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Bias and Uncertainty Under-Prediction in Monte Carlo Depletion

Alex Bennett, Brian Kiedrowski, Forrest Brown

July 25, 2013

1 Introduction

Two issues with Monte Carlo criticality calculation issues are bias in results from small batch sizes and uncertainty under-prediction because of inter-batch correlation. These phenomena have been known since the 1970's and were recently studied for realistic problems in the late 2000's. These recent studies were only for static cases, and did not look at how these phenomena impact depletion calculations.

This study used MCNP6 to investigate bias and uncertainty under-prediction in Monte Carlo depletion. An OECD/NEA Burnup Credit benchmark was used as the basis for this study. Results were obtained for these phenomena, and they showed that for this problem bias is not a concern, but the uncertainties are under-predicted by factors of 5-10 for capture of burnable poisons.

2 Theory

2.1 Bias

The Monte Carlo power iteration involves a renormalization between each cycle or batch. This process is a division by a random number, which introduces a bias. In the 1970s, the bias in the effective multiplication k was mathematically shown to be negative and decrease as the inverse of the batch size. Recent work on a 2-D Pressurized Water Reactor shows that the bias causes a spatial tilt in the localized power.

2.2 Uncertainty Under-Prediction

The uncertainties estimated in Monte Carlo criticality calculations are too low; in other words, the answers are reported to be more certain than they actually are. The reason

for this is because the uncertainties are computed with samples that are assumed to be statistically independent. In reality, they are correlated because neutrons in one fission generation tend to produce fissions nearby in subsequent generations. This correlation is always positive, implying that neglecting it causes the uncertainties to be too low.

3 Input File

3.1 Reference Case

The first case that was modeled is a simple 2D reflected assembly. The input case was moduled was from the “OECD/NEA Burnup Credit Criticality Benchmark Phase III B” that is a reflected 2D Boiling Water Reactor assembly. The specific power from the benchmark is 25.6 MW/tHW, the fuel burnup is 40 GWd/tHM, and the cooling time is 5 years. There are 4 different enrichments in the the fuel, 8 of the fuel pins contain gadolinium, and there is a water hole in the center of the assembly.

3.2 Assembly Geometry

Each fuel pin was modeled with its own material to accurately calculate the burnup in each pin. The pins that contained gadolinium were modeled with 10 different materials, each with the same radial distances to account for self shielding inside the pins. The assembly from the benchmark was then grouped into 4 assemblies in a 2x2 array with a 1 cm thick B₄C control blade between them. Four of these quad assemblies were then grouped together in a 2x2 array. Between these quad assemblies a 1 cm water gap was added. The outer edge of the geometry is still reflective. This geometry is shown in Fig. 1. The burnup time step are: one step of 1 day, 12 steps of 90 days, and a decay step of 5 years.

A python script was created to make these input files since they are very complicated.

3.3 Tallies

Tallies were taken along the diagonal to look at the effects of bias and uncertainty under-prediction. For the assemblies located along the diagonal, there were 6 tally locations in the fuel pins and 2 in the gadolinium pins. The location of the tallies are shown in green in Fig. 2. The tallies that were calculated are:

- Fission of U-235
- Fission of Pu-239
- Neutron Capture of U-238
- Neutron Capture of Pu-239

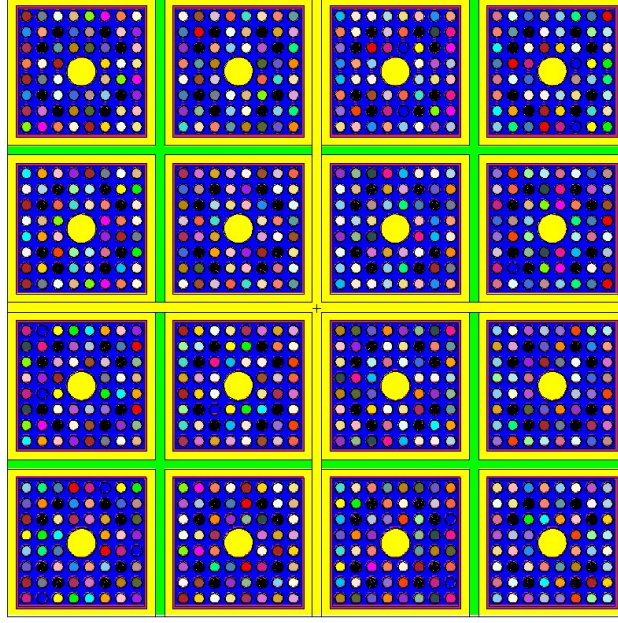


Figure 1: 2x2 quad assembly geometry

- Neutron Capture of Xe-135
- Neutron Capture of Gd-157

4 Memory Usage

Originally this case was not able to run on the Moonlight cluster since it required more than the 32 GB of memory available. A significant amount of memory was being used in the surface coefficient array when using “LIKE BUT TRCL”. “LIKE BUT TRCL” creates new surfaces and before doing so reserves enough memory for the largest macrobody case instead of the amount of memory that is needed. To decrease the amount of memory needed, the lines of source code,

$$mxj = mxj + 9 * ncl_like(m1c)$$

and

$$nsc = nsc + 32 * ncl_like(m1c)$$

where changed to,

$$mxj = mxj + 1 * ncl_like(m1c)$$

and

$$nsc = nsc + 4 * ncl_like(m1c)$$

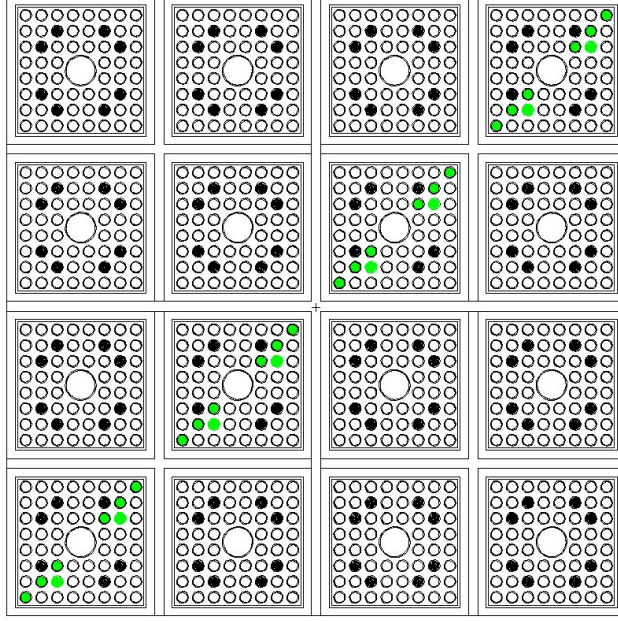


Figure 2: Tally locations colored green along diagonal

This change would not allow any cells with macrobodies to use LIKE BUT TRCL but it resulted in a factor of about 3 times less memory for the 4 quad assembly case.

Using the memory fix listed above, the amount of memory that was used for different amount of quad assemblies using 16 cores and 1 core is listed in Table I.

Table I: Memory Usage per Quad Assembly Using 16 Cores

Number of Quad Assemblies	Memory Usage(GB) Using 16 Cores	Memory Usage(GB) Using 1 Core
1	3.9	1.4
2	6.4	2.4
3	8.9	3.5
4	11.3	4.5
6	16.3	6.6
9	23.8	9.8

5 Cases

The reference case used 10,000 particles per cycle for 100 cycles, and 10 cycles were skipped. Both the Shannon entropy and the source converged within the first 10 cycles. To show the effects of bias, the total number of particles needs to be kept the same and the number of particles per cycle needs to decrease. The bias case used 100 particles per cycle for 10,000

cycles, and this case also skipped 10 cycles. Each case would be run 25 different times, each with a different random number seed so they would be independent. The bias case only ended up having 23 independent runs since two of the runtime files got corrupted and there wasn't enough time to re-run them. The reference cases took about 140 hours to run on 16 cores and the bias cases took about 240 hours to run on 16 cores.

6 Obtaining Results

A script was created to obtain the results from the output files. The script obtained k_{eff} , tally results, and the standard deviations of the tallies. This script would output a true and an averaged MCNP standard deviation. The true standard deviation was calculated directly from the results of the independent cases. The MCNP standard deviation was calculated as the average of the mcnp standard deviation over all the cases. The results for the uncertainty under-prediction are given in terms of the ratio of uncertainties, which is the ratio of the true uncertainty to the mcnp reported uncertainty. The reference case of 10,000 particles per cycle was used to calculate the ratio of uncertainties.

7 Results

7.1 Bias

Most of the biased tallies were found to be within 2 standard deviations of the mean to the reference tally. The tally that had the largest deviation from the reference tally was the neutron capture of Gd-157. The plot of neutron capture in Gd-157 as a function of location for timestep 11 is shown in Fig. 3. Even for the neutron capture in Gd-157, the biased results are still within 2 true standard deviations of the mean to the reference tally for most tallies, which shows that bias is not having much of an effect on the result.

Most of the other tallies have a closer comparison to the reference case. An example of the other tallies is the fission of Pu-239 as a function of location in the fuel pins for timestep 11 is shown in Fig. 4. The plots for all the tallies and timesteps are shown in Appendix.

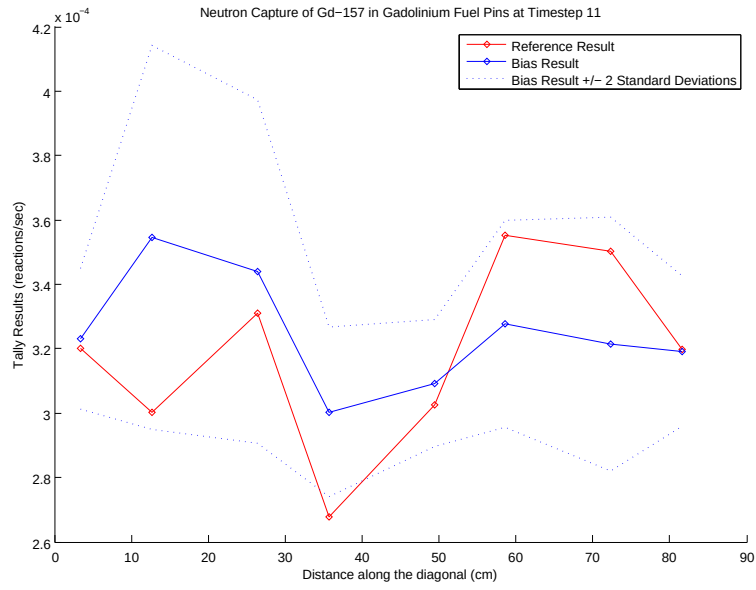


Figure 3: Neutron capture of Gd-157 for timestep 11

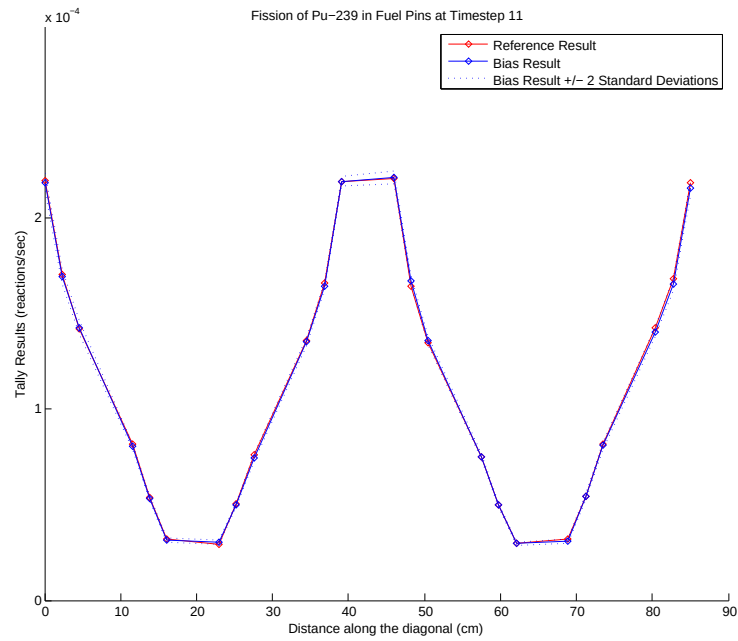


Figure 4: Fission of Pu-239 for timestep 11

7.2 Uncertainty Under-Prediction

The plot of the uncertainty under-prediction for the neutron capture of Gd-157 as a function of location at timesteps 1, 5, and 15 are shown in Fig. 5. The ideal result would be that the ratio of uncertainties be close to unity. In the first time step the ratio is such; however, at time step 5 the ratio of uncertainties is much greater. This increase in uncertainties occurs when the gadolinium is mostly depleted.

The plot of the uncertainty under-prediction of the fission of Pu-239 in the fuel pins as a function of location at timesteps 5, 10, and 14 are shown in Fig. 6. The ratio of uncertainties for the fission of Pu-239 are not nearly as high of a value as is seen in the neutron capture of gadolinium. They also do not show any considerable trend as a function of time. The ratio of uncertainties for the other tallies and timesteps show similar results to the fission of Pu-239. The other results can be found in Appendix.

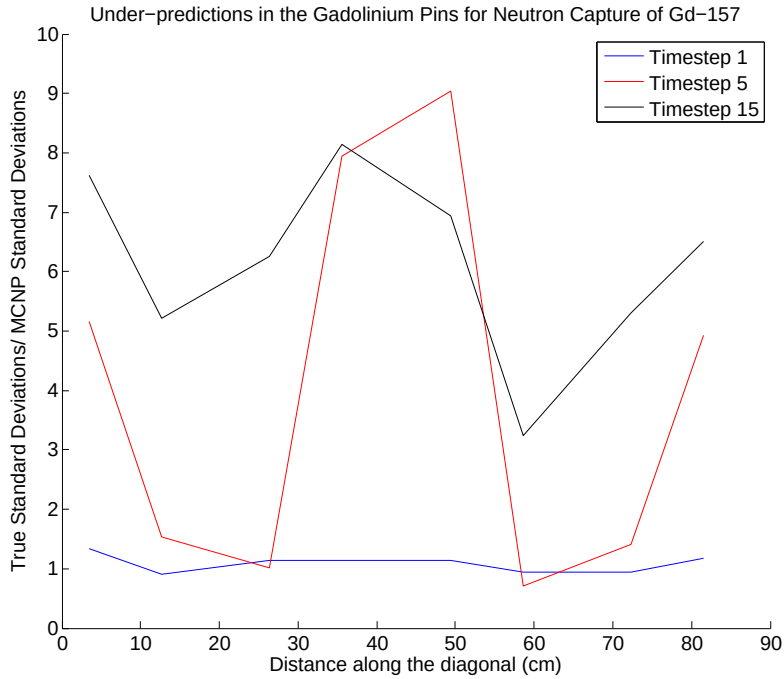


Figure 5: Uncertainty under-prediction of neutron capture in Gd-157

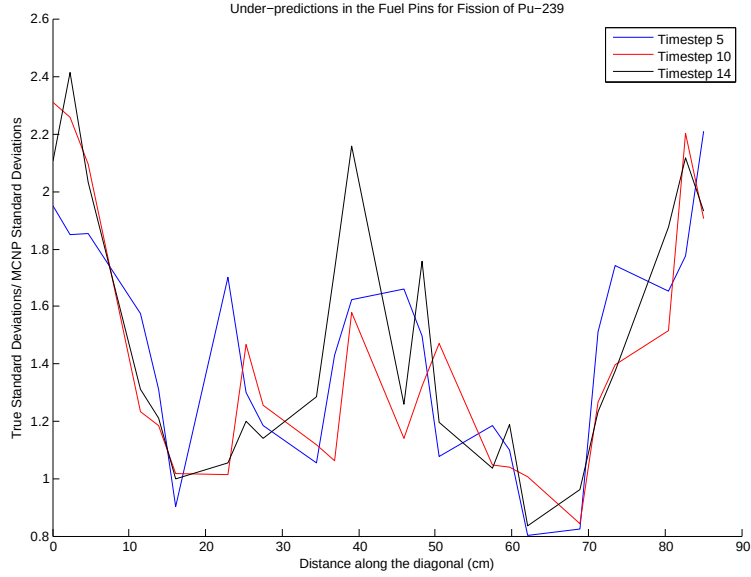


Figure 6: Uncertainty under-prediction of fission in fuel pins for Pu-239

To look closer at the uncertainty under-prediction as a function of time, the mean of the ratio of uncertainties over all the tally locations for each time step was taken. The plot of the mean ratio of uncertainties for the neutron capture of Gd-157 as a function of time step is shown in Fig. 7. The plot has an upward trend. The plot of the mean ratio of uncertainties of the fission of Pu-239 in the fuel pins as a function of time step is shown in Fig. 8. The ratio of uncertainties for the fission of Pu-239 does not show any considerable trend as a function of time. The other tallies show comparable results to the fission of Pu-239 and do not change as a function of time. These results can be found in Appendix.

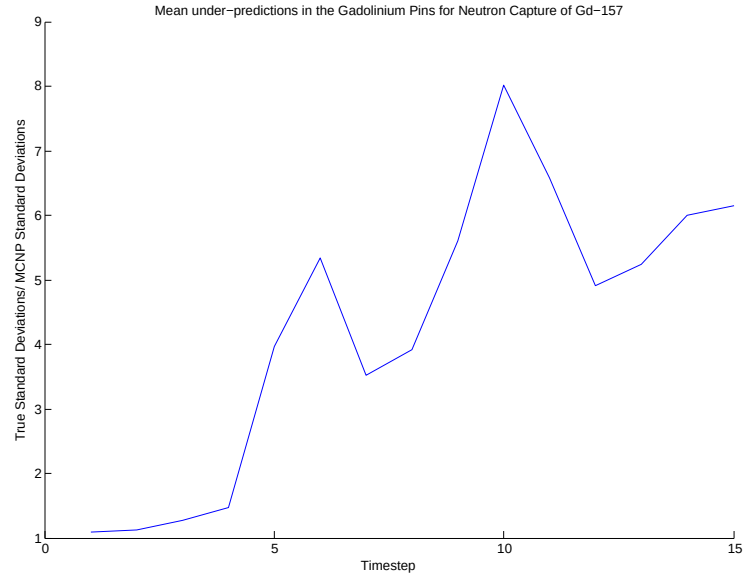


Figure 7: Mean uncertainty under-prediction of neutron capture in Gd-157

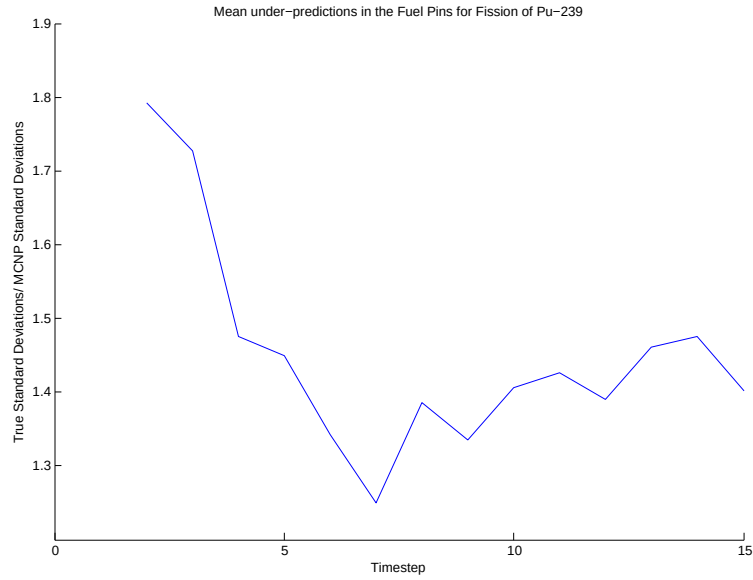


Figure 8: Mean uncertainty under-prediction of fission in fuel pins for Pu-239

Another effect that was looked at was the ratio of uncertainties as a function of distance from the gadolinium pins. The ratio of uncertainties for the fission of Pu-239 as a function timestep

was found for the two pins shown in Fig. 9. The results for these two pins are shown in Fig. 10. The fuel pin closer to the gadolinium pin has a larger ratio of uncertainties then the fuel pin further away from the gadolinium pin. This suggests uncertainty under-prediction is more serious near burnable poisons.

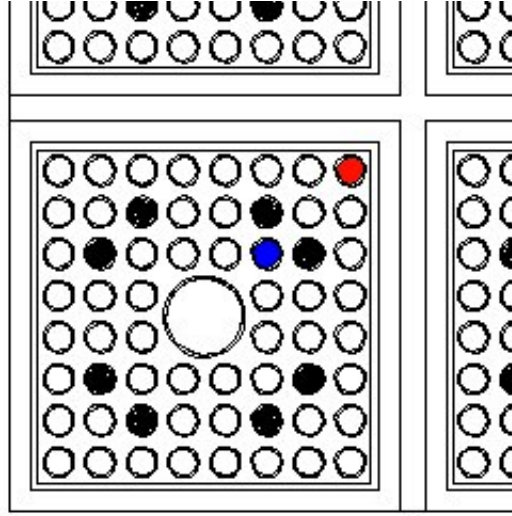


Figure 9: Location of the two tallies

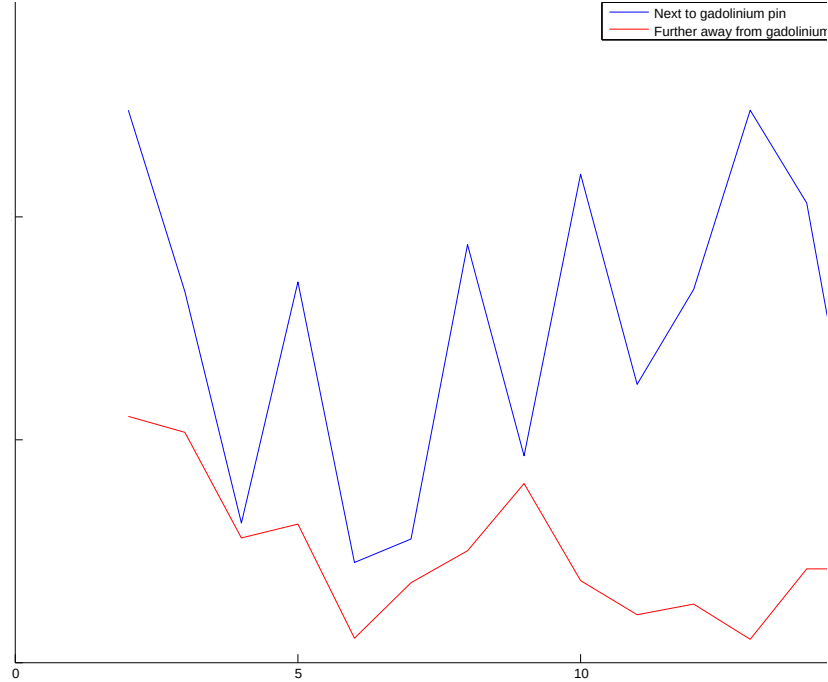


Figure 10: Uncertainty under-prediction of fission in two fuel pins for Pu-239

8 Summary and Future Work

Bias did not have much of an effect for this problem. Even for the neutron capture of the Gd-157 tally, most of the biased tallies were within 2 standard deviations of the reference tally. This was most likely caused by the symmetry and small size of the problem. For future work a larger problem or a less symmetric problem could be looked at to try to get a larger effect from bias. The gadolinium or a control blade could be taken out of one of the quad assemblies to obtain a less symmetric problem.

The uncertainties reported from MCNP are only under-predicted by factors of about 1 - 2.5, and burnup does not seem to have an effect on this under-prediction, except for the case of the neutron absorption of Gd-157. The under-prediction of the uncertainty of the neutron absorption of Gd-157 grew with time and seemed to be correlated with its depletion. For the later time steps the under-prediction is about a factor of 6 to 8 and was found to be 15 for one case. The gadolinium also had a local effect on other tally uncertainties. The tallies next to the gadolinium pins had a higher under-prediction of the uncertainty than tallies located further from the gadolinium pins.

Appendices

Appendix A: Tally Plots

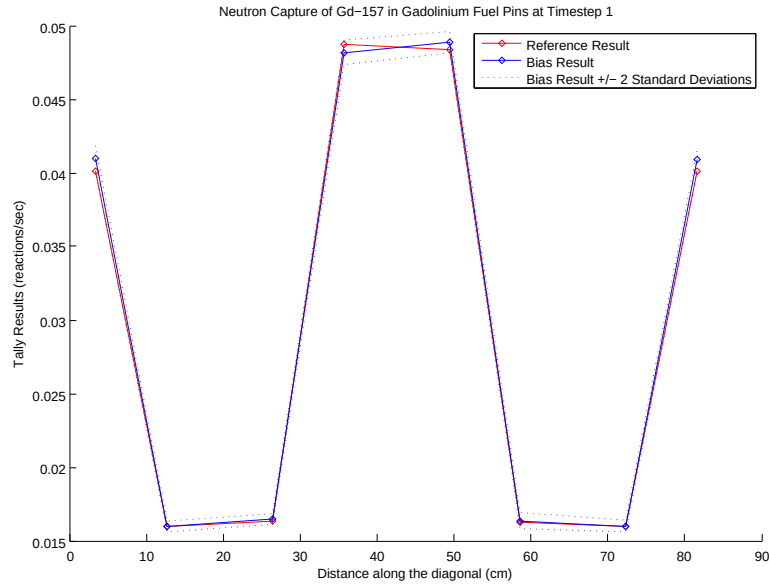


Figure 11: Capture of Gd-157 for timestep 1

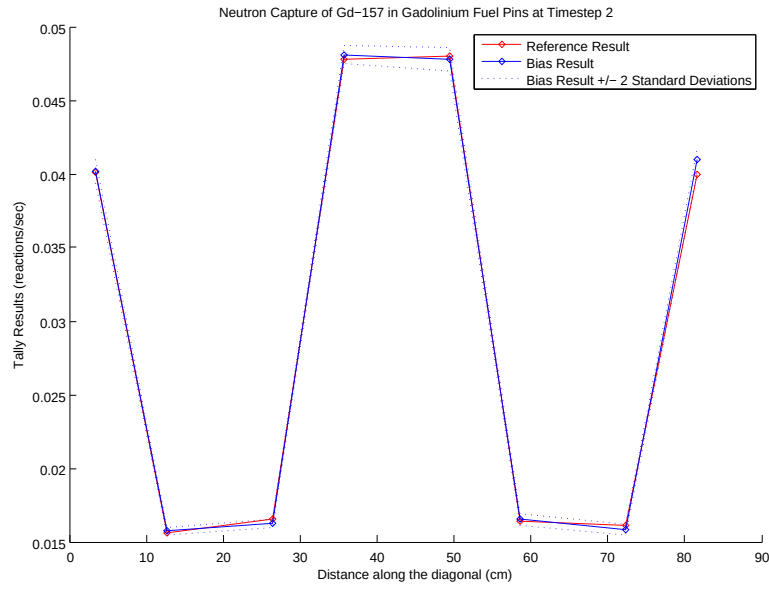


Figure 12: Capture of Gd-157 for timestep 2

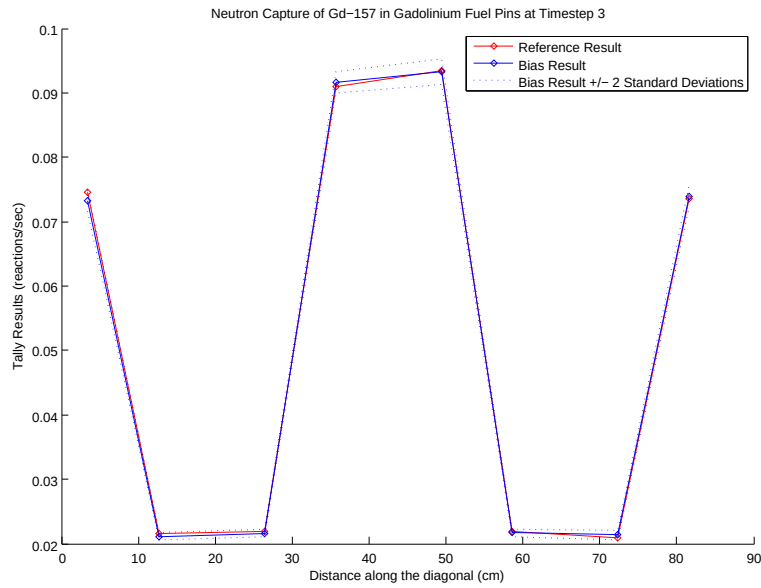


Figure 13: Capture of Gd-157 for timestep 3

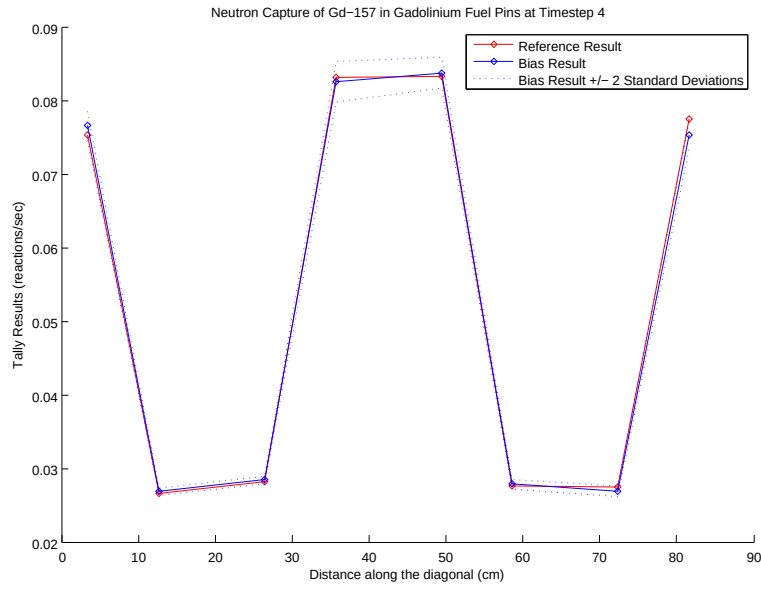


Figure 14: Capture of Gd-157 for timestep 4

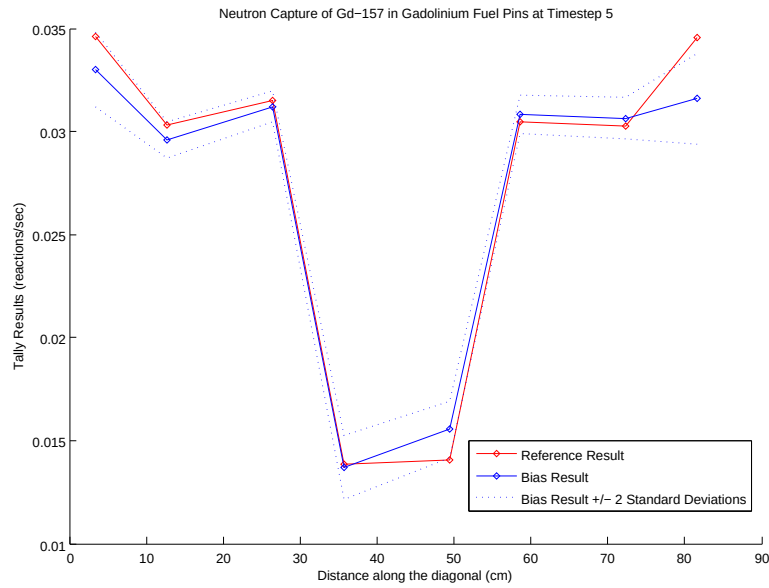


Figure 15: Capture of Gd-157 for timestep 5

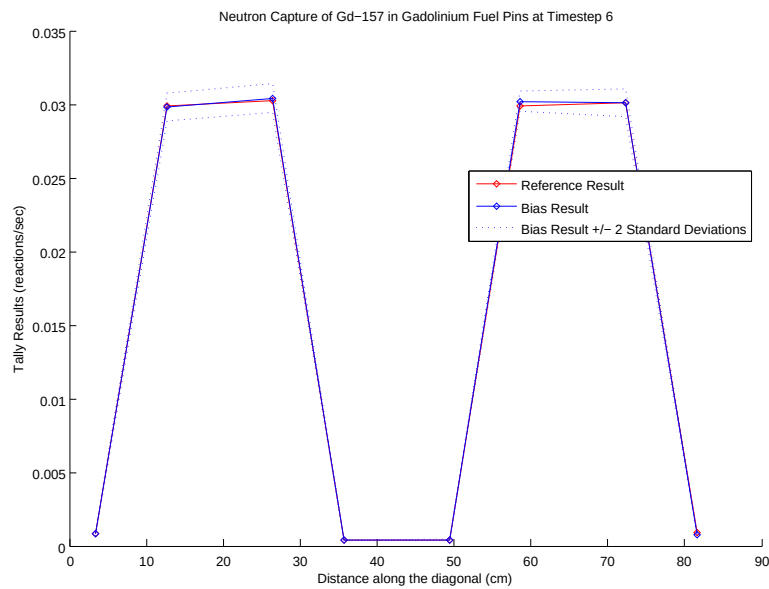


Figure 16: Capture of Gd-157 for timestep 6

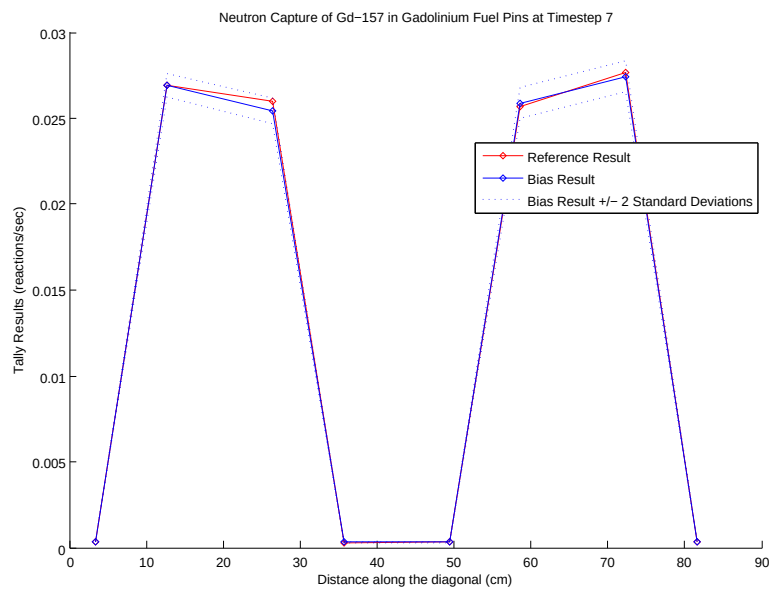


Figure 17: Capture of Gd-157 for timestep 7

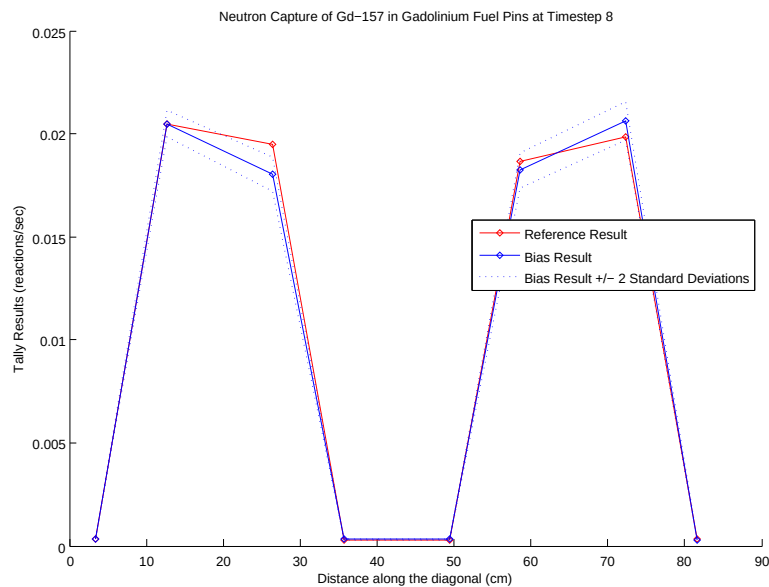


Figure 18: Capture of Gd-157 for timestep 8

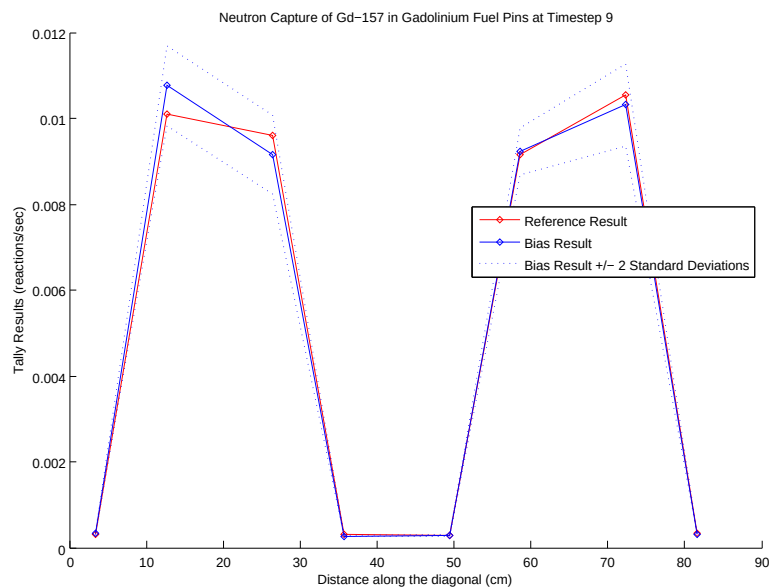


Figure 19: Capture of Gd-157 for timestep 9

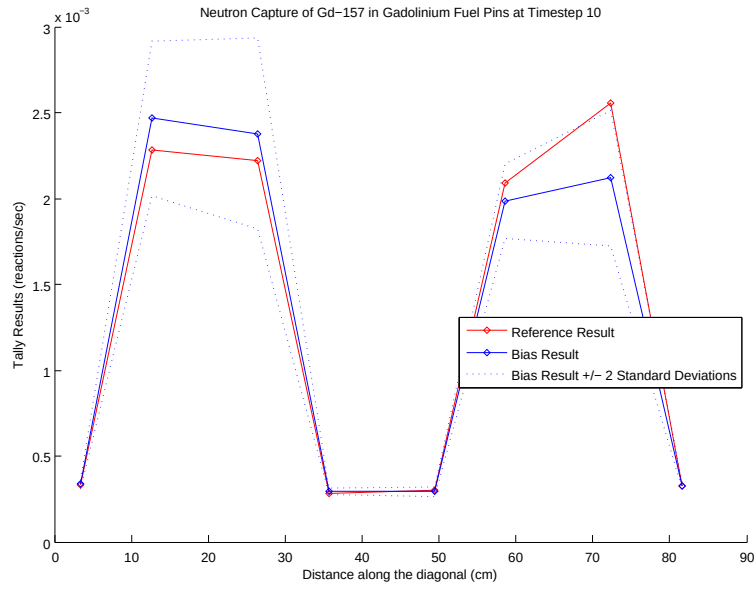


Figure 20: Capture of Gd-157 for timestep 10

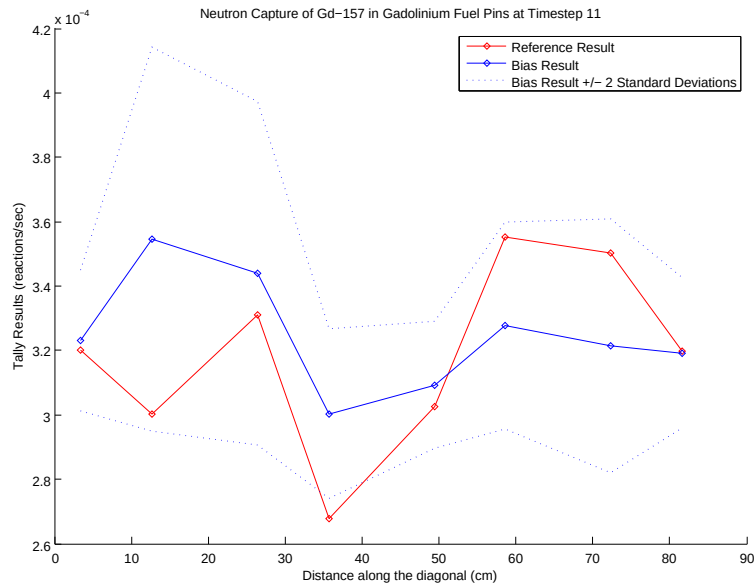


Figure 21: Capture of Gd-157 for timestep 11

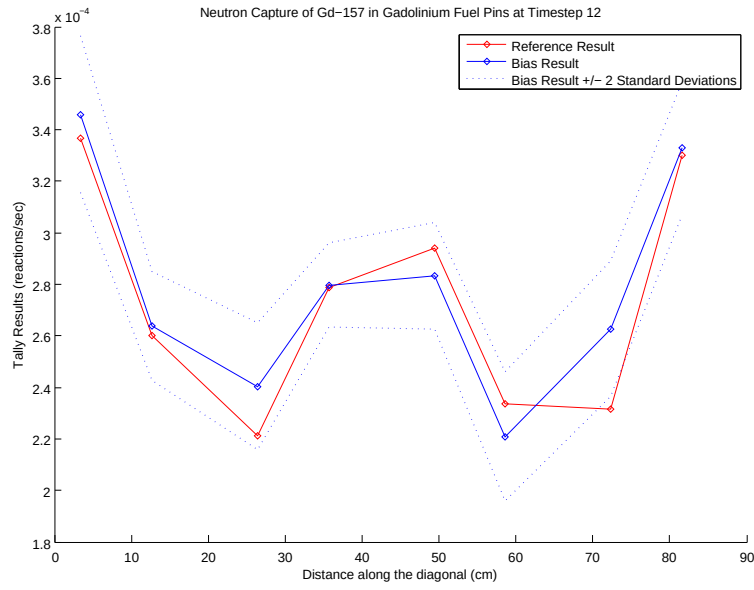


Figure 22: Capture of Gd-157 for timestep 12

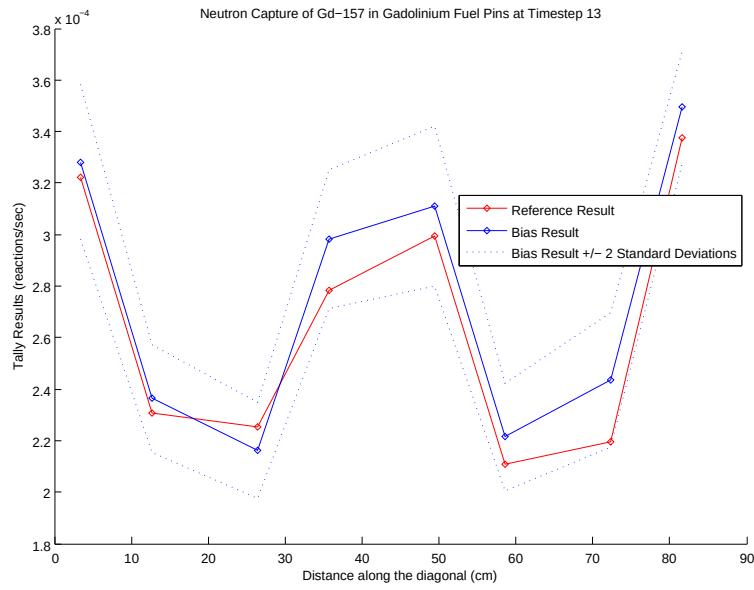


Figure 23: Capture of Gd-157 for timestep 13

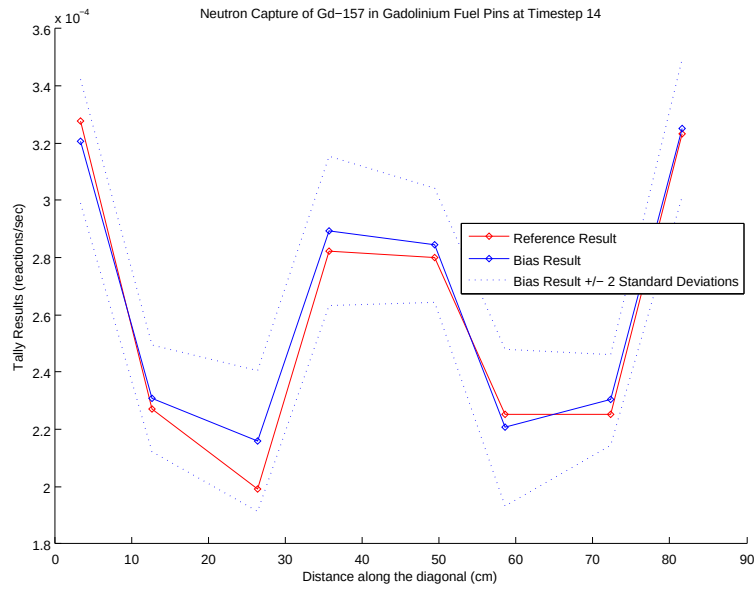


Figure 24: Capture of Gd-157 for timestep 14

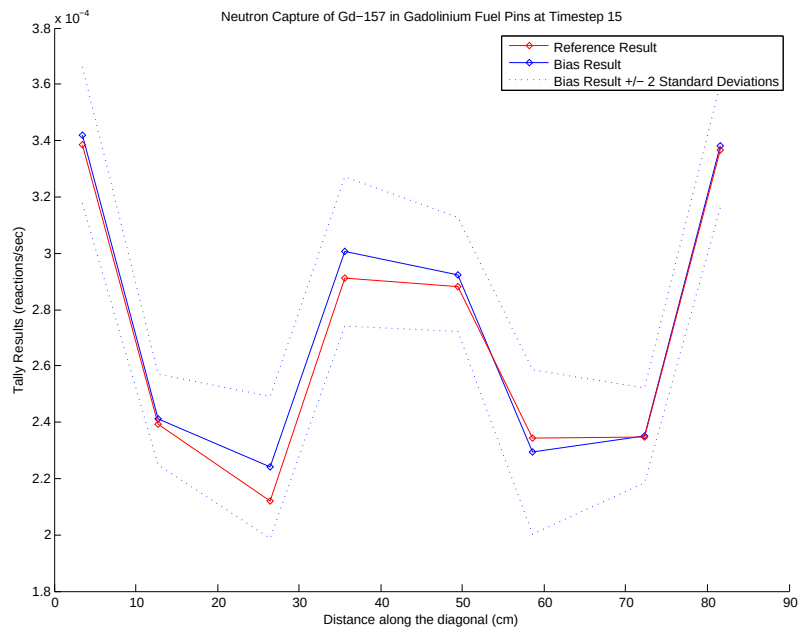


Figure 25: Capture of Gd-157 for timestep 15

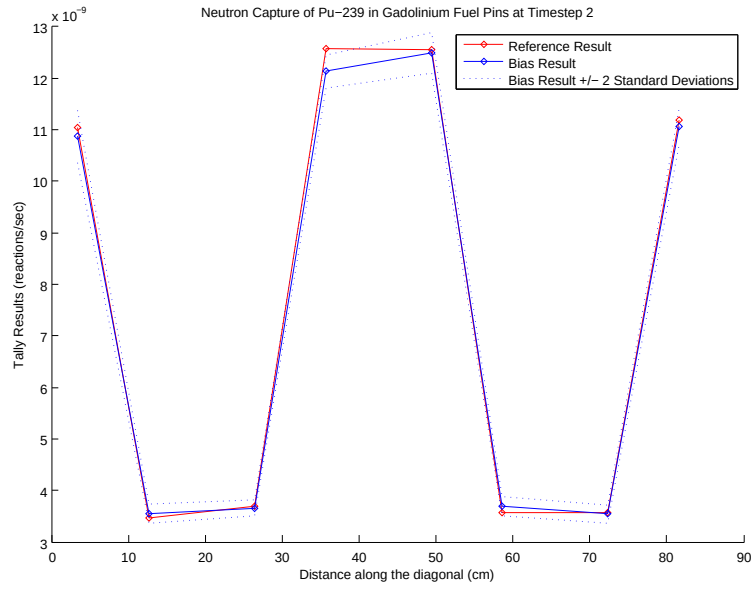


Figure 26: Capture of Pu-239 for timestep 2

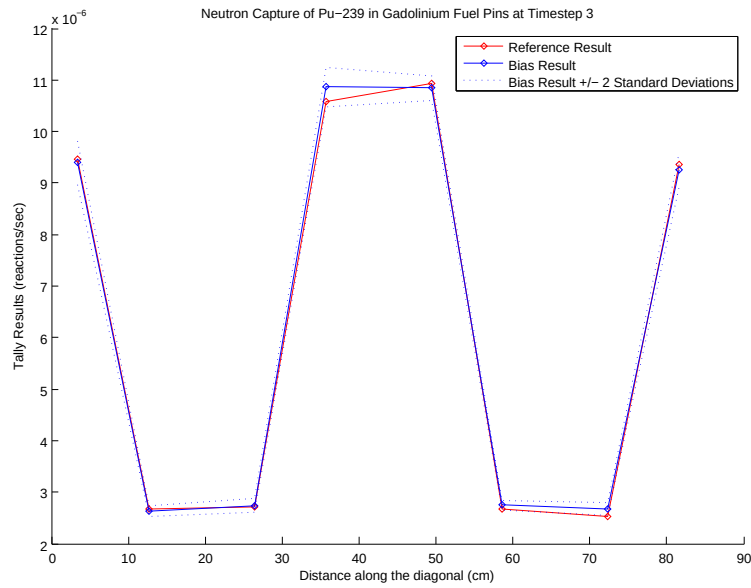


Figure 27: Capture of Pu-239 for timestep 3

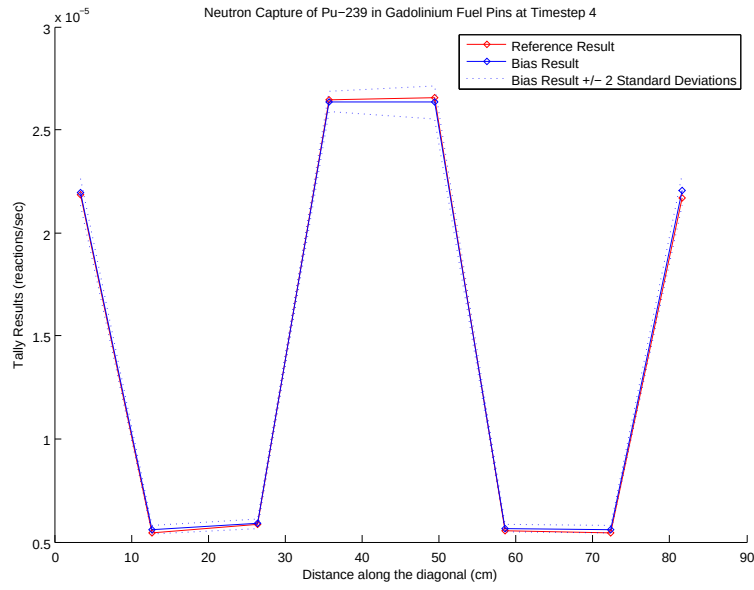


Figure 28: Capture of Pu-239 for timestep 4

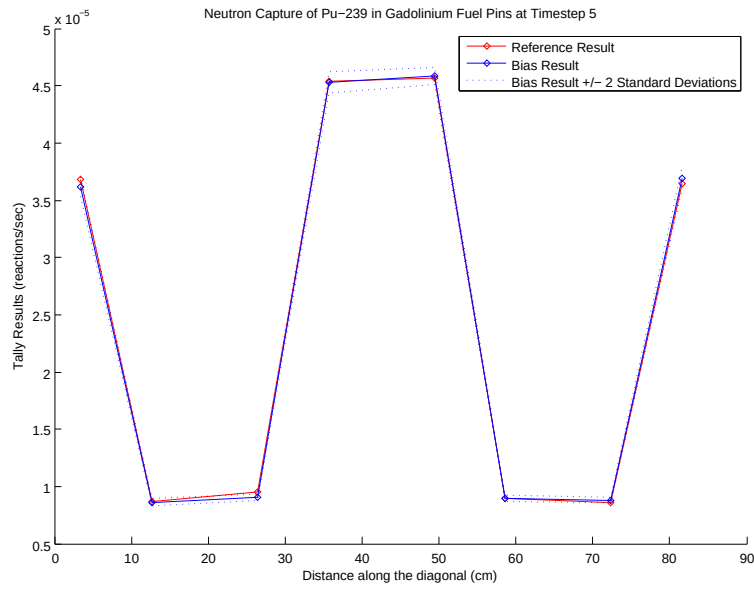


Figure 29: Capture of Pu-239 for timestep 5

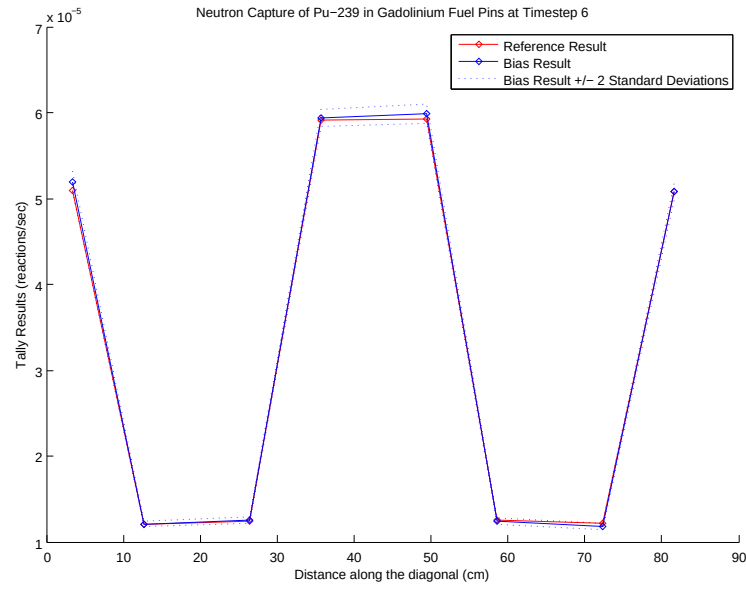


Figure 30: Capture of Pu-239 for timestep 6

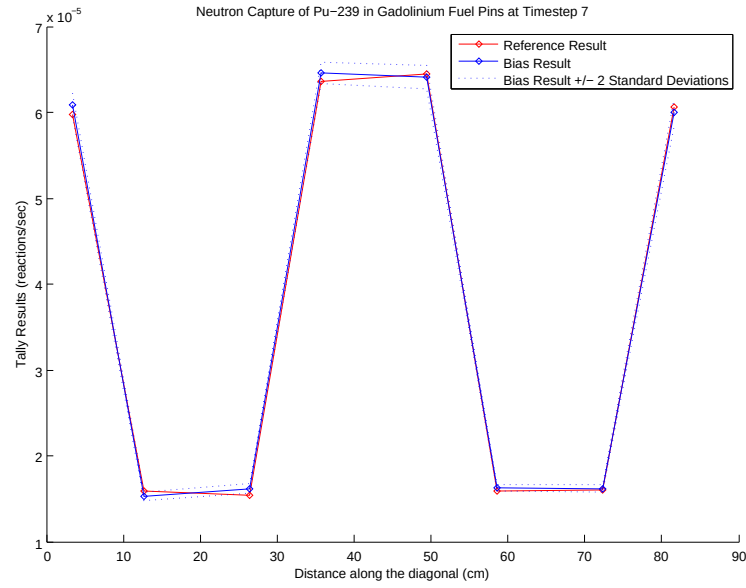


Figure 31: Capture of Pu-239 for timestep 7

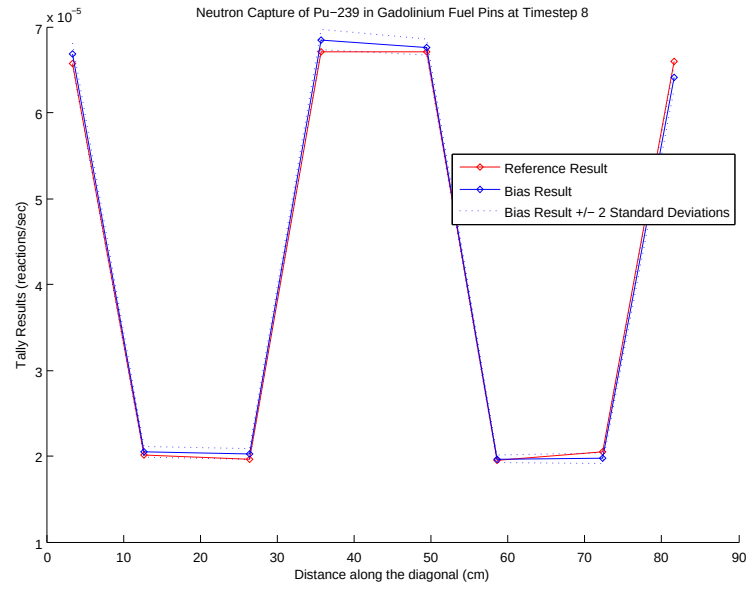


Figure 32: Capture of Pu-239 for timestep 8

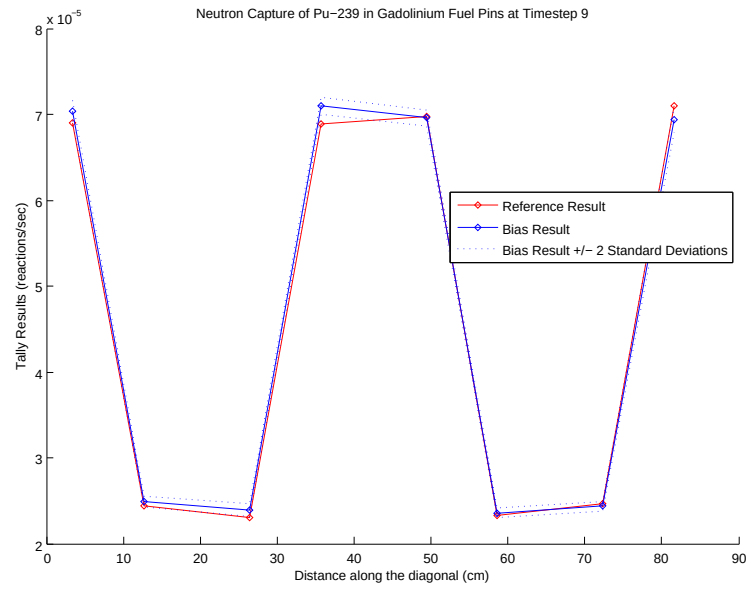


Figure 33: Capture of Pu-239 for timestep 9

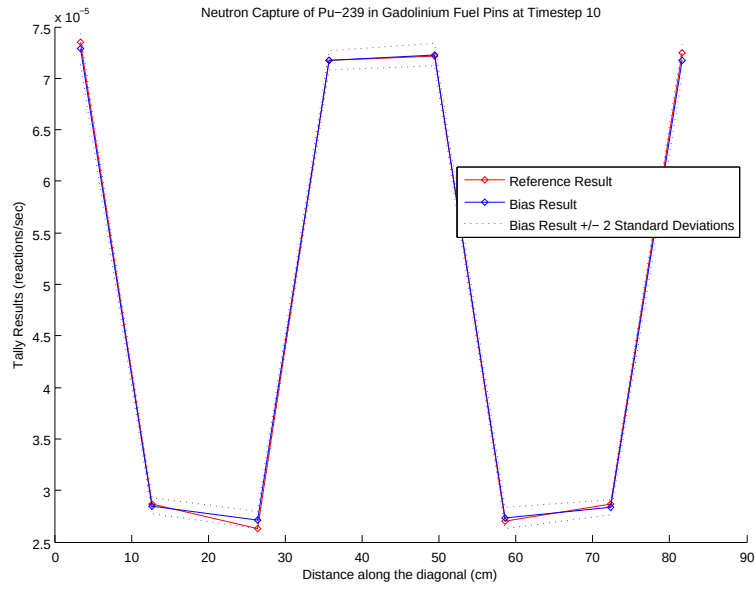


Figure 34: Capture of Pu-239 for timestep 10

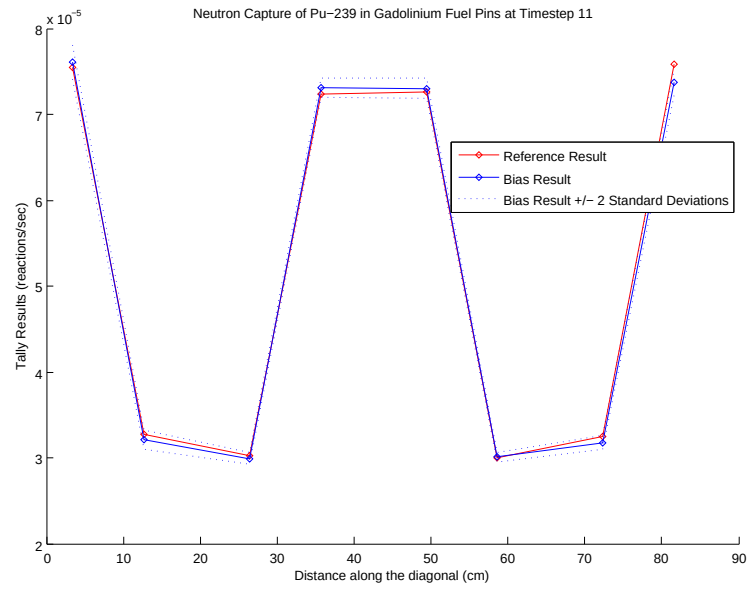


Figure 35: Capture of Pu-239 for timestep 11

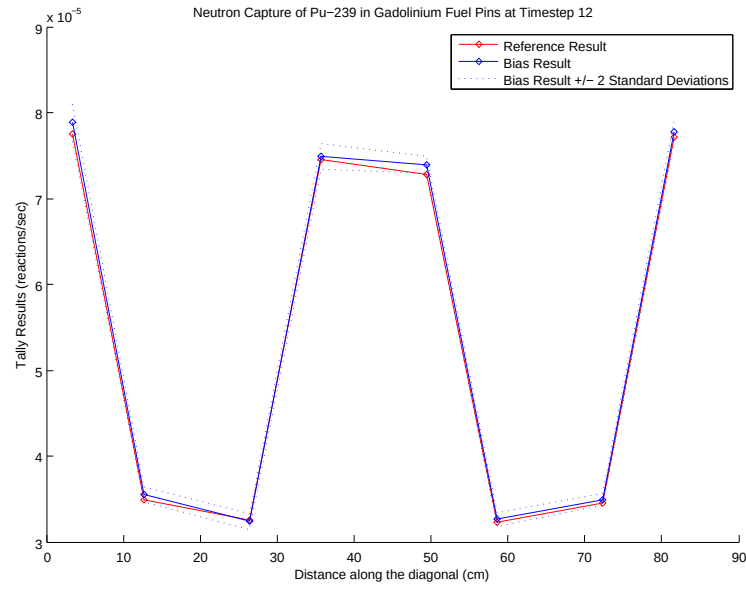


Figure 36: Capture of Pu-239 for timestep 12

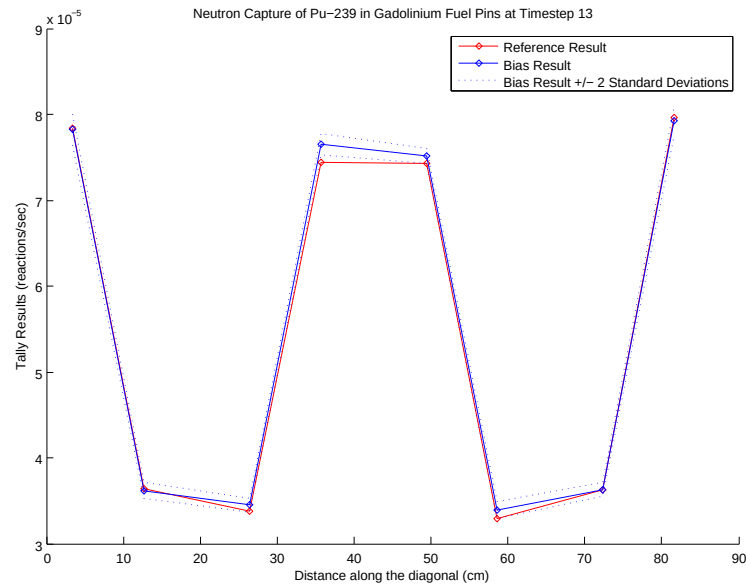


Figure 37: Capture of Pu-239 for timestep 13

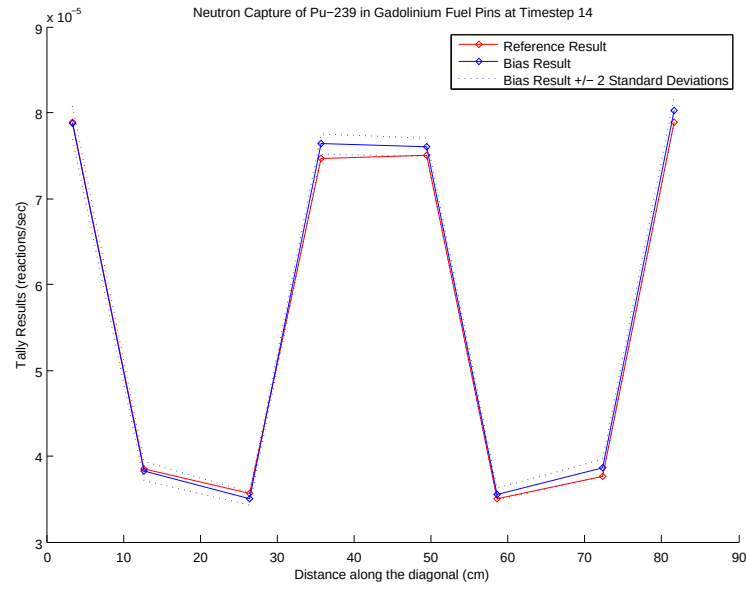


Figure 38: Capture of Pu-239 for timestep 14

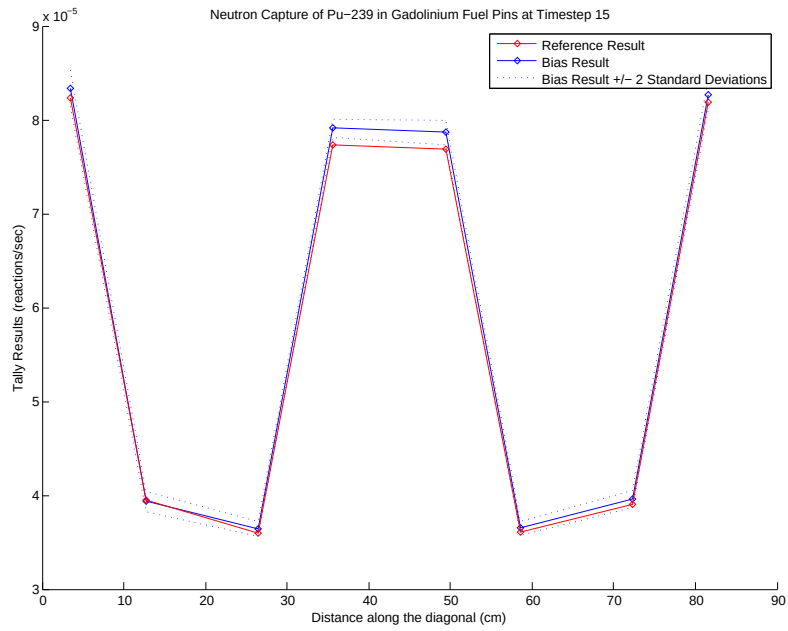


Figure 39: Capture of Pu-239 for timestep 15

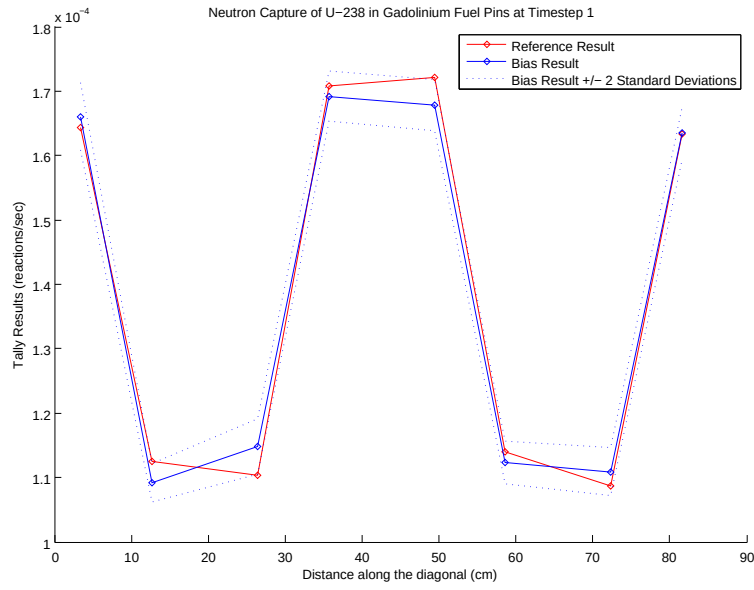


Figure 40: Capture of U-238 for timestep 1

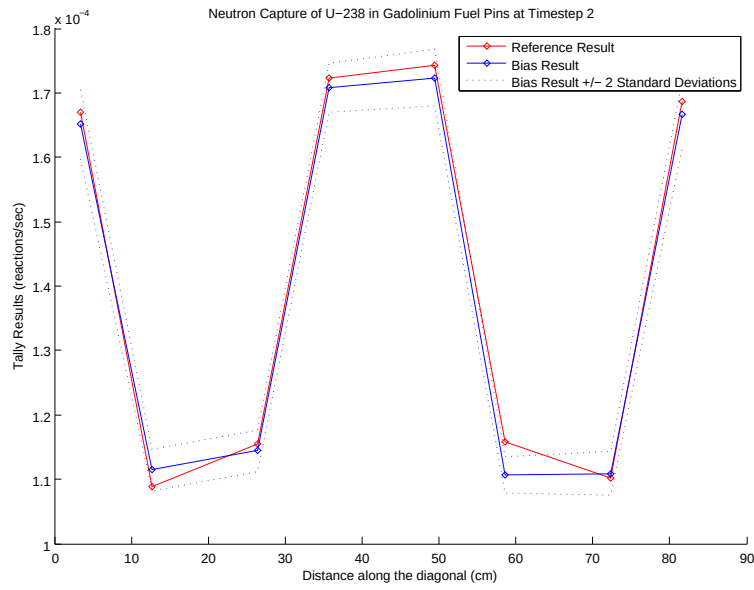


Figure 41: Capture of U-238 for timestep 2

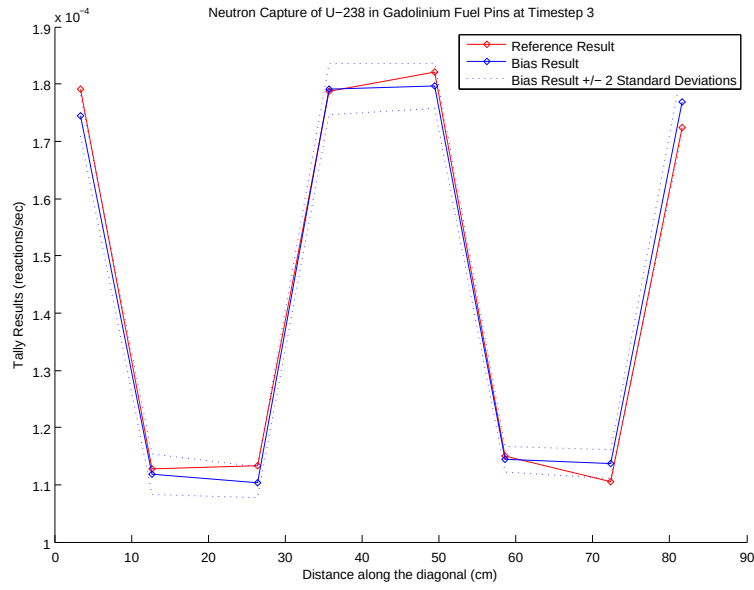


Figure 42: Capture of U-238 for timestep 3

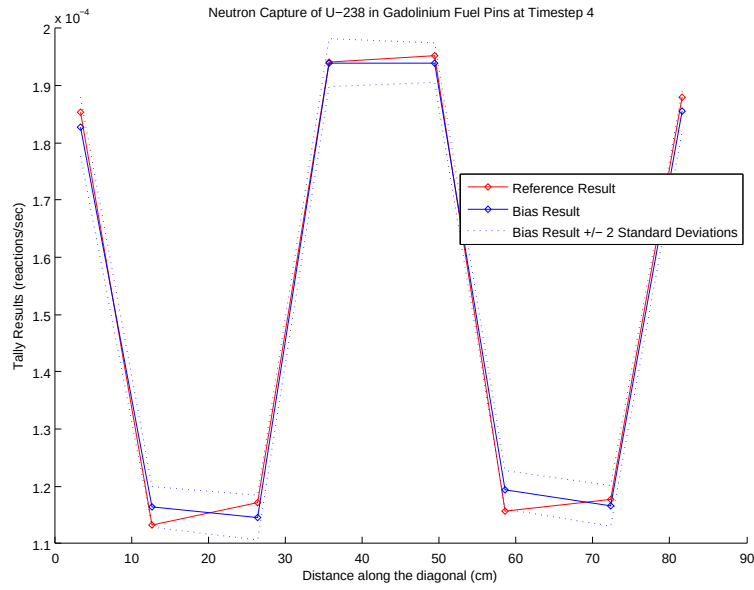


Figure 43: Capture of U-238 for timestep 4

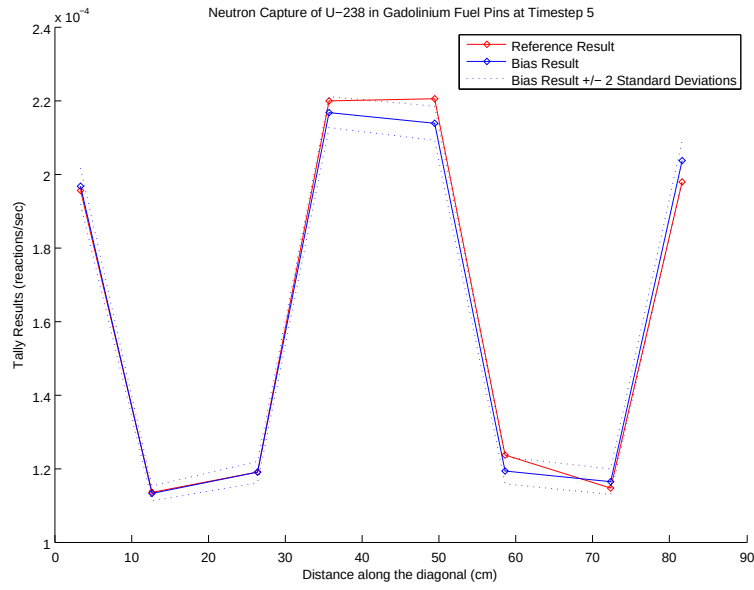


Figure 44: Capture of U-238 for timestep 5

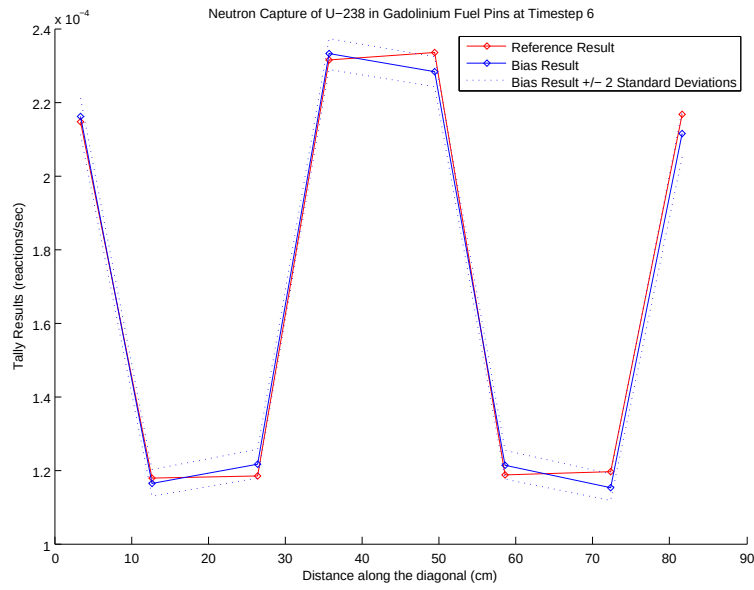


Figure 45: Capture of U-238 for timestep 6

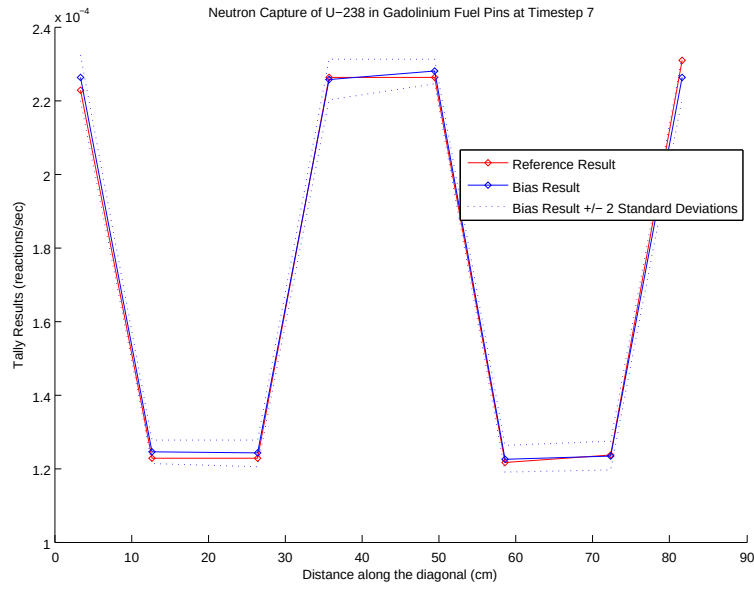


Figure 46: Capture of U-238 for timestep 7

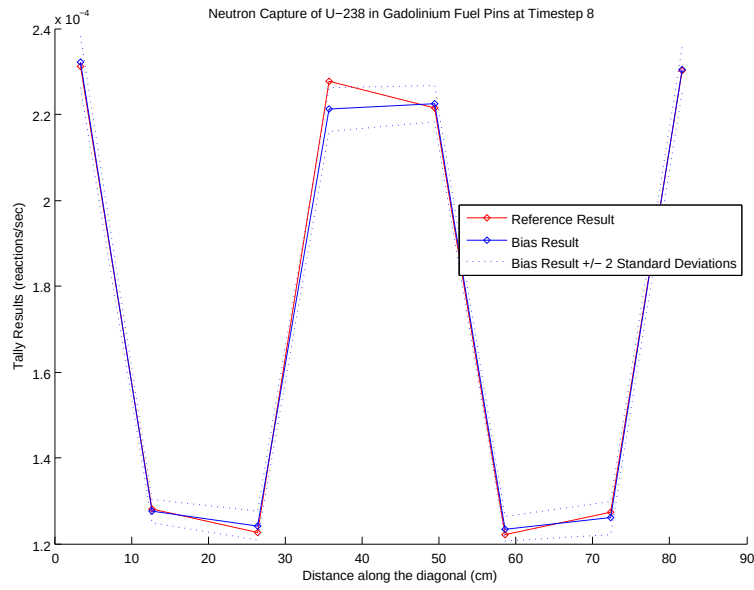


Figure 47: Capture of U-238 for timestep 8

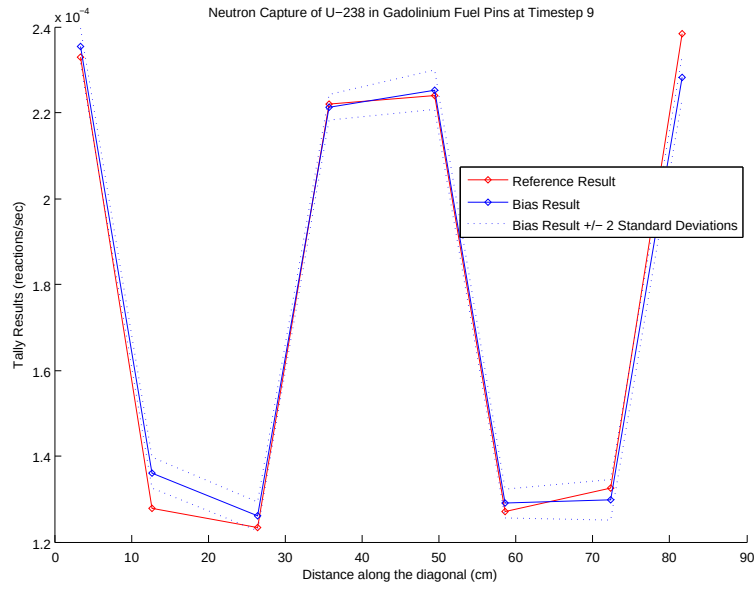


Figure 48: Capture of U-238 for timestep 9

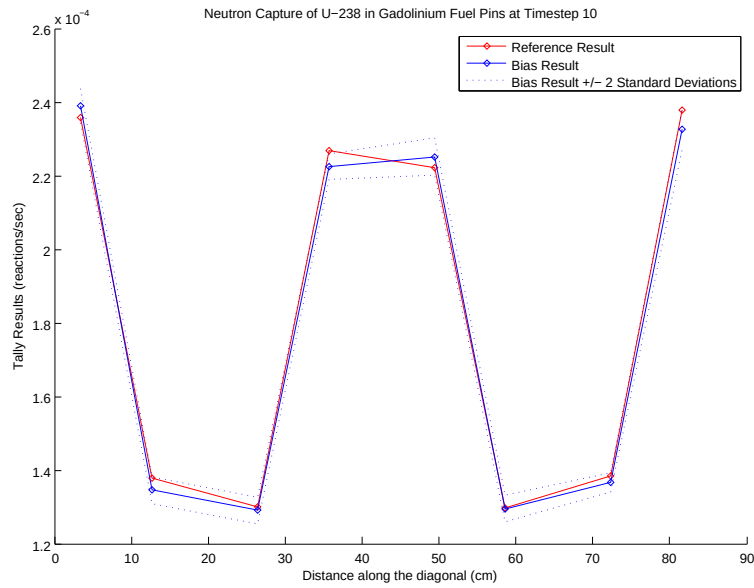


Figure 49: Capture of U-238 for timestep 10

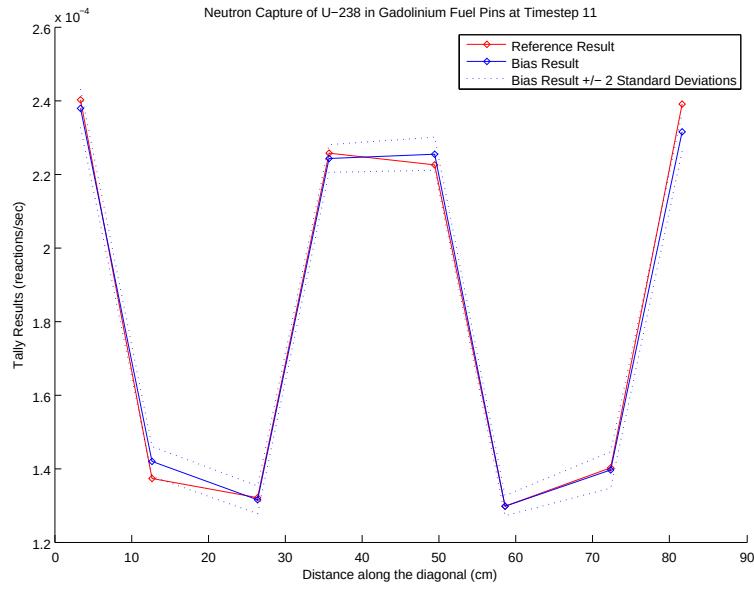


Figure 50: Capture of U-238 for timestep 11

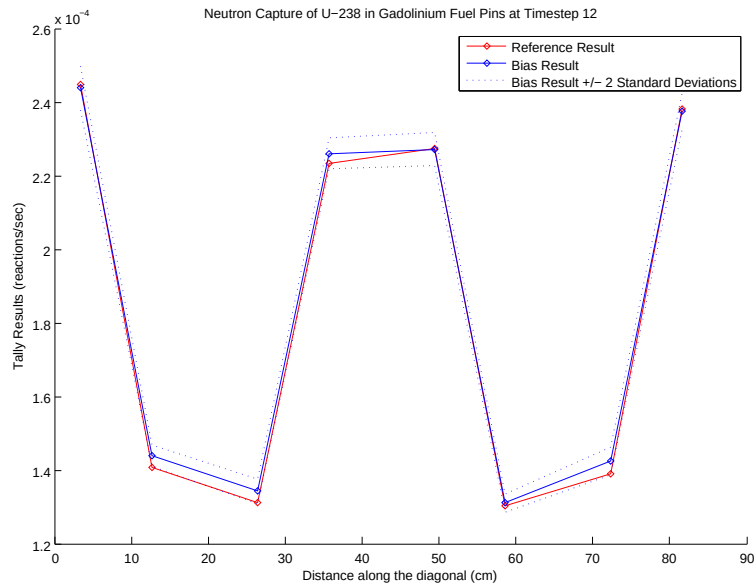


Figure 51: Capture of U-238 for timestep 12

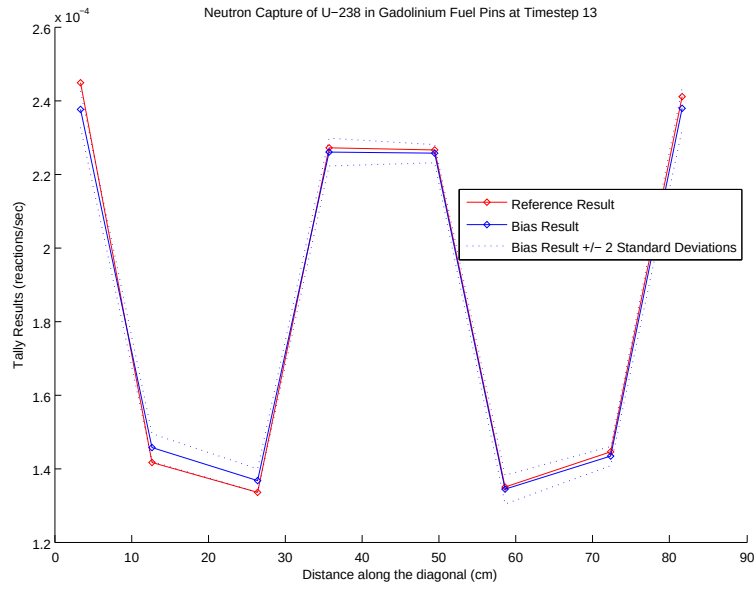


Figure 52: Capture of U-238 for timestep 13

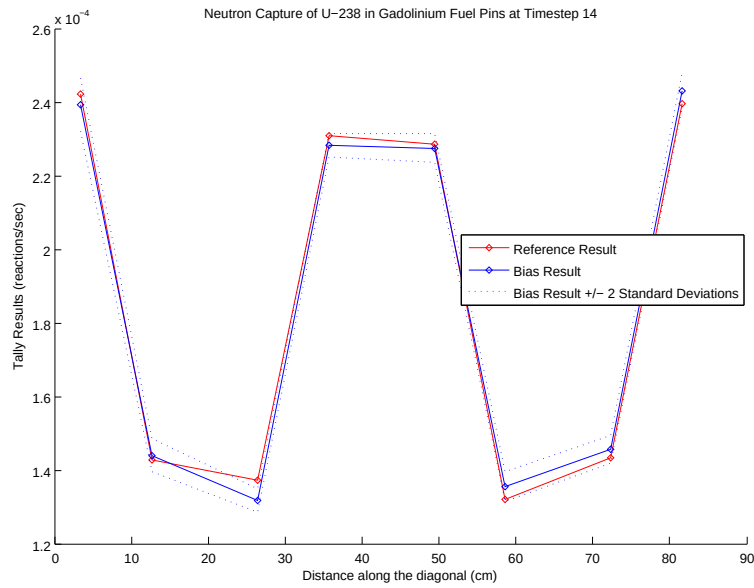


Figure 53: Capture of U-238 for timestep 14

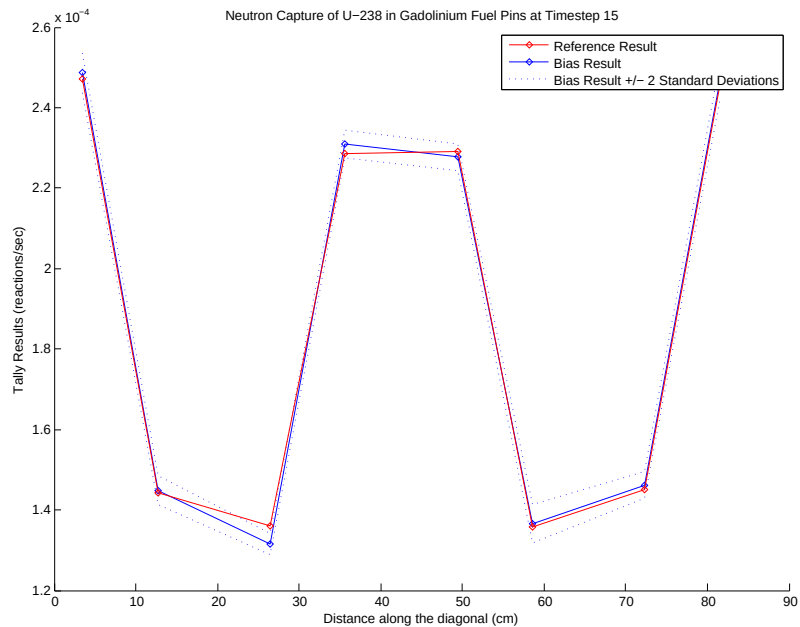


Figure 54: Capture of U-238 for timestep 15

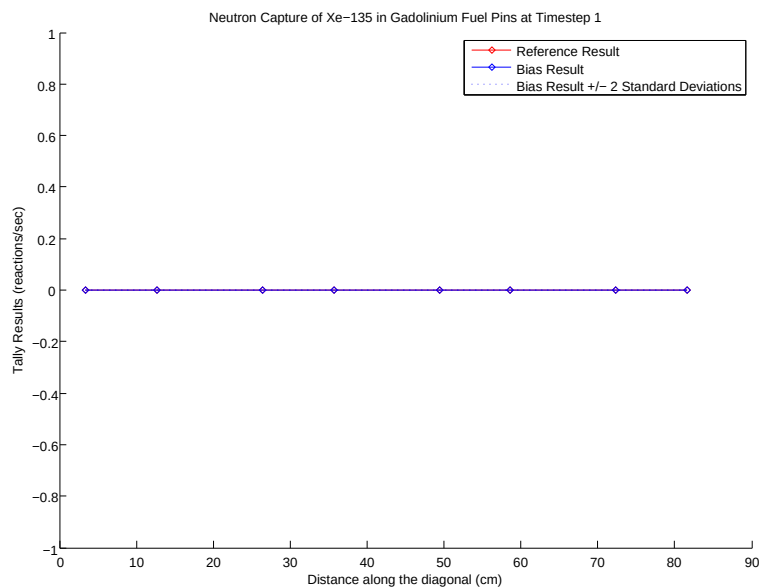


Figure 55: Capture of Xe-135 for timestep 1

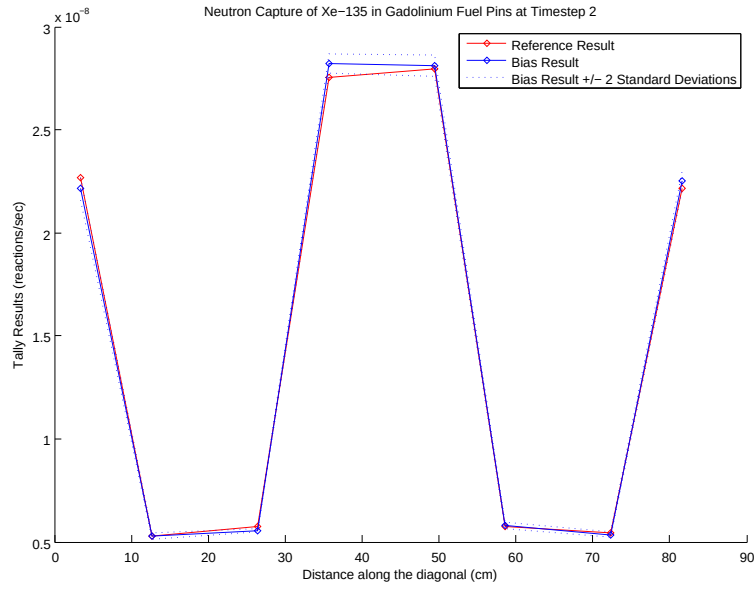


Figure 56: Capture of Xe-135 for timestep 2

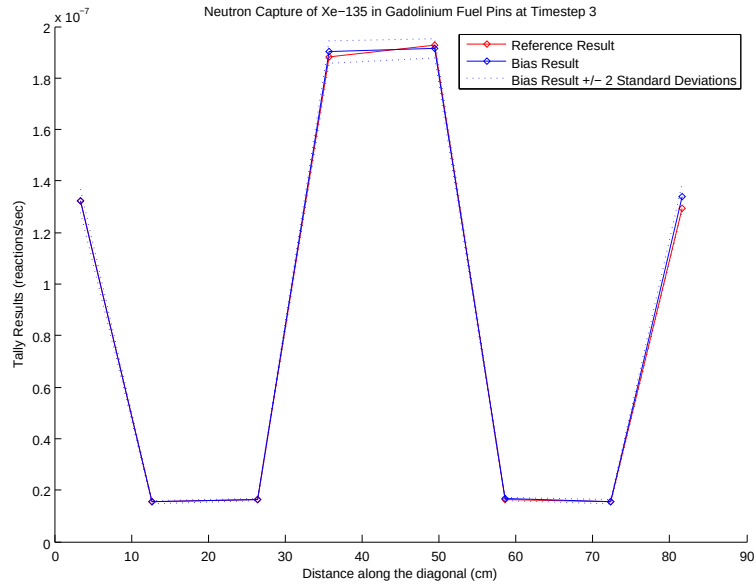


Figure 57: Capture of Xe-135 for timestep 3

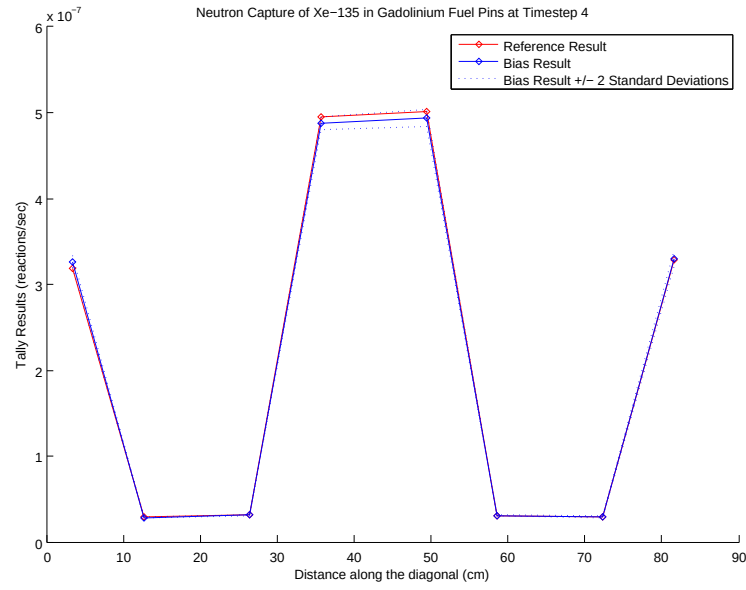


Figure 58: Capture of Xe-135 for timestep 4

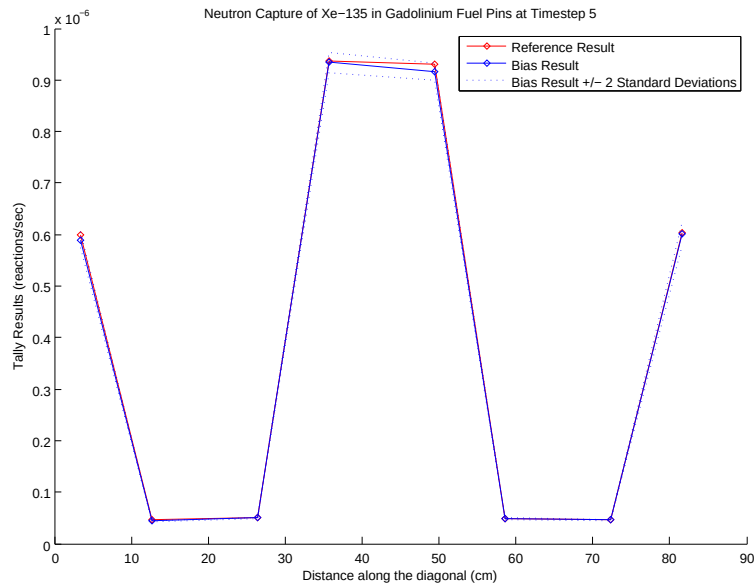


Figure 59: Capture of Xe-135 for timestep 5

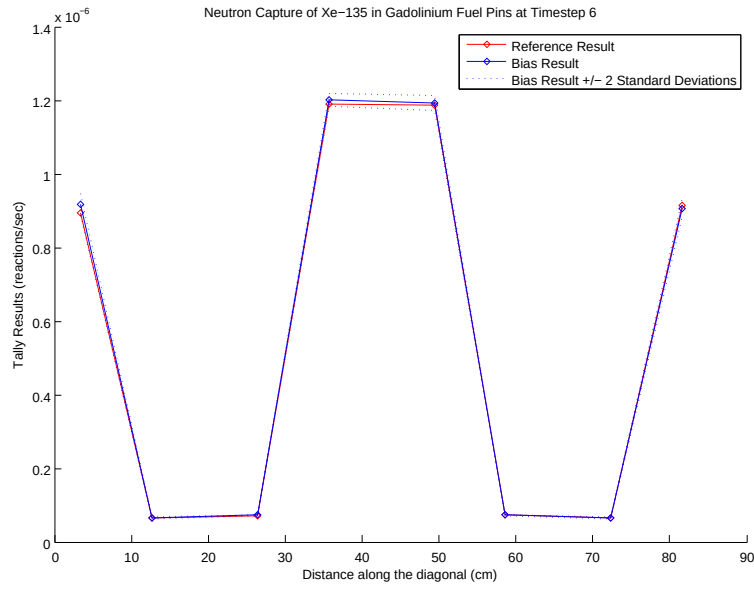


Figure 60: Capture of Xe-135 for timestep 6

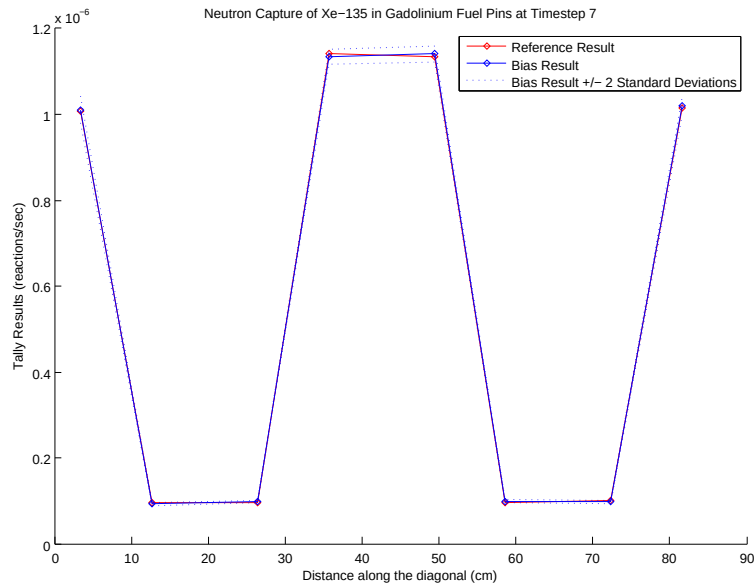


Figure 61: Capture of Xe-135 for timestep 7

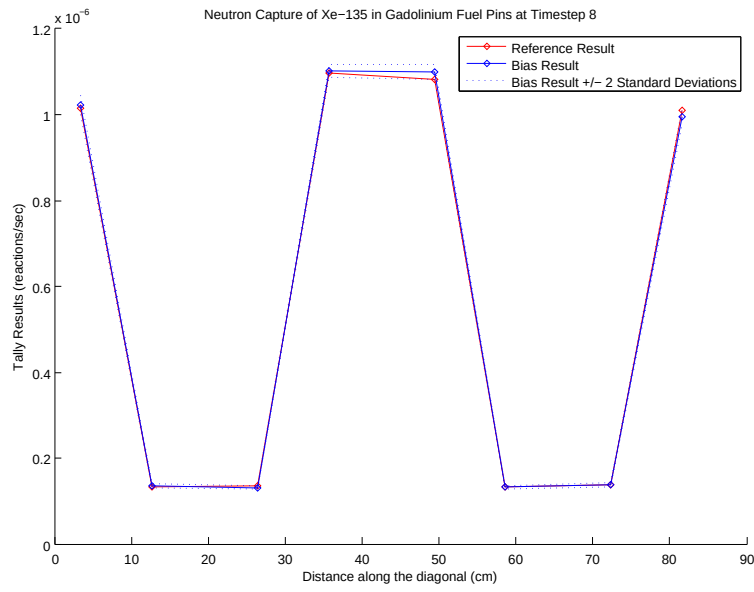


Figure 62: Capture of Xe-135 for timestep 8

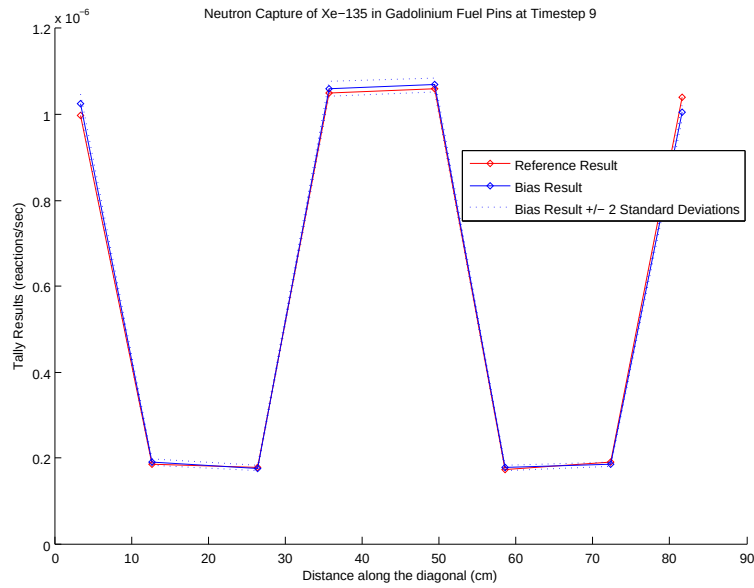


Figure 63: Capture of Xe-135 for timestep 9

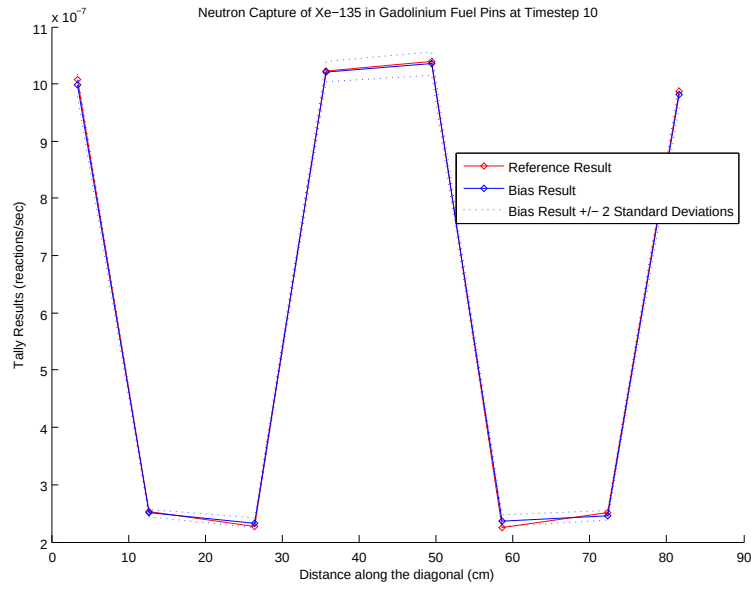


Figure 64: Capture of Xe-135 for timestep 10

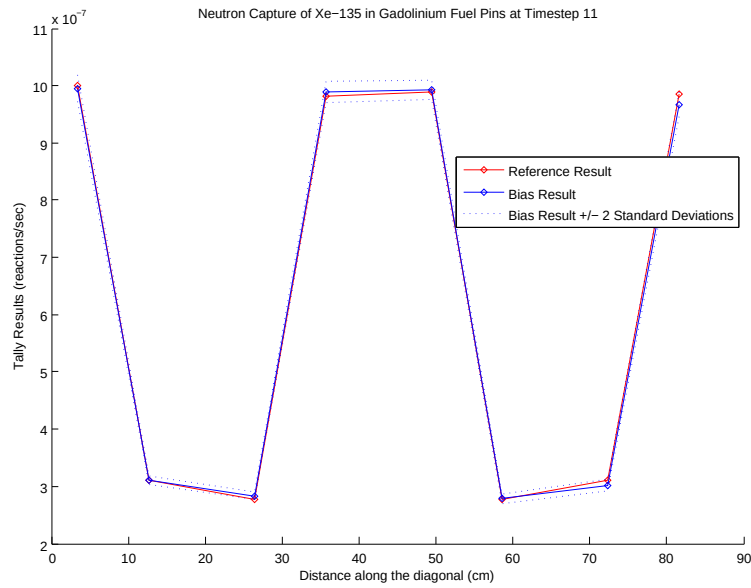


Figure 65: Capture of Xe-135 for timestep 11

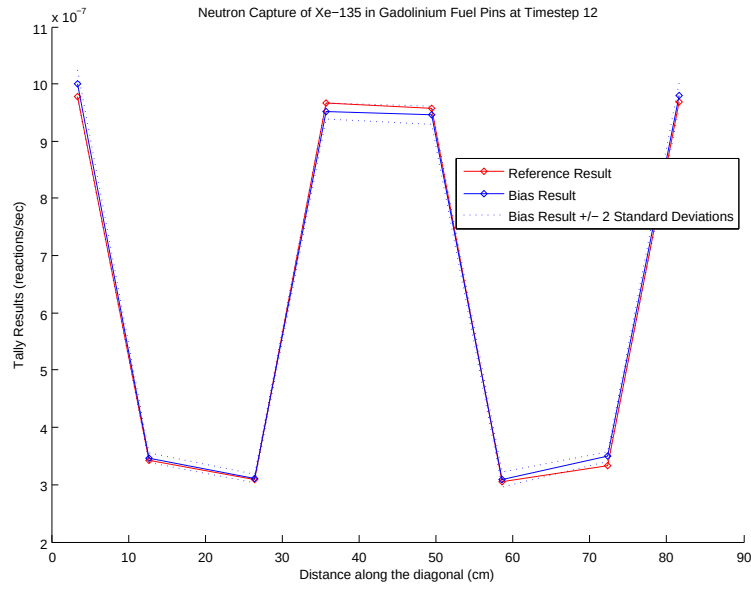


Figure 66: Capture of Xe-135 for timestep 12

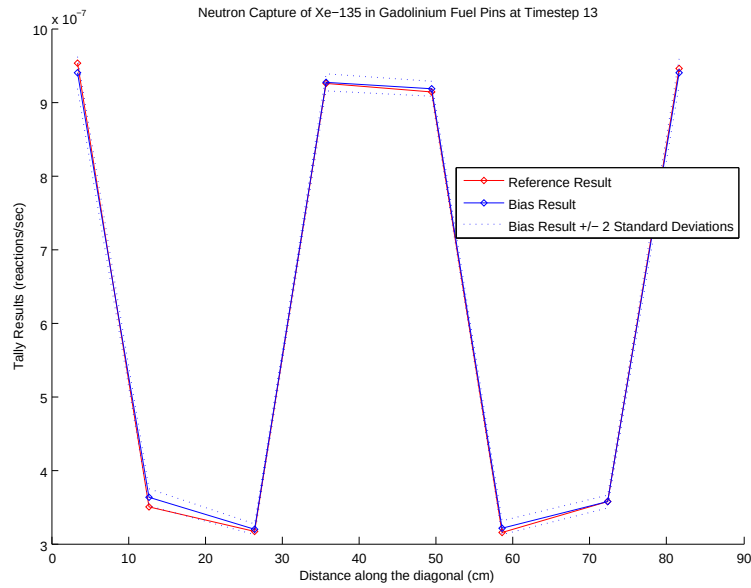


Figure 67: Capture of Xe-135 for timestep 13

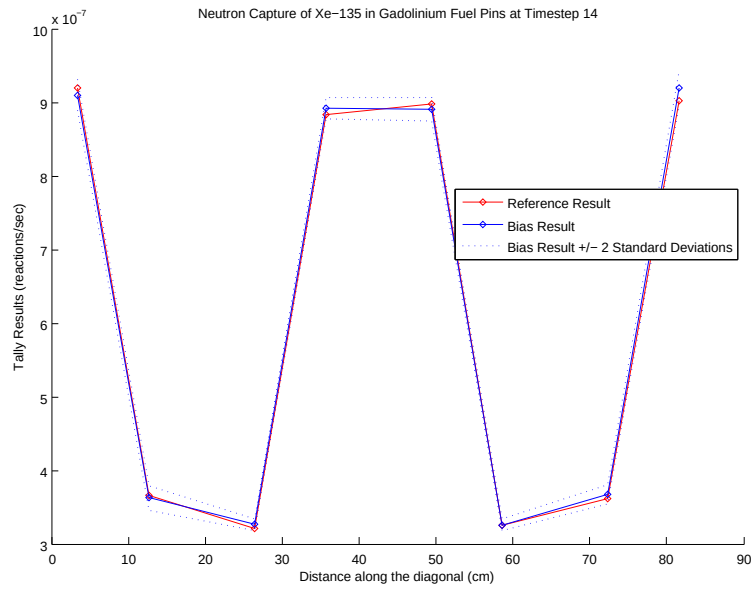


Figure 68: Capture of Xe-135 for timestep 14

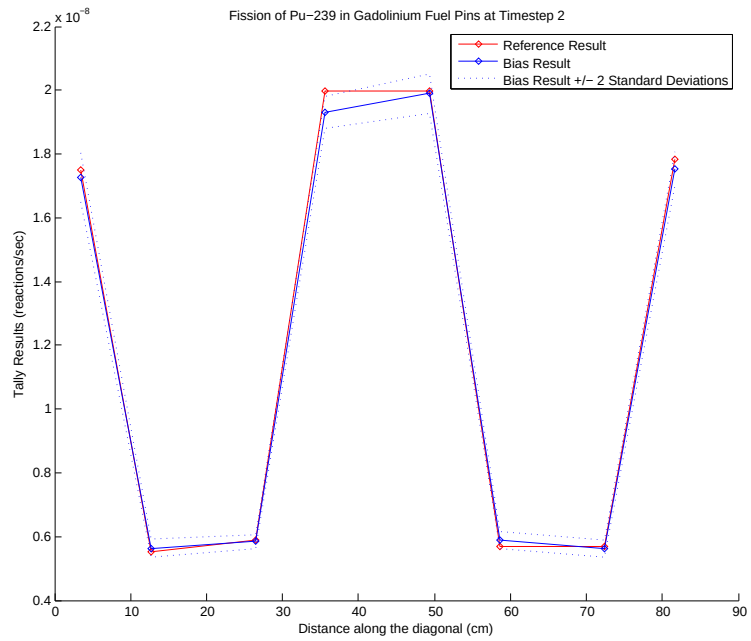


Figure 69: Fission of Pu-239 for timestep 2

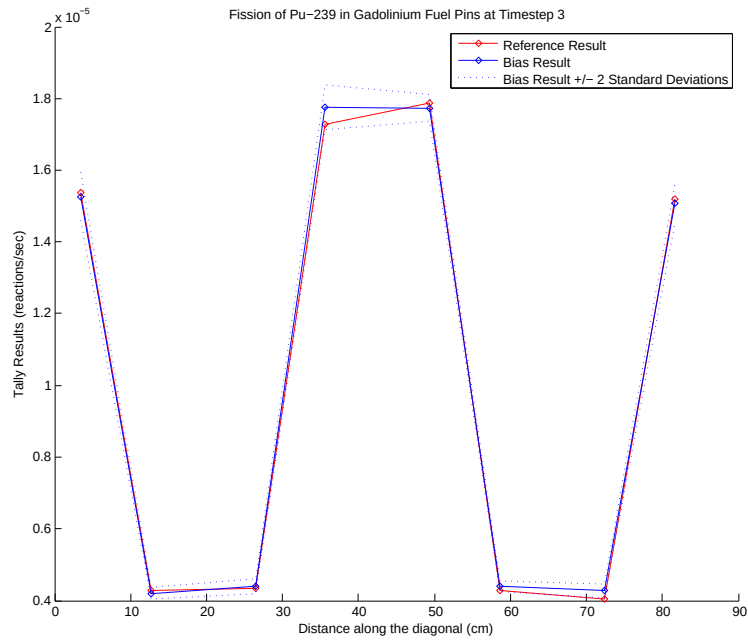


Figure 70: Fission of Pu-239 for timestep 3

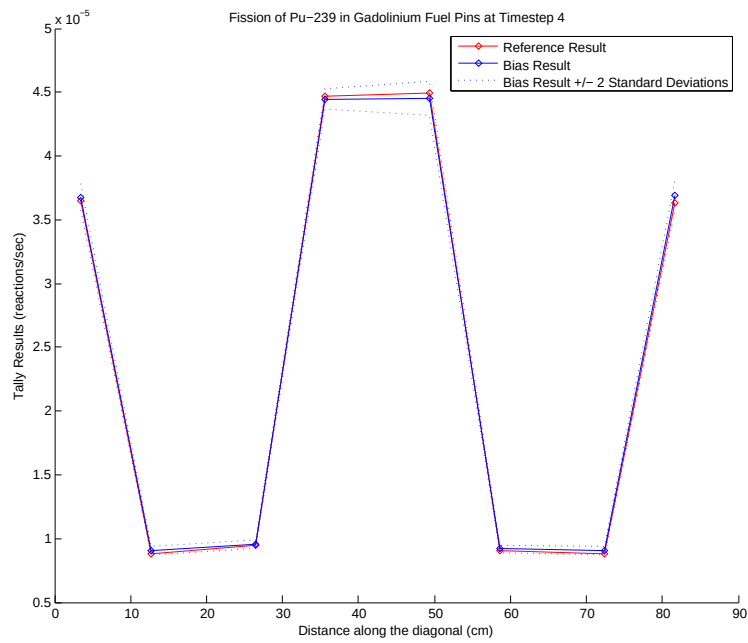


Figure 71: Fission of Pu-239 for timestep 4

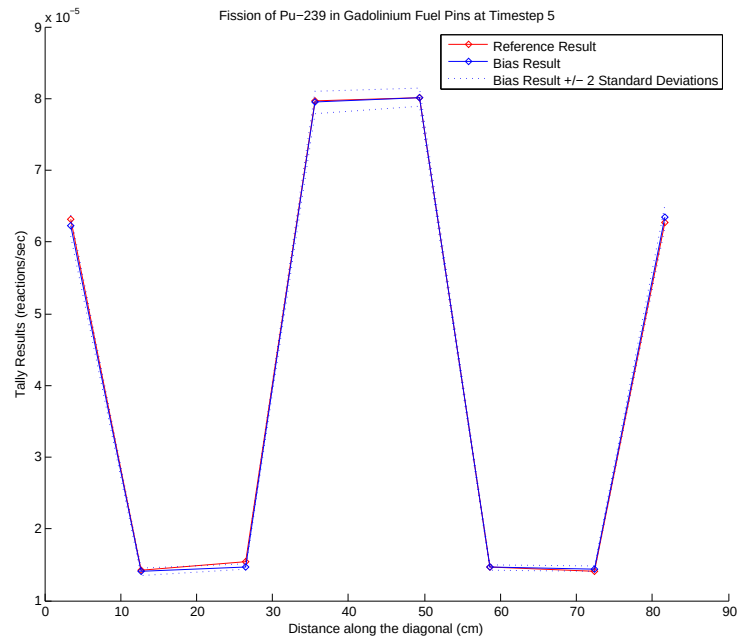


Figure 72: Fission of Pu-239 for timestep 5

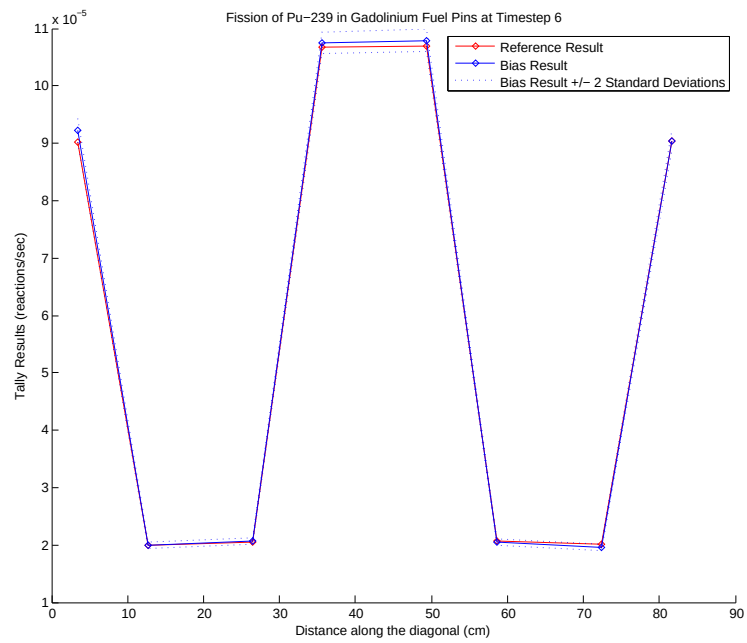


Figure 73: Fission of Pu-239 for timestep 6

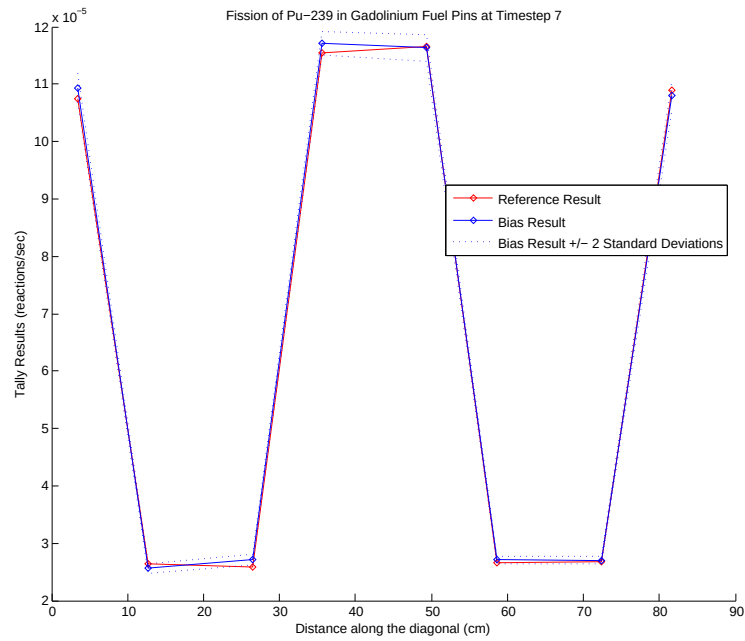


Figure 74: Fission of Pu-239 for timestep 7

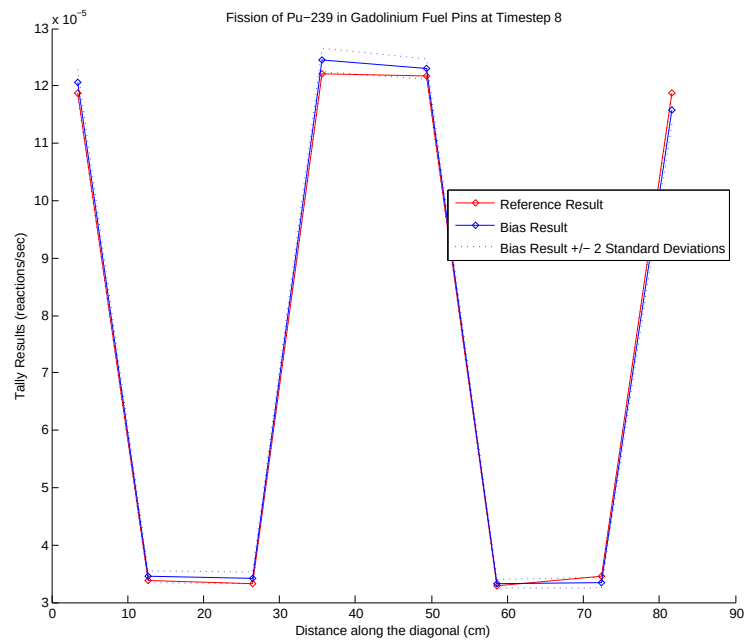


Figure 75: Fission of Pu-239 for timestep 8

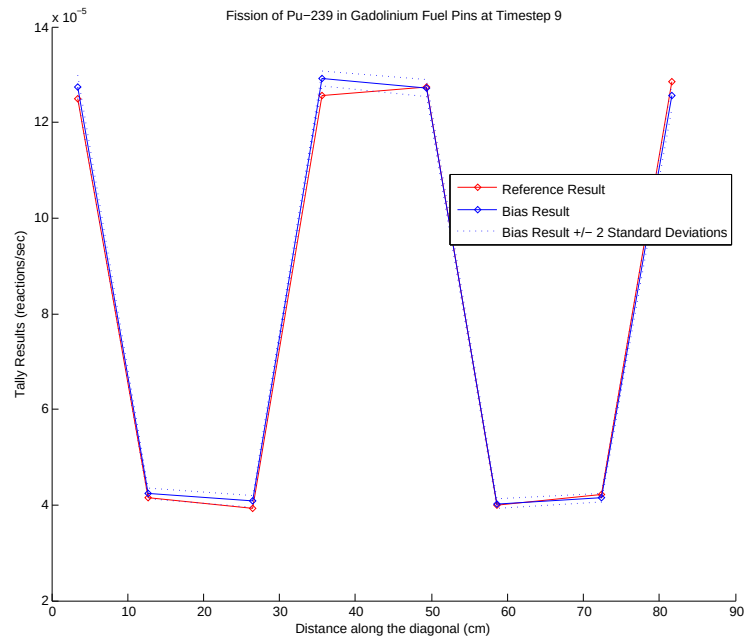


Figure 76: Fission of Pu-239 for timestep 9

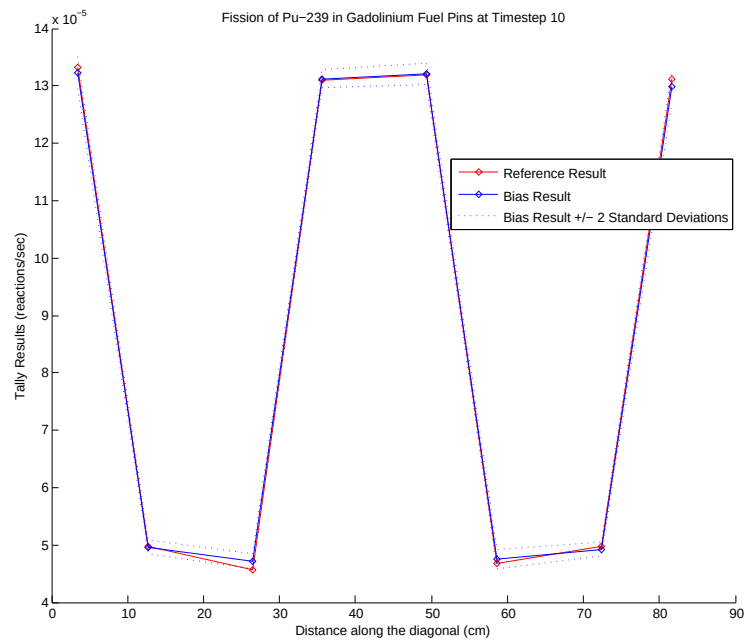


Figure 77: Fission of Pu-239 for timestep 10

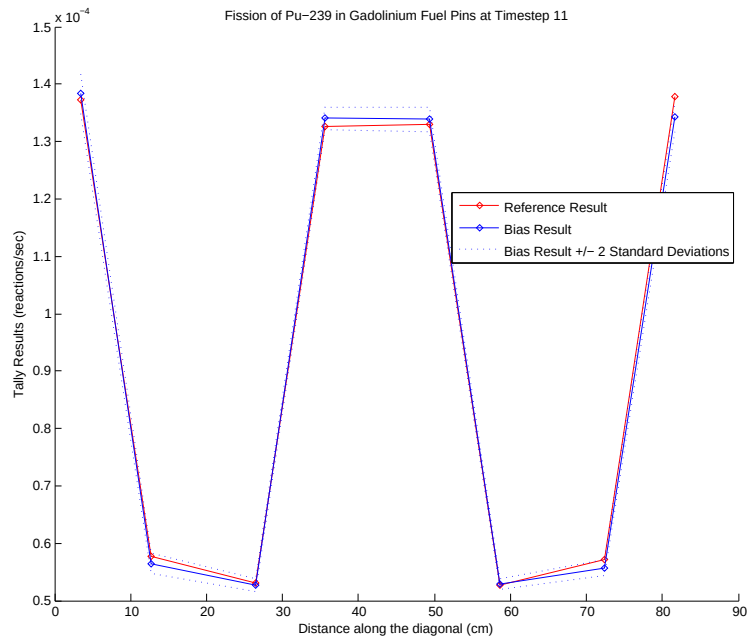


Figure 78: Fission of Pu-239 for timestep 11

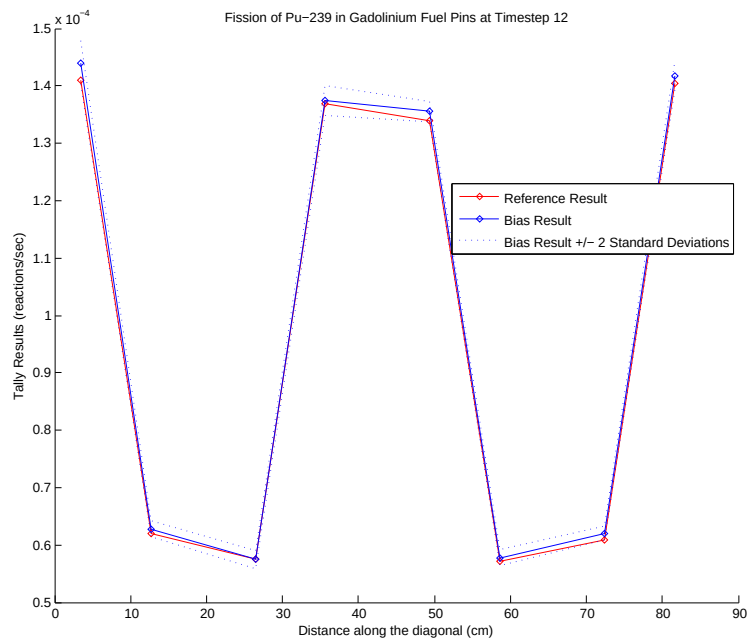


Figure 79: Fission of Pu-239 for timestep 12

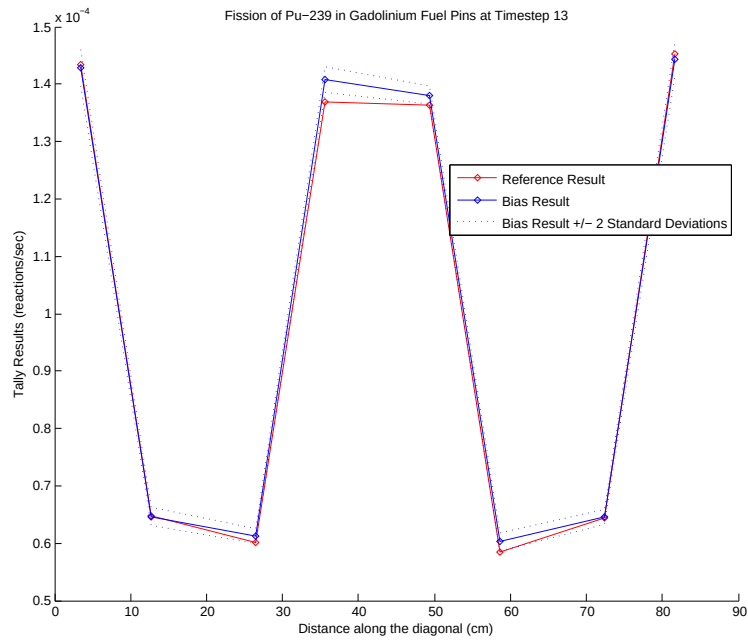


Figure 80: Fission of Pu-239 for timestep 13

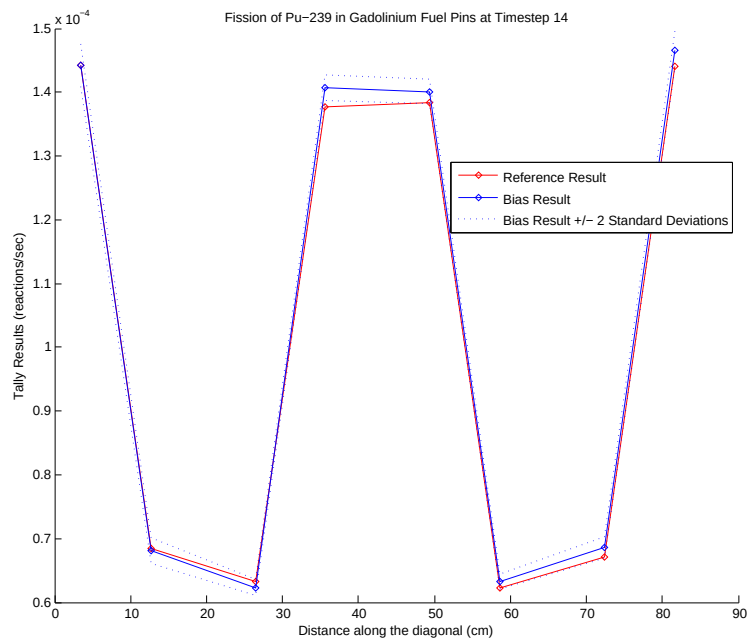


Figure 81: Fission of Pu-239 for timestep 14

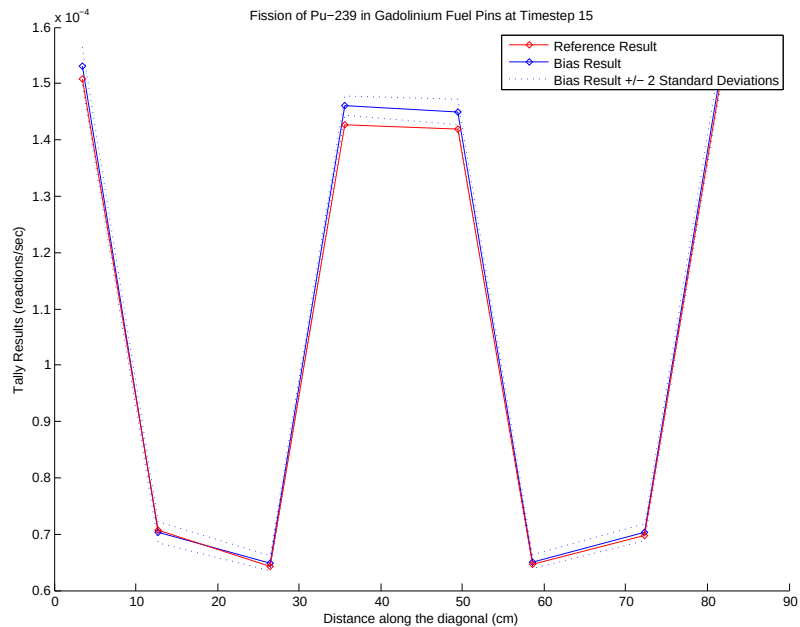


Figure 82: Fission of Pu-239 for timestep 15

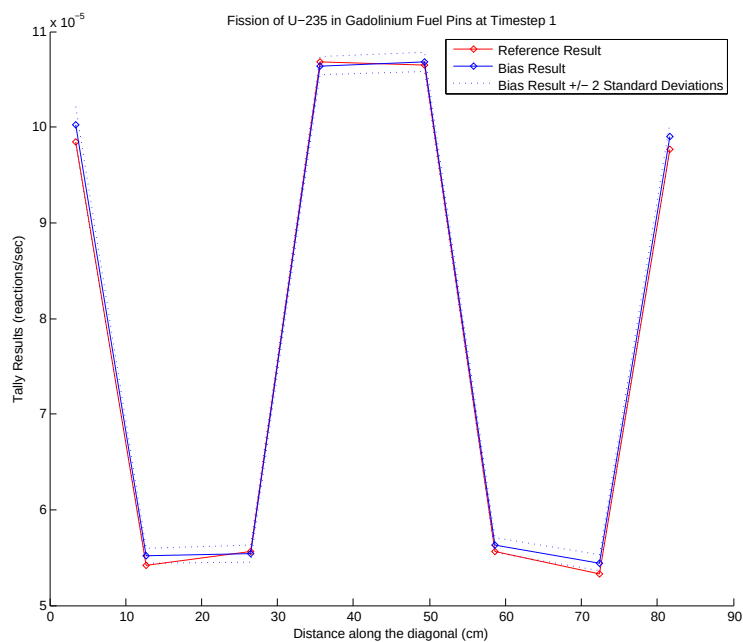


Figure 83: Fission of U-235 for timestep 1

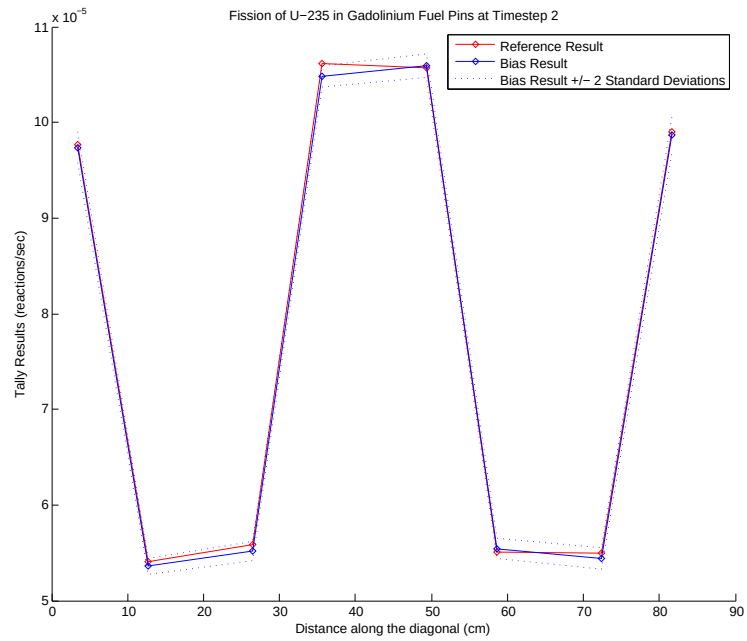


Figure 84: Fission of U-235 for timestep 2

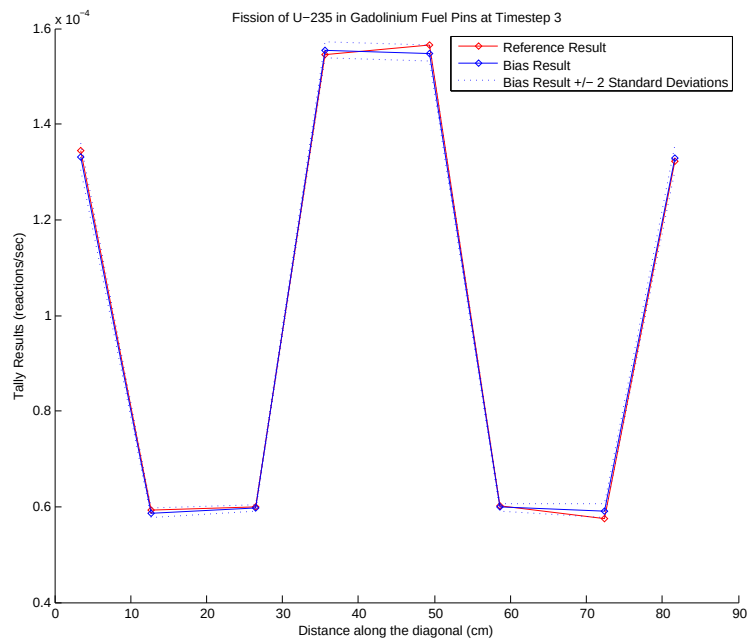


Figure 85: Fission of U-235 for timestep 3

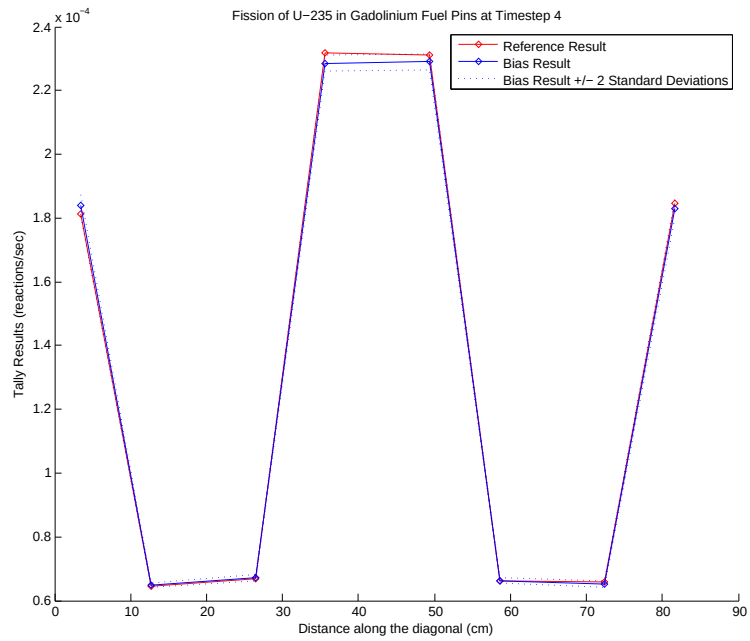


Figure 86: Fission of U-235 for timestep 4

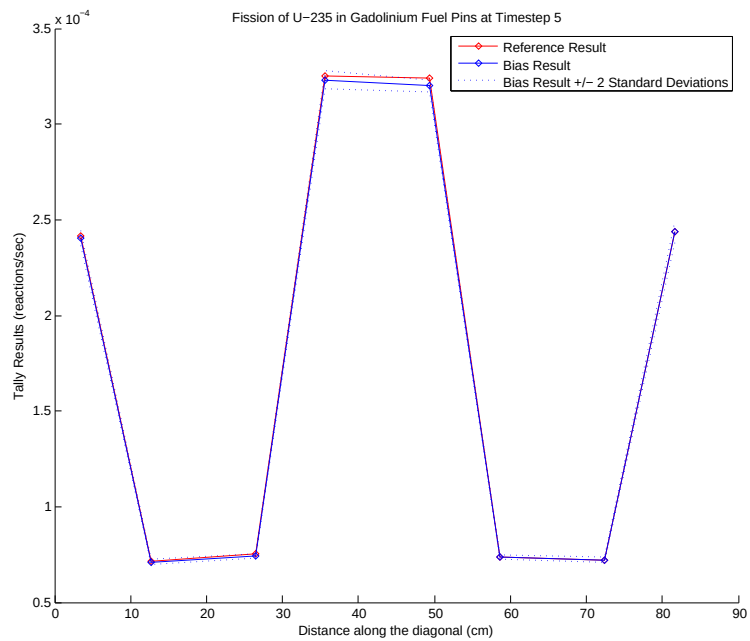


Figure 87: Fission of U-235 for timestep 5

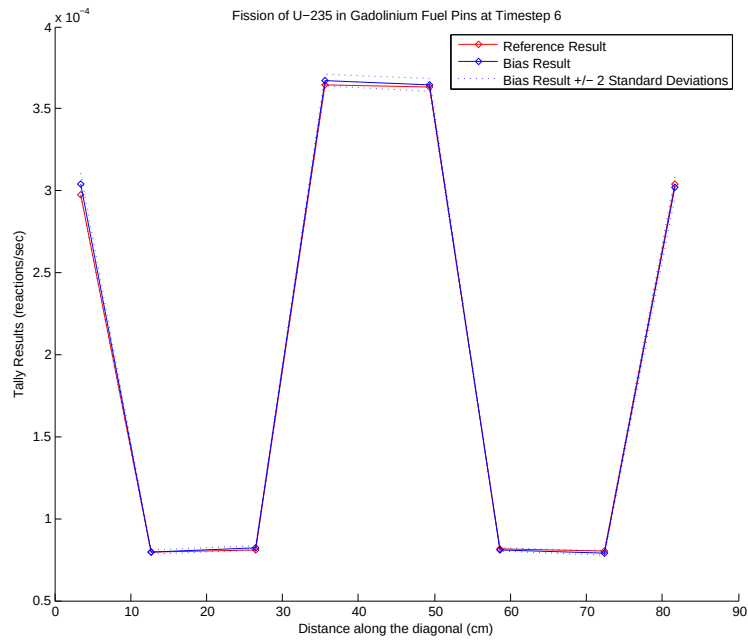


Figure 88: Fission of U-235 for timestep 6

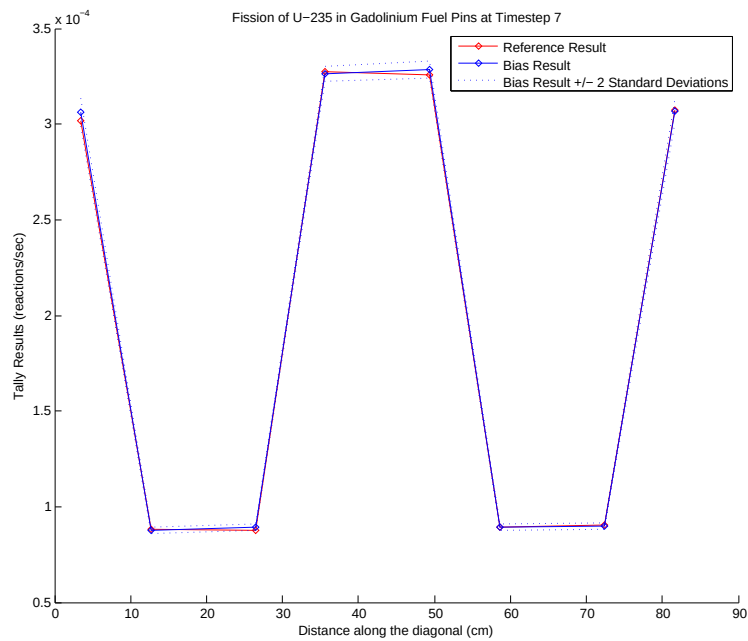


Figure 89: Fission of U-235 for timestep 7

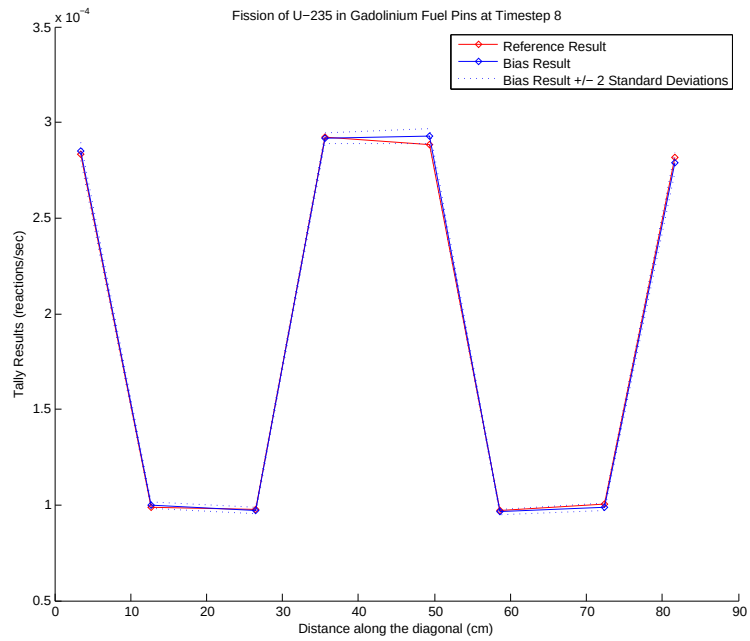


Figure 90: Fission of U-235 for timestep 8

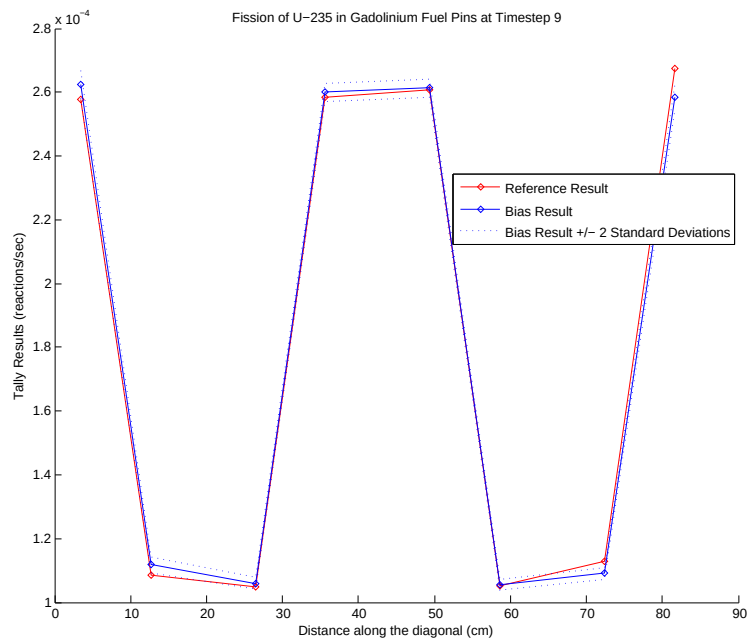


Figure 91: Fission of U-235 for timestep 9

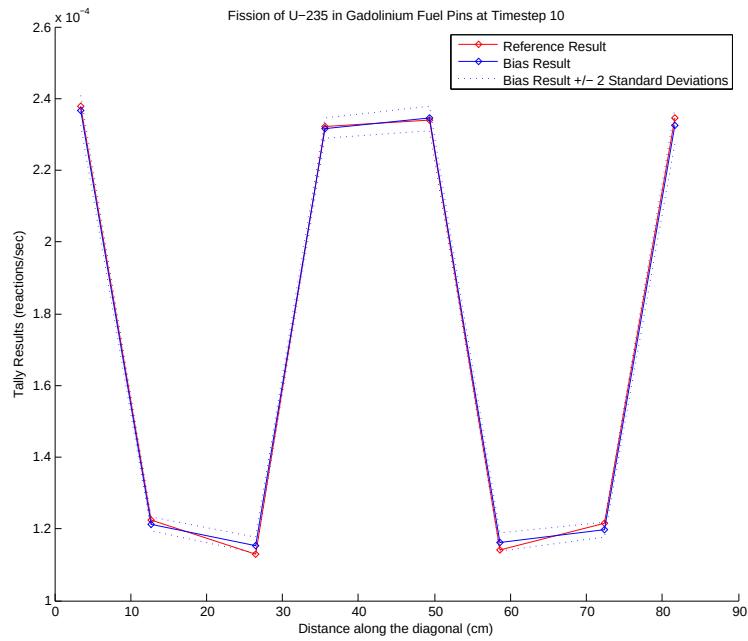


Figure 92: Fission of U-235 for timestep 10

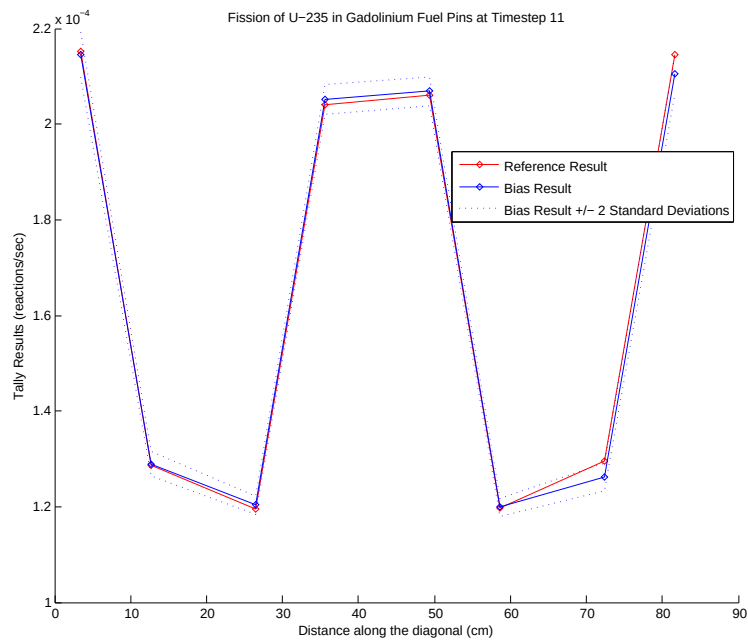


Figure 93: Fission of U-235 for timestep 11

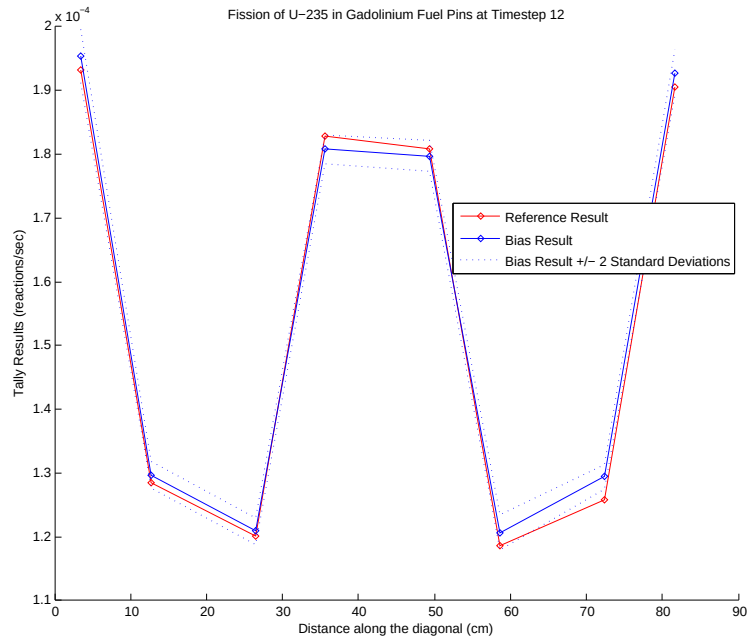


Figure 94: Fission of U-235 for timestep 12

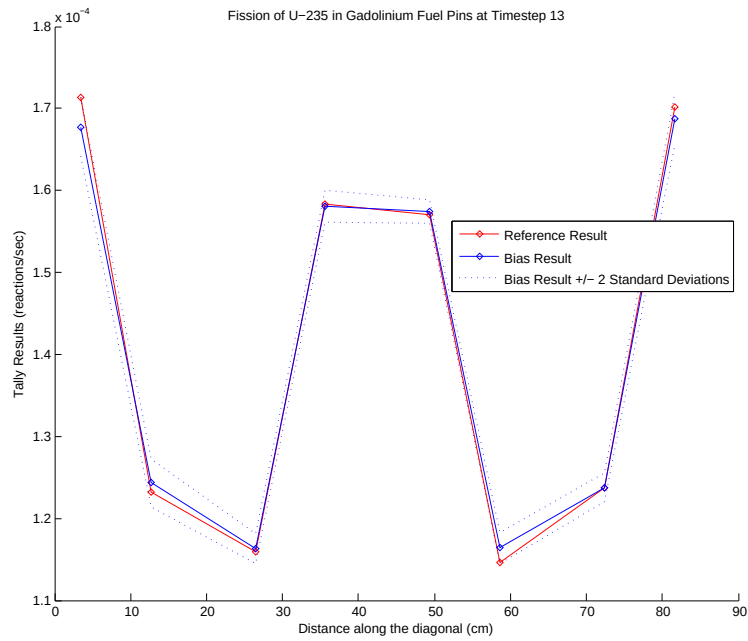


Figure 95: Fission of U-235 for timestep 13

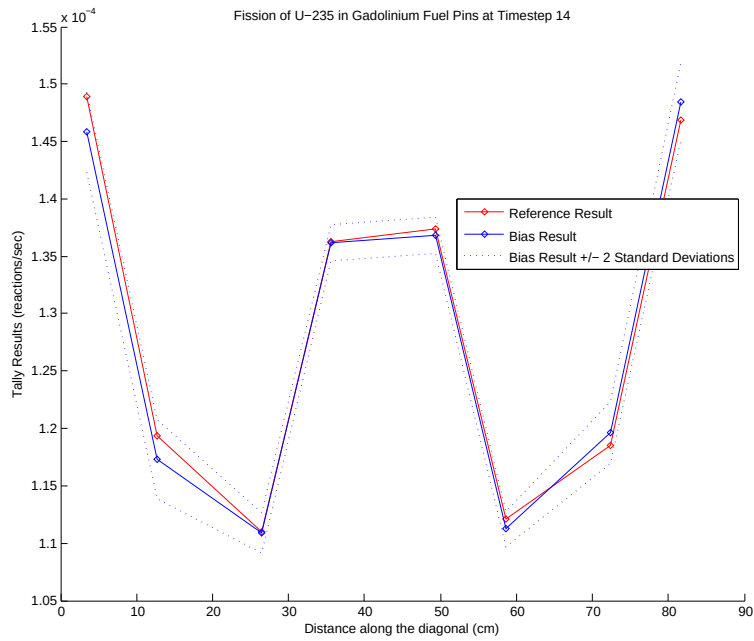


Figure 96: Fission of U-235 for timestep 14

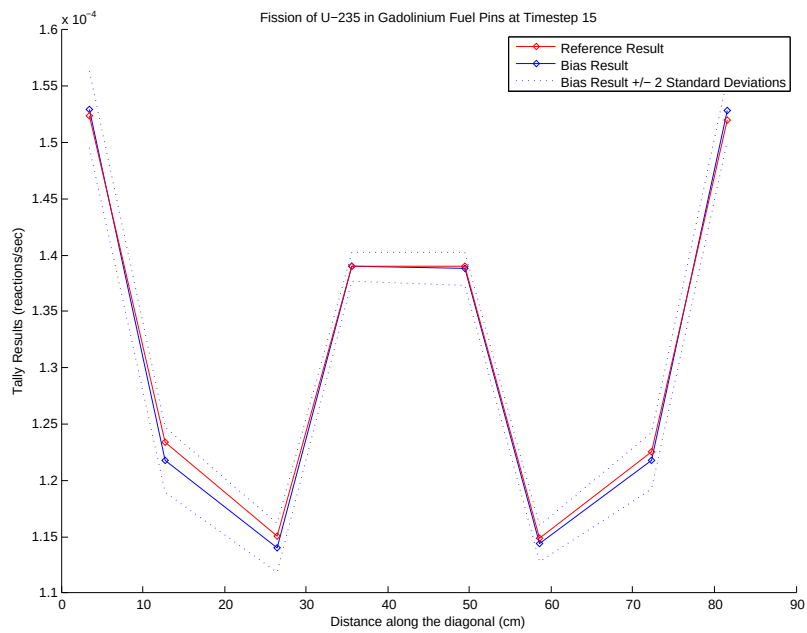


Figure 97: Fission of U-235 for timestep 15

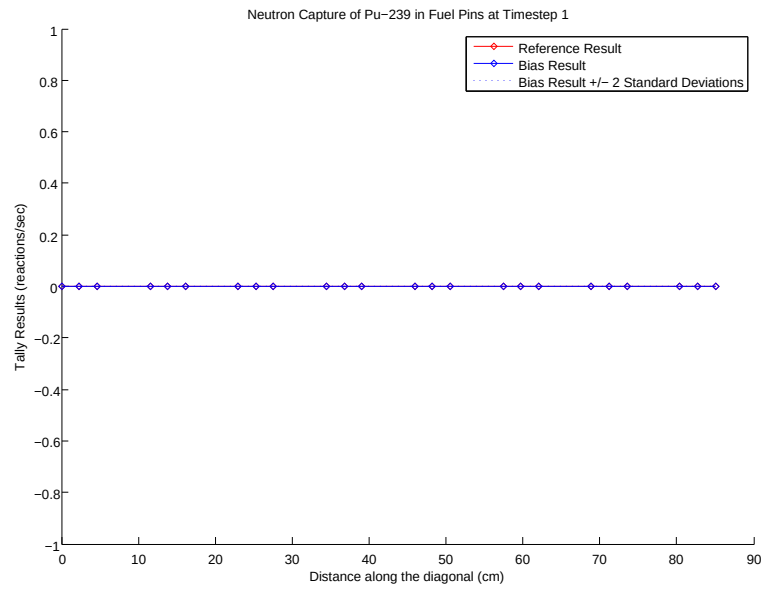


Figure 98: Capture of Pu-239 for timestep 1

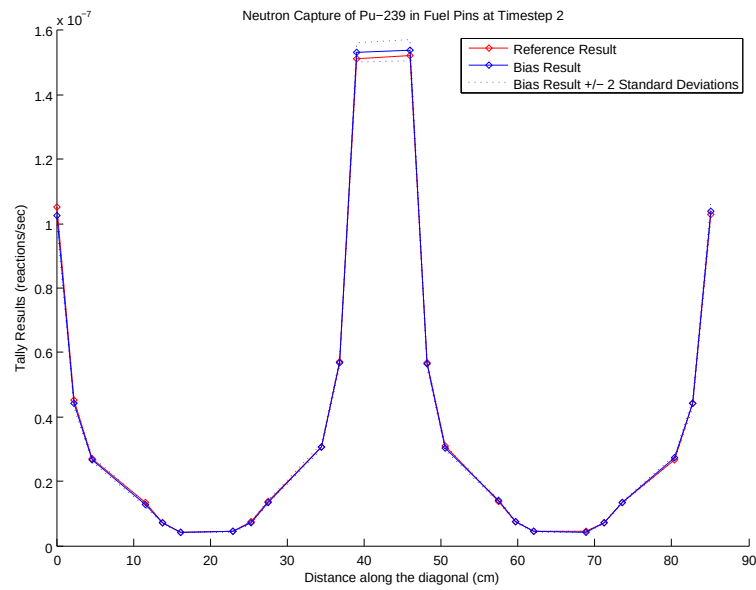


Figure 99: Capture of Pu-239 for timestep 2

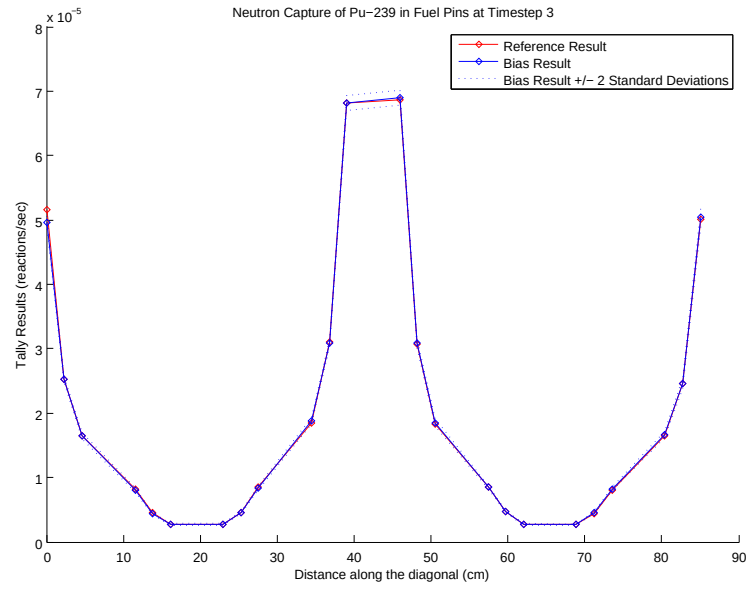


Figure 100: Capture of Pu-239 for timestep 3

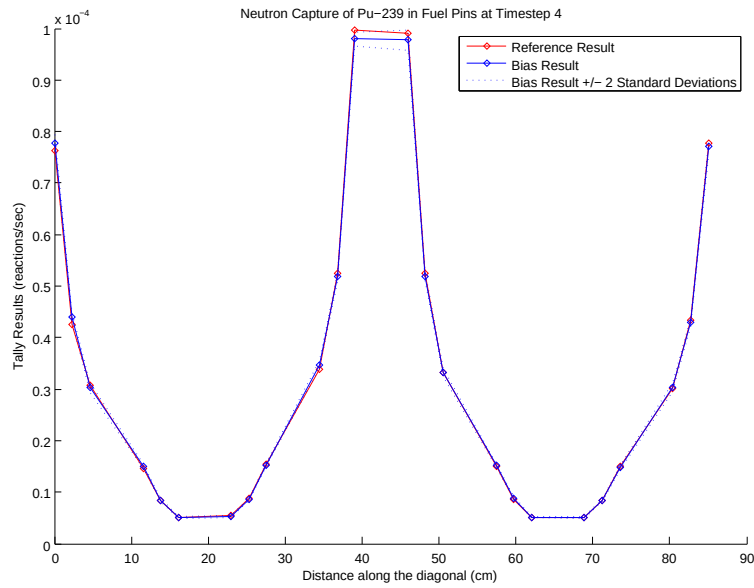


Figure 101: Capture of Pu-239 for timestep 4

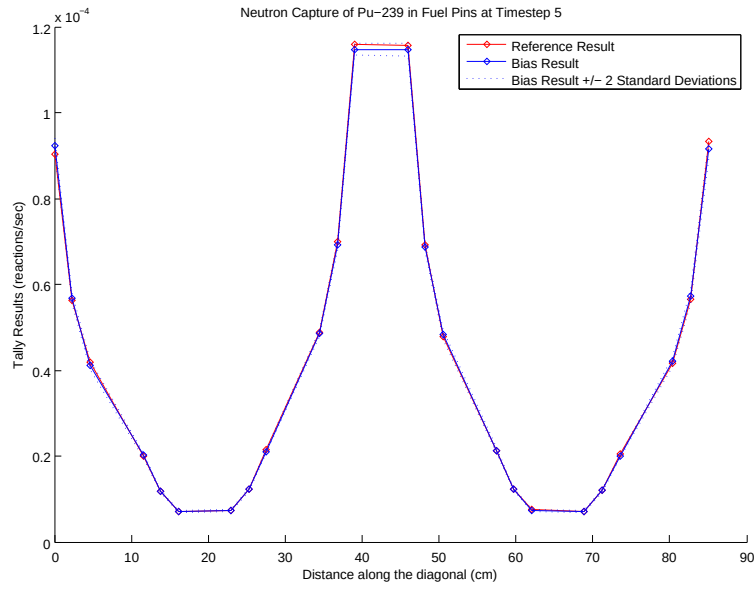


Figure 102: Capture of Pu-239 for timestep 5

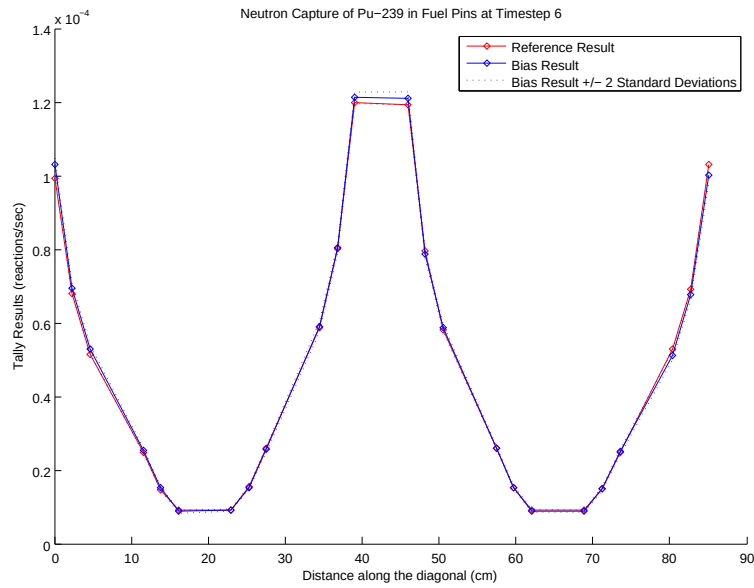


Figure 103: Capture of Pu-239 for timestep 6

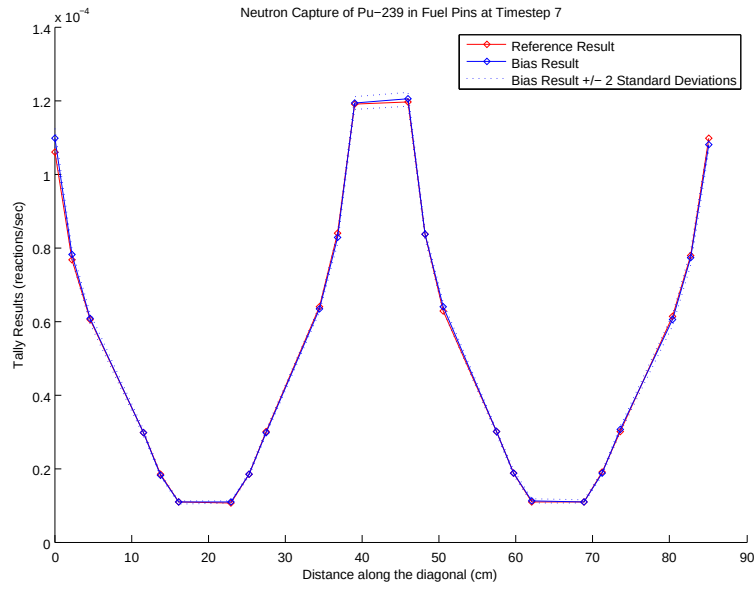


Figure 104: Capture of Pu-239 for timestep 7

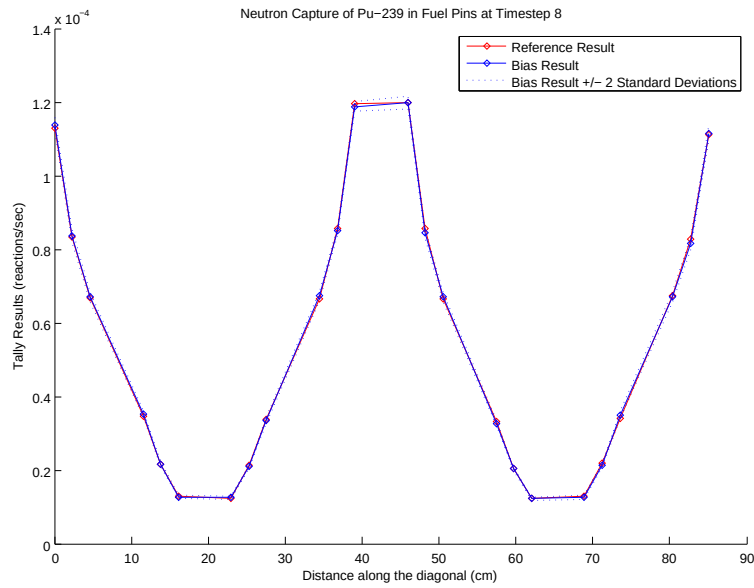


Figure 105: Capture of Pu-239 for timestep 8

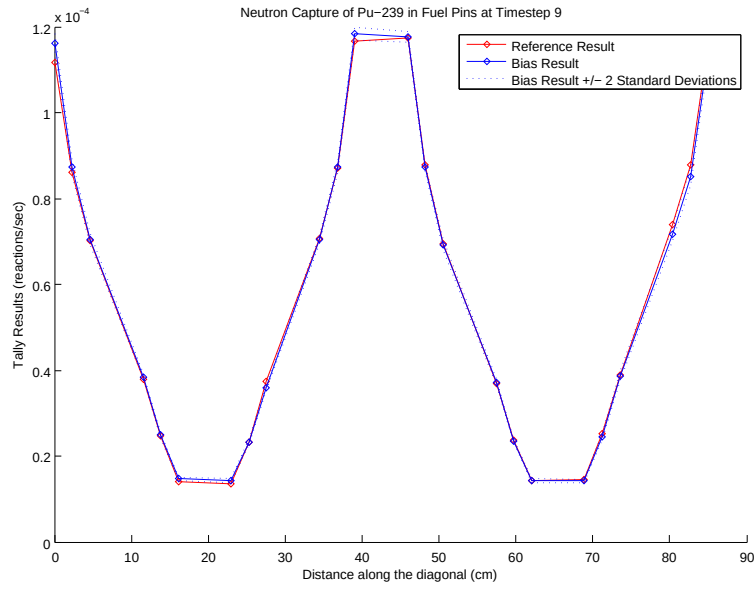


Figure 106: Capture of Pu-239 for timestep 9

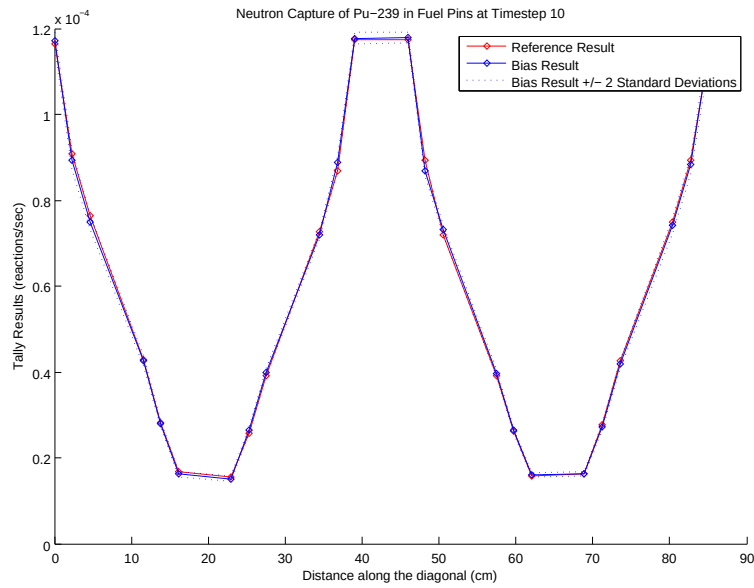


Figure 107: Capture of Pu-239 for timestep 10

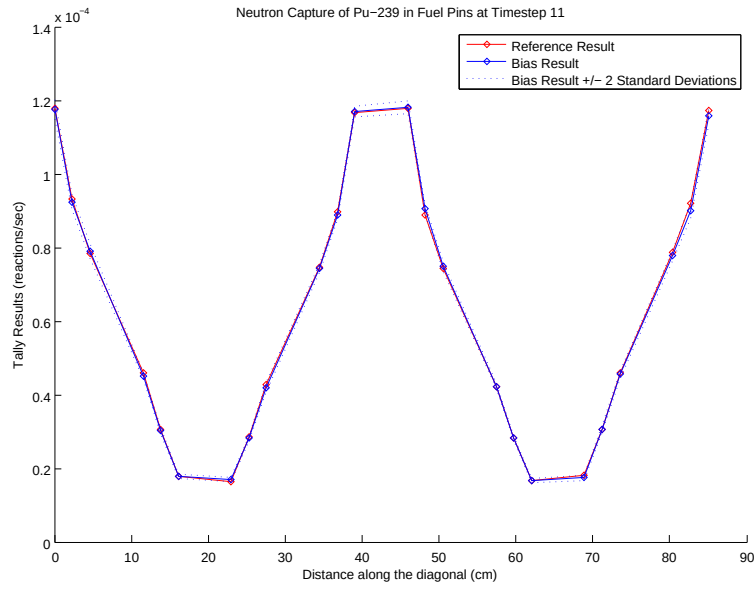


Figure 108: Capture of Pu-239 for timestep 11

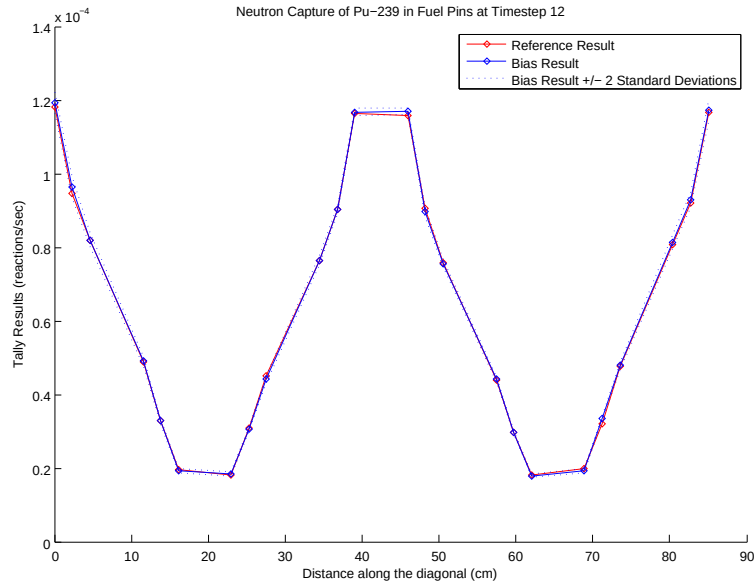


Figure 109: Capture of Pu-239 for timestep 12

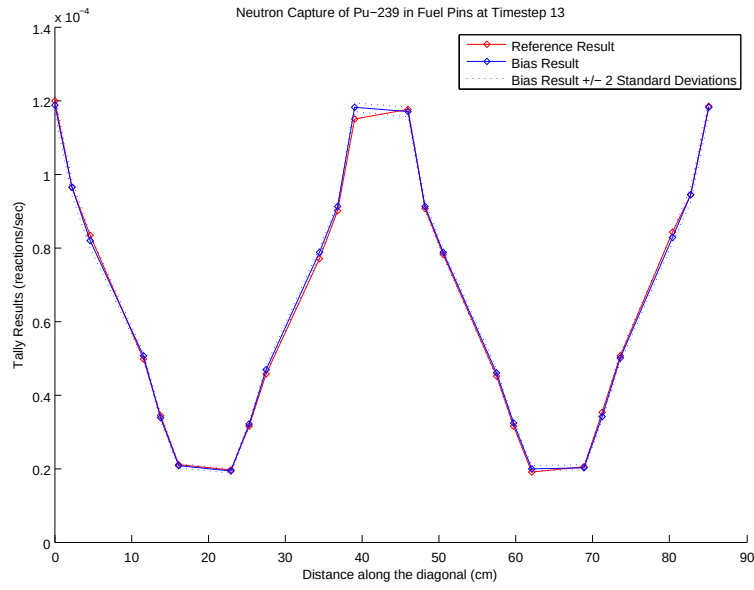


Figure 110: Capture of Pu-239 for timestep 13

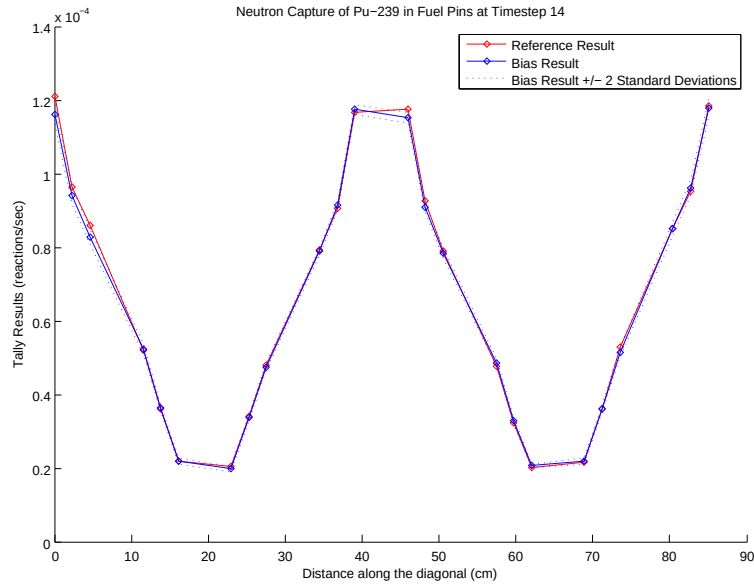


Figure 111: Capture of Pu-239 for timestep 14

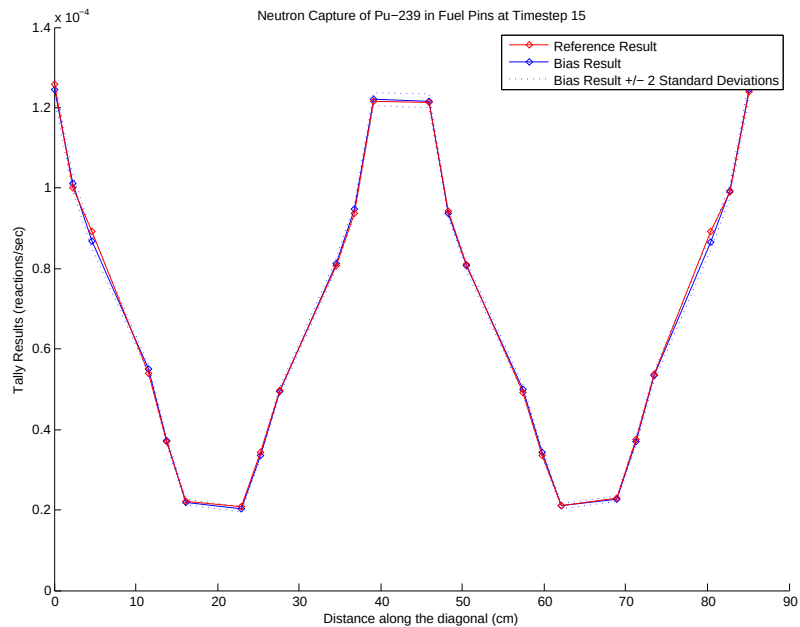


Figure 112: Capture of Pu-239 for timestep 15

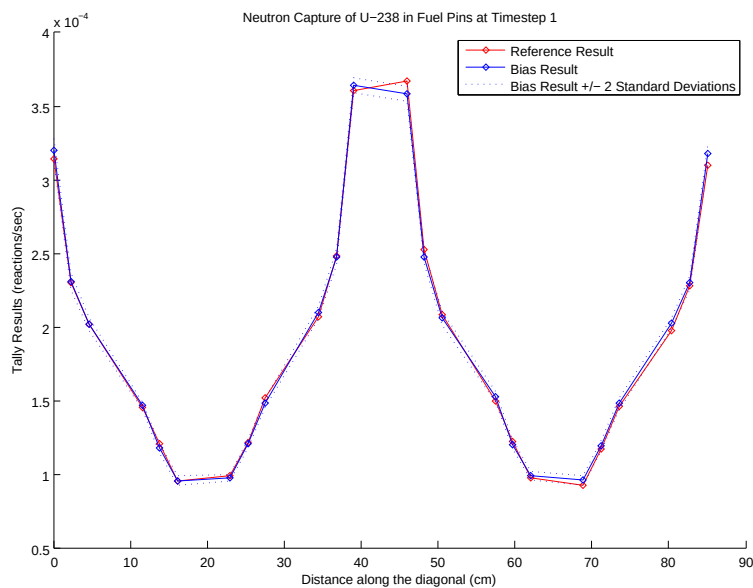


Figure 113: Capture of U-238 for timestep 1

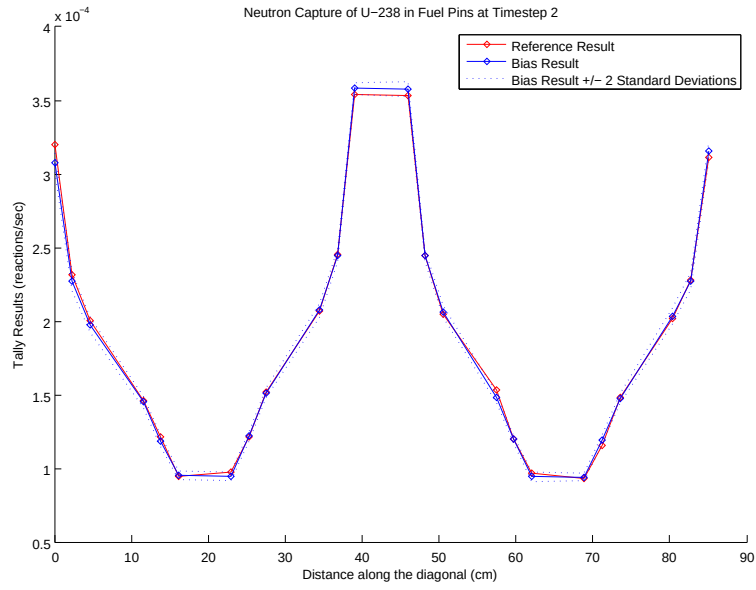


Figure 114: Capture of U-238 for timestep 2

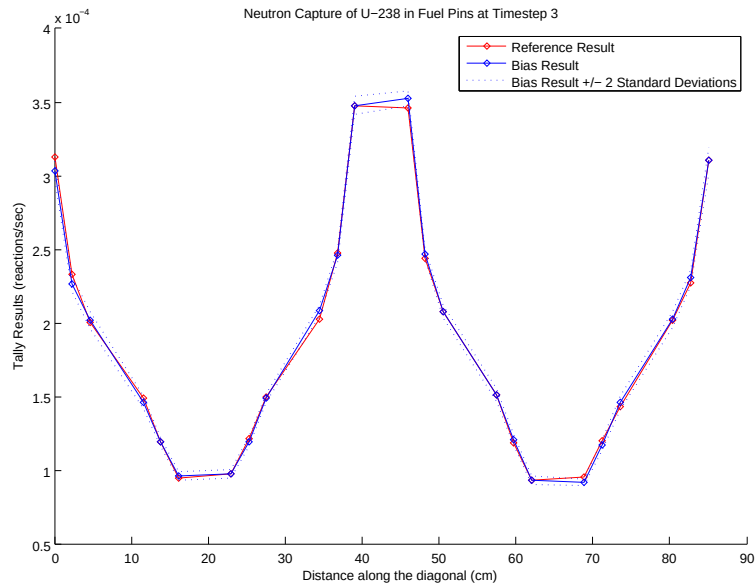


Figure 115: Capture of U-238 for timestep 3

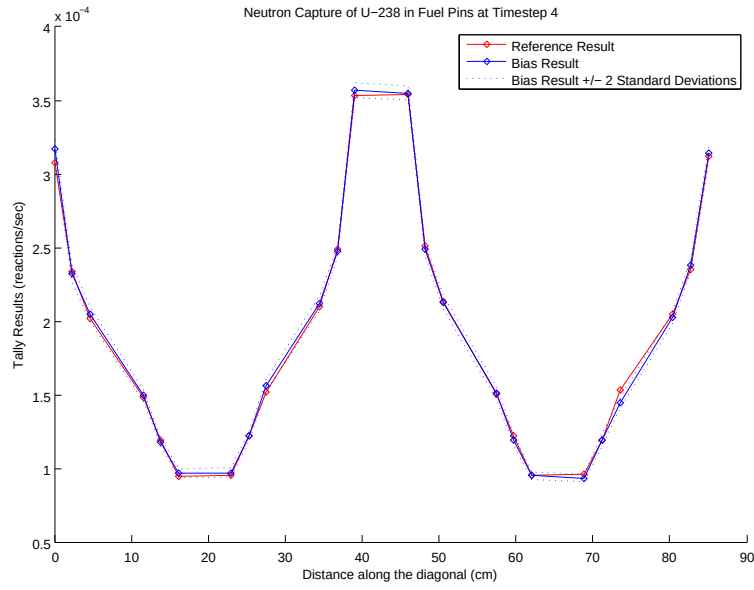


Figure 116: Capture of U-238 for timestep 4

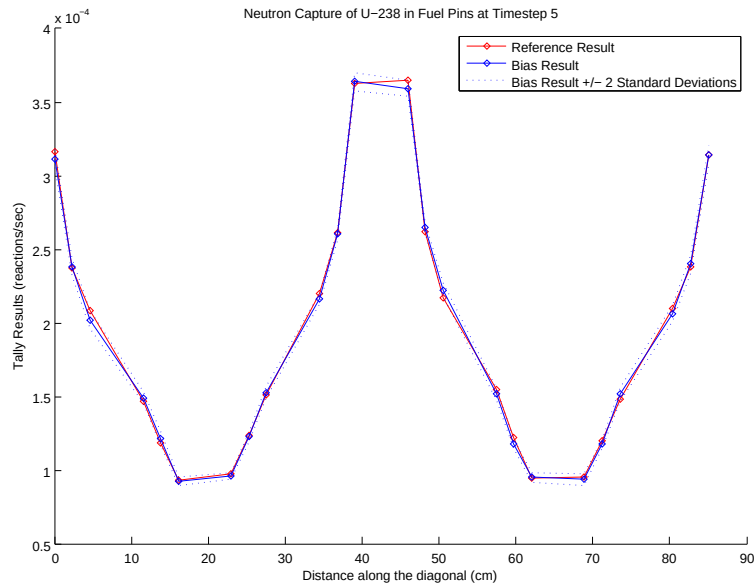


Figure 117: Capture of U-238 for timestep 5

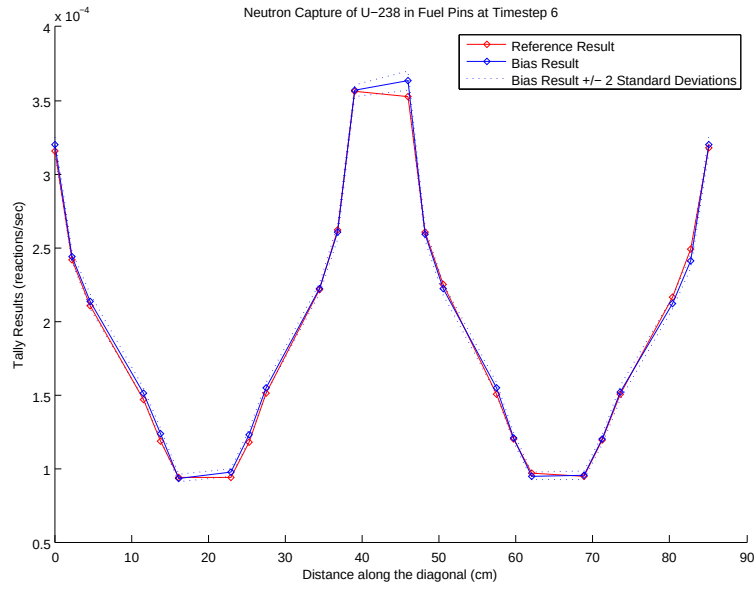


Figure 118: Capture of U-238 for timestep 6

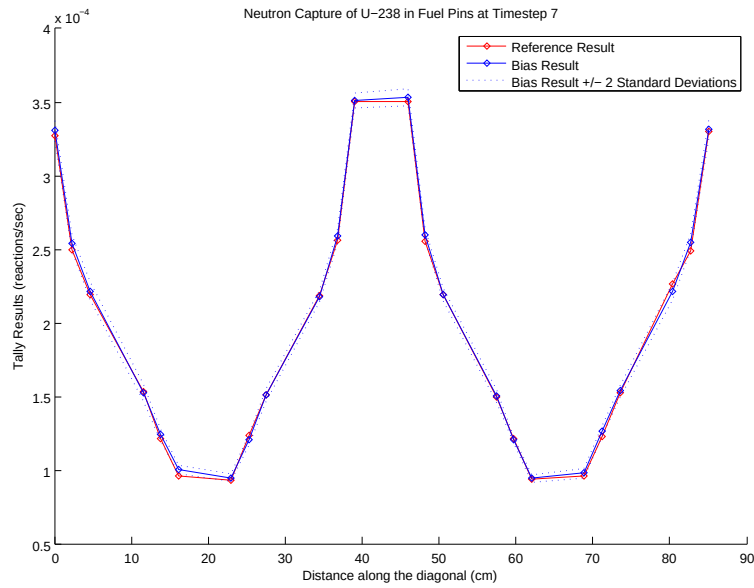


Figure 119: Capture of U-238 for timestep 7

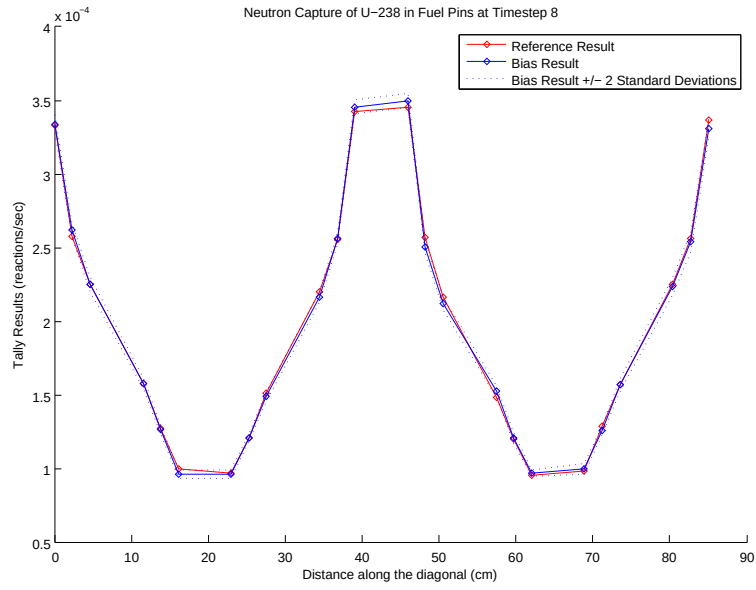


Figure 120: Capture of U-238 for timestep 8

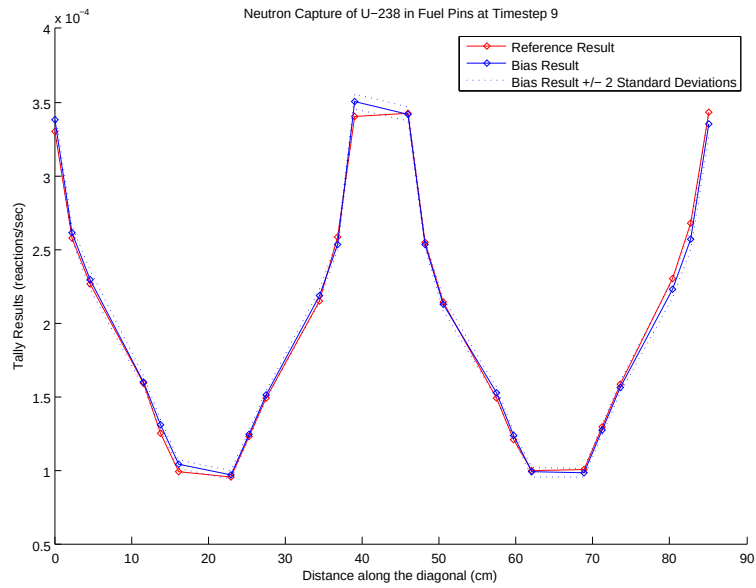


Figure 121: Capture of U-238 for timestep 9

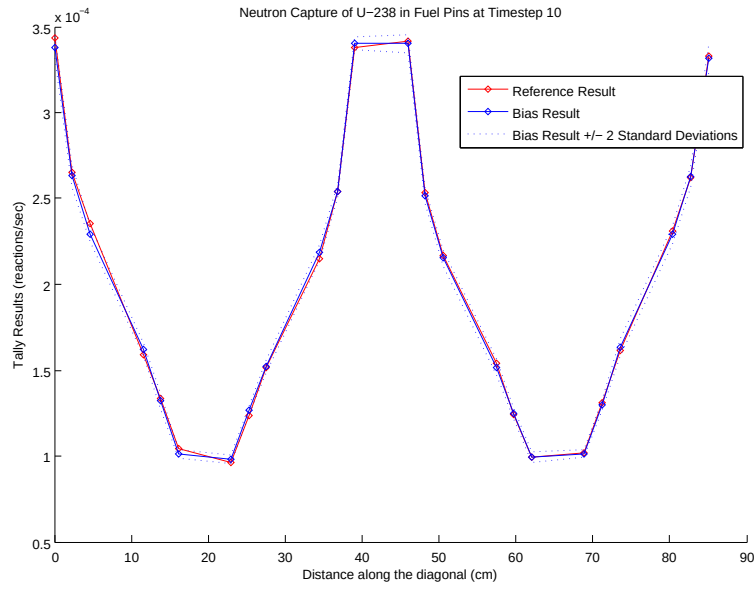


Figure 122: Capture of U-238 for timestep 10

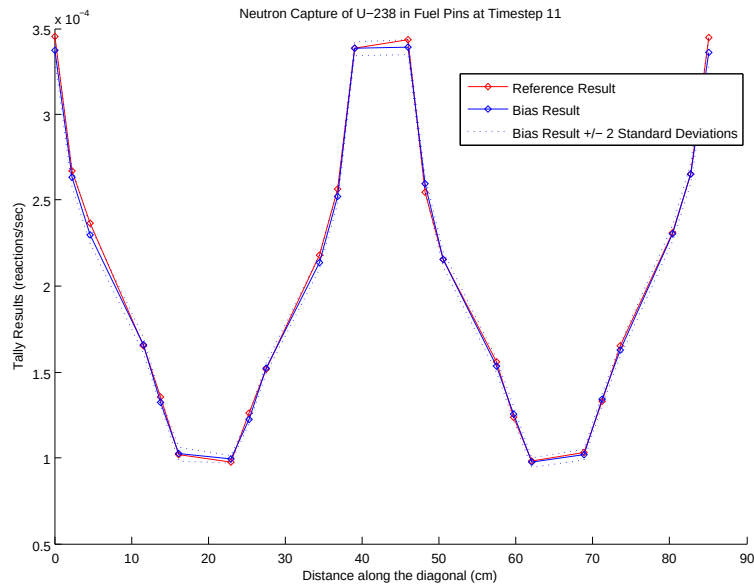


Figure 123: Capture of U-238 for timestep 11

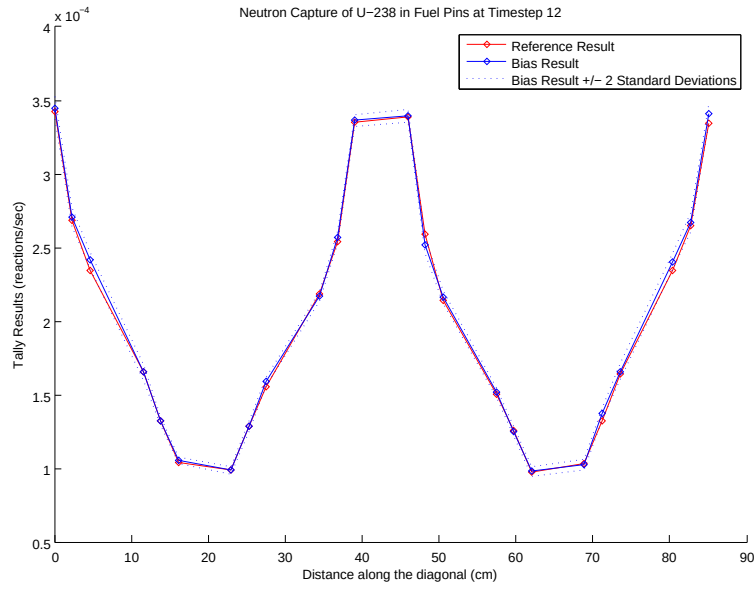


Figure 124: Capture of U-238 for timestep 12

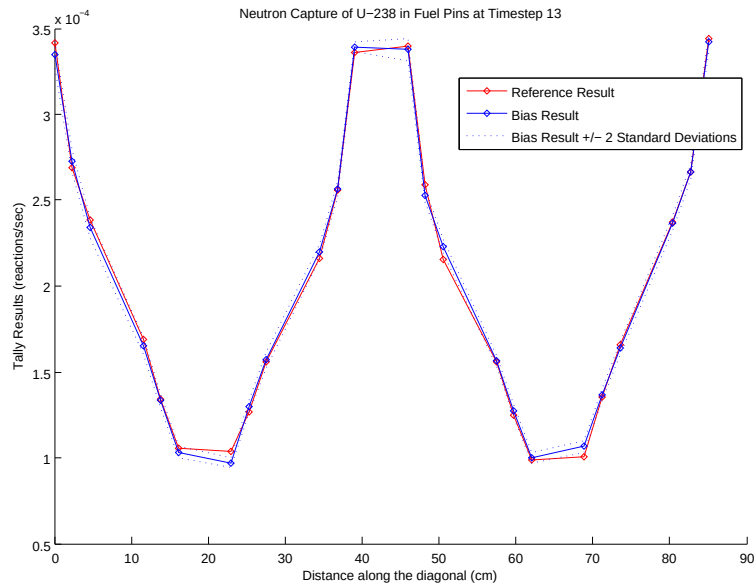


Figure 125: Capture of U-238 for timestep 13

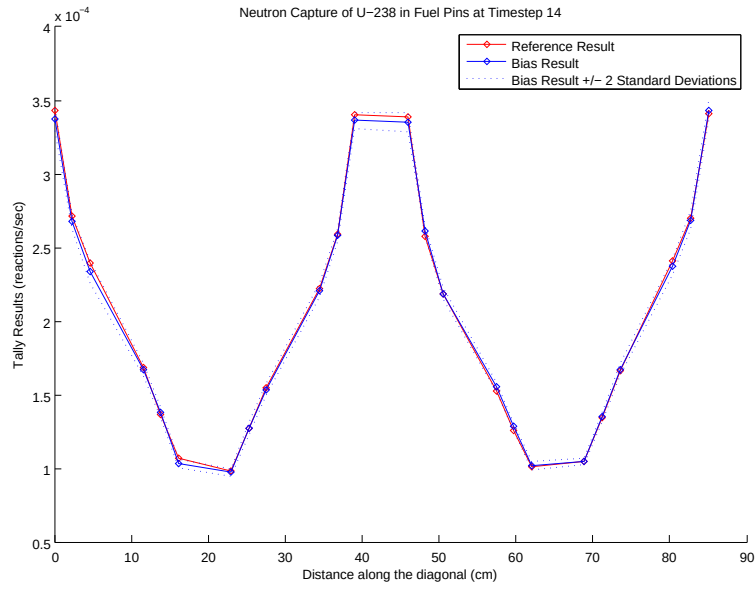


Figure 126: Capture of U-238 for timestep 14

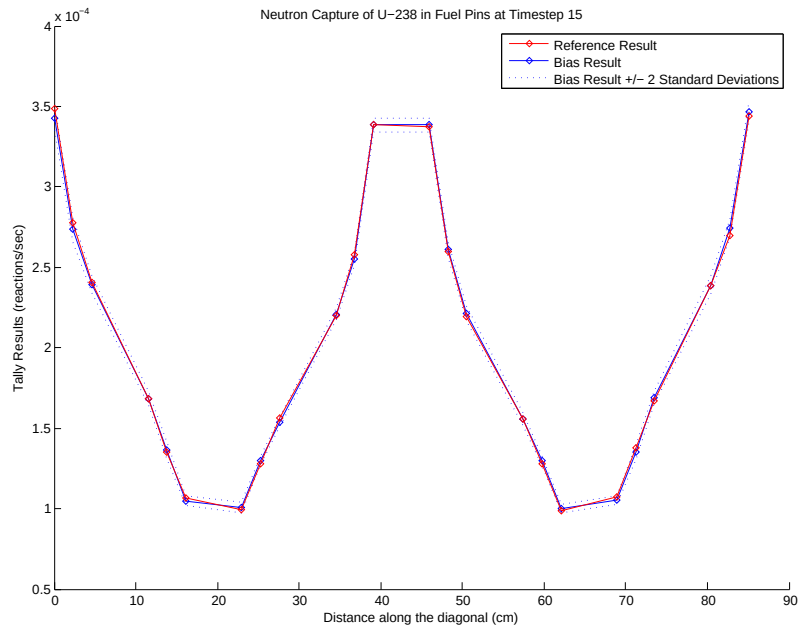


Figure 127: Capture of U-238 for timestep 15

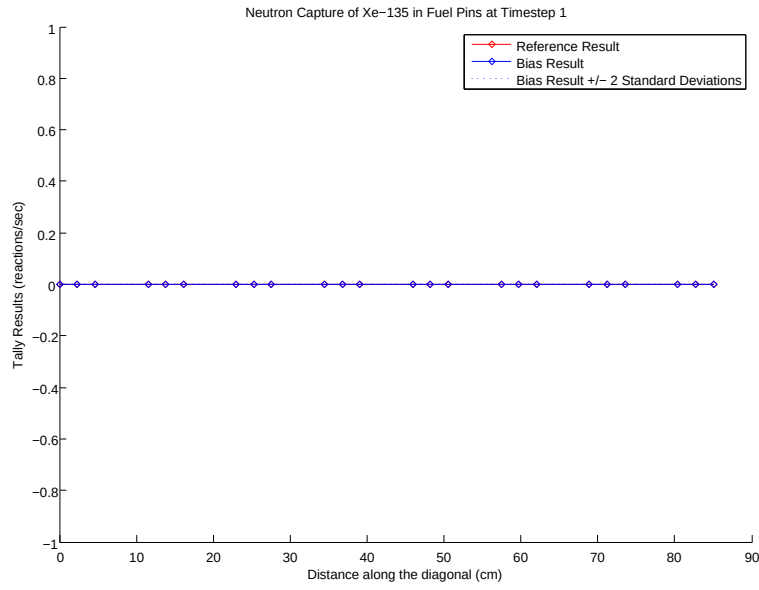


Figure 128: Capture of Xe-135 for timestep 1

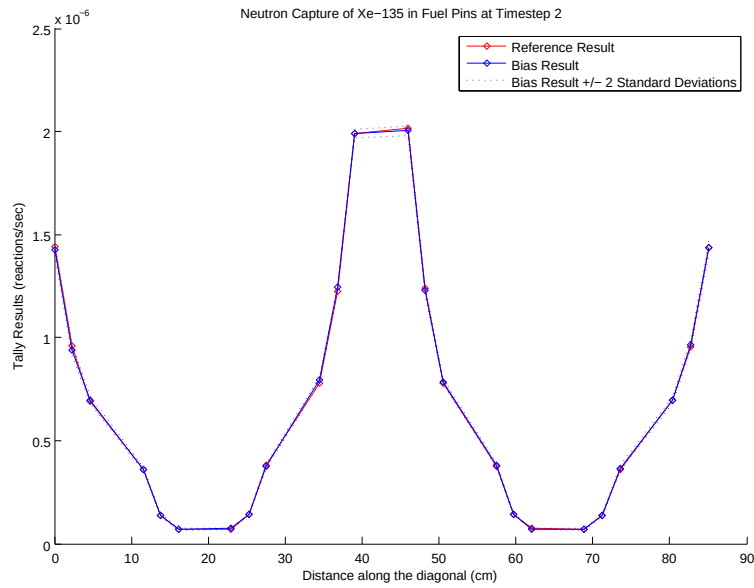


Figure 129: Capture of Xe-135 for timestep 2

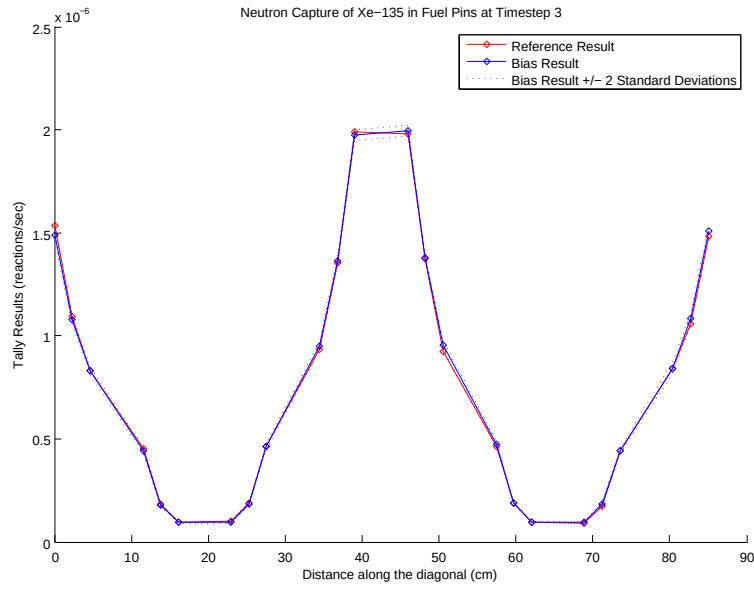


Figure 130: Capture of Xe-135 for timestep 3

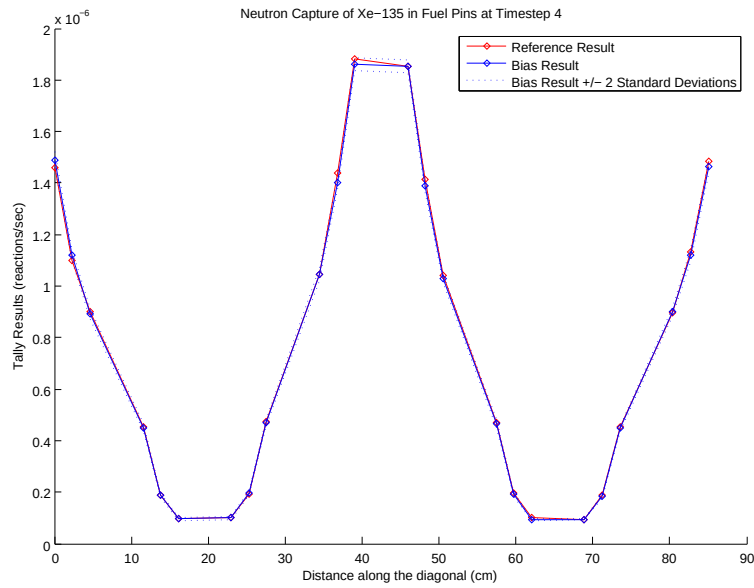


Figure 131: Capture of Xe-135 for timestep 4

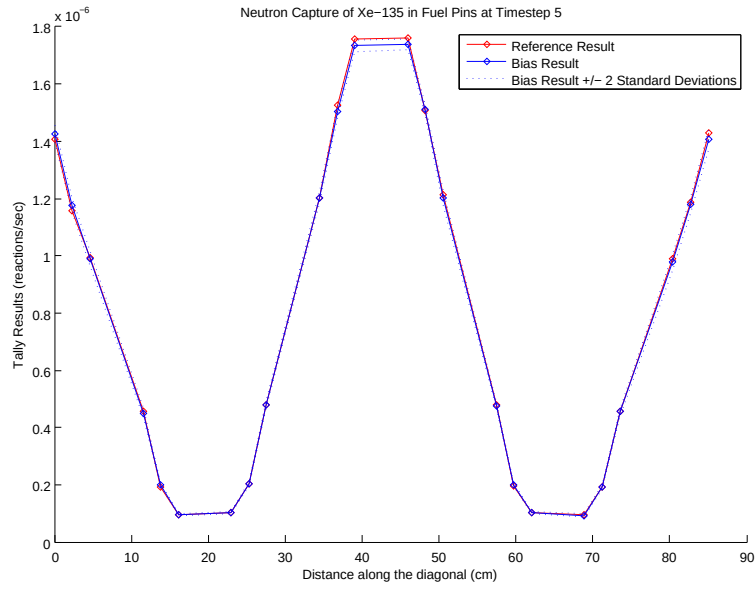


Figure 132: Capture of Xe-135 for timestep 5

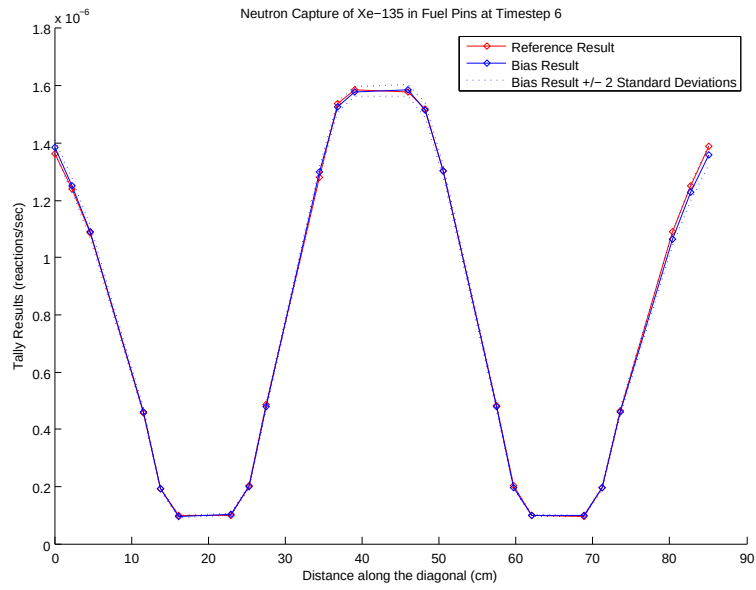


Figure 133: Capture of Xe-135 for timestep 6

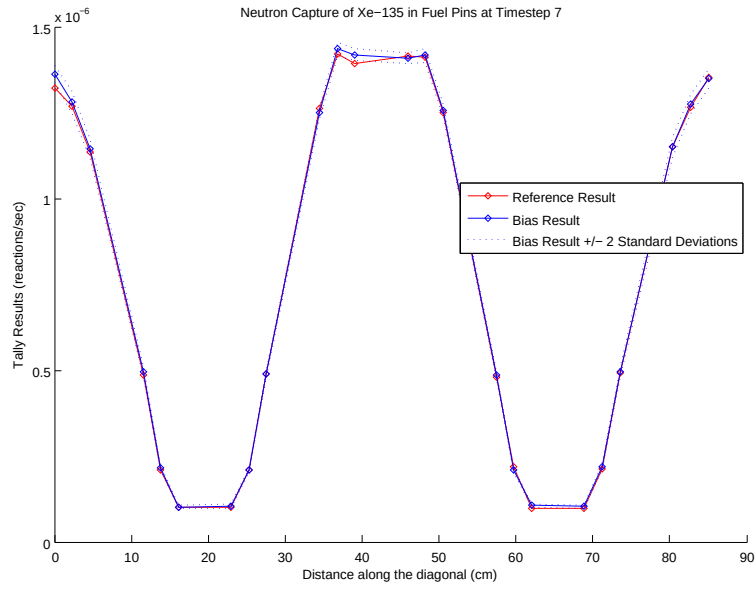


Figure 134: Capture of Xe-135 for timestep 7

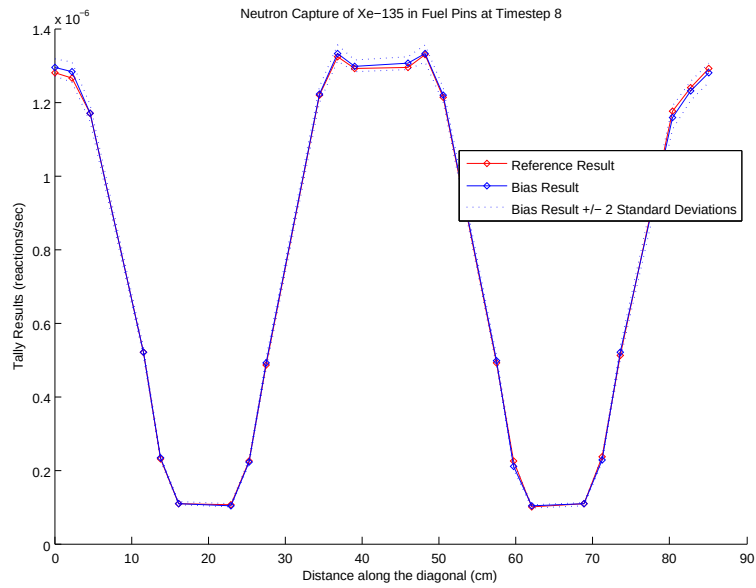


Figure 135: Capture of Xe-135 for timestep 8

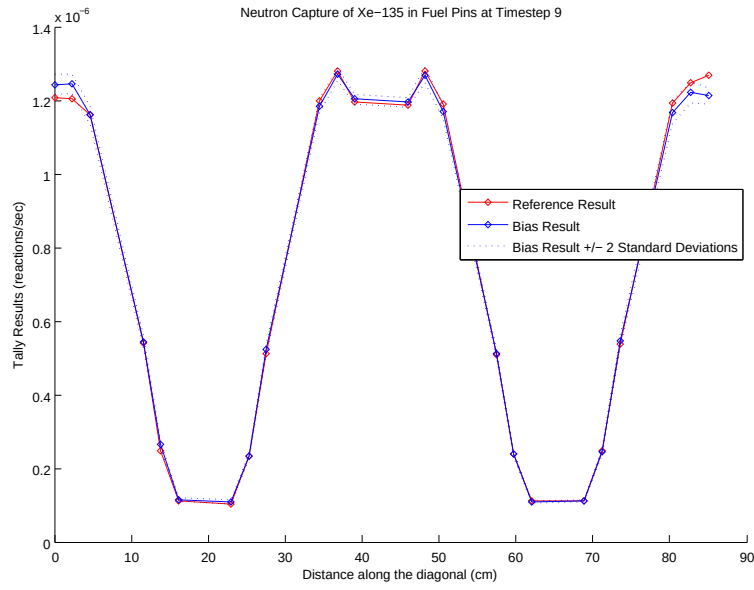


Figure 136: Capture of Xe-135 for timestep 9

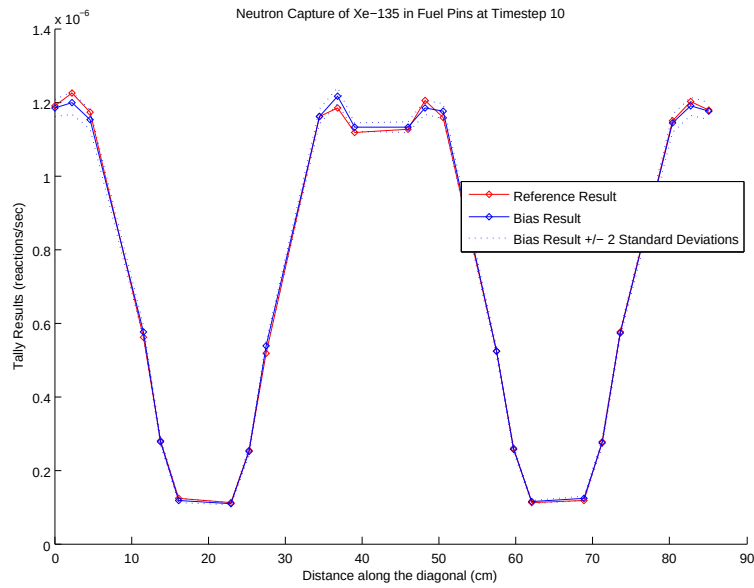


Figure 137: Capture of Xe-135 for timestep 10

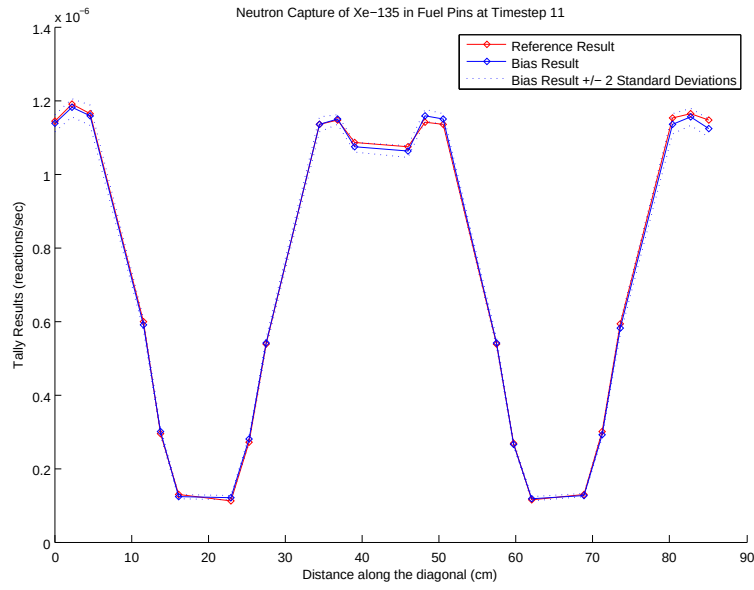


Figure 138: Capture of Xe-135 for timestep 11

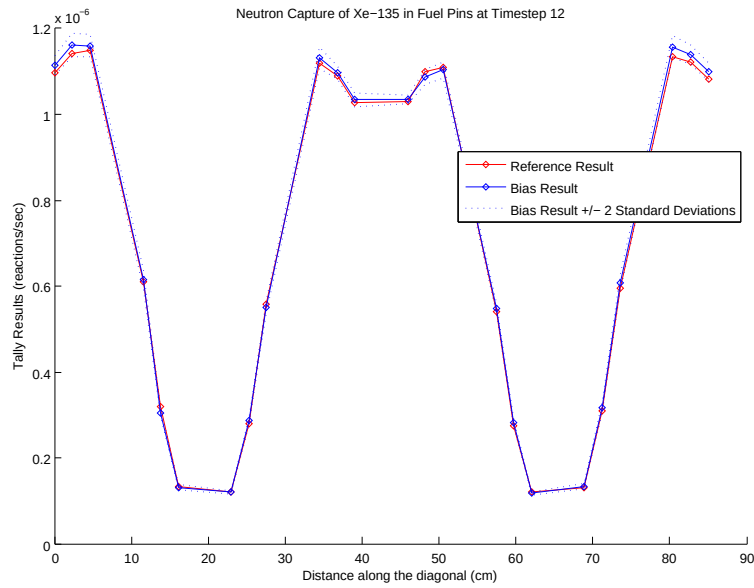


Figure 139: Capture of Xe-135 for timestep 12

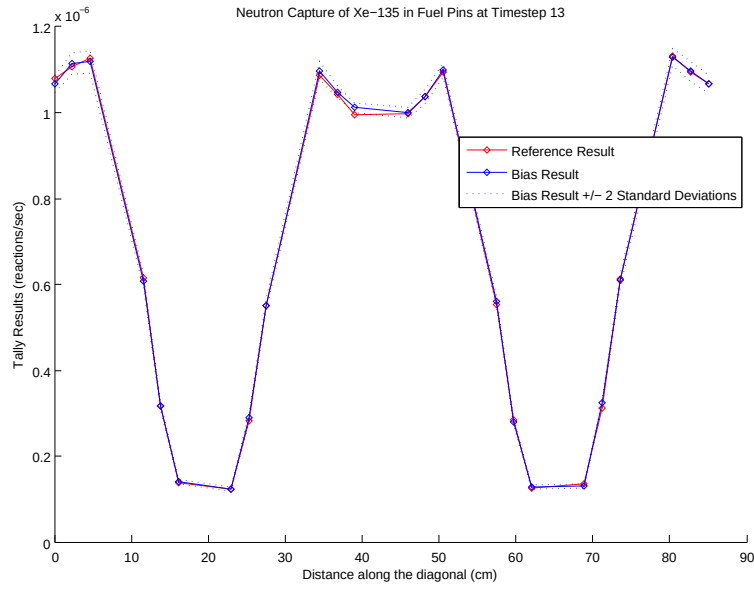


Figure 140: Capture of Xe-135 for timestep 13

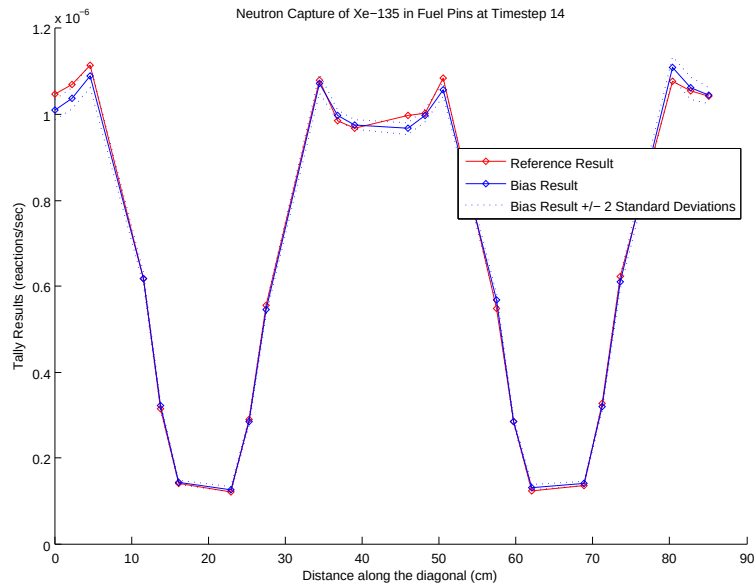


Figure 141: Capture of Xe-135 for timestep 14

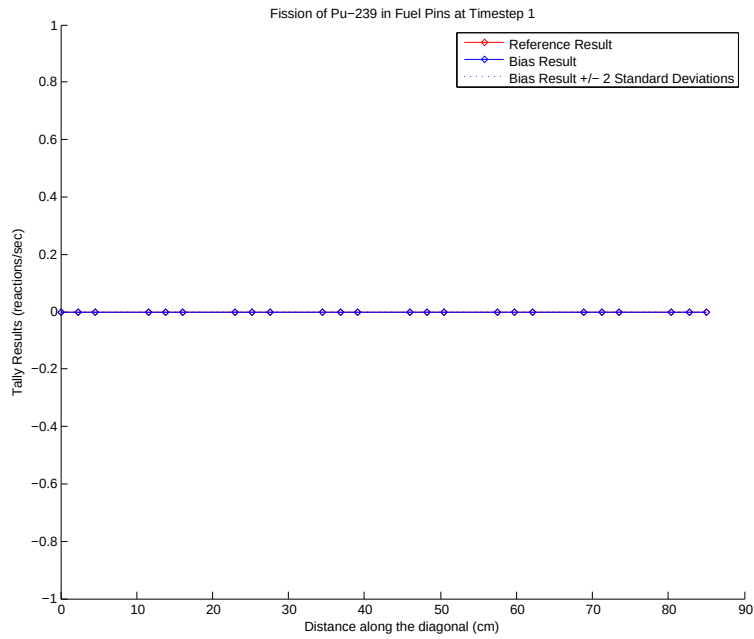


Figure 142: Fission of Pu-239 for timestep 1

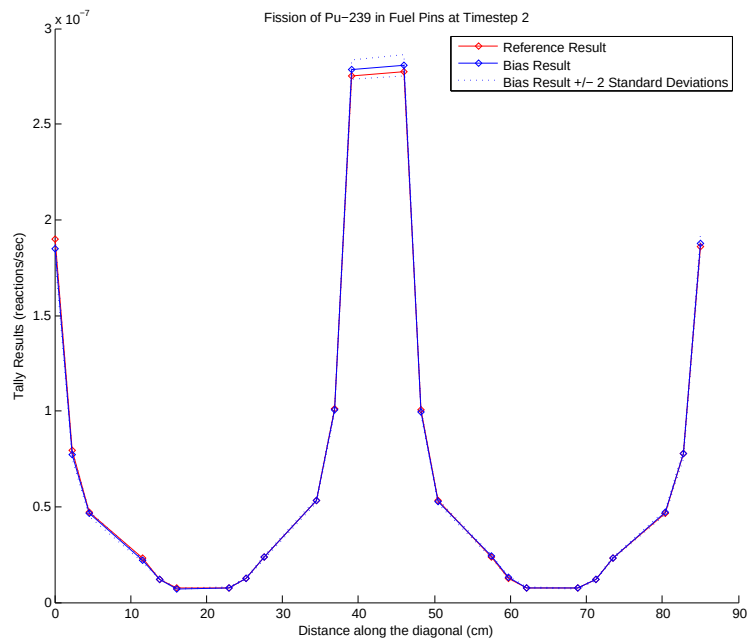


Figure 143: Fission of Pu-239 for timestep 2

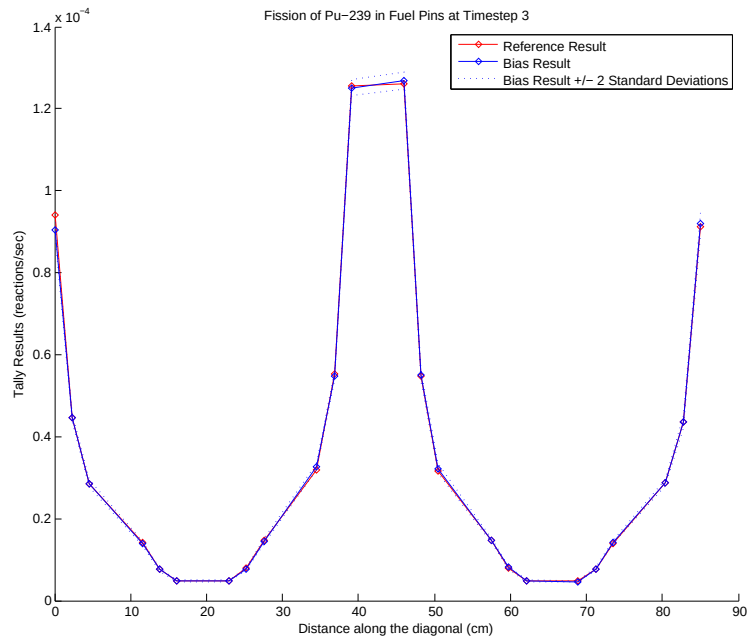


Figure 144: Fission of Pu-239 for timestep 3

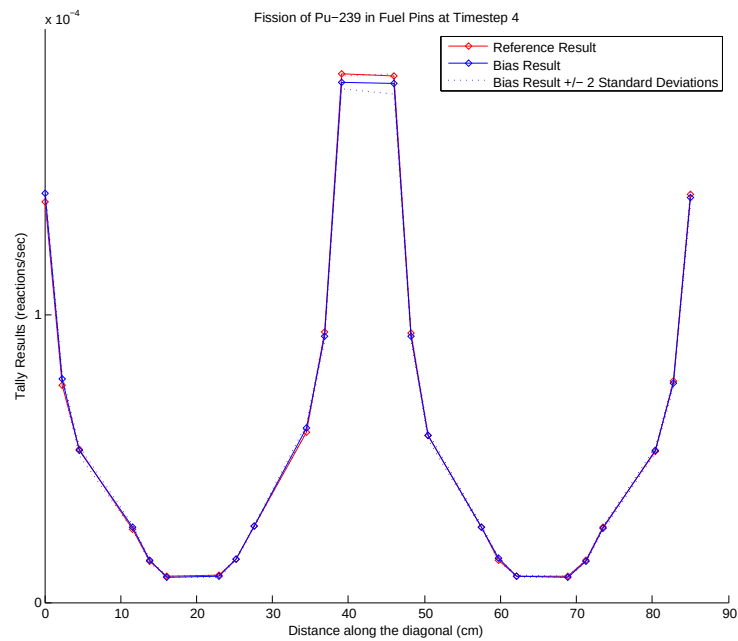


Figure 145: Fission of Pu-239 for timestep 4

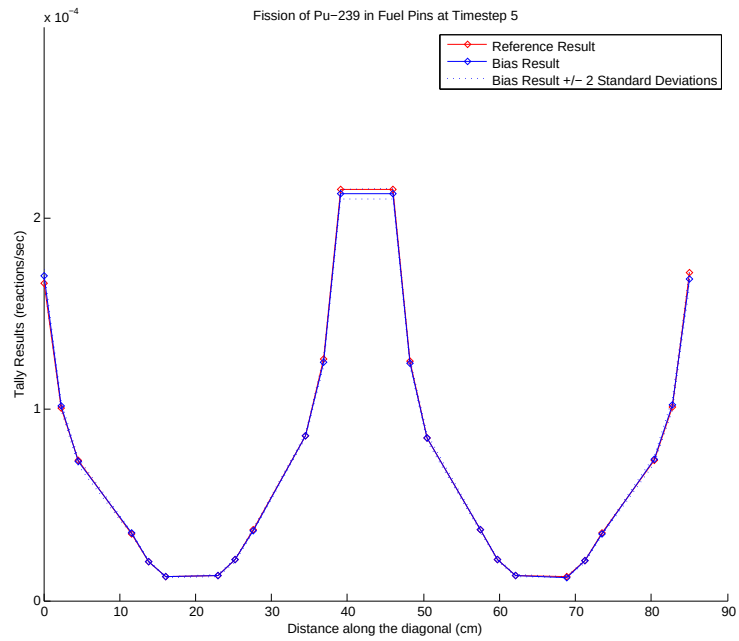


Figure 146: Fission of Pu-239 for timestep 5

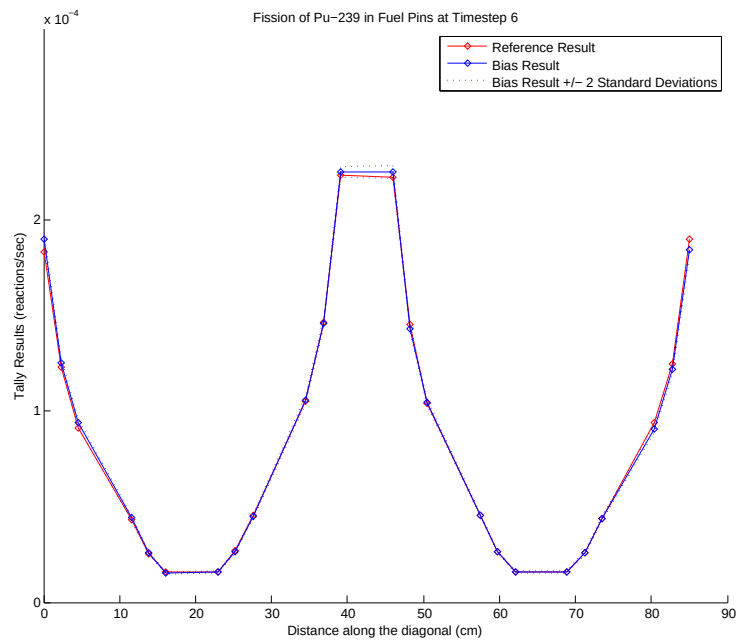


Figure 147: Fission of Pu-239 for timestep 6

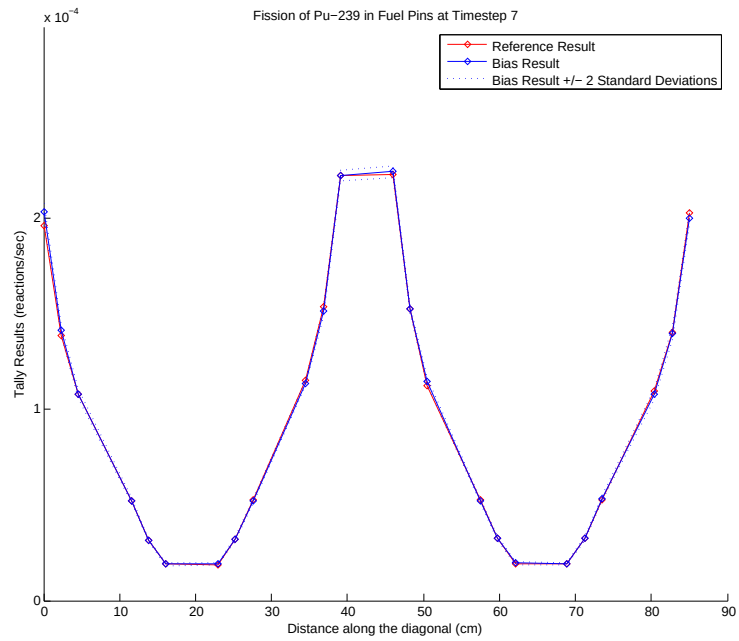


Figure 148: Fission of Pu-239 for timestep 7

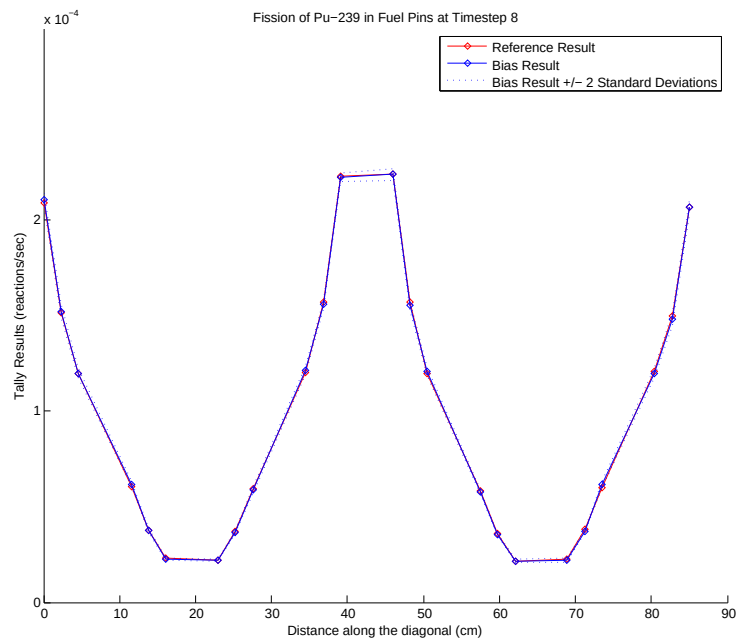


Figure 149: Fission of Pu-239 for timestep 8

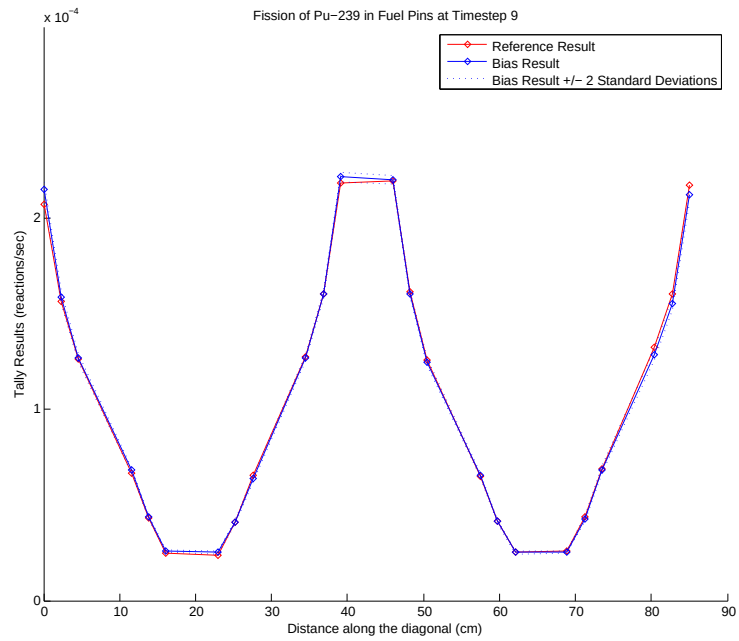


Figure 150: Fission of Pu-239 for timestep 9

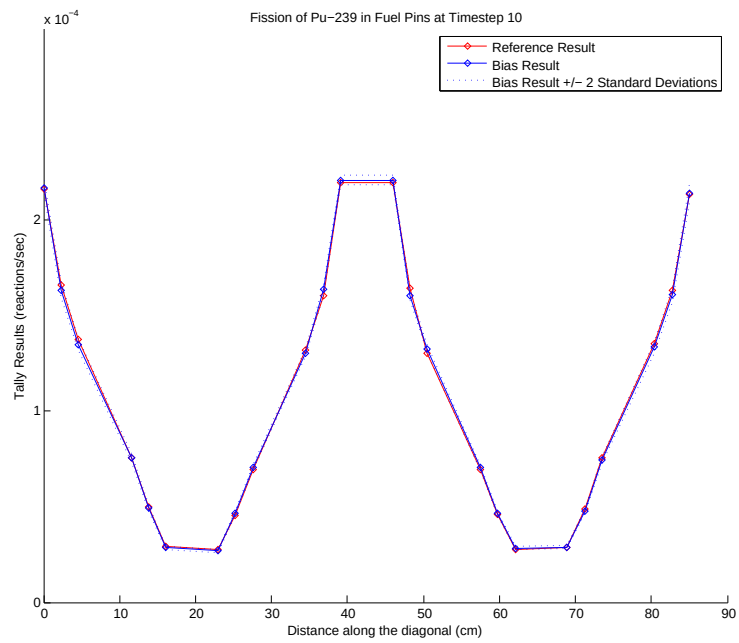


Figure 151: Fission of Pu-239 for timestep 10

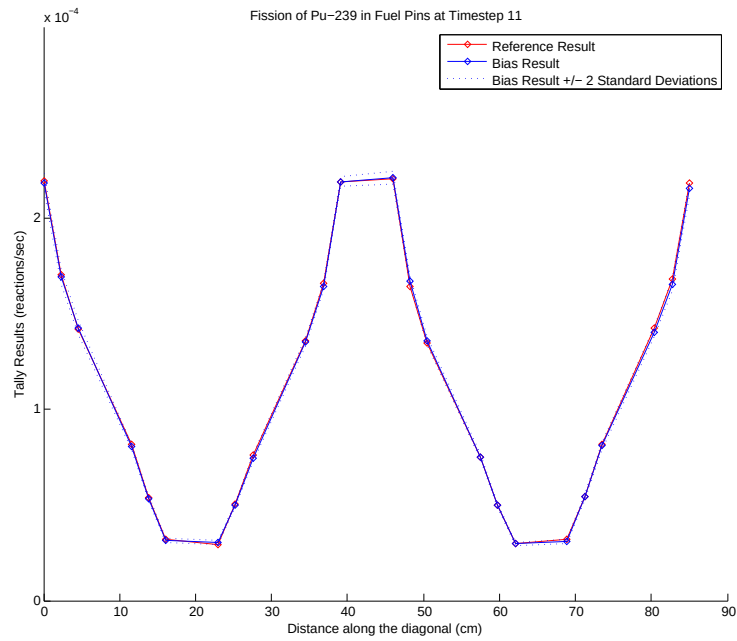


Figure 152: Fission of Pu-239 for timestep 11

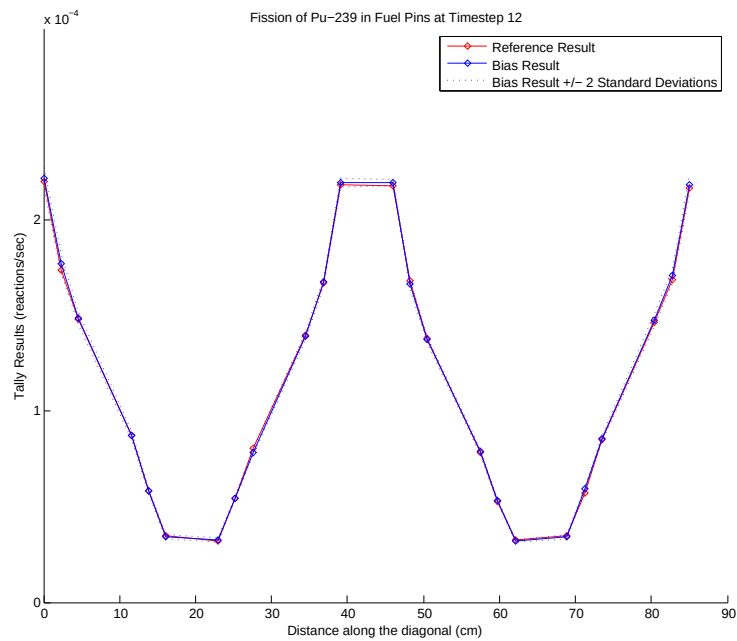


Figure 153: Fission of Pu-239 for timestep 12

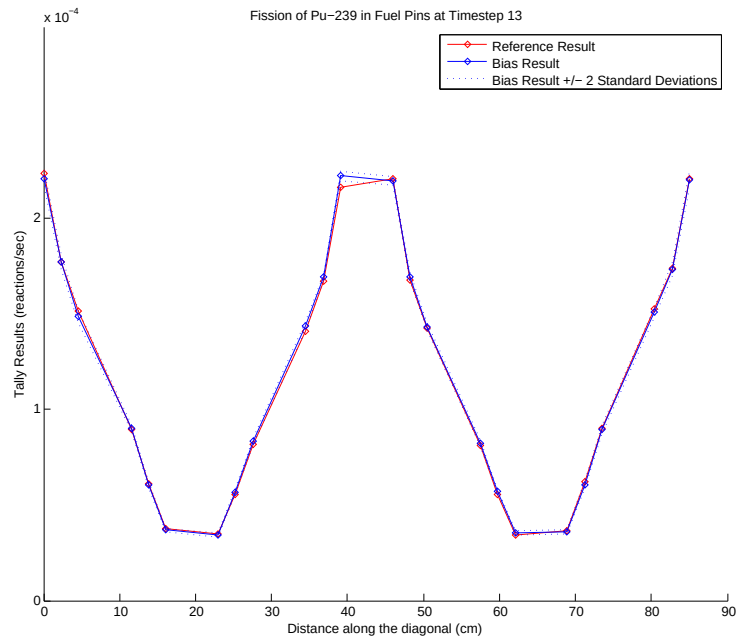


Figure 154: Fission of Pu-239 for timestep 13

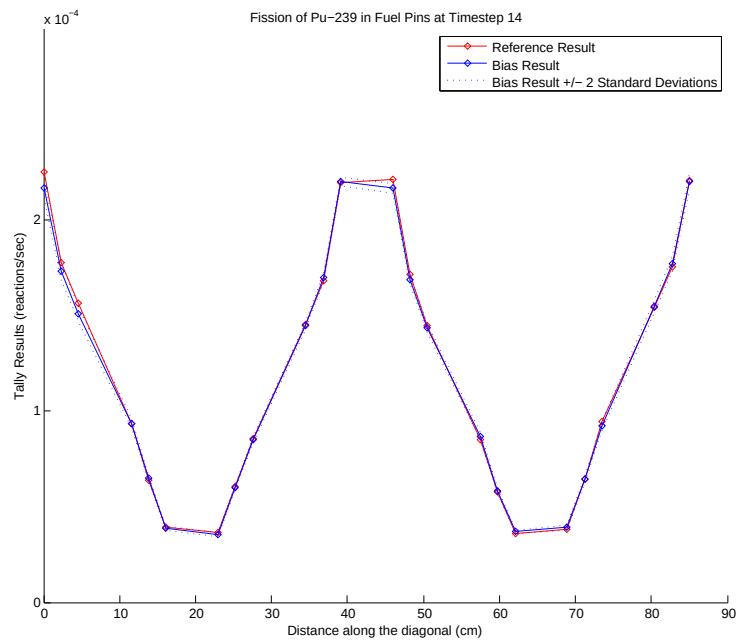


Figure 155: Fission of Pu-239 for timestep 14

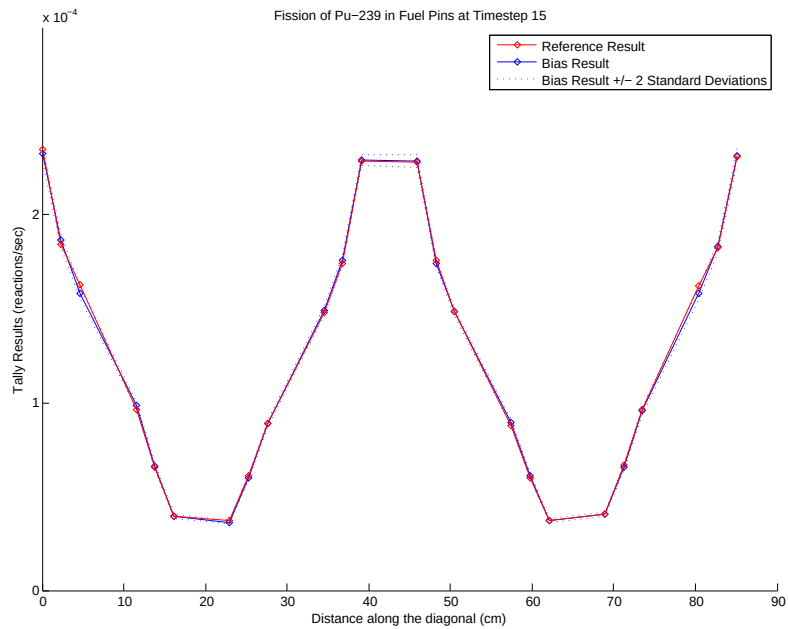


Figure 156: Fission of Pu-239 for timestep 15

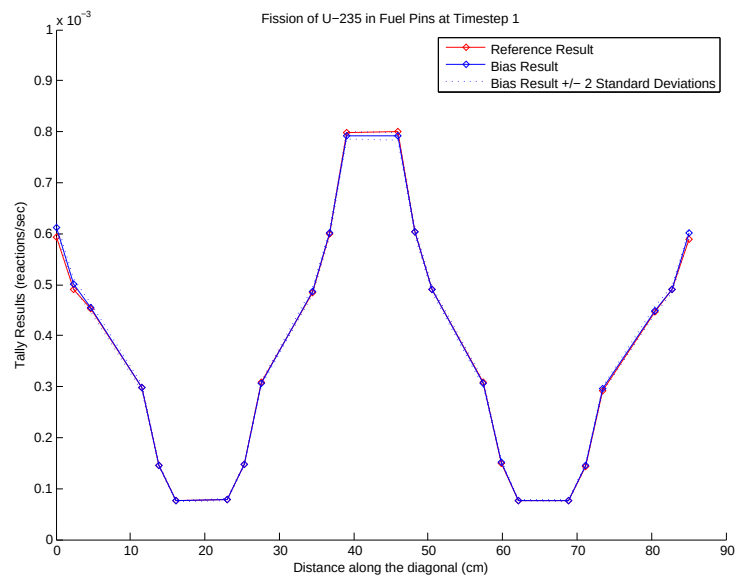


Figure 157: Fission of U-235 for timestep 1

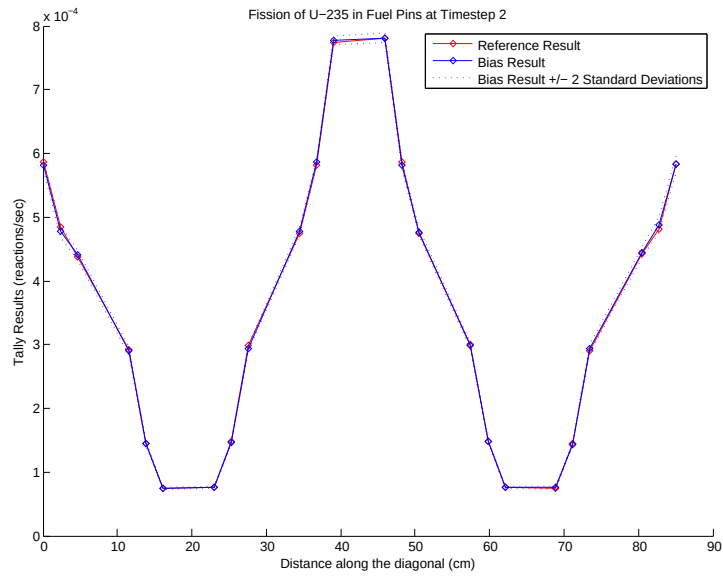


Figure 158: Fission of U-235 for timestep 2

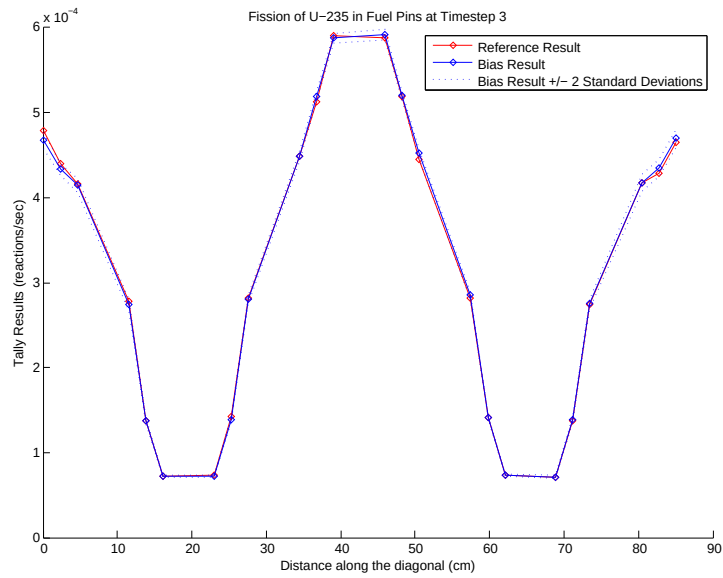


Figure 159: Fission of U-235 for timestep 3

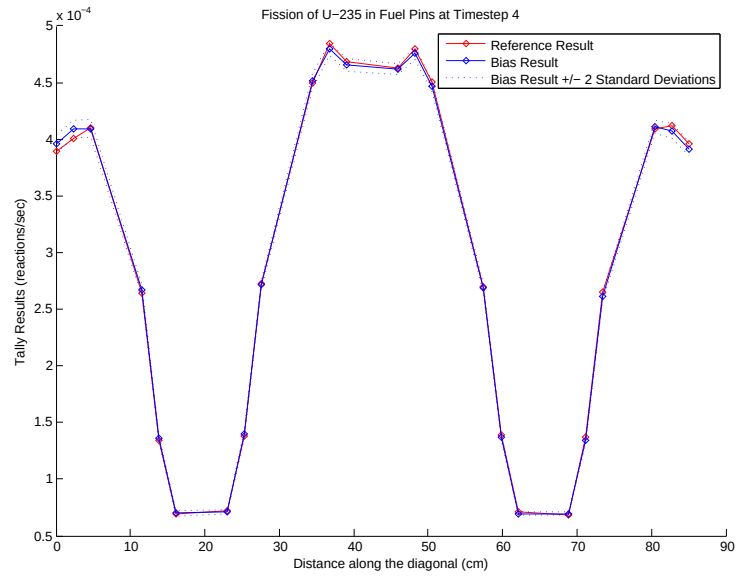


Figure 160: Fission of U-235 for timestep 4

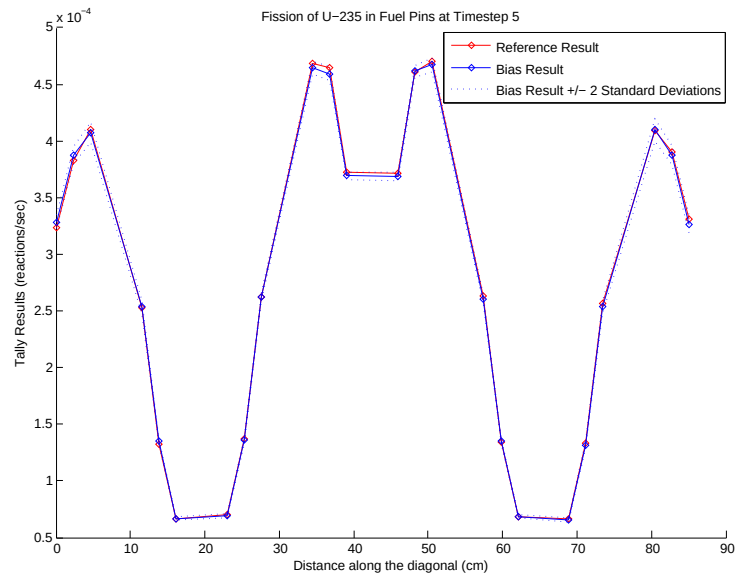


Figure 161: Fission of U-235 for timestep 5

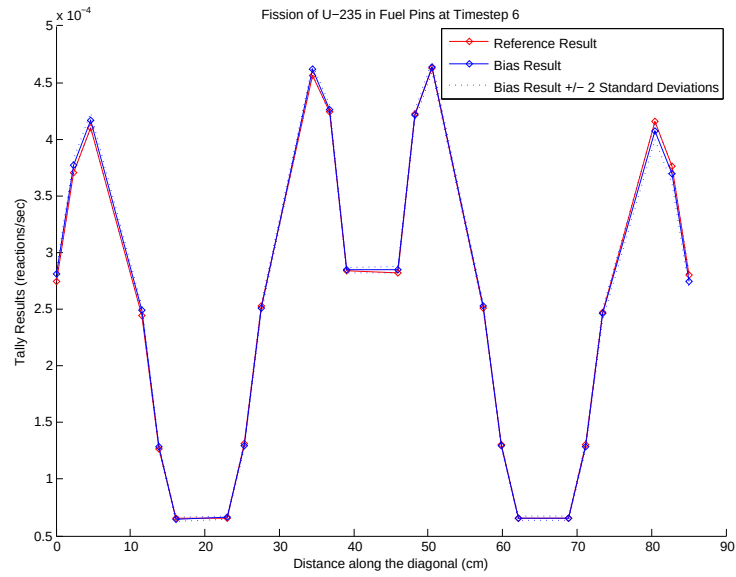


Figure 162: Fission of U-235 for timestep 6

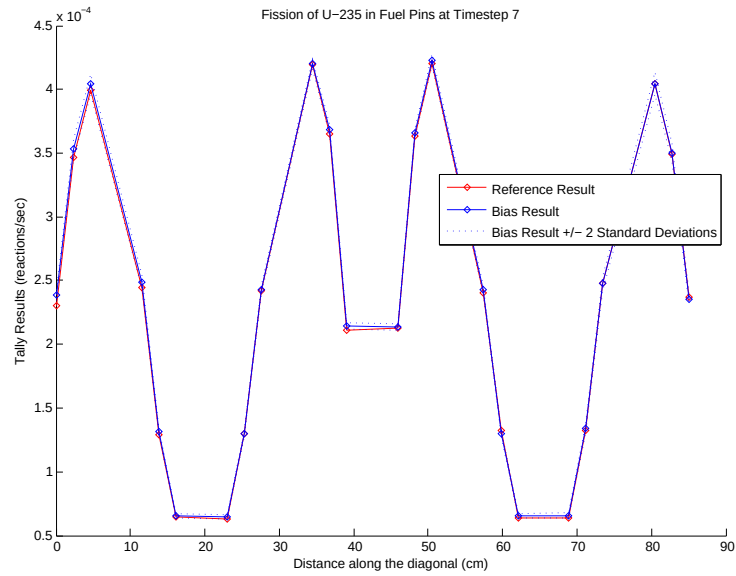


Figure 163: Fission of U-235 for timestep 7

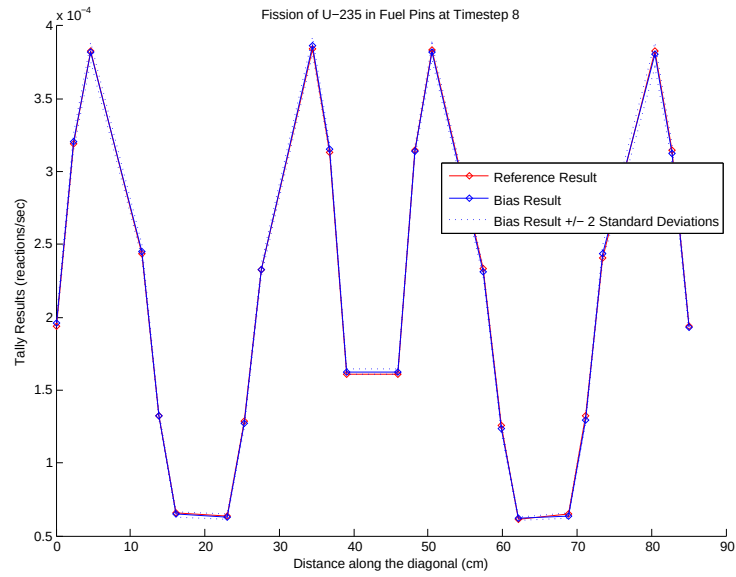


Figure 164: Fission of U-235 for timestep 8

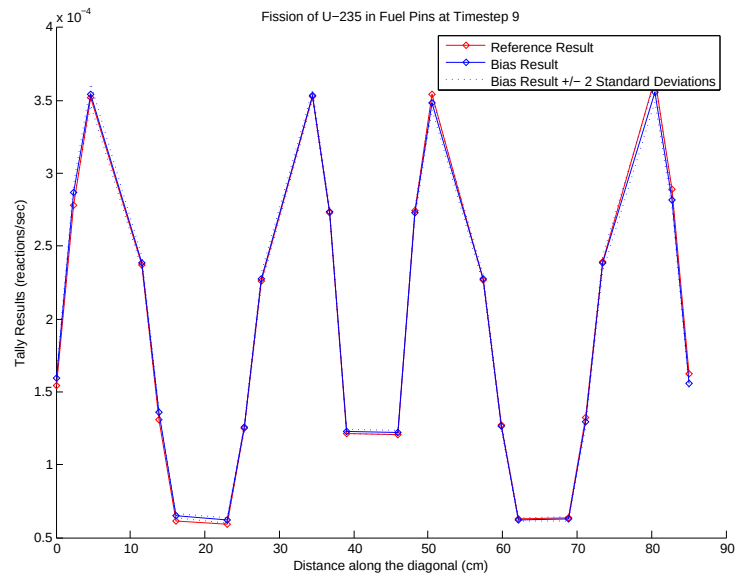


Figure 165: Fission of U-235 for timestep 9

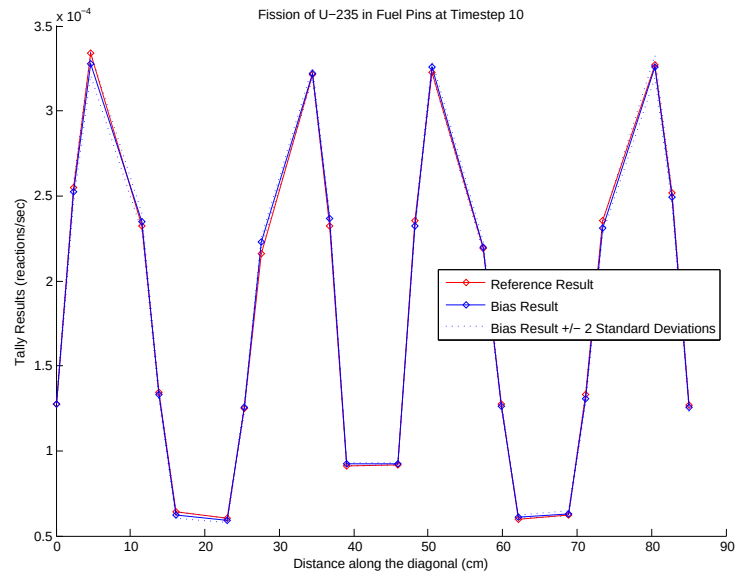


Figure 166: Fission of U-235 for timestep 10

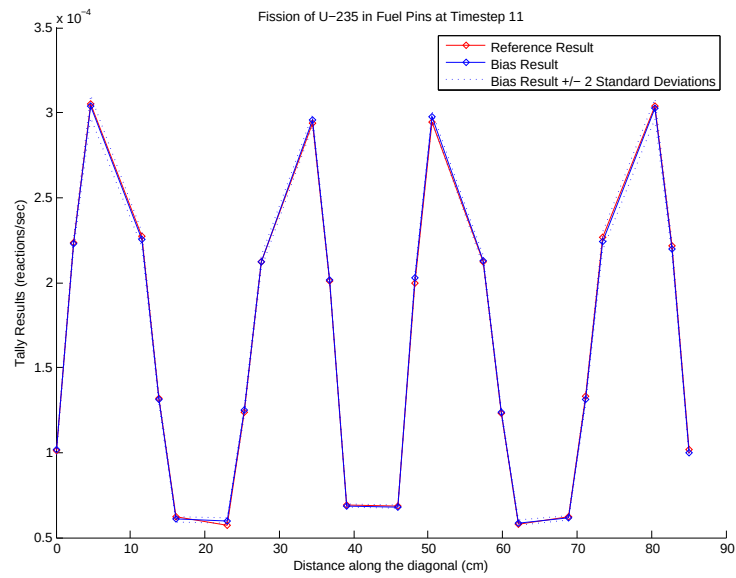


Figure 167: Fission of U-235 for timestep 11

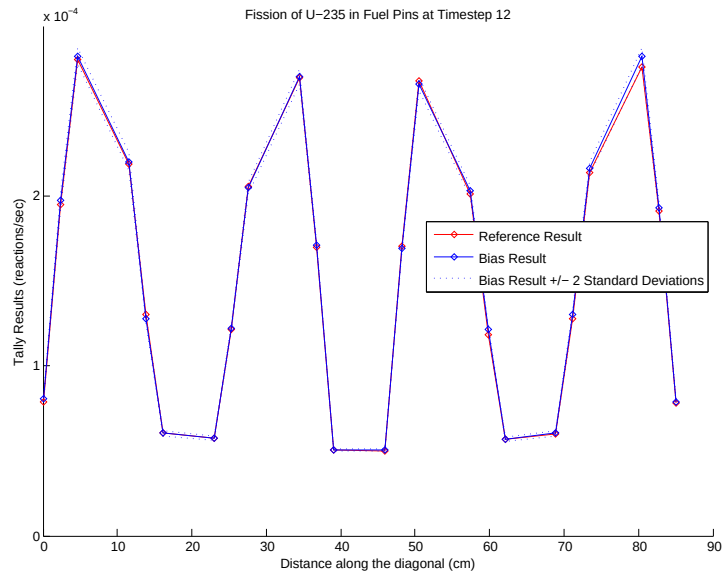


Figure 168: Fission of U-235 for timestep 12

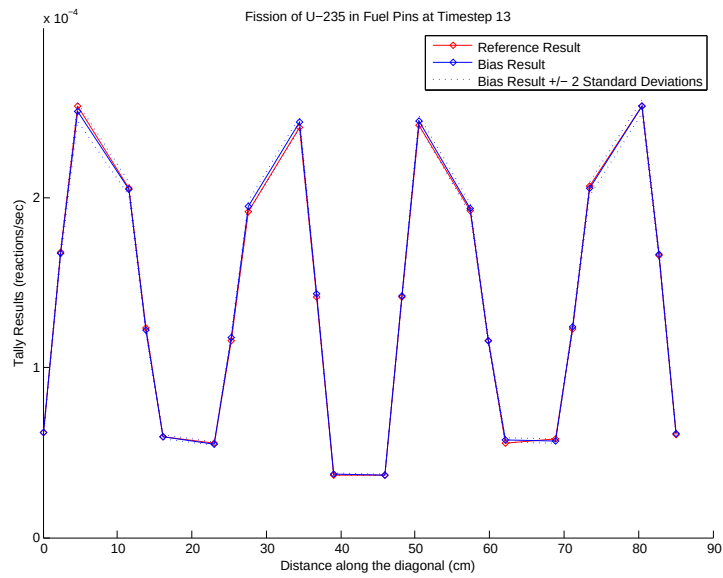


Figure 169: Fission of U-235 for timestep 13

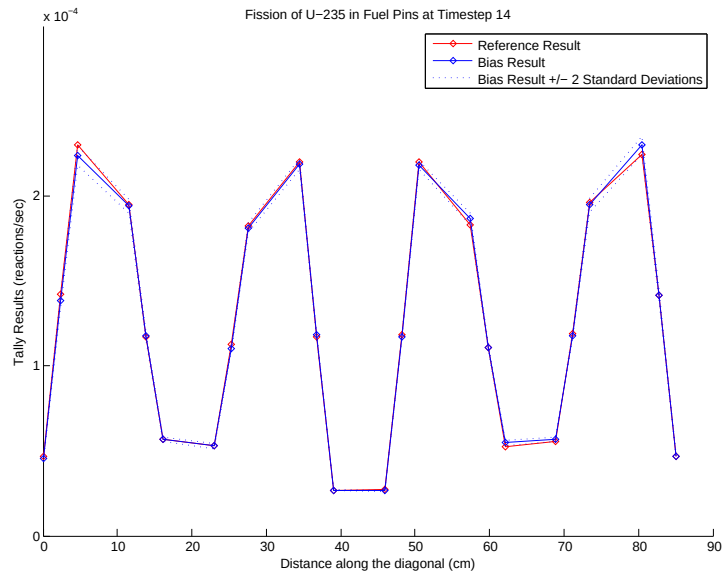


Figure 170: Fission of U-235 for timestep 14

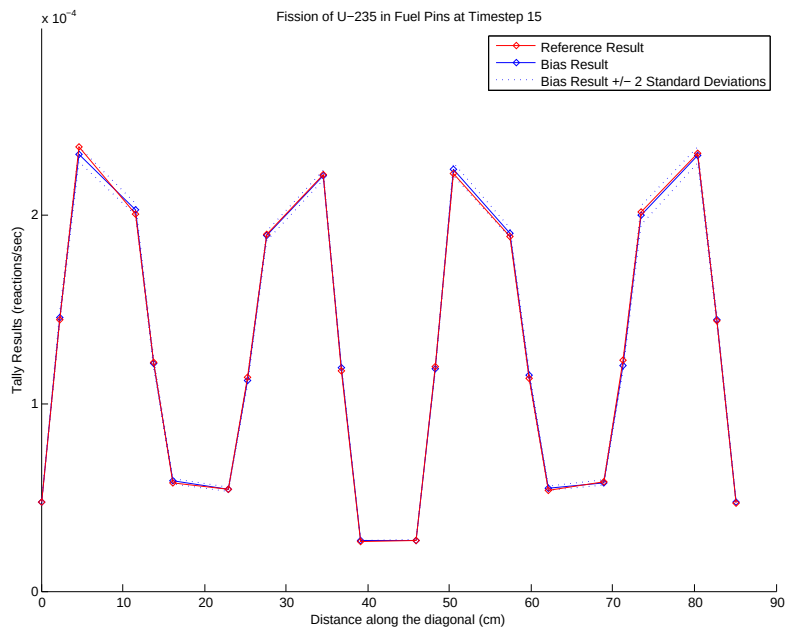


Figure 171: Fission of U-235 for timestep 15

Appendix B: Tally Plots

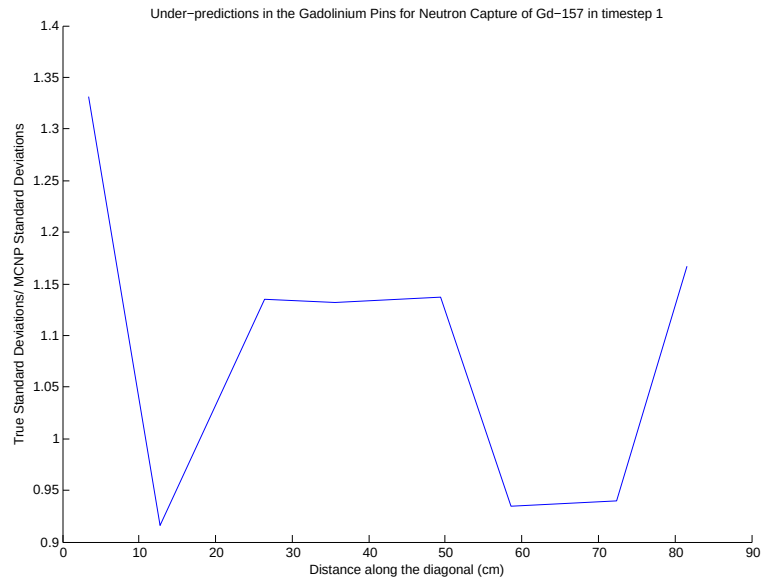


Figure 172: Uncertainty under-prediction of Capture in Gd pins for Gd-157 for timestep 1

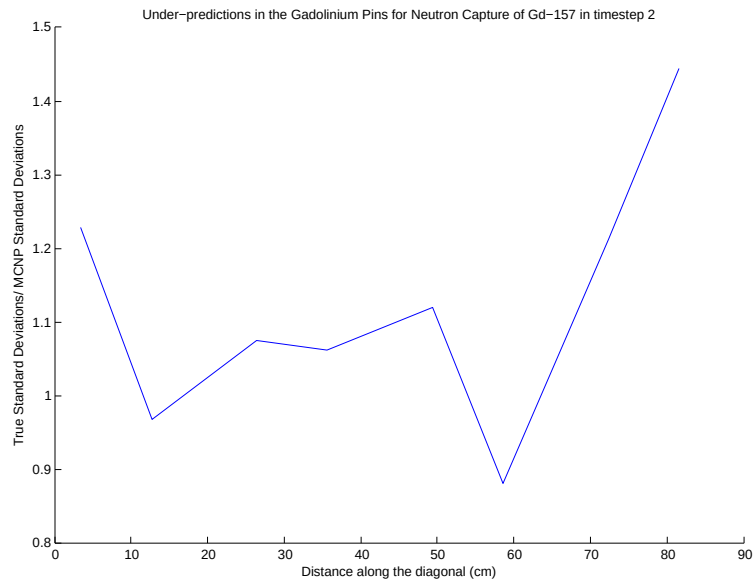


Figure 173: Uncertainty under-prediction of Capture in Gd pins for Gd-157 for timestep 2

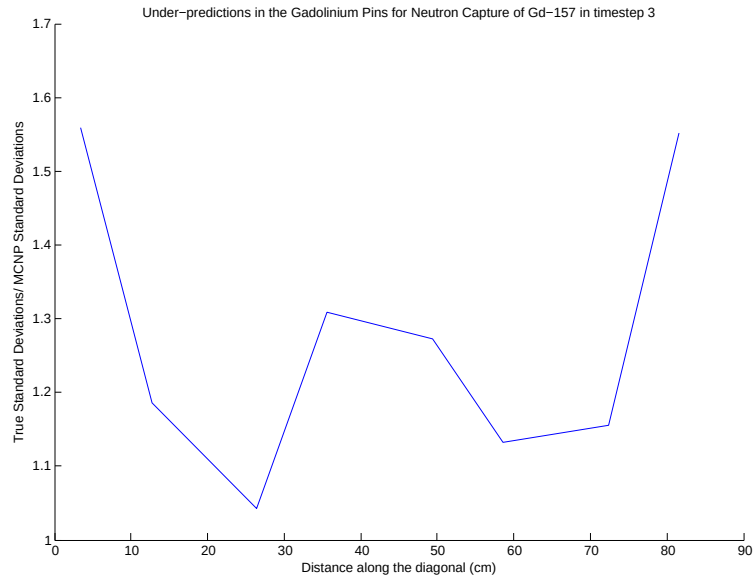


Figure 174: Uncertainty under-prediction of Capture in Gd pins for Gd-157 for timestep 3

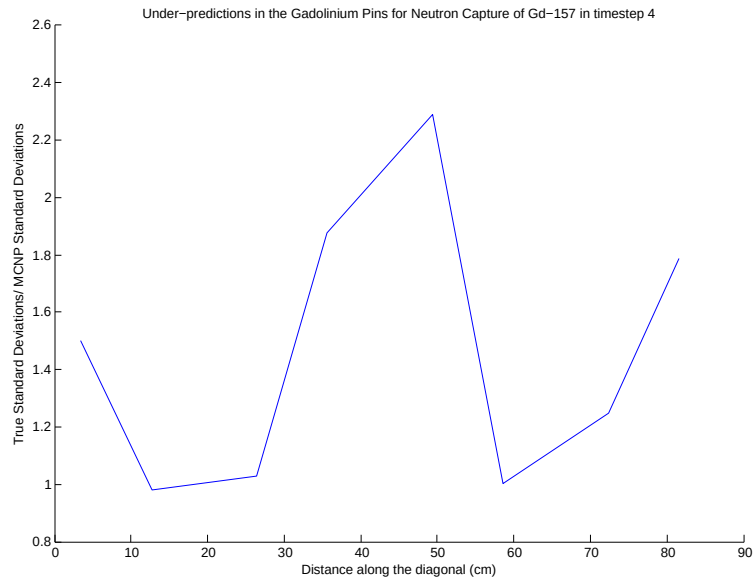


Figure 175: Uncertainty under-prediction of Capture in Gd pins for Gd-157 for timestep 4

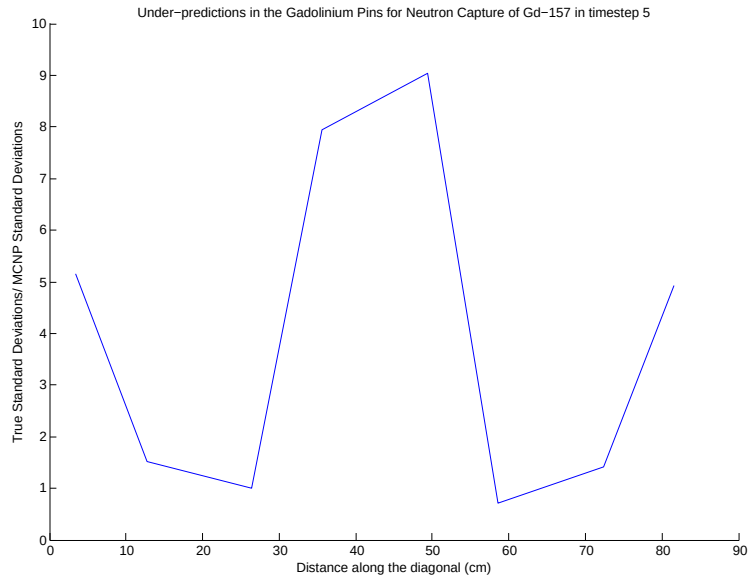


Figure 176: Uncertainty under-prediction of Capture in Gd pins for Gd-157 for timestep 5

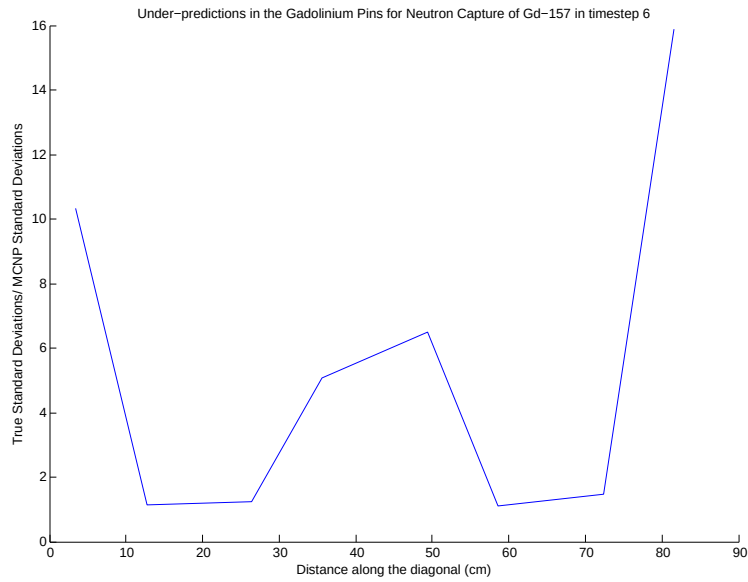


Figure 177: Uncertainty under-prediction of Capture in Gd pins for Gd-157 for timestep 6

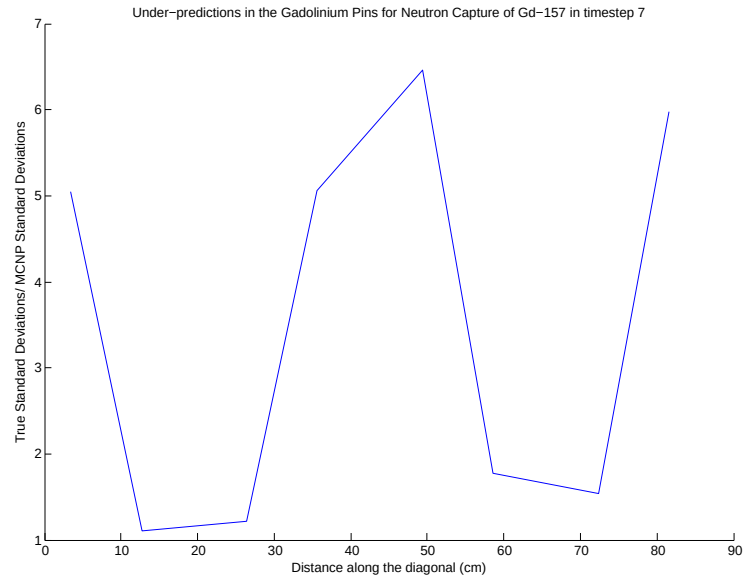


Figure 178: Uncertainty under-prediction of Capture in Gd pins for Gd-157 for timestep 7

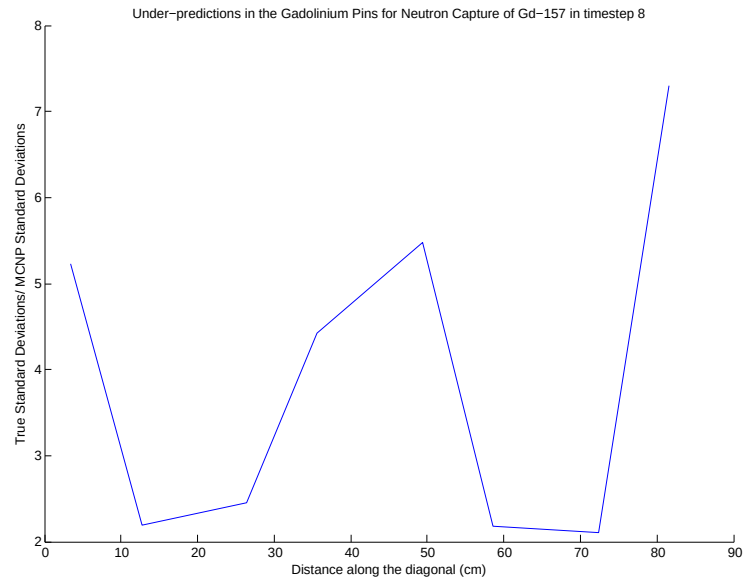


Figure 179: Uncertainty under-prediction of Capture in Gd pins for Gd-157 for timestep 8

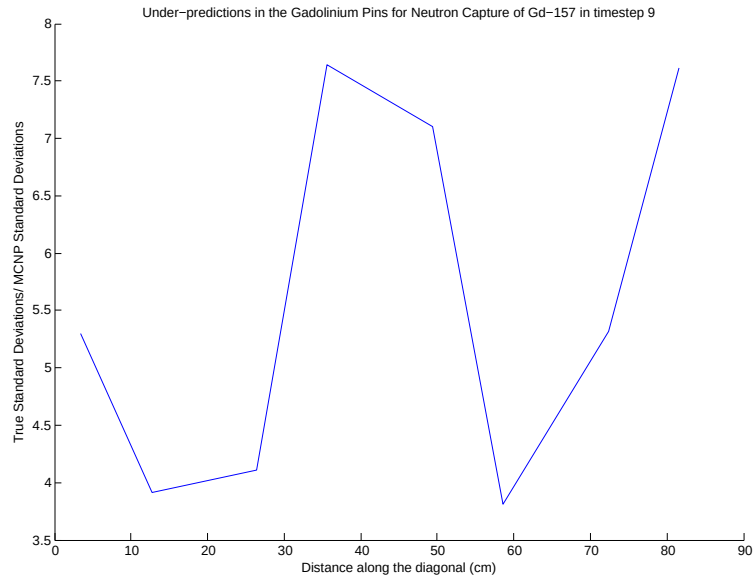


Figure 180: Uncertainty under-prediction of Capture in Gd pins for Gd-157 for timestep 9

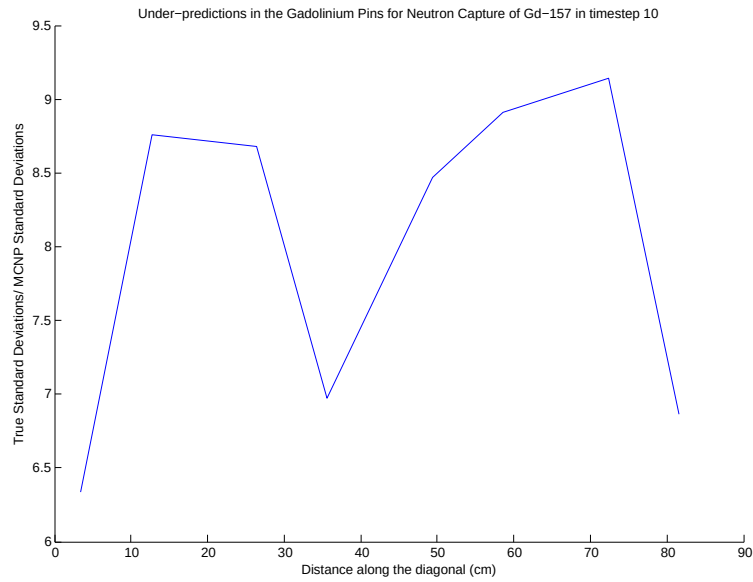


Figure 181: Uncertainty under-prediction of Capture in Gd pins for Gd-157 for timestep 10

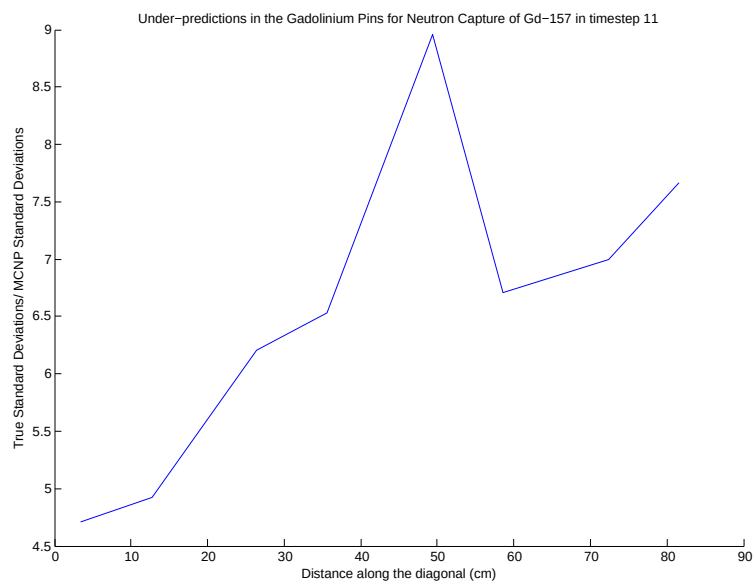


Figure 182: Uncertainty under-prediction of Capture in Gd pins for Gd-157 for timestep 11

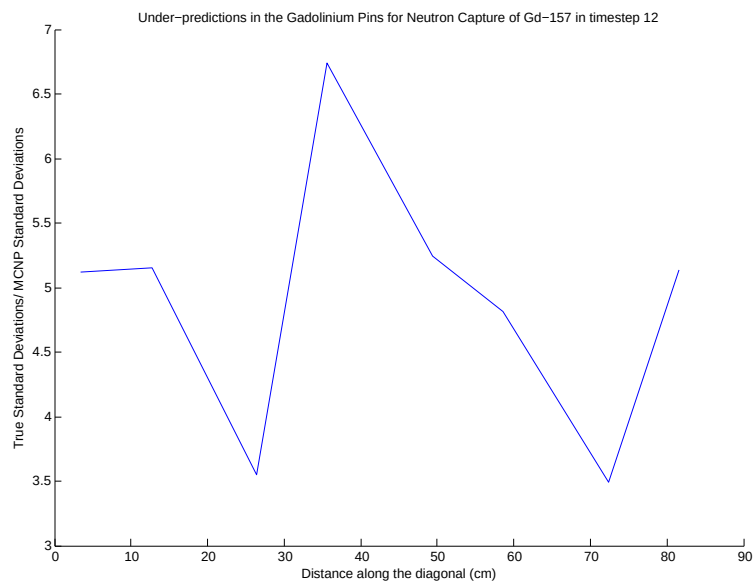


Figure 183: Uncertainty under-prediction of Capture in Gd pins for Gd-157 for timestep 12

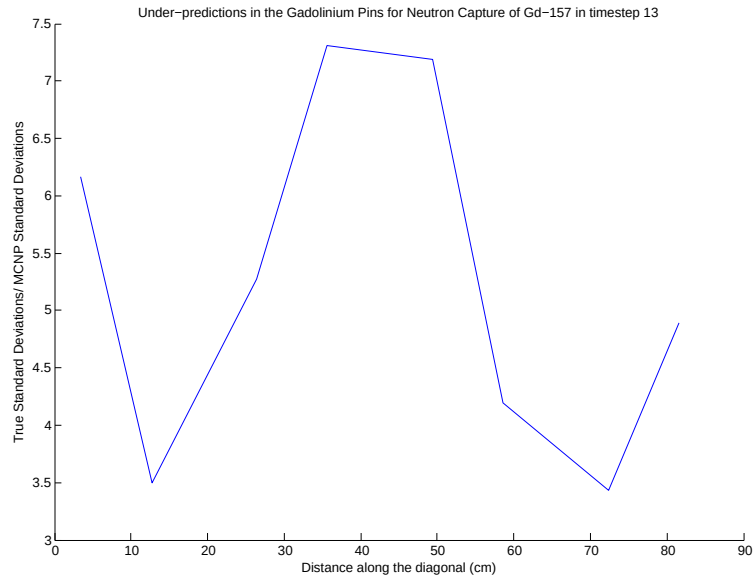


Figure 184: Uncertainty under-prediction of Capture in Gd pins for Gd-157 for timestep 13

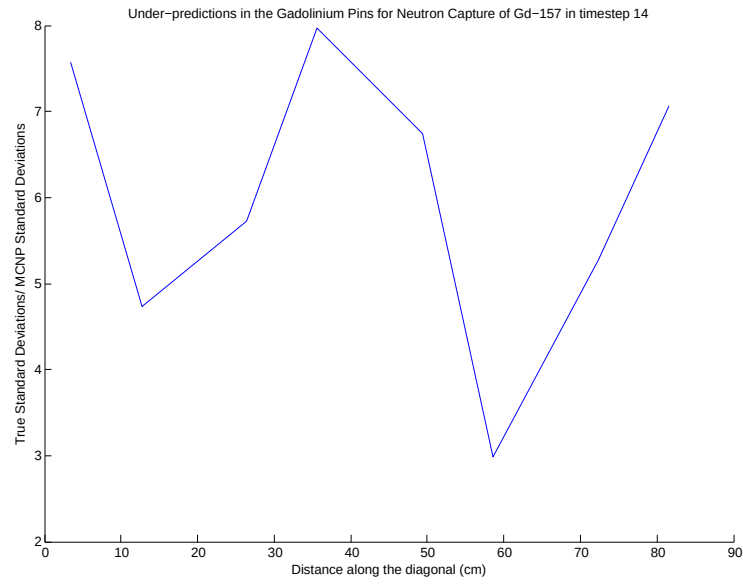


Figure 185: Uncertainty under-prediction of Capture in Gd pins for Gd-157 for timestep 14

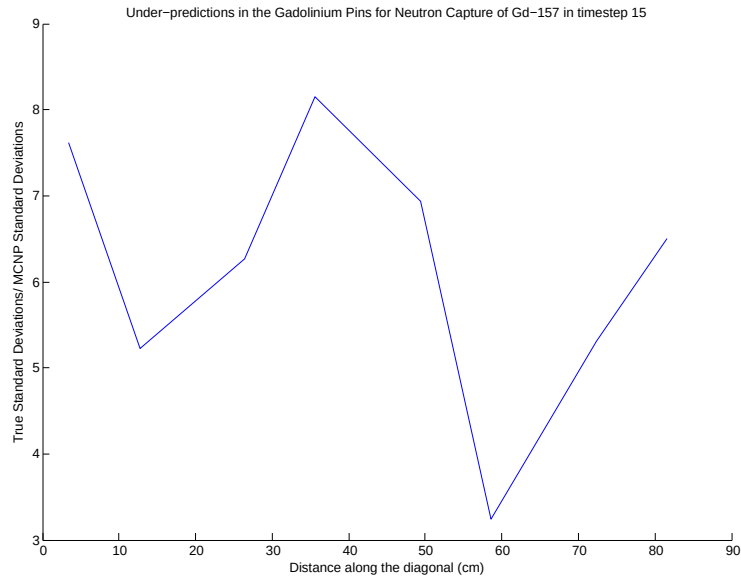


Figure 186: Uncertainty under-prediction of Capture in Gd pins for Gd-157 for timestep 15

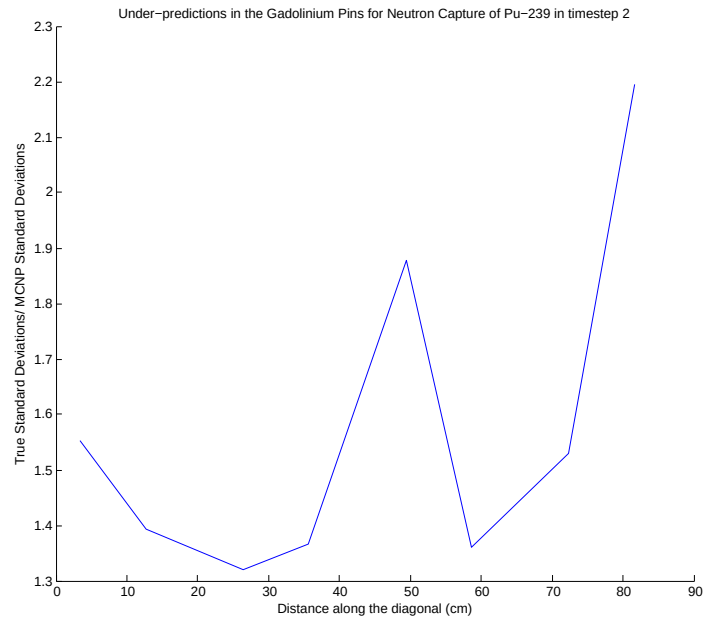


Figure 187: Uncertainty under-prediction of Capture in Gd pins for Pu-239 for timestep 2

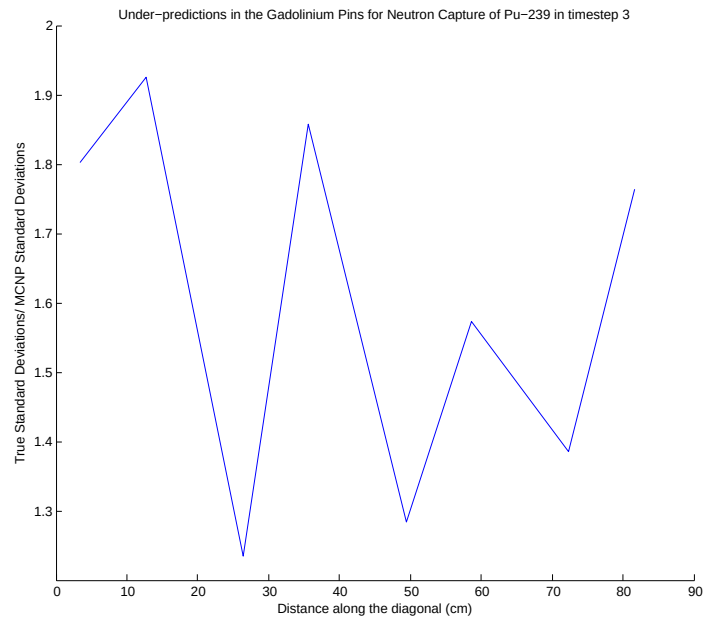


Figure 188: Uncertainty under-prediction of Capture in Gd pins for Pu-239 for timestep 3

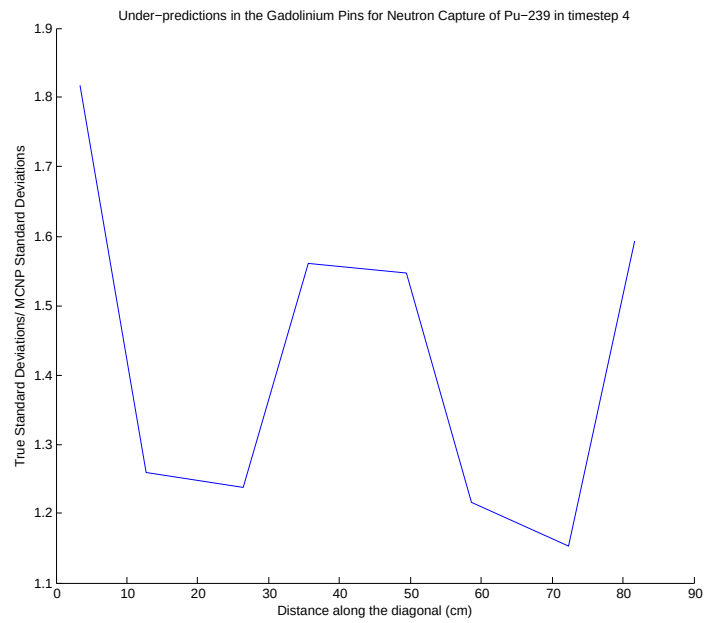


Figure 189: Uncertainty under-prediction of Capture in Gd pins for Pu-239 for timestep 4

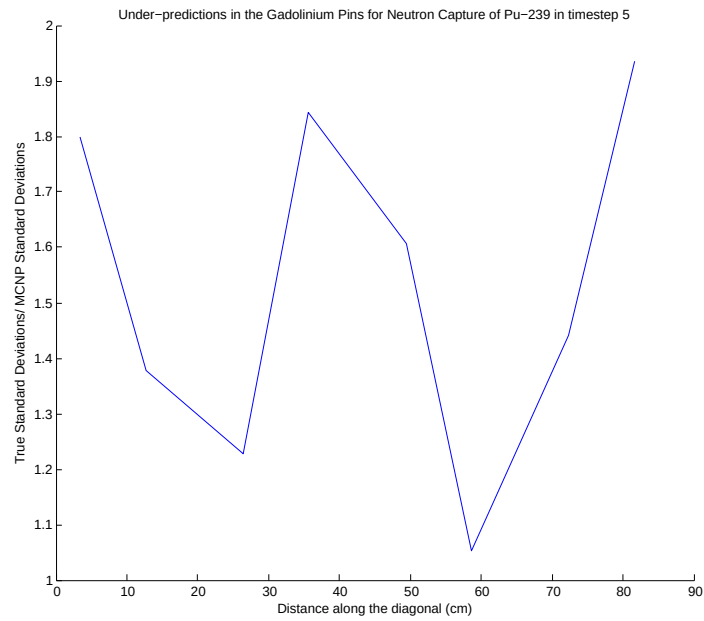


Figure 190: Uncertainty under-prediction of Capture in Gd pins for Pu-239 for timestep 5

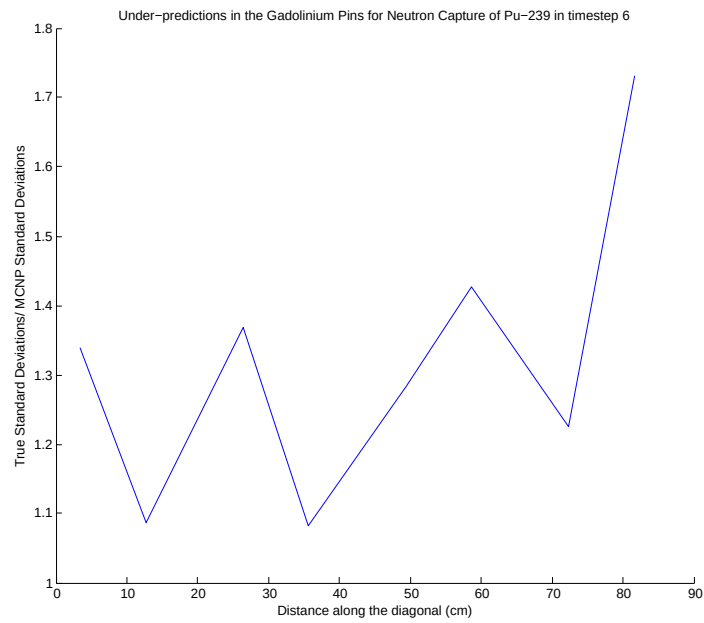


Figure 191: Uncertainty under-prediction of Capture in Gd pins for Pu-239 for timestep 6

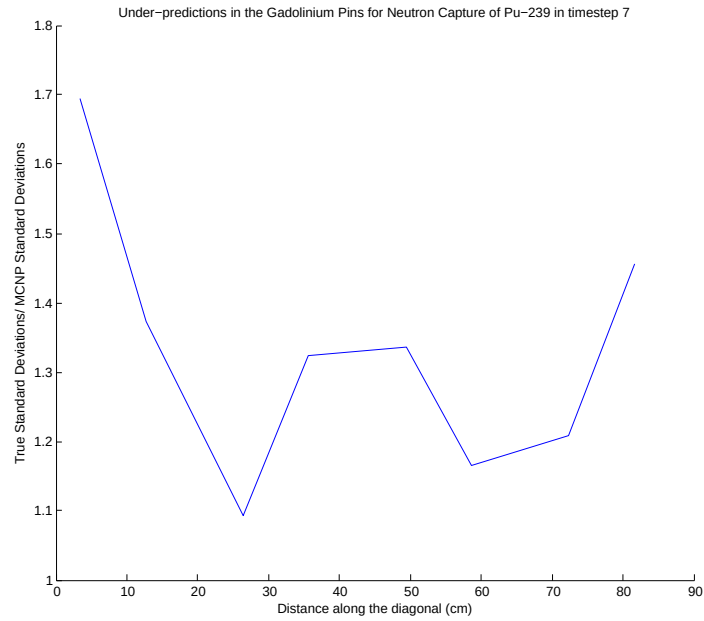


Figure 192: Uncertainty under-prediction of Capture in Gd pins for Pu-239 for timestep 7

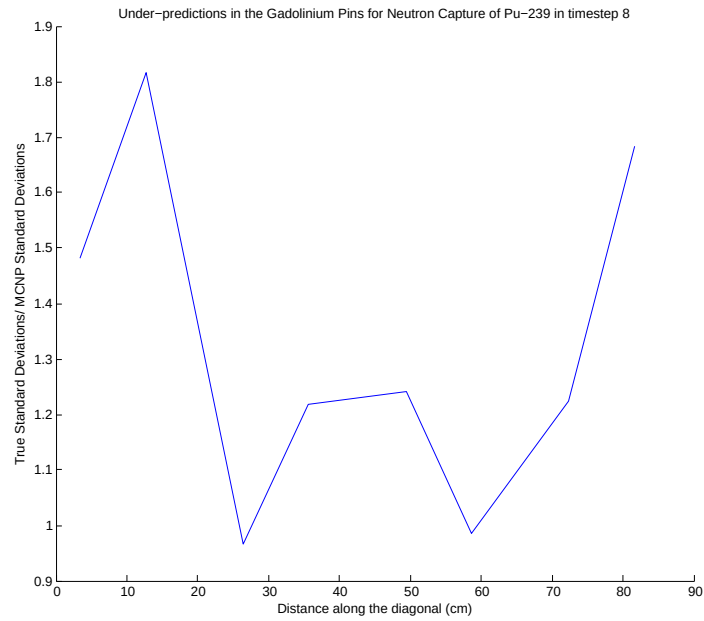


Figure 193: Uncertainty under-prediction of Capture in Gd pins for Pu-239 for timestep 8

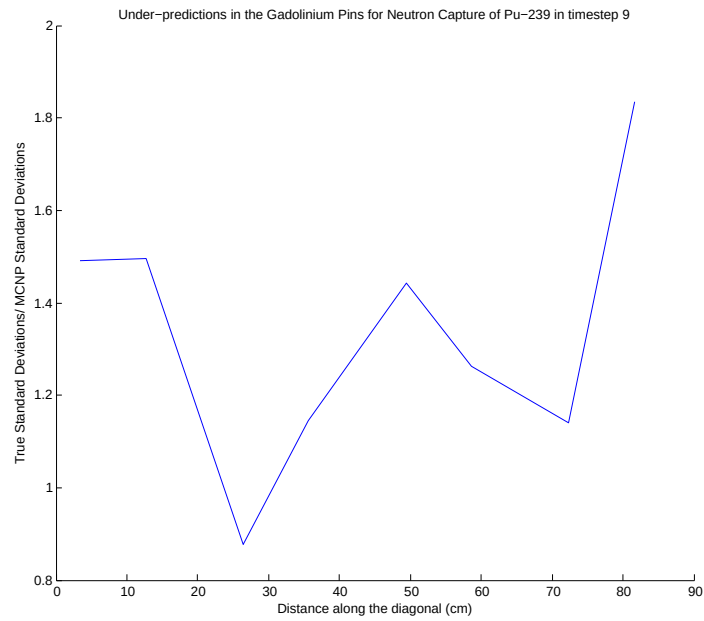


Figure 194: Uncertainty under-prediction of Capture in Gd pins for Pu-239 for timestep 9

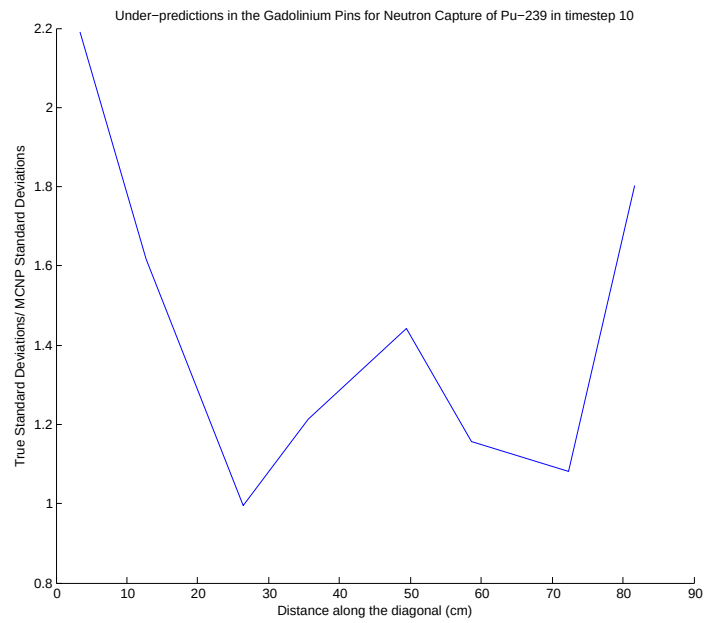


Figure 195: Uncertainty under-prediction of Capture in Gd pins for Pu-239 for timestep 10

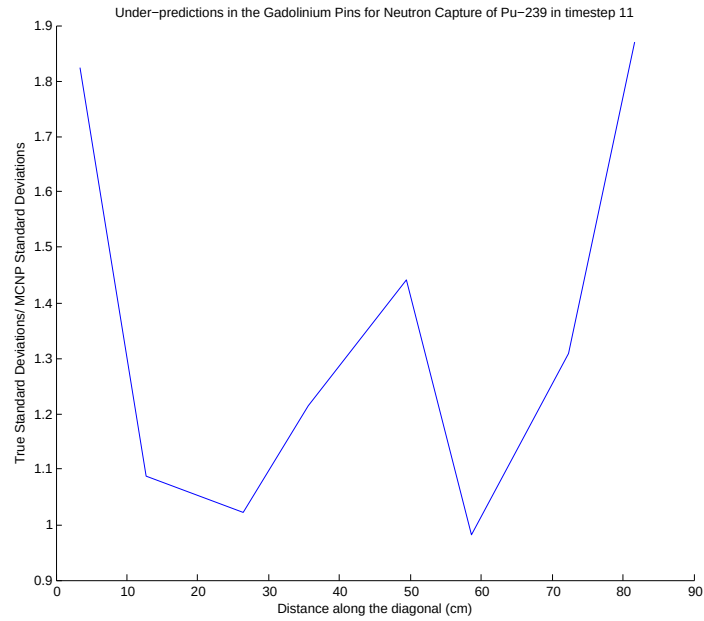


Figure 196: Uncertainty under-prediction of Capture in Gd pins for Pu-239 for timestep 11

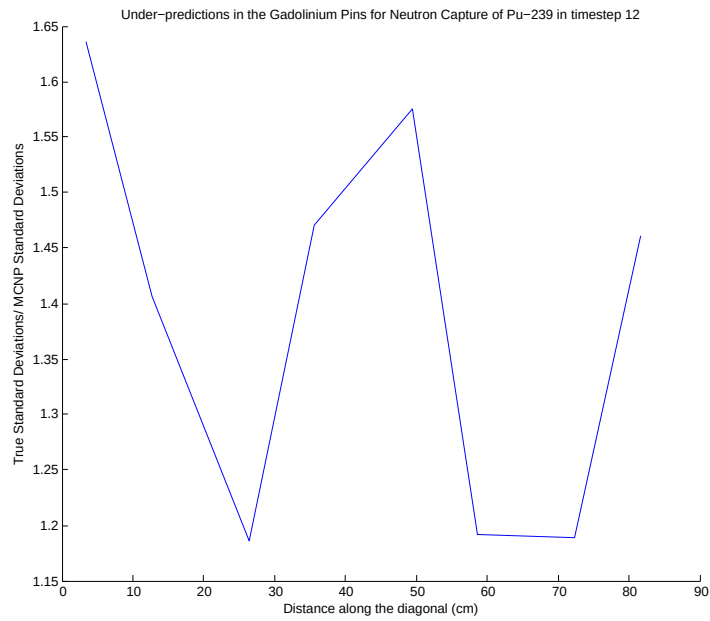


Figure 197: Uncertainty under-prediction of Capture in Gd pins for Pu-239 for timestep 12

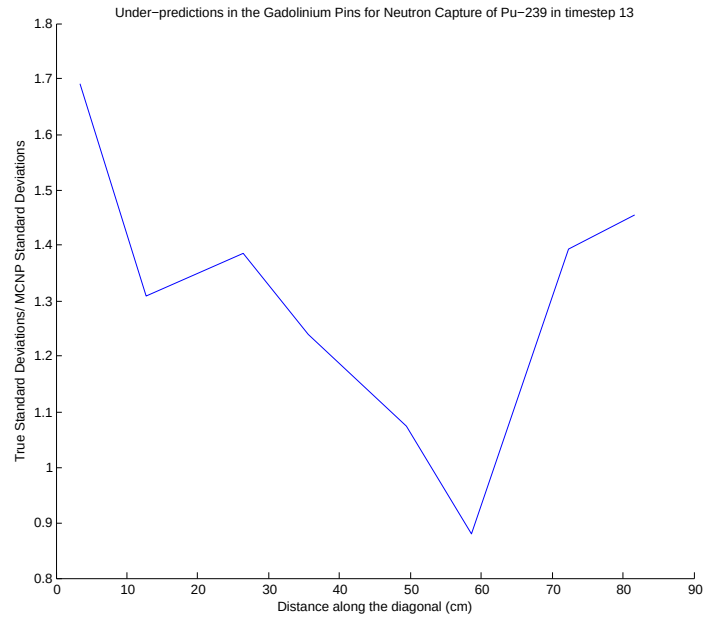


Figure 198: Uncertainty under-prediction of Capture in Gd pins for Pu-239 for timestep 13

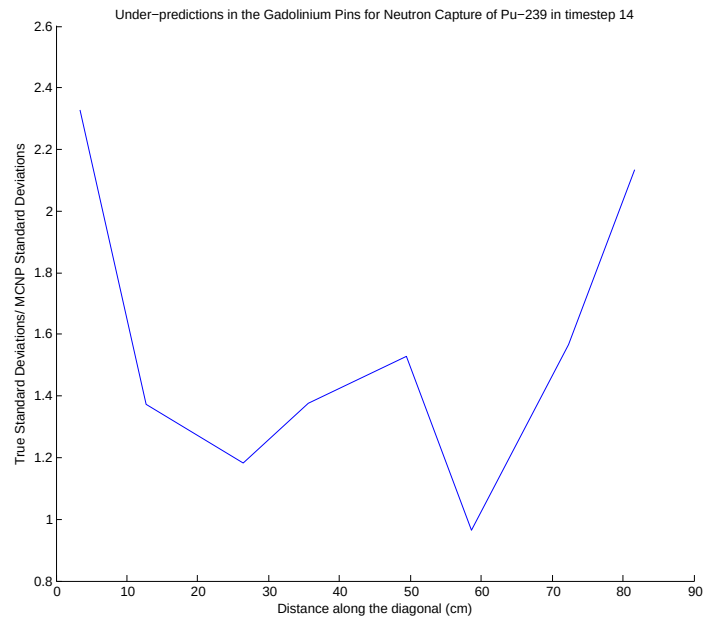


Figure 199: Uncertainty under-prediction of Capture in Gd pins for Pu-239 for timestep 14

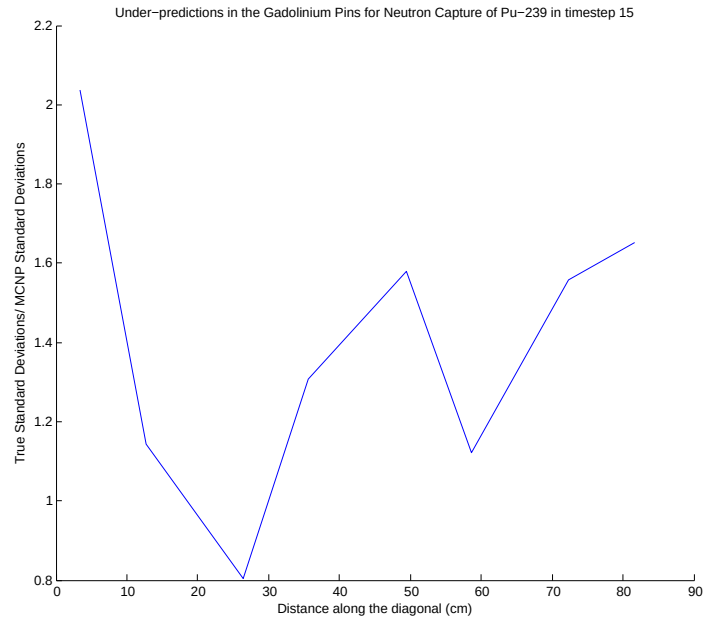


Figure 200: Uncertainty under-prediction of Capture in Gd pins for Pu-239 for timestep 15

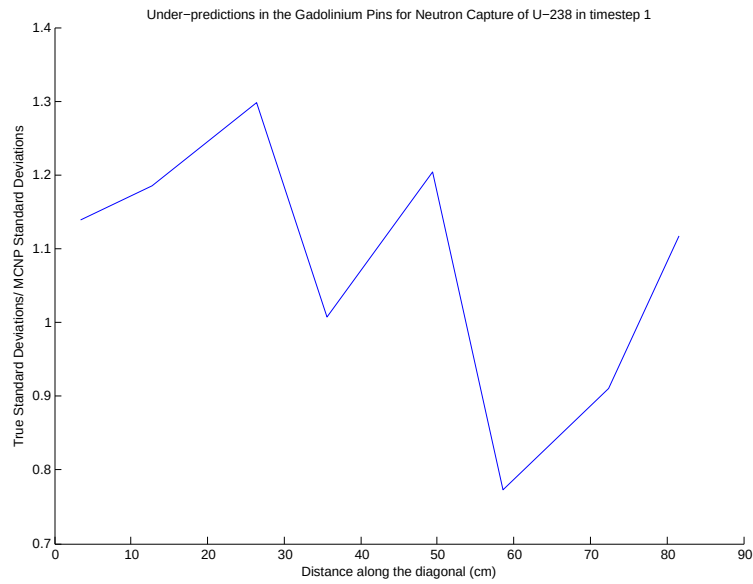


Figure 201: Uncertainty under-prediction of Capture in Gd pins for U-238 for timestep 1

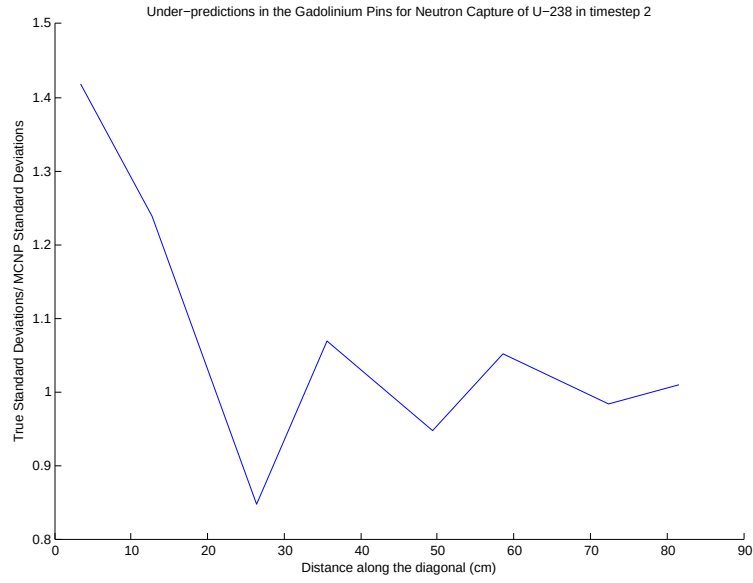


Figure 202: Uncertainty under-prediction of Capture in Gd pins for U-238 for timestep 2

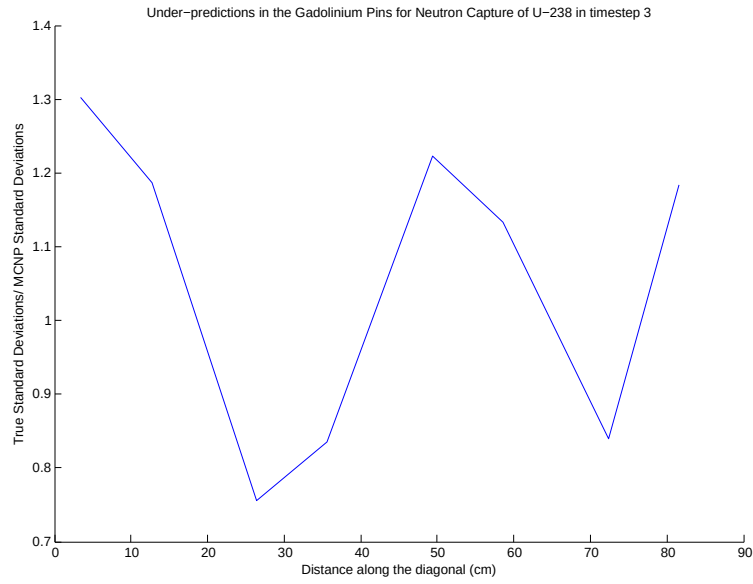


Figure 203: Uncertainty under-prediction of Capture in Gd pins for U-238 for timestep 3

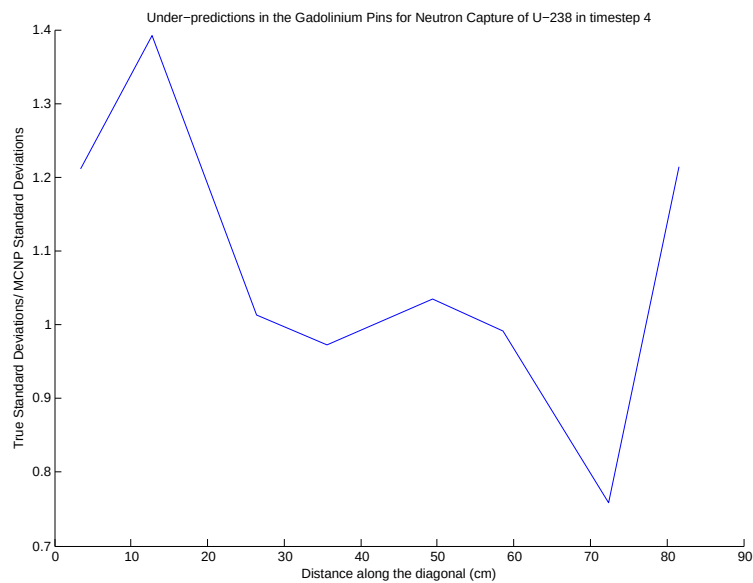


Figure 204: Uncertainty under-prediction of Capture in Gd pins for U-238 for timestep 4

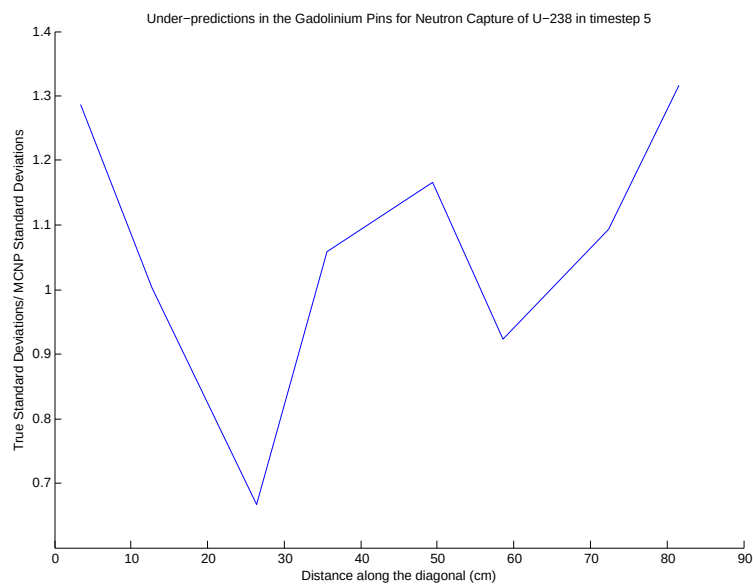


Figure 205: Uncertainty under-prediction of Capture in Gd pins for U-238 for timestep 5

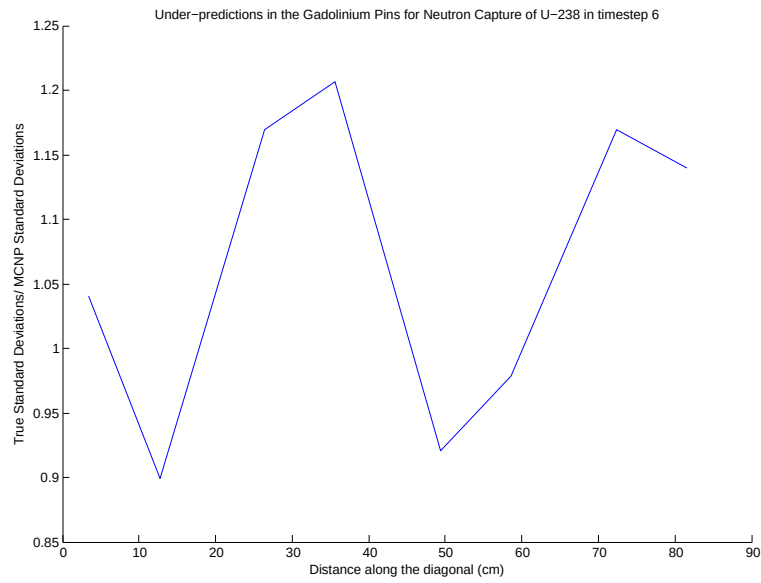


Figure 206: Uncertainty under-prediction of Capture in Gd pins for U-238 for timestep 6

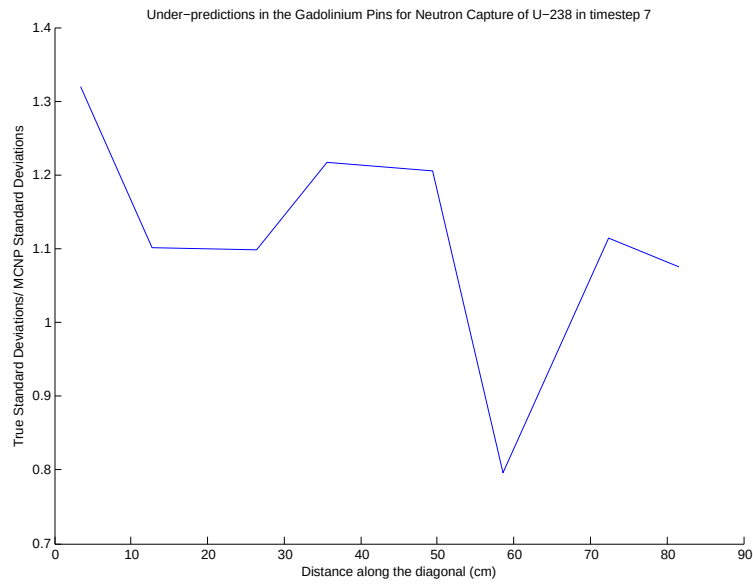


Figure 207: Uncertainty under-prediction of Capture in Gd pins for U-238 for timestep 7

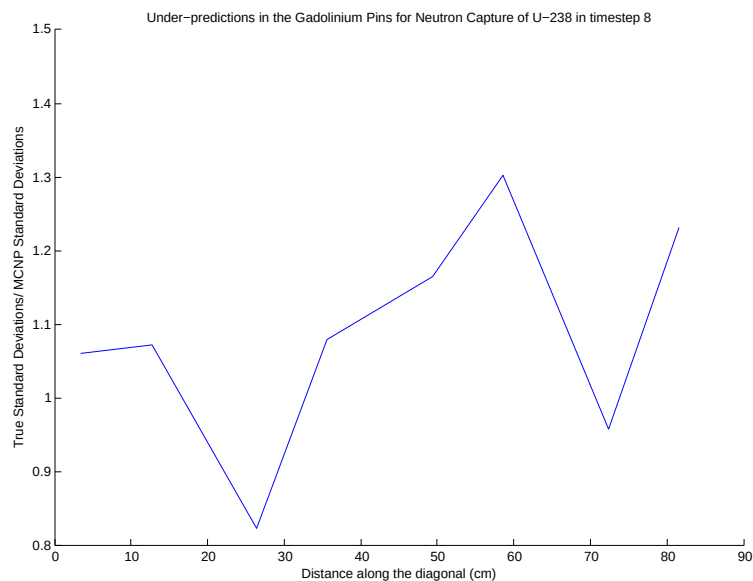


Figure 208: Uncertainty under-prediction of Capture in Gd pins for U-238 for timestep 8

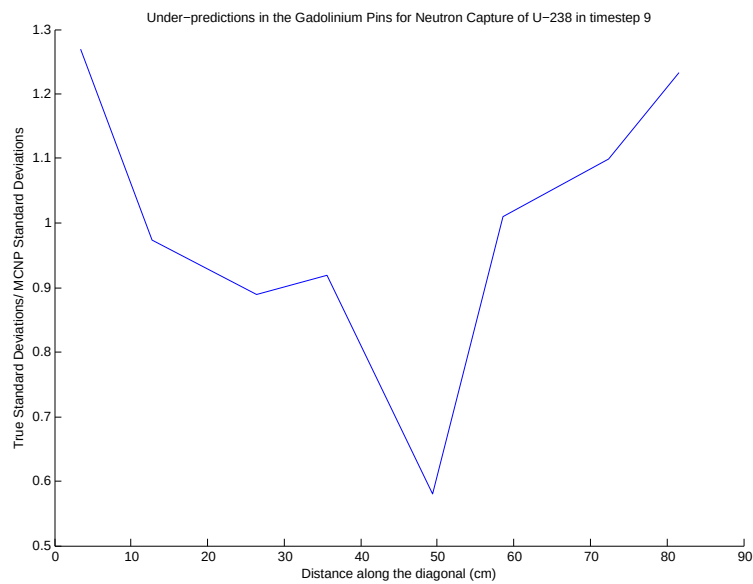


Figure 209: Uncertainty under-prediction of Capture in Gd pins for U-238 for timestep 9

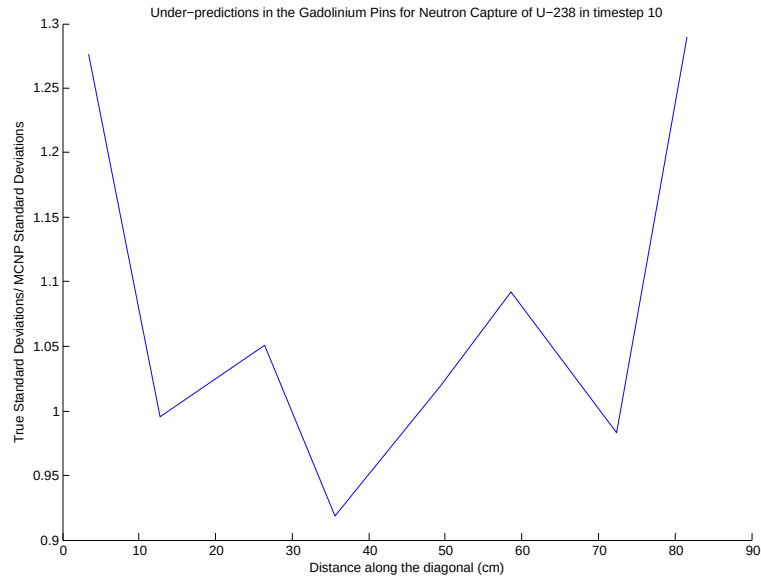


Figure 210: Uncertainty under-prediction of Capture in Gd pins for U-238 for timestep 10

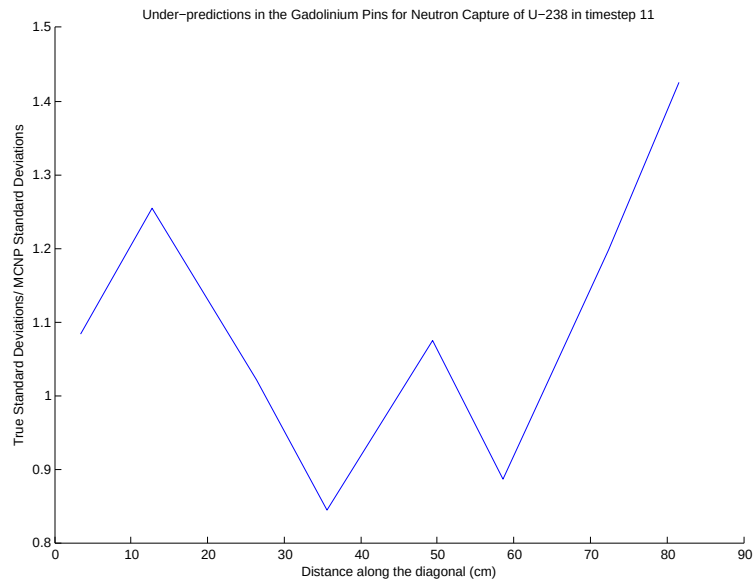


Figure 211: Uncertainty under-prediction of Capture in Gd pins for U-238 for timestep 11

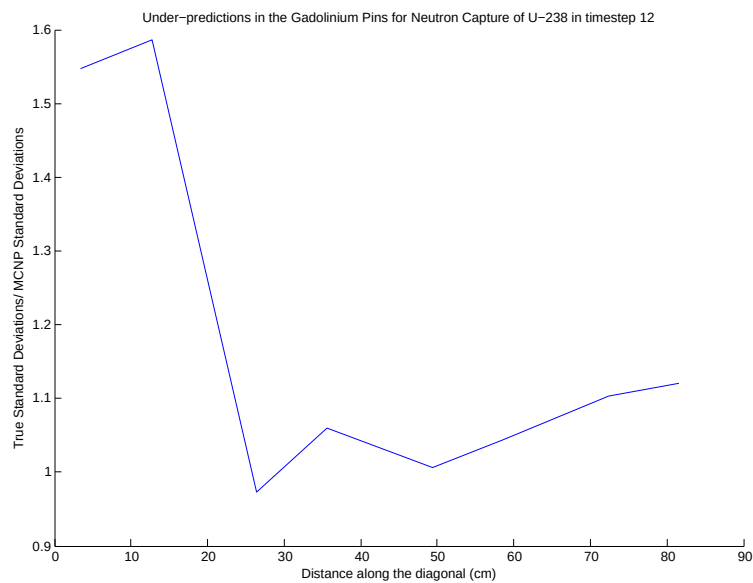


Figure 212: Uncertainty under-prediction of Capture in Gd pins for U-238 for timestep 12

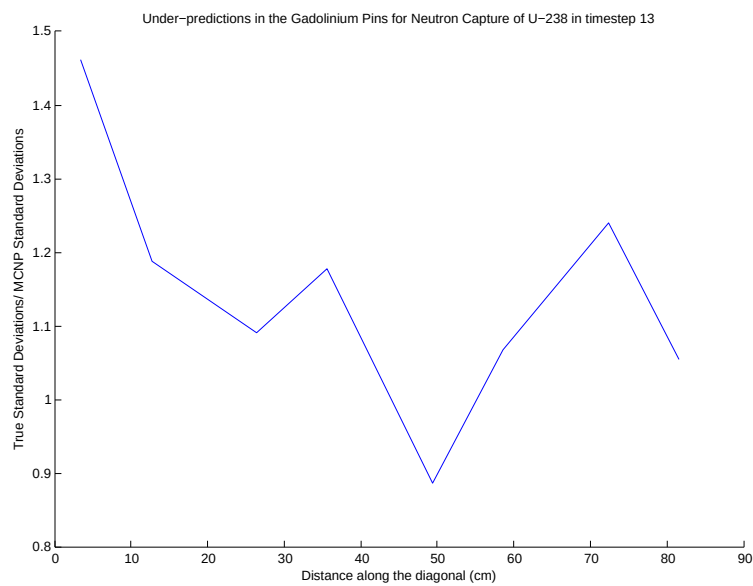


Figure 213: Uncertainty under-prediction of Capture in Gd pins for U-238 for timestep 13

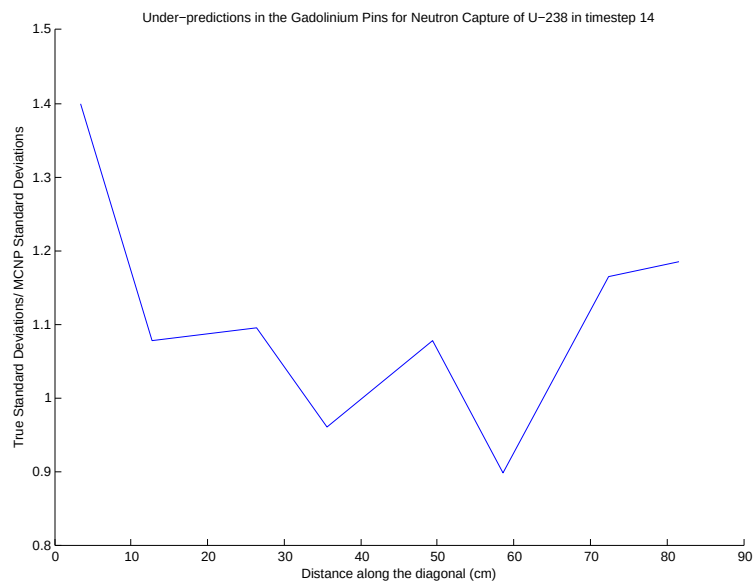


Figure 214: Uncertainty under-prediction of Capture in Gd pins for U-238 for timestep 14

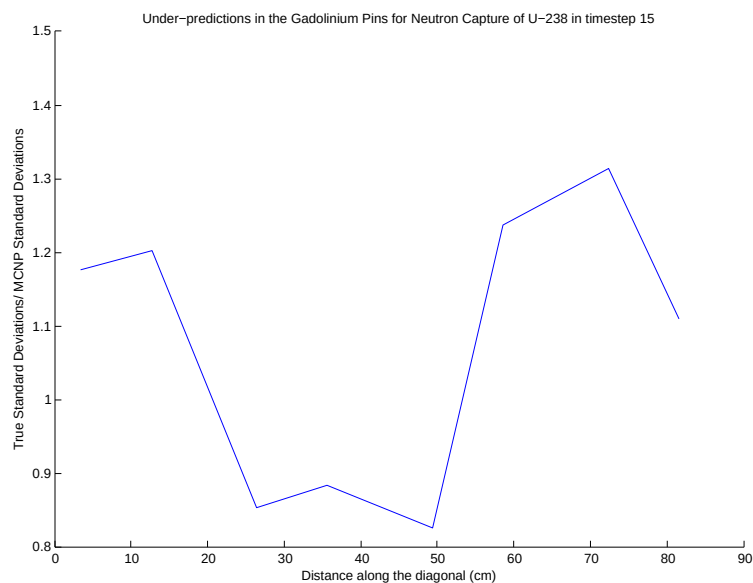


Figure 215: Uncertainty under-prediction of Capture in Gd pins for U-238 for timestep 15

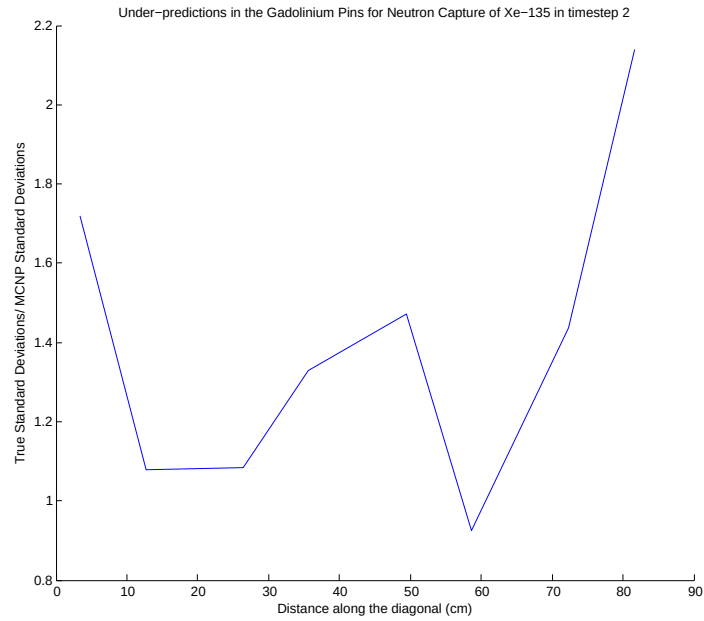


Figure 216: Uncertainty under-prediction of Capture in Gd pins for Xe-135 for timestep 2

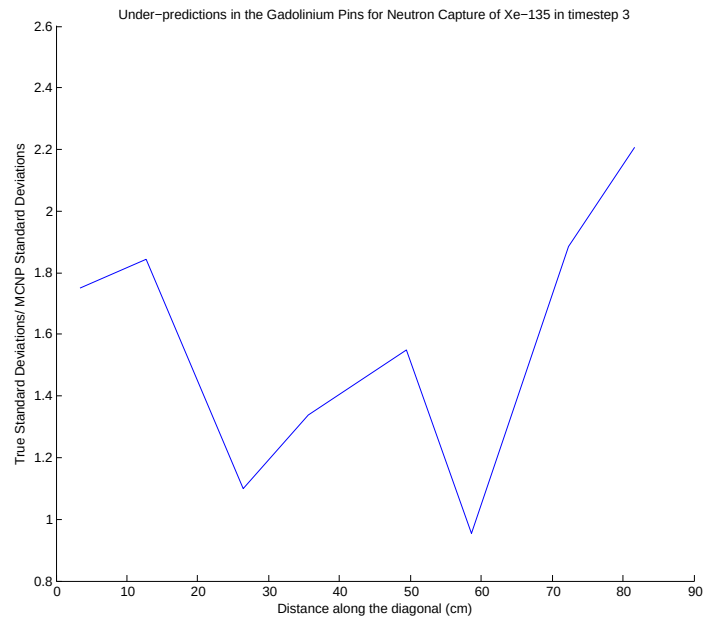


Figure 217: Uncertainty under-prediction of Capture in Gd pins for Xe-135 for timestep 3

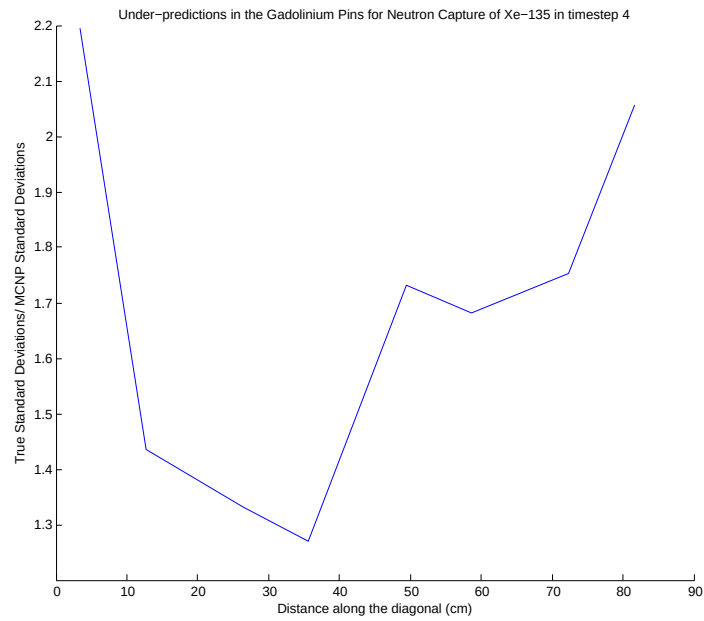


Figure 218: Uncertainty under-prediction of Capture in Gd pins for Xe-135 for timestep 4

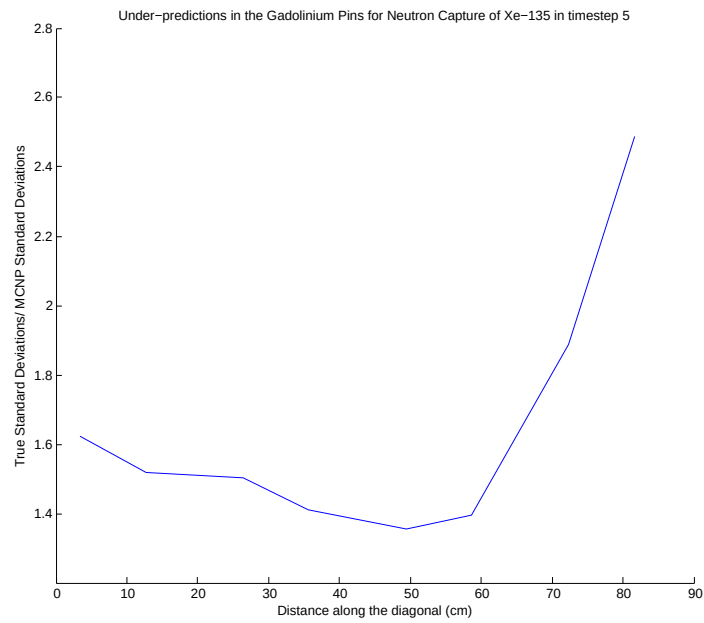


Figure 219: Uncertainty under-prediction of Capture in Gd pins for Xe-135 for timestep 5

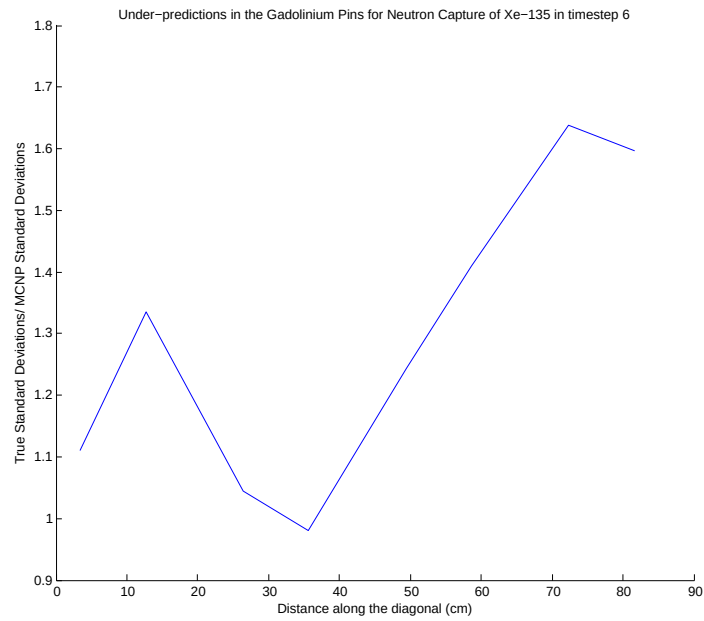


Figure 220: Uncertainty under-prediction of Capture in Gd pins for Xe-135 for timestep 6

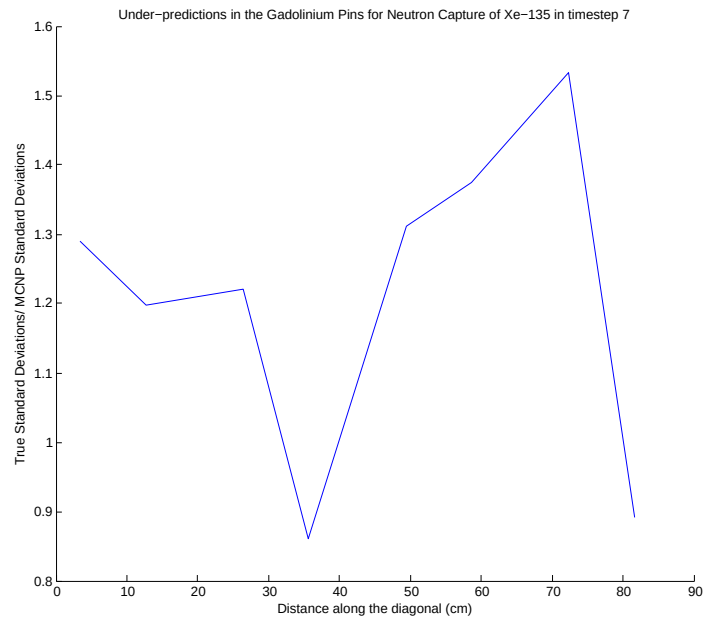


Figure 221: Uncertainty under-prediction of Capture in Gd pins for Xe-135 for timestep 7

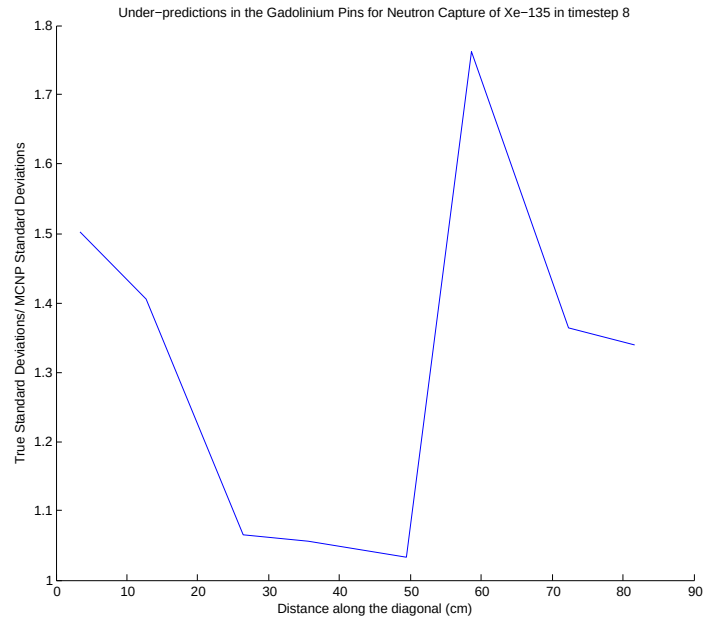


Figure 222: Uncertainty under-prediction of Capture in Gd pins for Xe-135 for timestep 8

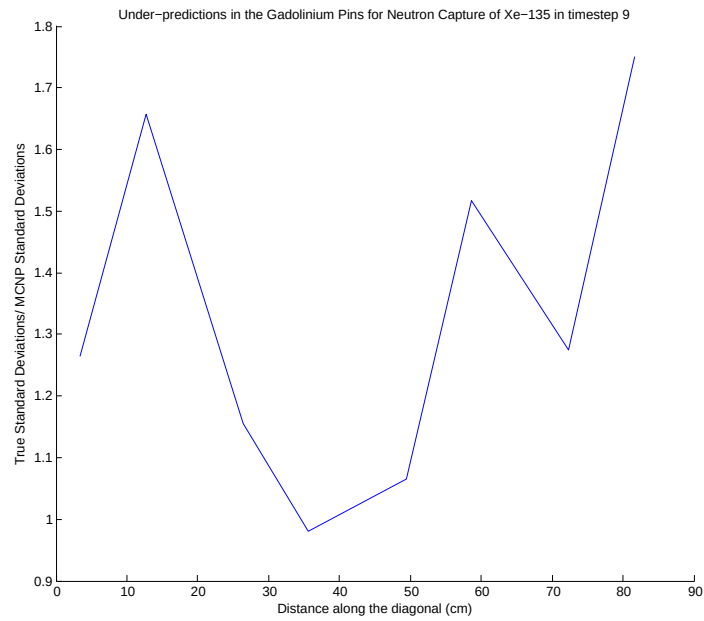


Figure 223: Uncertainty under-prediction of Capture in Gd pins for Xe-135 for timestep 9

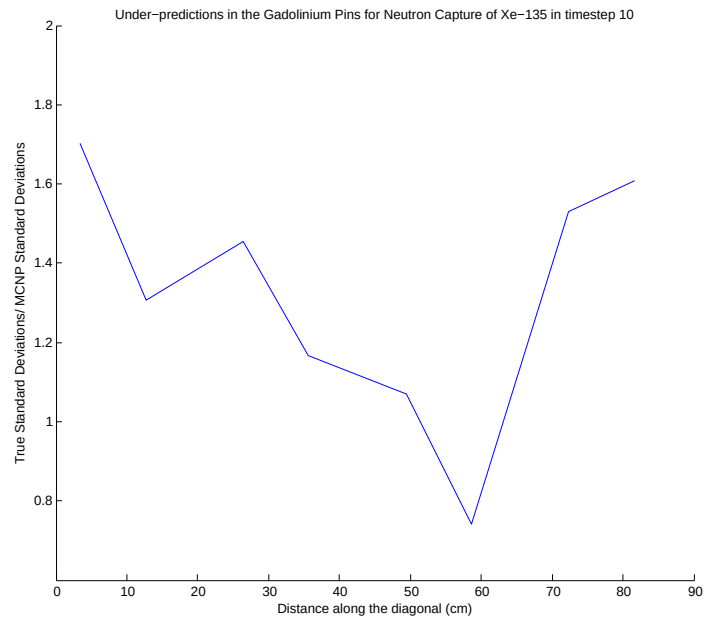


Figure 224: Uncertainty under-prediction of Capture in Gd pins for Xe-135 for timestep 10

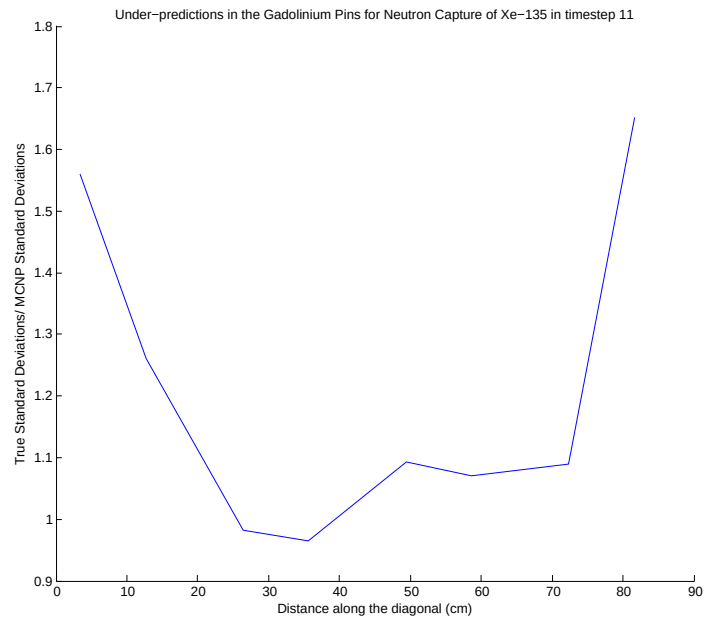


Figure 225: Uncertainty under-prediction of Capture in Gd pins for Xe-135 for timestep 11

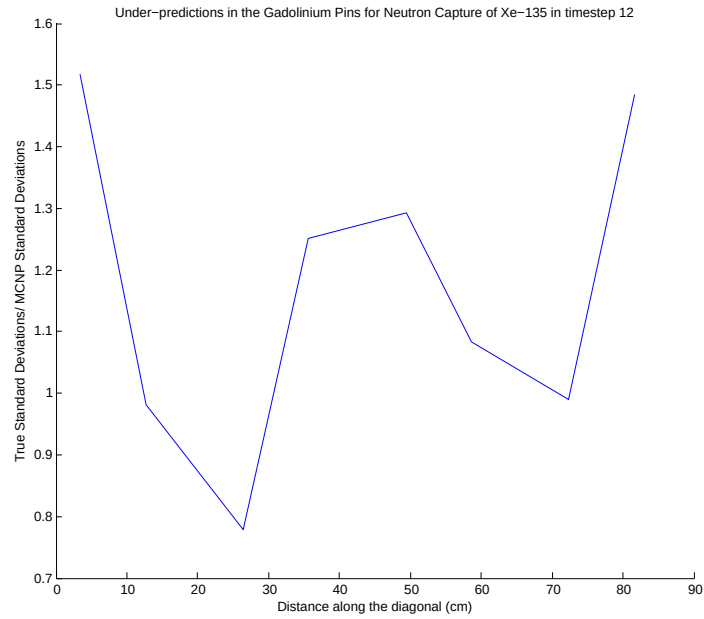


Figure 226: Uncertainty under-prediction of Capture in Gd pins for Xe-135 for timestep 12

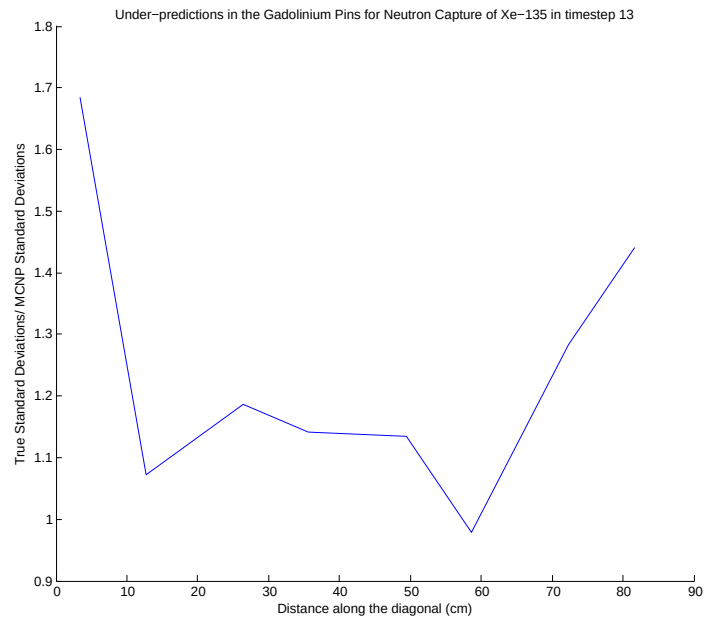


Figure 227: Uncertainty under-prediction of Capture in Gd pins for Xe-135 for timestep 13

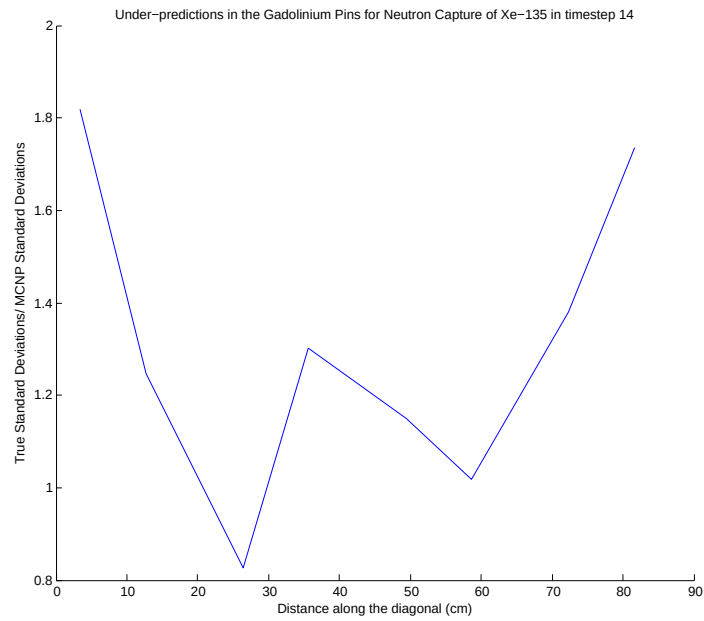


Figure 228: Uncertainty under-prediction of Capture in Gd pins for Xe-135 for timestep 14

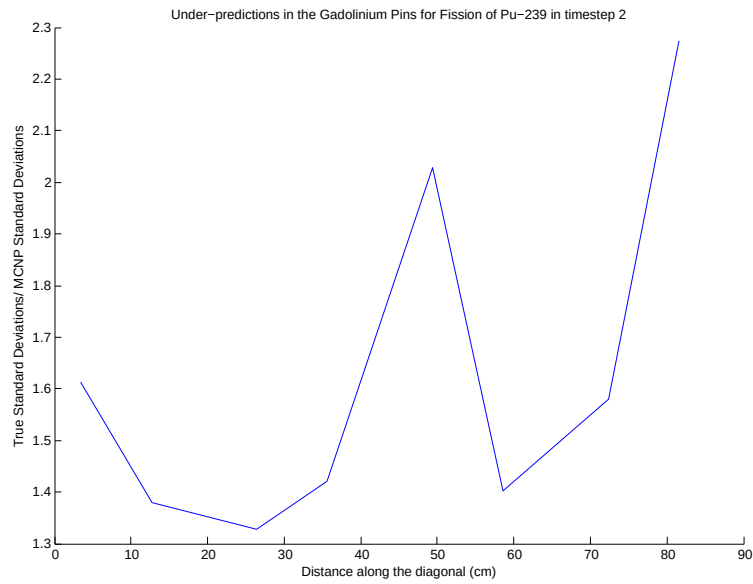


Figure 229: Uncertainty under-prediction of Fission in Gd pins for Pu-239 for timestep 2

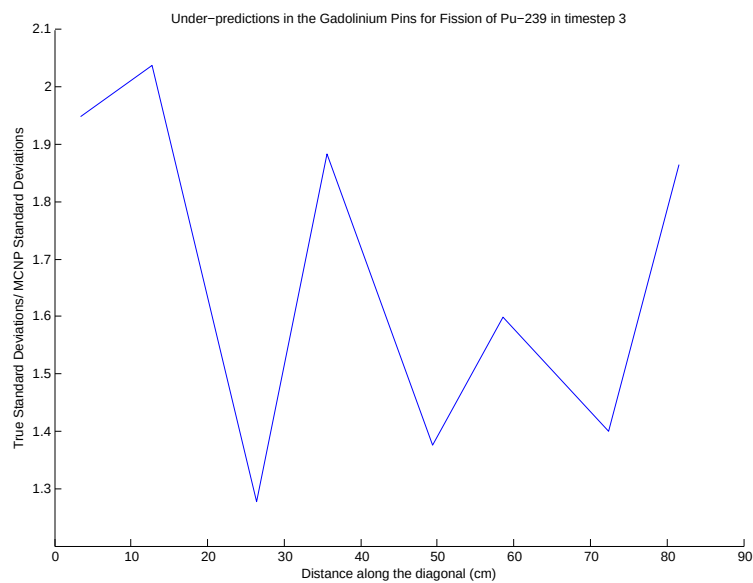


Figure 230: Uncertainty under-prediction of Fission in Gd pins for Pu-239 for timestep 3

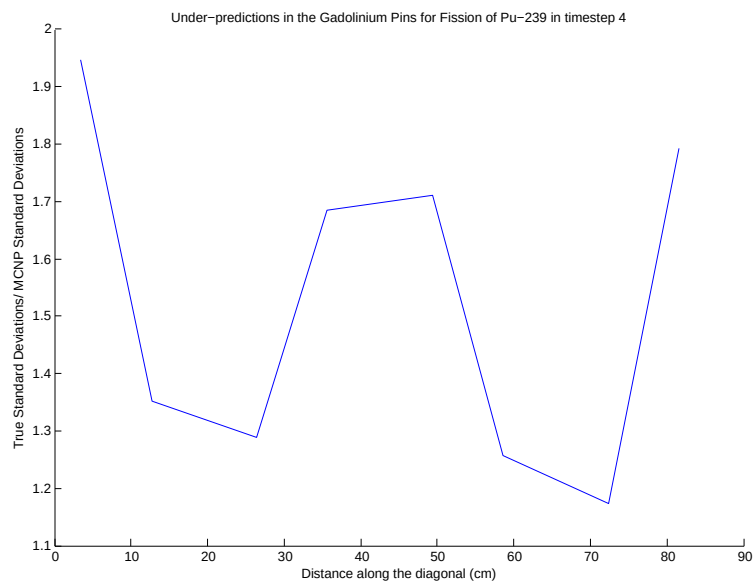


Figure 231: Uncertainty under-prediction of Fission in Gd pins for Pu-239 for timestep 4

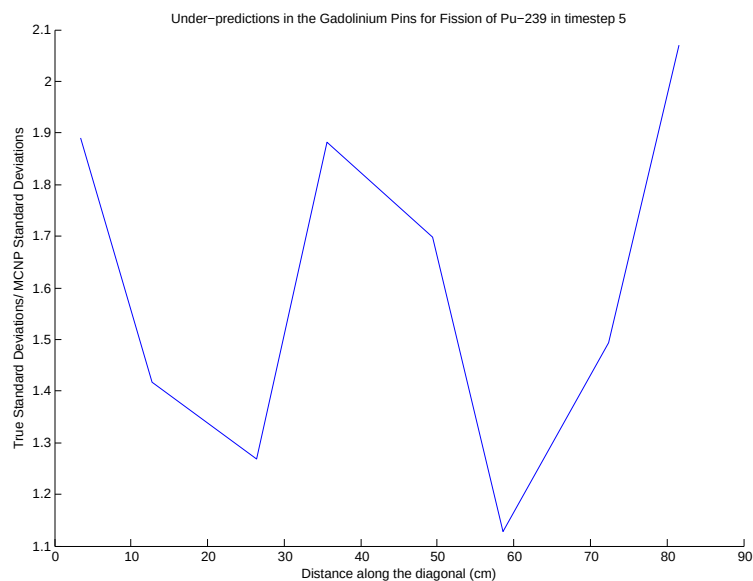


Figure 232: Uncertainty under-prediction of Fission in Gd pins for Pu-239 for timestep 5

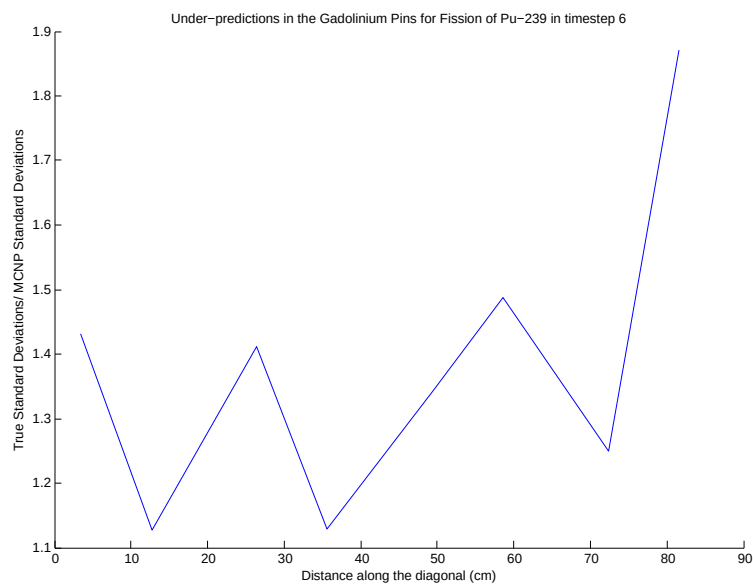


Figure 233: Uncertainty under-prediction of Fission in Gd pins for Pu-239 for timestep 6

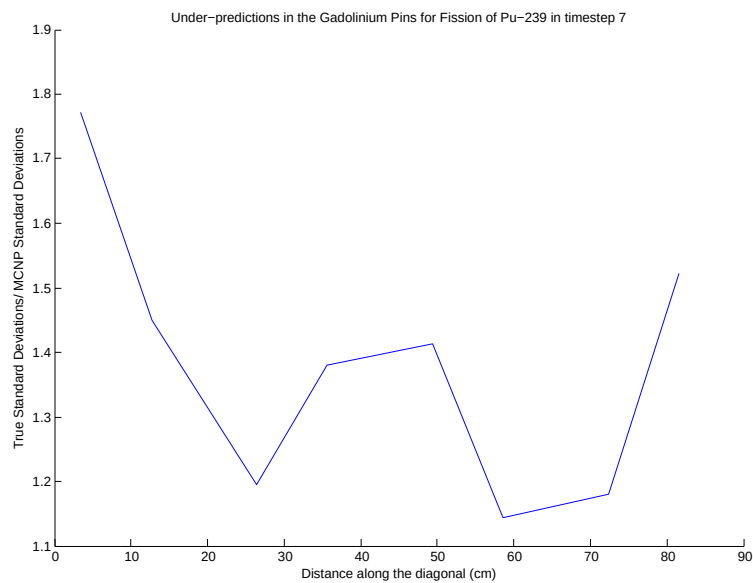


Figure 234: Uncertainty under-prediction of Fission in Gd pins for Pu-239 for timestep 7

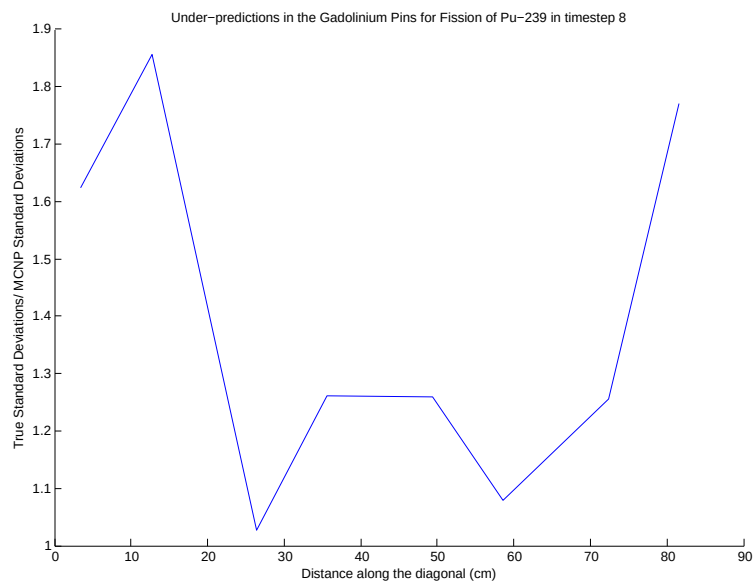


Figure 235: Uncertainty under-prediction of Fission in Gd pins for Pu-239 for timestep 8

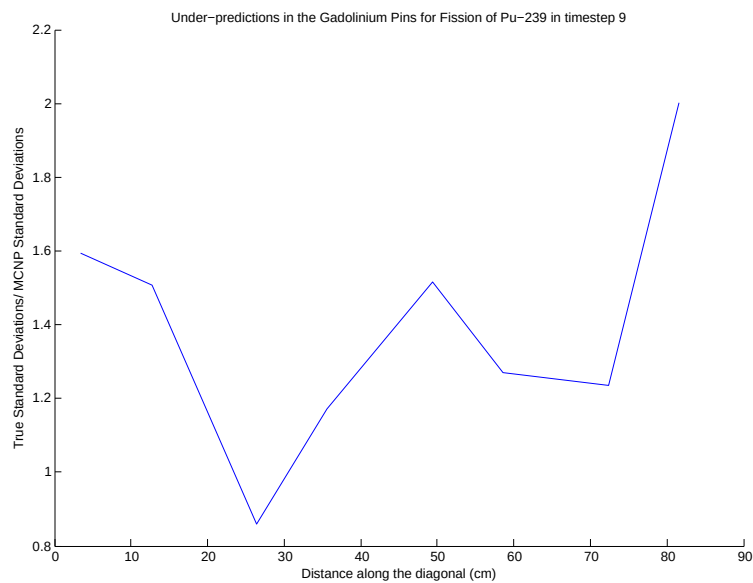


Figure 236: Uncertainty under-prediction of Fission in Gd pins for Pu-239 for timestep 9

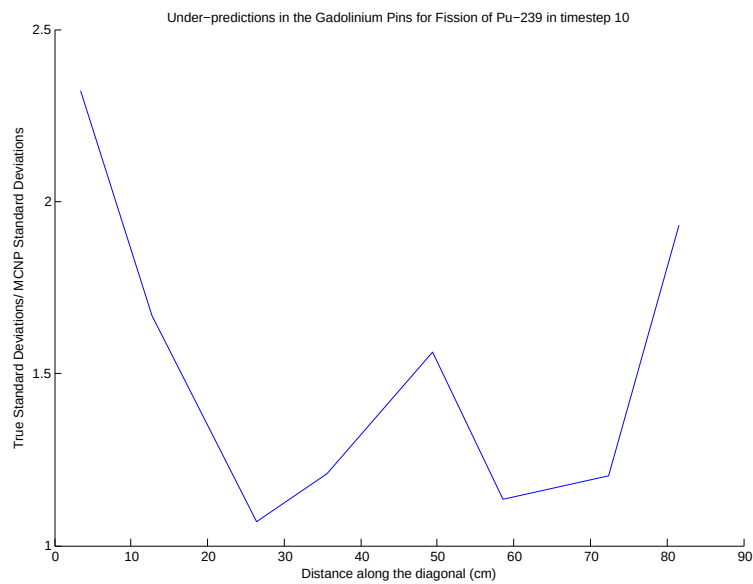


Figure 237: Uncertainty under-prediction of Fission in Gd pins for Pu-239 for timestep 10

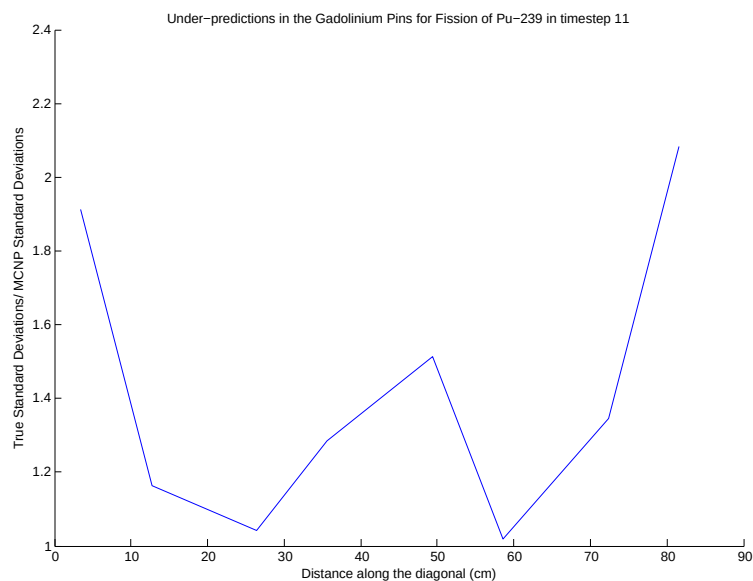


Figure 238: Uncertainty under-prediction of Fission in Gd pins for Pu-239 for timestep 11

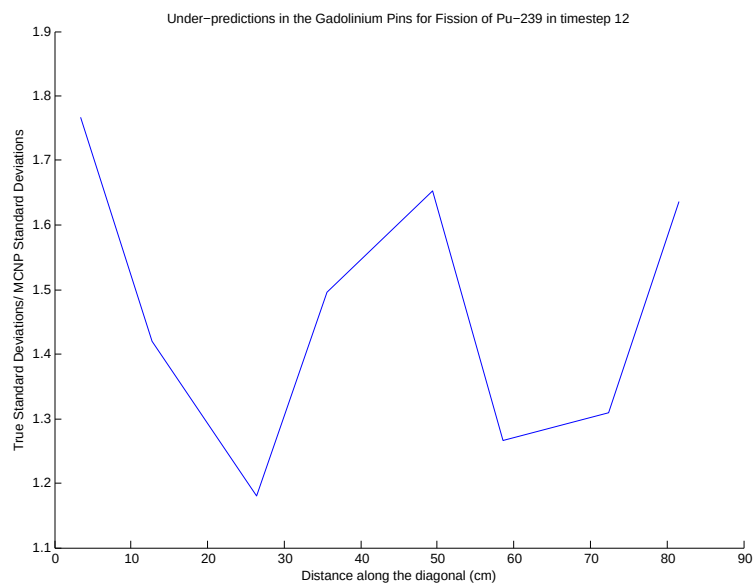


Figure 239: Uncertainty under-prediction of Fission in Gd pins for Pu-239 for timestep 12

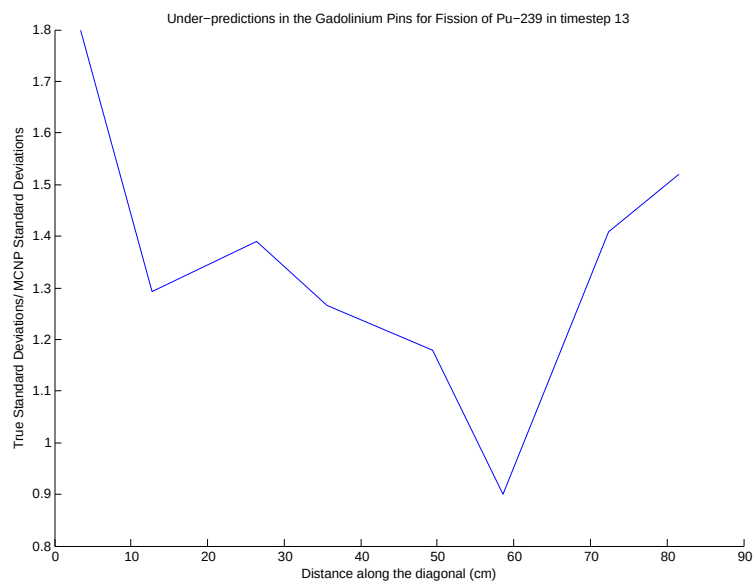


Figure 240: Uncertainty under-prediction of Fission in Gd pins for Pu-239 for timestep 13

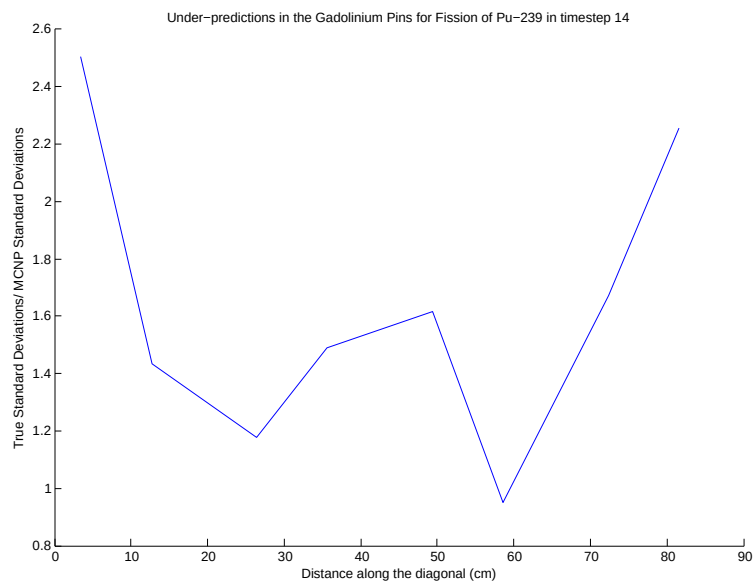


Figure 241: Uncertainty under-prediction of Fission in Gd pins for Pu-239 for timestep 14

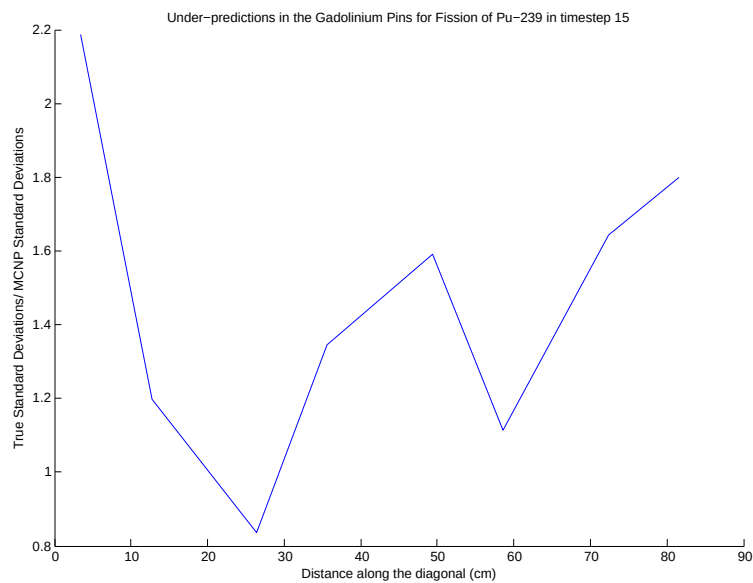


Figure 242: Uncertainty under-prediction of Fission in Gd pins for Pu-239 for timestep 15

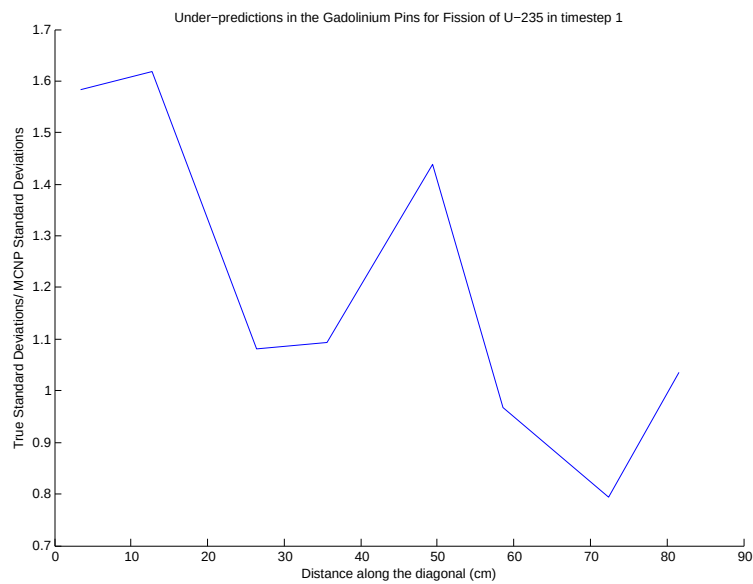


Figure 243: Uncertainty under-prediction of Fission in Gd pins for U-235 for timestep 1

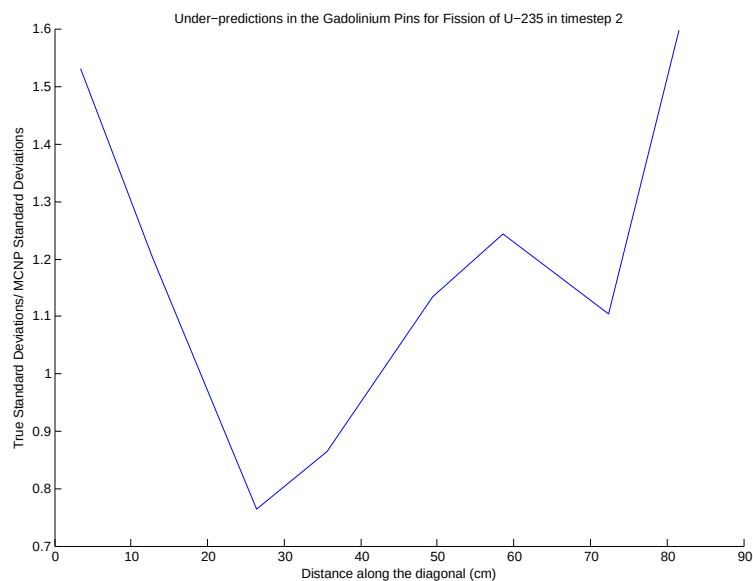


Figure 244: Uncertainty under-prediction of Fission in Gd pins for U-235 for timestep 2

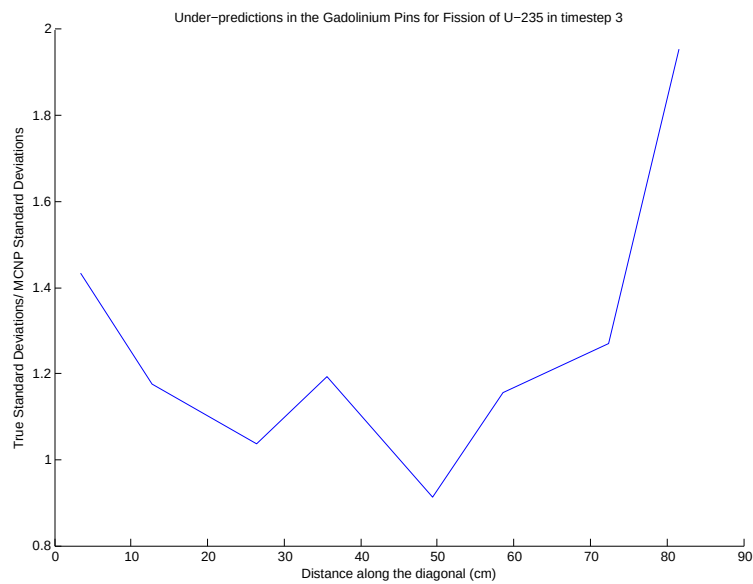


Figure 245: Uncertainty under-prediction of Fission in Gd pins for U-235 for timestep 3

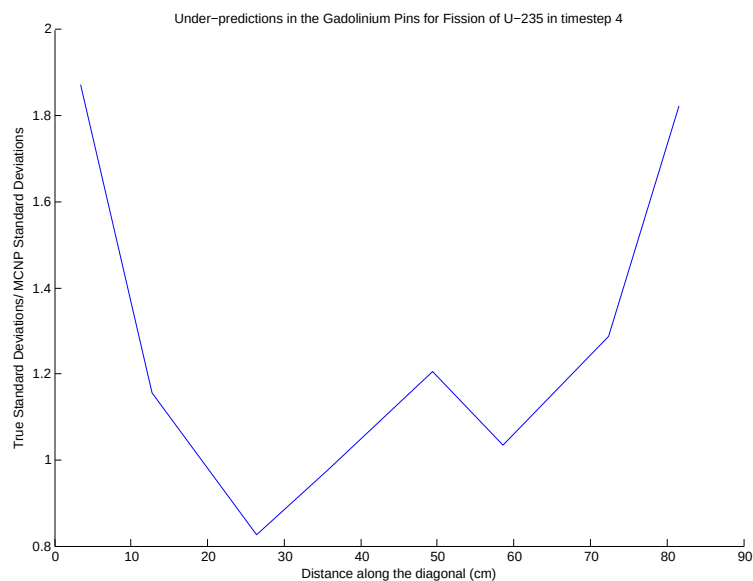


Figure 246: Uncertainty under-prediction of Fission in Gd pins for U-235 for timestep 4

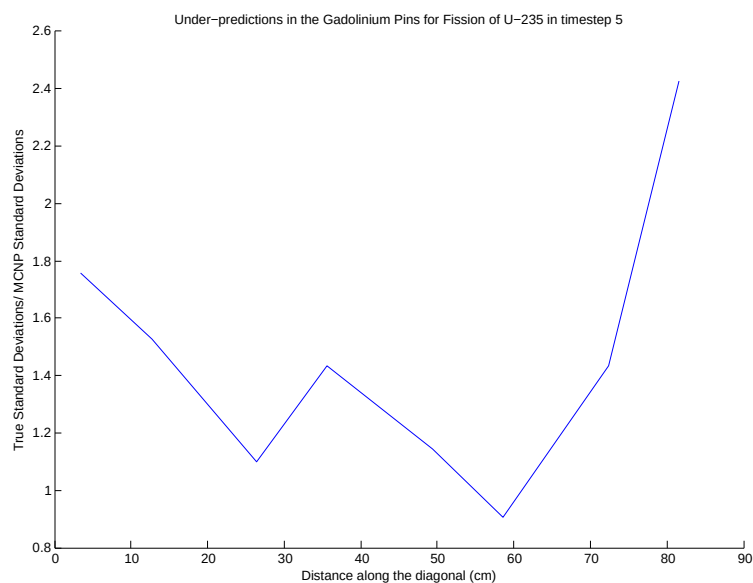


Figure 247: Uncertainty under-prediction of Fission in Gd pins for U-235 for timestep 5

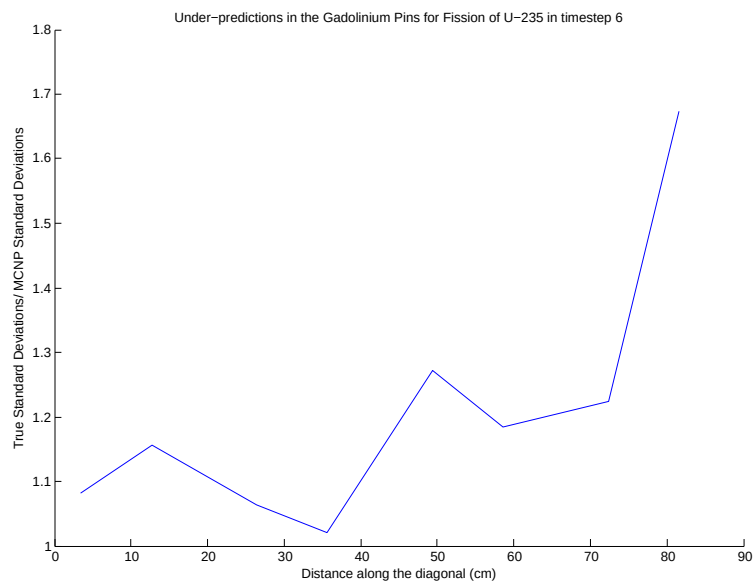


Figure 248: Uncertainty under-prediction of Fission in Gd pins for U-235 for timestep 6

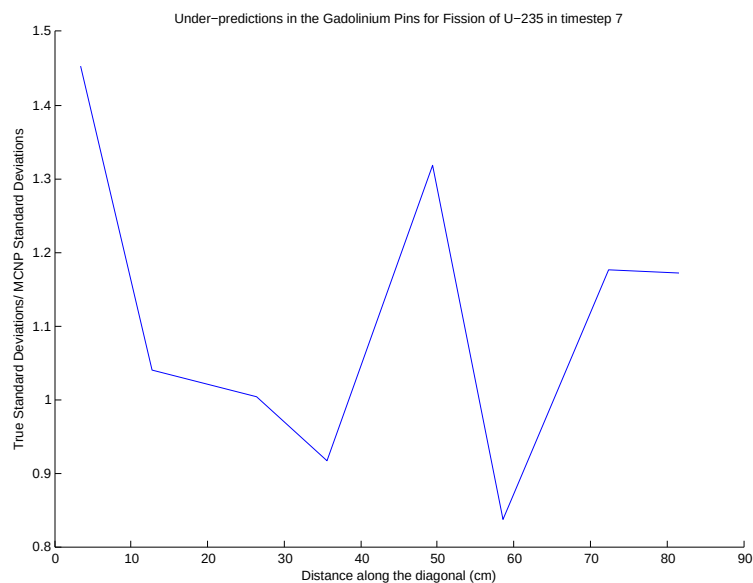


Figure 249: Uncertainty under-prediction of Fission in Gd pins for U-235 for timestep 7

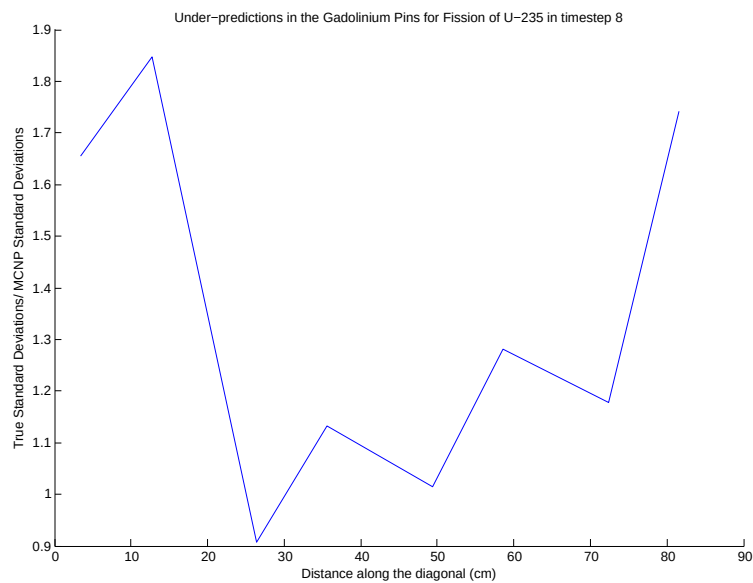


Figure 250: Uncertainty under-prediction of Fission in Gd pins for U-235 for timestep 8

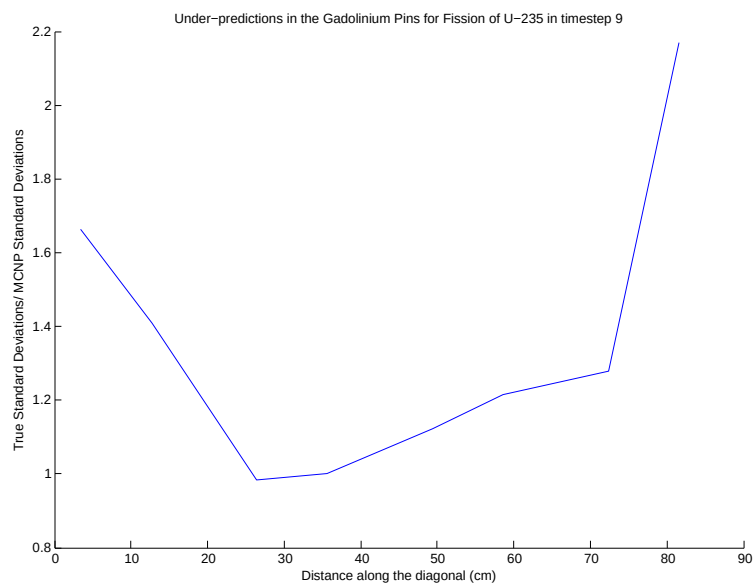


Figure 251: Uncertainty under-prediction of Fission in Gd pins for U-235 for timestep 9

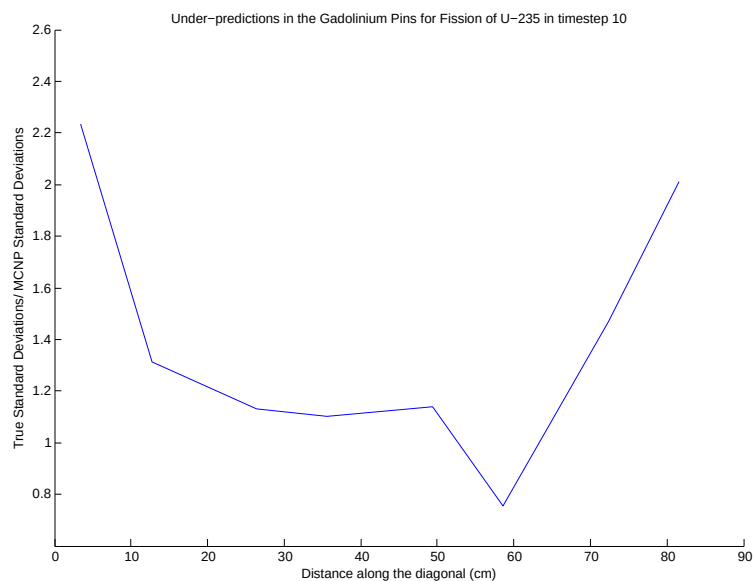


Figure 252: Uncertainty under-prediction of Fission in Gd pins for U-235 for timestep 10

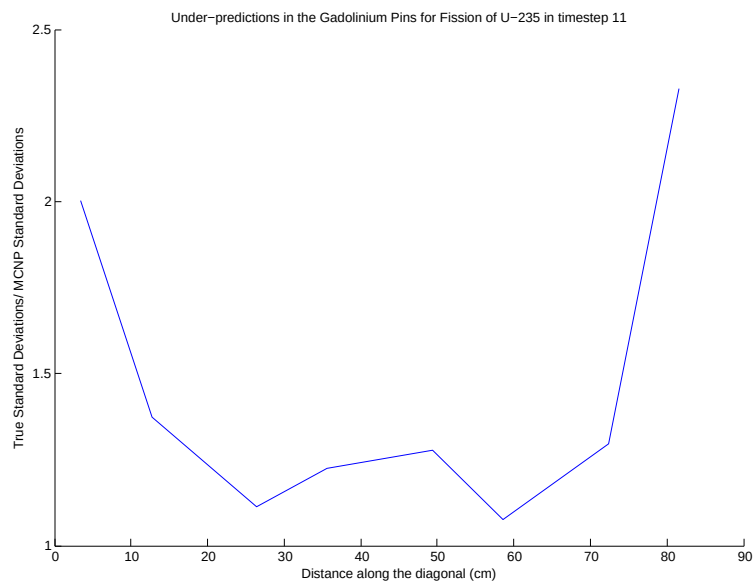


Figure 253: Uncertainty under-prediction of Fission in Gd pins for U-235 for timestep 11

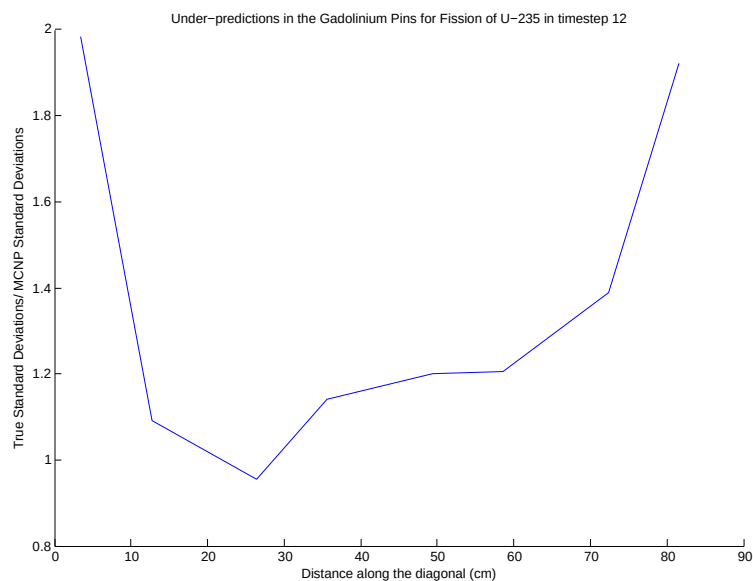


Figure 254: Uncertainty under-prediction of Fission in Gd pins for U-235 for timestep 12

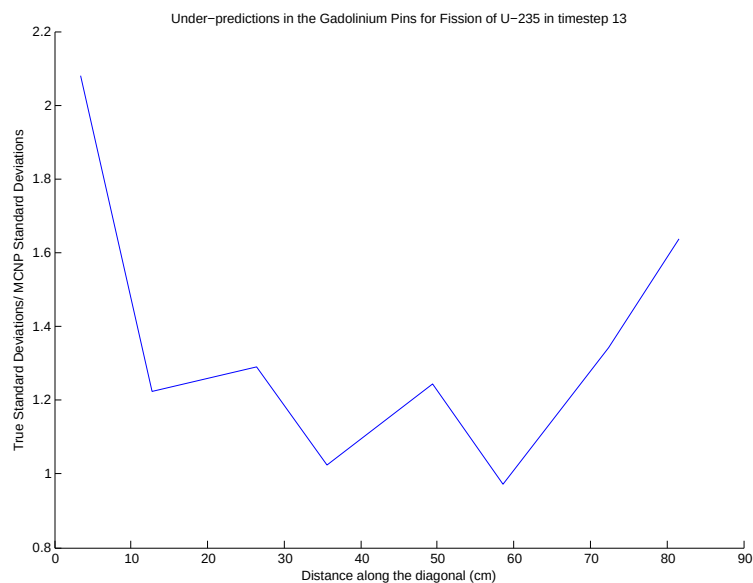


Figure 255: Uncertainty under-prediction of Fission in Gd pins for U-235 for timestep 13

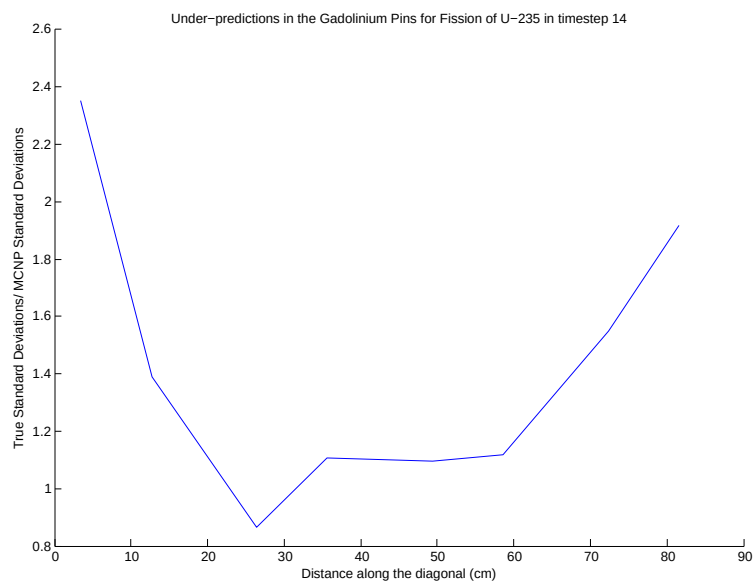


Figure 256: Uncertainty under-prediction of Fission in Gd pins for U-235 for timestep 14

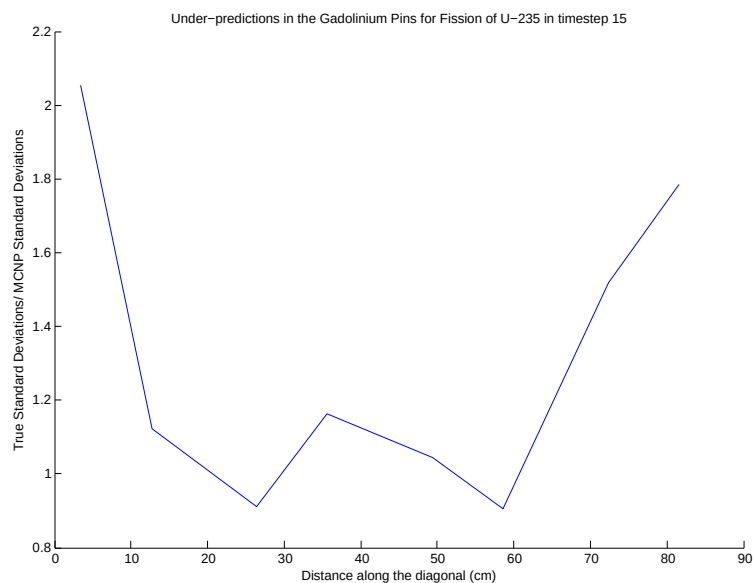


Figure 257: Uncertainty under-prediction of Fission in Gd pins for U-235 for timestep 15

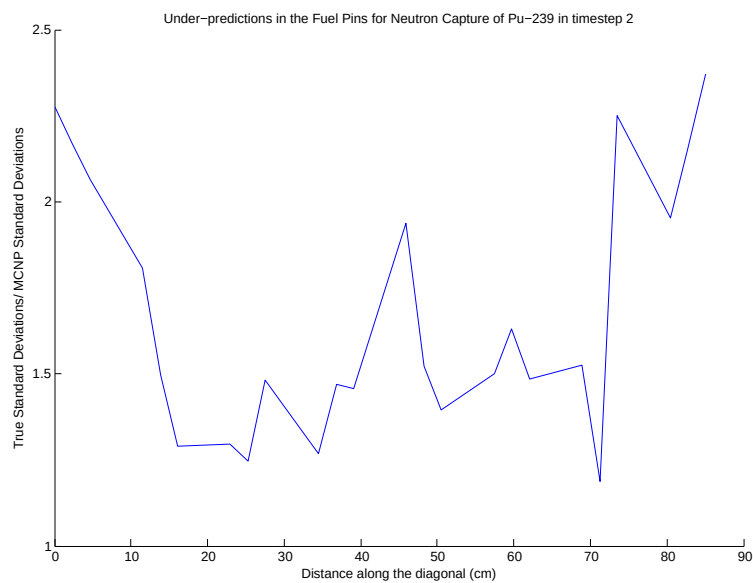


Figure 258: Uncertainty under-prediction of Capture in Fuel pins for Pu-239 for timestep 2

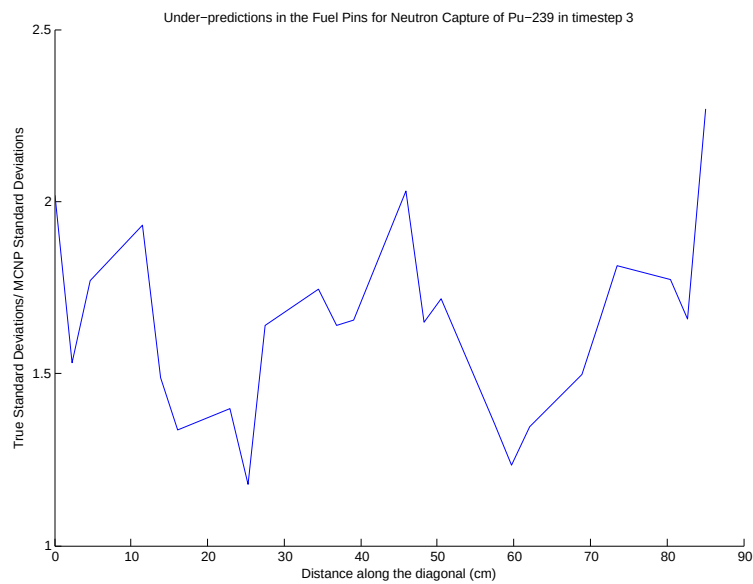


Figure 259: Uncertainty under-prediction of Capture in Fuel pins for Pu-239 for timestep 3

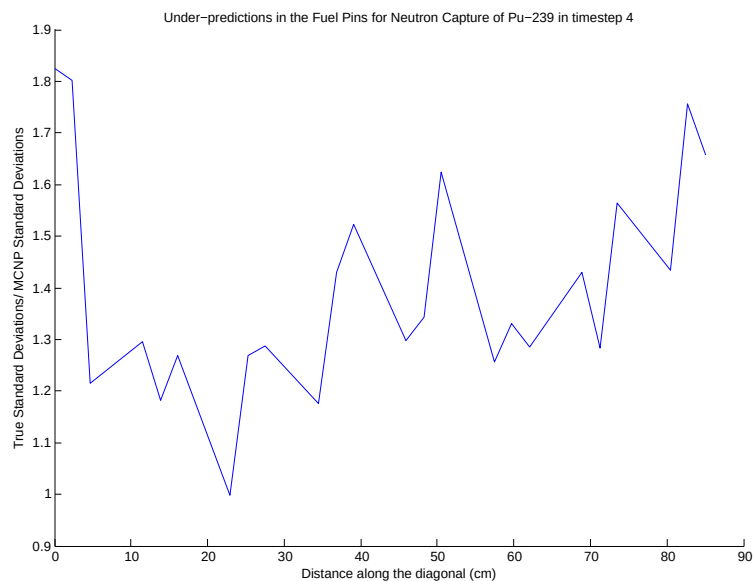


Figure 260: Uncertainty under-prediction of Capture in Fuel pins for Pu-239 for timestep 4

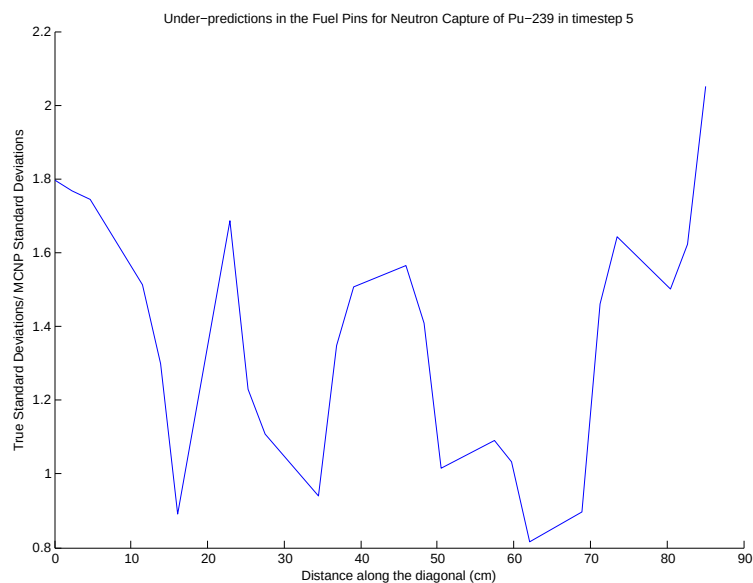


Figure 261: Uncertainty under-prediction of Capture in Fuel pins for Pu-239 for timestep 5

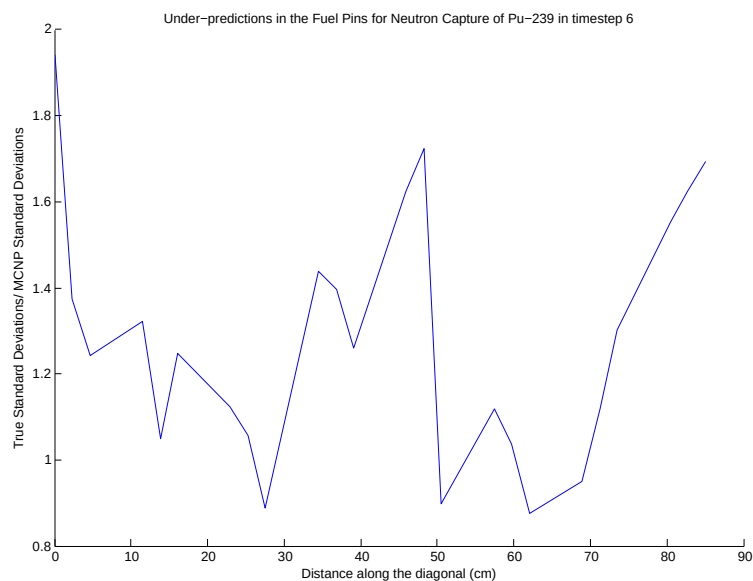


Figure 262: Uncertainty under-prediction of Capture in Fuel pins for Pu-239 for timestep 6

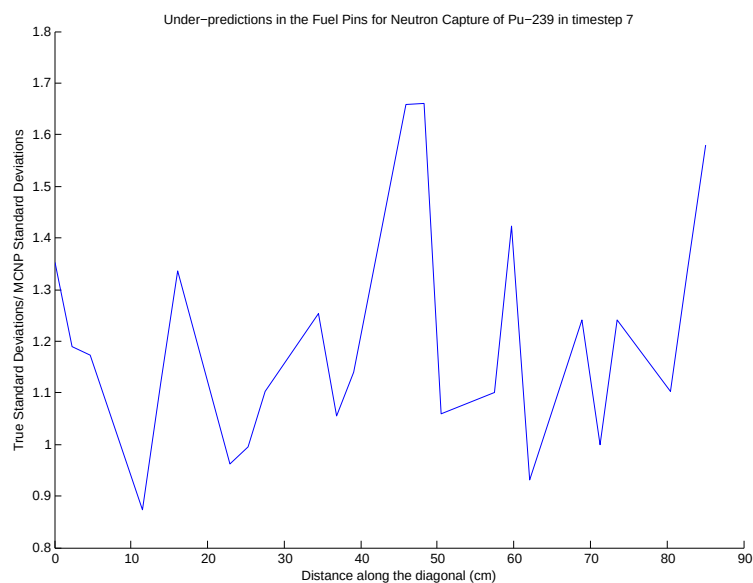


Figure 263: Uncertainty under-prediction of Capture in Fuel pins for Pu-239 for timestep 7

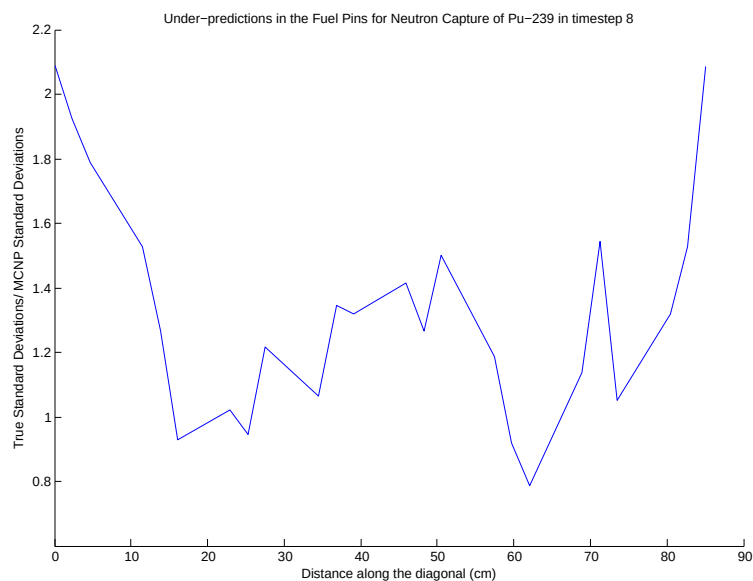


Figure 264: Uncertainty under-prediction of Capture in Fuel pins for Pu-239 for timestep 8

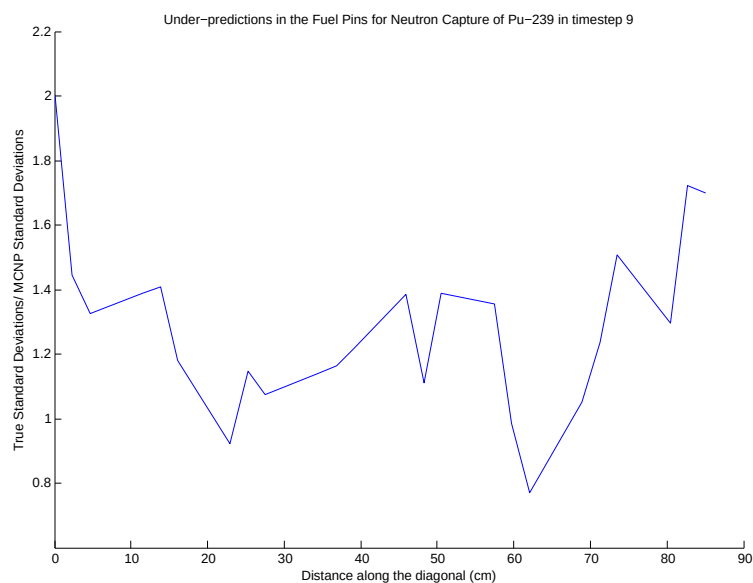


Figure 265: Uncertainty under-prediction of Capture in Fuel pins for Pu-239 for timestep 9

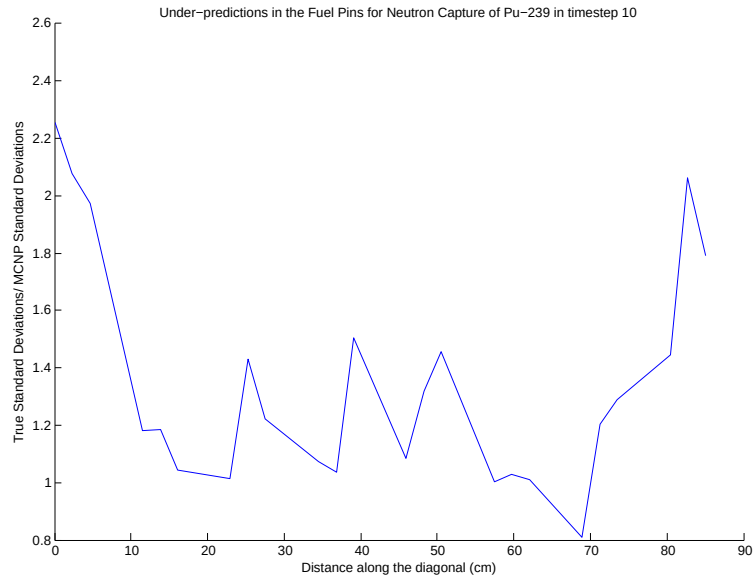


Figure 266: Uncertainty under-prediction of Capture in Fuel pins for Pu-239 for timestep 10

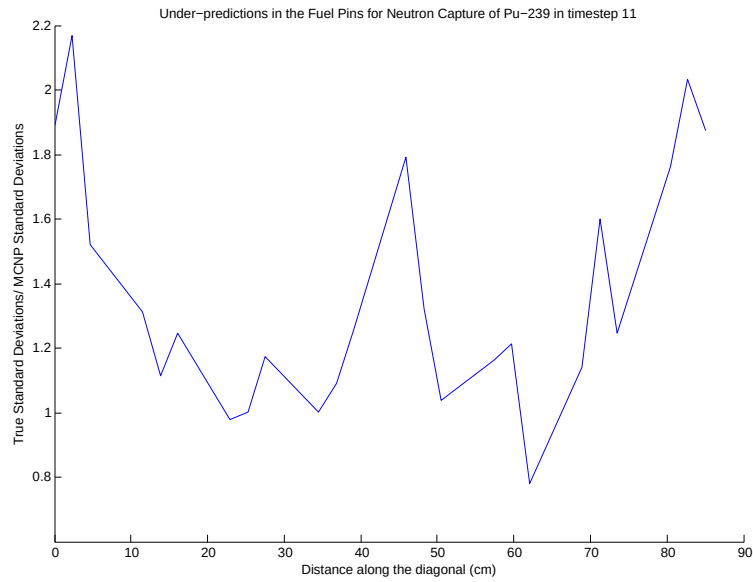


Figure 267: Uncertainty under-prediction of Capture in Fuel pins for Pu-239 for timestep 11

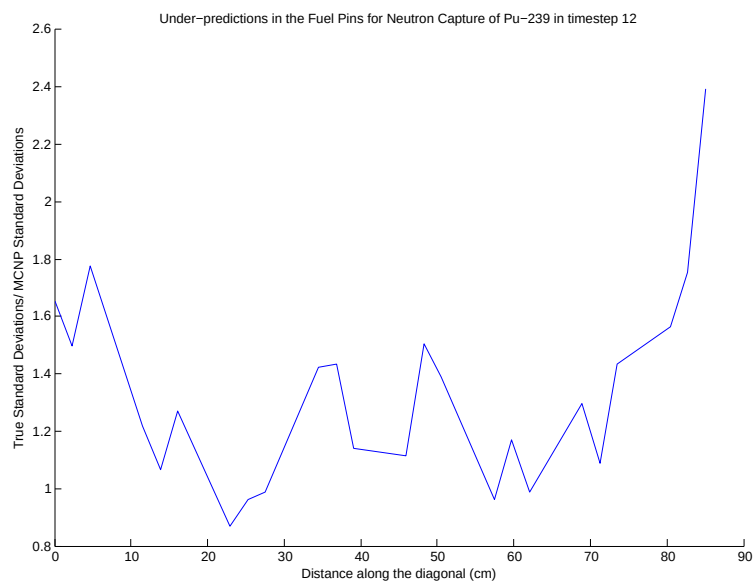


Figure 268: Uncertainty under-prediction of Capture in Fuel pins for Pu-239 for timestep 12

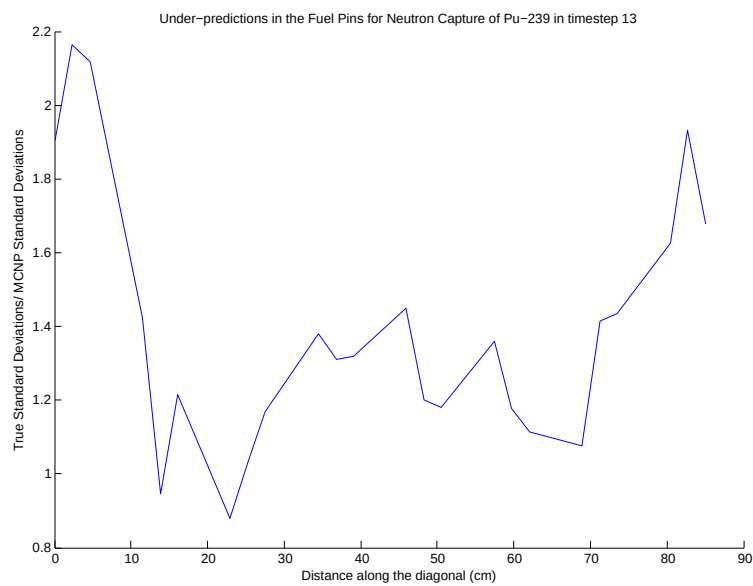


Figure 269: Uncertainty under-prediction of Capture in Fuel pins for Pu-239 for timestep 13

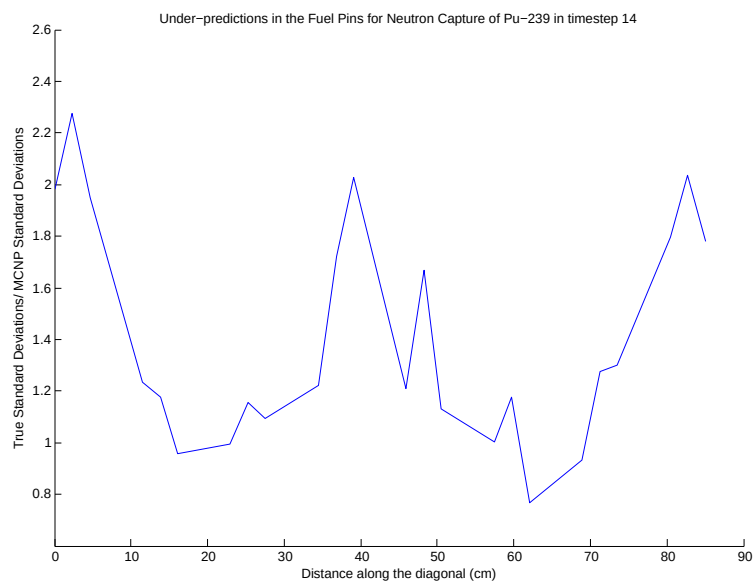


Figure 270: Uncertainty under-prediction of Capture in Fuel pins for Pu-239 for timestep 14

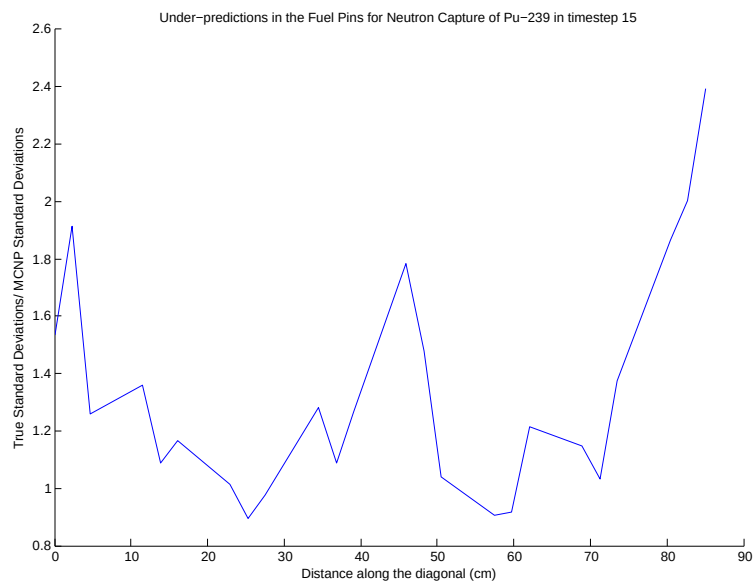


Figure 271: Uncertainty under-prediction of Capture in Fuel pins for Pu-239 for timestep 15

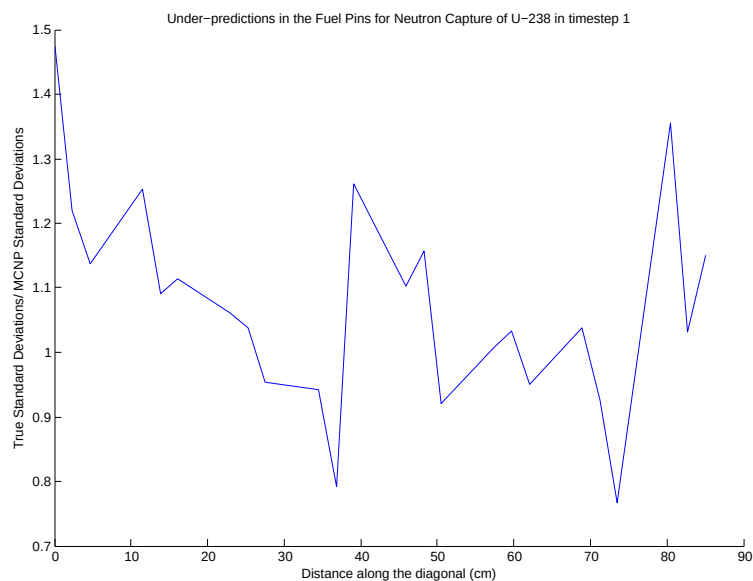


Figure 272: Uncertainty under-prediction of Capture in Fuel pins for U-238 for timestep 1

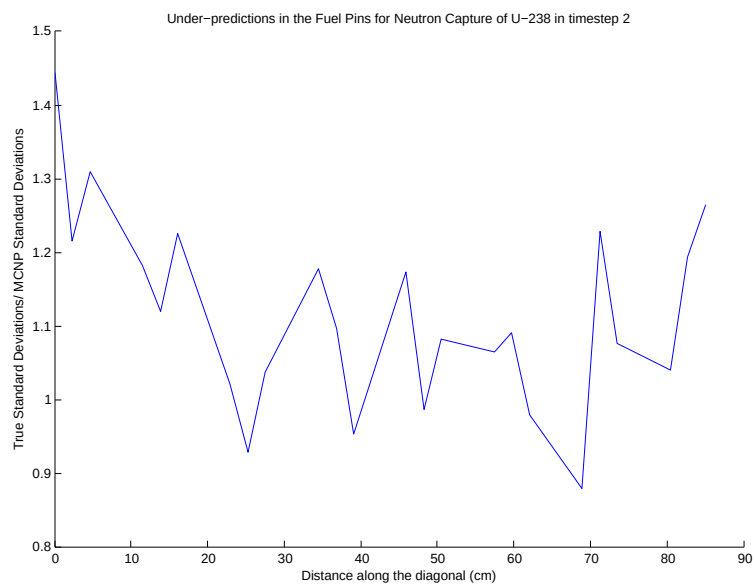


Figure 273: Uncertainty under-prediction of Capture in Fuel pins for U-238 for timestep 2

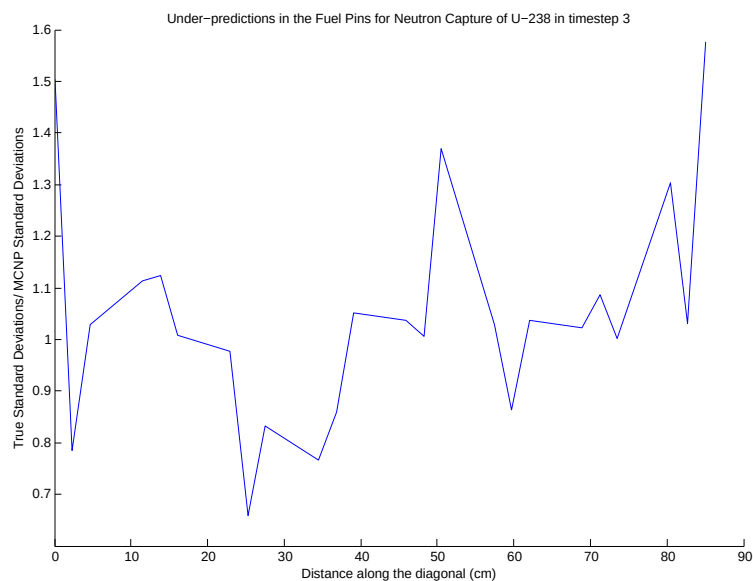


Figure 274: Uncertainty under-prediction of Capture in Fuel pins for U-238 for timestep 3

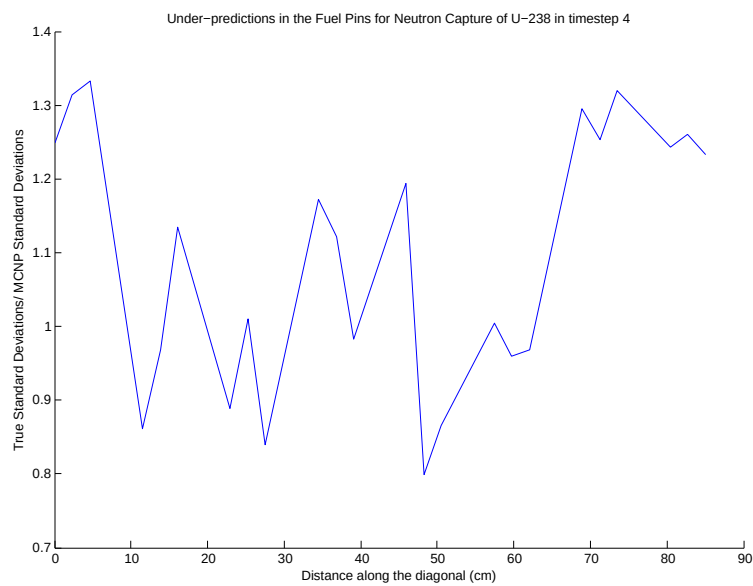


Figure 275: Uncertainty under-prediction of Capture in Fuel pins for U-238 for timestep 4

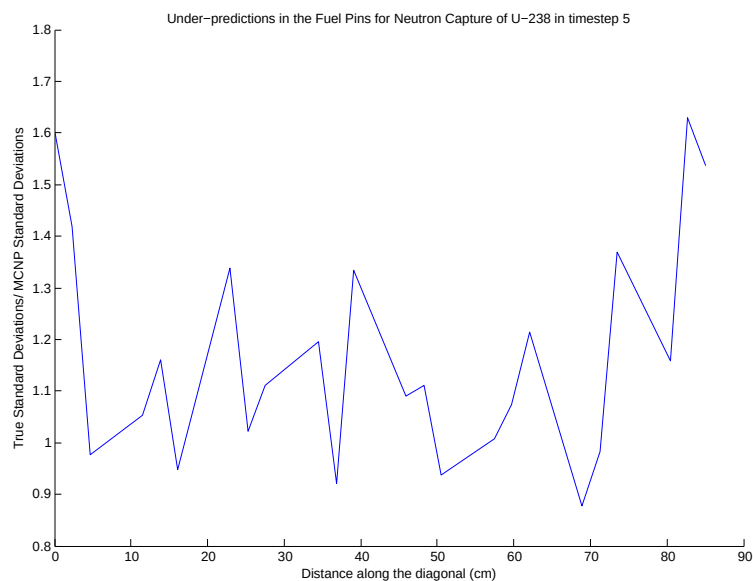


Figure 276: Uncertainty under-prediction of Capture in Fuel pins for U-238 for timestep 5

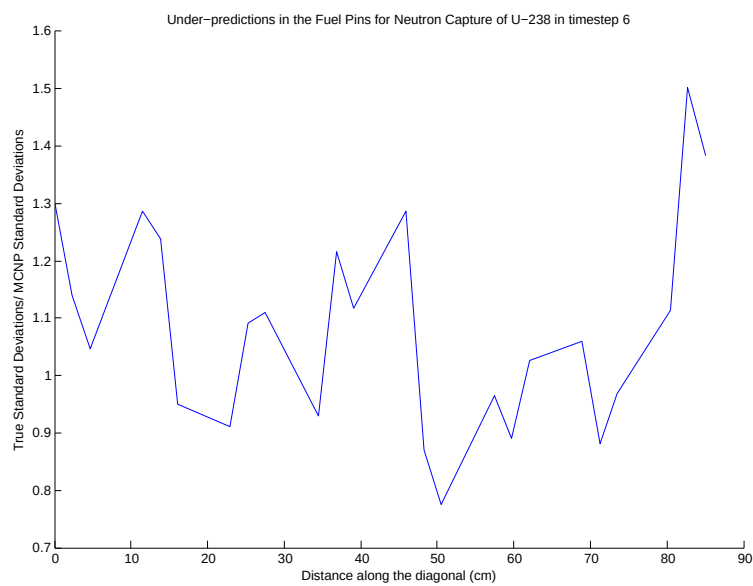


Figure 277: Uncertainty under-prediction of Capture in Fuel pins for U-238 for timestep 6

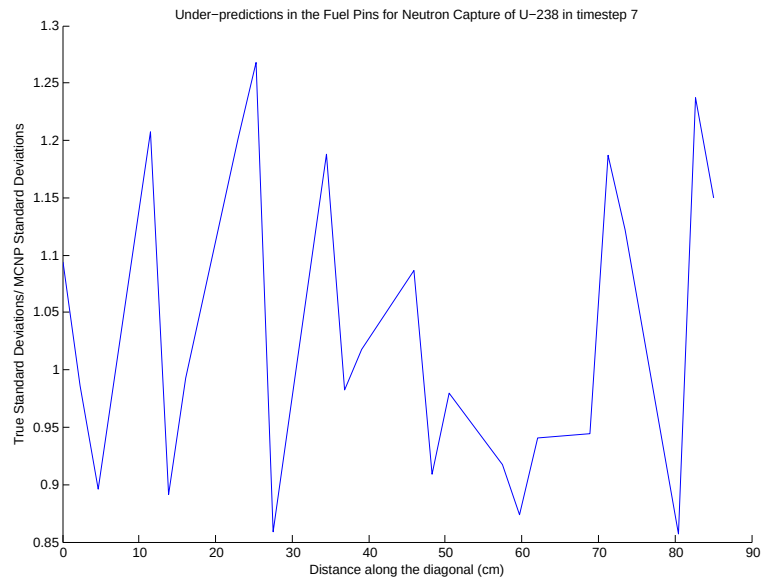


Figure 278: Uncertainty under-prediction of Capture in Fuel pins for U-238 for timestep 7

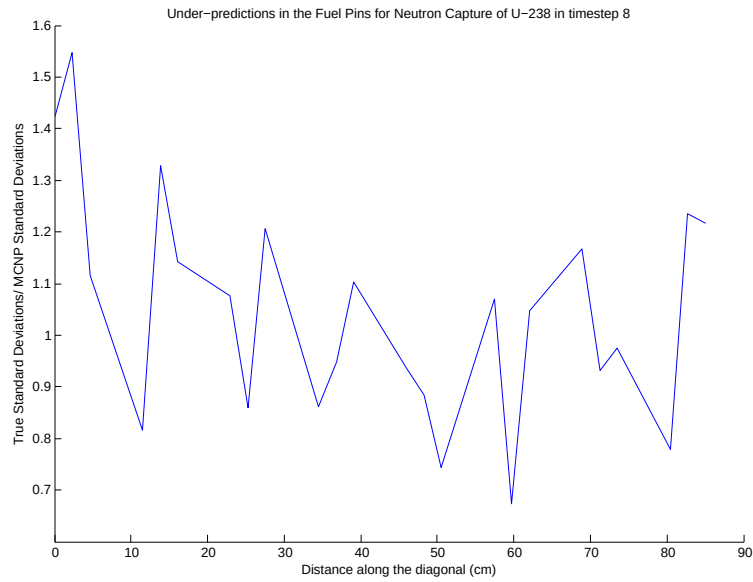


Figure 279: Uncertainty under-prediction of Capture in Fuel pins for U-238 for timestep 8

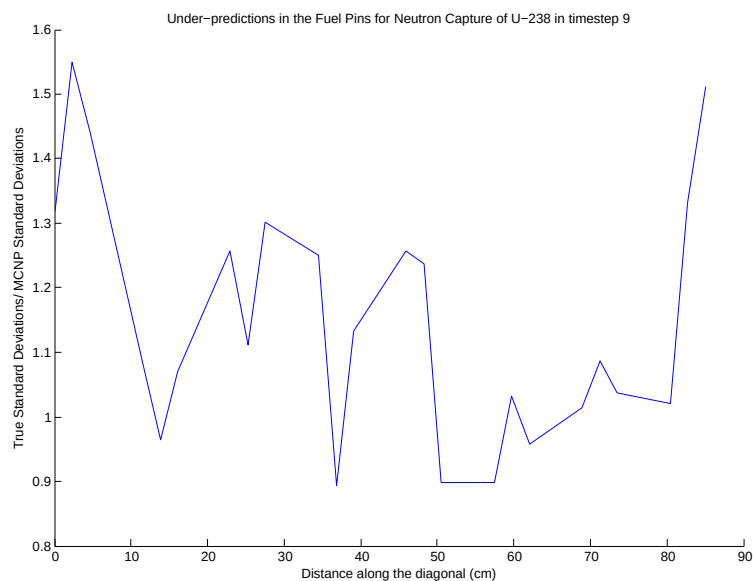


Figure 280: Uncertainty under-prediction of Capture in Fuel pins for U-238 for timestep 9

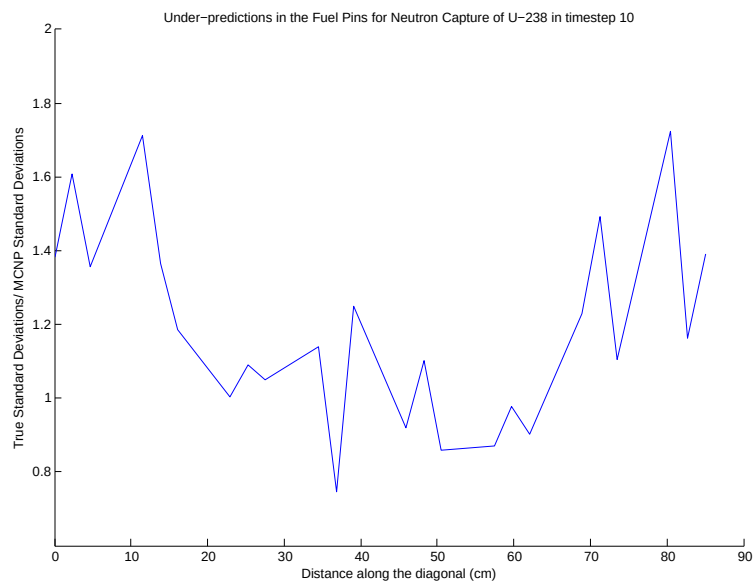


Figure 281: Uncertainty under-prediction of Capture in Fuel pins for U-238 for timestep 10

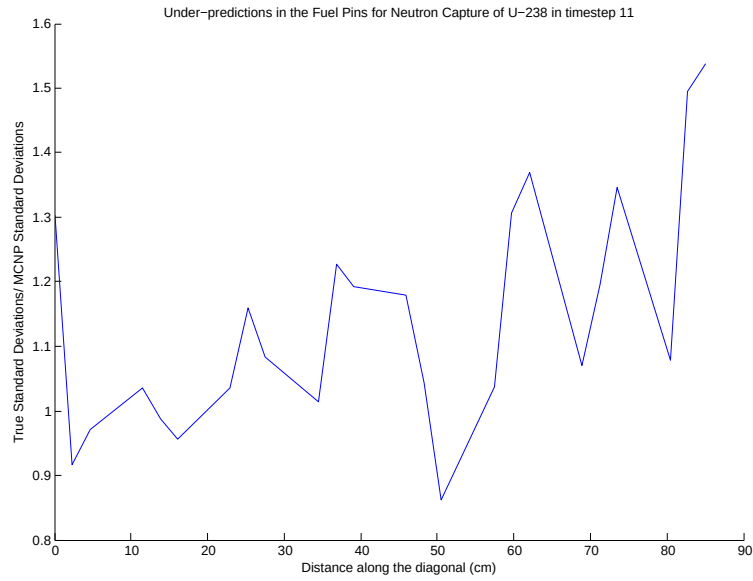


Figure 282: Uncertainty under-prediction of Capture in Fuel pins for U-238 for timestep 11

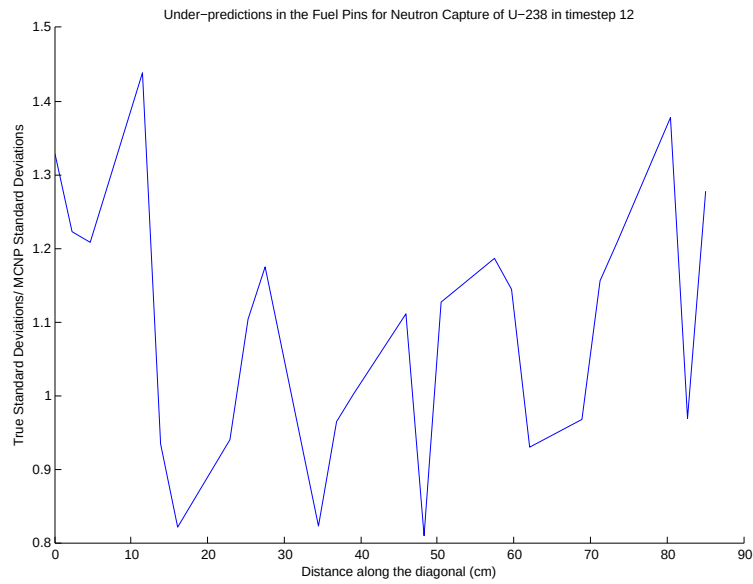


Figure 283: Uncertainty under-prediction of Capture in Fuel pins for U-238 for timestep 12

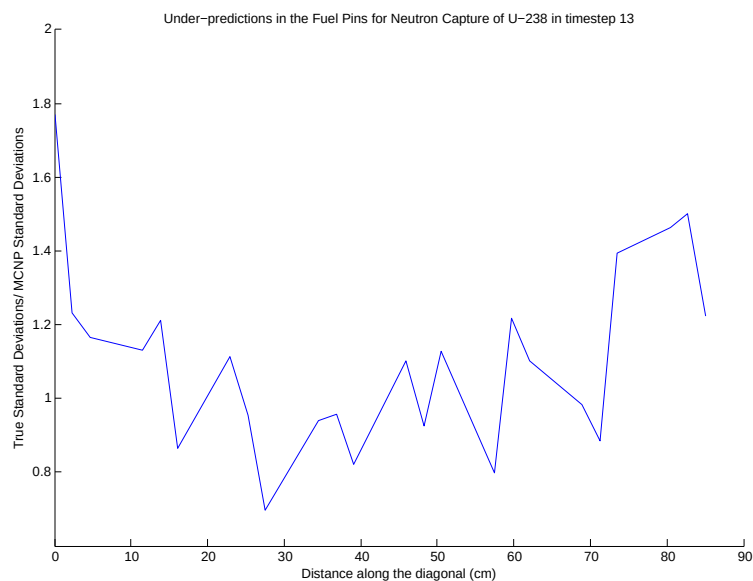


Figure 284: Uncertainty under-prediction of Capture in Fuel pins for U-238 for timestep 13

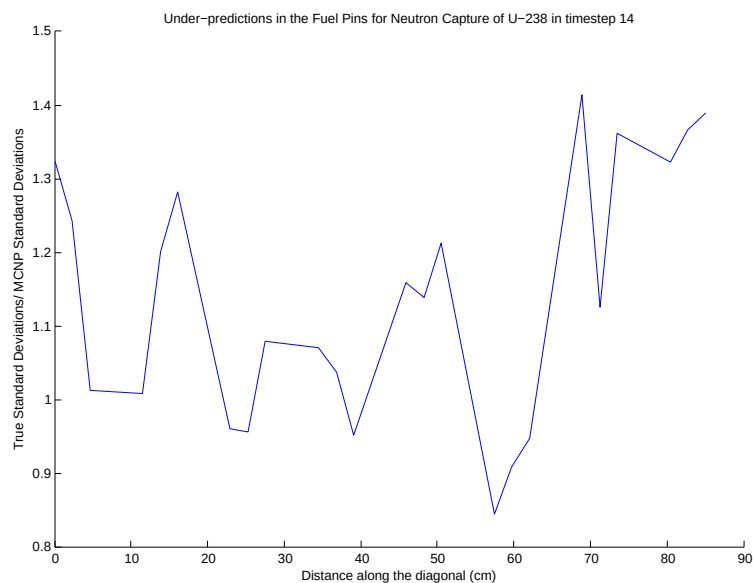


Figure 285: Uncertainty under-prediction of Capture in Fuel pins for U-238 for timestep 14

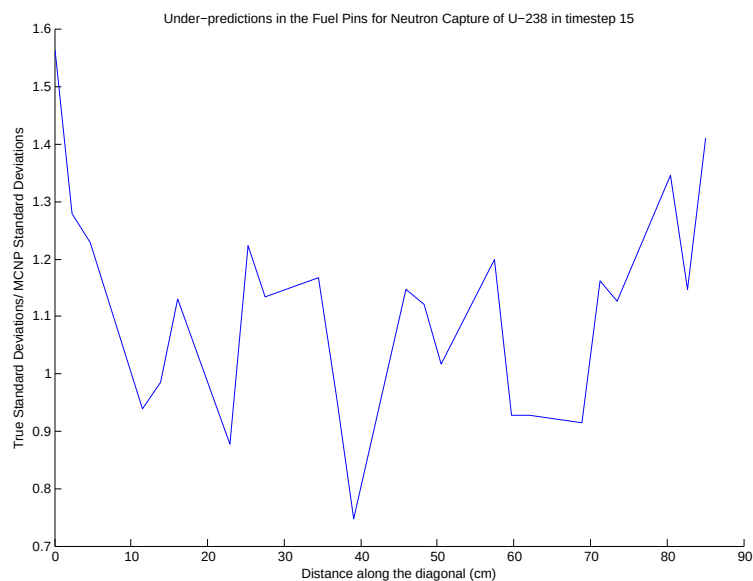


Figure 286: Uncertainty under-prediction of Capture in Fuel pins for U-238 for timestep 15

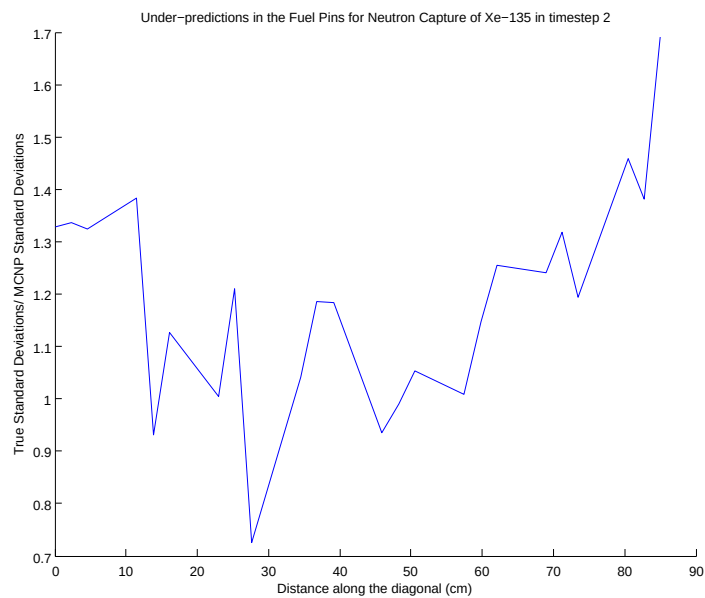


Figure 287: Uncertainty under-prediction of Capture in Fuel pins for Xe-135 for timestep 2

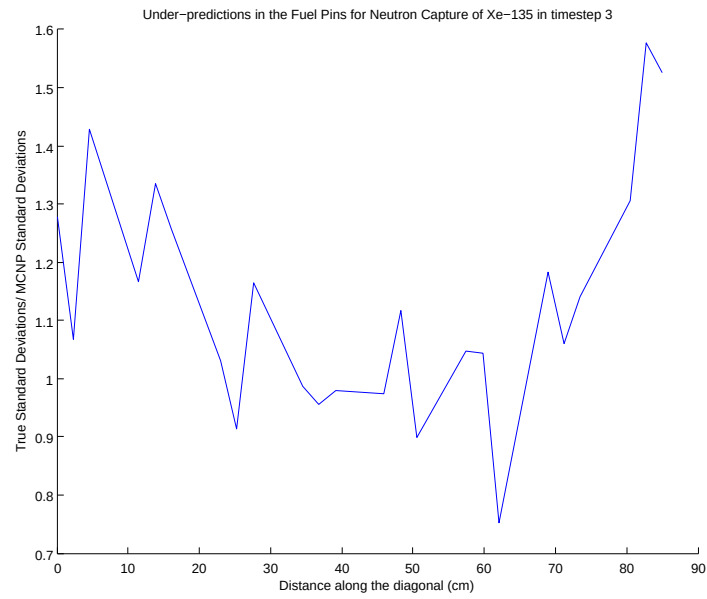


Figure 288: Uncertainty under-prediction of Capture in Fuel pins for Xe-135 for timestep 3

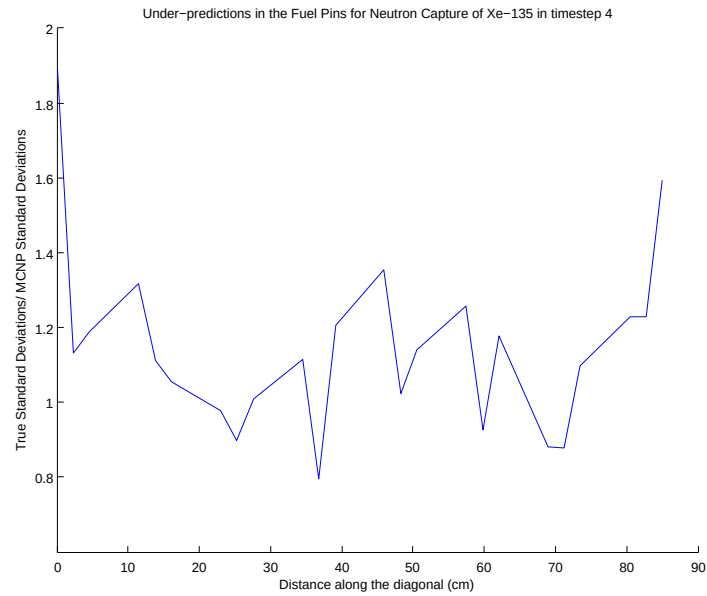


Figure 289: Uncertainty under-prediction of Capture in Fuel pins for Xe-135 for timestep 4

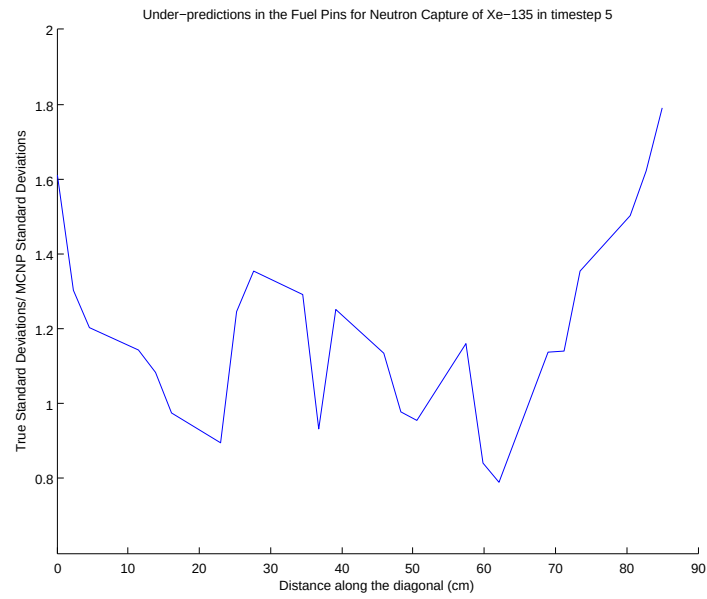


Figure 290: Uncertainty under-prediction of Capture in Fuel pins for Xe-135 for timestep 5

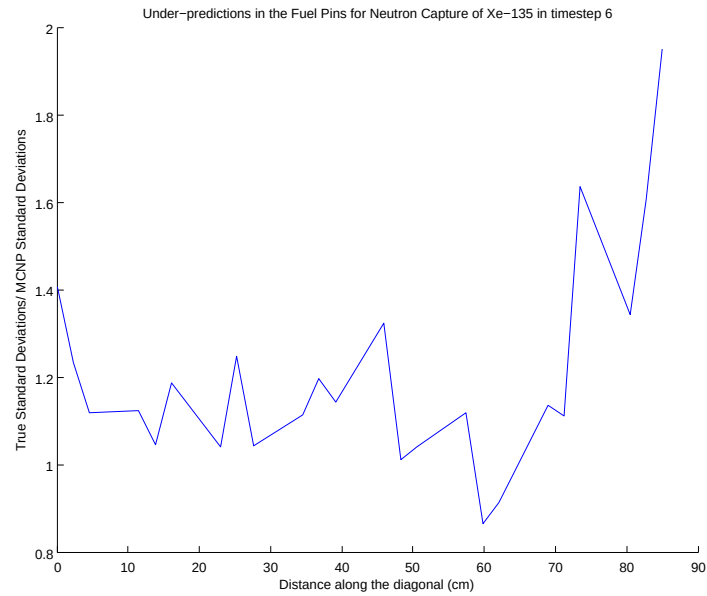


Figure 291: Uncertainty under-prediction of Capture in Fuel pins for Xe-135 for timestep 6

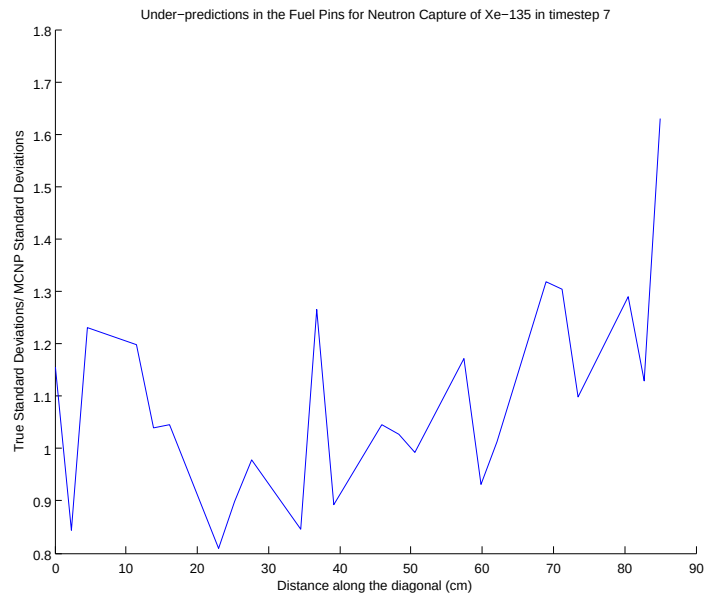


Figure 292: Uncertainty under-prediction of Capture in Fuel pins for Xe-135 for timestep 7

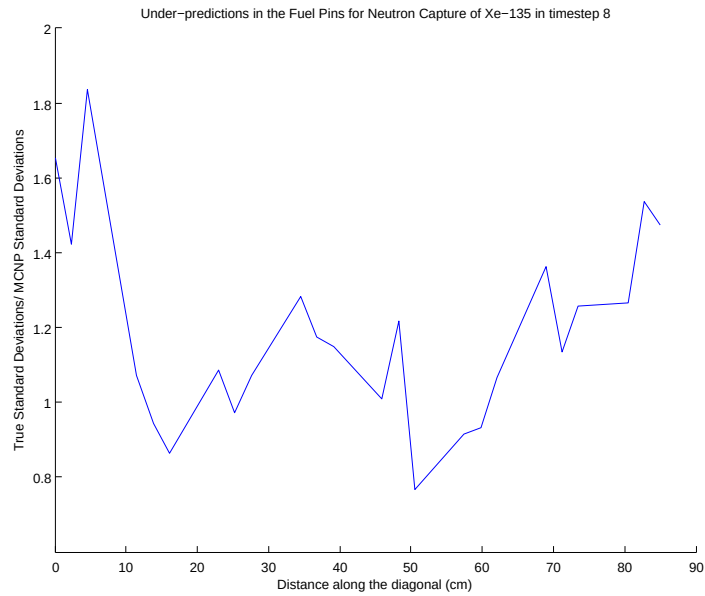


Figure 293: Uncertainty under-prediction of Capture in Fuel pins for Xe-135 for timestep 8

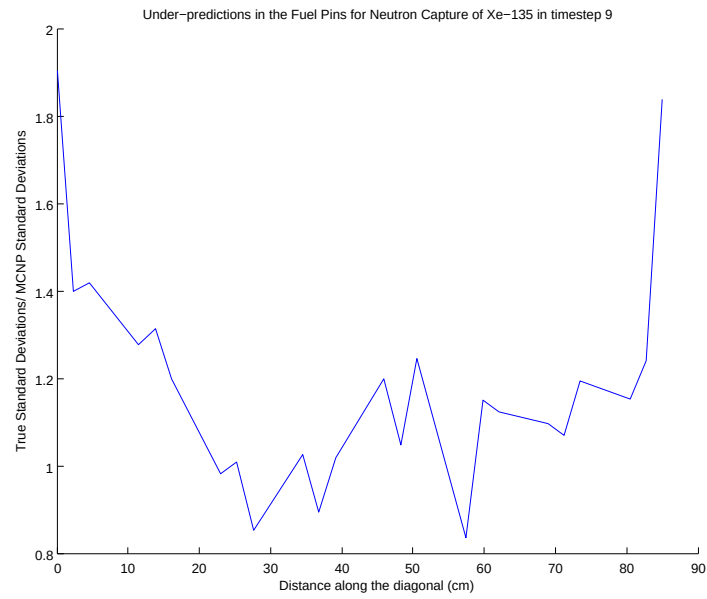


Figure 294: Uncertainty under-prediction of Capture in Fuel pins for Xe-135 for timestep 9

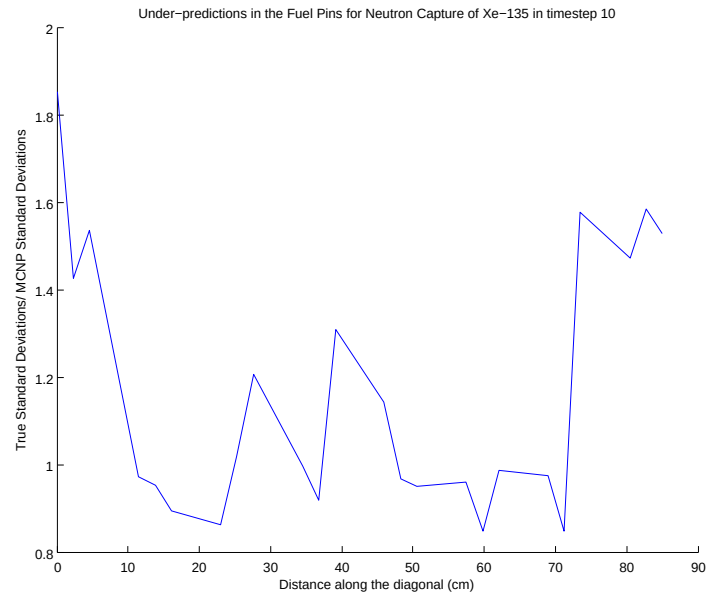


Figure 295: Uncertainty under-prediction of Capture in Fuel pins for Xe-135 for timestep 10

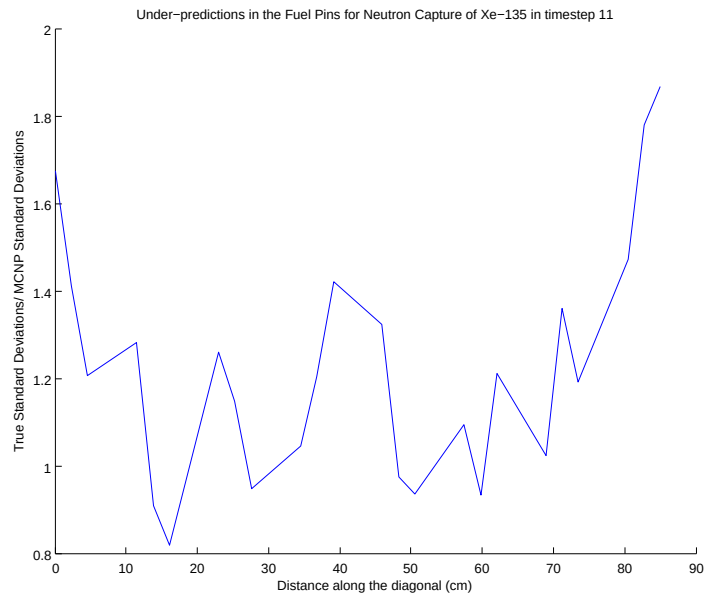


Figure 296: Uncertainty under-prediction of Capture in Fuel pins for Xe-135 for timestep 11

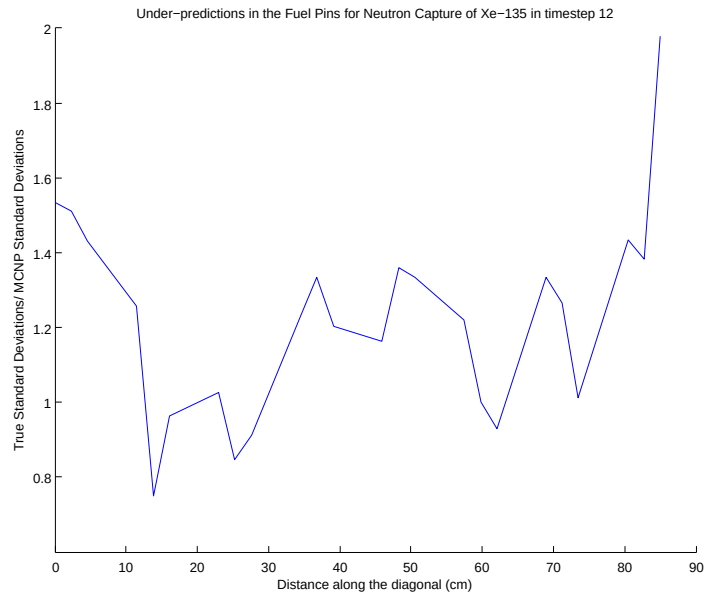


Figure 297: Uncertainty under-prediction of Capture in Fuel pins for Xe-135 for timestep 12

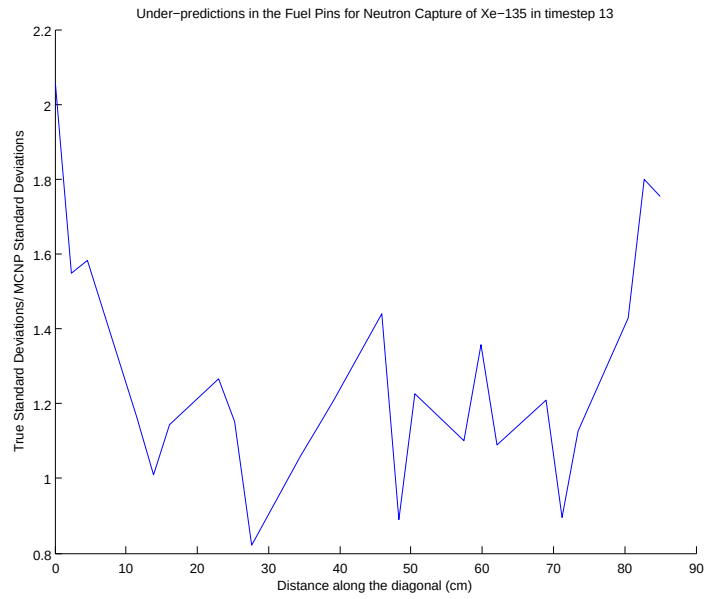


Figure 298: Uncertainty under-prediction of Capture in Fuel pins for Xe-135 for timestep 13

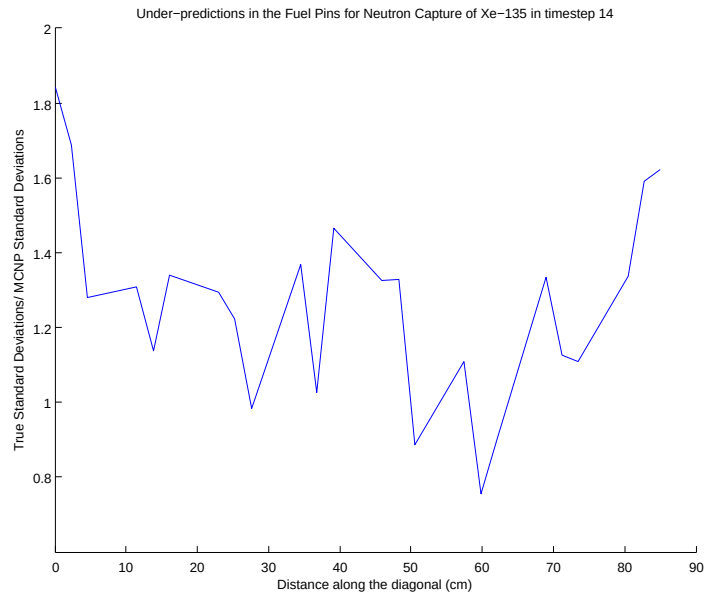


Figure 299: Uncertainty under-prediction of Capture in Fuel pins for Xe-135 for timestep 14

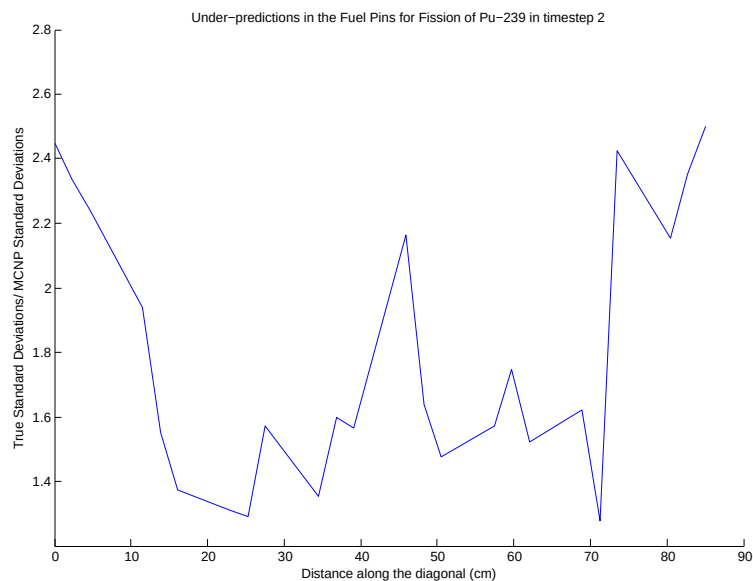


Figure 300: Uncertainty under-prediction of Fission in Fuel pins for Pu-239 for timestep 2

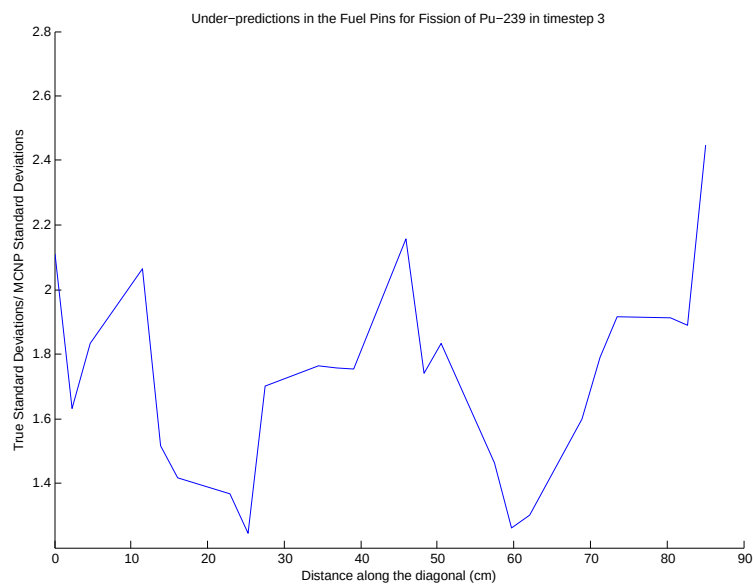


Figure 301: Uncertainty under-prediction of Fission in Fuel pins for Pu-239 for timestep 3

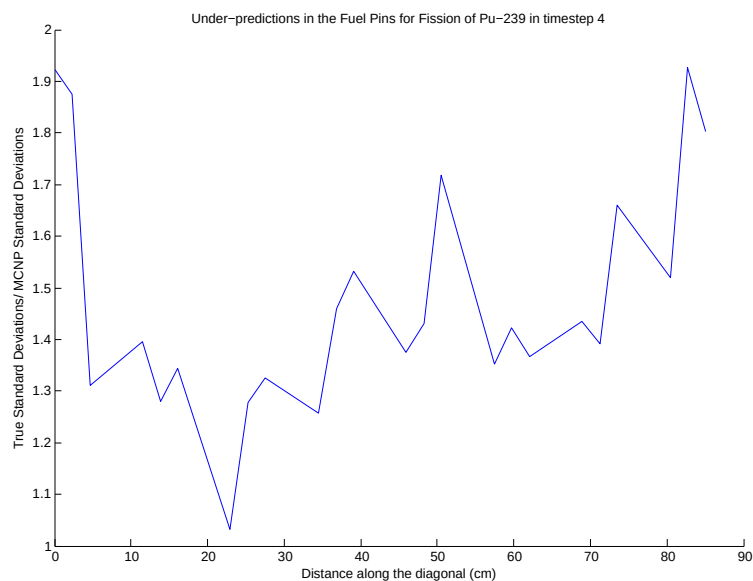


Figure 302: Uncertainty under-prediction of Fission in Fuel pins for Pu-239 for timestep 4

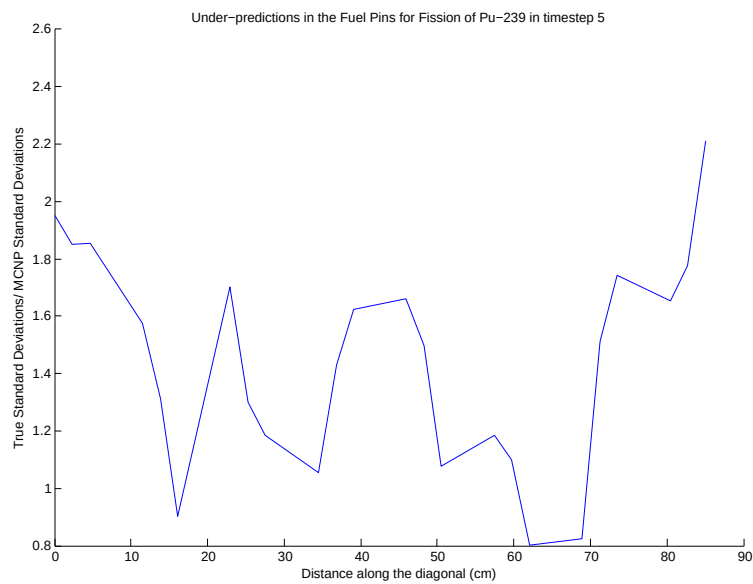


Figure 303: Uncertainty under-prediction of Fission in Fuel pins for Pu-239 for timestep 5

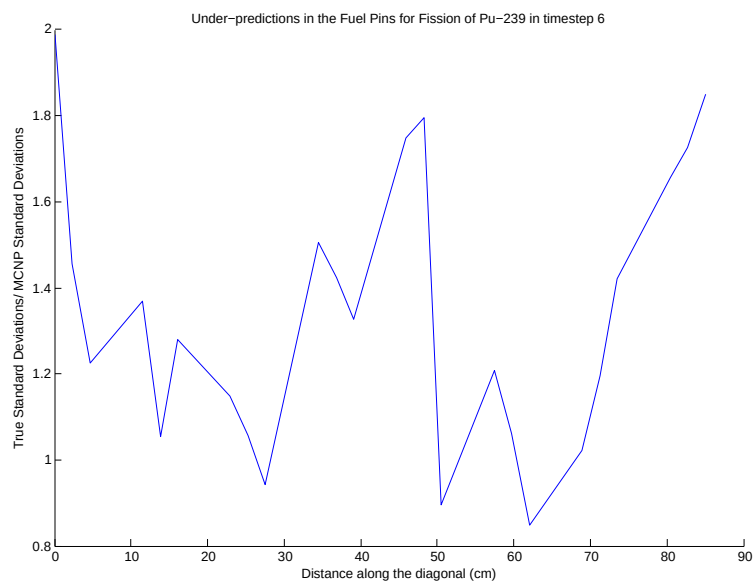


Figure 304: Uncertainty under-prediction of Fission in Fuel pins for Pu-239 for timestep 6

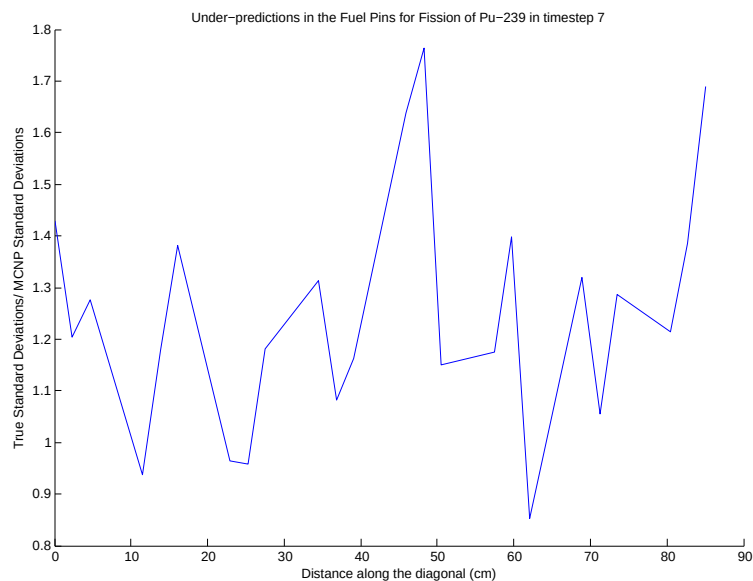


Figure 305: Uncertainty under-prediction of Fission in Fuel pins for Pu-239 for timestep 7

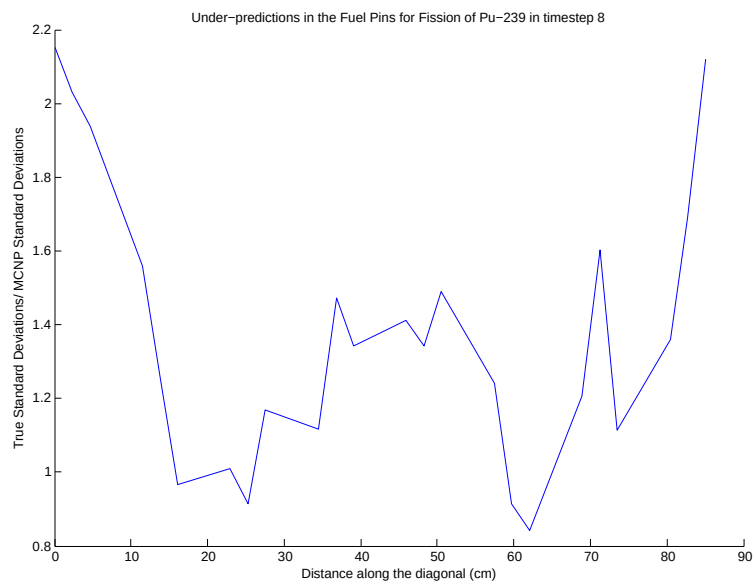


Figure 306: Uncertainty under-prediction of Fission in Fuel pins for Pu-239 for timestep 8

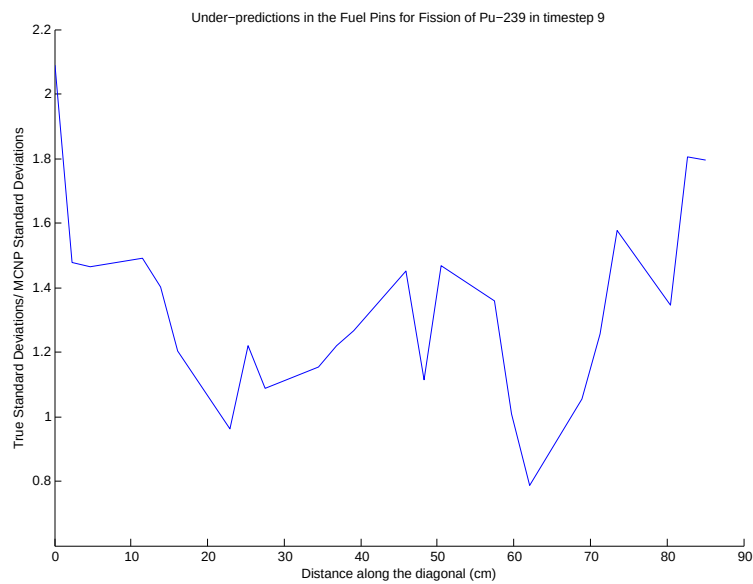


Figure 307: Uncertainty under-prediction of Fission in Fuel pins for Pu-239 for timestep 9

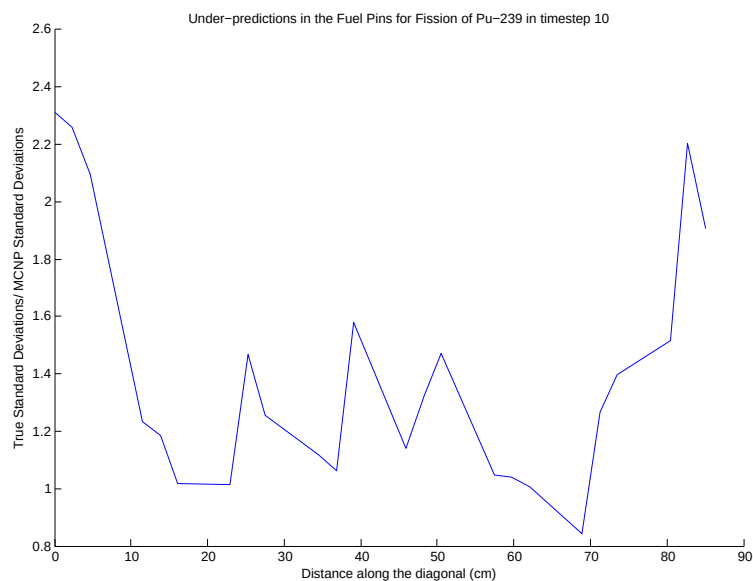


Figure 308: Uncertainty under-prediction of Fission in Fuel pins for Pu-239 for timestep 10

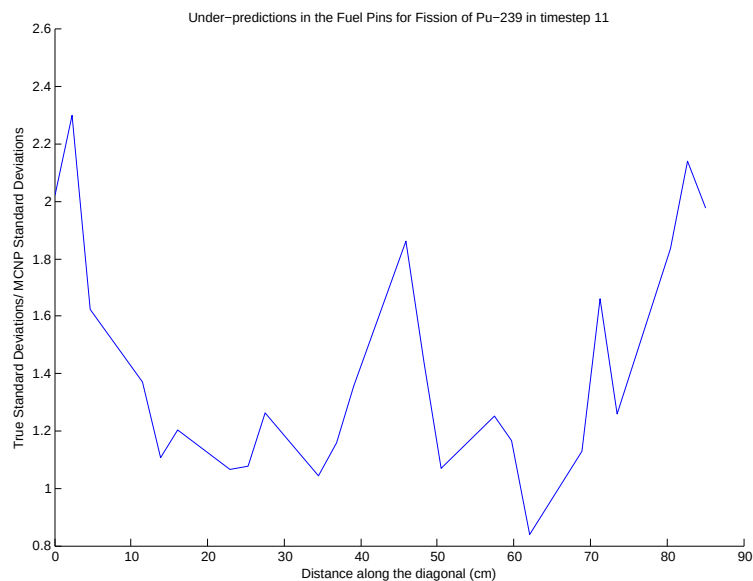


Figure 309: Uncertainty under-prediction of Fission in Fuel pins for Pu-239 for timestep 11

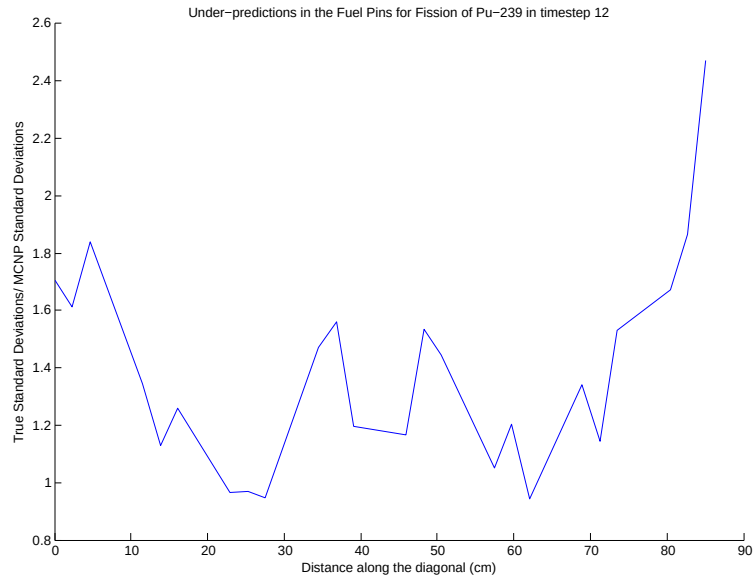


Figure 310: Uncertainty under-prediction of Fission in Fuel pins for Pu-239 for timestep 12

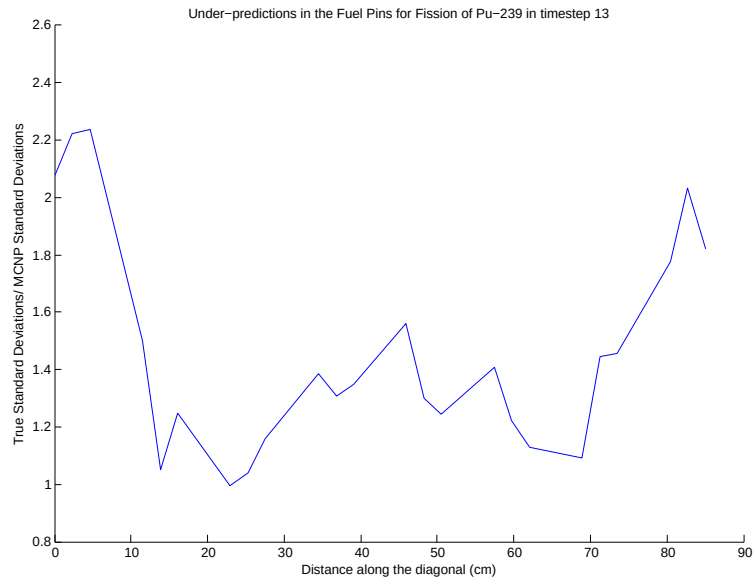


Figure 311: Uncertainty under-prediction of Fission in Fuel pins for Pu-239 for timestep 13

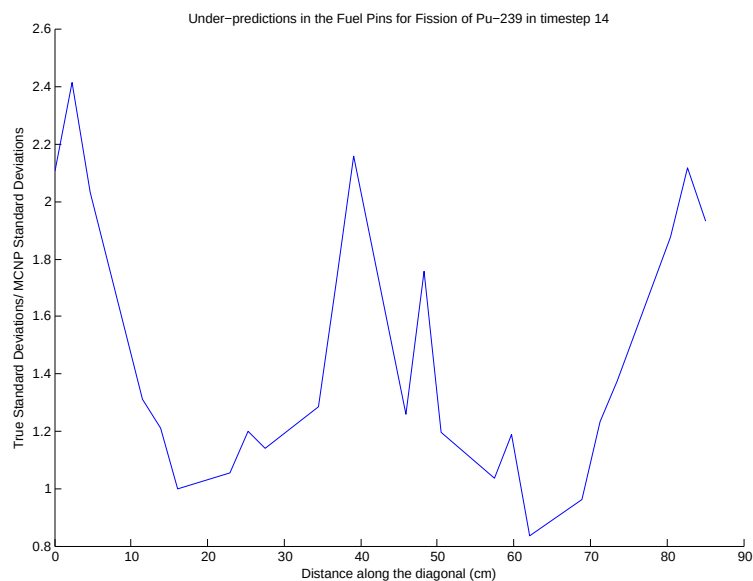


Figure 312: Uncertainty under-prediction of Fission in Fuel pins for Pu-239 for timestep 14

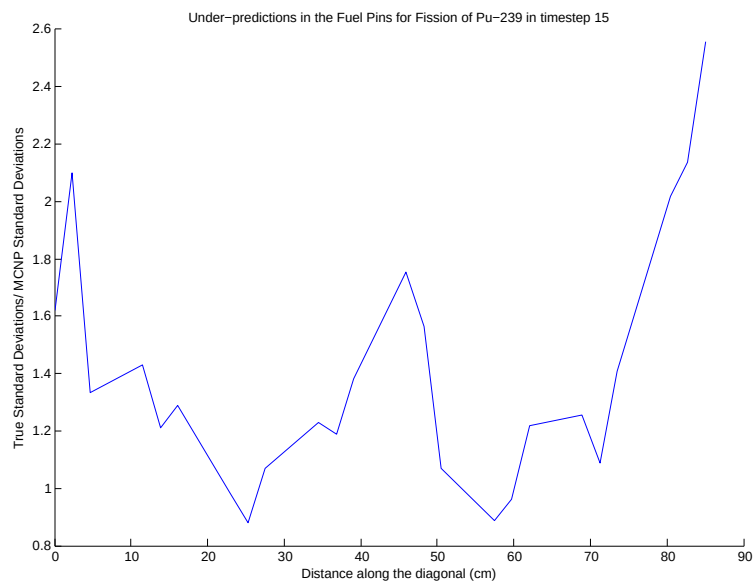


Figure 313: Uncertainty under-prediction of Fission in Fuel pins for Pu-239 for timestep 15

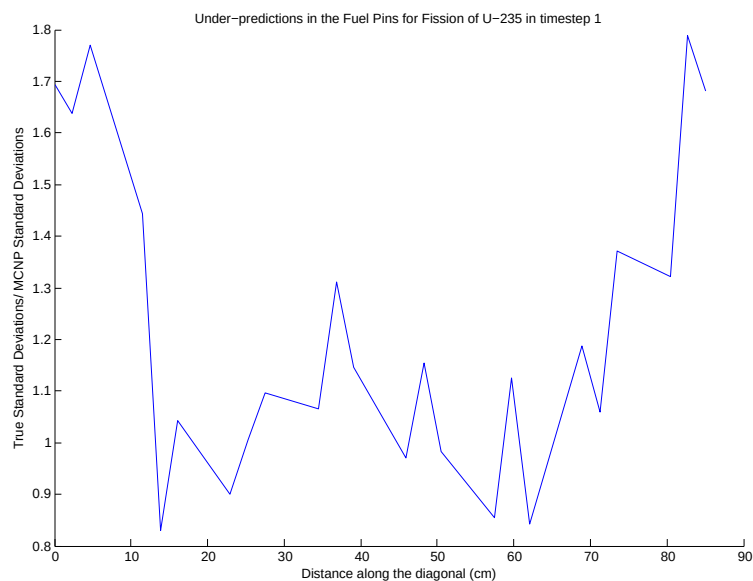


Figure 314: Uncertainty under-prediction of Fission in Fuel pins for U-235 for timestep 1

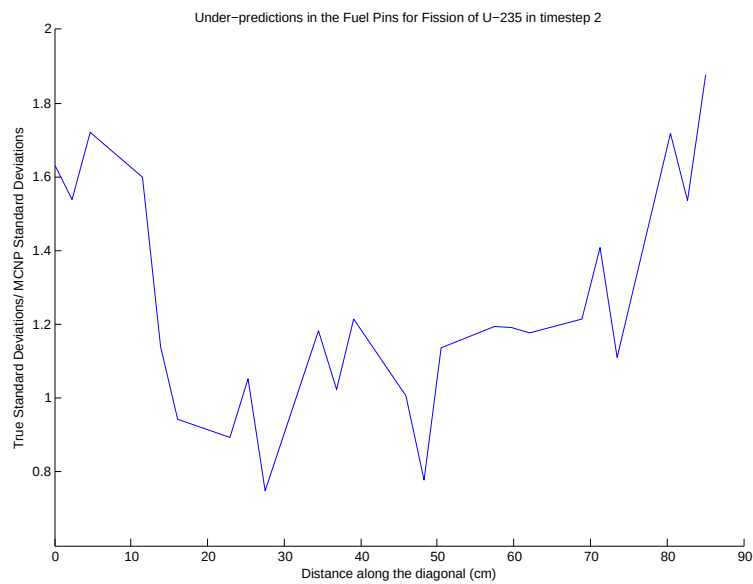


Figure 315: Uncertainty under-prediction of Fission in Fuel pins for U-235 for timestep 2

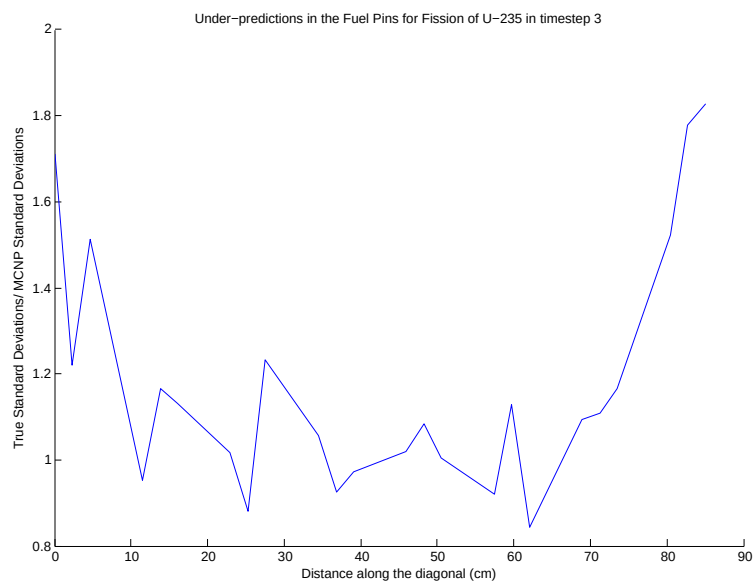


Figure 316: Uncertainty under-prediction of Fission in Fuel pins for U-235 for timestep 3

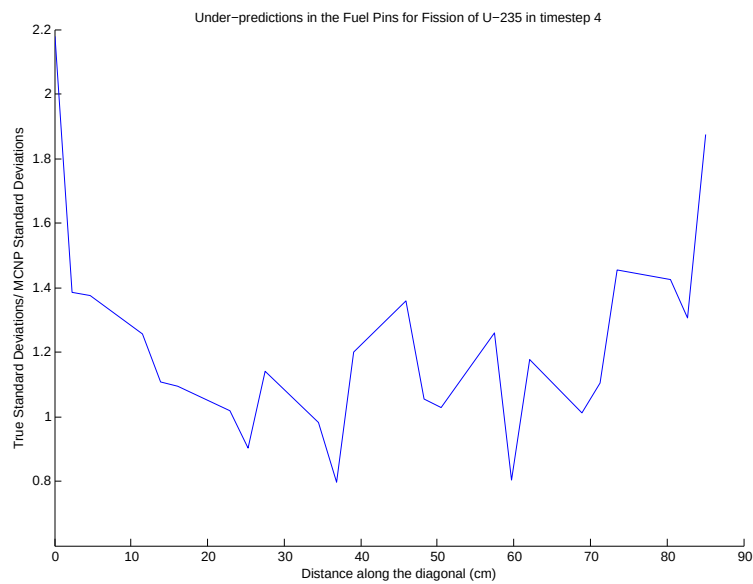


Figure 317: Uncertainty under-prediction of Fission in Fuel pins for U-235 for timestep 4

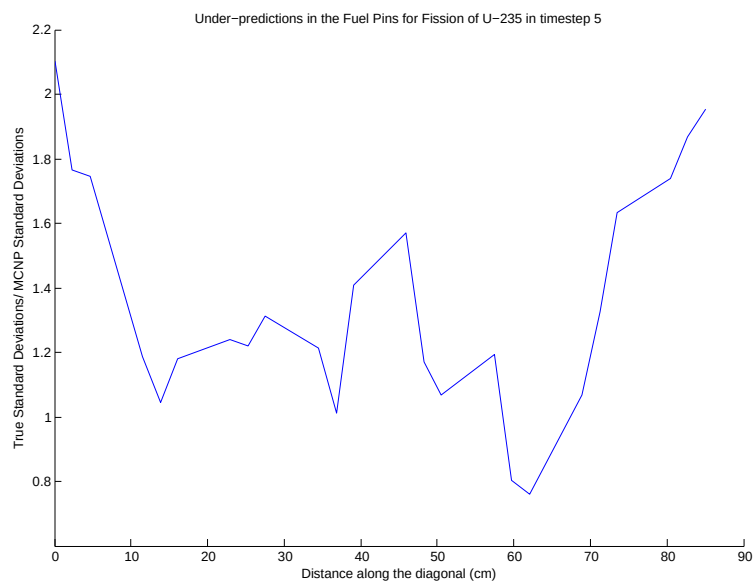


Figure 318: Uncertainty under-prediction of Fission in Fuel pins for U-235 for timestep 5

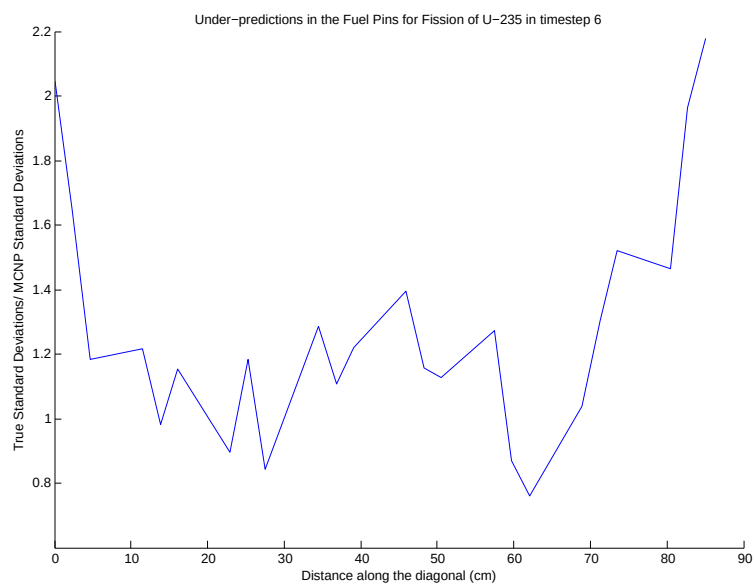


Figure 319: Uncertainty under-prediction of Fission in Fuel pins for U-235 for timestep 6

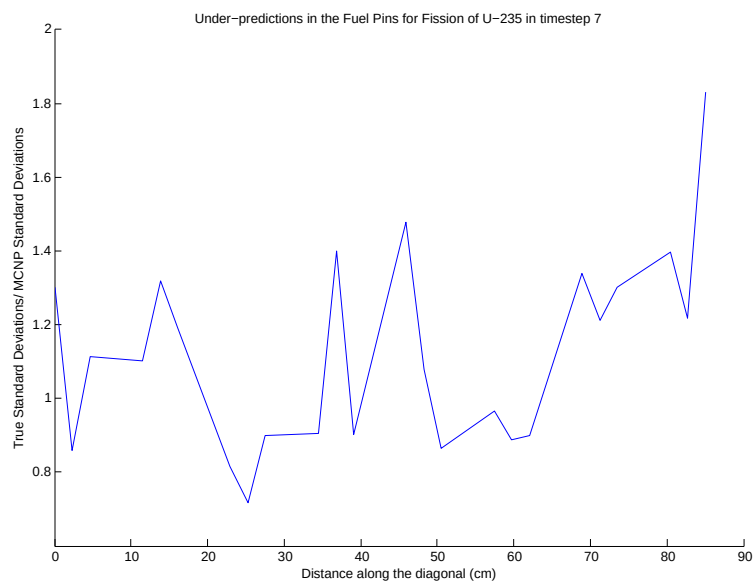


Figure 320: Uncertainty under-prediction of Fission in Fuel pins for U-235 for timestep 7



Figure 321: Uncertainty under-prediction of Fission in Fuel pins for U-235 for timestep 8

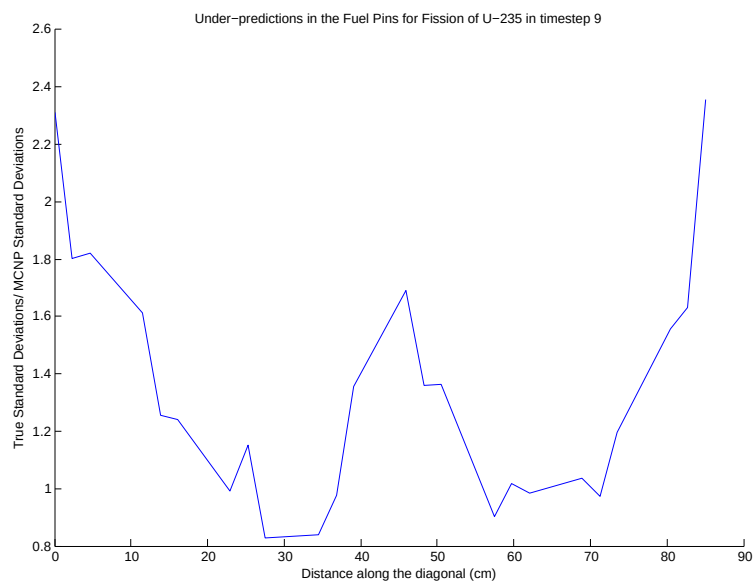


Figure 322: Uncertainty under-prediction of Fission in Fuel pins for U-235 for timestep 9

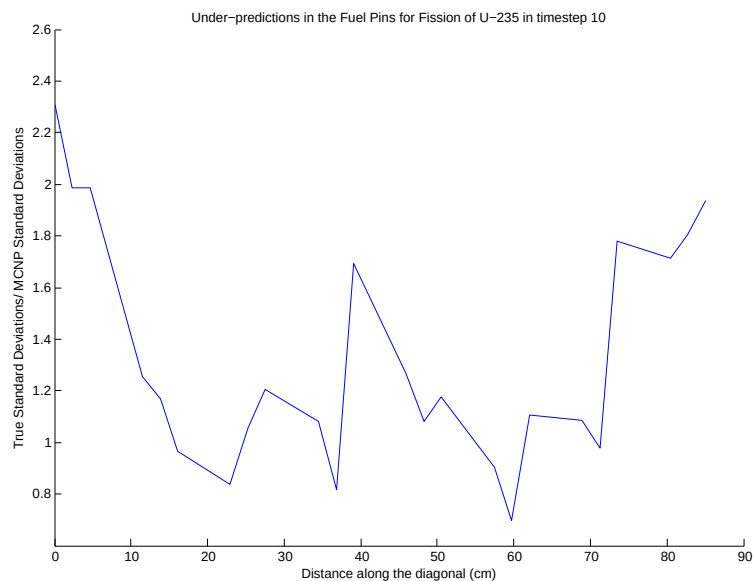


Figure 323: Uncertainty under-prediction of Fission in Fuel pins for U-235 for timestep 10

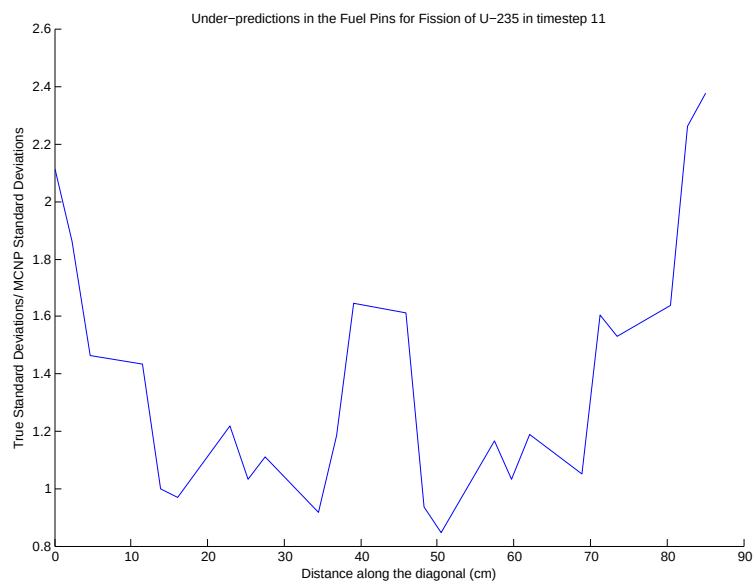


Figure 324: Uncertainty under-prediction of Fission in Fuel pins for U-235 for timestep 11

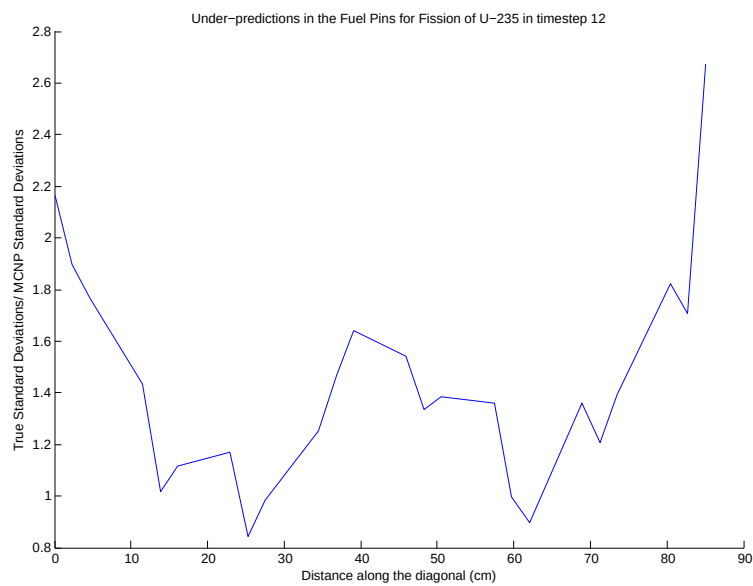


Figure 325: Uncertainty under-prediction of Fission in Fuel pins for U-235 for timestep 12

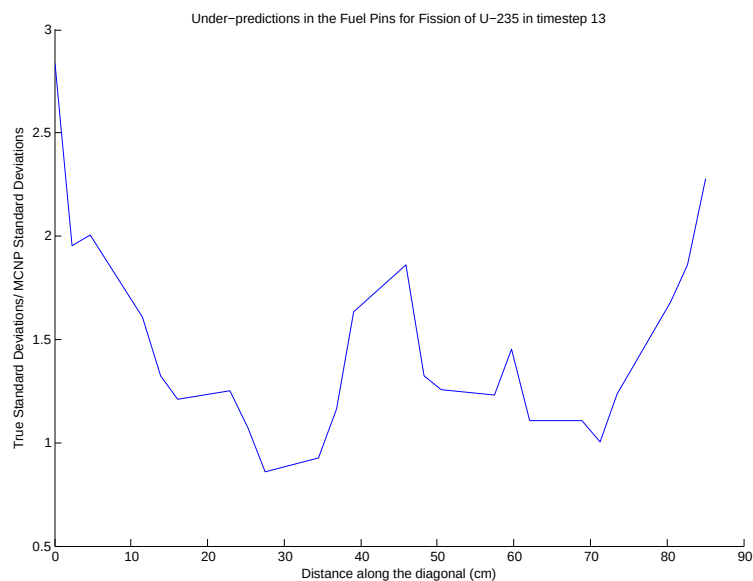


Figure 326: Uncertainty under-prediction of Fission in Fuel pins for U-235 for timestep 13

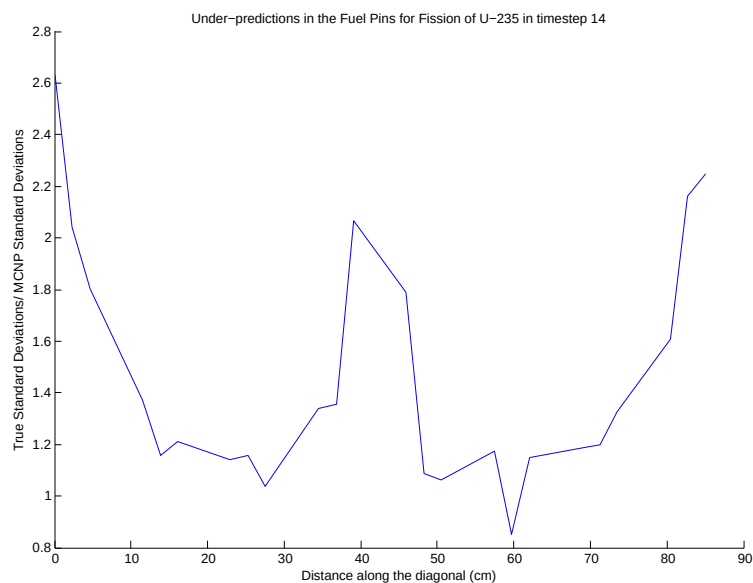


Figure 327: Uncertainty under-prediction of Fission in Fuel pins for U-235 for timestep 14

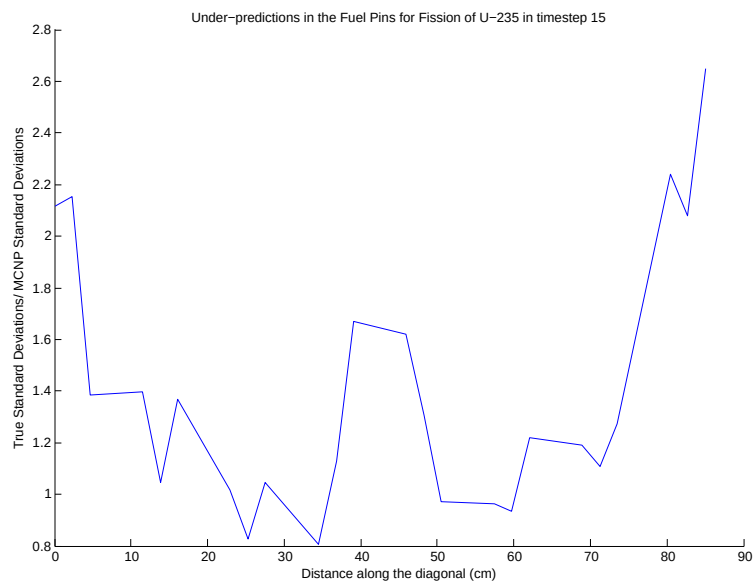


Figure 328: Uncertainty under-prediction of Fission in Fuel pins for U-235 for timestep 15

Appendix C: Tally Plots

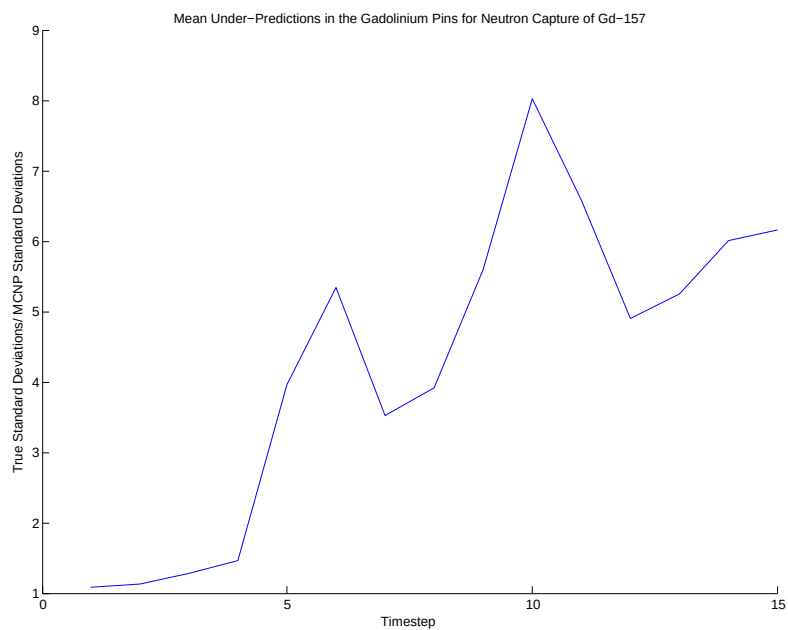


Figure 329: Mean uncertainty under-prediction of Capture in Gd pins for Gd-157

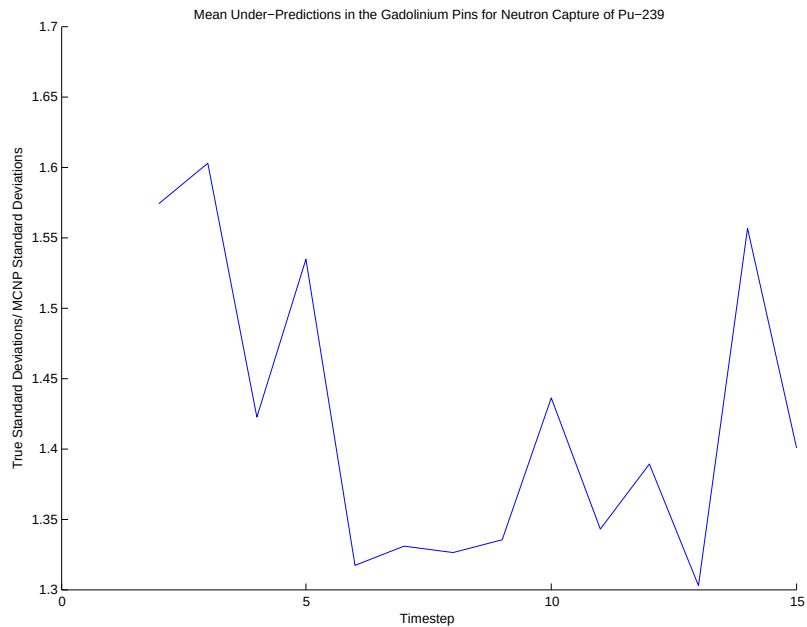


Figure 330: Mean uncertainty under-prediction of Capture in Gd pins for Pu-239

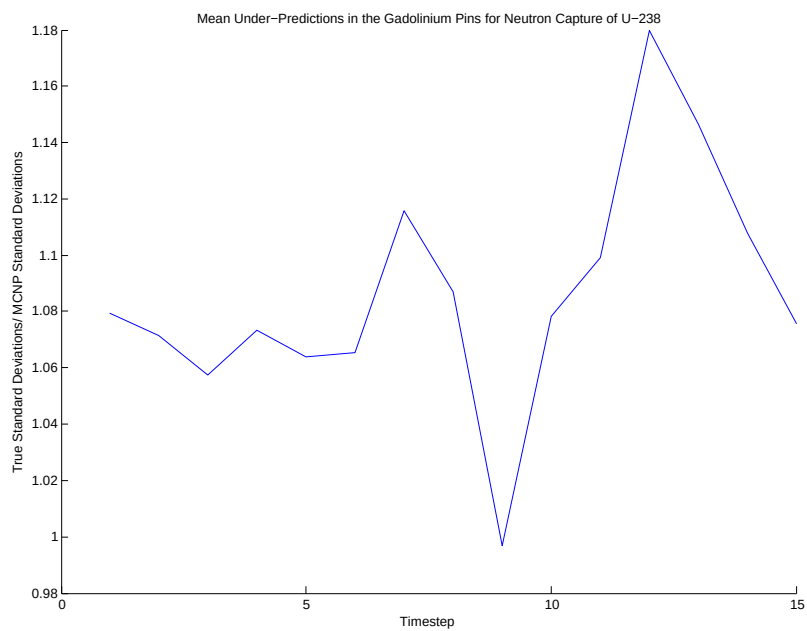


Figure 331: Mean uncertainty under-prediction of Capture in Gd pins for U-238

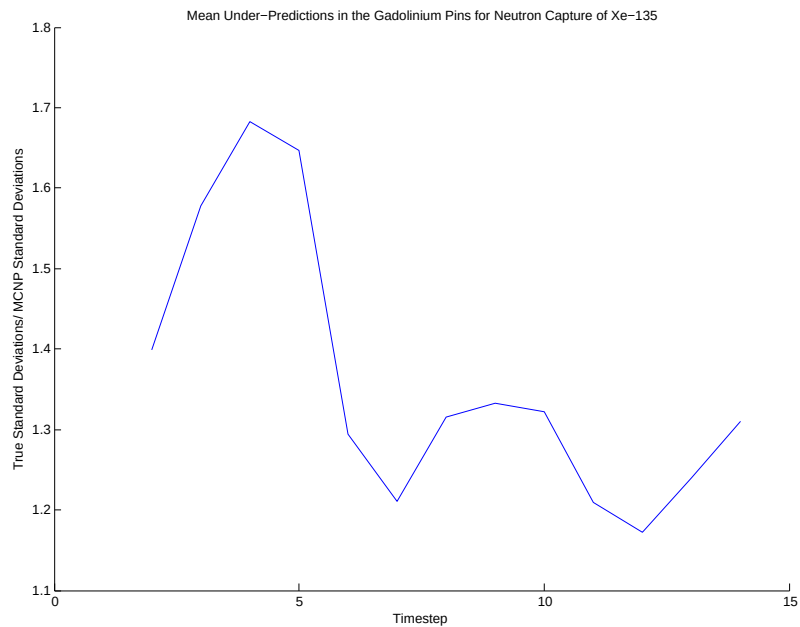


Figure 332: Mean uncertainty under-prediction of Capture in Gd pins for Xe-135

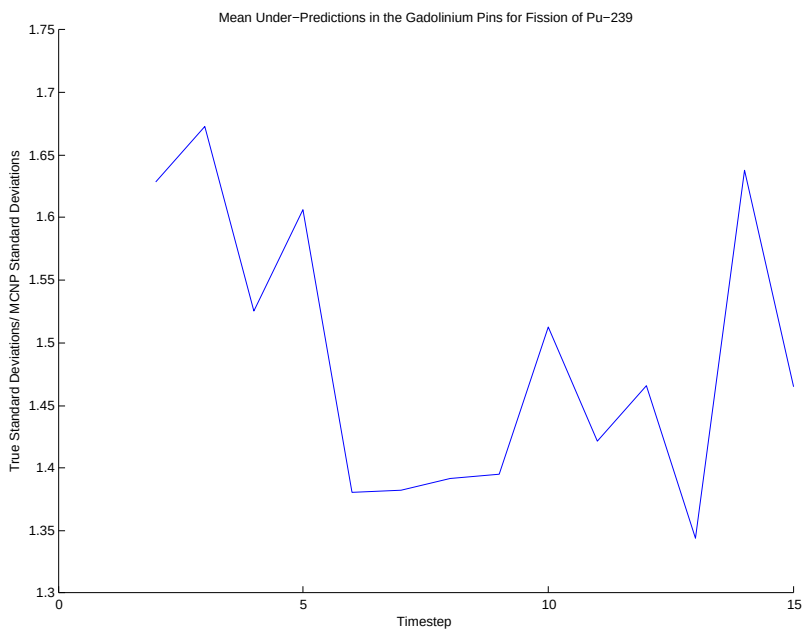


Figure 333: Mean uncertainty under-prediction of Fission in Gd pins for Pu-239

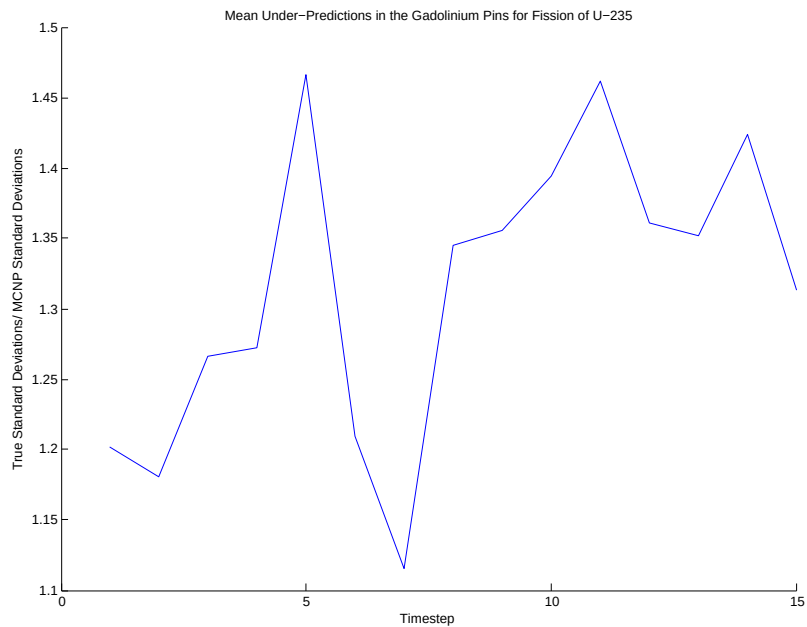


Figure 334: Mean uncertainty under-prediction of Fission in Gd pins for U-235

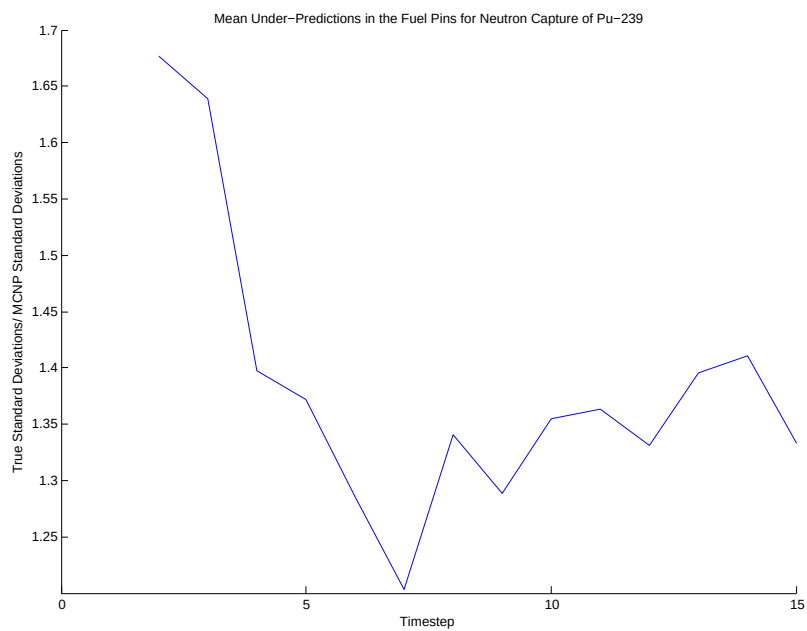


Figure 335: Mean uncertainty under-prediction of Capture in Fuel pins for Pu-239

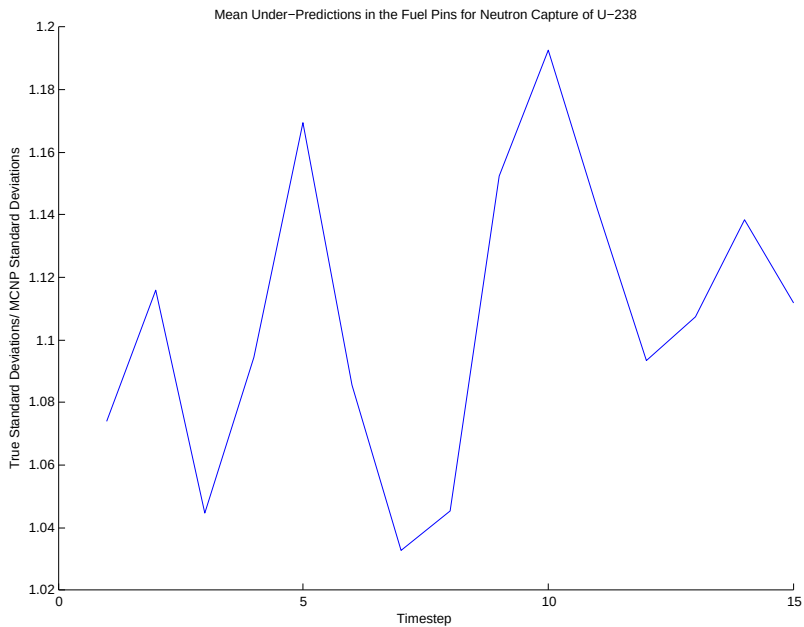


Figure 336: Mean uncertainty under-prediction of Capture in Fuel pins for U-238

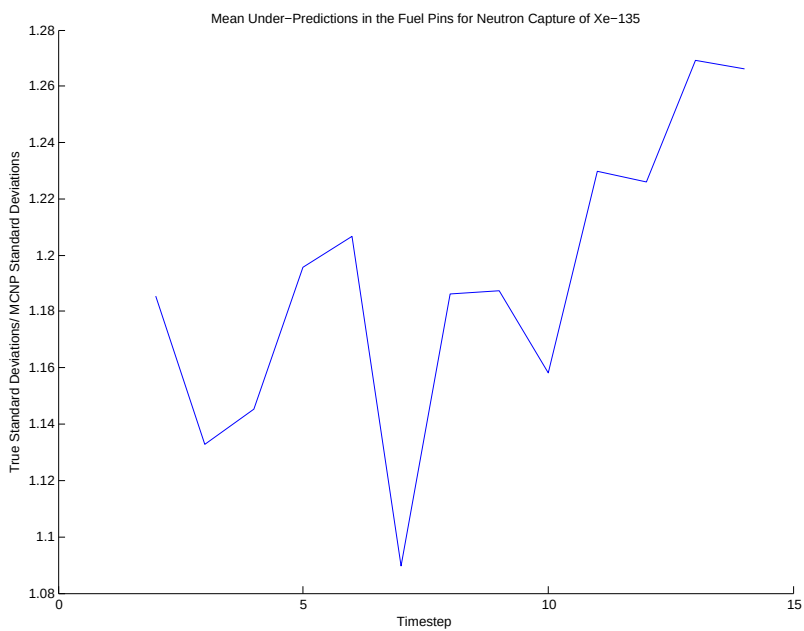


Figure 337: Mean uncertainty under-prediction of Capture in Fuel pins for Xe-135

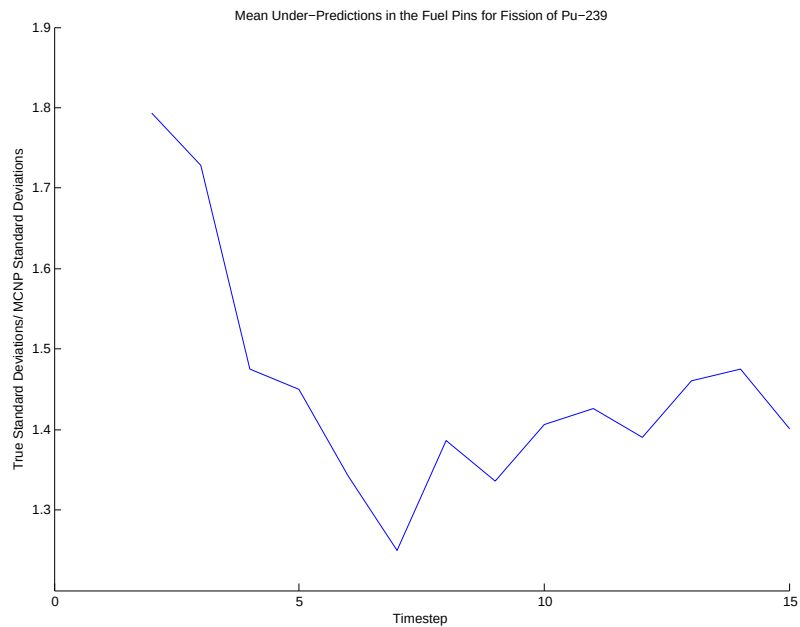


Figure 338: Mean uncertainty under-prediction of Fission in Fuel pins for Pu-239

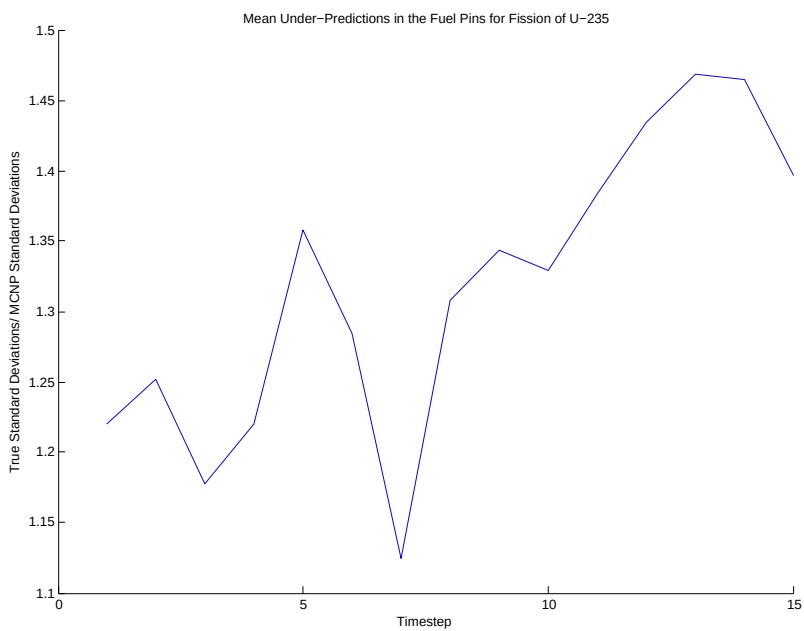


Figure 339: Mean uncertainty under-prediction of Fission in Fuel pins for U-235