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Evaluation of TANK water heater simulation model as embedded in HWSim

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This report evaluates the hot water temperatures and flow rates as calculated by the combined HWSim and TANK simulation models.

HWSim is a hot water piping simulation model originally written by DEG in the 1990s. DEG has updated the program using modern coding languages. For a specified hot water piping configuration HWSim will calculate the amount and timing of hot water to be drawn from a water heater to meet a schedule of given draws classified by type.

TANK is a computer simulation model of non-condensing center flue natural gas storage water heaters. Battelle developed TANK for GRI in the early 1990s. It was designed to simulate water heater operations only under test conditions. TANK was originally written in BASIC for DOS operating system in the early 1990s. For a specified water heater and a given amount and timing of draws, TANK will calculate the temperature of the delivered hot water. Energy consumption by the water heater is also calculated.

Many modern coding conventions are not followed in the TANK code. It was written before object-oriented code was developed. Variables are passed to and from functions both by value and by reference. Variables are not carefully typed. In addition, the TANK source code is not well documented.

LBNL put the TANK source code into a Visual Basic macro in an Excel spreadsheet. The TANK spreadsheet gives the same results as the original TANK computer program. LBNL incorporated some additional capabilities into the spreadsheet model. The TANK spreadsheet can simulate up to 100 draws in one day. The smallest time step can now be set to 1 second instead of 5 seconds. The inlet water temperature can be varied through out a day. This is to provide the capability of modeling recirc loops at some future point.

In addition to being written in different languages TANK and HWSim are coded very differently. TANK calculates conditions in the water heater by stepping through time using variable size time steps. When the water heater is in standby, not doing much, TANK will take larger and larger steps. This was done to speed calculation time. HWSim follows small volumes of water through the piping system. Conditions for the volumes of water are recalculated as they move through the pipes. When water is not moving, conditions are recalculated for the end of the stagnation time.

DEG embedded the TANK source code in HWSim. However, because TANK and HWSim are coded so differently the simulation procedures could not be integrated. The programming strategy is to run the same daily draw pattern sequentially over and over until the resulting temperatures and draw durations are consistent between TANK and HWSim. First HWSim calculates the rate and duration of hot water demanded from the

water heater by draws imposed on the hot water distribution system. The hot water demands for the first iteration in HWSim assume a constant delivery temperature by the water heater throughout the day.

Then TANK is run using that same one day hot water delivery schedule to calculate the actual temperatures of the delivered hot water. Because the water in a storage water heater is cooling off and reheating throughout the day the delivered hot water temperature is not constant. The temperature in the water heater also changes due to the cold water introduced at the bottom of a tank when hot water is drawn.

Different temperatures lead to a different mix of hot and cold water flow rates for temperature sensitive uses such as showers and a different duration for batch uses such as filling bathtubs. With the new, different hot water delivery temperatures for the day from TANK, HWSim recalculates the hot water draw flow rates and durations demanded from the water heater.

The process is repeated until the temperatures and durations of the daily draws stabilize.

The first assessment of the performance of the combined HWSim-TANK program was done for a simple 3 draw daily pattern.

The 3 draw test pattern includes a shower, a sink draw and a ghost draw. TANK was originally written for test patterns which start at the time of the first draw. To get it to start simulating correctly, we give TANK a 20 second 'ghost' draw at time zero totaling 0.002 gallons. The shower draw starts at 6:00am, with a mixed hot and cold water flow of 2 GPM at 105°F for 12 ½ minutes. The sink draw is a 1 GPM mixed draw at 105°F for 24 seconds. It starts at 6:30am.

For the initial 3 draw pattern, HWSim-TANK converged quickly. Figure 1 shows the temperature and flow rate for the shower and sink draw. Notice that after the first iteration (WDelTemp 1 and WDrawFlowRate 1) the temperatures and flow rates for the 2nd and 3rd iteration (WDelTemp 2, WDelTemp 3, and WDrawFlowRate 2, WDrawFlowRate 3) lay directly on top of each other.

Initially the timing variables that TANK uses to describe hot water draws were not being defined correctly. The variables TANK uses to describe draws are:
    WDRAWA – flow rate of draw, in GPM
    TIMDRAW – duration of draw, in seconds
    TMBTWDS – time to start of next draw, in minutes
These caused the change in duration of the shower and the timing of the sink draw.
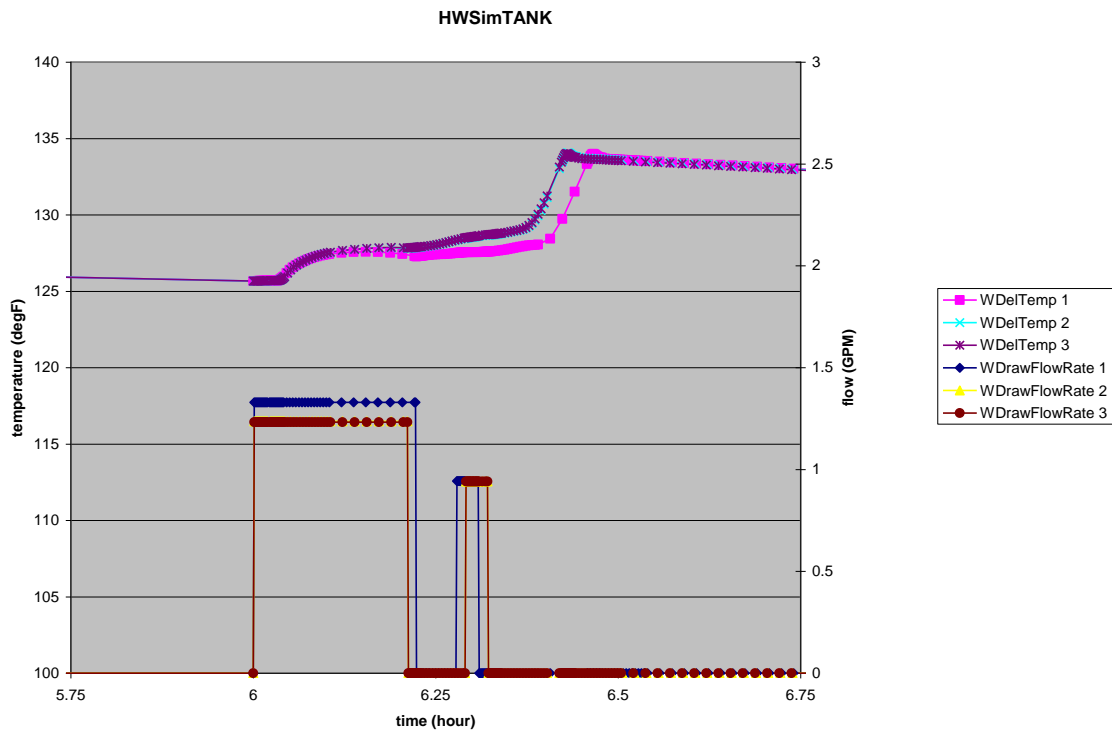
Figure 1 Convergence of Shower and Sink draws

When the TANK spreadsheet model was run with the same daily draw pattern as the final iteration of the 3 draw test, the results matched quite well. See Figure 2, Comparison of HWSim-TANK and TANK spreadsheet. The temperature and flow results from the TANK spreadsheet (Water Draw Flow Rate 019, Water Delivery Temp 019) lie directly over the results from HWSim-TANK (WDelTemp 3, WDrawFlowRate 3).

HWSimTANK vs TANK.xls
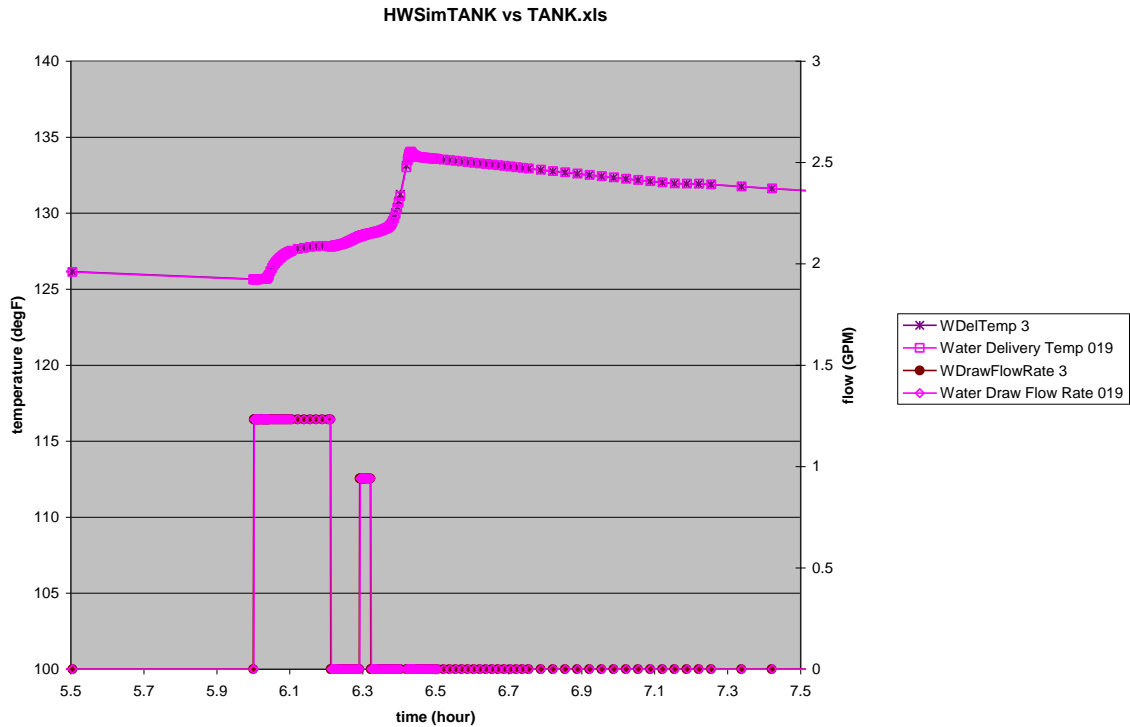
Figure 2 Comparison of HWSim-TANK and TANK spreadsheet

After fixing the definitions of the draw timing parameters another more realistic daily pattern of 27 draws was run through 5 iterations of HWSim-TANK. See Table 1, 27 Draw Test Pattern.

Table 1 27 Draw Test Pattern

Name	StartTime	EndTime	UseType	FlowRate	Temp
mshower1	06:00:00	06:05:30	MinTemp	2	105
msink1	06:20:00	06:20:41	MinTemp	1	105
msink2	06:30:00	06:30:23	MinTemp	1	105
msink2	06:36:00	06:36:17	MinTemp	1	105
bath2sink1	06:40:00	06:40:42	MinTemp	1	105
ksink	06:45:00	06:46:00	MinTemp	1	105
ksink	06:52:00	06:53:00	MinTemp	1	105
bath2sink1	07:42:00	07:42:12	MinTemp	1	105
bath2sink1	07:48:00	07:48:30	MinTemp	1	105
cw	08:10:00	08:13:01	Appliance	3	105
cw	08:40:00	08:43:01	Appliance	3	105
ksink	12:42:00	12:42:23	MinTemp	1	105
ksink	12:51:00	12:51:36	MinTemp	1	105
ksink	17:30:00	17:30:18	Appliance	1	105
ksink	17:39:00	17:39:42	MinTemp	1	105

bath2sink1	18:08:00	18:08:41	MinTemp	1	105
ksink	18:50:00	18:53:00	MinTemp	1	105
bath2shower 1	20:00:00	20:05:30	MinTemp	2	105
ksink	20:20:00	20:21:00	MinTemp	1	105
ksink	20:50:00	20:51:00	MinTemp	1	105
msink1	21:31:00	21:31:11	Appliance	1	105
msink1	21:39:00	21:39:30	MinTemp	1	105
mshower1	21:45:00	21:53:00	MinTemp	2	105
ksink	22:00:00	22:00:42	MinTemp	1	105
ksink	22:22:00	22:22:18	MinTemp	1	105
msink2	22:40:00	22:40:23	MinTemp	1	105
msink2	22:50:00	22:50:17	Appliance	1	105

Again the temperature and time results converged quite quickly. See Figure 3 HWSim-TANK Convergence for 27 Draw Pattern
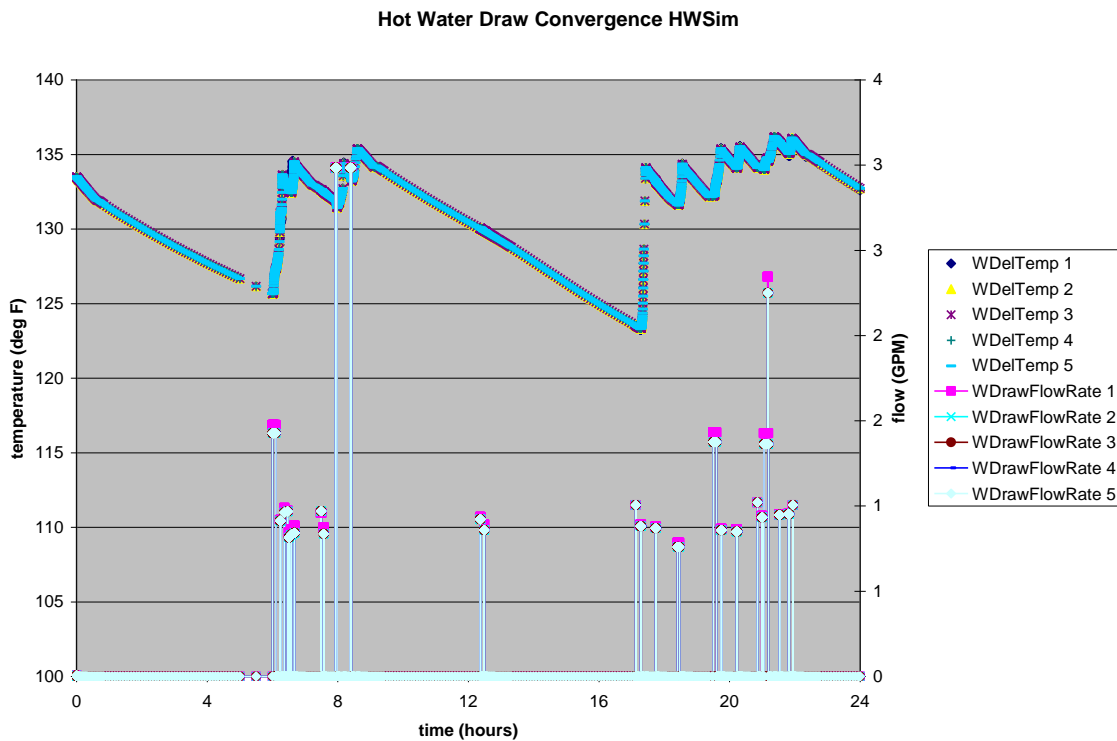

Figure 3 HWSim-TANK Convergence for 27 Draw Pattern

The rate of the convergence was determined by examining the data for each draw more closely. The temperature profiles and start and stop times for each draw were calculated from the output files from each iteration. See Table 2 Change in Draw Parameters by Iteration for the differences between iterations for the first 6 draws.

Table 2 Change in Draw Parameters by Iteration

Draw Num	Iter	Start Time Draw	Stop Time Draw	Start Temp Draw	Stop Temp Draw	Max Temp Draw	Min Temp Draw	Flow Draw	Volume Draw
#	#	(sec)	(sec)	(deg F)	(deg F)	(deg F)	(deg F)	(GPM)	(G)
1	1->2	0.00	0.00	0.000355	0.000355	0.000355	0.000355	0.000000	0.000000
	2->3	0.00	0.00	0.000001	0.000001	0.000001	0.000001	0.000000	0.000000
	3->4	0.00	0.00	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
	4->5	0.00	0.00	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
2	1->2	0.00	0.00	0.000292	-0.024252	-0.024252	0.000292	0.048446	0.151394
	2->3	0.00	0.00	0.000001	0.000001	0.000001	0.000001	0.000000	0.000000
	3->4	0.00	0.00	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
	4->5	0.00	0.00	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
3	1->2	-5.00	-5.00	-0.498176	-0.537693	-0.619605	-0.498176	0.004088	0.004089
	2->3	0.00	0.00	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
	3->4	0.00	0.00	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
	4->5	0.00	0.00	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
4	1->2	-5.00	0.00	-0.022926	-0.041495	-0.022926	-0.041495	0.027647	0.048099
	2->3	0.00	0.00	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
	3->4	0.00	0.00	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
	4->5	0.00	0.00	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
5	1->2	-10.00	-10.00	-0.036540	-0.048962	-0.036540	-0.048962	0.005557	0.003002
	2->3	0.00	0.00	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
	3->4	0.00	0.00	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
	4->5	0.00	0.00	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
6	1->2	-5.00	-5.00	-0.054518	-0.066061	-0.054518	-0.066061	0.030178	0.013835
	2->3	0.00	0.00	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
	3->4	0.00	0.00	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
	4->5	0.00	0.00	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000

The complete results are in the spreadsheet 'HWSimTANKvTANK converge 2010-12-20.xls' The differences in draw times between the first and second iteration were always 15 seconds or less. Temperature differences were usually within a few tenths of a degree. The largest difference was 1.07 °F for the seventh draw. The flow rate changes between the first and second iteration were a few hundredths of a GPM or less. Changes for all parameters for subsequent iterations were very small, often at the level of round off errors.

The TANK spreadsheet results matched the results of the HWSim-TANK results for the 5th iteration quite well. See Figure 4 Comparison of HWSim-TANK with TANK spreadsheet for a view of the temperatures and flow rates.
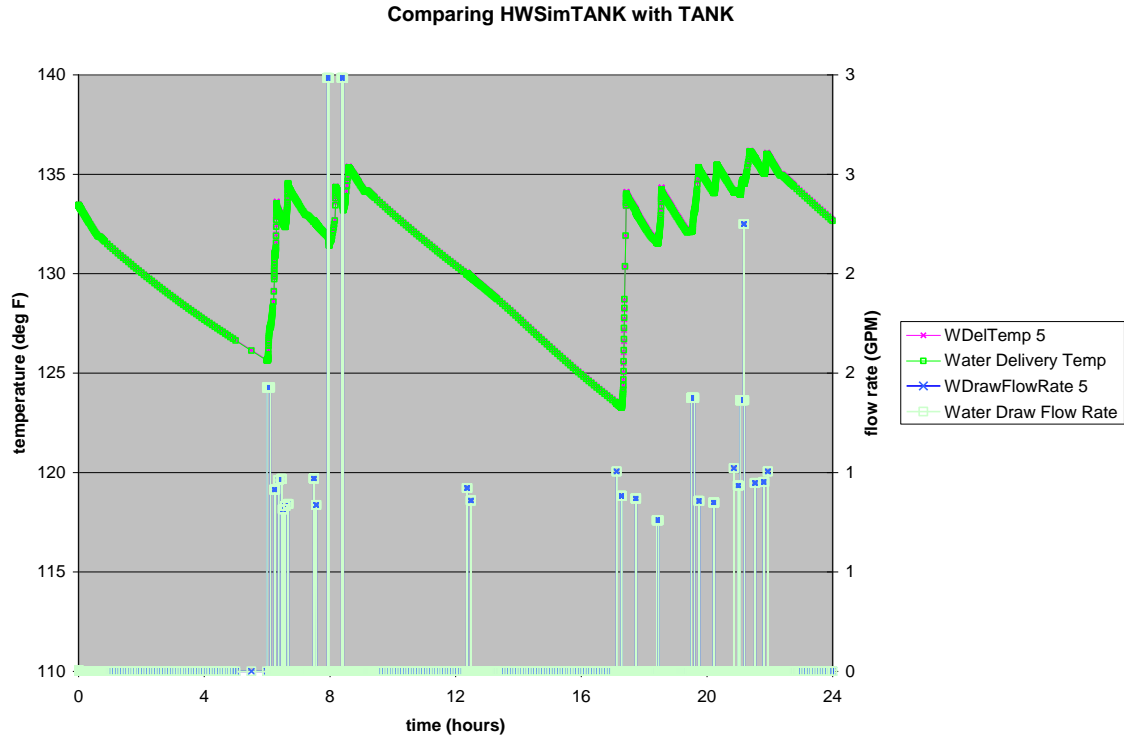
Comparing HWSimTANK with TANK

Figure 4 Comparison of HWSim-TANK with TANK spreadsheet

A similar comparison table of draw parameters between the 5th iteration of HWSim-Tank and the TANK spreadsheet by draws is shown in Table 3

Table 3 Draw Parameters, Difference between HWSim-TANK and TANK Spreadsheet

Draw	Start Time Draw	Stop Time Draw	Start Temp Draw	Stop Temp Draw	Max Temp Draw	Min Temp Draw	Flow Draw	Volume Draw
#	(sec)	(sec)	(deg F)	(deg F)	(deg F)	(deg F)	(GPM)	(G)
1	0.00	0.00	0.039	0.039	0.039	0.039	0.000000	0.000000
2	0.00	0.00	0.032	0.032	0.032	0.032	0.000000	-0.000006
3	0.00	0.00	0.078	0.081	0.089	0.078	0.000000	0.000004
4	0.00	0.00	0.095	0.095	0.095	0.095	0.000000	0.000010
5	0.00	0.00	0.094	0.094	0.094	0.094	0.000000	0.000000
6	0.00	0.00	0.094	0.093	0.094	0.093	0.000000	0.000002
7	0.00	0.00	0.093	0.062	0.062	0.085	0.000000	0.000006
8	0.00	0.00	-0.028	-0.024	-0.035	-0.024	0.000000	0.000006
9	0.00	0.00	-0.007	-0.007	-0.007	-0.007	0.000000	0.000010
10	0.00	0.00	-0.006	-0.006	-0.006	-0.006	0.000000	0.000005
11	0.00	0.00	0.003	0.023	0.020	0.023	0.000000	0.000000
12	0.00	0.00	0.032	0.030	0.032	0.030	0.000000	0.000000
13	0.00	0.00	0.053	0.053	0.053	0.053	0.000000	0.000000
14	0.00	0.00	0.052	0.052	0.052	0.052	0.000000	0.000012
15	0.00	0.00	0.055	0.055	0.055	0.055	0.000000	0.000028
16	0.00	0.00	0.055	0.037	0.037	0.055	0.000000	-0.000011
17	0.00	0.00	0.098	0.097	0.098	0.097	0.000000	0.000042

18	0.00	0.00	0.094	0.092	0.092	0.094	0.000000	-0.000024
19	0.00	0.00	0.097	0.105	0.105	0.097	0.000000	-0.000066
20	0.00	0.00	0.035	0.032	0.029	0.032	0.000000	-0.000014
21	0.00	0.00	0.037	0.041	0.040	0.040	0.000000	0.000035
22	0.00	0.00	0.032	0.032	0.032	0.032	0.000000	-0.000021
23	0.00	0.00	0.032	0.032	0.032	0.032	0.000000	-0.000007
24	0.00	0.00	0.032	0.024	0.024	0.032	0.000000	0.000021
25	0.00	0.00	0.035	0.035	0.035	0.035	0.000000	0.000016
26	0.00	0.00	0.035	0.037	0.036	0.037	0.000000	-0.000039
27	0.00	0.00	0.071	0.071	0.071	0.071	0.000000	0.000028

The differences in temperatures are less than one tenth of a degree.

During the investigation of the implementation of TANK within HWSim it was determined that the conversion of hot water end-use times were not being correctly translated to the form used by TANK. This discrepancy is shown in Table 4 Comparison of Draw Times Specified by HWSim.

Table 4 Comparison of Draw Times Specified by HWSim

INPUT			OUTPUT		
Name	StartTime	EndTime	Draw	StartTime	StopTime
'ghost'			1	00:00:00	00:00:20
mshower1	06:00:00	06:05:30	2	06:00:05	06:06:20
msink1	06:20:00	06:20:41	3	06:13:45	06:15:45
msink2	06:30:00	06:30:23	4	06:21:45	06:22:20
msink2	06:36:00	06:36:17	5	06:27:10	06:28:15
bath2sink1	06:40:00	06:40:42	6	06:30:05	06:31:00
ksink	06:45:00	06:46:00	7	06:34:10	06:35:20
ksink	06:52:00	06:53:00	8	06:40:00	06:40:55
bath2sink1	07:42:00	07:42:12	9	07:29:00	07:30:05
bath2sink1	07:48:00	07:48:30	10	07:33:55	07:34:20
cw	08:10:00	08:13:01	11	07:55:25	07:58:25
cw	08:40:00	08:43:01	12	08:22:25	08:25:25
ksink	12:42:00	12:42:23	13	12:21:25	12:22:50
ksink	12:51:00	12:51:36	14	12:29:00	12:29:35
ksink	17:30:00	17:30:18	15	17:07:25	17:07:40
ksink	17:39:00	17:39:42	16	17:16:10	17:17:40
bath2sink1	18:08:00	18:08:41	17	17:43:40	17:45:10
ksink	18:50:00	18:53:00	18	18:24:05	18:28:05
bath2shower1	20:00:00	20:05:30	19	19:30:05	19:36:05
ksink	20:20:00	20:21:00	20	19:44:05	19:46:00
ksink	20:50:00	20:51:00	21	20:12:10	20:14:10
msink1	21:31:00	21:31:11	22	20:51:10	20:51:20
msink1	21:39:00	21:39:30	23	20:59:00	21:00:50
mshower1	21:45:00	21:53:00	24	21:03:10	21:11:15
ksink	22:00:00	22:00:42	25	21:31:10	21:32:25
ksink	22:22:00	22:22:18	26	21:47:55	21:49:40
msink2	22:40:00	22:40:23	27	21:56:10	21:56:25
msink2	22:50:00	22:50:17			

Correcting the implementation of draw start and stop times is not likely to effect the rate of convergence to a stable daily draw pattern by TANK and HWSim. The agreement on temperatures between HWSim-TANK and the spreadsheet version of TANK will not be impacted by correcting the draw times.

Discussion

The current technique for embedding TANK in HWSim, while successful, has come with a significant increase in computing time. The original compiled DOS version of TANK runs much faster than HWSim-TANK. Now that the HWSim-TANK operations have been assured it may be possible to increase the calculation speed by reducing the output used for debugging purposes.

Another option to consider is finding a way to compile the modified TANK source code so that it can be run as an executable file separately from HWSim. This may allow calculating times closer to those exhibited by the original executable version of TANK.

Conclusion

The negligible hot water temperature and flow rate differences between the TANK spreadsheet and HWSim-TANK indicate that TANK has been correctly embedded in HWSim.

The quick convergence of hot water temperatures and flow rates in repeated iterations of a one day draw pattern indicate this scheme for operating TANK with HWSim is successful.