Residential Hot Water Distribution System Research Suggests Important Code Changes

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Background

The California Energy Commission and supporting research organizations have been investigating the impact of the hot water distribution system's design on the overall energy and water performance of the system in residential buildings. While our research and investigations are likely to lead to modifications in the Building Energy Efficiency Standards portion of California's Building Standards Code (Title 24), a number of potential ways to enhance the performance of these systems is influenced or governed by the requirements of plumbing codes, including the *Uniform Plumbing Code* (*UPC*).

Based on our research, the key factor in determining the performance of hot water distribution systems is to design and build them to have the smallest volume of water within that portion of the system between the plumbing fixture and the source of hot water. The length and the internal diameter of the pipe(s) determine the volume of water contained within the distribution system. Systems with the least internal volume waste the least amount of energy and water. They also typically provide hot water to the plumbing fixture with the shortest waiting period — typically the most important consideration to the hot water user.

Unfortunately, the current plumbing codes do not differentiate between hot and cold potable water piping in the design and installation of a distribution system. Without this differentiation, current hot water distribution systems typically become over-sized while following the guidance provided by plumbing codes. Excessive pipe size has little or no negative water or energy conservation impact on cold water systems but it is a big factor in reducing the performance of hot water distribution systems.

The purpose of this article is to share with you some of the implications of potential changes to plumbing codes stemming from our research.

Right Sizing

"Right sizing" of hot water distribution systems entails using the smallest diameter pipe that will provide adequate flow (at the available water pressure) to meet the real demand on the systems at an acceptable velocity. The *UPC* currently dictates a maximum velocity of 5 ft/sec for copper, and 10 ft/sec for other, hot water piping. Using the smallest diameter pipe allowed by code has several benefits: it will reduce the water and energy wasted down the drain while the user waits for hot water to arrive; it will reduce the temperature drop during the hot water event; and it will minimize the energy wasted as the water standing in the pipe between draws cools down to ambient. However, right sizing also requires that an adequate flow be maintained to meet the real demand on the system and that the velocity of the water be within acceptable limits to avoid erosion, water hammer, and excessive noise. These factors limit how small the diameter of pipe can be used.

Velocity, Not Pressure Loss, Usually Determines Sizing

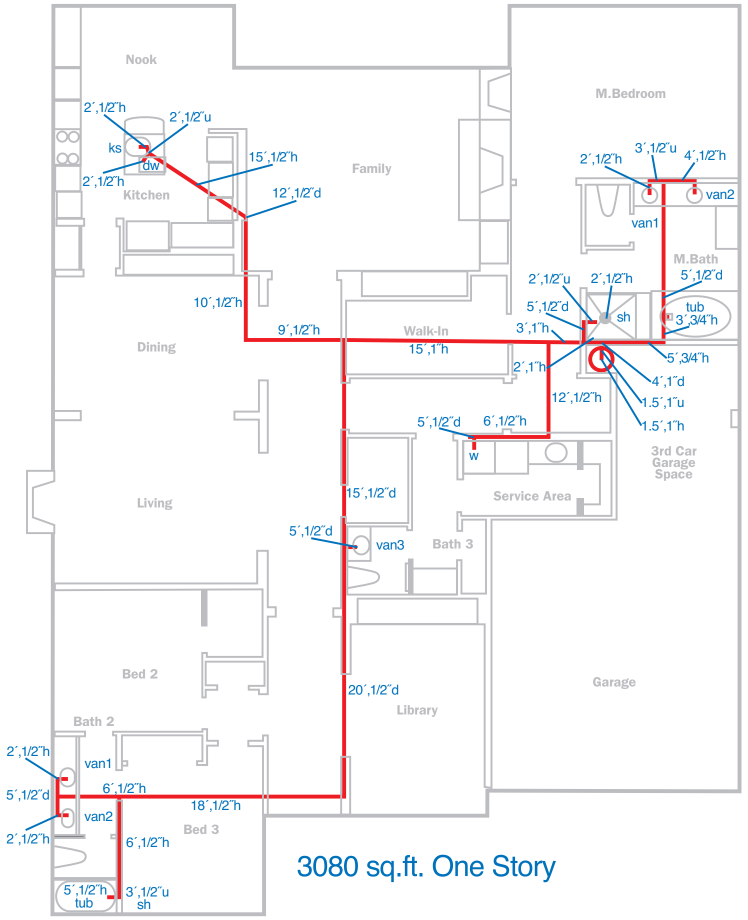
Knowing that smaller pipe can improve performance, we recognized that we had to consider both velocity and pressure drop due to friction losses. While is it certainly possible to install more pipe, for most single story homes under 3000 ft^2 and two story homes under 4000 ft^2, the maximum equivalent length of pipe from the hot water source to the fixture will likely be less than 100 ft. As a point of reference, the median size of new homes in 2006 is approximately 2500 ft^2.

Rough-in plumbing for a slab-on-grade bathroom.

To illustrate this point regarding pipe length, the 3080ft^2 single story house shown in Figure 1 has a maximum run from the water heater to the tub in the furthest bathroom (lower left corner) of approximately 88 lineal feet of pipe. This house was chosen because it portrays a very spread out distribution system. Many new houses do not have runs of this length.

Assuming the line runs through the attic there would be five "tees," two "Ls" and several couplings dependent on the type of pipe. These fittings would add another 18 to 20 feet of equivalent length to this part of the system for a total length of 106 to 108 feet.

Figure 1 Example 3080 ft^2 Single Story House



Since PEX tubing has become a dominant system in California for single-family homes, we will use it in the following example. In order to achieve a flow of 4 GPM to the tub/shower at a velocity under 10 ft/sec a 1/2-inch tube is the minimum size that can be used. The friction loss for this segment — assuming the 1/2-inch is used throughout — would be 20.8 psi X 1.08 (the added length) = 22.5 psi. This is no problem for most houses with their 50-60 psi pressure. The velocity in the 1/2-inch tube would be an acceptable 7.24 ft/sec.

However, because this house has a trunk and branch distribution system, the trunk from the water heater also serves the kitchen and laundry, so the maximum flow should be about 6 to 8 GPM. This segment of the system would therefore have to be 3/4-inch tubing. Recalculating the friction loss for the 3/4- and 1/2-inch pipes together yields an 18.6 psi loss at 7 GPM.

While the overall system friction loss has declined, the velocity on the segment to the tub remained constant at 7.24 ft/sec (see table 1).

From this example and other analyses of typical residential distribution systems, we have concluded that maximum acceptable velocity will usually dictate the pipe size rather than friction loss assuming adequate system pressure (≥ 50 psi) to the house. When the system pressure is <35 psi, then friction loss over a given length of pipe becomes the dominant factor in sizing. For a given diameter, a shorter pipe length is always better.

Table 1. Friction Loss (psi per 100 ft of tubing) and Velocity (ft/sec) vs. Flow Rate (GPM)PEX Tubing (CTS)

Nom Size	3/8″		1/2″		3/4″		1″	
Flow Rate	FLoss	Velocity	FLoss	Velocity	FLoss	Velocity	FLoss	Velocity
1	7.0	3.33	1.6	1.81	0.3	0.96	0.1	0.55
2	25.4	6.67	5.8	3.62	1.1	1.81	0.3	1.10
3	53.9	10.00	12.2	5.43	2.3	2.72	0.7	1.65
4	91.8	13.34	20.8	7.24	3.9	3.63	1.1	2.19
5	--	--	31.4	9.05	5.9	4.54	1.7	2.74
6	--	--	44.0	10.86	8.2	5.44	2.4	3.29
7	--	--	58.6	12.67	10.9	6.35	3.2	3.84

Source: http://www.ppfahome.org/pdf/PEX_Installation_Handbook_2006.pdf (page 13). Note: Red marked numbers are over the code permitted maximum hot water velocity of 10 ft/sec.

Table 2. Copper plumbing pipe sizes and hot water velocities

Nominal Sizes, Inch	OD, Inch	ID, Inch	Flow Rate, GPM 0.5	1	1.5	2	2.5	3	3.5	4	4.5	5	5.5	6	7
			Velocity, ft/sec												
1/4 (K)	0.375	0.305	2.20	4.40	6.59	8.79	11.00	13.20	15.40	17.60	19.80	22.00	24.20	26.40	30.80
1/4 (L)		0.315	2.07	4.13	6.19	8.25	10.31	12.38	14.44	16.50	18.56	20.63	22.69	24.75	28.87
1/4 (M)	*	*	–	–	–	–	–	–	–	–	–	–	–	–	–
3/8 (K)	0.500	0.402	1.27	2.53	3.79	5.06	6.33	7.59	8.86	10.12	11.39	12.65	13.92	15.18	17.71
3/8 (L)	–	0.430	1.11	2.21	3.32	4.42	5.53	6.63	7.74	8.84	9.95	11.06	12.16	13.27	15.48
3/8 (M)		0.450	1.01	2.02	3.27	4.04	5.04	6.05	7.06	8.07	9.08	10.09	11.10	12.11	14.13
1/2 (K)	0.625	0.527	0.74	1.47	2.21	2.94	3.68	4.41	5.15	5.88	6.62	7.35	8.09	8.82	10.29
1/2 (L)	–	0.545	0.69	1.37	2.06	2.75	3.44	4.12	4.81	5.50	6.18	6.87	7.56	8.25	9.62
1/2 (M)	–	0.569	0.63	1.26	1.89	2.52	3.15	3.78	4.41	5.04	5.67	6.30	6.94	7.57	8.83
5/8 (K)	0.750	0.652	0.48	0.96	1.44	1.92	2.40	2.88	3.36	3.84	4.32	4.80	5.28	5.76	6.72
5/8 (L)	–	0.666	0.46	0.92	1.38	1.84	2.30	2.76	3.22	3.68	4.14	4.60	5.06	5.52	6.44
5/8 (M)	*	*	–	–	–	–	–	–	–	–	–	–	–	–	–
3/4 (K)	0.875	0.745	0.37	0.73	1.10	1.46	1.83	2.19	2.56	2.92	3.29	3.65	4.02	4.38	5.11
3/4 (L)	–	0.785	0.33	0.66	0.99	1.32	1.64	1.97	2.30	2.63	2.96	3.29	3.62	3.95	4.60
3/4 (M)	–	0.811	0.31	0.62	0.92	1.23	1.54	1.85	2.16	2.46	2.77	3.08	3.39	3.70	4.31
1 (K)	1.125	0.995	0.21	0.41	0.61	0.82	1.03	1.23	1.44	1.64	1.85	2.05	2.26	2.46	2.87
1 (L)	–	1.025	0.20	0.39	0.58	0.77	0.97	1.16	1.35	1.55	1.74	1.93	2.12	2.34	2.73
1 (M)	–	1.055	0.18	0.36	0.55	0.73	0.91	1.09	1.28	1.46	1.64	1.82	2.01	2.19	2.55

** Pipe size not available. Note: Red marked numbers are over the recommended maximum hot water velocity of 5 ft/sec.*

Table 3. CPVC (CTS SDR 11 and Sch. 40) plumbing pipe sizes and hot water velocities

Nominal Sizes, Inch	OD, Inch	ID, Inch	Flow Rate, GPM 0.5	1	1.5	2	2.5	3	3.5	4	4.5	5	5.5	6	7
			Velocity, ft/sec												
1/4 (CTS)	*	*	–	–	–	–	–	–	–	–	–	–	–	–	–
3/8 (CTS)	*	*	–	–	–	–	–	–	–	–	–	–	–	–	–
1/2 (CTS)	0.625	0.469	0.93	1.86	2.79	3.71	4.64	5.57	6.50	7.43	8.36	9.29	10.22	11.14	13.00
3/4 (CTS)	0.875	0.695	0.42	0.85	1.27	1.69	2.11	2.54	2.96	3.38	3.81	4.23	4.65	5.07	5.92
1 (CTS)	1.125	0.901	0.25	0.50	0.75	1.01	1.26	1.51	1.76	2.01	2.26	2.52	2.77	3.02	3.52
1/4 (Sch.40)	0.540	0.344	1.73	3.45	5.18	6.91	8.63	10.36	12.08	13.81	15.54	17.26	18.99	20.72	24.17
3/8 (Sch.40)	0.675	0.473	0.92	1.83	2.74	3.65	4.57	5.48	6.39	7.30	8.22	9.13	10.04	10.96	12.78
1/2 (Sch.40)	0.840	0.602	0.56	1.13	1.69	2.25	2.82	3.38	3.95	4.51	5.07	5.64	6.20	6.76	7.89
3/4 (Sch.40)	1.050	0.804	0.32	0.63	0.95	1.26	1.58	1.90	2.21	2.53	2.84	3.16	3.48	3.79	4.42
1 (Sch.40)	1.315	1.029	0.19	0.39	0.58	0.77	0.96	1.16	1.35	1.54	1.74	1.93	2.12	2.32	2.70

** Pipe size not available. Note: Red marked numbers are over the code permitted maximum hot water velocity of 10 ft/sec.*

Table 4. PEX (CTS SDR 9) plumbing pipe sizes and hot water velocities

Nominal Sizes, Inch	OD, Inch	ID, Inch	Flow Rate, GPM 0.5	1	1.5	2	2.5	3	3.5	4	4.5	5	5.5	6	7
			Velocity, ft/sec												
1/4	0.375	0.250	3.27	6.54	9.81	13.07	16.34	19.61	22.88	26.15	29.42	32.68	35.95	39.22	45.76
3/8	0.500	0.350	1.67	3.34	5.00	6.67	8.34	10.00	11.67	13.34	15.01	16.68	18.34	20.01	23.35
1/2	0.625	0.475	0.91	1.81	2.72	3.62	4.53	5.43	6.34	7.24	8.15	9.05	9.96	10.86	12.67
3/4	0.875	0.681	0.44	0.88	1.32	1.76	2.20	2.64	3.08	3.52	3.96	4.40	4.85	5.28	6.17
1	1.125	0.862	0.27	0.55	0.82	1.10	1.37	1.65	1.92	2.20	2.47	2.75	3.02	3.30	3.85

Note: Red marked numbers are over the code permitted maximum hot water velocity of 10 ft/sec.

Tables 2-4, developed by ORNL, provide the velocity of water in various sized pipes of copper, CPVC, and PEX for a range of flow rates. Schedule 40 CPVC, which is not typically used in residential construction, was included because the more common CTS pipe does not include 3/8-inch and 1/4-inch sizes.

What About Water Hammer, Erosion, and Noise?

By now, some of you are ready to tell us that higher velocities will result in water hammer, erosion, and excessive noise. So let's look at how big of an issue these will be.

Water hammer is an audible thump that may result when quick closing valves generate excessive surge pressures that are poorly absorbed by the system. Surge pressure is a sudden spike (actually a series of diminishing spikes) in pressure produced by the abrupt change in velocity of the fluid in the line. The impact of the surge pressure depends on the velocity of the water, the wall thickness, and flexibility of the pipe material. Note that excessive surge pressures can occur in a system without audible water hammer. The Jukowski equation was used to determine the maximum surge pressure in pipes (see Table 5 below). This equation is the main equation referenced in the plumbing profession for water hammer.

Table 5. Maximum Calculated Surge Pressure in PSI

(This pressure is added to line pressure to determine total pressure)

Velocity ft/s	**PEX ¾″ SDR 9**	**CPVC ¾″ SDR 11**	**Copper ¾″ L**
1	13	22	55
2	27	44	109
3	40	66	164
4	53	88	218
5	67	110	273
6	80	132	327
7	93	154	382
8	107	176	436
9	120	198	491
10	133	220	546

As can be seen, higher water velocities increase the surge pressures. In addition, at a given velocity, the surge pressure for copper is roughly four times that of PEX and two and a half times that of CPVC for the same diameter pipe. Due to their flexibility, plastic pipes reduce the effect of surge pressure spikes and the resultant water hammer better than metallic pipes.

In an effort to control water hammer, engineering rules of thumb concerning surge pressure came into existence for metallic pipes and generally limited velocities to 4 ft/sec with use with quickly operating valves and 8 ft/sec depending on application, which is why these two values are commonly still used. With the increased use of plastic piping, it would be better to choose velocity limitations based on the characteristics of the piping system.

As the velocity of water in pipes increases, internal erosion and excessive noise can occur. At velocities over 5 ft/sec with hot water, cavitation based erosion has been determined to eat away at copper pipes, particularly in elbows or joints that were not properly reamed. The velocity of hot water in copper pipes is therefore limited to 5 ft/sec in plumbing codes to avoid these phenomena. Over 140˚F, the recommended velocity for copper pipe drops to 2-3 ft/sec.

In the research discussed in the last article (September/October 2006) we reported that wide radius elbows were better from a water and energy performance viewpoint than standard elbows. The impact of higher velocities in straight runs and around long radius turns should be investigated to determine if increased velocities could be accommodated with an improved system geometry that reduces water turbulence and cavitation.

Plumbing codes allow water velocities up to 10 ft/sec with plastic pipe. Efforts are under way to determine maximum velocities for CPVC and PEX, but this may take some time. A limiting concern is that a surge pressure (Table 5) of 150 psi, which occurs with rapid shut off valves, may be getting into a danger zone of some fixtures.

Continuous noise during use in piping systems, like erosion, can be related to cavitation that is created by the velocity of the water and the geometry of the piping system. Higher water velocities coupled with abrupt changes in direction in the system (elbows and tees) can induce cavitation that creates turbulence, vibration and generates noise. Rigid

Hot and cold potable supply piping (left) and 1/2 inch return lines (center) for a slab-on-grade house.

pipes would be expected to amplify and transmit the vibration as noise, while less rigid piping would be expected to dampen both the vibration and the noise. The use of wide radius bends rather than sharp elbows would also be expected to reduce cavitation and its associated vibration and noise. These factors and their impact on system noise should be investigated.

Proposed Code Changes

Our review of the *Uniform Plumbing Code* (*UPC*) identified several areas that could be changed in order to reduce the water and energy wasted in hot water distribution systems as well as the waiting period for hot water to arrive at the fixture. Some of these changes would apply to all occupancies, while others would apply to single-family housing and multi-family housing with individual water heaters for each unit and could save significant resources. We have submitted a proposed change to the 2009 revision cycle.

The first change we recommend is to distinguish between hot and cold (potable) water distribution systems. This differentiation makes it easier to propose changes that are needed to improve the energy and water conservation performance of a hot water system without needlessly impacting the cold water system (since many are not applicable to cold-water distribution). We would define hot water distribution systems as that portion of the potable water distribution system between the hot water source and a plumbing fixture using hot water.

Having separated hot from cold, we propose that the use of the alternative design method found in Appendix L become the standard method of design for single-family housing and multi-family housing with individual water heaters for each unit. This method includes a diversity factor for multiple bathrooms which impacts the Water Service Fixture Units (WFSUs) used in determining the required pipe size of the distribution system (see *UPC* Table L-1). This change is very important because it more accurately reflects real water use in residential systems and can result in a potential reduction in pipe size which reduces energy and water waste.

Table L-1 should also be modified to provide the same diversity factor for both cold and hot water systems. Right now the proportional decline in hot water WSFUs due to the diversity factor is much less than for cold water since the cold water piping also serves the toilet and has more WSFUs.

Based on our research and testing, we have also found significant energy and water waste associated with uninsulated hot water pipes, which cool down to an unusable hot water temperature in a very short time. This is particularly significant in pipes buried in or below floor slabs. Insulation increases the time the pipes can stay hot enough to use between hot water events. We propose adding a requirement that all hot water piping be insulated. In addition, we would propose, for instances where it cannot be avoided, buried pipes (both hot and cold) be installed in a waterproof conduit or sleeve so that they can be removed, repaired and replaced.

We could propose a number of additional changes such as requiring two handle faucets and providing guidance on system layout, but we feel that deferring these items to future *UPC* revision cycles would permit the impact and implementation of the initial revisions to be assessed and refinements made, if required, before going further. In addition, we feel that a number of topics (discussed earlier) warrant further scientific investigation. The knowledge gained from these investigations could also guide the selection and implementation of the potential changes in the future.

Impact of Proposed Changes on Pipe Size

To illustrate the impact on hot water pipe size and entrained water, we will use a median new home of about 2500 ft^2 with 2.5 bathrooms on a common trunk line, Figure 2. The distance from the water heater to the first bathroom grouping is 20 ft, to the second grouping an additional 15 ft, and to the third grouping 20 ft. The total system length from water heater to furthest bathroom grouping is 55 ft. The results are shown in Table 6.

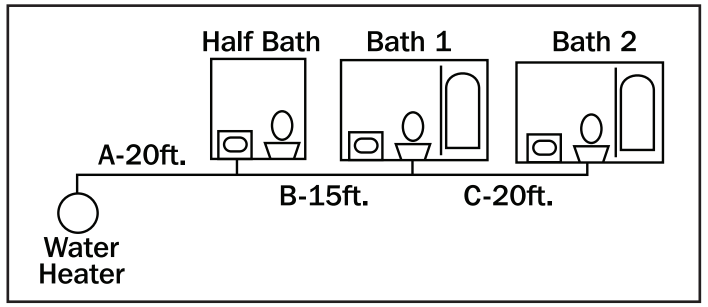


Figure 2. Conceptual layout of 2.5 baths on a common trunk line.

Table 6. Change in Hot Water Trunk Size with Proposed Change to *UPC*
(Pipe sizes from *UPC* Table 6-5 for 30-45 psi)

Method of calculating trunk pipe size	Example 2.5 bath house			
		Half Bath	Bath 1	Bath 2
Table 6-4 (Note 1: Both hot and cold the same)	Lavatory	1.0	1.0	1.0
	Toilet	2.5	2.5	2.5
	Tub/Shower	---	4.0	4.0
	Total WSFU	3.5	7.5	7.5
	Combined WSFUs	18.5	11.0	7.5
	Pipe size	A=1″	B=3/4″	C=3/4″
Table 6-4 (Note 3: Hot only, and at 3/4 of fixture total)	Lavatory	0.75	0.75	0.75
	Toilet	---	---	---
	Tub/Shower	---	3.0	3.0
	Total WSFU	0.75	3.75	3.75
	Combined WSFUs	8.25	7.50	3.75
	Pipe size	A=3/4″	B=3/4″	C=1/2″
Table L-1 (As written)	Bath Groups	2.5	2.0	1.0
	Combined WSFUs	8.0	7.0	5.0
	Pipe size	A=3/4″	B=3/4″	C=1/2″
Table L-1 (Revised, Hot and Cold same diversity factor)	Bath Groups	2.5	2.0	1.0
	Combined WSFUs	3.55	3.45	2.5
	Pipe size	A=1/2″	B=1/2″	C=1/2″

The volume of water entrained in the hot water trunk line would drop from 1.61 gallons (from Table 6.4 sizing) to 0.56 gallons (from Table L-1 revised sizing), or 65%. The water wasted waiting for hot water would also drop by 65% as would the energy used to heat the wasted water. The waiting time for hot water to arrive would also drop dramatically. With the revised sizing, CPVC and PEX piping could carry flows of about 5 GPM while copper could carry flows of 3-3.5 GPM without exceeding velocity limits.

Flows above these levels are possible with multiple bathrooms but unlikely. In order to exceed these flow rates there would have to be multiple showers or tub filling occurring simultaneously. This is unlikely because average household size is approximately 2.8 people, each of whom is likely to have somewhat differing schedules. In addition, the capacity of the water heater will also tend to limit simultaneous use.

If simultaneous use did occur it would be for a very limited period of time. Two concurrent 15-minute showers would deplete the hot water available and thereby suspend usage. During this period the velocity in copper would exceed the 5 ft/sec velocity. However, this episode constitutes only 1% of the day and is unlikely to recur day after day. Intermittent short-term usage that exceeds the velocity limits is not thought to impact issues such as potential erosion. This thought should be confirmed with testing.

Future Directions

During our research and the preparation of this article, it has become clear to us that there is a need for close collaboration between energy and plumbing researchers to investigate and address any outstanding issues or concerns that may arise from the code modification process. Through this collaboration and the increased knowledge it will provide, we are confident that meaningful improvements can be made to the *UPC* or other applicable codes and standards. These changes will assure appropriate levels of service from hot water distributions systems while minimizing energy and water waste.

About the Authors

Gary Klein

Gary Klein has been intimately involved in energy efficiency and renewable energy since 1973. One fourth of his career was spent in Lesotho, the rest in the USA. He currently works in the Demand Analysis Office assisting the California Public Utilities Commission with the evaluation, measurement, and verification of the energy efficiency programs run by California's investor-owned energy utilities. Klein has a passion for hot water: getting into it, getting out of it, and efficiently delivering it to meet customers' needs. He chairs the recently formed Task Force on Residential Hot Water Distribution Systems.

Bob Wendt

Bob Wendt is a research architect at the Oak Ridge National Lab in Tennessee where he has been focusing on residential energy efficiency including the design and layout of hot water distribution systems in support of the California Energy Commission. His other recent research has been investigating flood and hurricane damage resistant homes for use along the Gulf Coast. In addition to buildings research, Wendt's career has included roles as facilities planner and manager at three major DOE installations in California and Tennessee.