# APPENDIX I

Former Hazardous Water Management Facility (FHWMF)
Groundwater Modeling
Fate and Transport of Sr-90 Plume

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## Brookhaven National Laboratory

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Groundwater modeling simulations were performed by P.W. Grosser Consulting (PWGC) to aid BNL in estimating the attenuation of recently characterized Former Hazardous Waste Management Facility (FHWMF) Sr-90 plume concentrations to a concentration below the 8 pCi/L drinking water standard (DWS) and how far the plume could be expected to travel over time as it migrates towards the site boundary.

PWGC utilized BNL's existing regional 3-dimensional numerical groundwater model (GMS v10.1.3, 64 Bit, MODFLOW 2000) with modifications noted below to characterize flow conditions at the FHWMF and in the downgradient area to the south to evaluate the potential migration of the FHWMF Sr-90 plume, MT3DMS, a modular three-dimensional transport model for the simulation of advection, dispersion, and chemical reactions of dissolved constituents in groundwater systems (developed for the USACE (United States Army Corps of Engineers) by S.S. Papadopulos & Associates, Inc. and the University of Alabama) was used in conjunction with the groundwater flow model.

## Key Assumptions and Model Modifications

The key assumptions made for the modeling effort are:

- The 'onsite' model inherited hydraulic/hydrogeologic properties from the calibrated regional model. Modifications to the original model included converting the regional model to a local model. **Figure 1** depicts the model layering along with associated horizontal hydraulic conductivities assigned to the layers in the vicinity of the FHWMF Sr-90 plume.

- The regional model was converted to a local model so that transient condition fate and transport modeling could be conducted. An area roughly 2,800 ft (east-west direction) by 4,500 ft (north-south direction) was delineated around the FHWMF Sr-90 plume and subdivided into 25 ft by 25 ft grid spacings (see **Figure 2**). Constant head boundary conditions were created at the north and south boundaries of the local model to match regional model heads. **Figure 3** depicts the local model in relation to the BNL site boundary. **Figure 4** illustrates regional/local water table groundwater contours.

- Layer 1 of the local model was divided into two separate layers to more accurately represent and model the contaminant plume volume. Layer 1 of the model is the water table layer. After dividing the top layer of the local model into two separate layers the new layer 1 was adjusted to have a saturated thickness of approximately 18 feet.

- MT3DMS was utilized to simulate potential migration of the FHWMF Sr-90 plume. Plume concentrations (initial conditions) were generated using the most recent data available (March 2016). Plume concentrations ranged between 302 and 8 pCi/l and were input individually into model cells within the horizontal extents of the plume boundary (8 pCi/l contour). The plume was initialized only in layer 1 of the local model (approximate top elevation of layer 1 = 52 ft AMSL and approximate bottom elevation of layer 1 = 23 ft AMSL, water table elevation approximately 40.9 ft AMSL) consistent with actual sampling results. The model is based on the concept that there is no continuing source of Sr-90 at the FHWMF.

- No changes were incorporated into the model simulations that would have altered groundwater flow directions or rates over time. No new or revised pumping rates (i.e. remedial wells), recharge rates, boundary flow changes, etc. were considered. All flow conditions were considered to be steady state.

- Fate and transport simulations were run using the advection and chemical reaction modeling packages. Dispersion was not modeled to produce conservative modeling results, advection along with radioactive decay and adsorption are the dominant mechanisms with regards to fate and transport based on experience with site conditions.

- The advection package solution scheme was changed from the GMS default scheme of Third Order TVD scheme (ULTIMATE) to the Method of Characteristics (MOC). The basis for the change was that the MOC scheme is highly effective for eliminating numerical dispersion in strongly advection dominated situations where as the Third Order TVD scheme does minimize numerical dispersion but not to the same degree as the MOC scheme. This is a conservative approach as some dispersion can be reasonably expected to occur over time.

- The chemical reaction package was used to simulate retardation effects and adsorption. GMS calculates a retardation factor R for each layer based on the distribution coefficient of the specific contaminant and the bulk density and porosity of the material (layer) the contaminant is traveling through. The basic equation used by GMS to calculate the retardation factor is $R = 1 + (\rho_b K_d/n)$ where $\rho_b$ is the soil bulk density, $K_d$ is the distribution coefficient and n is the soil porosity. A soil bulk density of 100 lb/ft$^3$ was input for all layers as this is a typical or common value for regional sands. $K_d$ was estimated based on actual observed or monitored conditions for Sr-90 traveling through shallow Upper Glacial materials. Field observations indicate an approximate travel rate of 40 to 50 ft/yr for the Sr-90 plume. A travel rate of 45 ft/yr then equates to a retardation of approximately 8 (R=8). Solving for $K_d$ using the equation $R = 1 + (\rho_b K_d/n)$ yields a value of 0.0168 ft$^3$/lb. The regional model porosity of 0.24 was used in the calculations as that is what the model was calibrated to.

- The chemical reaction package was also used to model radioactive decay using a first order irreversible kinetic reaction. The basic equation for this is $C = C_o e^{-kt}$, where C is the final concentration, $C_o$ is the initial concentration, k is the rate constant and t is time. The rate constant for radioactive decay is given in terms of half-life and is calculated based on the equation $k = (\ln 2)/t_{1/2}$, where $t_{1/2}$ is the half-life of Sr-90 in days ($t_{1/2}$ = 28.81 years or 10,515,65 days). Solving for k yields a value of

0.0000659 1/d which is consistent with the value used in previous BNL groundwater modeling efforts for Sr-90.

Groundwater flow and transport were simulated under steady-state conditions. A 60 year time period with 4 time steps per stress period (1 year = 1 stress period). One time step equates to 91.25 days or approximately 3 months. A 60 year time period starting January 1, 2016 would therefore end in 2076. The time period was ultimately extended out to 68 years to see how far into the future and how far offsite the remnants of the plume would travel before it attenuates to below the drinking water standard of 8 pCi/l.

## Discussion of Model Simulations and Predictions

Modeling simulations were conducted using MT3DMS to predict durations to achieving groundwater concentrations of less than 8 pCi/l of Sr-90. Under the conservative case conditions where dispersion is effectively removed from the model both numerically and physically, after 60 years of travel time Sr-90 plume concentrations remain above 8 pCi/l with a maximum concentration of 10.8 pCi/l observed approximately 600 feet south of the BNL site boundary and right at the Long Island Expressway that originated from the 302 pCi/l hot spot in at the FHWMF. **Figures 5** thru **9** depict the FHWMF Sr-90 plume under the conservative case (no dispersion scenario) beginning at day 1 and advancing through year 40, **Figure 10** is the predicted plume at year 60 and **Figure 11** is an enlarged version of **Figure 10** to show greater detail of the remaining plume concentrations. The main body of the plume is predicted to encounter the site south boundary at concentrations above 8 pCi/l sometime around year 42 (see **Figure 9**). By year 60 (**Figures 10** and **11**) the plume would be anticipated to be off site and reduced to a slug right at the Long Island Expressway with a peak concentration as stated above of 10.8 pCi/l.

Though a conservative approach was taken in the modeling effort (eliminating dispersion) as the time period into the future increases the model accuracy starts to become less certain as groundwater parameters can change over time. These can include hydraulic gradients and flow directions. For instance, new pumping wells can come online or existing wells may be taken out of service, new recharge basins may be constructed, prolonged droughts may be experienced or perhaps periods of greater recharge may occur. None of these variables can be fully accounted for and thus the model is based on 60 years of essentially identical average current steady state conditions. Thus in reality plume transport and attenuation can change in terms of velocity and direction. Continued and future groundwater monitoring will allow BNL to monitor plume and aquifer hydrologic conditions.

The plume is currently mapped with a long but narrow shape, indicating advection is the principal fate and transport mechanism along with radioactive decay and adsorption. The half-life for Sr-90 is 28.81 years, 60 years is a little over 2 half-lives, thus, straight radioactive decay from a starting concentration of 302 pCi/l would mean a concentration of a little less than 75.5 pCi/l would remain if no other attenuation mechanisms are being modeled. However, adsorption is being modeled as well and accounts for the further reduction of Sr-90 concentrations (i.e., peak concentration of 10.8 pCi/l after 60 years of transport time). Given the discussion above, the Sr-90 concentrations and durations of persistence in the shallow aquifer appear reasonable. Observations of Sr-90 concentrations migrating within the monitoring well network are also consistent with the assumptions. This approach is consistent with previous Sr-90 plume modeling efforts performed by BNL in 2005 and 2009 which also did not model physical or mechanical dispersion and eliminated numerical dispersion by using the MOC advection scheme.

As the plume was predicted to have concentrations above the drinking water standard of 8 pCi/l beyond the BNL site boundary further analyses were performed to predict how far into the future and how far offsite might the plume migrate before it attenuates to below the standard. The model time steps were increased from 60 to 68 years. The model then predicted a travel of 64.5 years before the plume completely attenuates below 8 pCi/l and would end up approximately 800 south of the BNL site boundary between the LIE and North Street. This prediction is under very conservative modeling assumptions for this plume.

Vertical migration of the plume was also investigated. The plume was created and released in layer 1 of the model at the FHWMF. Layer 1 at the point of origin of the Sr-90 plume has a surface elevation of 52.64 ft AMSL, a water table elevation of 41.78 ft AMSL and a layer bottom elevation of 23.82 ft AMSL, and therefore equates to a layer 1 saturated thickness of 17.96 ft (starting plume thickness). The plume is predicted to reach the site boundary above the drinking water standard in 42 years and at that point has migrated to the bottom of layer 2 which has an elevation of -10 ft AMSL. The surface elevation at the site boundary is 65.89 ft AMSL and the water table elevation is 38.4 ft AMSL. The top of the plume at this time and location (year 42 at the site boundary) is predicted to have migrated to an elevation of 19.4 ft AMSL which means a plume thickness of 29.4 ft (approximately 45 to 75 feet below land surface).

Lastly, a constant concentration source was modeled to simulate plume conditions under exceptionally conservative conditions. A constant source was created at the highest observed Sr-90 concentration at GP-42 with a value of 302 pCi/l, see **Figure 4**. Under this case a long narrow plume of contamination is generated that ultimately reaches equilibrium (no longer either expanding or contracting horizontally or vertically) with the plume extending southward from the source area at the FHWMF to between the site boundary and the LIE (see **Figure 12**). The highest predicted off site concentration under this case is 11.7 pCi/l occurring around 45.5 years and just immediately south of the site boundary at the railroad tracks (see **Figure 13**).

## Conclusion

Due to the long and narrow shape of the Sr-90 plume advection is believed to be the dominant fate and transport mechanism along with adsorption and radioactive decay. Though some dispersion is likely to occur over a 40 to 60 year travel time it was removed from the analysis to produce conservative results. An initial starting peak plume concentration of 302 pCi/l of Sr-90 originating at the FHWMF was modeled over a 60 year period. Sr-90 concentrations above 8 pCi/l (the drinking water standard) are used to define the extents of the plume. After 42 years of travel time the leading edge of the main body of the Sr-90 plume is predicted to reach the BNL site south boundary at a concentration of just over 8 pCi/l. By year 60 the remaining portions of the original plume are predicted to have migrated off site with the southernmost portion just at the Long Island Expressway with a peak concentration of 10.8 pCi/l approximately 600 feet south of the site boundary (see **Figures 10** and **11**). If the effects of dispersion are included in the model the plume extents and concentrations are predicted to be considerably lower and depending on how much dispersion is accounted for under some circumstances the plume does not reach the BNL site boundary.

The 68 year time period over which the FHWMF Sr-90 plume is modeled is a long duration over which changes in groundwater conditions may occur which could affect the accuracy of the model predictions. Additional groundwater monitoring between the FHWMF and the site boundary in the area of the Sr-90 plume with either permanent or temporary wells will allow for enhanced tracking of the plume. Comparison of the data collected to the model predicted plume concentrations and locations in 3 years will provide insight into how well the current model is simulating the Sr-90 fate and transport. Three (3) years is the minimum recommended time to compare results as the Sr-90 plume travels at a fairly slow rate per year (on the order of 45 ft/yr versus a little over 1 ft/day for groundwater in the area or over 365 ft/yr) so to a get a better understanding of the fate and transport of the plume in this area a longer time period is required. The current predication is for the main body of the plume to reach the site boundary above the drinking water standard of 8 pCi/l for Sr-90 after 42 years under conservative conditions, so 3 years of groundwater monitoring will not impact any additional actions that may be required to prevent off-site migration. .

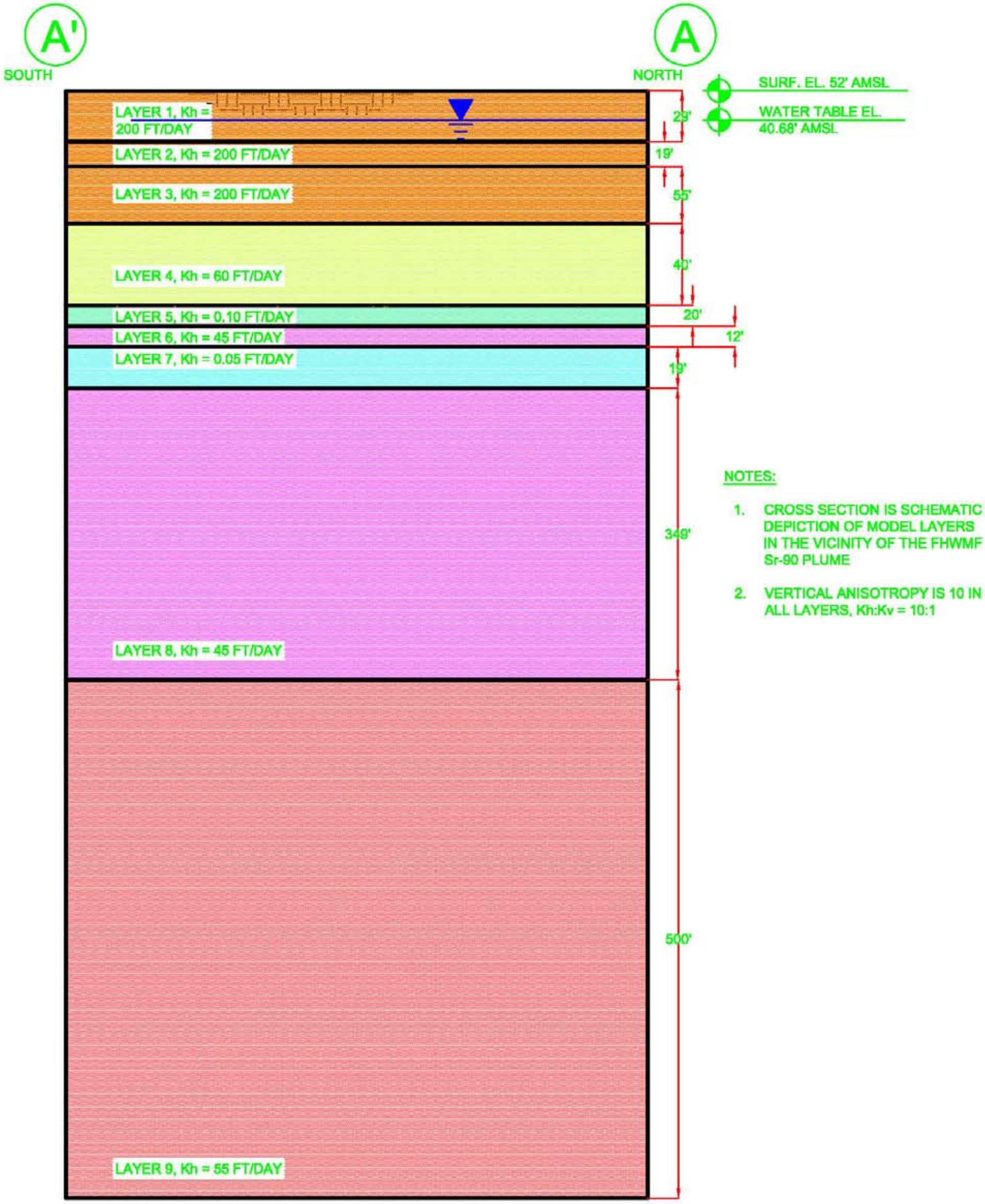


**Figure 1** – Model Layering Structure in Vicinity of FHWMF Sr-90 Plume – NOT TO SCALE

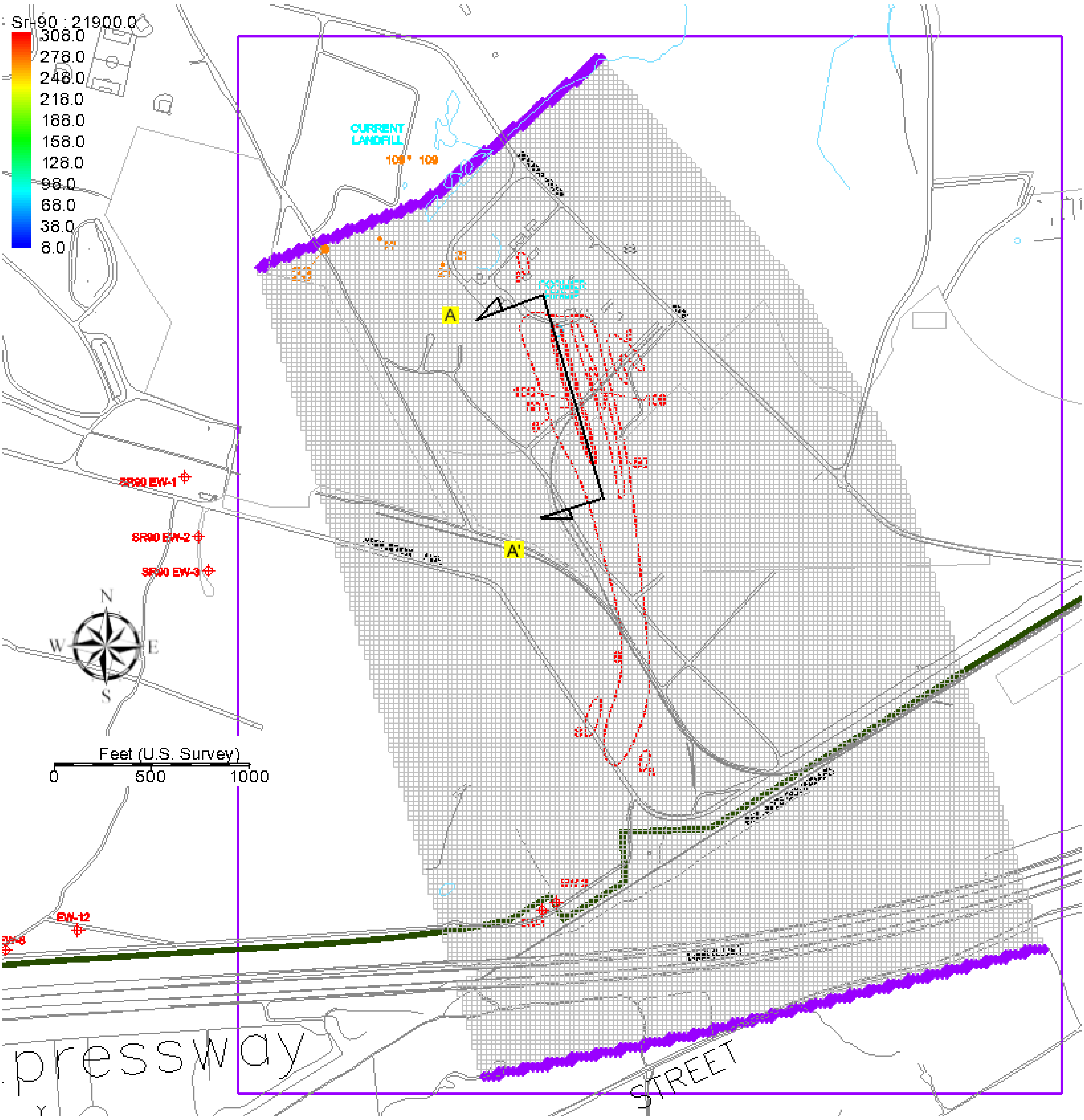


**Figure 2** – Figure 1 cross-section line and extents of local model

Local grid spacing is approximately 25' x 25'.

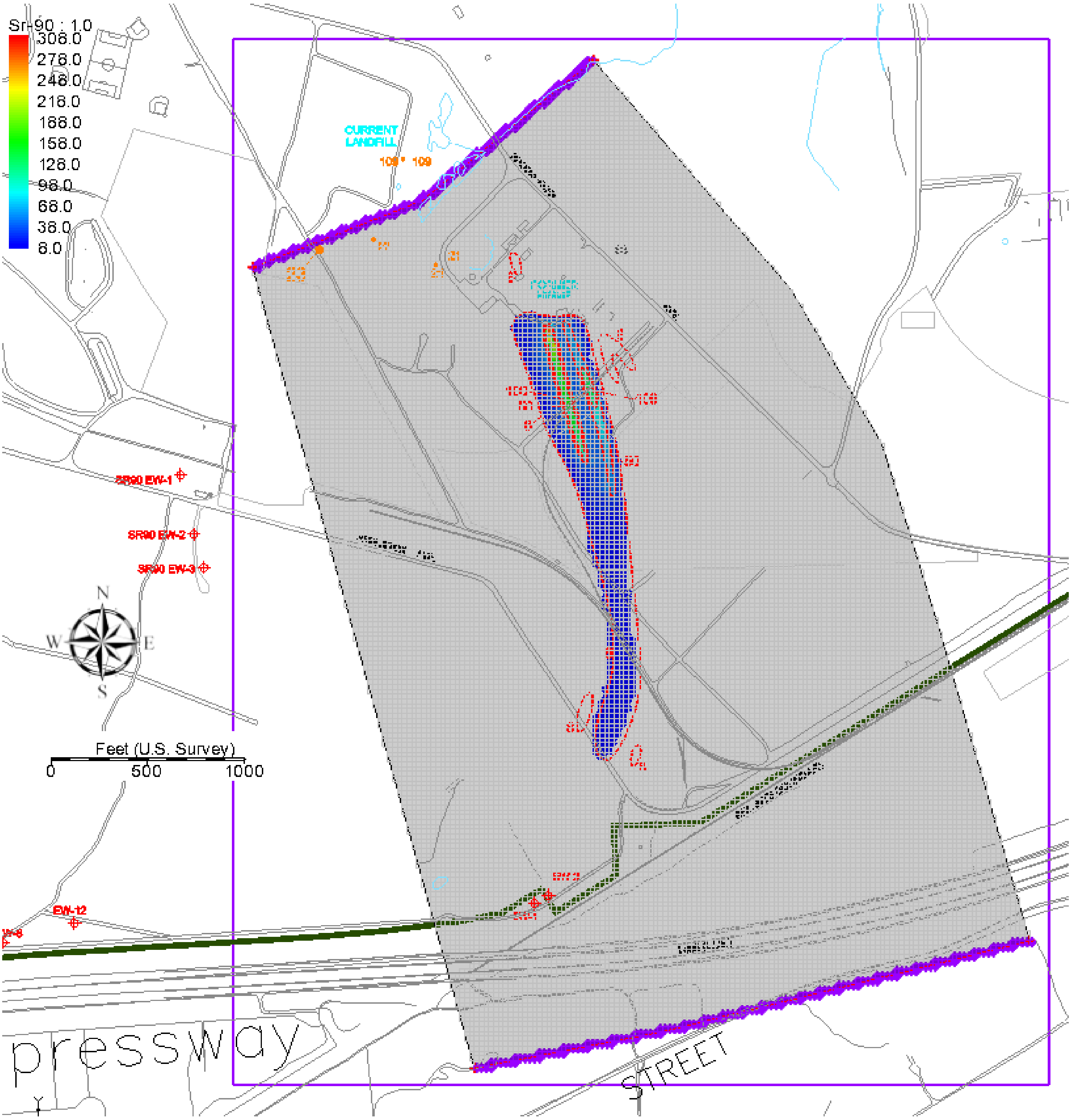


**Figure 3** – Model Study Area in Relation to BNL Site Boundary

Local grid spacing is approximately 25' x 25'.
Gray shaded represents the limits of the local model.
Magenta border is extents of grid frame.
Magenta lines at north and south of gray shaded area are constant head boundaries imported from regional model.

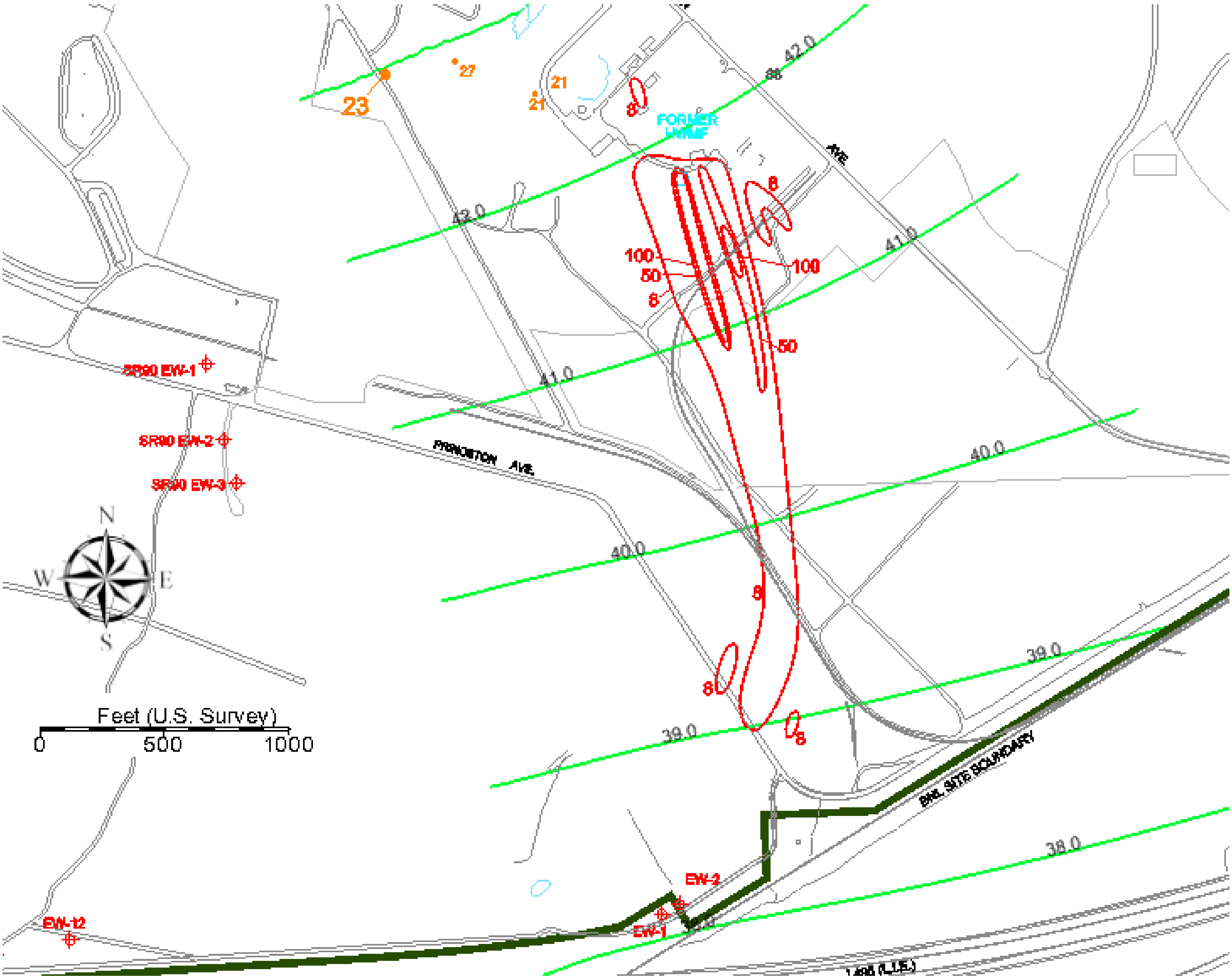


**Figure 4** – Layer 1 Groundwater Head Contours

Green lines represent groundwater head contours, head is in feet.
Red lines represent original plume location at beginning of model simulations.

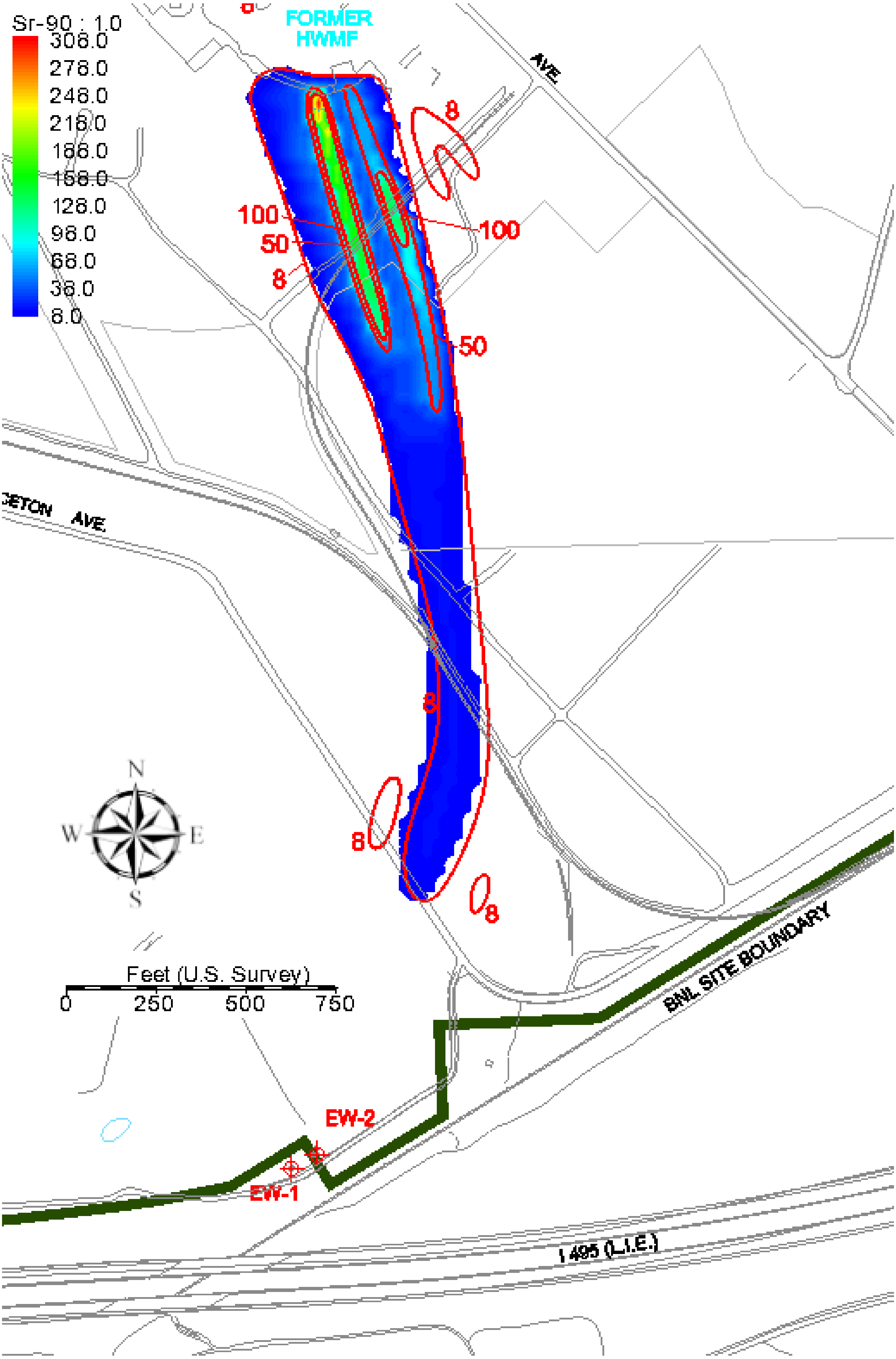


**Figure 5** – FHWMF Sr-90 Plume at t = 1 day

Color chart at upper left presents Sr-90 concentrations in pCi/l.
Number in extreme upper left above color chart is time since start in days.
Red outline is original plume definition.

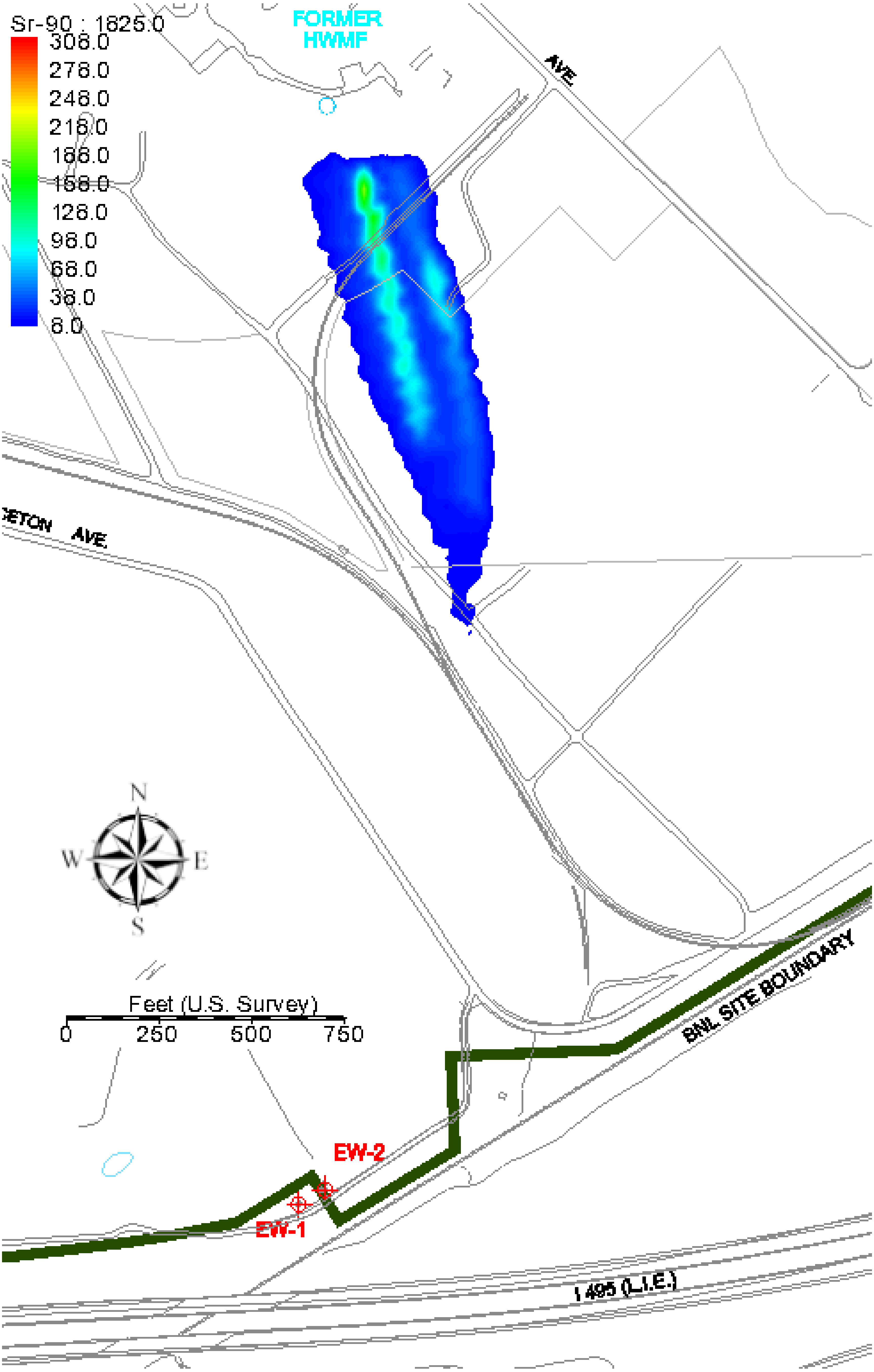


**Figure 6** –FHWMF Sr-90 Plume at t = 5 yrs

Color chart at upper left presents Sr-90 concentrations in pCi/l.
Number in extreme upper left above color chart is time since start in days.

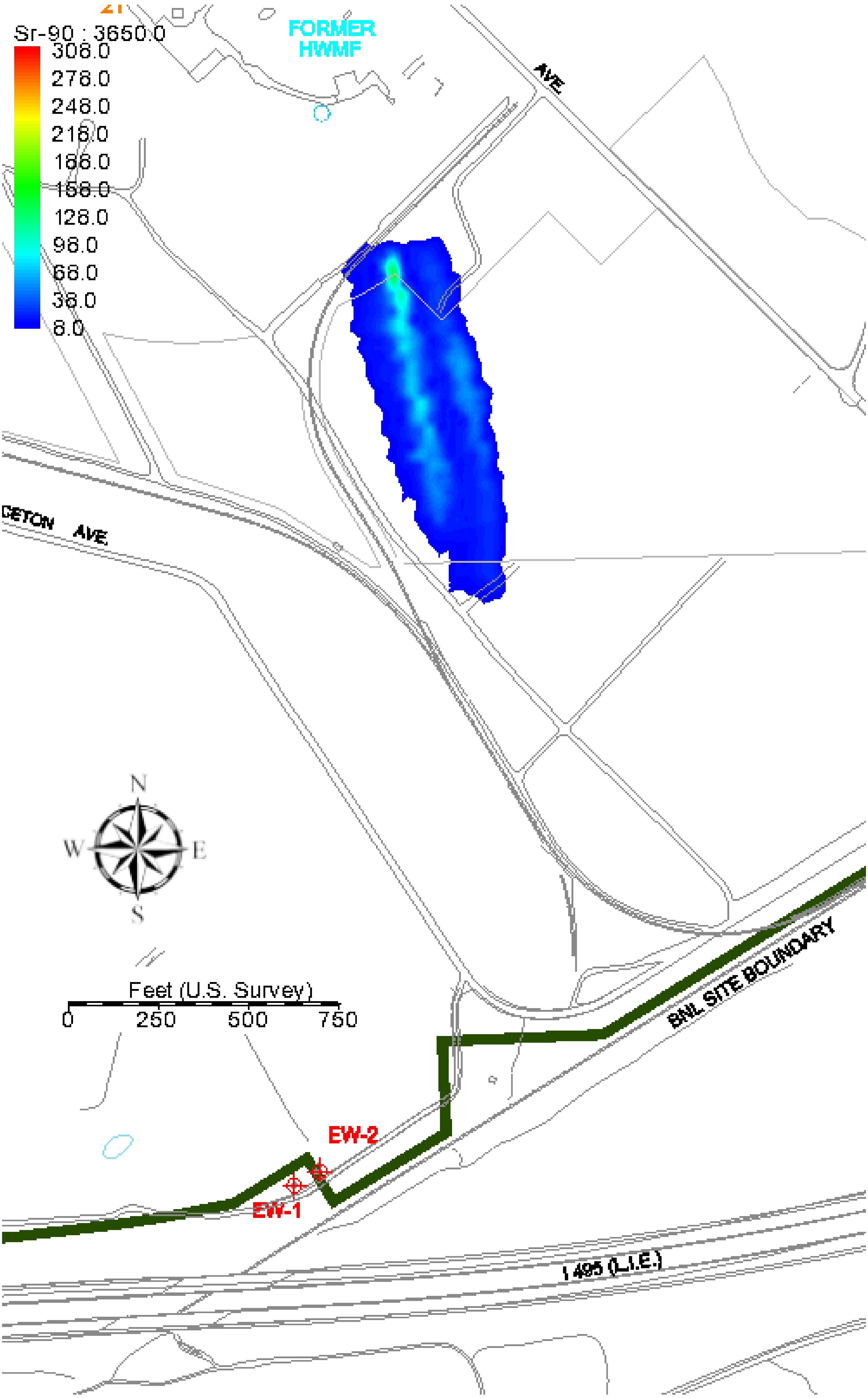


**Figure 7** – FHWMF Sr-90 Plume at t = 10 years

Color chart at upper left presents Sr-90 concentrations in pCi/l.
Number in extreme upper left above color chart is time since start in days.

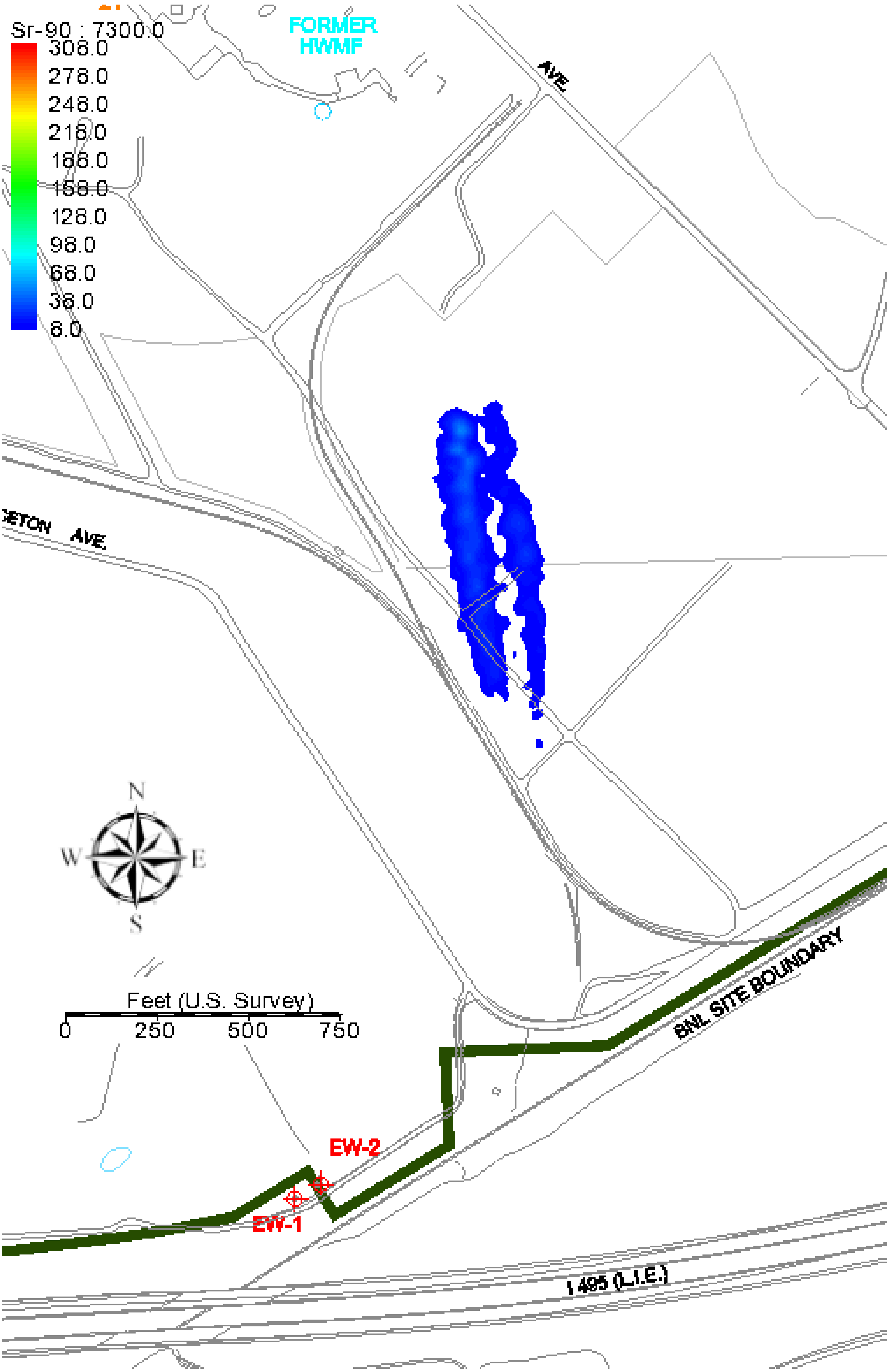


**Figure 8** – FHWMF Sr-90 Plume at t = 20 years

Color chart at upper left presents Sr-90 concentrations in pCi/l.
Number in extreme upper left above color chart is time since start in days.

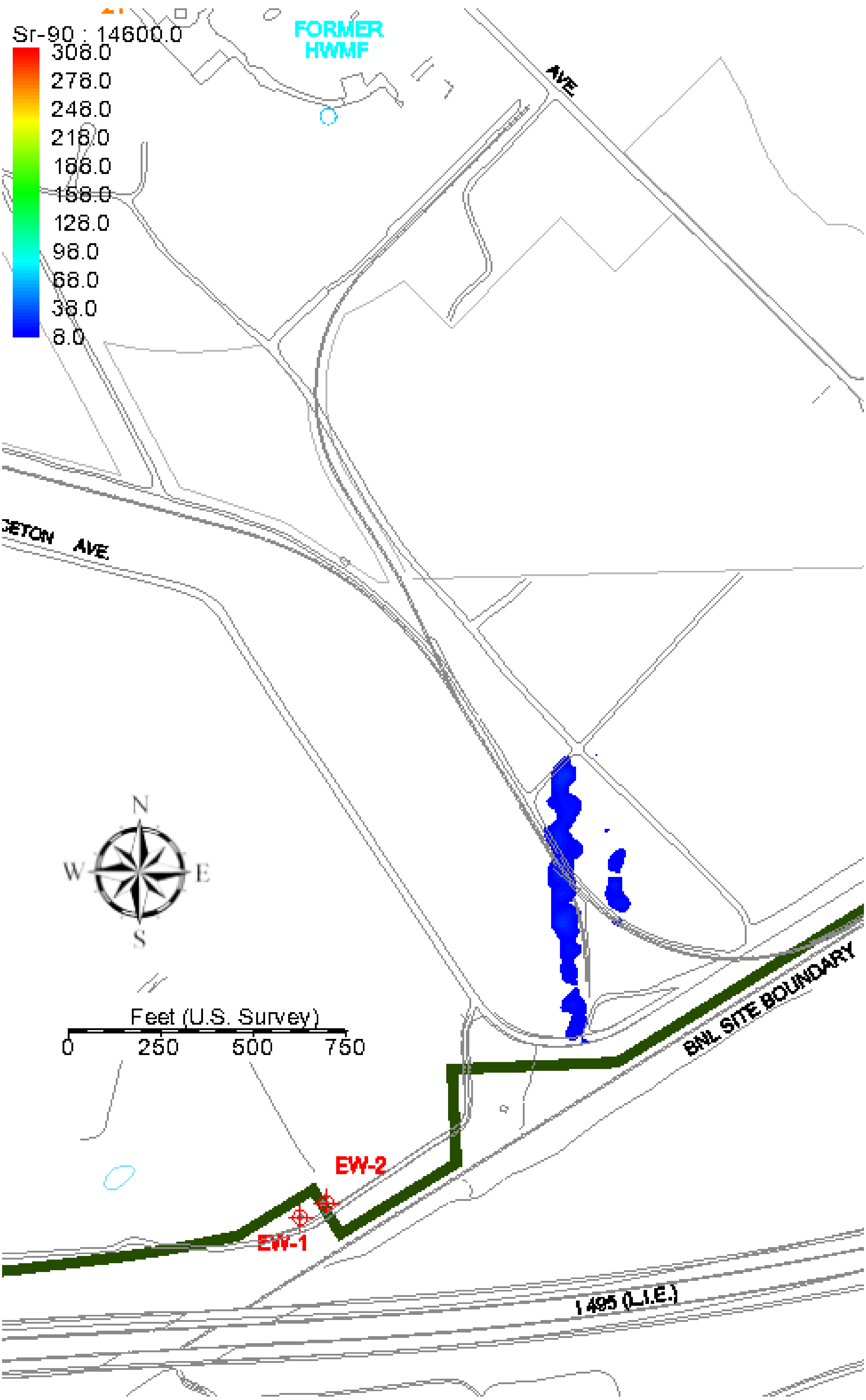


**Figure 9** – FHWMF Sr-90 Plume at t = 40 years

Color chart at upper left presents Sr-90 concentrations in pCi/l.
Number in extreme upper left above color chart is time since start in days.

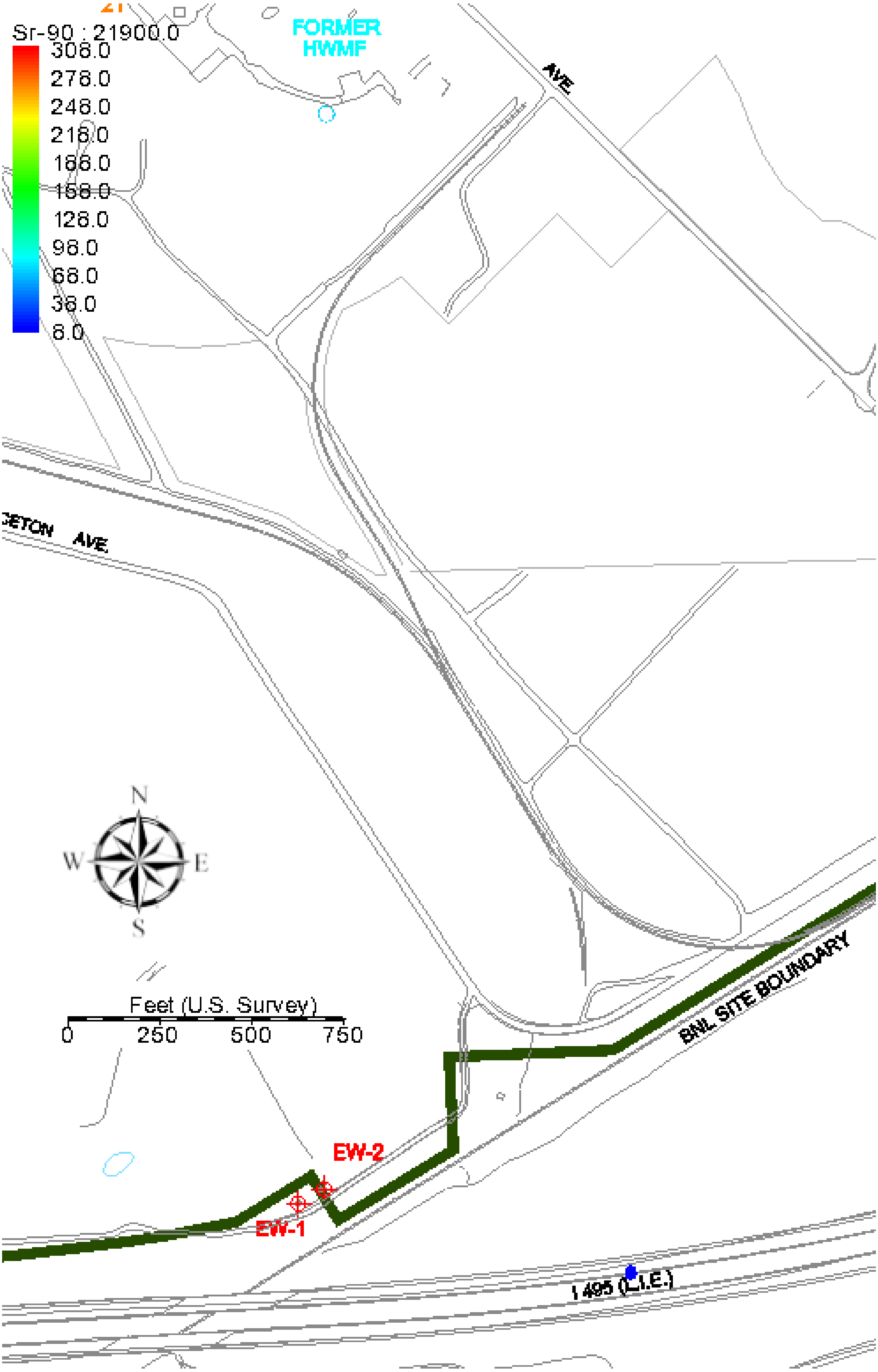


**Figure 10** – FHWMF Sr-90 Plume at t = 60 years

Color chart at upper left presents Sr-90 concentrations in pCi/l.
Number in extreme upper left above color chart is time since start in days.

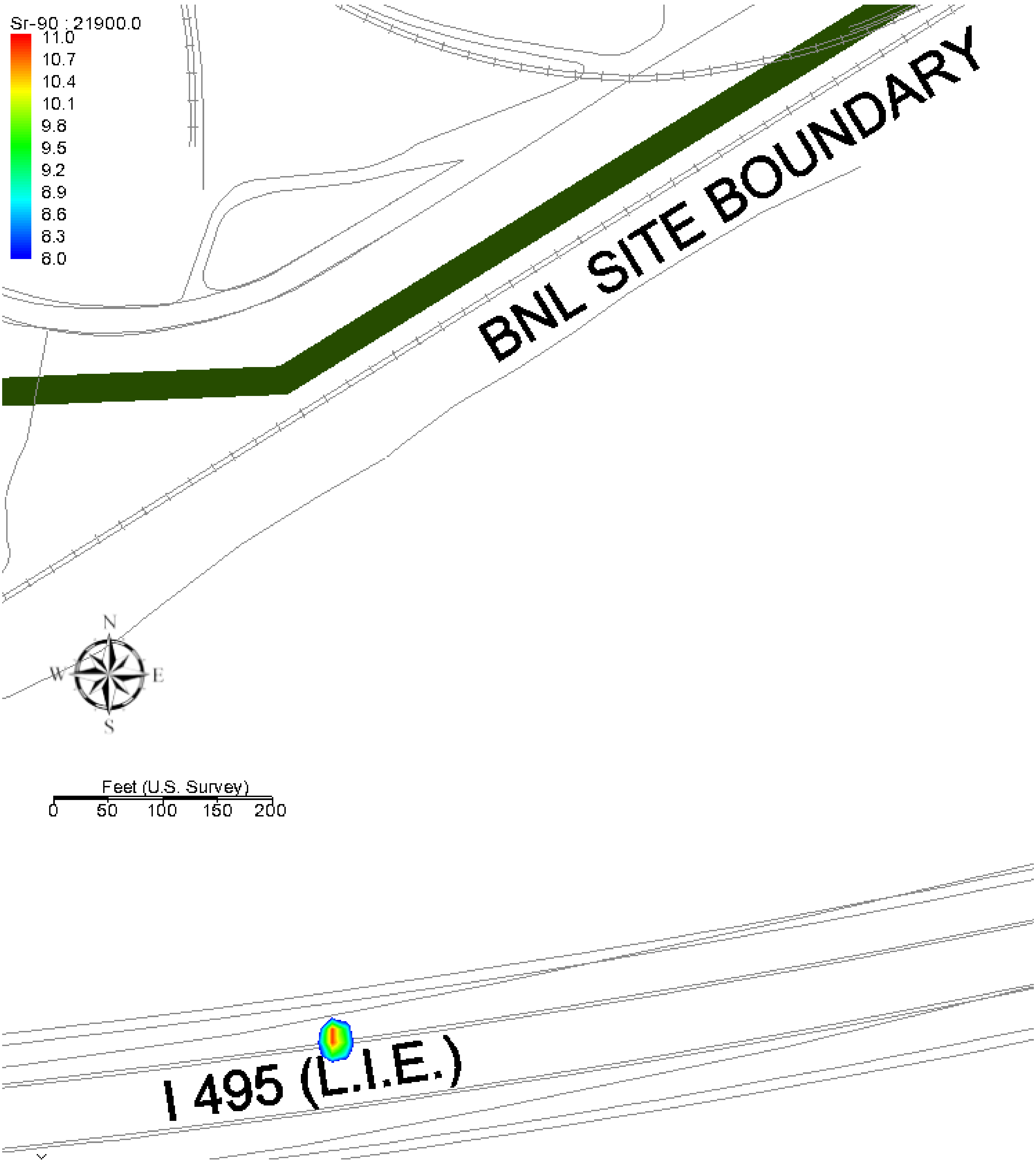


**Figure 11** – FHWMF Sr-90 Plume at t = 60 years (enlarged)

Color chart at upper left presents Sr-90 concentrations in pCi/l.
Number in extreme upper left above color chart is time since start in days.

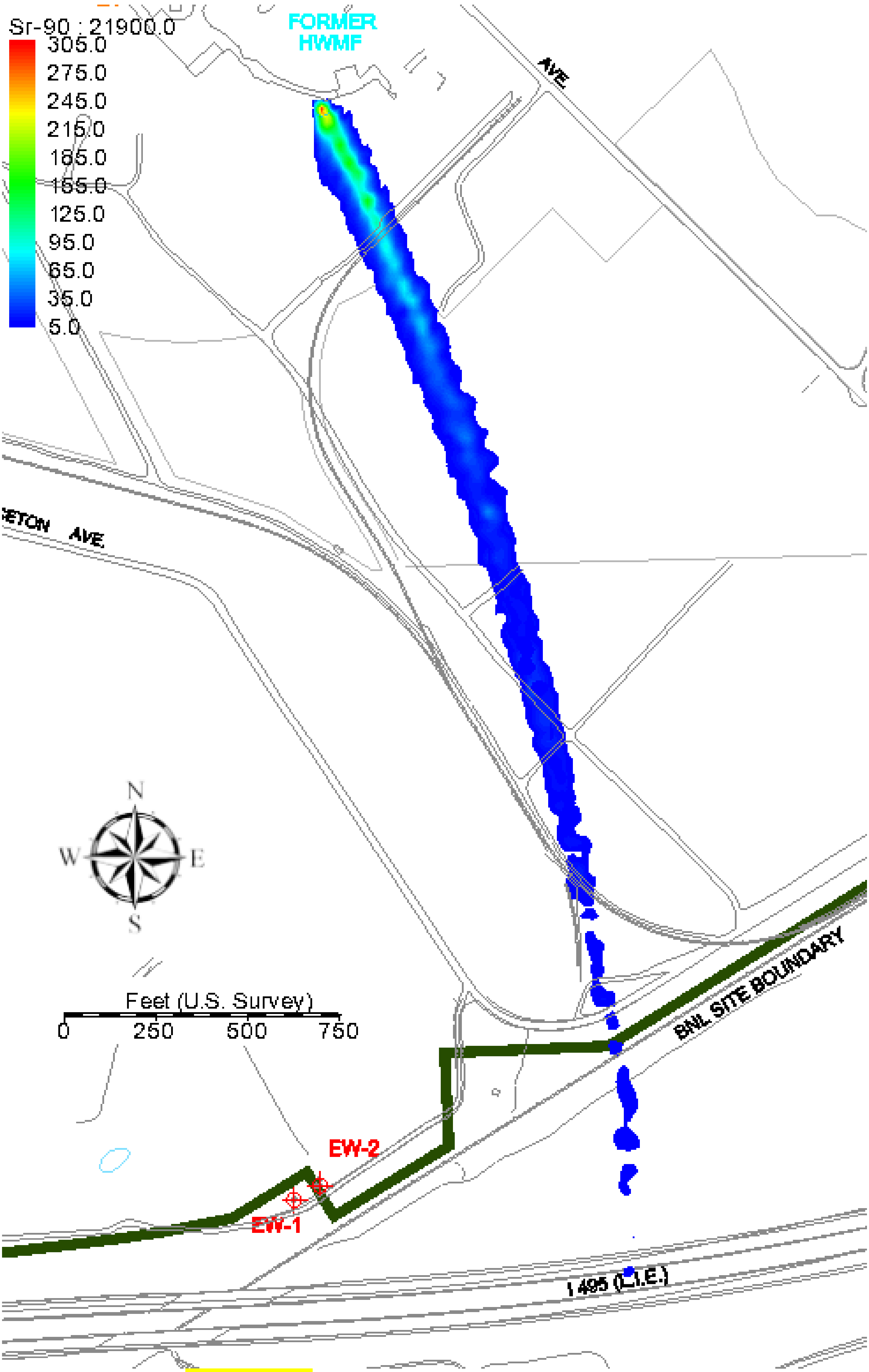


**Figure 12** – FHWMF Sr-90 Continuous Source Plume at t = 60 years

Color chart at upper left presents Sr-90 concentrations in pCi/l.
Number in extreme upper left above color chart is time since start in days.

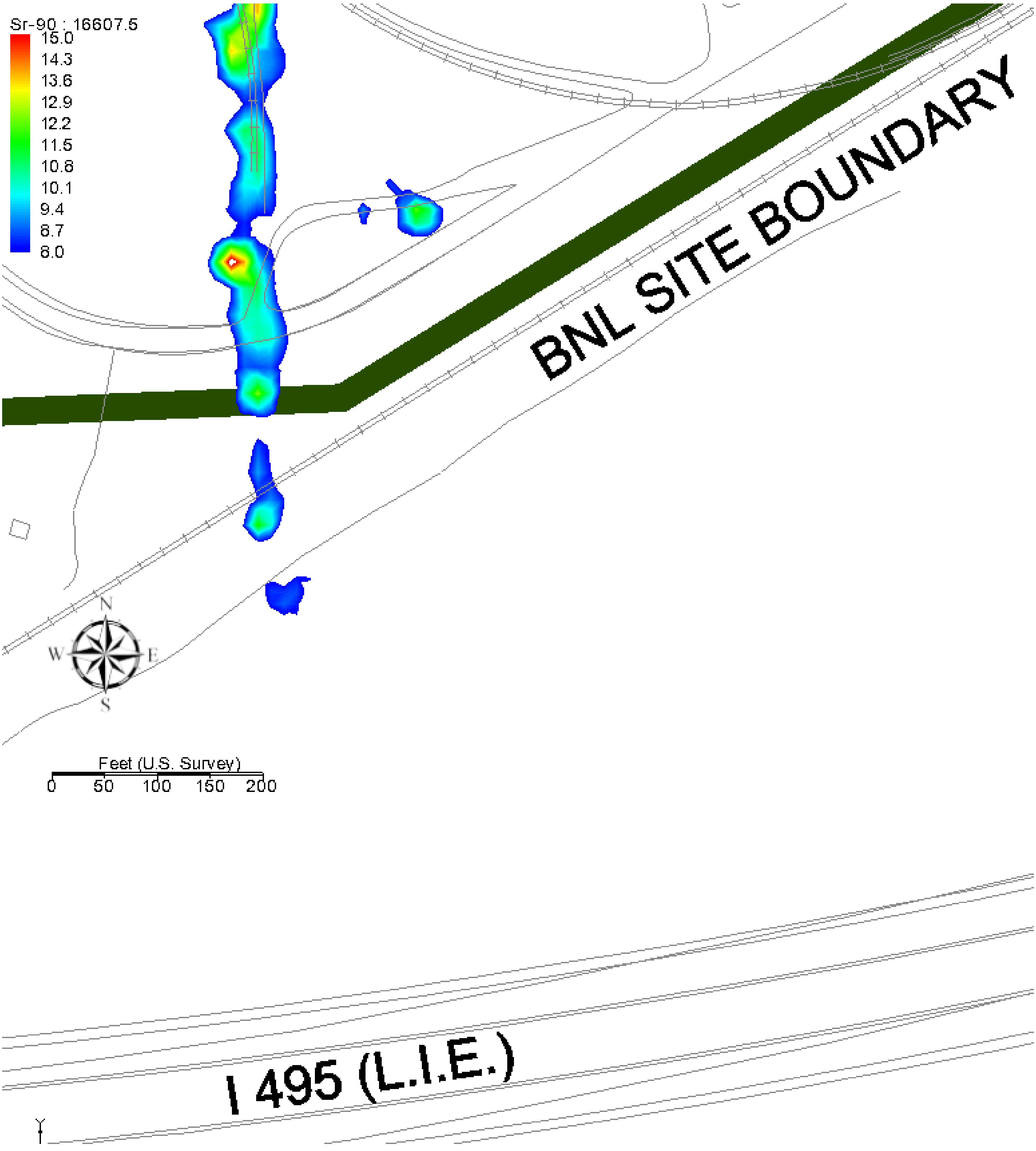


**Figure 13** – FHWMF Sr-90 Continuous Source Plume at t = 45.5 years

Color chart at upper left presents Sr-90 concentrations in pCi/l.
Number in extreme upper left above color chart is time since start in days.

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