations for Solids 1 and 9 are very similar in and around the pump and are approximately 0.2 g/L within the pump, as shown in Figures 4.30 and 4.31, respectively.

At four simulation minutes, Figures 4.32 and 4.36 show predicted concentrations of non-plutonium Solids 3 through 7 in the 9 o'clock position (the direction toward the tank center) in and around the pump housing for Case 1. The jets are injecting the sludge at the 3 and 9 o'clock positions for Case 1, as shown in Figures 4.4 through 4.6. These figures show that the rotating jets have been mixing the sludge and supernatant liquid vigorously around the pump and that solid concentrations in the pump housing are from 12 to 14% of the original concentrations in the sludge layer. Thus, the solids withdrawn by the pump suction in the pump housing are diluted seven to eight times by the supernatant liquid after four minutes of pump jet mixing.

As presented in Figures 4.10 through 4.13, predicted plutonium concentrations within the pump housing are below 0.1 g/L at four minutes for both Cases 1 and 2. Predicted plutonium concentrations in the 9 o'clock position in and around the pump housing for Case 1 at four minutes are shown in Figures 4.37 through 4.40 for Solids 1, 2, 8, and 9, respectively. These figures show that the sludge layers around the pump are homogenized by the jet mixing. Plutonium concentrations in and around the pump range from 0.059 to 0.071 g/L. Although Solid 9 (the heaviest and largest) has slightly higher plutonium concentrations near the tank bottom than Solid 1 (the lightest and smallest), the difference is negligible (less than 1%) around the pump. The predicted plutonium concentrations of 0.059 to 0.071 g/L result from the seven to eight times dilution of the sludge by the supernatant liquid and the homogenized sludge layer in and around the pump induced by the pump jet mixing. These plutonium levels are 26 to 32 times less than the maximum plutonium concentration (1.88 g/L) used in the model. These plutonium concentrations in the pump are only to 2.3 to 2.7 times higher than 0.026 g/L, which is the average plutonium concentration over the entire AZ-101 tank (the sludge and supernatant liquid) in the AZ-101 model. Since the AZ-101 model contains nine times more plutonium mass that the actual amount in the tank, the average concentration over the entire tank is 0.0028 g/L.

Figures 4.41 and 4.42 summarize the model results, showing the total amount of plutonium and its average concentration over the entire pump housing for both Case 1 (initially 11 and 5 o'clock jet directions) and Case 2 (initially 3 and 9 o'clock jet directions). These two figures reveal that the plutonium trends are similar to those shown in Figures 4.10 though 4.13. The total amount of plutonium within the pump housing peaks at 75 g at 10 simulation seconds and decreases with time to less than 10 g at four minutes. The difference between Cases 1 and 2 at 40–50 seconds is attributed to Case 2's more vigorous early mixing of sludge near the tank wall, because its jet is initially pointed in the direction of shortest distance to the tank wall while the Case 1 jet is initially pointed in the direction of the farthest distance to the wall. But these differences disappear as the time of simulation increases to 80 seconds. The average plutonium concentration in the entire pump housing peaks at 0.60 g/L at 10 seconds and is reduced to below 0.1 g/L at four minutes.

Since the minimum critical concentration of plutonium for an infinite system of tank waste solids under optimum conditions is 2.6 g/L (Vail 1997), the predicted highest plutonium concentration of 0.60 g/L within the pump housing is 4.3 times less than the minimum required. Moreover, the minimum plutonium mass under ideal plutonium-water conditions is 520 g, and the maximum plutonium amount within the pump housing is 75 g; thus, the plutonium amount in the pump is 6.9 times less than the minimum required plutonium mass. These predicted maximum total amounts (75 g) and concentrations (0.6 g/L) in the pump housing are much lower than the minimum plutonium conditions needed to reach a criticality level. The predicted nondimensional plutonium concentration in the pump housing normalized by the highest plutonium concentration (1.88 g/L) in the original model sludge layer as shown in Figure 4.43. This figure shows that the maximum plutonium concentration in the pump is one-third of the maximum in the sludge layer and reduces to 4% after four minutes of pump operation.

As discussed previously, the maximum plutonium concentration assigned in the current AZ-101 model is 1.88 g/L, which is 30 times higher than the actual average plutonium concentration of 0.062 g/L in the AZ-101 sludge. Since using the maximum plutonium concentration of 1.88 g/L still results in a plutonium concentration in the pump housing that is 4.3 times lower than the minimum critical plutonium concentration of 2.6 g/L, the maximum plutonium concentration in the sludge could be up to 8.08 g/L (4.3 times more than 1.88 g/L) before the plutonium reaches 2.6 g/L in the pump. This is 130 times (4.3 times 30) more than the average plutonium concentration (0.062 g/L) in the sludge, as stated in Section 3.2.2. Note that the segregation factor of 130 is greater than the one-dimensional model results of 94 obtained by Whyatt et al. (1996). Even in this 130-time segregation case, the total plutonium amount in the pump would be 323 g, which is still less than the minimum plutonium critical mass of 520 g. Therefore, the AZ-101 jet pump operation will not cause a criticality problem in the pump housing.

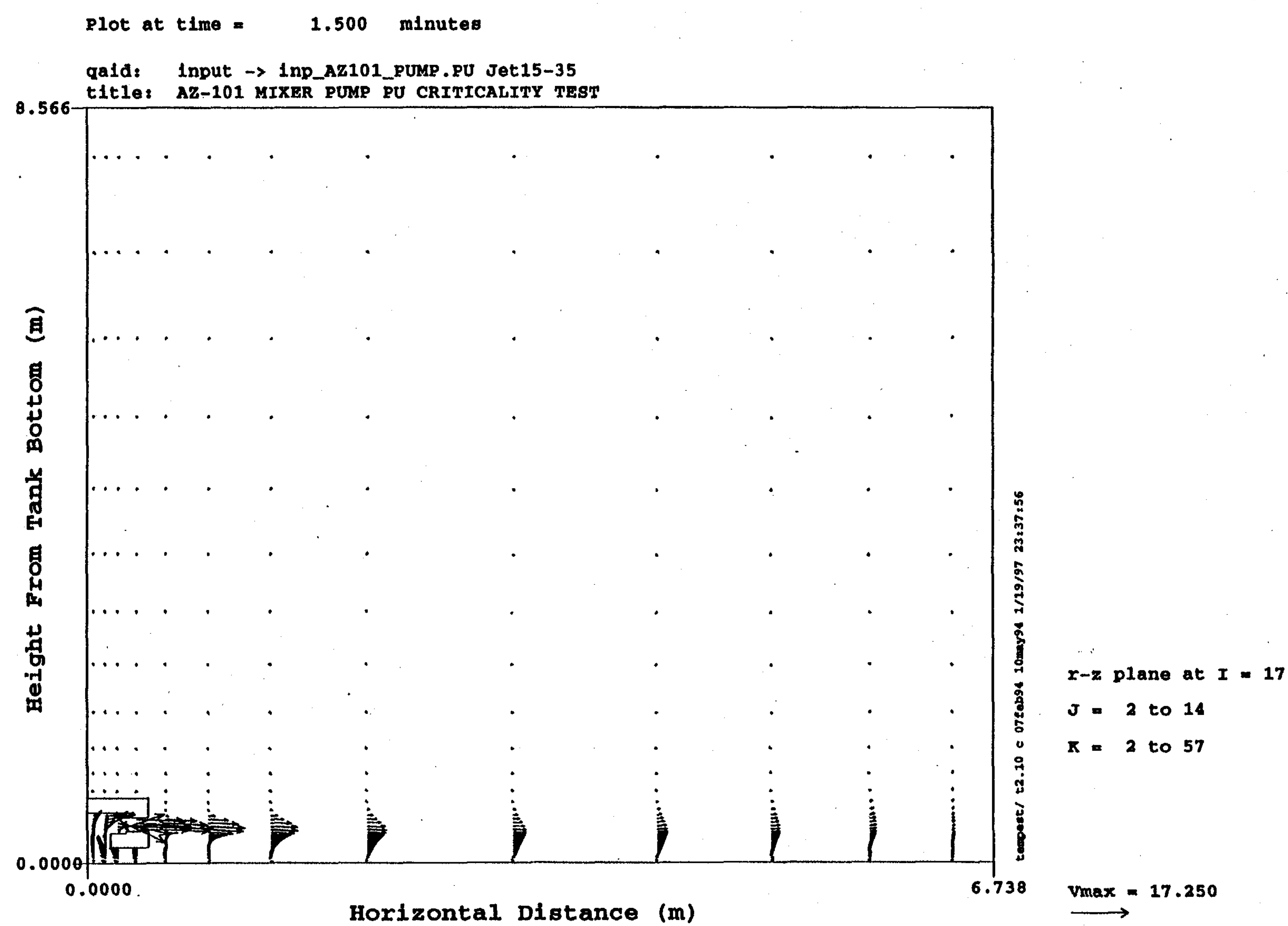

Figure 4.1. Predicted Velocity Distribution in the 10:30 O' Clock Position at 1.5 Simulation Minutes for Case 1

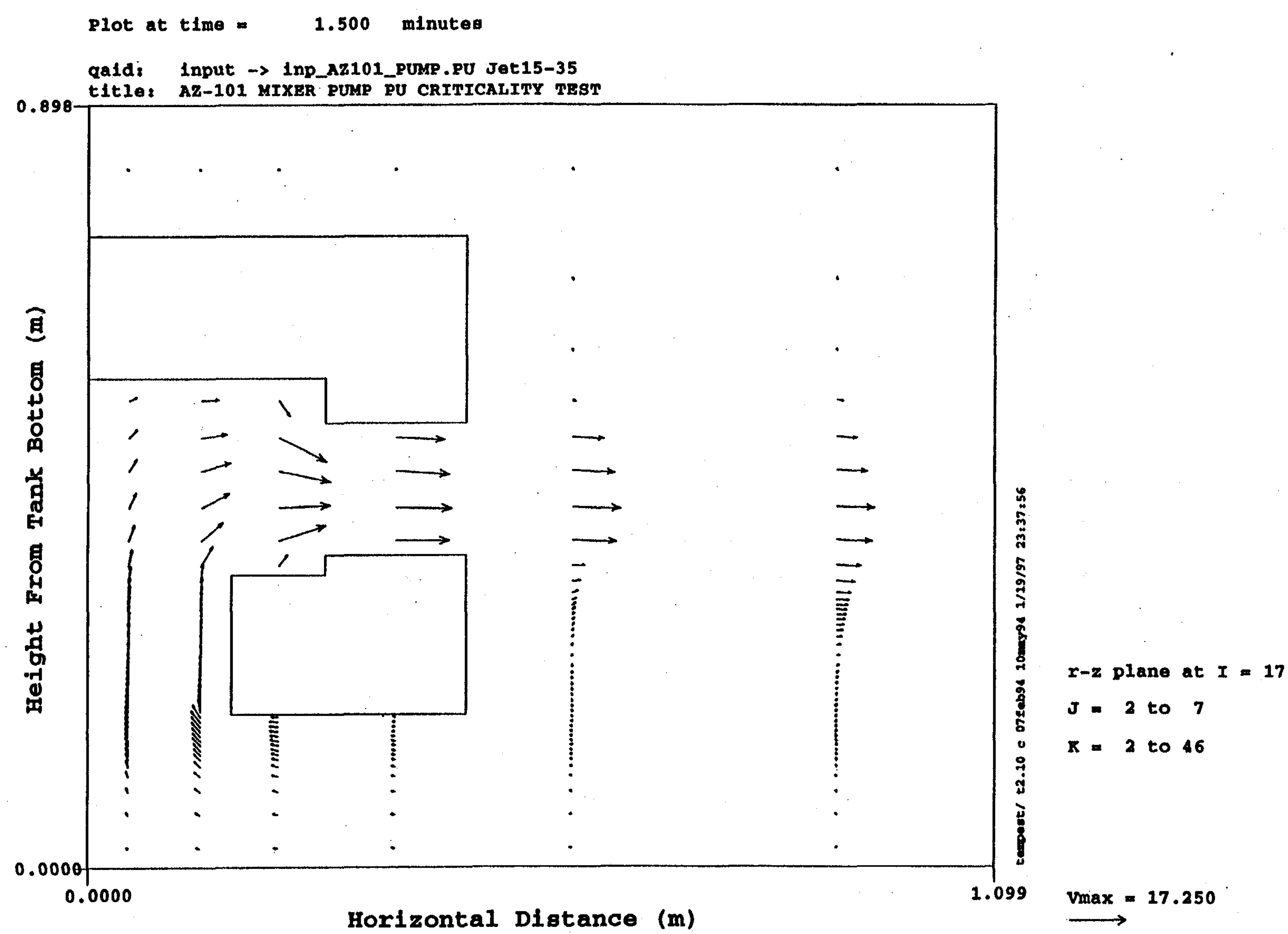

Figure 4.2. Predicted Velocity Distribution in and Around the Pump in the 10:30 O'Clock Position at 1.5 Simulation Minutes for Case 1

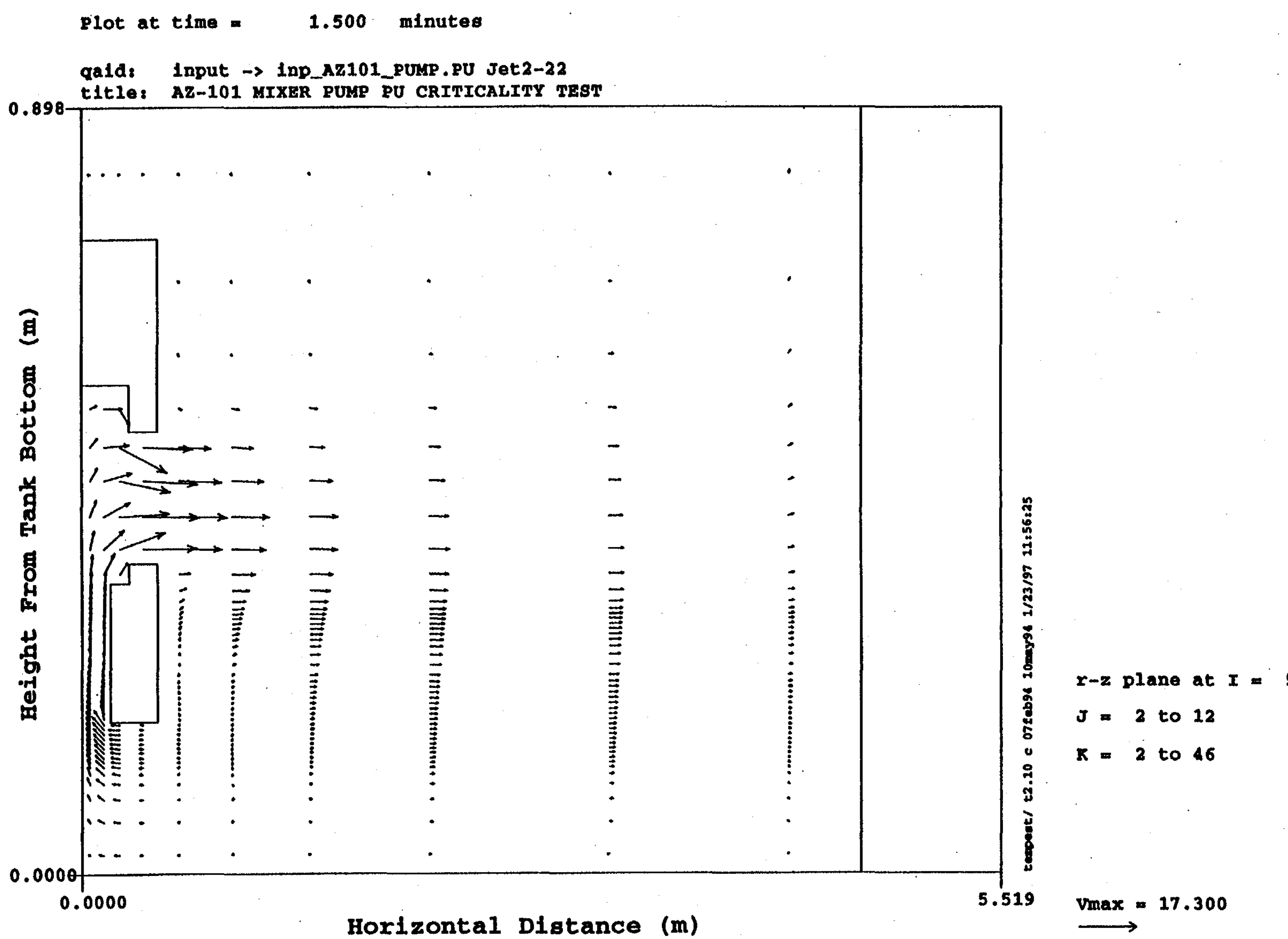

Figure 4.3. Predicted Velocity Distribution in the 2:30 O'Clock Position near the Tank Bottom at 1.5 Simulation Minutes for Case 2

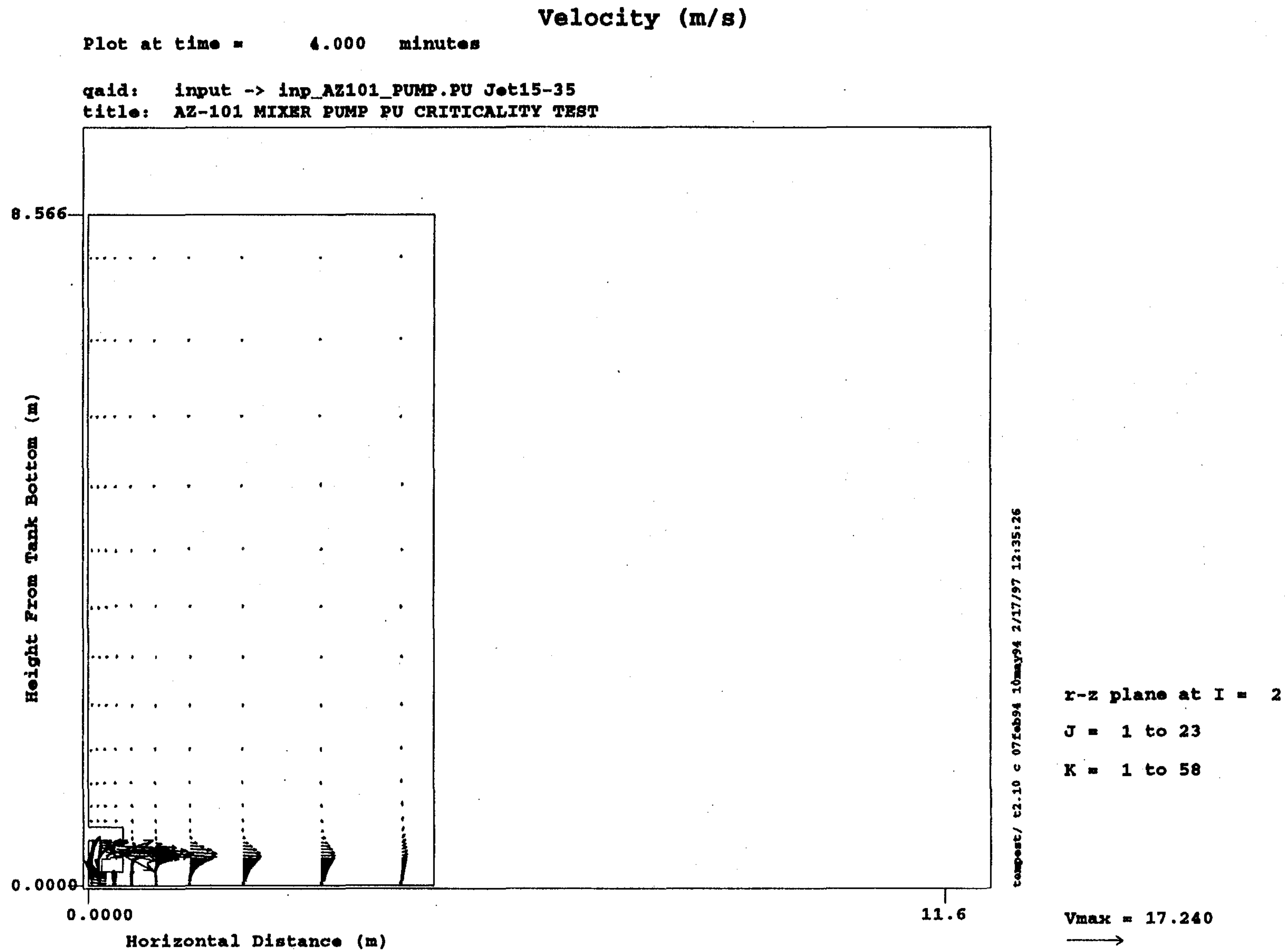

Figure 4.4. Predicted Velocity Distribution in the 3 O' Clock Position at 4 Simulation Minutes for Case 1

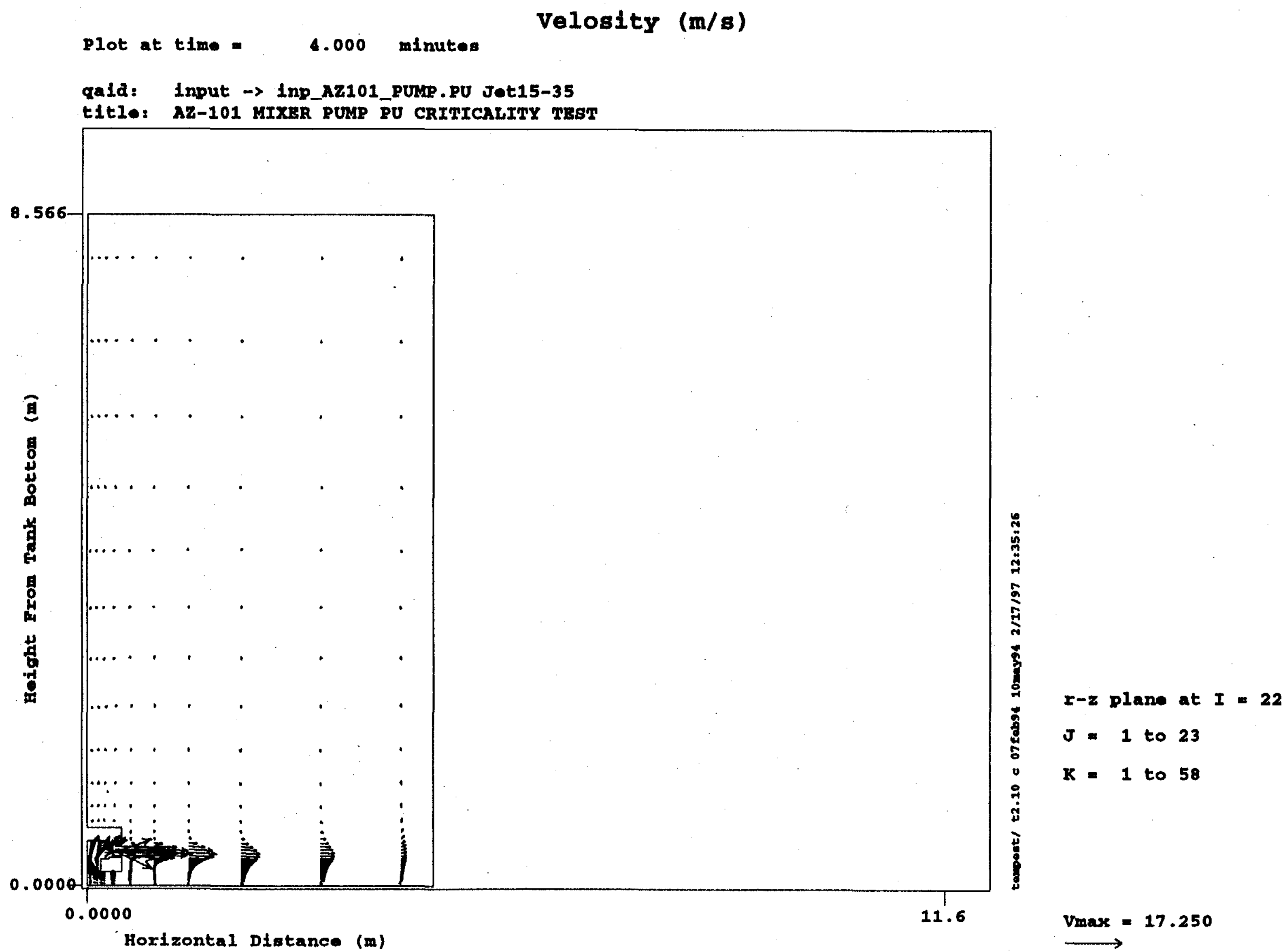

Figure 4.5. Predicted Velocity Distribution in the 9 O' Clock Position at 4 Simulation Minutes for Case 1

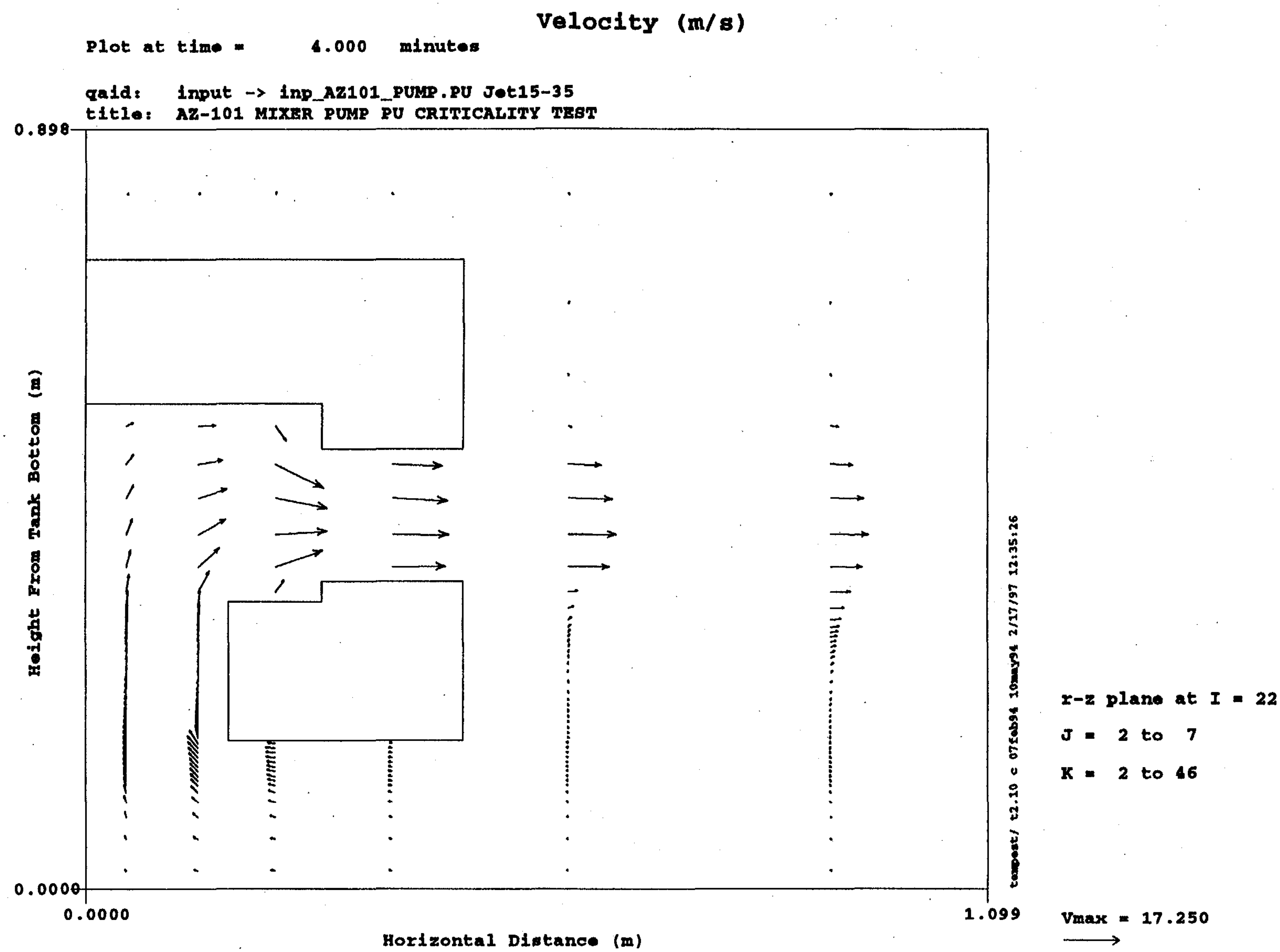

Figure 4.6. Predicted Velocity Distribution in and around the Pump in the 3 O' Clock Position at 4 Simulation Minutes for Case 1

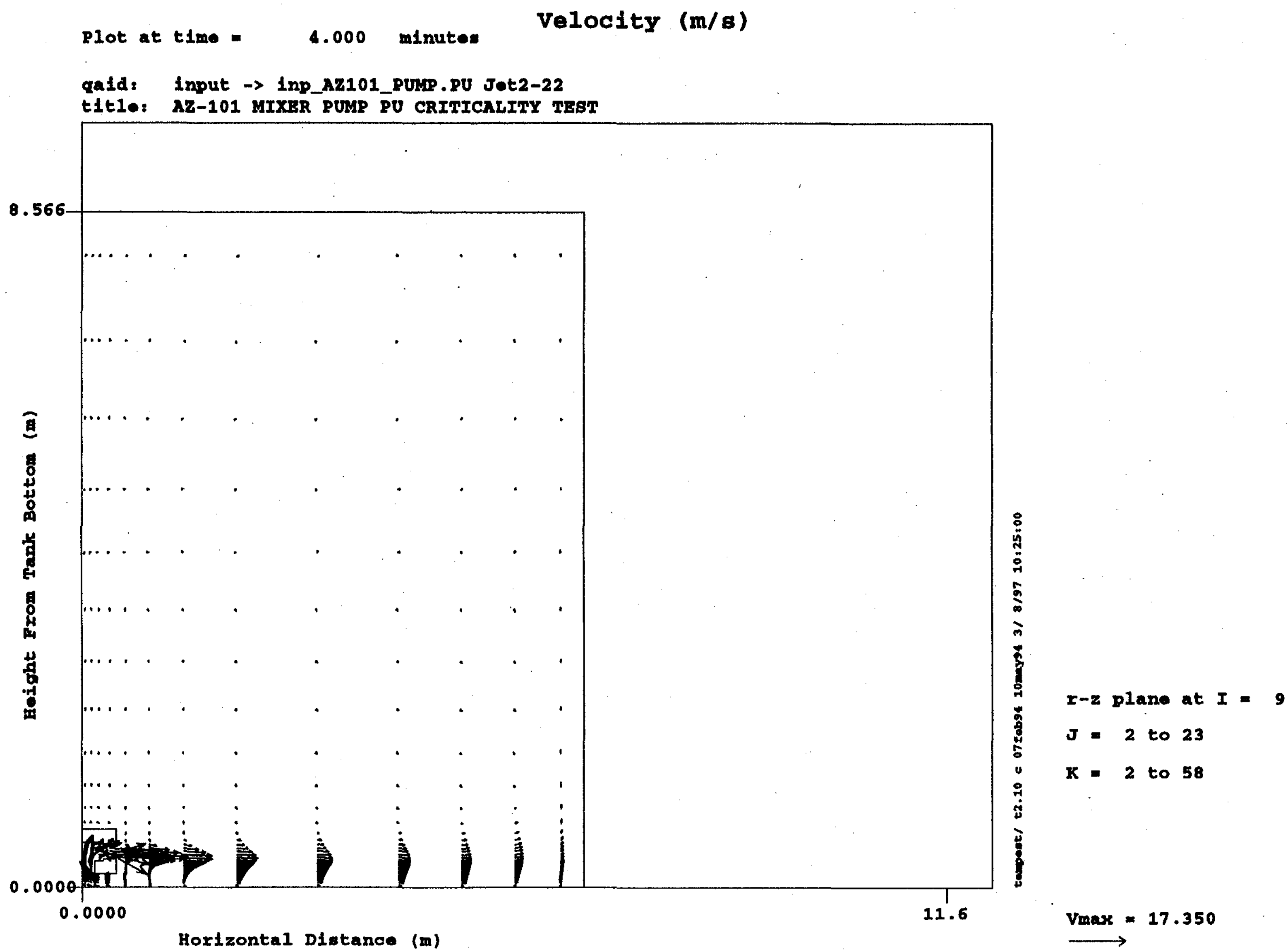

Figure 4.7. Predicted Velocity Distribution in the 1 O' Clock Position at 4 Simulation Minutes for Case 2

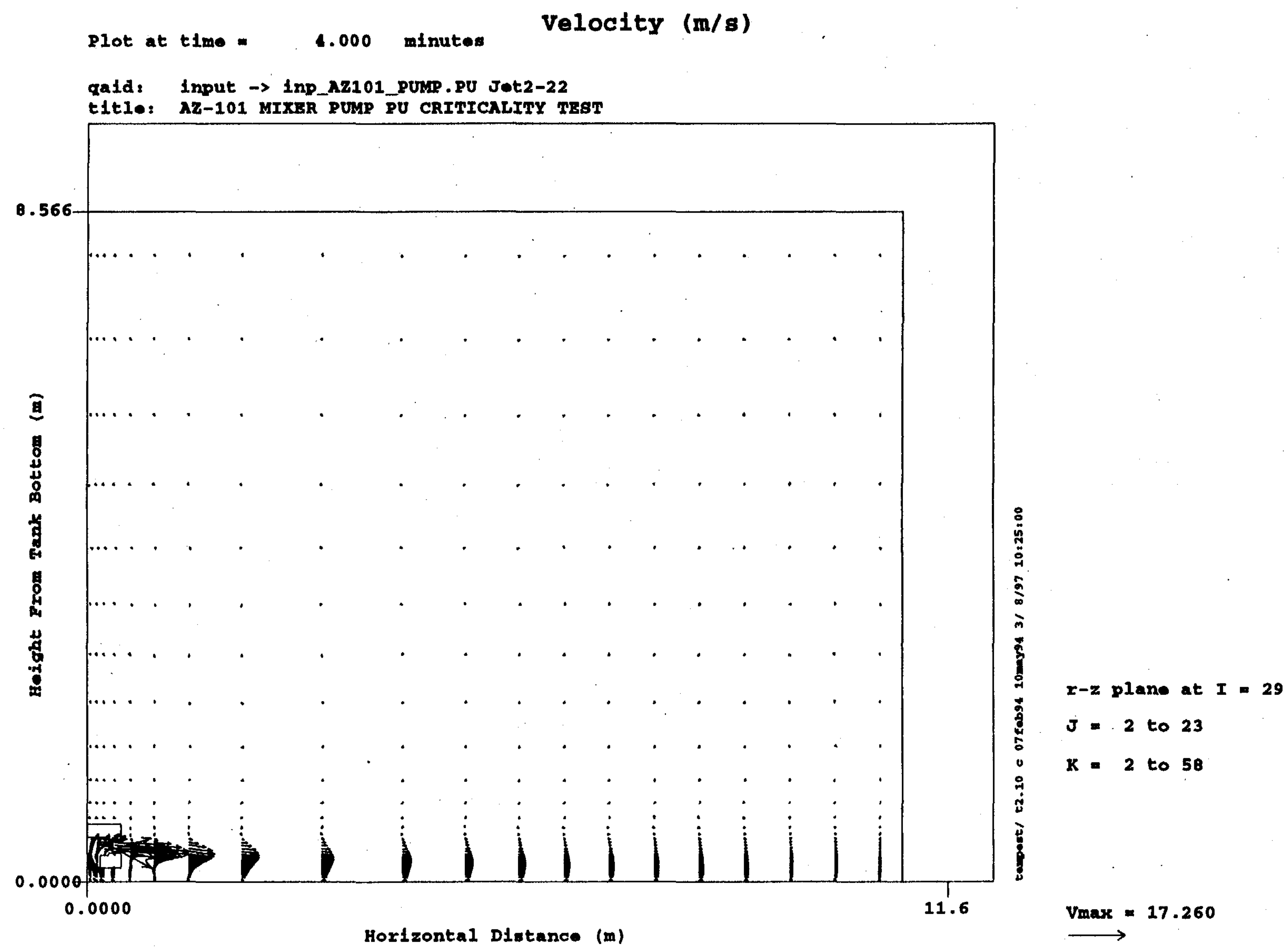

Figure 4.8. Predicted Velocity Distribution in the 7 O' Clock Position at 4 Simulation Minutes for Case 2

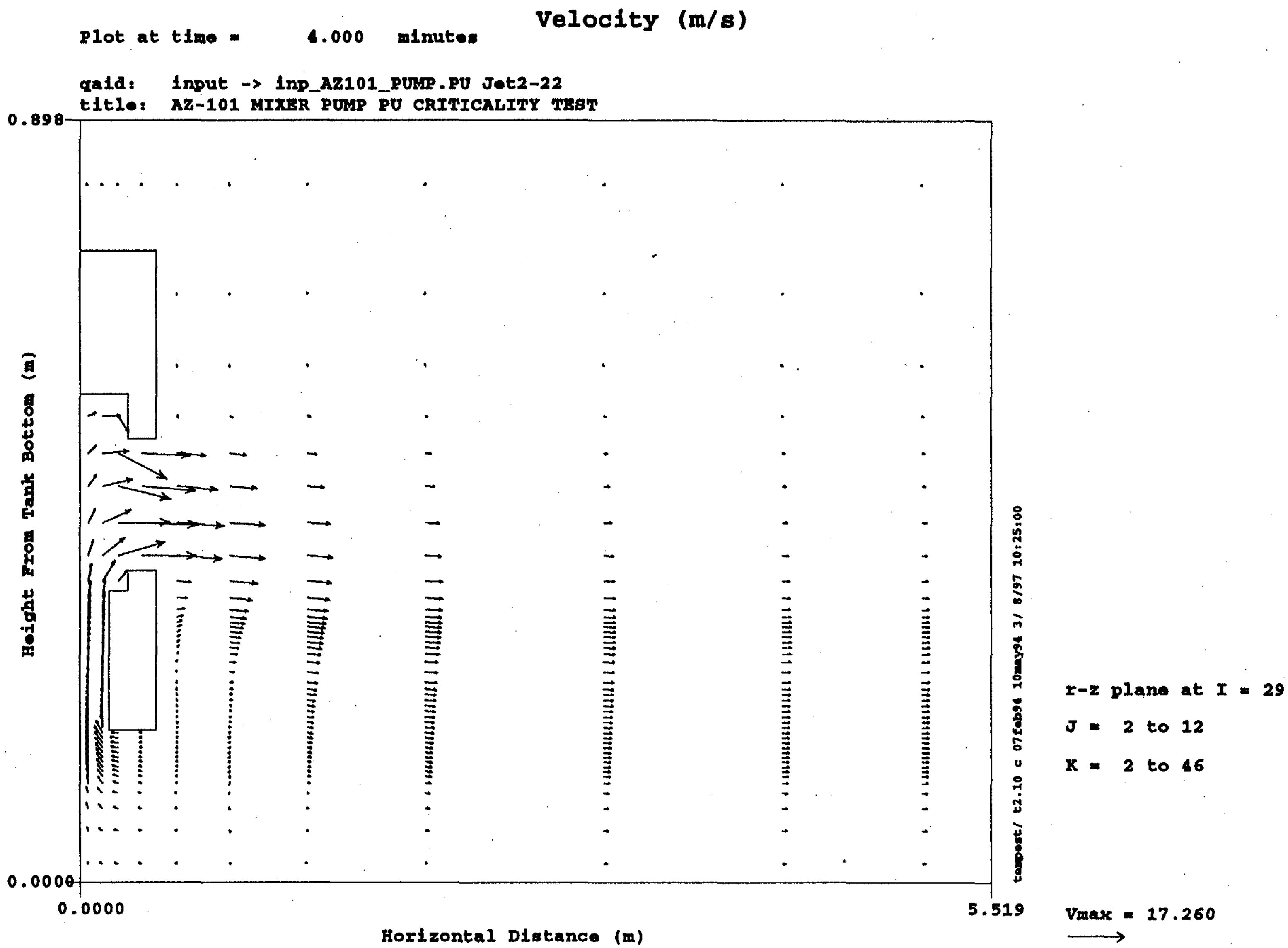

Figure 4.9. Predicted Velocity Distribution in and around the Pump in the 7 O' Clock Position at 4 Simulation Minutes for Case 2

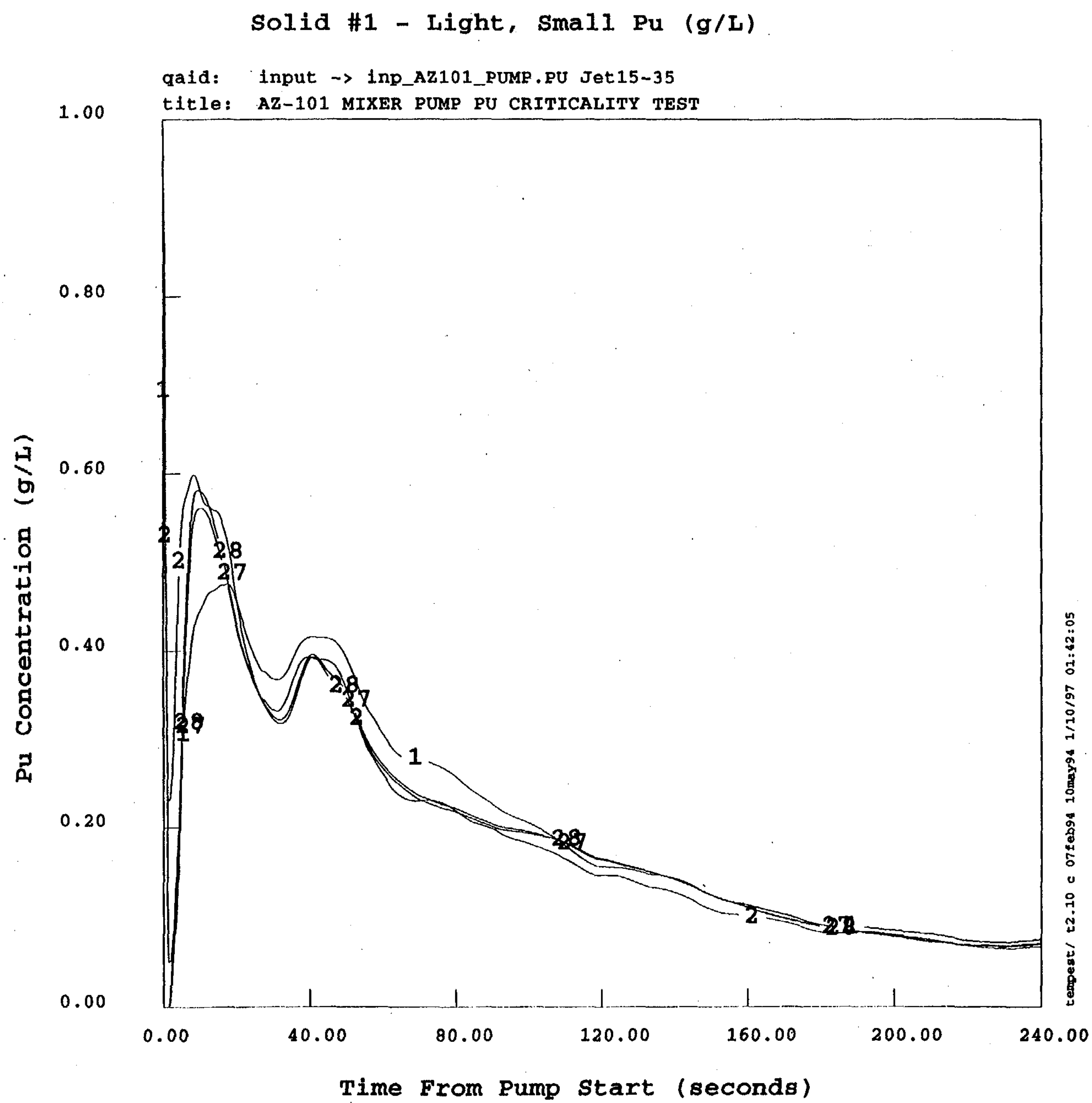

Figure 4.10. Predicted Time-Varying Solid 1 Plutonium Concentrations within the Pump Housing over 4 Simulation Minutes for Case 1

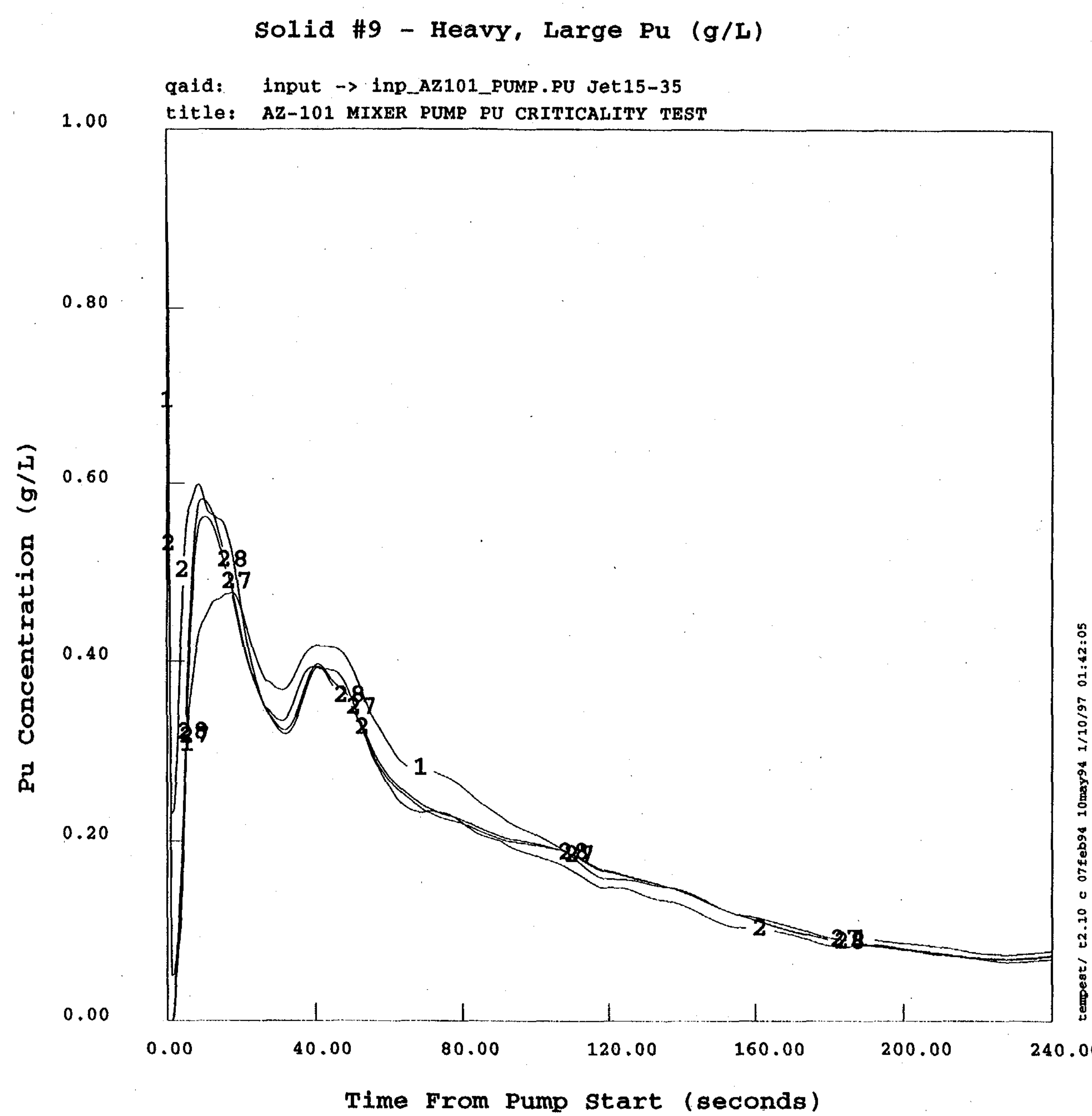

Figure 4.11. Predicted Time-Varying Solid 9 Plutonium Concentrations within the Pump Housing over 4 Simulation Minutes for Case 1

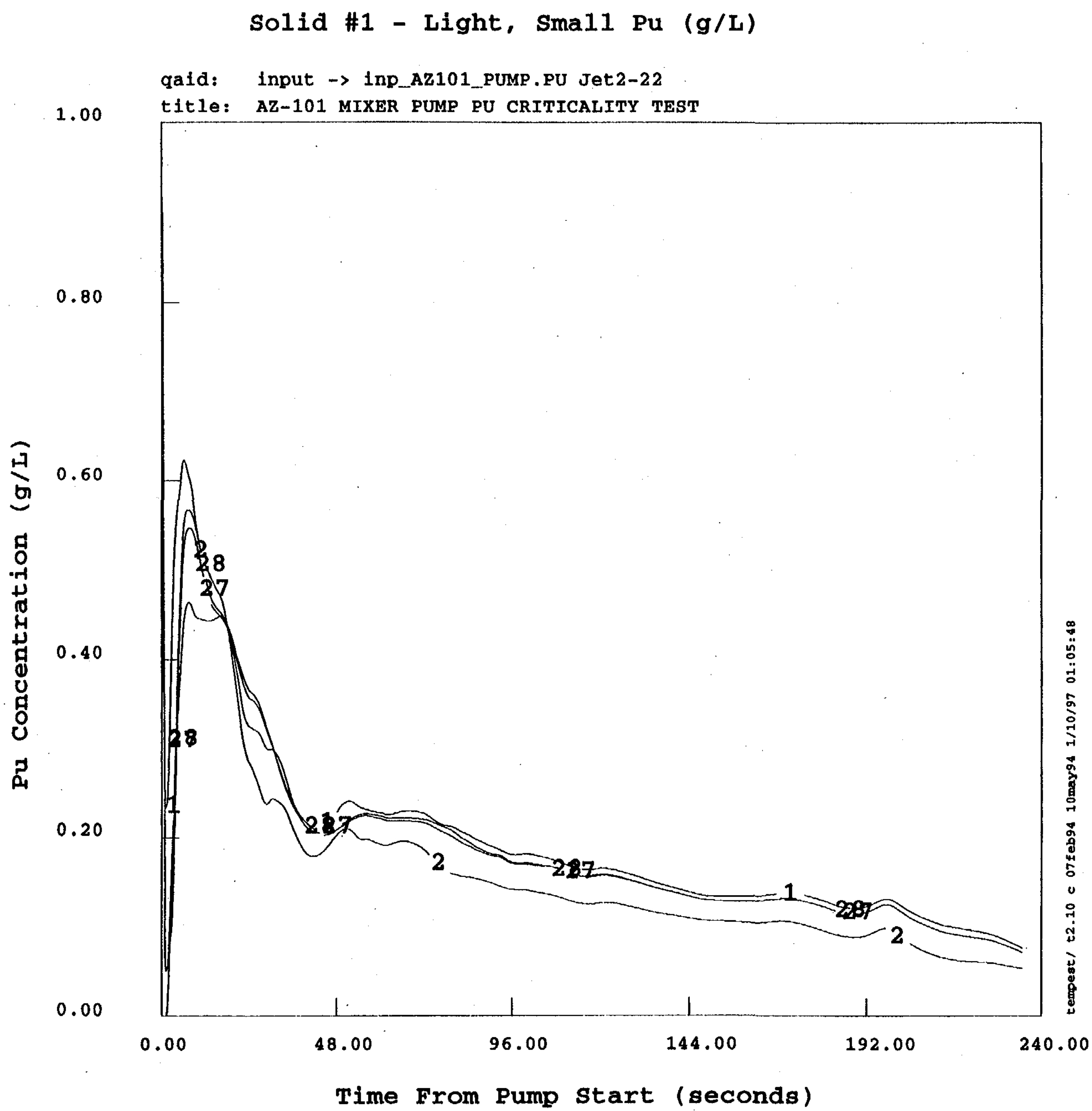

Figure 4.12. Predicted Time-Varying Solid 1 Plutonium Concentrations within the Pump Housing over 4 Simulation Minutes for Case 2

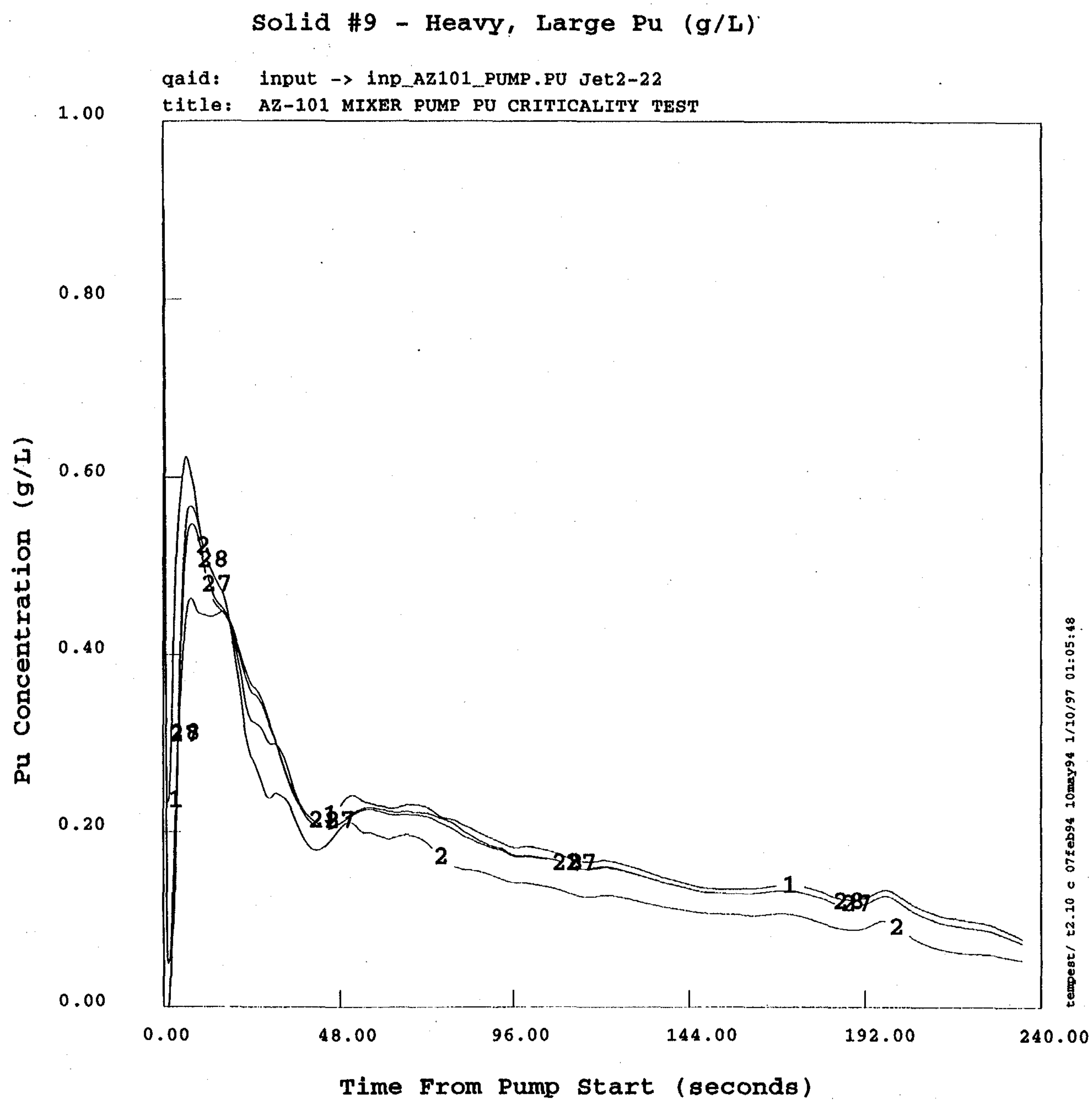

Figure 4.13. Predicted Time-Varying Solid 9 Plutonium Concentrations within the Pump Housing over 4 Simulation Minutes for Case 2

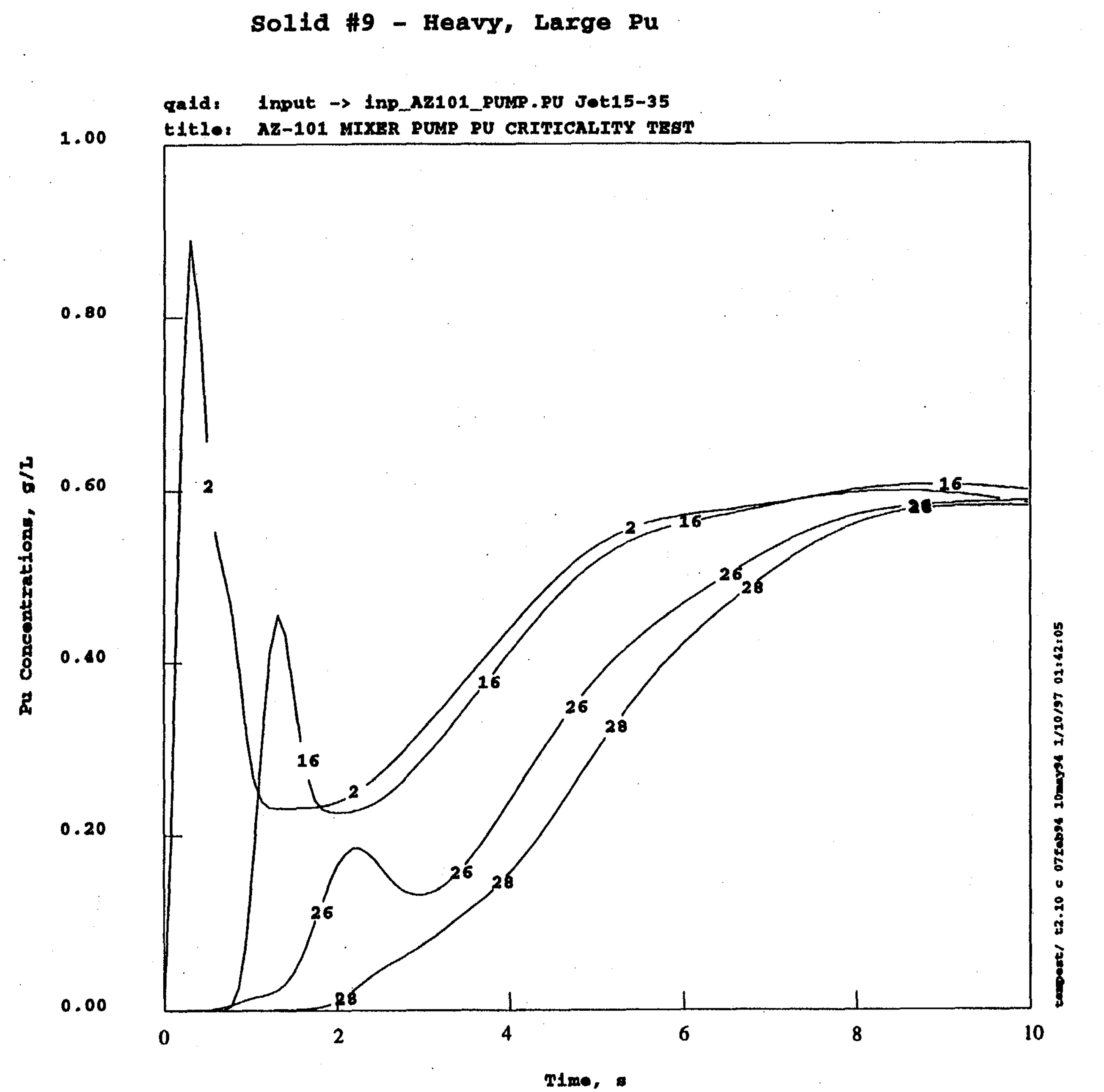

Figure 4.14. Predicted Time-Varying Solid 9 Plutonium Concentrations within the Pump Housing over 10 Simulation Seconds for Case 1

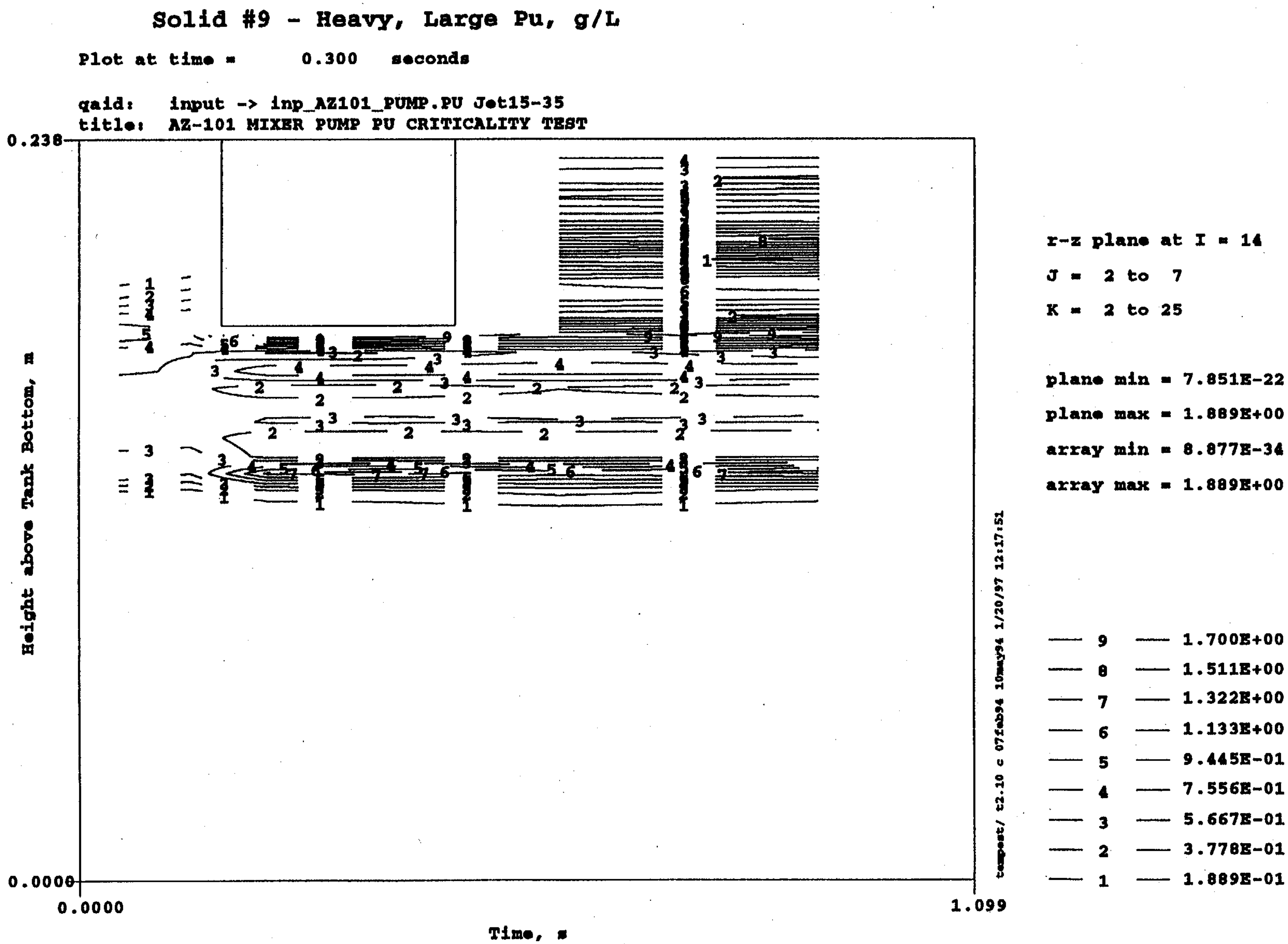

Figure 4.15. Predicted Distribution of Solid 9 Plutonium Concentrations in 11 O'Clock Position at 0.3 Simulation Second for Case 1

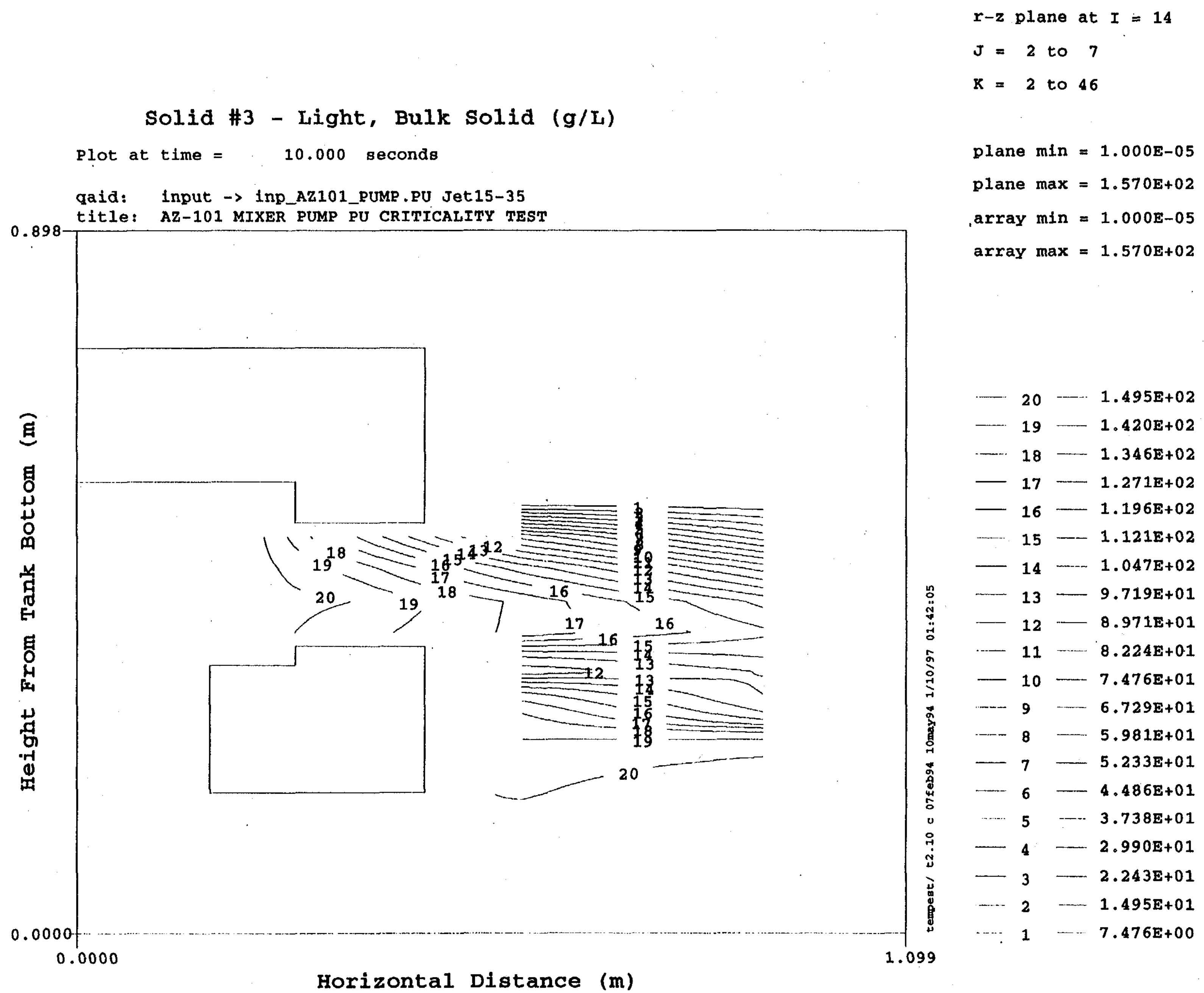

Figure 4.16. Predicted Distribution of Solid 3 Concentrations in 11 O'Clock Position at 10 Simulation Second for Case 1

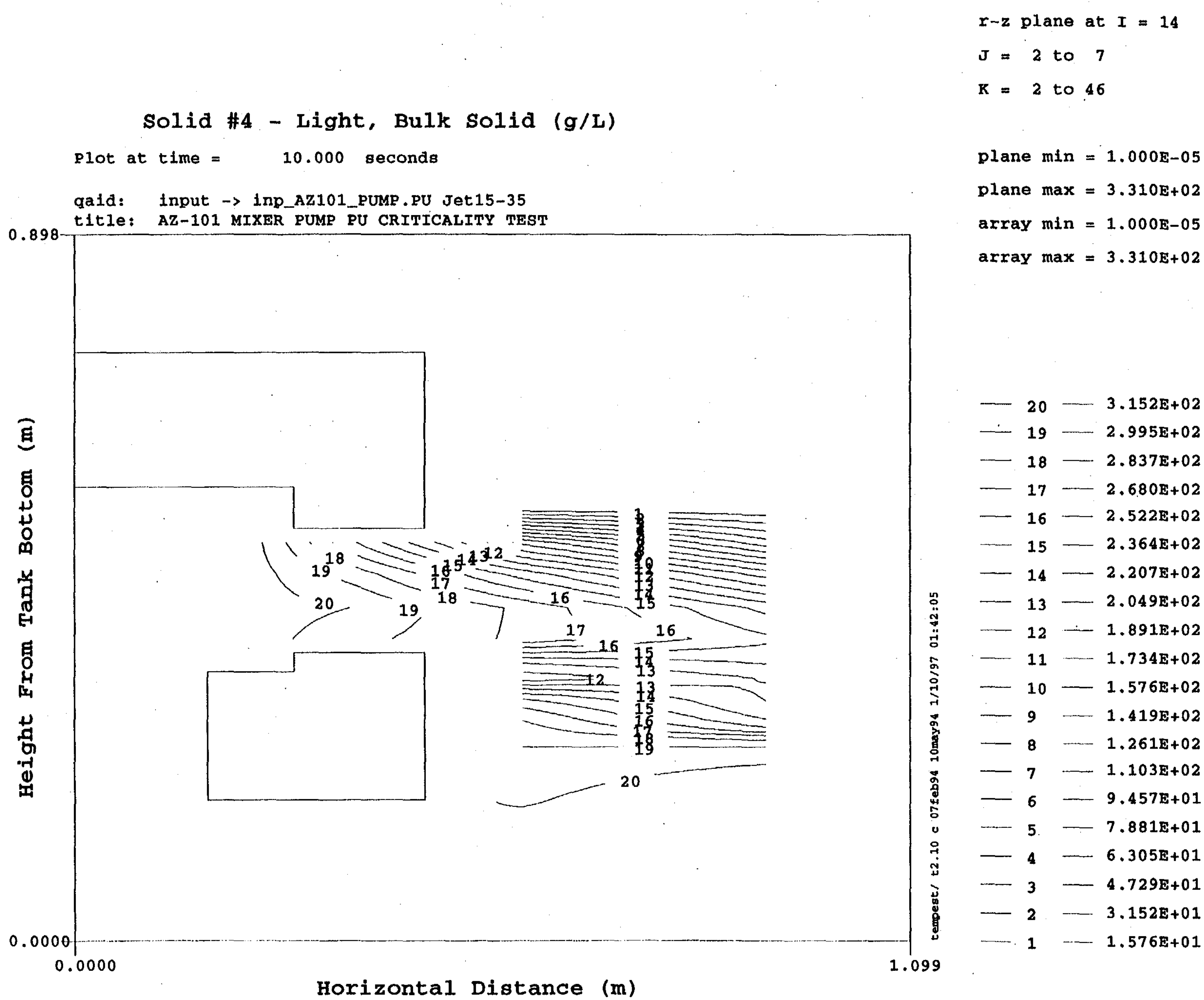

Figure 4.17. Predicted Distribution of Solid 4 Concentrations in 11 O'Clock Position at 10 Simulation Second for Case 1

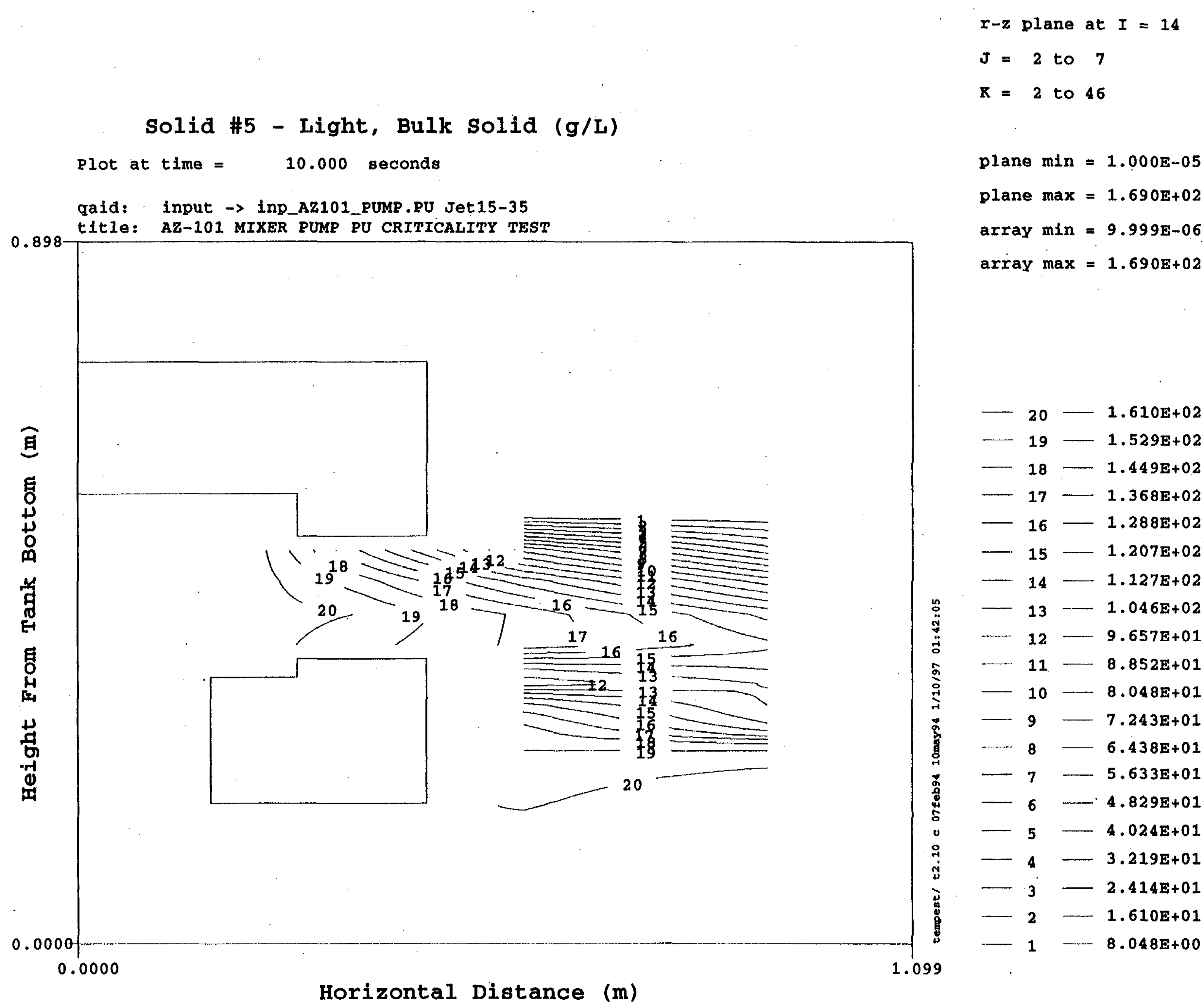

Figure 4.18. Predicted Distribution of Solid 5 Concentrations in 11 O'Clock Position at 10 Simulation Second for Case 1

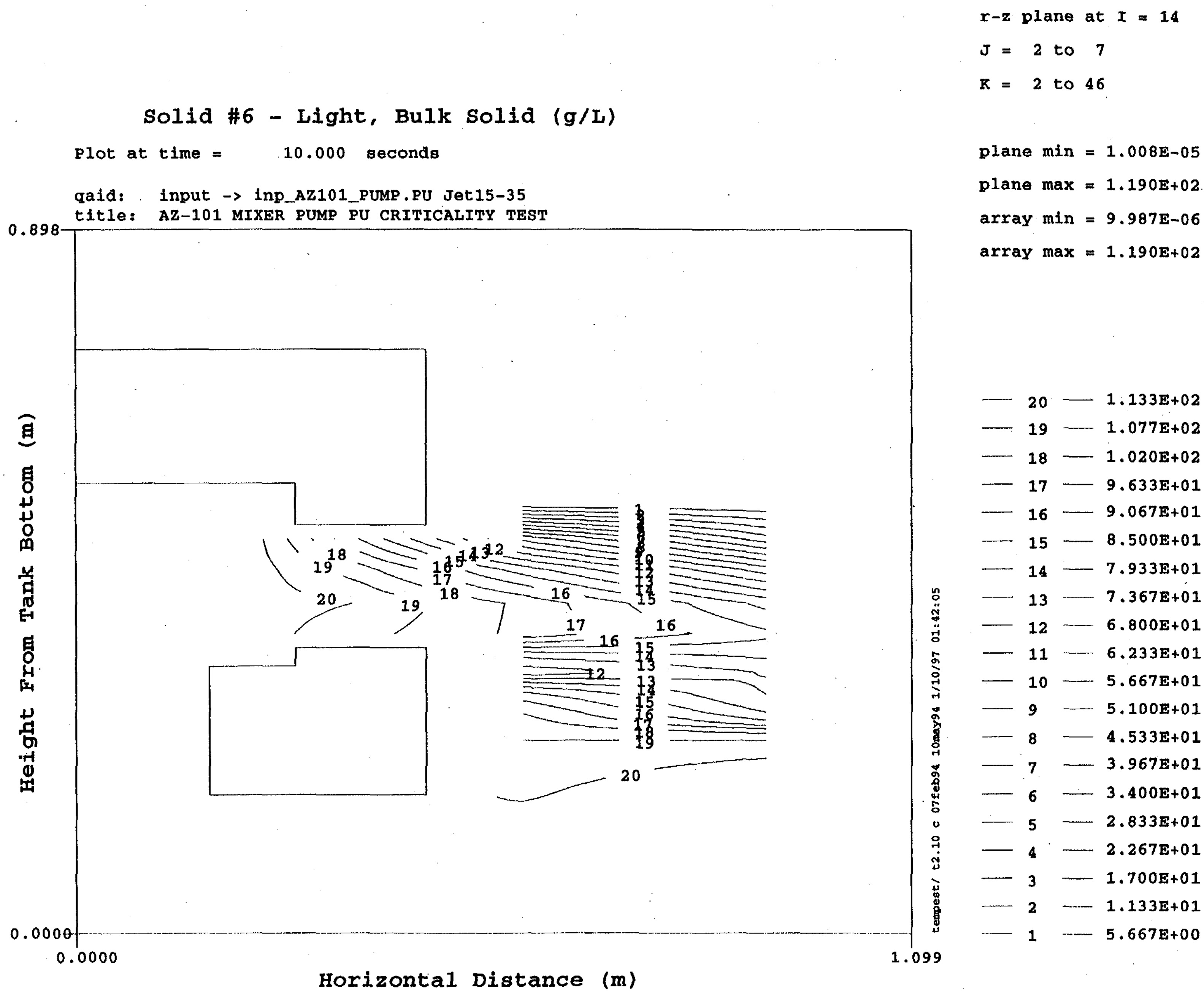

Figure 4.19. Predicted Distribution of Solid 6 Concentrations in 11 O'Clock Position at 10 Simulation Second for Case 1

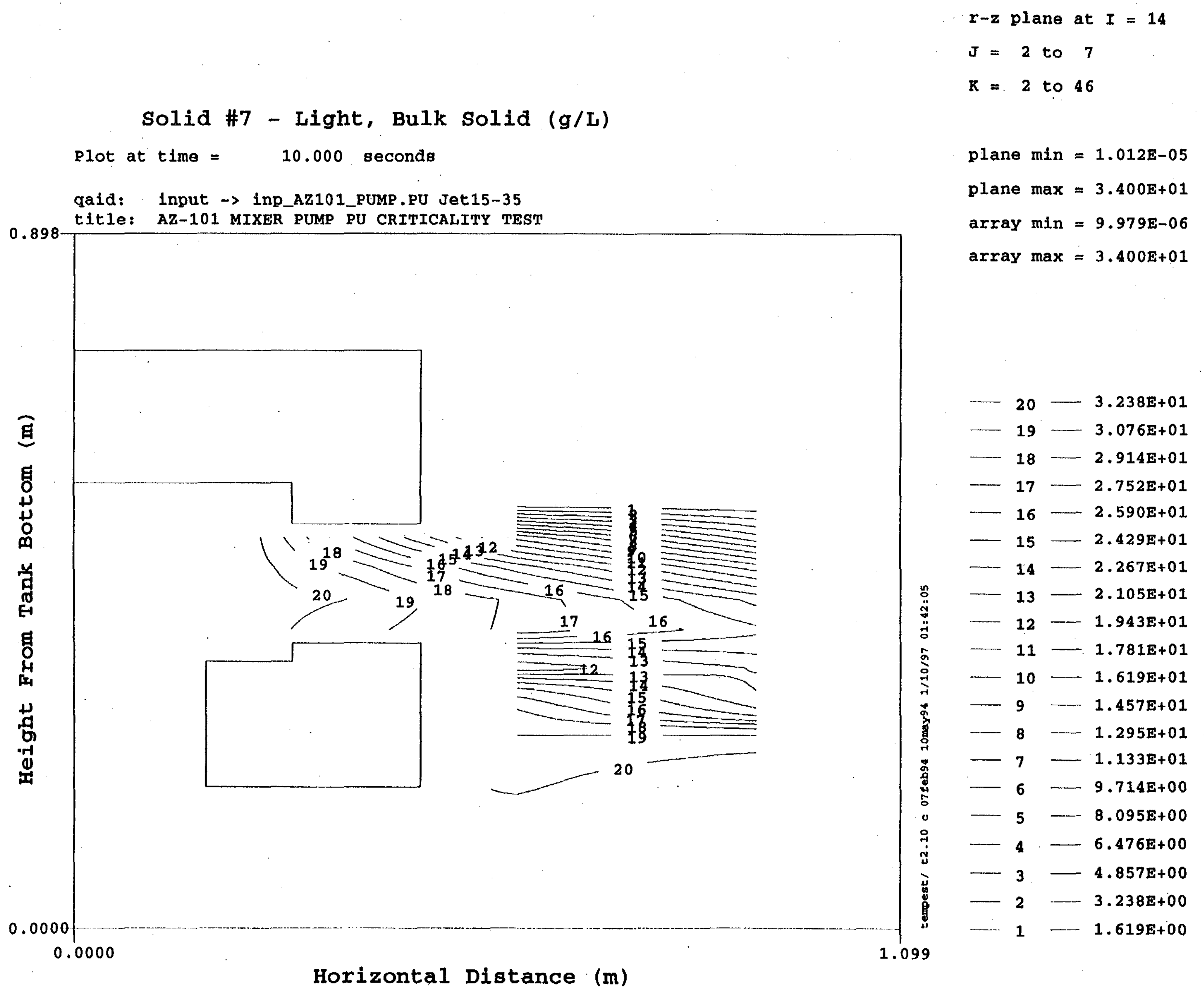

Figure 4.20. Predicted Distribution of Solid 7 Concentrations in 11 O'Clock Position at 10 Simulation Second for Case 1

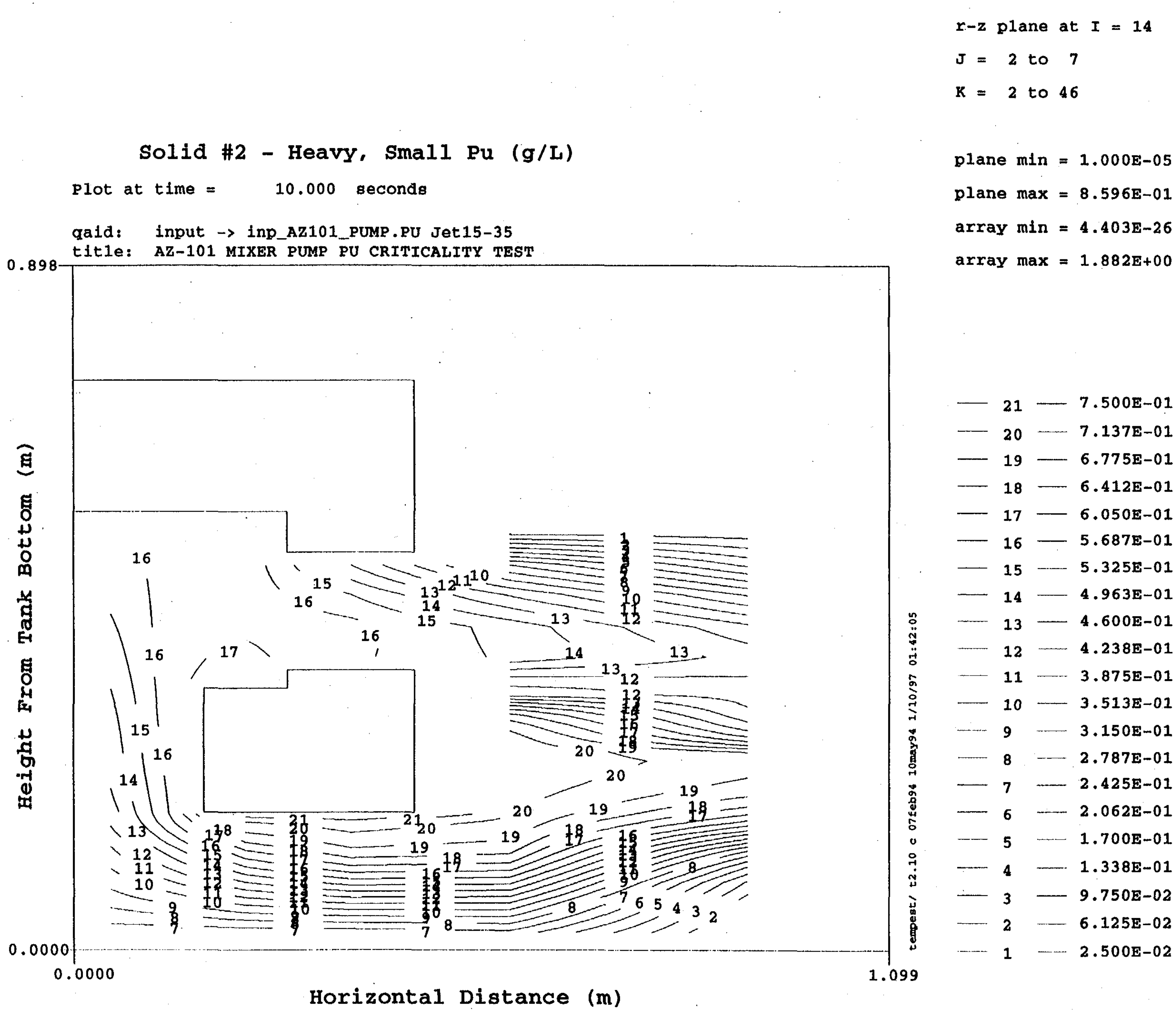

Figure 4.21. Predicted Distribution of Solid 1 Plutonium Concentrations in 11 O'Clock Position at 10 Simulation Second for Case 1

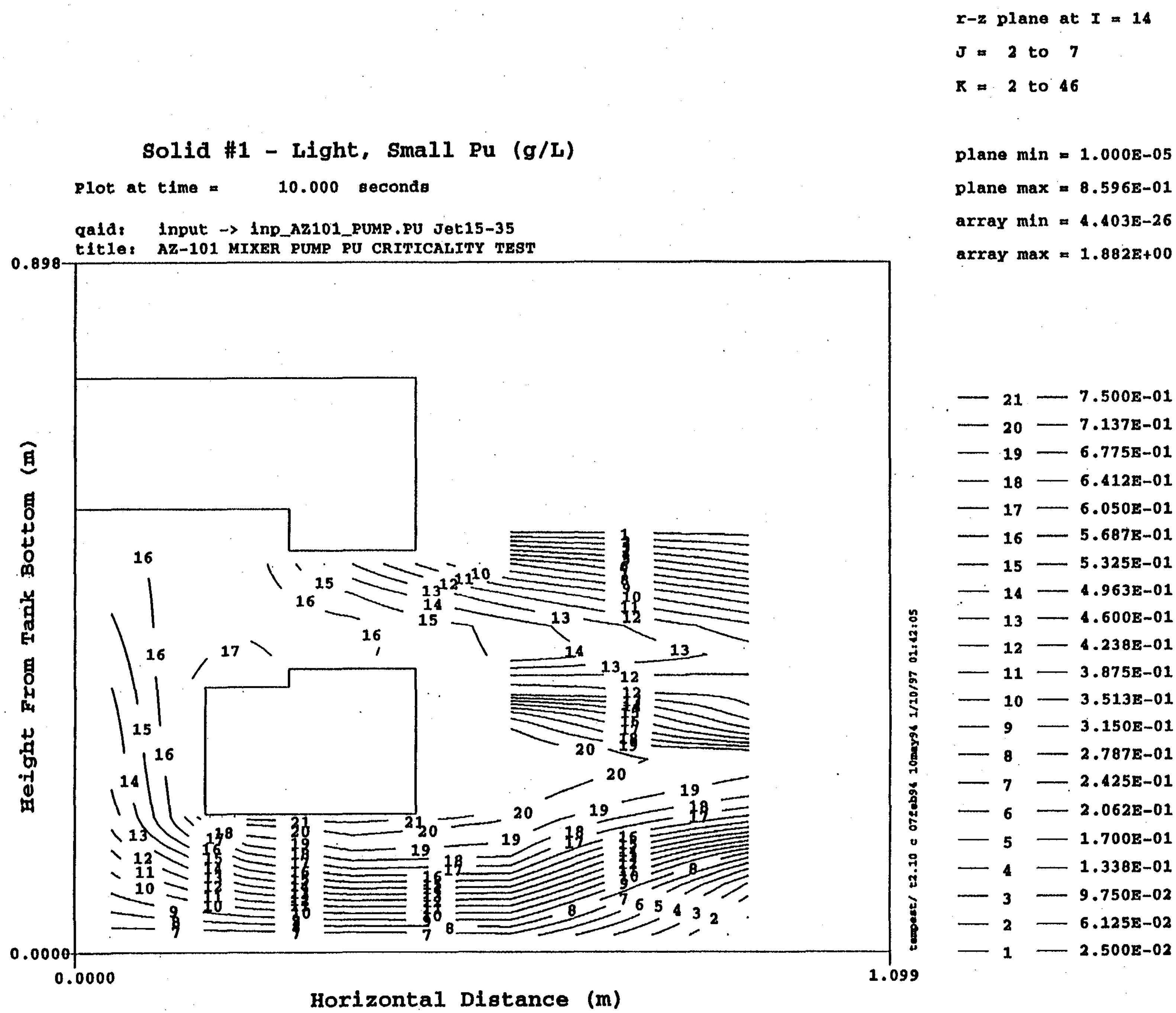

Figure 4.22. Predicted Distribution of Solid 2 Plutonium Concentrations in 11 O'Clock Position at 10 Simulation Second for Case 1

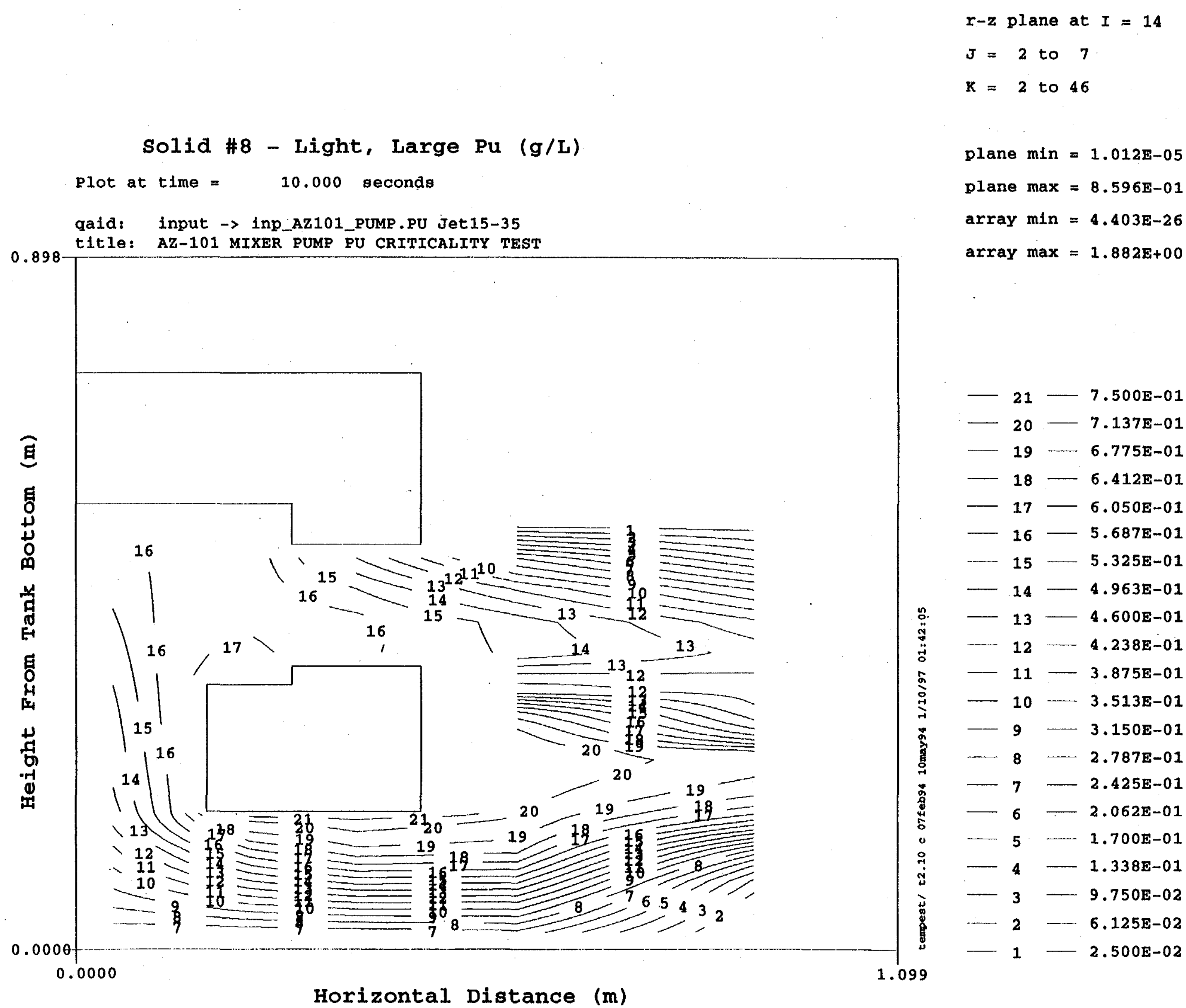

Figure 4.23. Predicted Distribution of Solid 8 Plutonium Concentrations in 11 O'Clock Position at 10 Simulation Second for Case 1

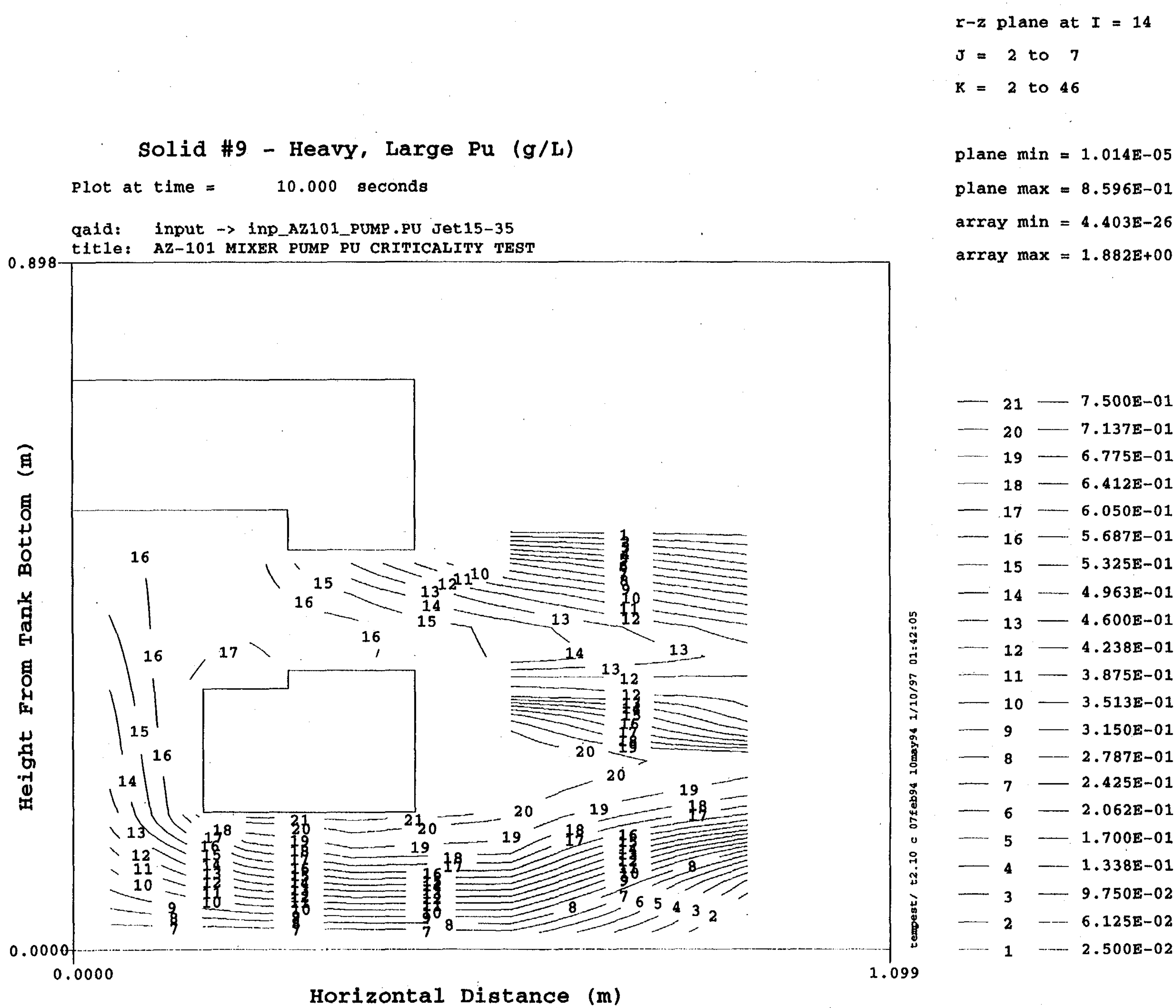

Figure 4.24. Predicted Distribution of Solid 9 Plutonium Concentrations in 11 O'Clock Position at 10 Simulation Second for Case 1

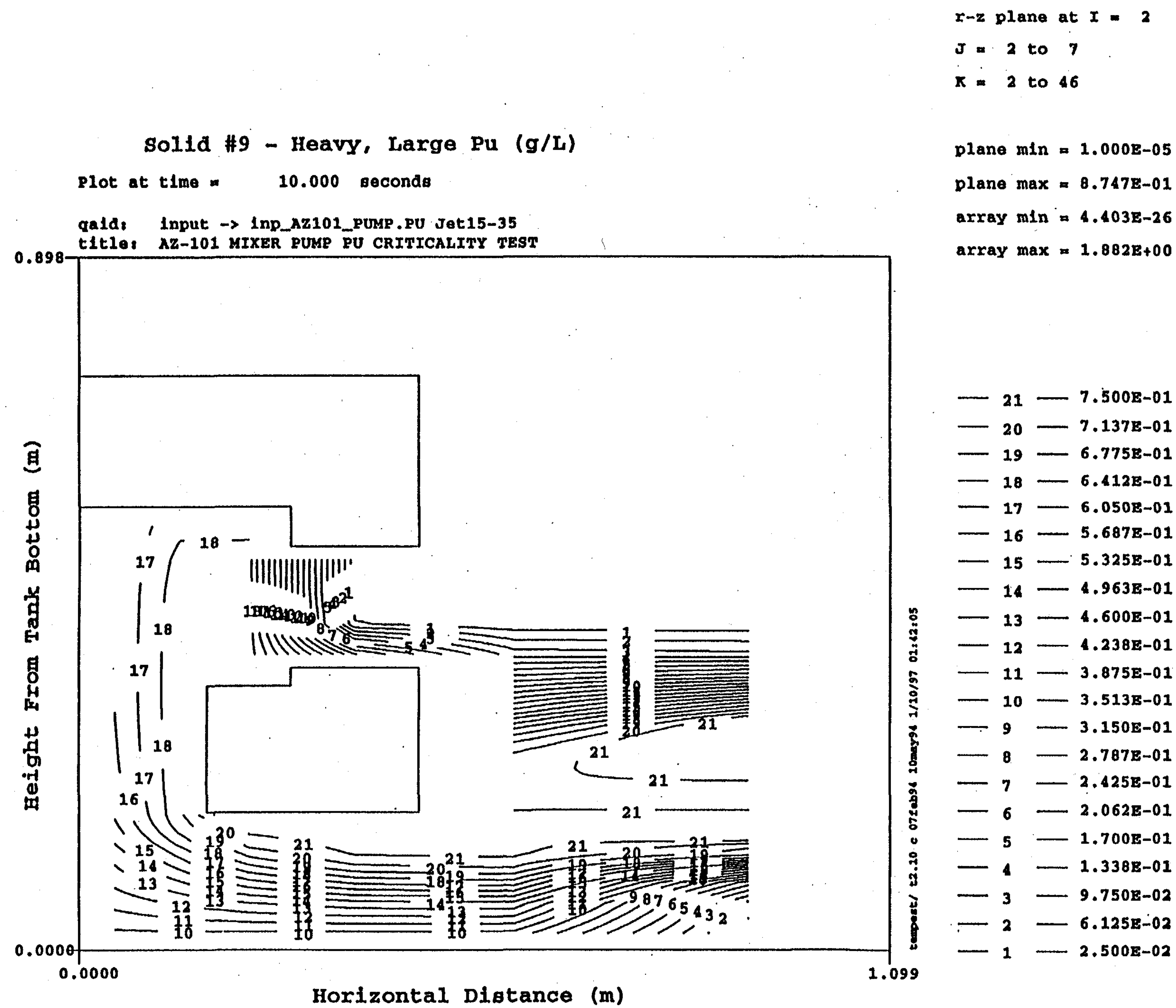

Figure 4.25. Predicted Distribution of Solid 9 Plutonium Concentrations in 3 O'Clock Position at 10 Simulation Second for Case 1

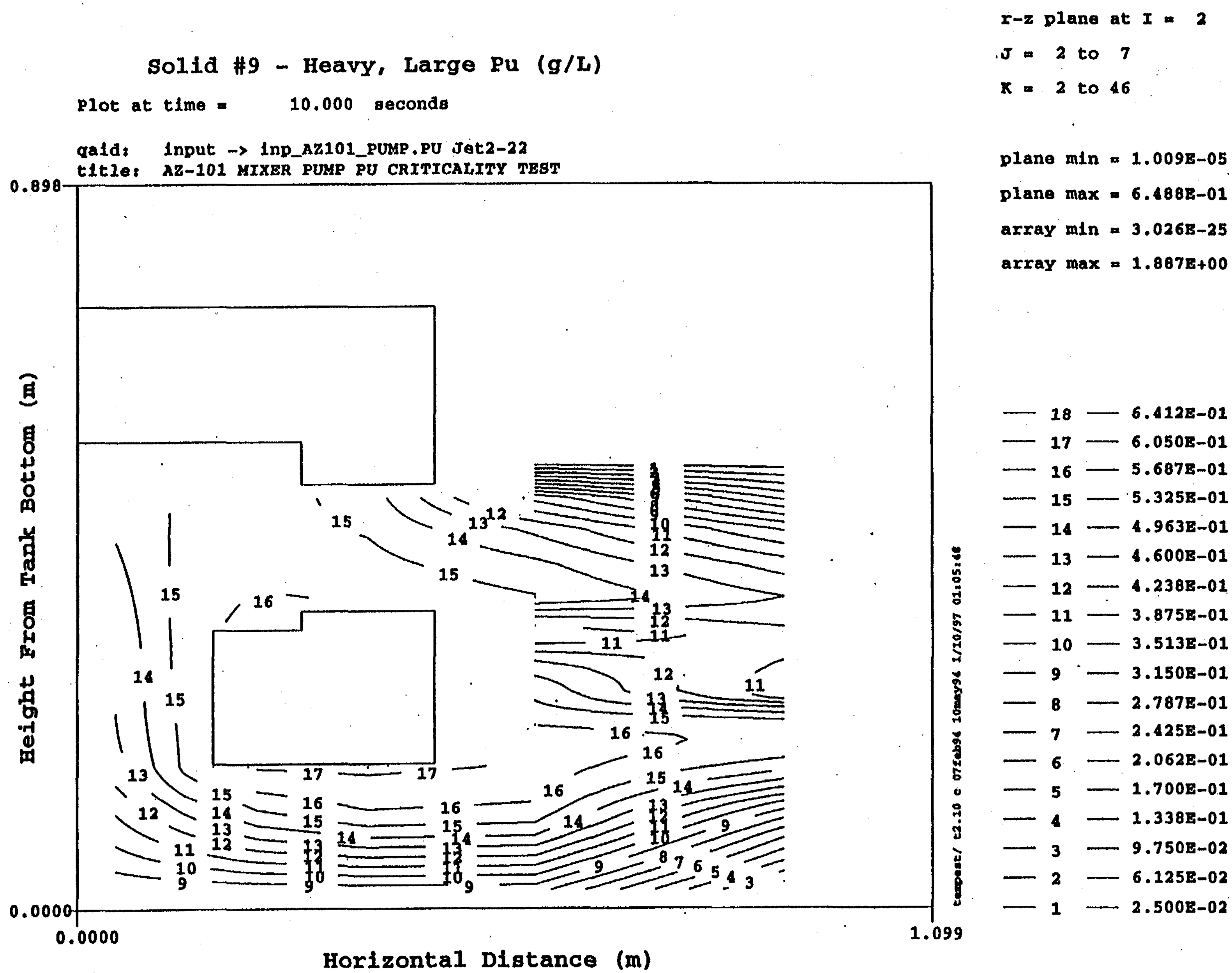

Figure 4.26. Predicted Distribution of Solid 9 Plutonium Concentrations in 3 O'Clock Position at 10 Simulation Second for Case 2

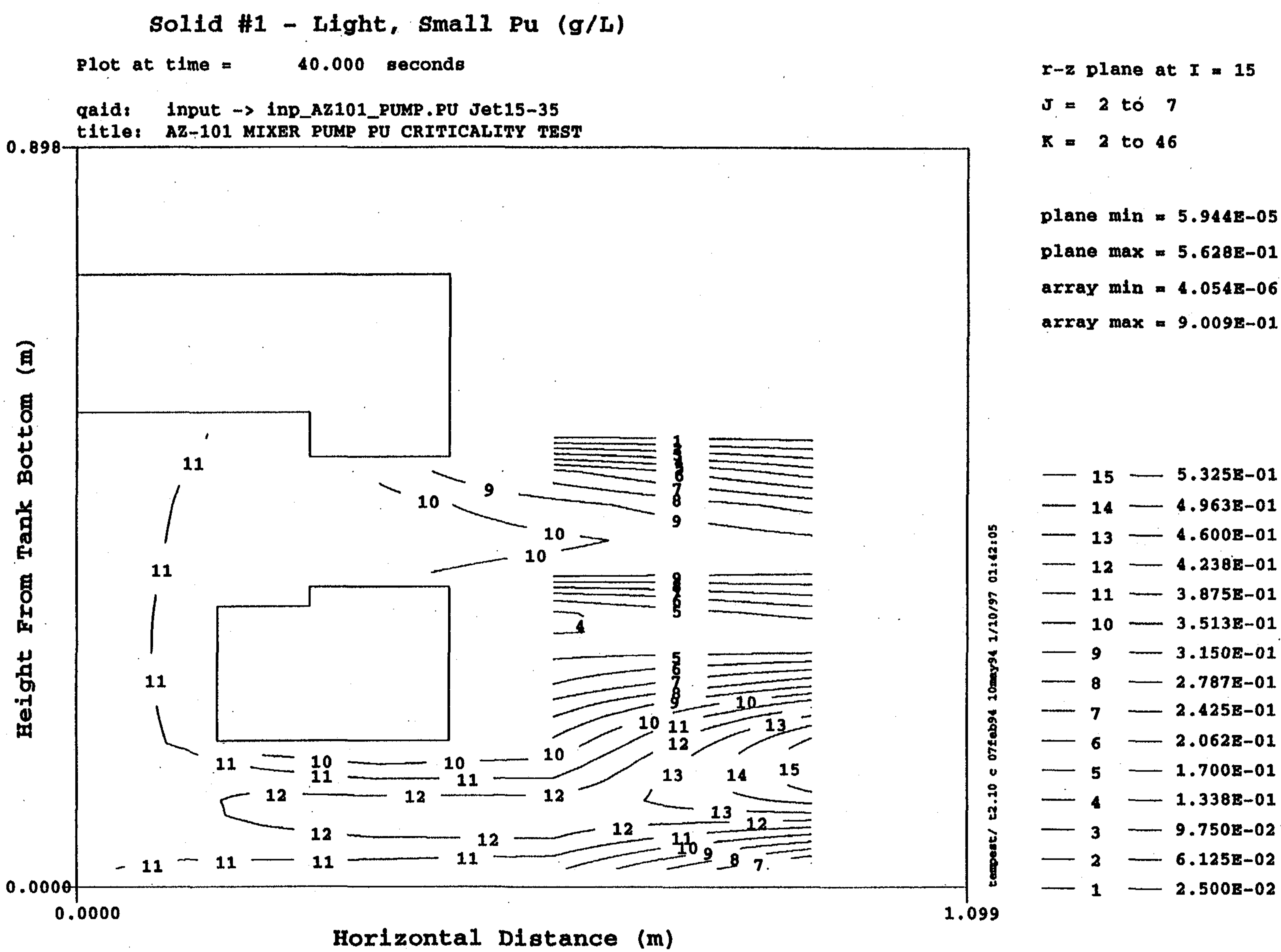

Figure 4.27. Predicted Distribution of Solid 1 Plutonium Concentrations in 10:50 O'Clock Position at 40 Simulation Second for Case 1

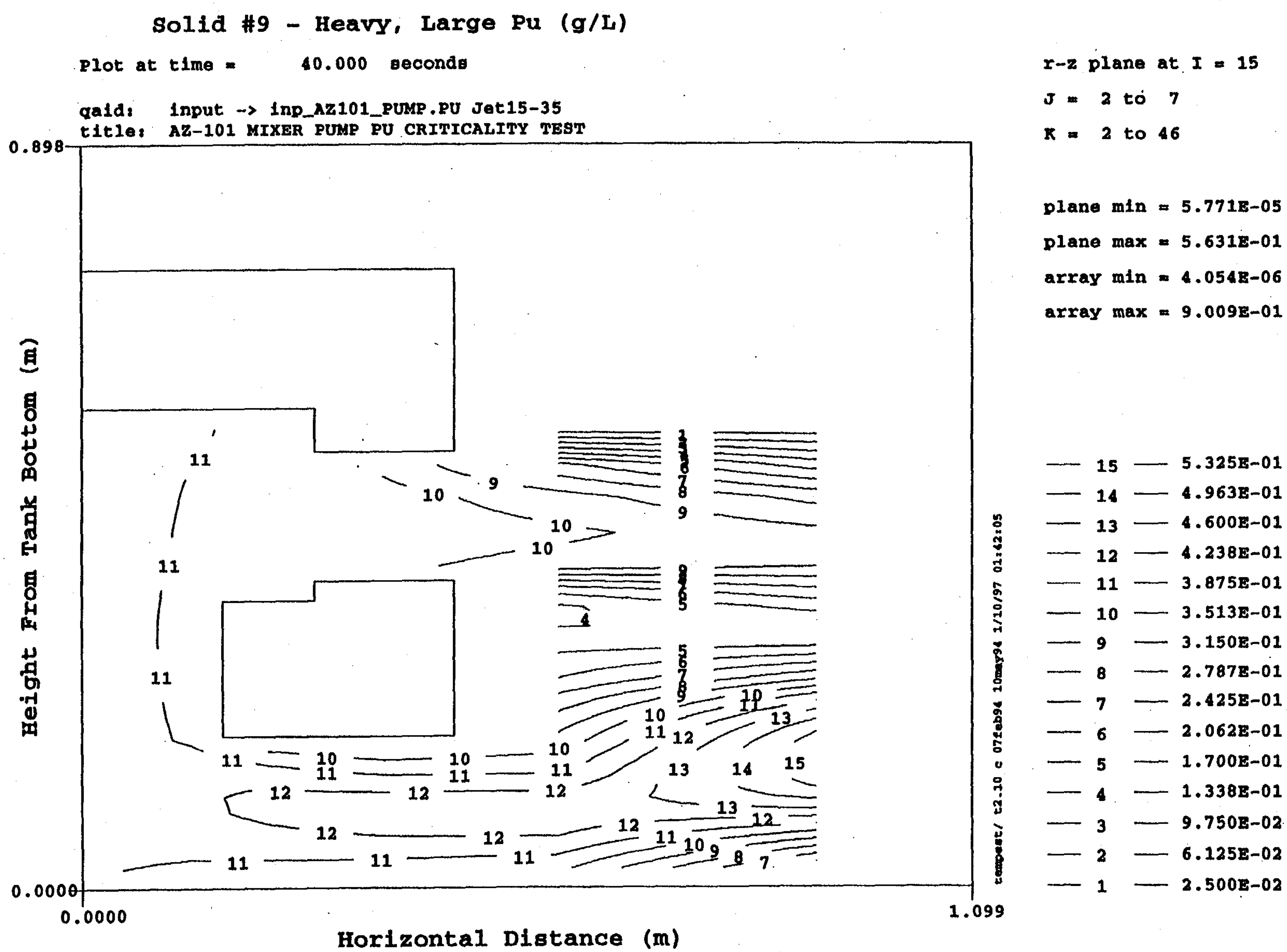

Figure 4.28. Predicted Distribution of Solid 9 Plutonium Concentrations in 10:50 O'Clock Position at 40 Simulation Second for Case 1

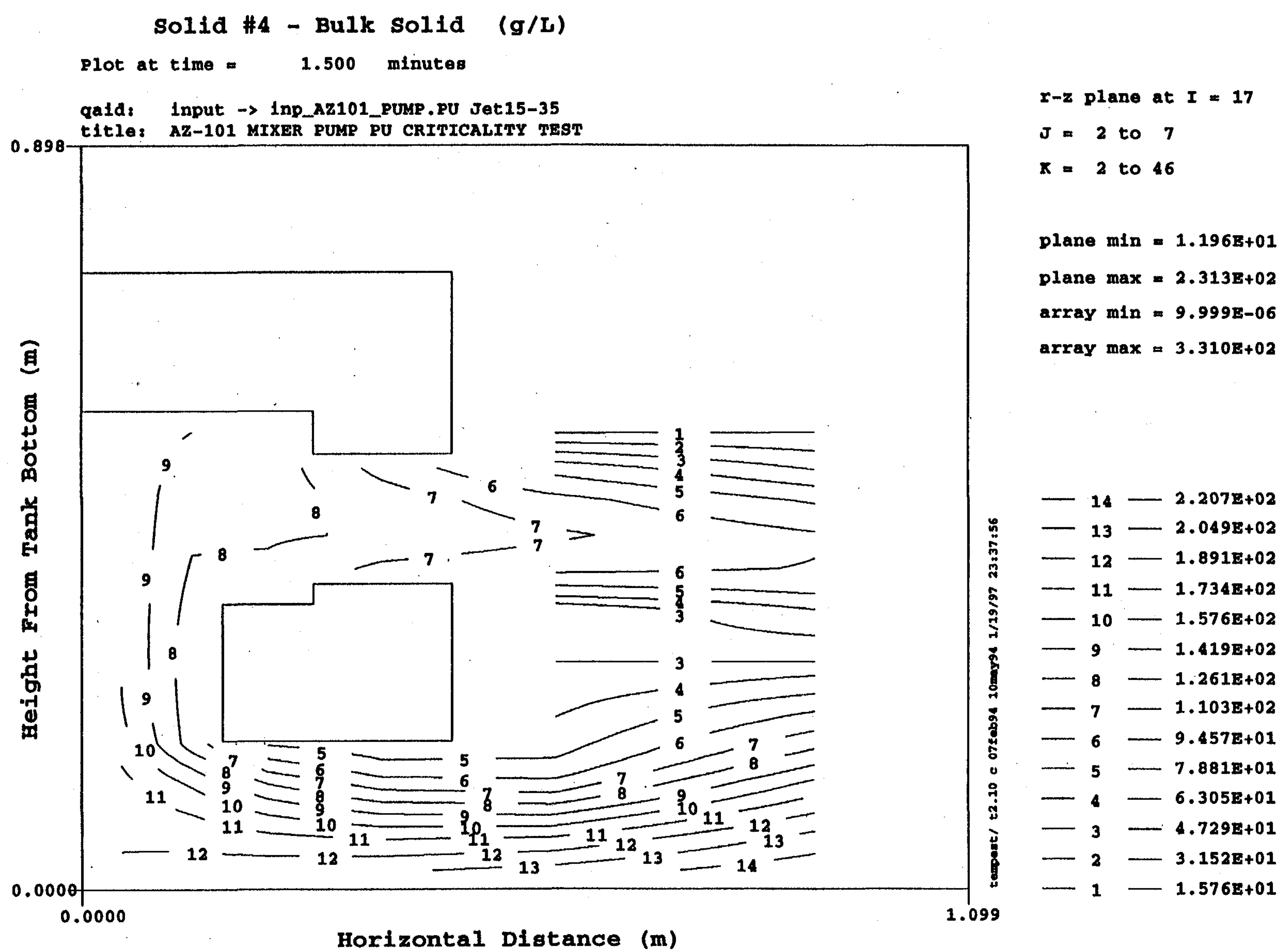

Figure 4.29. Predicted Distribution of Solid 4 Concentrations in 10:30 O'Clock Position at 1.5 Simulation Minutes for Case 1

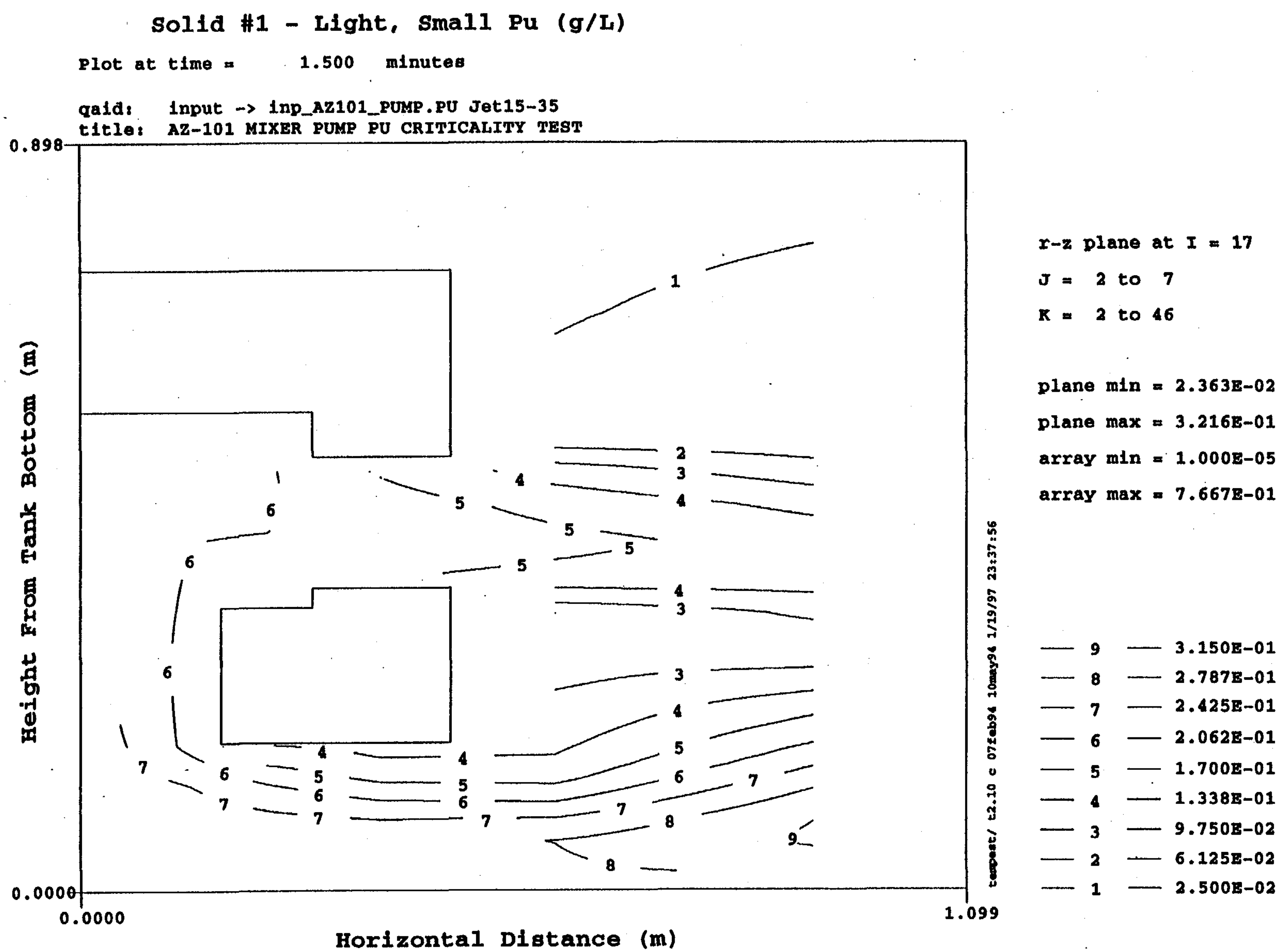

Figure 4.30. Predicted Distribution of Solid 1 Plutonium Concentrations in 10:30 O'Clock Position at 1.5 Simulation Minutes for Case 1

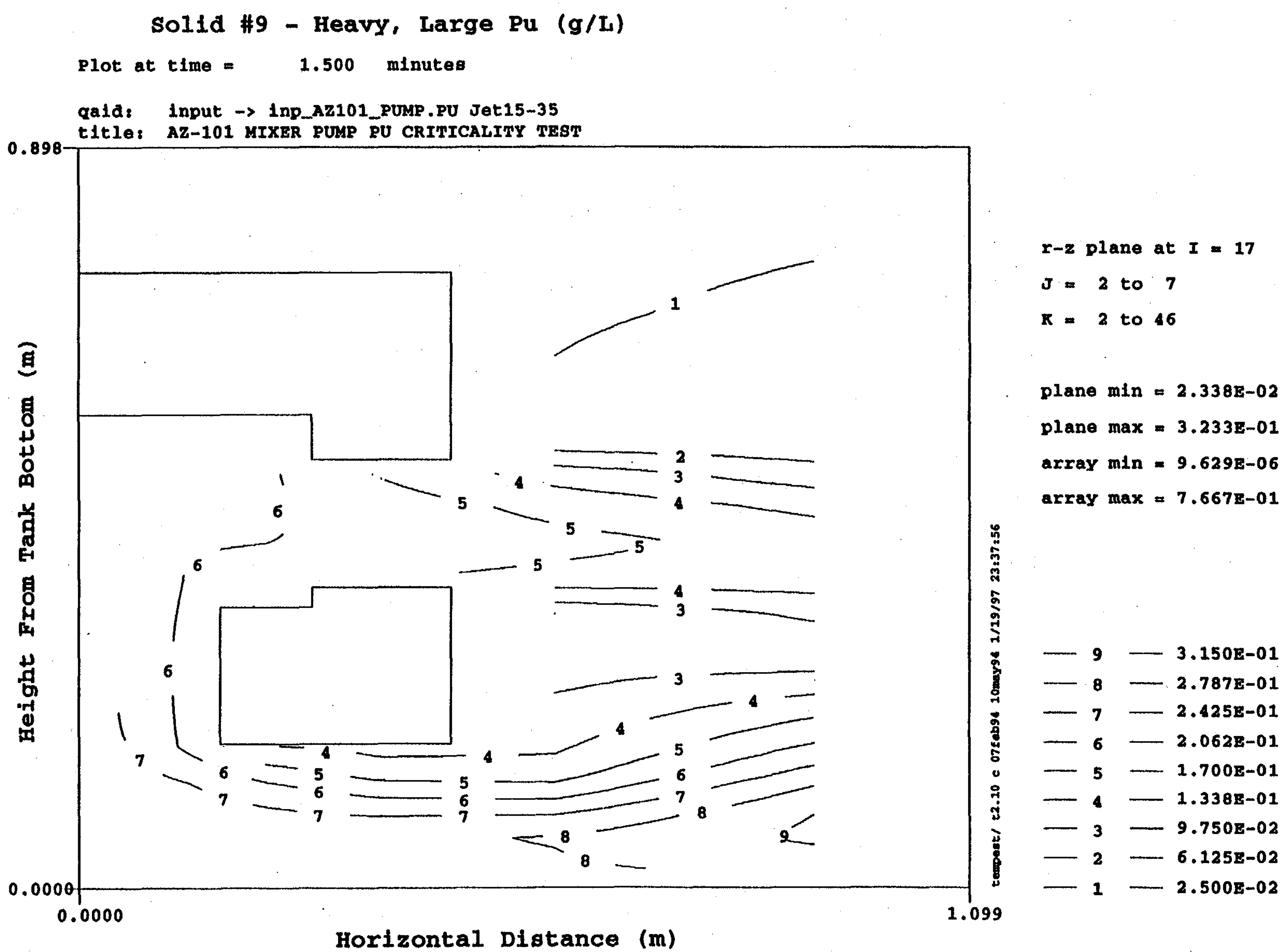

Figure 4.31. Predicted Distribution of Solid 9 Plutonium Concentrations in 9 O'Clock Position at 1.5 Simulation Minutes for Case 1

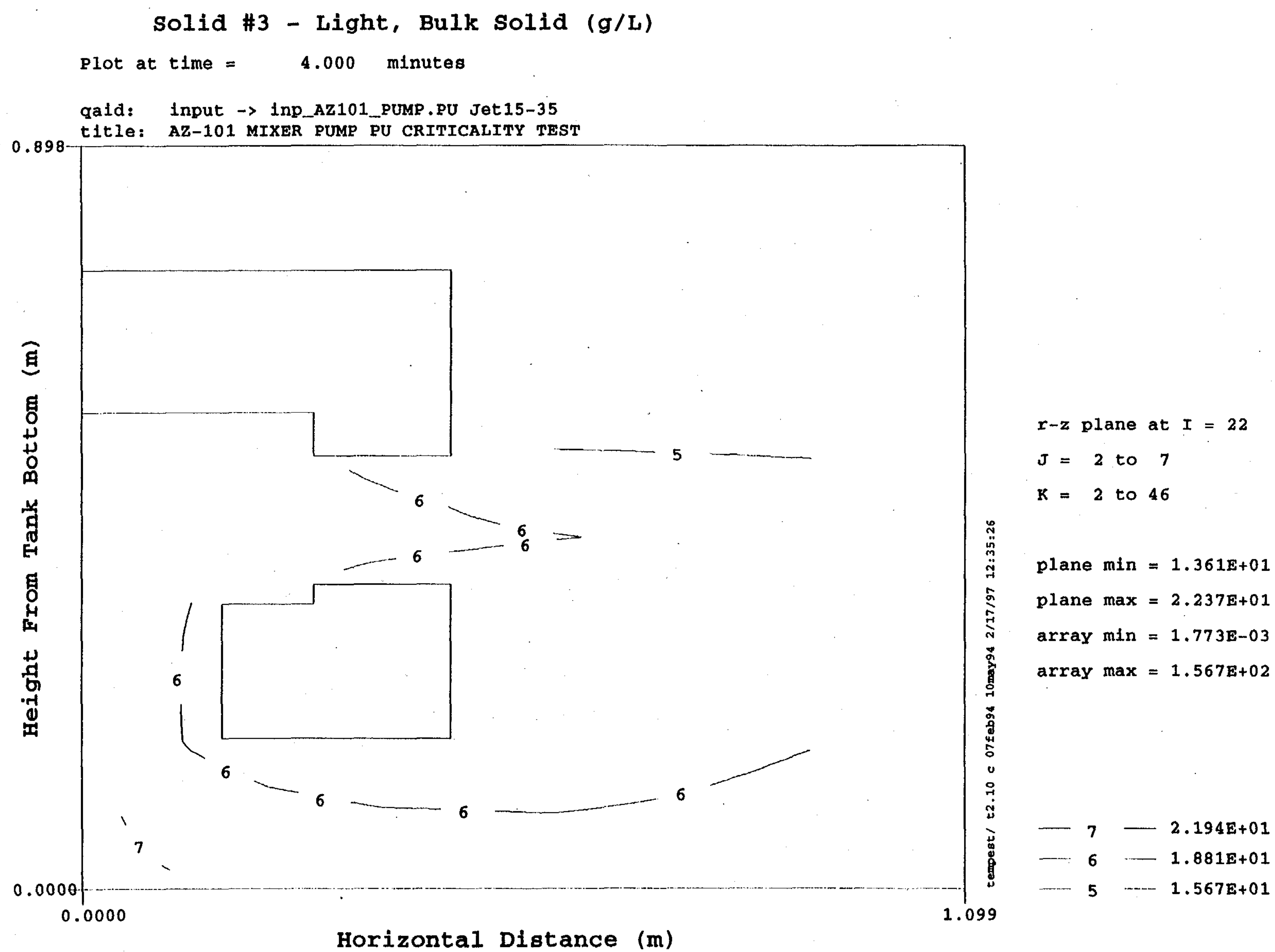

Figure 4.32. Predicted Distribution of Solid 3 Concentrations in 9 O'Clock Position at 4 Simulation Minutes for Case 1

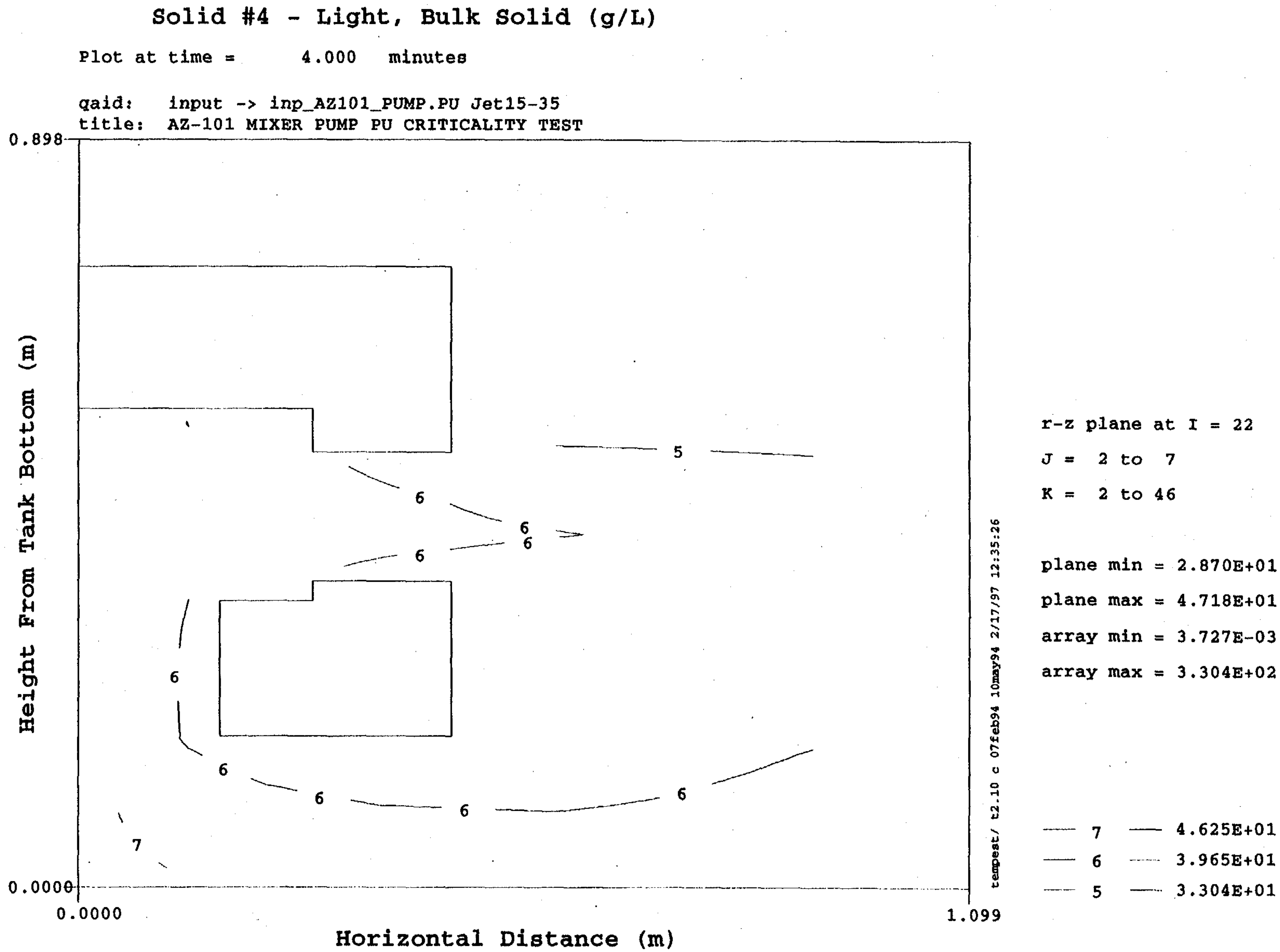

Figure 4.33. Predicted Distribution of Solid 4 Concentrations in 9 O'Clock Position at 4 Simulation Minutes for Case 1

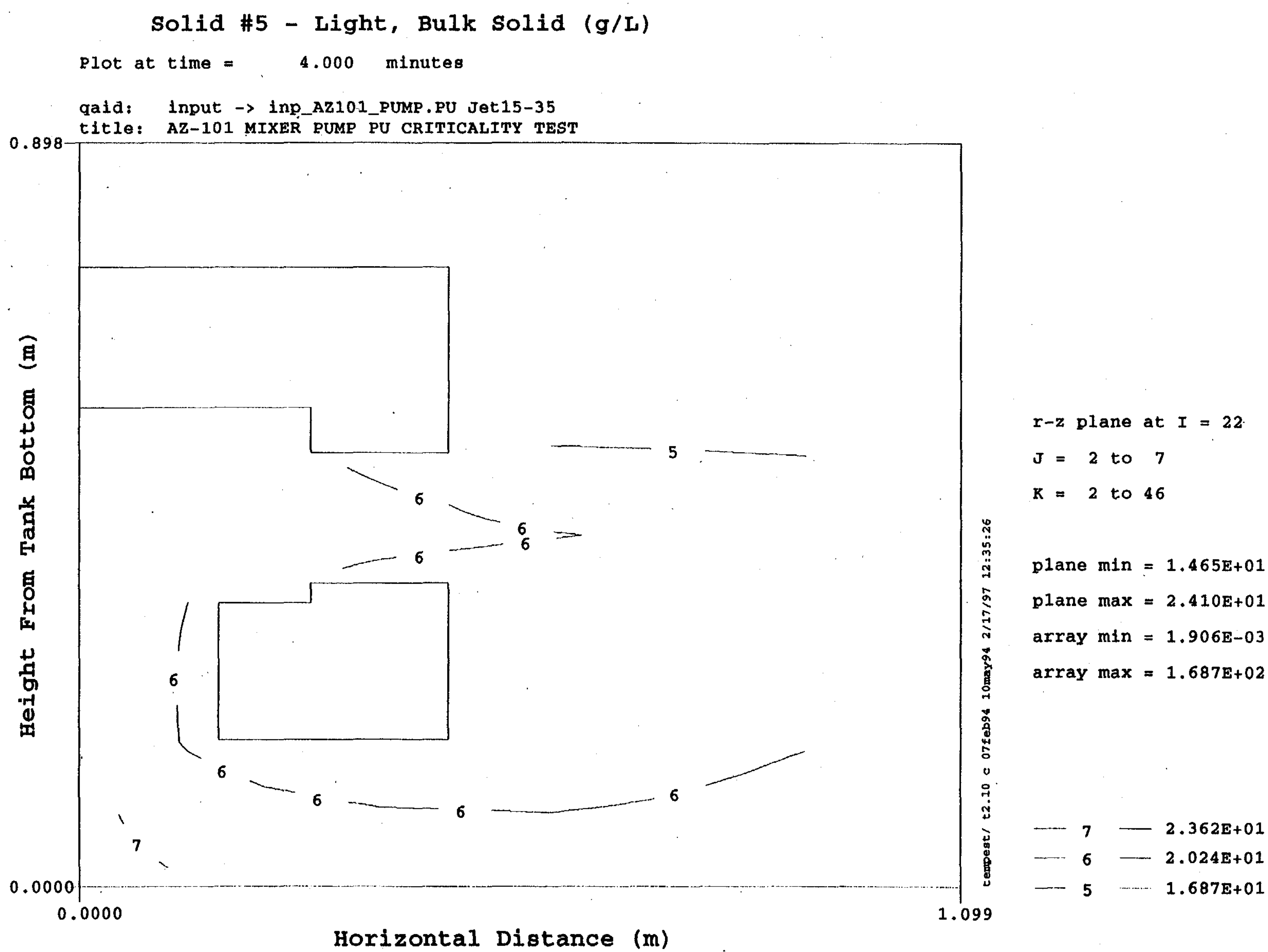

Figure 4.34. Predicted Distribution of Solid 5 Concentrations in 9 O'Clock Position at 4 Simulation Minutes for Case 1

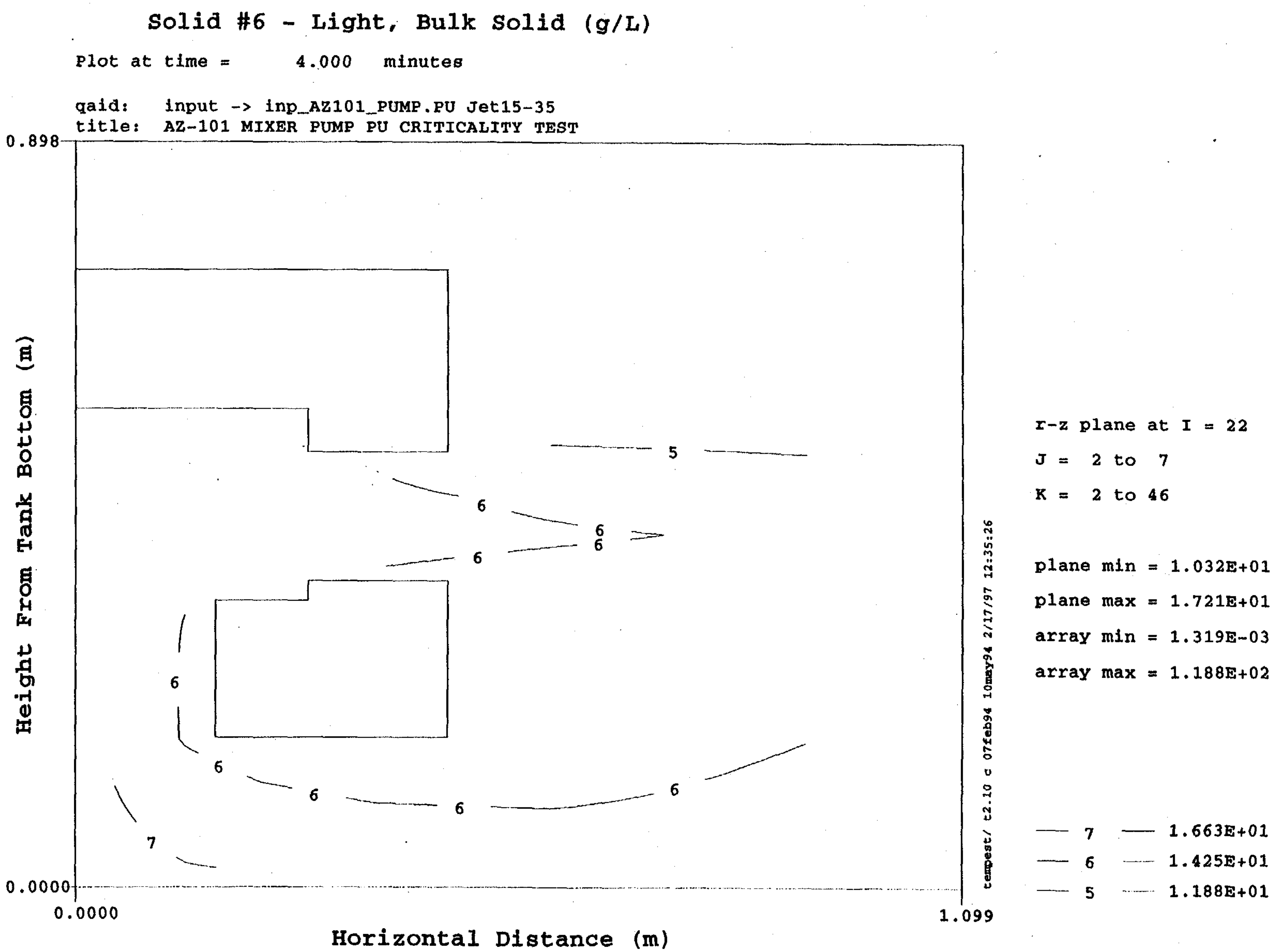

Figure 4.35. Predicted Distribution of Solid 6 Concentrations in 9 O'Clock Position at 4 Simulation Minutes for Case 1

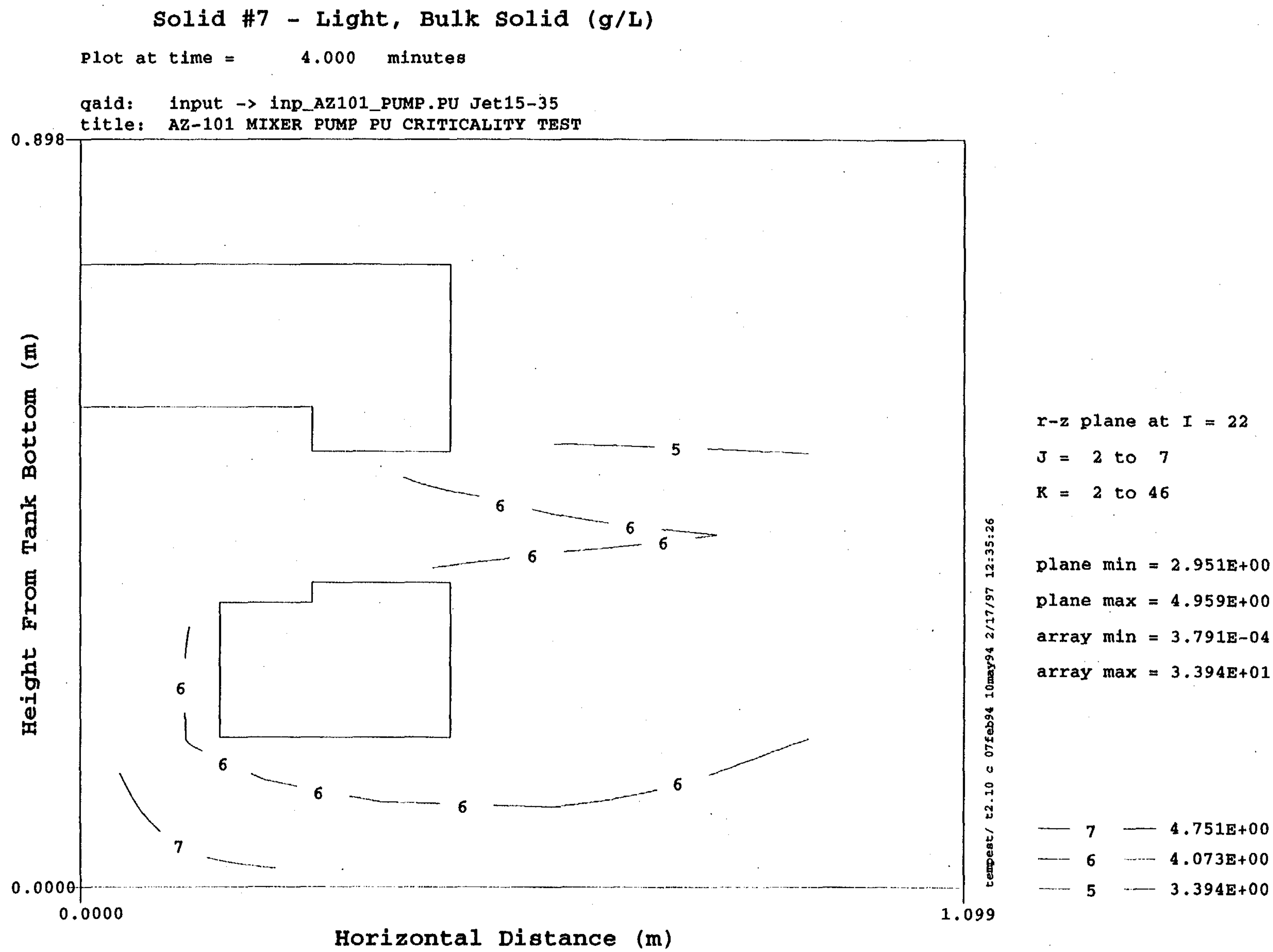

Figure 4.36. Predicted Distribution of Solid 7 Concentrations in 9 O'Clock Position at 4 Simulation Minutes for Case 1

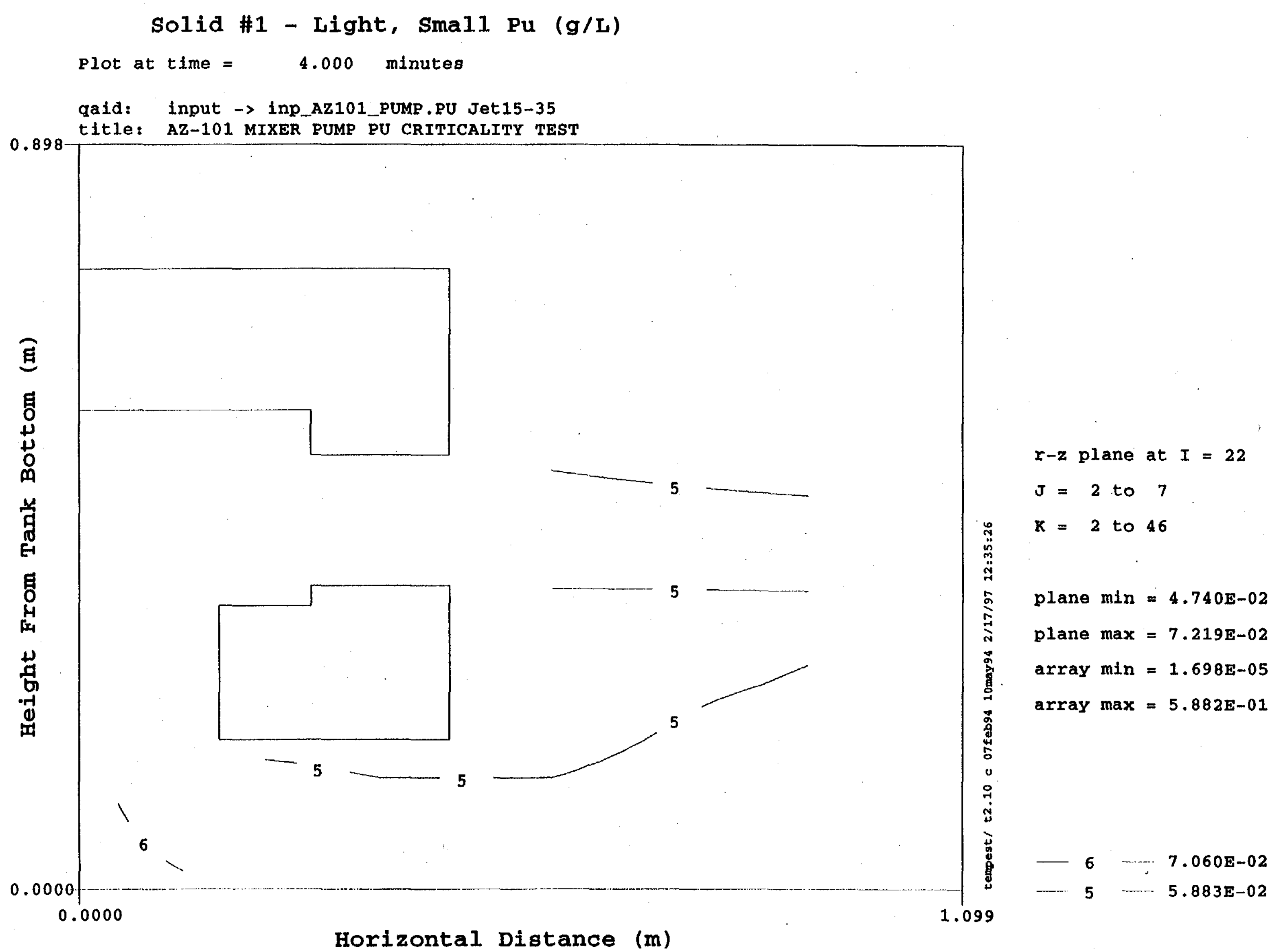

Figure 4.37. Predicted Distribution of Solid 1 Plutonium Concentrations in 9 O'Clock Position at 4 Simulation Minutes for Case 1

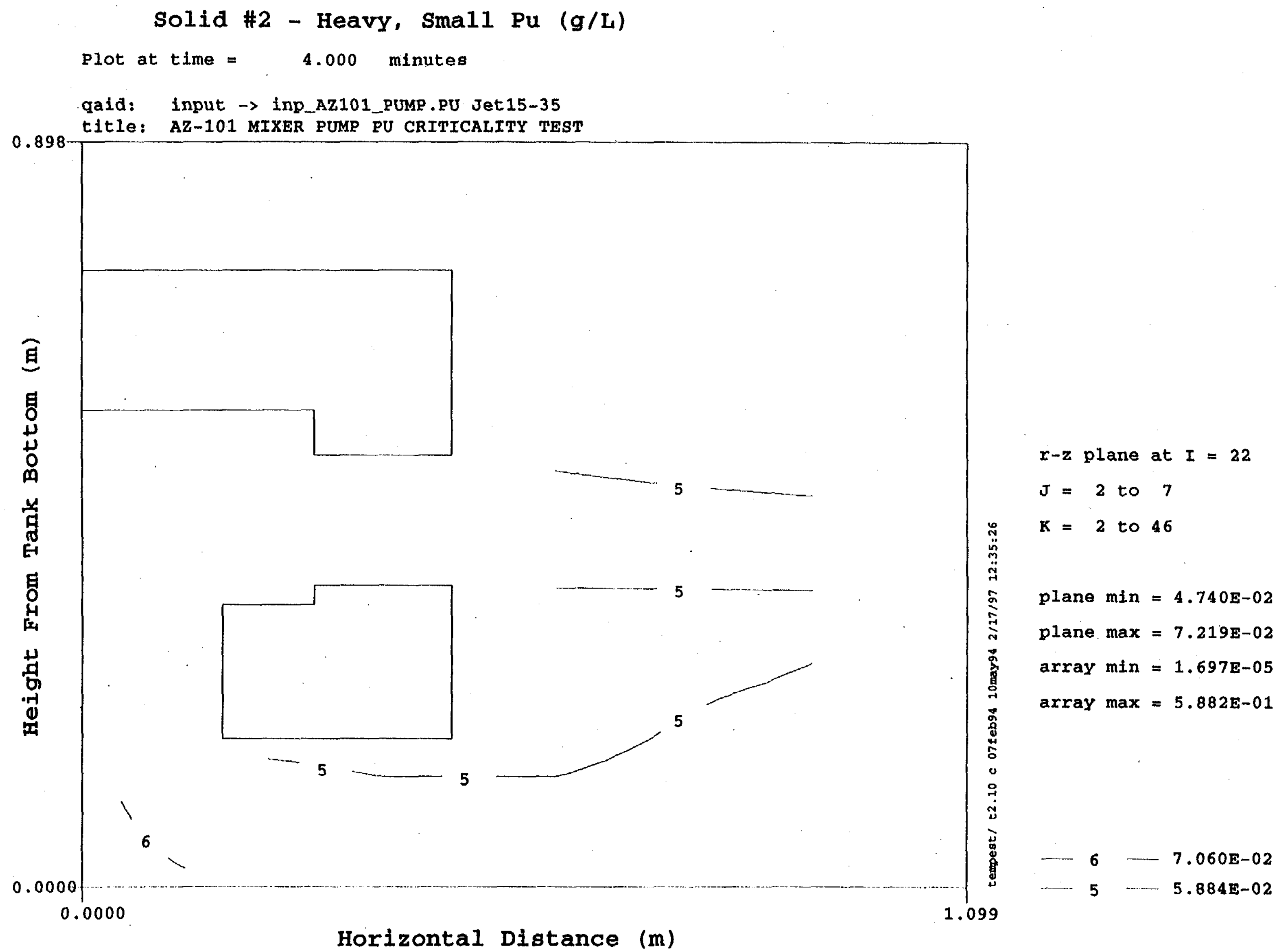

Figure 4.38. Predicted Distribution of Solid 2 Plutonium Concentrations in 9 O'Clock Position at 4 Simulation Minutes for Case 1

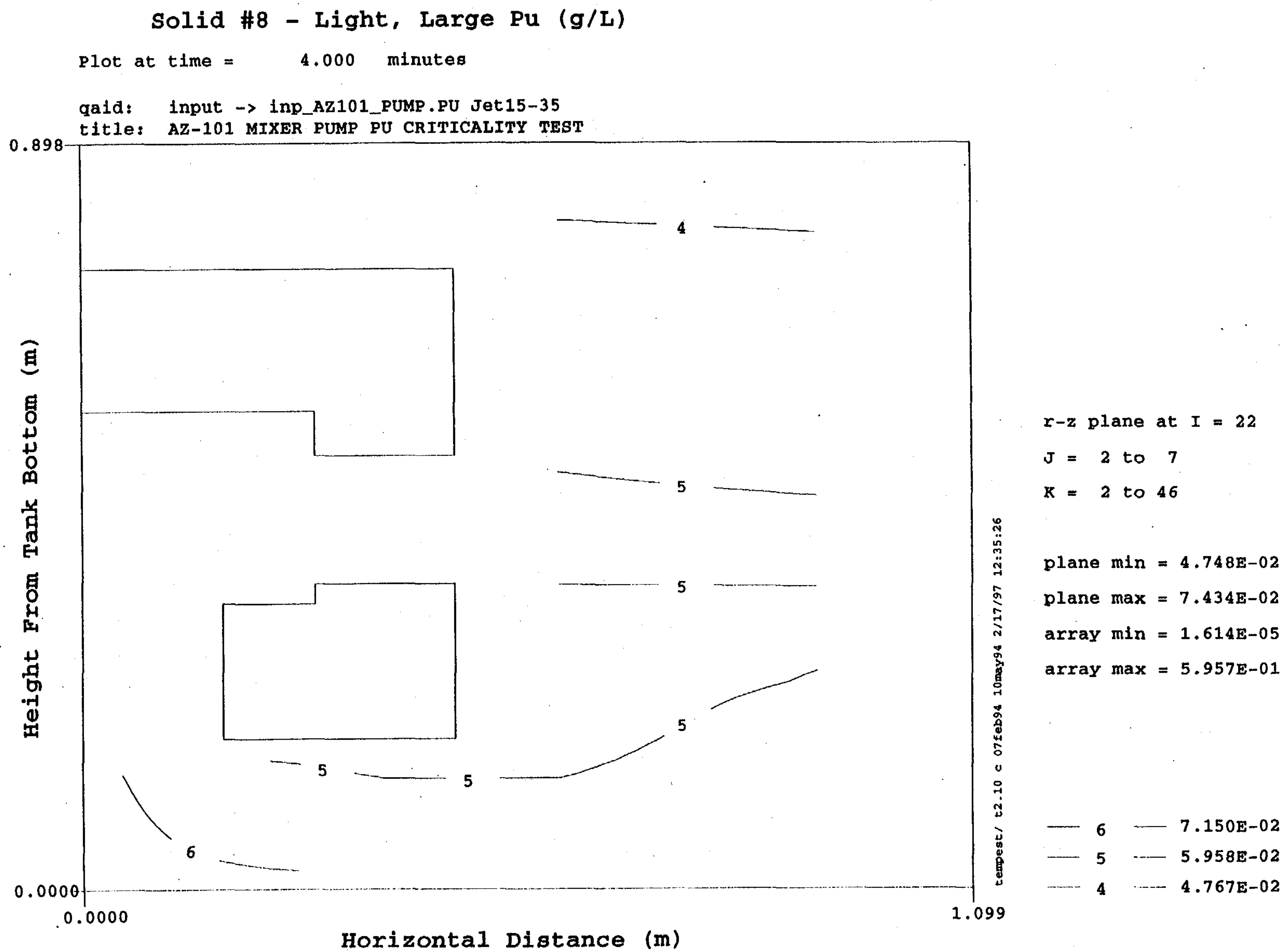

Figure 4.39. Predicted Distribution of Solid 8 Plutonium Concentrations in 9 O'Clock Position at 4 Simulation Minutes for Case 1

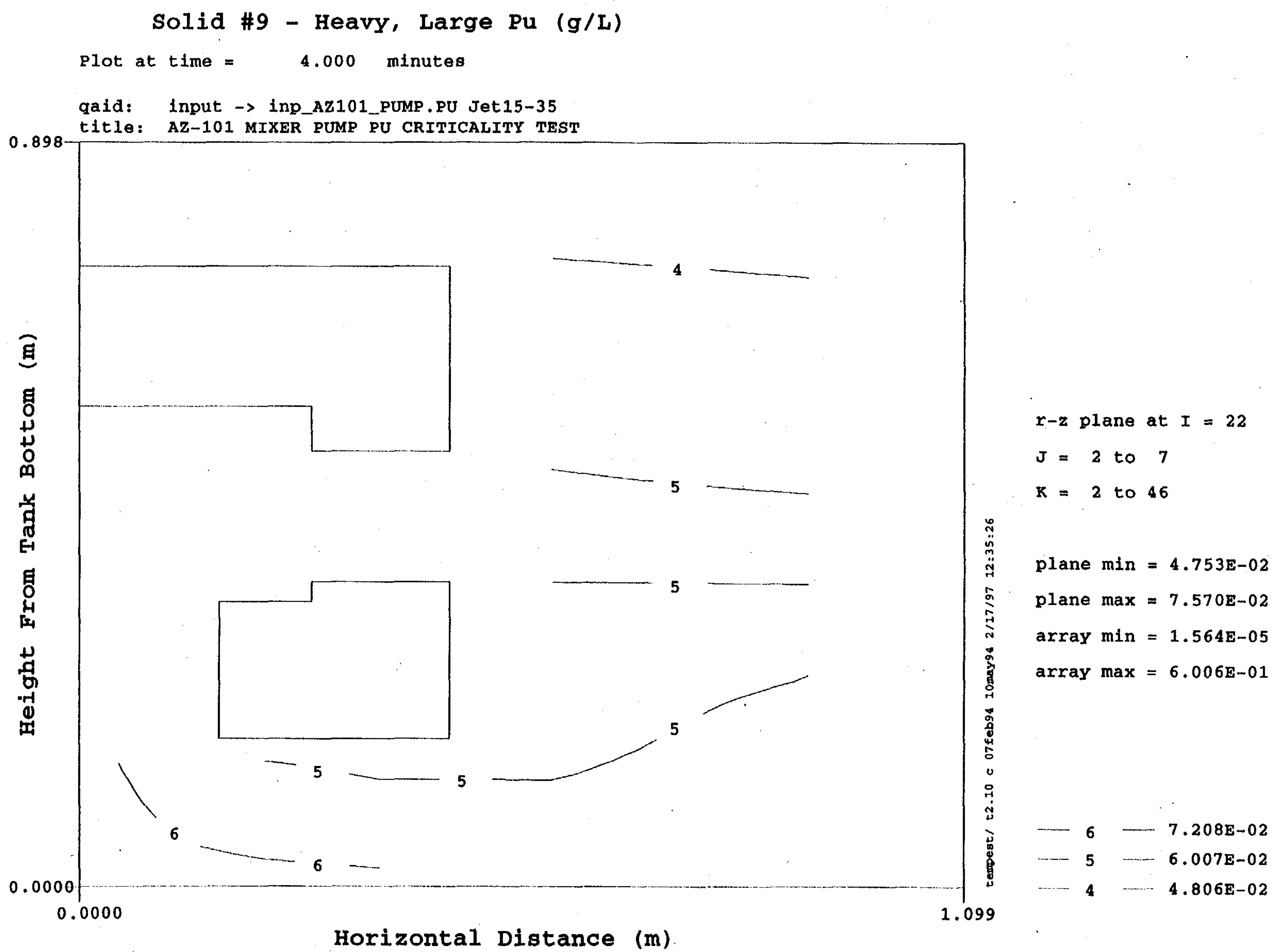

Figure 4.40. Predicted Distribution of Solid 9 Plutonium Concentrations in 9 O'Clock Position at 4 Simulation Minutes for Case 1

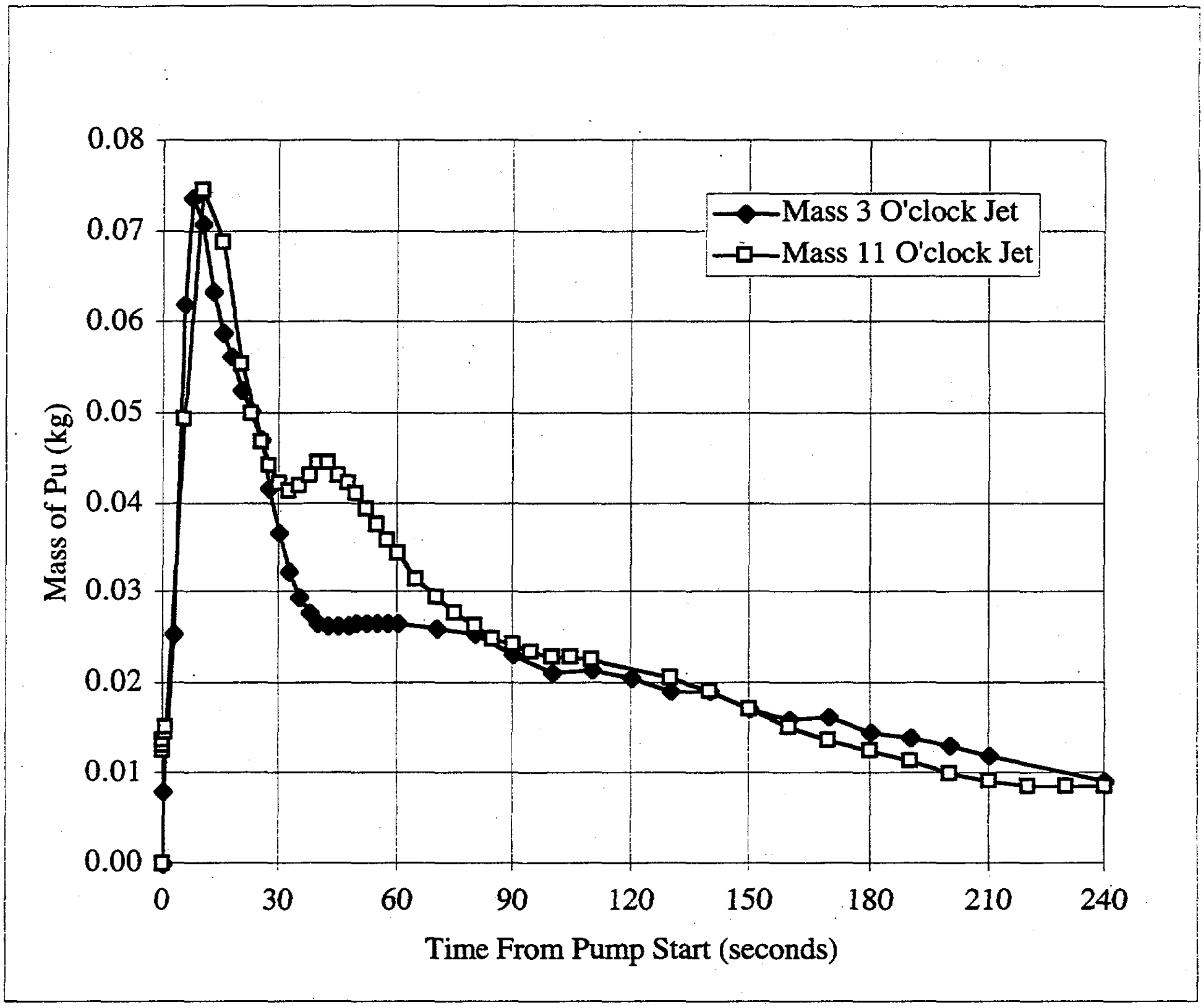

Figure 4.41. Predicted Total Plutonium Amount (kg) Within the Pump

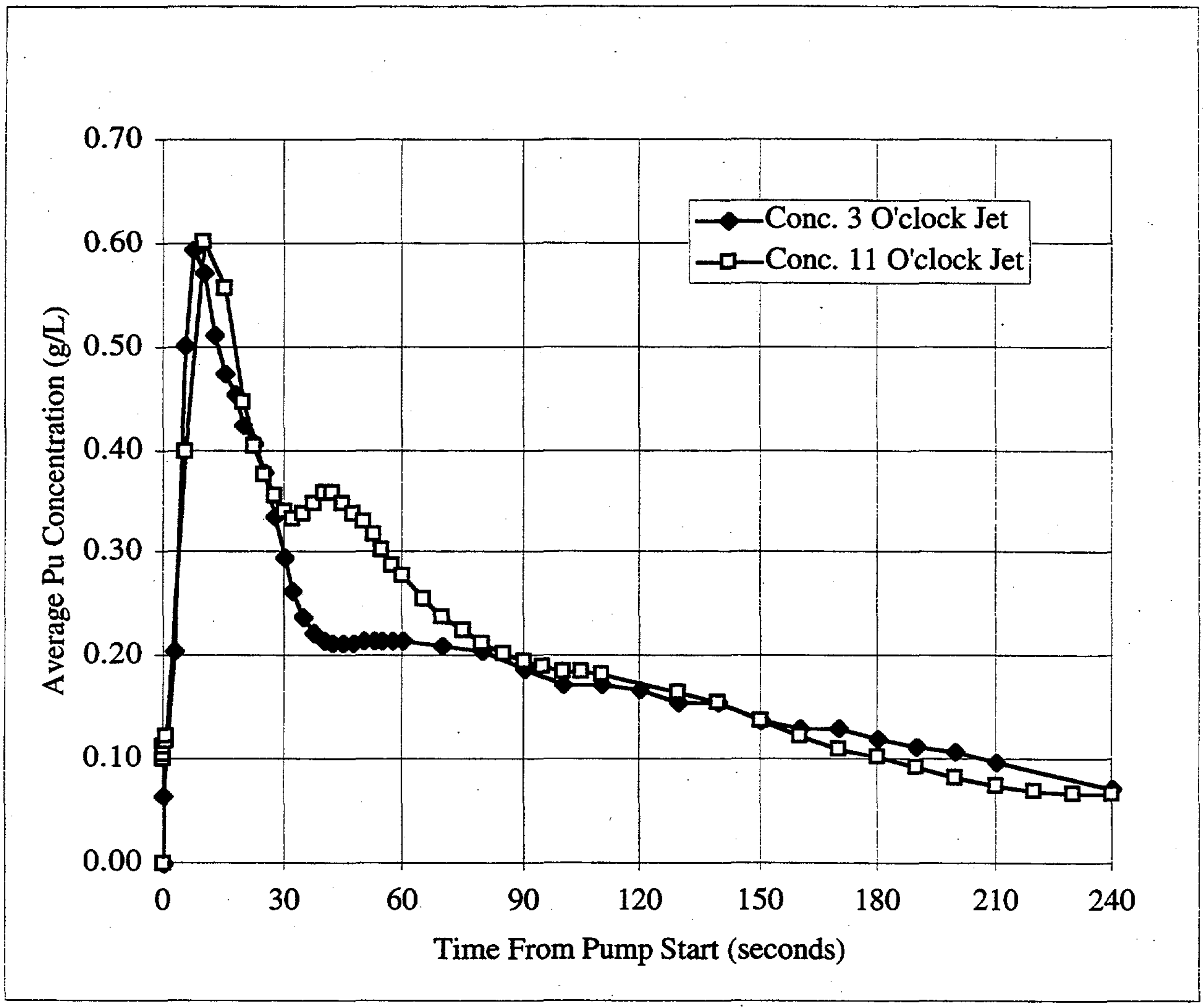

Figure 4.42. Predicted Average Plutonium Concentration (g/L) Within the Pump

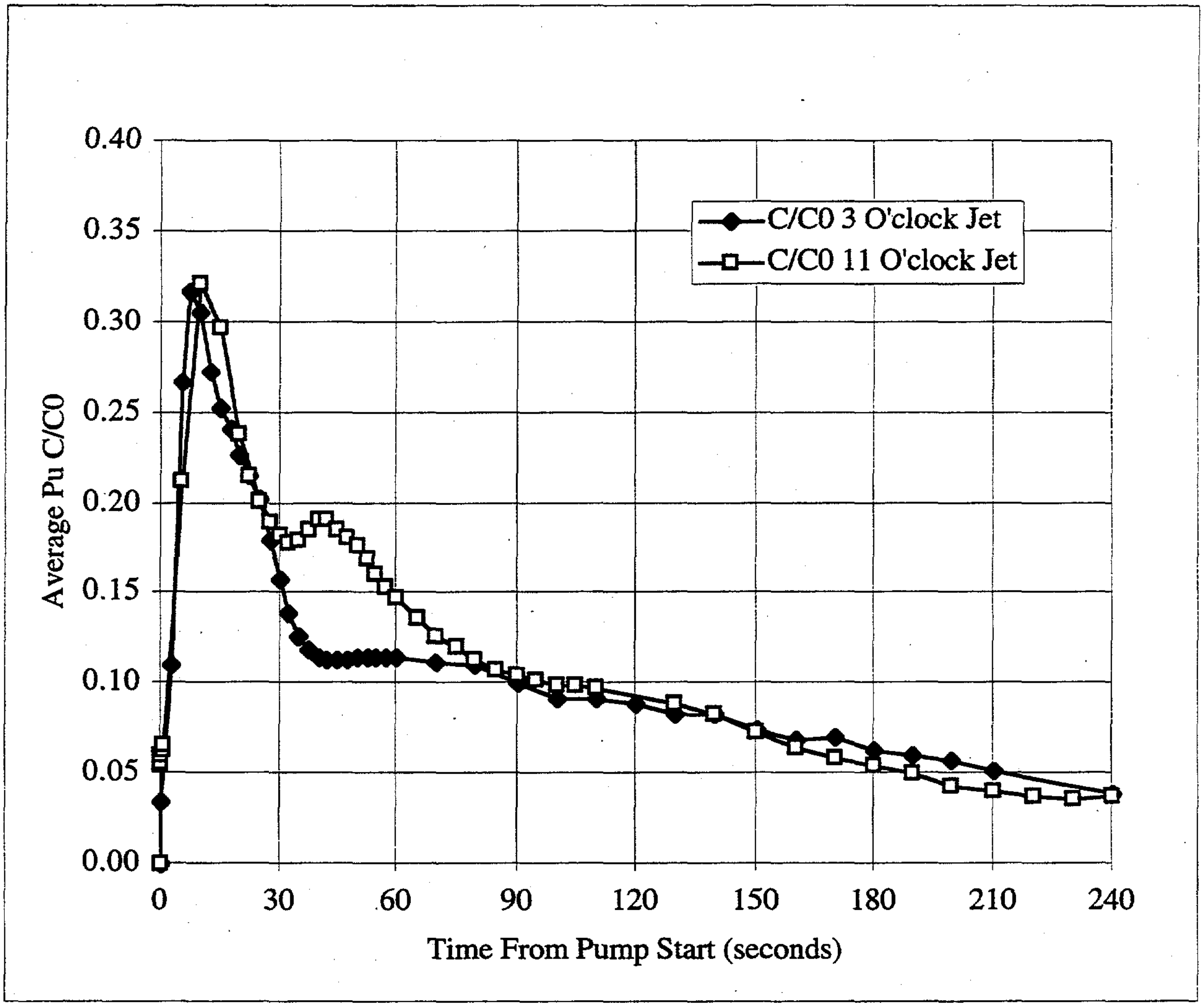

Figure 4.43. Predicted Average Plutonium Concentrations Within the Pump Normalized by the Highest Plutonium Concentration (1.88 g/L) Within the Model Sludge Layer

5.0 Summary and Conclusions

The three-dimensional simulation was performed with the time-varying, three-dimensional TEMPEST code to determine whether the pump jet mixing operation in Tank AZ-101 would concentrate plutonium in the pump housing and cause a criticality.

Tank AZ-101 has 22 air lift circulators that had been operated continuously for many years to mix the sludge, both during and after the period when plutonium-bearing wastes were added. Since the more heterogeneous the plutonium distribution within the sludge, the greater the chance of higher plutonium concentrations in the pump housing at some point in time, we neglected the mixing effects of the ALC operation to obtain the conservative initial plutonium distribution within the sludge.

Two main factors that can cause heterogeneous distributions of plutonium within the sludge are the 262 sequential discharges of the plutonium-bearing wastes into AZ-101 and the preferential settling of heavier, larger solids affected by the three-dimensional, dynamic, interactive, flow/solid transport/rheological processes. Even though the dynamic slurry flow movements will not keep the segregation due to the sequential waste discharges totally intact, we added these two segregation factors together to produce a conservative initial plutonium distribution. This addition resulted in the maximum plutonium concentration of 1.88 g/L, which is 30 times greater than the actual average plutonium concentration of 0.062 g/L in the AZ-101 sludge. The segregation factor of 30 is very conservative in light of the fact that even in the mining industry, the 10 to 20 μm size range is below the normal particle range for either gravity or flotation segregation processes without spacial chemical additives and very specialized equipment that would provide rhythmic shaking, thin liquid films, or high centrifugal forces coupled with selective collection and concentration to achieve it. Furthermore, the total plutonium mass used in the model was nine times the actual amount in the tank—9.782 kg.

The two sets of AZ-101 models with the very conservative plutonium initial condition indicate that the total amount of plutonium within the pump housing peaks at 75 g at 10 simulation seconds and decreases with time to less than 10 g at four minutes. The plutonium concentration in the entire pump housing peaks at 0.60 g/L at 10 seconds and is reduced to below 0.1 g/L as time goes to four minutes. Since the minimum critical concentration of plutonium is 2.6 g/L and the minimum critical plutonium mass under idealized plutonium-water condition is 520 g, these predicted maximum plutonium concentrations and the total mass in the pump housing are much lower than the minimum conditions needed to reach a criticality level.

The plutonium maximum concentration of 1.88 g/L still results in 4.3 times less plutonium concentrated in the pump housing than the minimum critical plutonium concentration of 2.6 g/L. Thus, even with the plutonium segregation factor of 130 (4.3 times 30), the total plutonium amount in the pump will be 323 g, which is still less than the minimum plutonium critical mass of 520 g. These model results clearly indicate that the pump jet mixing operation of AZ-101 will not produce large enough plutonium distributions in the pump housing to cause a criticality.

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