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Water Consumption from Freeze Protection Valves for Solar Water Heating Systems

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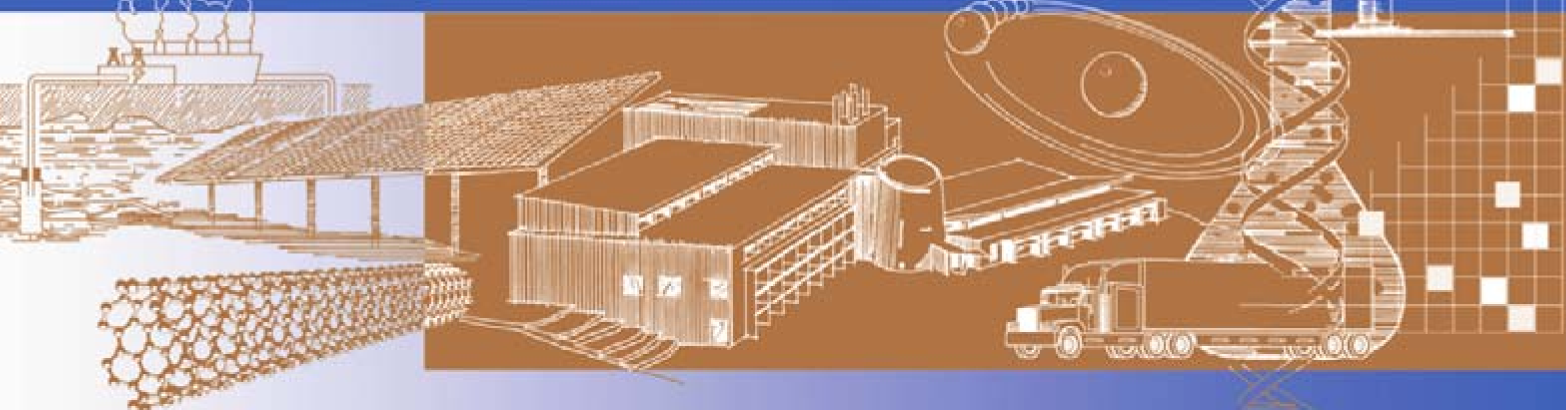

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WATER CONSUMPTION FROM FREEZE PROTECTION VALVES FOR SOLAR WATER HEATING SYSTEMS

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ABSTRACT

Freeze protection valves (FPV) have been used in direct solar domestic water heating systems (SDWH) in mild climates to prevent freeze damage of the collector. Pipe freezing in passive systems can also be prevented using these valves. A limiting factor on where FPVs might be used is the amount of water consumed through use of the valve. An experiment was performed to determine the average flow rate through FPVs over a range of air and water supply temperatures. The experimental flow rate data was then used in a simulation to determine the annual flow through FPVs for 215 sites throughout the continental United States. A correlation between the annual flow and the site air-freezing index (AFI) was then developed in order to increase the spatial data density to over 3,300 sites using AFI data. U.S. maps were generated to display the results graphically. The maps show that there is great potential to increase the market of direct and passive SDWH by using FPV versus using pipe insulation only, although valve reliability remains a concern.

1. INTRODUCTION

Freeze protection valves (FPV) are also called “freeze prevention valves” and “dribble valves.” FPVs can be used to freeze-protect piping (1) and solar collectors (2). In the state of Florida, direct solar domestic water heating systems (SDWH) commonly use an FPV located near the collector outlet to protect the collector tubes from freezing during the occasional freezing episodes, as in Fig. 1. FPV for collectors were studied in (3), including reporting of open/close temperatures, fully-open flow rates, and limited reliability testing. An FPV can also be used so as to freeze-protect supply and return piping, as in Fig. 2 for an indirect thermosiphon system. Note that in this case the FPV should be located near the ceiling level in the attic, to allow mains water to travel through both supply and return piping. In this geometry, an FPV could be used to extend the geographical market for passive systems, which have pressurized supply/return piping in the attic. This would presumably be only for passive systems with load-side heat exchangers. For passive systems with direct, pressurized storage, FPV actuation would purge tank energy and would presumably not be advisable. Using FPV for freeze protection of passive system piping as in Fig. 2 is somewhat novel in the solar field, and is the motivation for the work here.

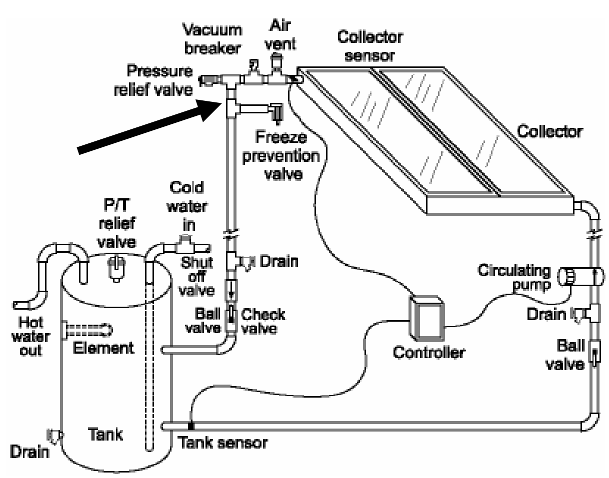

Fig. 1. A direct circulation system schematic. The freeze prevention valve (FPV) is shown near the collector outlet.

Continental U.S. maps of pipe freeze probability for passive SDWH due to freezing of insulated pipes were published in (4). A map of the 20-year freeze probability for attic piping freeze-protected with insulation only is shown in Fig. 9. The regions with zero or near-zero freeze probability (where passive systems can safely be installed) is limited to warmer parts of Florida, Arizona, and California. Although it appears that FPV manufacturers’ literature places no geographical limit on where FPVs can be used, water consumption is certainly one limiting factor. The average flow rate is affected both by valve geometry (subsumed in the fitting factor C_v) and by complex cycling behavior. However, data for flow versus temperature conditions are not available from manufacturers or from previous studies. The goal of this paper is to quantify the loss of water from use of FPVs for protecting collectors and/or piping.

Freeze protection valves operate by using the volume change upon freeze of a wax-like material filling a small enclosure to open the valve, which allows relatively warm supply water to circulate. The valves require no electricity to operate. The setpoint temperature (T_{set}) is the temperature at which the valve starts to open, and is determined by the wax makeup. T_{set} is typically chosen to be either 35°F (for protecting pipes) or 45°F (for protecting collectors). The higher setpoint is used for collectors because they can freeze above 40°F, due to infrared flux to the cold sky. The fully open position is reached when the effective valve temperature drops a few degrees below the setpoint. Table 1 lists and Figure 3 shows five freeze prevention valves. Note that the maximum temperature limit (available for two FPV) may be exceeded during stagnation events on active collectors. Such events may lead to premature valve failure.

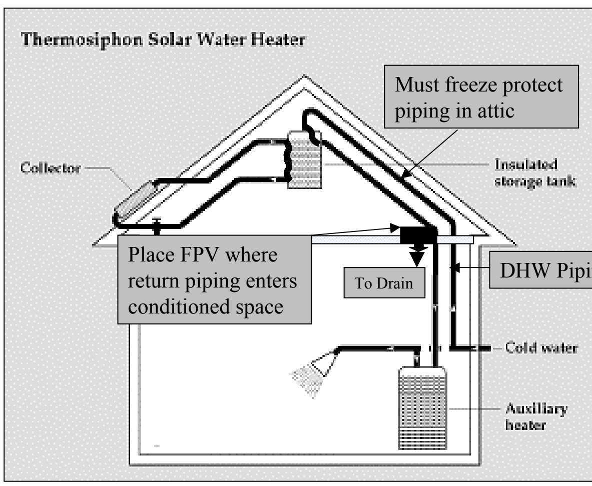

Fig. 2. FPV protecting supply and return piping for an indirect thermosiphon system. The valve is placed just before piping enters conditioned space.

The wax-actuator is immersed in the water within the piping. When cold ambient temperatures drive the stagnant water below the setpoint, the valve begins to open and allow water flow. At this point, warmer water from mains will flow through the valve, warming the valve (and pipes/collector). The valve will then generally modulate back to the closed position. An example of this cycling behavior is shown in Fig. 5. The time constant and dynamics of this cyclic behavior depend on complex heat transfer mechanisms, and would be very difficult to predict. The specific objectives of this paper are to: i) present experimental results for the flow rate through representative FPVs as a function of water, ambient, and setpoint temperatures; ii) calculate and map annual water consumption in solar water heating systems for continental U.S. locations.

TABLE 1: FREEZE PROTECTION VALVE SPECS

Freeze Prevention Valve Manufacturer	Model	Maximum Pressure	Maximum Temperature	Set Point Temperature
		(psi)	(F)	(F)
Dole/Eaton	FP - 45	150		45
Dole/Eaton	FP - 35	150		35
Therm-Omega-Tech	IC/FP - 35	100	200	35
Ogontz	F 35 BDT	200		35
ProFlo	V243T	150	200	35

Fig. 3: Five freeze protection valves. From left to right: *Dole/Eaton* FP-45, *Dole/Eaton* FP-35, *Therm-Omega-Tech* IC/FP-35, *Ogontz* F 35 BDT, and *ProFlo* V243T. Only the first three were tested.

2. FREEZE PROTECTION VALVE EXPERIMENT

An experiment was set up to measure the average flow rate through an FPV as a function of water and ambient temperatures. A schematic diagram of the experiment is given in Fig. 4. A freezer was used to create a cold air temperature environment for the FPVs. The temperature range of the freezer is 0 to -40 °C, and the deviation from setpoint is ~1 °C. The freezer is equipped with an internal fan to promote an even temperature distribution. The internal dimensions of the freezer are 19x49x17 inches and there are four 1-inch diameter ports on the two 19x17-inch sides of the freezer. The ports allow water to be piped to the FPVs inside the freezer and sensors to be routed inside of the freezer. Originally, copper was used for piping from outside the freezer to the FPV. However, conduction caused an unacceptable upward bias to valve temperature; valves would not open when freezer temperature was significantly below setpoint. To eliminate this bias, a section of Tygon tubing was rolled up and placed between the copper pipe from outside and the FPV, as shown in Fig. 4.

A circulator was used to supply constant-temperature water to the FPVs. The circulator is capable of chilling or heating the reservoir fluid to a desired setpoint in the range -15 ^{o}C to +35 ^{o}C. The circulator is equipped with a positive displacement pump that is capable of supplying a flow rate of 3.0 GPM at a maximum pressure of 60 psi. The half-gallon reservoir of the circulator is open to atmosphere. The circulator is placed below the freezer so that the return line from the FPV could be open to atmospheric pressure and drain to the circulator's reservoir under gravity.

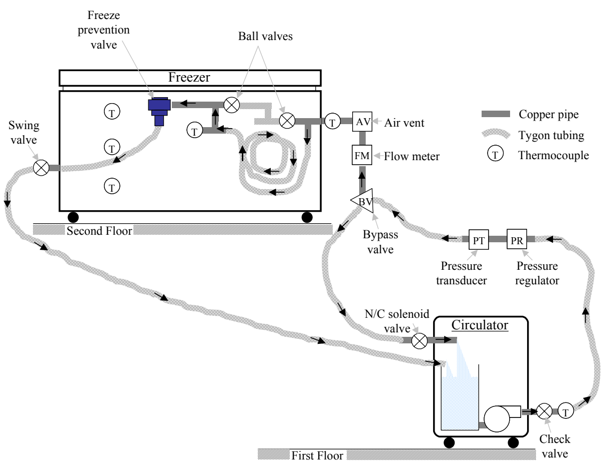

Fig. 4: Schematic diagram of the FPV experiment.

A nutating disc, positive displacement flow meter was used to measure the water flow rate through the FPV. The flow meter's electronic transmitter has a pulse output of 0.0418 gal/pulse, preventing detailed examination of flow during the open-close cycle. The typical operating range of the meter is listed as 0.5 to 25 GPM, with a maximum error of 1.5% in that range. Accuracy of the flow meter was checked by a "bucket test." The relatively-inexpensive meter met error specification, although the error increased to ~-7% (underestimate) at ~.08 gpm.

A pressure regulator was installed to dampen out any spikes in pressure on the supply side of the FPV, and was set to 40 psi. A bypass valve was used on the supply side just outside the freezer to allow for water circulation in the piping when a FPV is closed. This was done to prevent damage to the pump related to deadheading and to condition the water supply piping (so that the temperature set at the circulator is the same temperature that the FPV will sense when it opens). A swing valve was installed just outside the freezer on the polymer drain line from the FPV. This was done to stop the natural convection of air up the drain line, which is open to atmosphere and could also affect the temperature that the FPV is sensing.

A typical profile of flow versus time is shown in Fig. 5. The cycling behavior is evident. Quasi-steady behavior sets in quickly, and flow rate is averaged over at least 10 cycles. At the highest temperatures, cycle time could be larger than an hour, requiring lengthy test duration. Flow rate data were collected for a matrix of freezer and water supply temperatures intended to correspond to the range of ambient air and water mains temperatures where an FPV might be used. The nominal matrix of temperatures is 0, -10, and -20 ^{o}C for the freezer temperature and 5, 10, 15, and 25 ^{o}C for the water supply temperature. An additional freezer temperature of 5 ^{o}C was tested for the FP-45 valve since it starts to open at a higher temperature. These are nominal setpoint temperatures and the actual temperatures recorded during testing were somewhat different; data are reported with actual temperature averages during the test. Three of the five valves shown in Fig. 3 were tested: the *Dole/Eaton* FP-45, the *Dole/Eaton* FP-35, and the *Therm-Omega-Tech* IC/FP-35. This was done because the two valves tested with T_{set} = 35 ^{o}F yielded very similar results, and it was felt unnecessary to test other 35 F valves to roughly characterize water consumption. The flow rate data for the three tested valves are given in Tables 2 to 4. The flow rates are results at 40 psi water mains pressure. Extrapolation to other pressures would depend on details of the flow circuits. However, neglecting pressure drop down the piping (a good assumption for the experiment), flow at other mains pressures would be estimated by Eqn. 1:

$$\dot{m}_{use} = \sqrt{P_{use} / P_{test}} * \dot{m}_{test} \qquad (1)$$

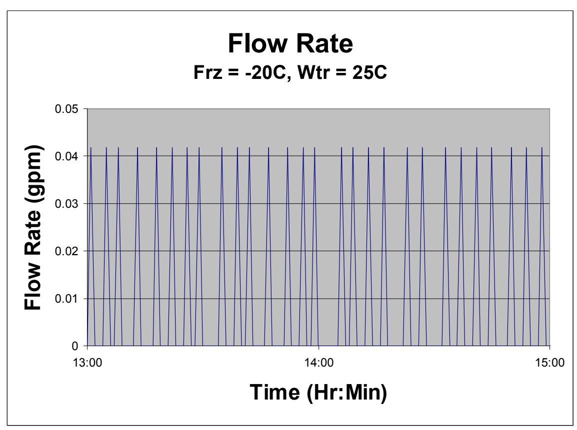

Fig. 5. Flow rate versus time for the Eaton/Dole FP35 valve. Data were stored in one minute intervals. The valve cycled on about every four minutes, although cycles can be missed due to flow meter pulse resolution.

As expected, as the freezer and water temperature are lowered, the flow rate increases. The flow rates are comparable for the FP-35 and the IC/FP-35, with both valves having the same setpoints of ~35 ^{o}F. The flow rates for the FP-45 are considerably higher at a given condition, since it opens at a higher temperature of 45 ^{o}F.

3. FPV SIMULATION AND CORRELATION

The experimental data that relates FPV flow rate as a function of freezer and water supply temperature was used to simulate the annual flow through a valve installed in a solar water heating application. The well-known software tool TRNSYS (5) was used for the simulations. The simulation uses hourly time steps, and linearly interpolates within the flow-rate matrices to obtain the flow. The data interpolation routines imbedded in standard TRNSYS were used for the interpolation. The simulation is carried out for one year using Typical Meteorological Year (TMY2) weather data (6). Mains water temperature was derived from air-temperature data using the algorithm laid out in (7). A total of 215 sites throughout the continental United States were simulated in order to obtain the total annual flow through the three tested FPVs.

TABLE 2: FLOW (GPM), EATON/DOLE FP-45.

		Freezer Temperature (°C)			
		-17.3	-8.4	0.6	4.9
Water Temperature (°C)	5.3	0.965	0.951	0.967	0.962
	9.5	0.305	0.184	0.072	0.031
	14.8	0.053	0.031	0.014	0.0062
	24.2	0.023	0.011	0.0055	0.0019

TABLE 3: FLOW (GPM), EATON/DOLE FP-35

		Freezer Temperature (°C)		
		-18.9	-9.3	-0.3
Water Temperature (°C)	6.6	0.0883	0.0393	0.0043
	10.7	0.0360	0.0192	0.0030
	15.5	0.0199	0.0063	0.0014
	24.5	0.0090	0.0052	0.00088

TABLE 4: FLOW, THERM-OMEGA-TECH IC/FP-35

		Freezer Temperature (°C)		
		-18.6	-9.4	-0.6
Water Temperature (°C)	4.6	0.113	0.098	0.014
	10.8	0.033	0.013	0.0029
	15.6	0.016	0.0063	0.0012
	24.8	0.0049	0.0019	0.00031

Correlations to the annual flow data for the three valves simulated were carried out using the air-freezing index (AFI). AFI is defined as:

$$AFI = \sum_{i=1}^{365} (T_{freeze} - T_{day,i})^{+} \qquad (2)$$

where $T_{day,i}$ is the average air temperature on Julian day i, T_{freeze} is the freezing point of water, and the + sign indicates only positive values are summed. AFI is essentially degree-days to base T_{freeze}. The AFI data set used contains AFI data at over 3,300 sites in the continental United States (8). This increases data density by over 15 times. An empirical correlation form was arbitrarily chosen:

$$V_{water,s} = a_1 * AFI_s + a_2 * AFI_s^2 \qquad (3)$$

where $V_{water,s}$ is the annual water consumption through the valve at site s, AFI_s is the air-freeze-index at site s, and a_i are regression constants. The TMY2-based simulation data set was used to regress the values a_i. Eqn. 2 was then used to extend the $V_{water,s}$ results to the entire NCDC data set without simulation. Correlation results are shown in Fig. 6 for one FPV. The correlation provided a good fit to the simulation data, with $R^2 \cong 0.97$. The fit for the Dole/Eaton FP45 valve was not as good, having $R^2 \cong 0.67$. It is believed that degree-days to base T_{set} (i.e. 35 °F or 45 °F) would provide a better correlation variable than the AFI at base 32 °F. However, variable-base data that would be needed for such analysis are not available, and the extra precision does not justify the expense to develop such data.

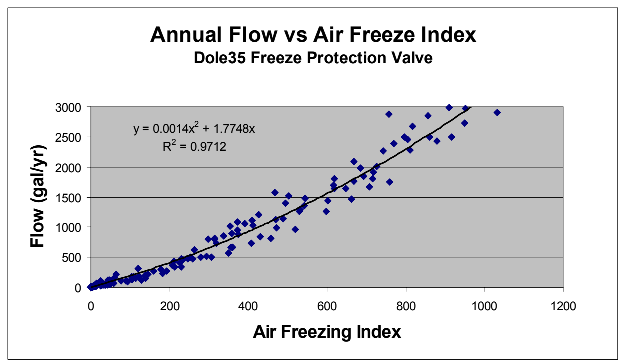

Fig. 6. Correlation between annual flow of consumed water (y) and the Air Freezing Index (x).

4. RESULTS

Maps of the continental United States that show the annual flow through three FPVs were generated using the results from the correlation on the NCDC AFI data. Annual flow maps for the Eaton/Dole FP-45 and FP-35 valves are given in Fig. 7 and Fig. 8, respectively. The map for the Therm-Omega-Tech IC/FP-35 is nearly identical to the Eaton/Dole FP35, and is not shown. The FP-45 valve loses considerably more water than the FP-35, as expected, since it opens at a higher temperature.

There is no clear-cut answer to the question where to draw the “Mason-Dixon line” between an acceptable and unacceptable amount of water consumed. Considerations include long-term water availability, climate, likelihood of drought, and local codes restricting water use. Water consumption here should be considered relative to monthly average water consumption in U.S. homes of 12 kGal/month (9). Even though boundaries of FPV use are not definitive, the water-consumption maps clearly indicate that there is great potential to increase the market of solar water heating systems by using these valves, as in the example of the next paragraph.

Let us assume for purposes here an acceptable boundary is defined by flows less than 1000 gal/yr. By examining Fig.8, the resulting "FPV Mason-Dixon Line" for that valve would extend across the U.S. at about the 40th parallel, excepting the higher mountains and extending further north yet along the coasts. This should be contrasted to the domain where passive systems can be safely installed using only insulated piping, as shown in one case in Fig. 9. The "pipe-insulation Mason-Dixon Line" is limited to parts of Florida, Arizona, and California. *If an FPV were used as in Fig. 2, the passive system domain would be extended by several orders of magnitude.* Note it is assumed here that the rest of the system would not freeze. Although this would be true for indirect thermosiphons at any continental U.S. location, it is uncertain where ICS collectors (even with their large thermal mass) will begin to suffer freeze damage.

With freeze-intolerant piping (such as copper), FPV for pipe freeze protection may not be reliable enough to be used as the sole mechanism of freeze protection. The one study we have found to date on FPV reliability tabulated SDWH damage after a severe freeze in Florida (10). This report indicated that about 25% of wax-based FPV failed in that event, although an unknown fraction of these failures was due to improper installation. A gas-driven mechanism (apparently no longer on the market) was said to have much lower failure rates (10). Pipe freeze protection is a critical need, as one incident can cause damages far in excess of system life-cycle savings. *It thus is prudent that freeze protection of piping should be "multi-leveled," such that failure of the dominant freeze-protection mechanism (e.g., FPV) should not lead to burst pipes.* For example, one might promote use the FPV in combination with use of freeze-tolerant polymer piping (such as PEX, as in (11)). Other possible freeze protection mechanisms that could be additionally employed in a multi-level approach include devising buoyancy-driven heat circulation loops in piping (12) and using heat tape.

5. CONCLUSIONS

The average flow rates of three FPVs were measured over a range of ambient air and water supply temperatures. Using TMY2 weather, the flow rate data were used to simulate the annual water consumption of the FPV. A correlation between the annual flow and the air-freezing index was developed, to use the NCDC AFI data and increase the spatial data density to over 3,300 sites. Maps of the continental U.S. showing the annual water consumption were generated. Annual water consumption is one input helping define the regions of the United States where it might be acceptable to install FPVs. The results indicate there is significant potential to increase the market of passive and direct solar water heating systems by using FPVs. However, failure data dictate caution, and FPVs should not be used as the *sole* protection mechanism, especially for copper pipes where failure of the freeze protection can be disastrous.

6. ACKNOWLEDGMENTS

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7. REFERENCES

1. Pipe-freeze protection using FPVs is described at: http://www.ogontz.com/products/freezeprotection.htm
2. *Standard OG-300 Operating Guidelines and Minimum Standards for Certifying Solar Water Heating Systems*. Available at http://solar-rating.org/standards/ogdocuments/OG300SEP02.pdf
3. Tiedemann, T., "A Study of Freeze Protection Valves for Solar Collectors", Florida Solar Energy Center, Cocoa Beach, FL
4. Salasovich, J., Burch, J., and Barker, G., "Pipe Freeze Probability for Passive-solar Water Heating Systems in the United States", Proc. ASES 2004, ASES, Boulder, CO
5. TRNSYS description and other information can be found at http://sel.me.wisc.edu/trnsys/default.htm
6. Marion, W. and Urban, K., "User's Manual for TMY2s", available at http://rredc.nrel.gov/solar/pubs/tmy2/
7. Hendron, B., "Building America Research Benchmark Definition." Available at: http://www.eere.energy.gov/buildings/building_america/pa_resources.html
8. NCDC data products, including the AFI data set, are available at http://www.ncdc.noaa.gov/oa/ncdc.html
9. P. Mayer, et. al., "Residential End Uses of Water," ISBN 1-58321-016-4; Cat. No. 90781, AWWA, Denver, CO
10. Stutzman, G., "Survey of the Solar Industry after the December 1983 Freeze," FSEC-RM-15-85, Florida Solar Energy Center, Cocoa Beach, FL
11. Heater, M., and Burch, J., "Freeze Tolerance of PEX Piping," to be published ASES 2006
12. Darbaheshti, M., Burch, J., Gawlik, K., and Johnson, T., "Freeze Protection for Potable Water Piping Using Natural Convection Loops," Proc. ASES 1999, ASES, Boulder, CO

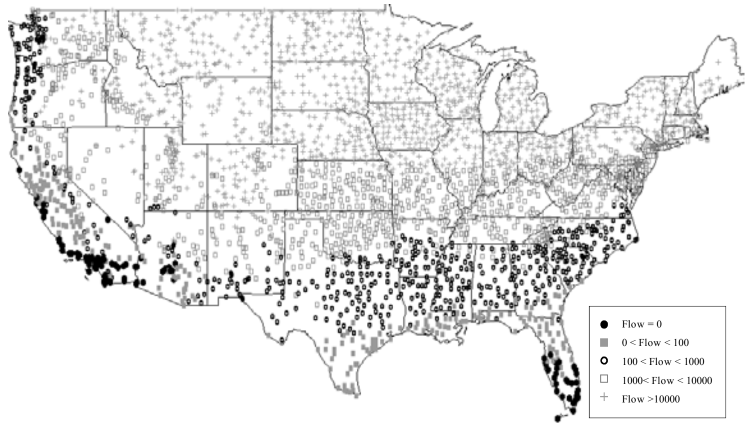

Fig. 7: Flow (gallons/year) through the Eaton/Dole FP-45 freeze prevention valve. This valve would be chosen for freeze-protecting solar collectors.

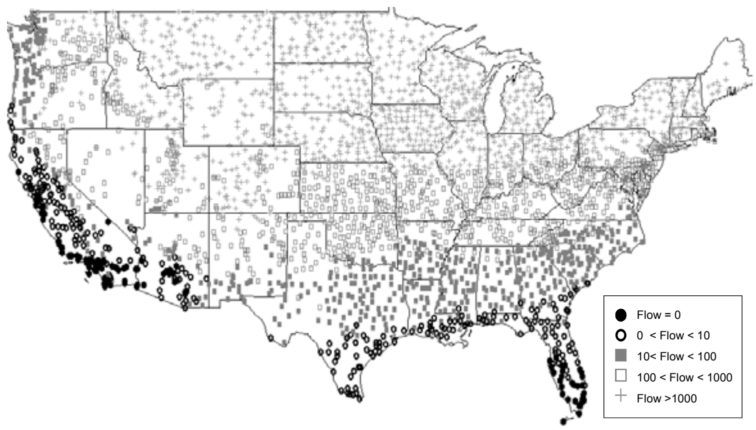

Fig. 8: Flow (gallons/year) through an Eaton/Dole FP-35 pipe freeze prevention valve. This valve would be chosen for freeze-protection of piping in the attic. The 1000 gal/yr border might be a reasonable cutoff for use of FPV.

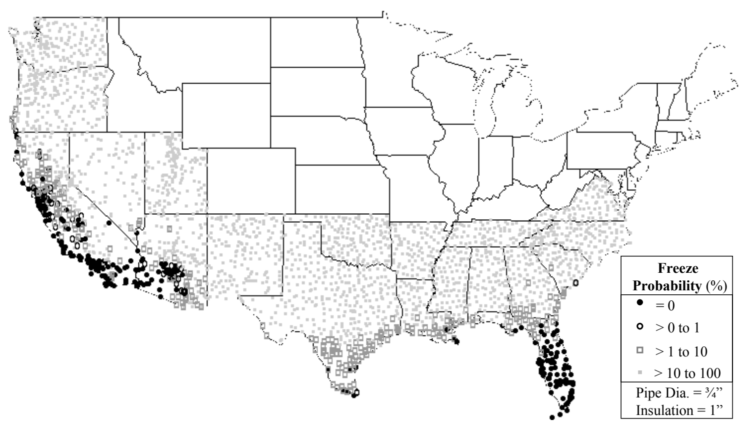

Fig. 9: Probability of at least one freeze in 20 years, for mild climate states, 3/4" pipe with 1" insulation. The dark dots indicate regions where it would be safe to install passive systems with insulated pipes in the attic. The region is quite small, and corresponds to where passive ICS are installed today. The region could be extended by using FPVs for pipe freeze protection, although reliability concerns demand multi-leveled, fail-safe protection for such a critical function.

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