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HYDRONIC DISTRIBUTION SYSTEM COMPUTER MODEL

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ABSTRACT

A computer model of a hot-water boiler and its associated hydronic thermal distribution loop has been developed at Brookhaven National Laboratory (BNL). It is intended to be incorporated as a submodel in a comprehensive model of residential-scale thermal distribution systems developed at Lawrence Berkeley Laboratory (LBL). This will give the combined model the capability of modeling forced-air and hydronic distribution systems in the same house using the same supporting software. This report describes the development of the BNL hydronics model, initial results and internal consistency checks, and its intended relationship to the LBL model. A method of interacting with the LBL model that does not require physical integration of the two codes is described. This will provide capability now, with reduced up-front cost, as long as the number of runs required is not large.

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INTRODUCTION

As part of its responsibility to promote energy efficiency in buildings, the U.S. Department of Energy (DOE) has an interest in the efficiency with which thermal energy (heat or cooling) is transported from the equipment in which the heat or cooling effect is produced to the building spaces in which it is used. The systems that transport this energy are usually called thermal distribution systems. In the United States today, the most common type of thermal distribution systems in residential and small commercial buildings is the forced-air system that employs ductwork to distribute air that is moved by a fan. A recent government survey [RECS 1990] disclosed that in 1990, 53% of households were served by a central warm-air furnace and a forced-air distribution system. Another 7% were served by heat pumps, nearly all of which use forced-air systems to distribute their output energy. Thus, a clear majority of existing housing uses forced-air distribution systems.

The next most common type of distribution system is one that uses pipes to distribute hot water or steam to the building spaces. This type of system is usually called hydronic. In 1990, these systems served 15% of households.

Although forced-air systems have captured the bulk of the space-conditioning market in the United States, there is nevertheless great interest in hydronic systems for the following reasons:

- o They are the second-largest category of thermal distribution systems in existing housing today.
- o They are believed to have potential for very high efficiency if constructed with this in mind.

With regard to this second point, the high efficiency potential for hydronic systems derives from the fact that they avoid some of the loss factors commonly met with in forced-air systems:

1. Leakage. Duct systems often have leakage rates in excess of 10% of flow. Hydronic systems cannot leak without disastrous consequences to the building; therefore leaks are prevented for reasons other than energy efficiency.
2. System effects. Duct systems are subject to losses through various kinds of system interactions, such as an increase in the air infiltration rate of the house when the fan comes on, and thermosyphoning in the duct system when the fan is off. Hydronic systems do not have a fan, and the hydrodynamics of most piping systems usually prevents thermosyphoning.

3. Conductive losses. Both pipes and ducts conduct heat through their containment walls. Ducts, however, are larger than pipes and therefore heat conduction will be greater, all else being equal. They are also harder to insulate than pipes because of their greater cross-sectional area.

These things being said, it must also be noted that hydronic systems can produce losses of their own. For one thing, many piping systems are not insulated where they pass through unconditioned spaces. For another, the equipment efficiency may be greatly reduced in certain types of systems that come under the heading "hydronic," such as single-pipe steam systems. Also, condensing furnaces with Annual Fuel Utilization Efficiencies (AFUE) above 90% can be easily linked to forced-air systems, but because of the higher return-water temperatures usually found in hydronic systems, the maximum seasonal efficiencies of hot-water boilers, even if designed to support condensing, may be expected to fall in the 85%-89% range.

All these considerations having been noted, there is strong reason to believe that a well-designed hydronic system that is well insulated where it passes through the unconditioned space and that uses an efficient hot-water boiler can easily achieve an overall system efficiency in excess of 80%, where system efficiency is defined as the ratio of heating load to fuel used. Forced-air systems, if properly designed and installed can achieve similarly high efficiencies, but as commonly implemented in practice, they may commonly produce system efficiencies below 50%. [ASHRAE 1992]

To evaluate the potential for hydronic systems to provide an efficient alternative to forced air, at least two scientifically useful paths are possible:

- o Side-by-side field evaluations of efficient embodiments of both forced-air and hydronic systems, possibly in conjunction with simultaneous evaluations of "run-of-the-mill" versions of both systems.
- o Development of a simulation model that would permit an "apples-to-apples" comparison of the two system types in the same house under the same weather conditions.

Because the second alternative was judged to be much the less expensive, it was chosen as the first DOE-sponsored effort relating to hydronic systems. To capitalize on work that had already been undertaken, the Lawrence Berkeley Laboratory (LBL) model of forced-air systems was chosen as the platform on which a hydronic modeling capability would be added. Brookhaven National Laboratory (BNL) was chosen to develop a hydronic submodel that could be incorporated into the LBL thermal distribution model.

INTERACTION WITH THE LBL MODEL

Since the hydronic systems model described here is intended to be incorporated in the LBL model, a brief description of this model is appropriate. A complete description is best given by the model's originators [Treidler et al. 1993], but we need to give a brief account sufficient to understand the relationship of the hydronic submodel (developed by us) to the intended main model developed at LBL.

The LBL model is based on the widely used building simulation program DOE-2, but in addition it has subprograms that provide more accurate predictions of air flows driven by pressure and temperature differences (subprogram COMIS) and duct heat- and mass-transfer dynamics (subprogram DUCTSIM) than are available in the standard DOE-2 package.

Figure 1 shows this schematically. DOE-2 generates the building-space temperatures and heating (cooling) loads that have to be met by the equipment and distribution system. COMIS then computes the air flows that would be encountered in both the ducts and the zones of the house under fan-on and fan-off conditions. DUCTSIM uses this information to simulate the hour's running of the equipment and distribution system necessary to meet the given load.

The LBL model can also be run without ducts. When running without ducts, the LBL model replaces the DUCTSIM program with a simple routine that just meets the loads as calculated by DOE-2 without perturbing the system in any way. LBL's "no-ducts" energy supply meets the loads supplied by DOE-2 without depending on any thermal distribution system at all, which in the heating mode is conceptually equivalent to having individual heating systems in each zone.

So far we have not discussed how the LBL model accounts for interactions between the duct system and the space-conditioning load. That is, if heat is lost from ducts to a basement, and this heat serves to reduce the amount of heat lost from the house through the basement ceiling, how is this taken into account by the model. After all, when DOE-2 computed the loads, it didn't know how much heat would be lost from the ducts.

This problem is addressed in the following way. The model is run for an entire heating or cooling season with the hourly loads as calculated by DOE-2, assuming that there is no impact of the duct system on the building. (This in effect assumes that the ductwork is not thermally connected to the conditioned space except through the registers.) The heat losses from the ducts to the buffer zone in which they are located is computed by DUCTSIM. These losses are then input to DOE-2 during a second run (over the same entire heating or cooling season), in which their effect on the building is taken into account. The impact on the load affects

the required run time of the heating or cooling system, and hence the duct losses will change. These losses are input to DOE-2 during a third iteration (again another run over the entire season), which is generally enough to give adequate convergence, but if not a fourth iteration can be run.

The intended interaction of the hydronic submodel with the LBL model is shown in Figure 2. The LBL model is run in a mode in which DUCTSIM is deactivated and COMIS computes only in-zone air flows, not those in the ducts (because there are no ducts). For each hour simulated, the hydronic submodel accepts the load computed by DOE-2 and computes the energy flows through the boiler and distribution system needed to meet this load. It also computes the heat lost to spaces other than the conditioned space. Thus, it plays a role analogous to DUCTSIM in the basic LBL model.

Figure 1. Schematic representation of the LBL thermal distribution model.

Figure 2. Intended interaction of the hydronic submodel with the LBL model.

APPROACH TO HYDRONIC SYSTEM MODELING

The approach we have taken was to write a HYDRONIC program that would substitute for DUCTSIM in the LBL model. HYDRONIC has as inputs a set of fixed parameters that define the boiler and the distribution system, which in this first version is conceptualized specifically as a baseboard hot-water loop. Other types of hydronic systems, such as radiant systems, steam systems, and systems that employ fan-coil units, may be added later.

The fixed parameters include boiler input rate, stack and jacket loss rates in both the on-cycle and off-cycle, boiler thermal mass, circulator flow rate, and hydronic-system physical parameters such as pipe diameter, pipe-system layout and dimensions (by building zone), and effective heat-transfer coefficient (UA) to each zone.

In addition to the fixed parameters, HYDRONIC will depend on the LBL model in which it is embedded to provide it, on an hourly basis, with the zone temperatures, the outside ambient temperature, and the space heating load it is required to meet for each given hour.

The program will use the load from DOE-2 and the current zone temperatures as inputs. It will operate the hydronic system so as to meet the load and therefore maintain the setpoint temperature of the conditioned space. Its outputs will consist of heat deposited (intentionally or unintentionally) in each zone, including the buffer zone that contains whatever piping is not in the conditioned space.

A boiler model has been included in the package, so that the overall energy use, stack and jacket losses, as well as piping losses can be handled. This model is a relatively simple one that fit the data well in a study done in the mid-1980's on low-firing-rate systems.

MODEL DESCRIPTION

The model is predicated on a boiler and a hydronic loop. The loop is split into sections of pipe, each having the same fluid storage capacity (Figure 3). The requirement that each section have the same fluid storage capacity was set so that during each timestep the fluid in one section will move entirely to the next section. This was done to make it easier to program the operation of the loop. It should not prove to be an undue limitation, since the loop can be divided into as many sections as needed. For example, a typical hydronic loop is about 150 ft long. If this is divided into 6-foot sections, a total of 25 sections would be required. This should permit reasonable accuracy for most situations. The program is fast enough that more sections can be used if this is seen to be desirable.

The main subroutine of the model, named HYDRO, is flowcharted in Figure 4. In order to operate, this program needs three sets of inputs. The first is the parameter set that describes the hydronic system. These parameters are as follows:

1. Zone in which boiler is located (conditioned or buffer space)
2. Boiler thermal mass
3. Upper and lower limits on boiler-water temperature
4. Boiler firing rate
5. Stack efficiency of the boiler in steady-state operation
6. Jacket-loss heat transfer coefficient (UA)
7. Off-cycle stack-loss heat transfer coefficient (UA)
8. Maximum circulator cycles per hour (at 50% ontime)
9. Number of pipe sections
10. Water flow rate in pipe
11. Internal volume of a pipe section
12. For each pipe section:
 - 12A. Zone in which section is located
 - 12B. Heat-transfer coefficient (UA) to the zone
 - 12C. Heat-transfer coefficient (UA) to the exterior
 - 12D. Thermal mass of the pipe material (including fins if any)

The second set of inputs is the ones provided to the hydronic model by the LBL model. These are as calculated by DOE-2 in that model. These inputs are:

1. Heating load for the hour
2. Temperature in the conditioned space
3. Temperature in the buffer space
4. Outdoor ambient temperature

The third set of inputs is generated by the hydronic model itself in a preliminary run that is done on the first hour's call from the LBL model. This consists of a table that defines the circulator fractional ontime and number of cycles per hour as functions of the hourly heating load. This table is generated by

a subprogram called LOADCURVE. We now describe the operation of HYDRO, the principal subroutine of the hydronic model, assuming that this table has been generated. The theory and operation of LOADCURVE is described following this.

HYDRO begins by calling on LOADCURVE to generate the table described above. Following this, for each hour of the simulation, HYDRO uses this table to decide what circulator fractional ontime and number of cycles per hour it will use. For example, if the fractional ontime is 0.2 and 4 cycles per hour are called for, then that hour's simulation will have the circulator on for 3 minutes and off for 12 minutes for four successive 15-minute cycles within that hour.

The program then runs through a loop in which the time moves through the 3600 seconds of the hour, with a timestep DTHX equal to the number of seconds required for a particle of water to pass from the beginning of one pipe section to the beginning of the next. Within each step of the loop, the program first determines whether the circulator is on. If it is, it first shifts the water in the pipe forward one section. It then calculates the heat transfer from the water to the pipe and then from the pipe to the surroundings, using the log-mean temperature difference approach. Starting with a given inlet temperature to a pipe section, the outlet temperature that gives consistency between heat transfer from the section and heat lost by the thermal mass of the section is used as the "flow heat transfer."

If the circulator is off, the program allows the water in the pipe section to relax in temperature as a single mass losing heat to the outside with a time constant equal to the thermal mass of the section divided by the UA value. This is called the "relaxation heat transfer."

The next step is to calculate the boiler heat flows. The details of the boiler model are given below, following the description of LOADCURVE. This model decides whether the burner is off or on and then computes the heat flows into and out of the boiler from/to the burner, the stack, the jacket, and the hydronic loop.

The next step is to decide whether the heating load will be met if the circulator is shut down at this point. This step is necessary because heat continues to flow into the conditioned space even after circulator shutdown, because of stored heat in the pipes. Because the LBL model is load-driven and not thermostat-driven, the submodel must ensure that it meets the given load as nearly as possible. Thus, a calculation is made of the heat that would be delivered to the conditioned space by the end of the hour, under the assumption that the circulator is shut down for the rest of the hour, overriding any previous decision concerning fractional

ontime. If the answer is that the heat would be insufficient to meet the load, control of the circulator remains with HYDRO according to the schedule established at the beginning of the hour. If the answer is that enough heat would be delivered with no further operation of the circulator, then the circulator is shut down and the tentative calculation of heat transfer to the end of the hour is made permanent and the clock is advanced to the end of the hour also.

When the end of the hour is reached, the program passes on to the next hour. In general, we find that agreement between the heat given up to the conditioned space and the heating load is not exact. Usually the difference is less than 100 Btu. In any case, a modification to the program that will carry over any difference to the next hour needs to be made to avoid cumulative discrepancies. That is, if in any hour the system provided somewhat more heat than called for, then in the next hour it needs to provide a little less. This is an easy change to make and will be done early in the next phase of the project.

For each hour of operation, HYDRO outputs all the relevant energy flows involving the boiler or the hydronic loop. These include fuel used, stack losses, jacket losses, heat delivered to the hydronic loop, heat given up from the hydronic system to the conditioned space, heat from hydronic to buffer space, and heat from hydronic directly to the outside (if any). Also, the boiler-water temperature and temperatures in the pipe loop are recorded, allowing a determination of net heat storage in the boiler and the loop.

Figure 3. Hydronic Loop Divided into Sections

Figure 4. HYDRO Program Flow Chart

Figure 5. LOADCURVE Program Flow Chart

Subprogram LOADCURVE

As mentioned above, HYDRO's first job, which it performs once on the first call from the main program (the LBL model), is to establish a baseline relationship between the heating load and the number and duration of circulator on-periods for that hour. This is performed by a subroutine called LOADCURVE. The objective is to force HYDRO to operate as nearly as possible within the standard parabolic relationship of cycles per hour versus fractional on-time:

$$N = 4 N_{\max} f (1-f) \quad (1)$$

where N is the number of cycles per hour, $N_{\max}$ is the maximum number of cycles per hour, and f is the fractional ontime of the circulator. This relationship ensures that $N=N_{\max}$ when $f=0.5$ and that N drops off toward zero as f approaches zero or one. In the real world, N need not be an integer, but in the simulation we will have to use integral values of N since the simulation goes in one-hour timesteps.

The derivation of this formula, which is a standard assumption in much modeling work (and which was verified in the ASHRAE SP-43 project [Jakob et al. 1987] for forced-air systems), follows from some simple assumptions that should hold at least approximately:

- o The rate at which heat is delivered to the building when the circulator is on is approximately constant (with value Q_{in} Btu/h). The rate at which heat is delivered to the building when the circulator is off can be ignored.
- o The rate of heat loss from the building is constant (with value Q_{out} Btu/h).
- o The thermal mass of the house is a constant (htmass, Btu/F).
- o The thermostat deadband is constant (with value ΔT in °F).

Given these assumptions, the on-period of the circulator is given by the time needed to warm the building through the thermostat deadband:

$$t_{on} = \text{htmass } \Delta T / (Q_{in} - Q_{out}) \quad (2)$$

while the off-period is the time needed for the building to cool down through the same thermostat deadband:

$$t_{off} = \text{htmass } \Delta T / Q_{out} \quad (3)$$

The sum of these two quantities is then

$$t_{on} + t_{off} = \text{htmass } \Delta T / [Q_{out} (Q_{in} - Q_{out})] \quad (4)$$

But this is just the time for one complete cycle, so the number of cycles per hour is the inverse of this quantity

$$N = (t_{on} + t_{off})^{-1} = [Q_{out}(Q_{in} - Q_{out})] / (ht_{mass} \Delta T Q_{in}) \quad (5)$$

The fractional ontime is defined as the ratio of on-period to total on- plus off-period

$$f_{ontime} = t_{on} / (t_{on} + t_{off}) \quad (6)$$

and using equations 2 and 4, this can be reduced to

$$f_{ontime} = Q_{out} / Q_{in} \quad (7)$$

Equation 5 is now rearranged slightly to

$$\begin{aligned} N &= (Q_{out} / Q_{in}) [1 - (Q_{out} / Q_{in})] Q_{in} / (ht_{mass} \Delta T) \\ &= f_{ontime} (1 - f_{ontime}) Q_{in} / (ht_{mass} \Delta T) \end{aligned} \quad (8)$$

This is seen to have the parabolic dependence referred to above.

An initializing program called LOADCURVE (Figure 5) generates a table of loads and fractional ontimes leading to all possible integer values of N. This is done, first, by solving Equation 1 for f as a function of N and then getting the circulator ontime $t_{on} = f/N$ and offtime $t_{off} = (1-f)/N$. These values are then run through the same algorithm as the main program HYDRO (see above) for one hour, with the boiler-water temperature and the temperature in the pipes beginning at a preset value, and with the boiler-water temperature (but not the pipe temperatures) held constant for the rest of the hour.

A hypothetical example of such a table is given below:

Load Met (kWh)	Cycles per hour	Fractional Ontime
0	0	0
0.7	1	0.044
1.4	2	0.092
2.2	3	0.146
3.1	4	0.211
4.2	5	0.296
6.4	6	0.500
8.2	5	0.704
8.8	4	0.789
9.2	3	0.853
9.5	2	0.908
9.8	1	0.956
10.0	continuous	1.000

Note that while the cycles-per-hour curve will be symmetric about the 0.5 fractional on-time point, the load met at 50% ontime will be more than 50% of the load met at full ontime, because the thermal mass of the water will still be releasing heat even when the circulator is off.

One other small task is to compute $dthx$, the time for a given elemental volume of water to be pumped from the beginning to the end of a pipe section. This is just the volume of the section divided by the pumping rate of the circulator.

Boiler Model

The boiler model is relatively simple. It is based on the idea that, when the boiler is on, it operates at steady-state efficiency, with stack and jacket losses dependent on boiler water temperature (BWT), and when it is off it delivers no heat but incurs stack and jacket losses that are (possibly different) functions of BWT. Such a model fit the data well in earlier BNL work.[Andrews 1985] This approach to modeling the boiler is summarized as follows:

Boiler Section (Circulator ON)

1. Remove boiler water for first section of loop @ beginning boiler-water temperature (BWT) and replace with water from last pipe section at whatever temperature it is now at.
2. Recompute BWT.
3. Decide whether the boiler is ON or OFF for this section's time slot.

If OFF, leave it OFF unless $BWT < T_{min}$

If ON, leave it ON unless $BWT > T_{max}$

(T_{min} and T_{max} are the minimum and maximum allowed boiler-water temperatures. Typical values would be $T_{min} = 150$ F (65 C) and $T_{max} = 180$ F (85 C).

If boiler is now OFF: Remove stack-loss heat.
 Remove jacket-loss heat.
 Dump jacket-loss heat to
 zone the boiler is in.

If boiler is now ON: Add heat to boiler water
 @ stack efficiency.
 Remove jacket-loss heat.
 Dump jacket-loss heat to
 zone the boiler is in.

4. Recompute BWT at end of this section's time slot.

Boiler Section (Circulator OFF)

1. If boiler was ON at beginning of the circulator-off period, calculate how long to leave it on so that BWT hits $T_{\max}$ (maximum time: to end of circulator-off period).

IF boiler was OFF at beginning of circulator-off period, leave it off. (BWT might go a degree or two below $T_{\min}$.)

2. Compute jacket, stack losses and BWT at end of circulator-off period.

Energy Accounting

The program keeps track of all energy flows in the boiler-hydronic subsystem. This includes fuel use, heat delivered to the heated space, heat lost to the buffer space, stack losses, and jacket losses. Temperatures within the boiler and all parts of the hydronic loop are also tracked. The program does its best to exactly meet the load presented to it by DOE-2; however, small discrepancies are expected because the number of pipe sections through which water is pumped during any timestep must be an integer. Any such discrepancy is added to or subtracted from the next timestep's load.

Multiple Zones

DOE-2 requires that the building equipment exactly meet the calculated load for the hour. In the event that there is more than one heated zone, three possibilities present themselves. One is that each zone is served by a separate loop with its own circulator. This could easily be handled by modifying the program to keep track of two or more loops simultaneously. The second possibility is that a single circulator is used with a zone valve. This might be handled by substituting a multiple circulator arrangement and letting it meet the loads, or it might require additional program development. The third possibility is that a single loop with a single circulator serves both zones. In this case, it will generally not be possible to satisfy both (or all) loads simultaneously. This is true in the real world as well as in the model. To handle such a situation it will be necessary to modify DOE-2. None of the modifications necessary to handle multiple zones was included in the scope of the current project.

Algorithms and Computer Code

A description of certain algorithms developed for the model is given in Appendix 1. The code for the program, as of October 5, 1994, is given in Appendix 2.

RESULTS OF PRELIMINARY RUNS

Boiler and Circulator Cycling

Several runs were made to look at the cycling behavior of the boiler in conjunction with that of the circulator. In general, it was found that if a constant circulator cycling rate and fractional ontime are forced onto the system, that the boiler very quickly falls into step with the circulator, though not necessarily with the same number of cycles per hour. That is, the boiler cycles at a rate that involves an integral number of boiler on-cycles during a time period that also contains an integral number of circulator on-cycles. This type of behavior is expected for a system driven by a periodic input, and therefore lends some confidence that the coupling between the circulator and the boiler in the model is proceeding in a reasonable fashion.

Figures 6 and 7 show the progression of the boiler-water temperature and the average water temperature in three pipe sections over a one-hour period. The distribution system had 12 pipe sections. Section 2 was in the conditioned space, with a high heat-exchange UA representing finned baseboard. Section 6, near the middle of the loop, was in the basement and had no fins. In Figure 6, this pipe was uninsulated, with a UA of 6 Btu/h-F for a 15-foot section. In Figure 7, the pipe was insulated to approximately an R-3 value, with the overall UA reduced to 1 Btu/h-F for the same 15-foot section. Section 11 was similar to section 2, but was located near the end of the loop.

As can be seen from the figures, the boiler comes on every other time the circulator comes on. This behavior is dependent on the characteristics of the boiler, in particular of its thermal mass. In this run, the circulator came on for three minutes out of 15 minutes (20% ontime). The thermal mass of the boiler was enough to get it through one circulator on-cycle without needing to fire; the next circulator-on cycle then drew the boiler-water temperature down sufficiently to incite the burner.

The temperatures in the pipes are seen to follow what generally would be expected: earlier sections have higher water temperatures than later ones when the circulator is on. When the circulator is off, the temperatures in the pipes relax in accordance with their heat-exchange UA values. Thus, the insulated pipe section in the basement (Figure 6) relaxes more slowly than the uninsulated one (Figure 7).

Energy Balances

Energy balances on boiler and circulating loop were taken for the several cases. Each case represents a run in which the boiler and hydronic loop end in the same state at which they started.

Figure 6. Boiler water and pipe temperatures, insulated pipe.

Figure 7. Boiler water and pipe temperatures, uninsulated pipe.

Table 1 shows the results of these runs. Energy balances on both the boiler and the hydronic loop showed closure. In several respects the behavior of the system was as expected. Equipment efficiency declines with decreasing boiler fractional ontime. For a given circulator fractional ontime, slightly more heat is delivered to the hydronic loop when the pipes are uninsulated; this is due to the fact that the return water is cooler under that condition. Insulating the pipe improves the delivery efficiency of the hydronic loop, but it degrades the equipment efficiency slightly because of the lower boiler fractional ontime.

An additional run was done with all the pipe sections in the conditioned space and all having identical UA values. This was done to check whether the heat transfer from the pipe to the zone was reasonable. In this case, the heat delivered per hour to the conditioned space by the 12 pipe sections was calculated, using a one-minute slice of time after the system had reached steady state. The results were as follows:

1. The heat stated by the program as delivered to the zone was 805.32 Btu for the minute, or 48,319 Btu/h.
2. A calculation based on the temperature difference between the entering and leaving water was as follows:

Flow rate: 24 ft³/h

Volume specific heat of water: 62.4 Btu/ft³-F

Temperature of water entering loop from boiler: 167.78 F

Temperature of water returning to boiler from loop: 135.56 F

$$\text{Delivered heat} = 24 \times 62.4 \times (167.78 - 135.56) = 48253 \text{ Btu/h}$$

3. A calculation of the expected heat transfer using the overall UA and the log-mean temperature difference between the water and the conditioned space:

Overall UA = 50 Btu/h-F per section, or 600 Btu/h-F for all 12 sections

$$\Delta T_{\max} = 167.78 - 70.0 = 97.78 \text{ F}$$

$$\Delta T_{\min} = 135.56 - 70.0 = 65.56 \text{ F}$$

$$\Delta T_{\log\text{-mean}} = \frac{97.78 - 65.56}{\ln\left(\frac{97.78}{65.56}\right)} = 80.60$$

$$\text{Delivered heat} = 600 \times 80.60 = 48360 \text{ Btu/h}$$

These three values are within 0.3 percent of one another.

Table 1. Energy Balances on Six Cases. Energies in Btu/h.

Case	A.1	B.1	C.1	A.6	B.6	C.6
Circulator Fractional Ontime	0.5	0.2	0.1	0.5	0.2	0.1
Circulator Cycles/Hour	6	4	2	6	4	2
Pipes in Basement Insulated?	Yes	Yes	Yes	No	No	No
Fuel Used	25,420	15,546	10,798	27,727	17,372	11,855
Stack Loss	5,282	4,123	3,489	5,569	4,345	3,621
Jacket Loss	2,158	2,215	2,163	2,157	2,209	2,161
Heat to Hydronic Loop	17,979	9,208	5,147	20,000	10,818	6,073
Boiler Residual	1	0	1	1	0	0
Boiler Fractional Ontime	0.318	0.194	0.135	0.347	0.217	0.148
Heat to Conditioned Space	17,560	8,750	4,675	17,247	8,518	4,337
Heat to Basement	419	458	472	2,753	2,300	1,736
Hydronic Loop Residual	0	0	0	0	0	0
Delivery Eff.	0.977	0.950	0.908	0.862	0.787	0.714
Equipm't Eff.	0.707	0.592	0.477	0.721	0.623	0.512

MODEL OPERATION WITH A SERIES OF HOURLY HEATING LOADS

The next step was to bring the program to the point where it included the "front end" in HYDRONIC, where it computes the table of loads vs. fractional on-times. Given a maximum number of circulator on-cycles per hour (which is related to the thermostat deadband and the thermal mass of the house, as described above) the program generates a table of fractional on-times and cycles-per-hour as functions of hourly heat loads. For each hour of actual running, the program interpolates in this table to pick out a circulator fractional ontime and number of circulator cycles per hour that would deliver this amount of heat.

This program was exercised for two 24-hour runs, one assuming the pipes in the unconditioned space to be uninsulated, the other assuming them to be insulated at approximately R-3 (English units). The 24 heating load values were selected to approximate a moderately cold winter day in which significant solar gain occurred during the daytime, reducing the minimum hourly demand to less than one-third the maximum. The actual loads used were:

Time at start of hour	Heat Load (Btu)	Time at start of hour	Heat Load (Btu)
0000	20,000	1200	7,000
0100	21,000	1300	7,000
0200	22,000	1400	8,000
0300	23,000	1500	10,000
0400	24,000	1600	12,000
0500	25,000	1700	13,000
0600	24,000	1800	14,000
0700	22,000	1900	15,000
0800	19,000	2000	16,000
0900	16,000	2100	17,000
1000	12,000	2200	18,000
1100	9,000	2300	19,000

Other information relevant to these runs is as follows:

Temperature in living space:	70 F
Temperature in basement:	50 F
Boiler Location:	Basement
Boiler Thermal Mass:	200 Btu/F
Boiler Water Temperature Bounds:	150 F - 180 F
Firing Rate:	80000 Btu/h
Stack Efficiency:	0.85
Jacket Heat-Loss Coeff. (UA):	20 Btu/F-h
Off-Cycle Stack-Loss Coeff. (UA):	20 Btu/F-h
Maximum Circulator Cycles per Hour:	6
Number of Pipe Sections	12
Water Flowrate:	2.88 gallons per minute
Thermal Mass Water/15-ft Pipe Section	2.08 Btu/F

The section-specific thermal characteristics of the hydronic loop are as follows:

Section	Location	UA (Btu/F-h)	Pipe Thermal Mass (Btu/F)
1	Basement	1 or 6	0.7
2	Living Space	50	1.0
3	Basement	1 or 6	0.7
4	Living Space	90	1.4
5	Living Space	90	1.4
6	Basement	1 or 6	0.7
7	Living Space	70	1.2
8	Basement	1 or 6	0.7
9	Living Space	100	1.5
10	Basement	1 or 6	0.7
11	Living Space	100	1.5
12	Basement	1 or 6	0.7

Note: UA for sections in basement is 1 Btu/F-h if pipe is insulated and 6 Btu/F-h if pipe is uninsulated.

Energy Balances

A check of the energy balances on the boiler and the distribution system for the day's runs was made. For the boiler, the fuel input should equal the sum of stack losses, jacket losses, heat delivered to the distribution system, and net heat stored in the boiler (due to any boiler-water temperature increase or decrease between the beginning and end of the day). For the distribution system, the heat delivered by the boiler should equal the heat given up to the conditioned space, the heat lost to the basement, and net heat stored in the pipes (due to any temperature increase or decrease in the hydronic loop between the beginning and end of the day). These balances are shown in Table 2.

The striking things to note here are the small residuals on the energy balances and the dramatic increase in hydronic system delivery efficiency gained by insulating the pipes. Figure 8 shows a breakdown of the delivery efficiency as a function of hourly heating load. The "droop" in the uninsulated-pipe efficiencies with decreasing heating loads is reminiscent of a boiler efficiency curve. The raggedness of the insulated-pipe values is in part due to the fact that the hourly values were not corrected for changes in heat stored in the pipes.

Another thing to note is that the boiler efficiency decreases slightly when the hydronic delivery efficiency increases. This is in line with expectation, due to the greater cycling of the boiler when the need for heat is reduced. The effect is small (a 2.5% decrease in boiler efficiency accompanying a 12.5% increase in hydronic delivery efficiency) but it is not negligible. It is to

be noted that the boiler modeled here is a fairly inefficient model, and that better boilers would suffer smaller losses in efficiency than this.

Table 2. Energy Balances on Boiler and Thermal Distribution System. All Energy Values in Btu Over a 1-Day Period.

	Pipes in Basement Uninsulated	Pipes in Basement Insulated
1. Fuel Input	638,022	582,873
2. Stack Loss	131,918	125,528
3. Jacket Loss	53,954	54,429
4. Stored in Boiler	2,340	2,300
5. Delivered to Distribution System	449,794	400,425
6. To Conditioned Space	393,675	394,523
7. Loss to Basement	58,255	7,754
8. Net Heat Stored in Hydronic System	-2,017	-1,677
Boiler Residual (#1-#2-#3-#4-#5)	16	191
Hydronic Residual (#5-#6-#7-#8)	-119	-175
Boiler Efficiency [(#5+#4)/#1]	0.709	0.691
Delivery Efficiency of the Hydronic System [(#6+#8)/#5]	0.871	0.981

Figure 8. Hydronic Efficiency vs. Heating Load

RECOMMENDED FUTURE WORK

The hydronic model is now ready to be exercised over a heating season. A low-cost way to work with the LBL model, without requiring the BNL submodel to be integrated physically with it, would run as follows:

1. Run the LBL model to generate hourly heating loads over a season. Transmit these to BNL on disk.
2. Run the BNL submodel over the season using these heating loads as inputs. Outputs from the BNL model will include hourly values for heat delivered to the conditioned space (which should equal the heating loads) and heat lost to the basement. Transmit to LBL.
3. Run the LBL model again, with the heat losses to the basement as additional inputs that will alter the heating loads computed by DOE-2 (which is an integral part of the LBL model). Transmit these new heating loads to BNL.
4. Rerun the BNL model with the new heating loads. Compare the heat losses to the basement this time with the losses to the basement on the previous run. If convergence is sufficiently close, stop. If not, iterate steps 3 and 4 until convergence is obtained (one more time should be enough).

We are still working on some details of the model. One such item is the fact that the heat-transfer UA is likely to be lower when the water is stagnant than when it is moving, because of the higher film coefficient for moving water. Another is that the capability of modeling direct heat transfer from the pipes to the outside (as would occur due to baseboard units being in contact with an outside wall) has not been exercised. Also, as mentioned in the body of the report, a change to carry over any discrepancy between heating load and delivered heat to the next hour needs to be implemented.

Following sufficient exercise of the model in this fashion, together with validation using real-world data, actual integration of the submodel into the LBL main program would be appropriate.

APPENDIX 1. ESSENTIAL ALGORITHMS

In order to model the hydronic system successfully, it was necessary to derive the computational procedures necessary to follow the heat flows in various parts of the system.

Heat Loss from Pipe

This section derives the equations for the heat loss from a section of hydronic piping, where it is assumed that a heat flow path exists not only to the zone in which the pipe is located, but also an effective heat loss to the outside ambient. This can come about, for example, where pipes run against an outside wall, heating that wall to a warmer temperature than would be the case in the absence of the system. The effective UA for this heat-flow path must be calculated separately; this analysis takes it as an input. We first define the quantities of interest:

Quantity	Units	
T = Temperature of water and pipe	F	C
T _a = Ambient temperature	F	C
T _z = Zone temperature	F	C
h _a = Heat-loss coefficient (UA) to ambient	Btu/h-F	kJ/h-C
h _z = Heat-loss coefficient (UA) to zone	Btu/h-F	kJ/h-C
m _t = Thermal mass of water and pipe	Btu/F	kJ/C

1. Solve the basic equation:

$$\begin{aligned}
 \frac{dT}{dt} &= -\frac{h_z}{m_t} (T - T_z) - \frac{h_a}{m_t} (T - T_a) \\
 &= -\frac{h_z + h_a}{m_t} (T - T_z) - \frac{h_a}{m_t} (T_z - T_a)
 \end{aligned}
 \tag{A1-1}$$

Let $k = (h_z + h_a)/m_t$, $k_a = h_a/m_t$, $k_z = h_z/m_t$, and $T_{za} = T_z - T_a$. Then

$$\begin{aligned}
 \frac{dT}{dt} &= k(T - T_z) - k_a T_{za} \\
 &= -k(T - T_z + \frac{k_a}{k} T_{za})
 \end{aligned}
 \tag{A1-2}$$

Let $U = T - T_d$, where $T_d = T_z - T_{za} (k_a/k)$. Then $dU/dt = dT/dt$, and $dU/dt = -kU$. This has the solution $U = U_0 e^{-kt}$, where U_0 is the value of U at time $t=0$.

Substituting the definition of U above, we obtain:

$$T = T_d + (T_o - T_d) e^{-kt} \quad (A1-3)$$

If we let x equal the final value of time, then

$$T(x) = T_d + (T_o - T_d) e^{-kx} \quad (A1-4)$$

2. Heat flows:

Let ΔQ_{tot} equal the total heat loss from the pipe section between the times $t=0$ and $t=x$. Then

$$\begin{aligned} \Delta Q_{tot} &= m_t (T_o - T(x)) \\ &= m_t (T_o - T_d) (1 - e^{-kx}) \end{aligned} \quad (A1-5)$$

Let $\dot{Q}_a$ and $\dot{Q}_z$ represent the instantaneous heat-loss rates from the pipe section to ambient and to the zone, respectively. Then

$$\begin{aligned} \dot{Q}_a &= h_a (T - T_a) \\ &= m_t k_a [T_d - T_a + (T_o - T_d) e^{-kt}] \end{aligned} \quad (A1-6)$$

and

$$\begin{aligned} \dot{Q}_z &= h_z (T - T_z) \\ &= m_t k_z [T_d - T_z + (T_o - T_d) e^{-kt}] \end{aligned} \quad (A1-7)$$

Let ΔQ_a and ΔQ_z equal the heat loss from the pipe section to ambient and to the zone, respectively, between $t=0$ and $t=x$, and note that $\Delta Q_a + \Delta Q_z$ must equal ΔQ_{tot} . Then:

$$\begin{aligned} \Delta Q_a &= \int_0^x \dot{Q}_a dt = m_t k_a (T_d - T_a) x + m_t k_a (T_o - T_d) \int_0^x e^{-kt} dt \\ &= m_t k_a (T_d - T_a) x + \frac{m_t k_a}{k} (T_o - T_d) (1 - e^{-kx}) \end{aligned} \quad (A1-8)$$

We check this by adding Equations 8 and 9, and find:

$$\begin{aligned}\Delta Q_z &= \int_0^x \dot{Q}_z dt = m_t k_z (T_d - T_z) x + m_t k_z (T_o - T_d) \int_0^x e^{-kt} dt \\ &= m_t k_z (T_d - T_z) x + \frac{m_t k_z}{k} (T_o - T_d) (1 - e^{-kx})\end{aligned}\quad (A1-9)$$

$$\begin{aligned}\Delta Q_a + \Delta Q_z &= [k_a (T_d - T_a) + k_z (T_d - T_z)] x m_t + m_t \frac{(k_a + k_z)}{k} (T_o - T_d) (1 - e^{-kx}) \\ &= [k_a (T_d - T_a) + k_z (T_d - T_z)] x m_t + \Delta Q_{tot}\end{aligned}\quad (A1-1)$$

in view of Equation 5 and $k_a + k_z = k$. The first term to the right of the equal sign in the second line of Equation 10 should therefore equal zero. But using the definition of T_d we find:

$$\begin{aligned}k_a (T_d - T_a) + k_z (T_d - T_z) &= k_a \left(1 - \frac{k_a}{k}\right) T_{za} - k_z \frac{k_a}{k} T_{za} \\ &= k_a T_{za} - (k_a + k_z) \frac{k_a}{k} T_{za} \quad (A1-11) \\ &= k_a T_{za} - k_a T_{za} \\ &= 0\end{aligned}$$

3. Correction Factor

In computing the heat delivered to the zone and that lost to the outside, we have to account for the fact that in the absence of the distribution system, there would still be the heat-loss path h_z in series with h_a from the zone to the outside, which the distribution system masks. That is, if the hydronic system is off, the pipes will float at the temperature T_d . Since putting pipes in a room doesn't increase the heat loss from the room when the system is not operating, it stands to reason that the heat loss from the system to the ambient under these conditions should come out to be zero. Similarly, the heat flow from the system to the room should equal zero. But because of the above-mentioned series heat-flow path, Equations 8 and 9 will not yield zero values. We therefore should subtract from ΔQ_a and add to ΔQ_z the amount of this series heat flow, which is given by

$$\frac{h_z h_a}{h_a + h_z} (T_z - T_a) x = \frac{m_t k_a k_z}{k} (T_z - T_a) x \quad (A1-12)$$

By using the definition of T_d along with some algebra, it is possible to show that the right hand side of Equation 12 is equal to $m_t k_a (T_d - T_a) x$, and it is also equal to $-m_t k_z (T_d - T_z) x$. But now we can see that by subtracting the former expression from Equation 8, as prescribed above, and adding the latter expression to Equation 9, the first term to the right of the equal sign in each equation is removed, which simplifies them both, and yields results in which the heat flow from the hydronic system to either the zone or the ambient is zero if the system is shut down ($T_o = T_d$). The simplified expressions for ΔQ_a and ΔQ_z are then:

$$\Delta Q_a = \frac{m_t k_a}{k} (T_o - T_d) (1 - e^{-kx}) \quad (A1-13)$$

$$\Delta Q_z = \frac{m_t k_z}{k} (T_o - T_d) (1 - e^{-kx}) \quad (A1-14)$$

Pipe-Water Equilibrium

This section calculates the equilibrium temperature between a slug of water coming into a pipe section, and the pipe section itself. The assumptions are those of simple calorimetry.

Quantity	Units	
T_w = Temperature of water coming into pipe section	F	C
T_p = Temperature of pipe section before the move of water	F	C
T_{eq} = Equilibrium temperature of water and pipe after the move	F	C
m_{tw} = Thermal mass of water	Btu/F	KJ/C
m_{tp} = Thermal mass of pipe section	Btu/F	KJ/C
m_t = Thermal mass of water and pipe	Btu/F	KJ/C

The thermal masses are additive:

$$m_{tw} + m_{tp} = m_t \quad (A1-15)$$

The enthalpies are additive:

$$T_w m_{tw} + T_p m_{tp} = T_{eq} m_t \quad (A1-16)$$

Hence,

$$T_{eq} = (T_w m_{tw} + T_p m_{tp}) / m_t \quad (A1-17)$$

Boiler Heat Flows

This section performs develops relationships that will permit calculations relating to the boiler to be performed.

Quantity	Units	
T_{bo} = Initial boiler water temperature (BWT)	F	C
T_b = BWT at a later time	F	C
T_z = Temperature of zone in which boiler is located	F	C
h_j = Jacket-loss UA (on or off cycle)	Btu/h-F	kJ/h-C
h_s = Stack-loss UA (off cycle only)	Btu/h-F	kJ/h-C
$h = h_j + h_s$ = Overall UA (off cycle)		
η_s = Steady-state stack efficiency	--	--
m_b = Boiler thermal mass	Btu/F	kJ/C
$\dot{Q}$ = Net heat flow into boiler	Btu/h	kJ/h
$\dot{Q}_{in}$ = Fuel input rate	Btu/h	kJ/h

1. Off Cycle

BWT Relaxation

$$T_b - T_z = (T_{bo} - T_z) \exp(-ht/m_b) \quad (A1-18)$$

$$T_b = T_z + (T_{bo} - T_z) \exp(-ht/m_b) \quad (A1-19)$$

Time for BWT to relax to a given T_b

$$(T_{bo} - T_z) / (T_b - T_z) = \exp(ht/m_b) \quad (A1-20)$$

$$t = m_b/h \ln[(T_{bo} - T_z) / (T_b - T_z)] \quad (A1-21)$$

Stack, jacket losses

$$\text{Total loss } \Delta Q = m_b (T_{bo} - T_b) \quad (A1-22)$$

$$\text{Stack loss } \Delta Q_s = \Delta Q h_s/h \quad (A1-23)$$

$$\text{Jacket loss } \Delta Q_j = \Delta Q h_j/h \quad (A1-24)$$

2. On Cycle

Here we need to make some assumptions. We begin with the simple case where steady-state efficiency is a constant independent of BWT. (This is not strictly true, but should be all right if we work within a normal range of BWT variation.) We also assume that the instantaneous stack efficiency during the on-cycle is equal to the steady-state efficiency. This is also not strictly true, since it ignores startup conditions, but was found to fit data fairly well in a previous analysis. If we need a more complicated set of assumptions later we can always add them, but this should work well enough at this time.

We start with two equations for the instantaneous energy flow into the boiler:

$$\dot{Q} = \dot{Q}_{in} \eta_s - h_j (T_b - T_z) \quad (A1-25)$$

$$\dot{Q} = m_b Dt_b/dt \quad (A1-26)$$

Let $W = T_b - T_z - \dot{Q}_{in} \eta_s / h_j$. Then,

$$dW/dt = - (h_j / m_b) W \quad (A1-27)$$

This yields the usual solution

$$W = W_0 \exp (-h_j t / m_b) \quad (A1-28)$$

which translates to

$$T_b - T_z - \dot{Q}_{in} \eta_s / h_j = (T_{bo} - T_z - \dot{Q}_{in} \eta_s / h_j) \exp (-h_j t / m_b) \quad (A1-29)$$

For small $t \ll h_j / m_b$, once can check that

$$T_b \approx T_{bo} - (T_{bo} - T_z) h_j t / m_b + \dot{Q}_{in} \eta_s t / m_b \quad (A1-30)$$

which represents initial BWT minus a linear drop due to jacket loss plus a linear rise due to heat input. For longer times, things aren't linear due to changing temperatures.

The time for T_{bo} to rise to a certain temperature T_b is:

$$t = \frac{m_b}{h_j} \ln \frac{T_{bo} - T_z - \dot{Q}_{in} \eta_s / h_j}{T_b - T_z - \dot{Q}_{in} \eta_s / h_j} \quad (A1-31)$$

Net heat into the boiler is:

$$\Delta Q = m_b (T_b - T_{bo}) \quad (A1-32)$$

Heat put in by the burner over a time t is given by:

$$\Delta Q_{burn} = \dot{Q}_{in} \eta_s t \quad (A1-33)$$

The jacket loss is the difference between these two quantities

$$\begin{aligned} \Delta Q_{jac} &= \Delta Q_{burn} - \Delta Q \\ &= \dot{Q}_{in} \eta_s t - m_b (T_b - T_{bo}) \end{aligned} \quad (A1-34)$$

We can check this expression for small t :

$$\begin{aligned} \Delta Q_{jac} &= \dot{Q}_{in} \eta_s t - m_b (T_z - \dot{Q}_{in} \eta_s / h_j - T_{bo}) [1 - \exp(-h_j t / m_b)] \quad (A1-35) \\ &\approx \dot{Q}_{in} \eta_s t - m_b (T_z - \dot{Q}_{in} \eta_s / h_j - T_{bo}) (h_j t / m_b) \\ &= m_b (T_{bo} - T_z) t \end{aligned}$$

which is what it should be for short times when the boiler water temperature has not deviated much from T_{bo} !

Comparison of Two Methods to Model Heat Flows in Hydronic Systems

This analysis compares two alternative methods that have been proposed to model the heat flows from pipes in hydronic heating systems. The two methods are termed here the "block approach" and the "end-points approach." The block approach follows discrete "chunks" of water as they move around the loop, somewhat like linked sausages, while the end-points approach keeps track of the temperatures at evenly spaced points on the pipe loop, like stationary sentries watching a river go by.

Block Approach. The block approach is incorporated in the flow charts and program language previously included in discussions of this project. In the block approach, the water in the pipe loop is divided into blocks of equal volume, each of which is characterized by a temperature that varies over time as the block moves through the loop. The model is set up in such a way that the blocks make discontinuous jumps between timesteps, and each timestep is sufficiently long that the size of the jump is just enough to get each block into the space previously occupied by the block ahead of it. An initial wait of one-half timestep is included in the algorithm, so that the jumps effectively occur in the middle of the timesteps.

Because the blocks are considered to be stationary between jumps, we can model the heat flow by means of the standard heat-loss equation

$$\frac{dT}{dt} = -\frac{UA}{mc_p} (T - T_z) \quad (36)$$

where T is the temperature of the water in the block, T_z is the temperature of the space surrounding the pipe, UA is the overall heat-flow coefficient between the block and the surrounding space, m is the mass of a block of water, and c_p is the specific heat of the water. For the moment we ignore the thermal mass of the pipe wall. This would be handled in somewhat different ways in the two approaches.

If t_{sec} is the timestep, and T_0 and T_1 are the block temperatures at the beginning and end of a period of time in which the blocks are stationary, then

$$T_1 = T_z + (T_0 - T_z) \exp\left(-\frac{UA}{mc_p} t_{sec}\right) \quad (37)$$

If $\dot{m}$ is the flow rate of the water (lb/h or kg/h) then the timestep is related to m and $\dot{m}$ by the equation $m = \dot{m} t_{sec}$.

End-Points Approach. The end-points approach makes use of the log-mean temperature difference between the water and the surrounding zone, together with the temperature drop experienced by the water as it passes through a pipe segment. Two equations for the heat flow $\dot{Q}$ from the pipe section are:

$$\dot{Q} = UA \Delta T_{\log\text{-mean}} = UA \frac{T_0 - T_1}{\ln\left(\frac{T_0 - T_z}{T_1 - T_z}\right)} \quad (38)$$

and

$$\dot{Q} = \dot{m} c_p \Delta T = \dot{m} c_p (T_0 - T_1) \quad (39)$$

Eliminating $\dot{Q}$ from these equations yields:

$$\frac{UA}{\dot{m} c_p} = \ln\left(\frac{T_0 - T_z}{T_1 - T_z}\right) \quad (40)$$

This can be solved for T_1 with the result:

$$T_1 = T_z + (T_0 - T_z) \exp\left(-\frac{UA}{\dot{m}c_p}\right) \quad (41)$$

We note the similarity of equations 2 and 6.

An Example. We now do a sample calculation to see how the two methods compare. The calculations will be done in SI units, with approximate American equivalents given in parentheses.

We assume there are 6 pipe sections, all identical, each with a UA value of 90 kJ/h-C (50 Btu/hr-F). This permits a heat transfer of 32,400 kJ/h (30,000 Btu/h) for a 60 C (108 F) temperature difference.

For realism, let us consider the pipe to be 3/4 in. ID, with each section 20 ft long. The volume of this section in SI units will be 0.001738 m³ (0.06 ft³). Each section will contain 1.738 kg (3.8 lb) of water. If we specify a flow rate of 450 kg/h (1000 lb/h or 2 gpm) this will be sufficient to support the heat release rate specified in the preceding paragraph at a temperature drop of 17.20 C (31 F), since the SI specific heat of water is 4.186 kJ/C.

Since the volume of 450 kg of water is 0.45 m³, this allows us to calculate the timestep associated with these assumptions:

$$t_{\text{sec}} = v/\dot{v} = 0.001738/0.45 = 0.003862 \text{ h} = 13.90 \text{ seconds.}$$

Now let us calculate the groups in the exponentials in Equations 2 and 6:

Equation	Group	Calculation
2	$UA/\dot{m}c_p$	$90/(450 \times 4.186) = 0.04778$
6	$UA t_{\text{sec}}/\dot{m}c_p$	$90 \times 0.003862/(1.738 \times 4.186) = 0.4778$

So now we can calculate the exponential $\exp(-UA/\dot{m}c_p) = \exp(-UA t_{\text{sec}}/\dot{m}c_p) = 0.9533$. Also, for the block approach we will need $\exp(-UA/2\dot{m}c_p) = 0.9764$.

Successive powers of 0.9533 are:

0.9533
0.9089
0.8665
0.8260
0.7875
0.7508

For our test case the water in the pipe starts at 20 C, while boiler water at 90 C is ready to start feeding into the pipe. As shown in Figure A1-1, for the end-points approach, with each timestep the warm water progresses one section, losing heat as it does so. By the end of timestep 6, the water temperatures at the section boundaries have achieved an exponentially decreasing profile which they will retain there on out.

The block approach, in contrast, is shown in Figure A1-2. This is a somewhat busier chart, and requires some explanation. The half-timestep pipe states have a split set of temperatures. This is because of the sudden shift that occurs at these times. The temperature before the slash is that just before the shift, while the temperature after the slash is that just after the shift.

Heat loss between half-timestep points occurs at a rate consistent with the end-points approach. The dotted arrows show how the numbers in a typical box are generated. The first number (pre-shift) reflects heat loss relative to the (post-shift) value immediately above. The second number (post-shift) comes from the pre-shift value of the block immediately to its left.

The last half timestep (from 5.5 to 6.0) represents heat loss of the stationary blocks for that half timestep. The final temperatures can be considered to be the temperature at the midpoint of the block. The values obtained in this way can be seen to be consistent with the end-point temperatures in Figure A1-1, forming a smooth, continuous curve with them.

Timesteps	0.0	90	20	20	20	20	20	20
	0.5	90						
	1.0	90	86.7	20	20	20	20	20
	1.5	90						
	2.0	90	86.7	83.6	20	20	20	20
	2.5	90						
	3.0	90	86.7	83.6	80.7	20	20	20
	3.5	90						
	4.0	90	86.7	83.6	80.7	77.8	20	20
	4.5	90						
	5.0	90	86.7	83.6	80.7	77.8	75.1	20
	5.5	90						
	6.0	90	86.7	83.6	80.7	77.8	75.1	72.6
			1	2	3	4	5	6
			Section Number					

Figure A1-1. Temperatures in pipes for the end-points approach.

Timesteps	0.0	90	20	20	20	20	20	20
	0.5	90	20/90	20/20	20/20	20/20	20/20	20/20
	1.0	90						
	1.5	90	86.7/90	20/86.7	20/20	20/20	20/20	20/20
	2.0	90						
	2.5	90	86.7/90	83.6/86.7	20/83.6	20/20	20/20	20/20
	3.0	90						
	3.5	90	86.7/90	83.6/86.7	80.7/83.6	20/80.7	20/20	20/20
	4.0	90						
	4.5	90	86.7/90	83.6/86.7	80.7/83.6	77.8/80.7	20/77.8	20/20
	5.0	90						
	5.5	90	86.7/90	83.6/86.7	80.7/83.6	77.8/80.7	75.1/77.8	20/75.1
	6.0	90	88.3	85.1	82.1	79.2	76.5	73.8
			1	2	3	4	5	6
			Section Number					

Figure A1-2. Temperatures in pipes for the block approach.

APPENDIX 2. HYDRONIC PROGRAM CODE

A verbatim transcript of the program code used in this project, as of October 5, 1994, is included here. This code was used to obtain the results for the 24-hour runs reported on in the above text. The code is divided into three main sections: hydro.bas, loadcurv.bas, and hydronic.inc.

Hydro.bas contains the main program. Loadcurv.bas is the "front end" that computes the expected number of cycles per hour and fractional on-time corresponding to any given hourly heating load. It is run once at the beginning of a heating season's simulation; the table it generates then determines the cycling behavior in all subsequent hours. Hydronic.inc contains the subroutines called by the other two programs. Aside from "housekeeping" routines, these are:

- o CIRCPROF: Determines the circulator pump on-off times from the percent-on-time & cycle information obtained from the "front-end" table.
- o PLUGSHIFT: Moves the slugs of water forward 1 section and mixes boiler water.
- o HXON: Calculates heat transfer when the circulator is on.
- o HXOFF: Calculates heat transfer when the circulator is off.
- o BOILER: Determines the heat flows for the boiler; calls two additional routines below.
- o BOILERON: Subroutine for BOILER; handles the burner-on period.
- o BOILEROFF: Subroutine for BOILER; handles the burner-off period.

PROGRAM: HYDRO.BAS

This program models the thermal performance of a hydronic heating system where the system piping passes through two zones. Zone 1 is the buffer (non living) space and zone 2 is the conditioned space. The heating load that the program uses comes from the program DOE-2. This heating load is assumed to apply to the conditioned zone only.

'PROGRAM NOTES:

'1) The variables in the program follow the standard FORTRAN naming conventions: variables beginning with the letters I through 'N are integers, all others are assumed to be single precision floating point values.

'-----
'Initialization section for main hydronic program; INIT in flowcharts.

'Variables are declared (set to some default value)

```

CLEAR                                'ZERO OUT MEMORY
DEFINT I-N                          'DEFAULT INteger type
DEFSNG A-H,O-Z                      'DEFAULT SiNGle precision floating point
%DEBUGMODEOFF=1                     'SET TO 0 FOR DEBUGGING CODE ON, OTHERWISE

1
ISCIRCON=0                          'FLAG: IS THE CIRCULATOR PUMP ON OR NOT
ISBOILERON=IOFF                    'FLAG: IS THE BOILER ON OR OFF
i=0                                 'generic loop counter
idum=0                              'integer dummy variable
dummy1=0: dummy2=0                  'floating point
dummy3=0: dummy4=0                  'dummy variables
dum$=""                             'dummy string variable
ifile$=""                           'input file name
ofile$=""                           'output file name
tfile$=""                           'fractional ontime profile file
SSOP$="N"                           'steady state operations flag
A$="Hour=## Time= ##.### (min) Boiler Temp.= ###.# (F) Circ= #
Boiler= #"
B$="Boiler ops: Stack=###,###,### Jacket=###,###,### Fuel=###,###,###
Net=###,###"
C$="Heat delivered to dist system= ###,###,###.###"
D$="Heat into: Z1= ###,###,### Z2= ###,###,### Amb1= ###,###,###
Amb2=###,###,###"
E$="Sect TWin TWout Tpipe Heat Acc.(pipe) Heat Acc.
(water)"
F$=" ## ##.## ##.## ##.## ##,###,###.##
##,###,###.##"
'-----
btmass=0 'Boiler thermal mass (Btu/F)
bwt=0 'Boiler water temperature (F)
bwtold=0 'Boiler water temp. (saved value)
bwtorig=0 'Original boiler water temperature (for steady state
only)
bwtll=0 'Boiler water temperature: lower limit (F)
bwtul=0 'Boiler water temperature: upper limit (F)
carryover=0 'Amount of heat that is carried over to the next
hour (Btu)
dthx=0 'Time step: time required to move 1 slug of water 1
section (sec)
fire=0 'Firing rate (Btu/hr)
flowrate=0 'Water flowrate (ft^3/hr)
fracton=0 'Circulator pump fractional ontime (decimal %)
hload=0 'Target heatling load (Btu/hour)
ibzone=1 'Boiler zone (DEFAULT=1)
icntcyc=0 'Counter variable: # of circulator cycles
isdone=0 'Flag: has the heat delivered caught up to hload
items=0 '# of entries in the circulator profile table
maxcirc=0 'Maximum # of circulator cycles per hour
ncyc=0 'Actual # of circulator cycles expected this hour
Nextprint=0 'When the results should be printed to disk
nsecs=0 'Total # of pipe sections in the hydronic loop
pipevol=0 'Interior volume of each pipe sections (ft^3)

```



```

prntint=0      'Print interval (sec)
Qboiler=0      'Heat lost by the boiler due to mixing per time step
(Btu)
Qboiler2=0
Qfuel=0        'Fuel used per time step (Btu)
Qjacket=0      'Jacket losses per time step (Btu)
Qstack=0       'Stack losses per time step (Btu)
rhocp=62.5     'Specific Heat of water (Btu/cu. ft)
Rfuel=0        'Fuel used (Btu): CUMULATIVE
Rjacket=0      'Jacket losses (Btu): CUMULATIVE
Rstack=0       'Stack losses (Btu): CUMULATIVE
sseff=0        'Steady state efficiency (0->1)
Tamb=0         'Outdoor air temperature (F)
Time=0         'Loop counter
UAjacket=0     'Jacket loss heat transfer coeff. (Btu/hr F)
UAsack=0       'Stack loss heat transfer coeff. (Btu/hr F)
wtmass=0       'Thermal mass of water in each pipe section

DIM Circoff(1:24) 'Time circulator cycle i starts
DIM Circon(1:24)  'Time circulator cycle i stops
DIM FTable(1:50)  'Fractional ontime entries in profile table
DIM HLoads(1:24)  'Hourly heating load data
DIM HLTable(1:50) 'Heating Load entries in profile table
DIM IZone(1:50)   'Zone section i is located in
DIM NTable(1:50)  'Circulator cycle entries in profile table
DIM Pipenet(1:50) 'Net heat gained by the pipes
DIM PTmass(1:50)  'Pipe thermal mass for section i
DIM Qamb(1:50)    'Heat from each pipe section lost to ambient
DIM Qzone(1:50)   'Heat from each pipe section into the zone
DIM Ramb(1:2)     'Heat lost to ambient from each zone
DIM Rzone(1:2)    'Heat delivered into each zone (Btu)
DIM TOutside(1:24) 'Outdoor air temperature (hourly basis)
DIM Tpipe(1:50)   'Average temperature of the pipe wall in each
section
DIM TTmass(1:50)  'Total thermal mass for section i
DIM TWin(1:50)    'Entering water temperature for each section
DIM TWout(1:50)   'Exiting water temperature for each section
DIM Tzone(1:2)    'Zone temperature
DIM UAext(1:50)   'Heat trans. coeff. between pipe & ambient
DIM UAzone(1:50)  'Heat trans. coeff. between pipe & zone
DIM Waternet(1:50) 'Net heat gained by the water
'-----
'Clear out random junk
ERASE Circoff(),Circon(),IZone(),OTpipe(),Pipenet(),PTmass()
ERASE Qamb(),Qzone(),Ramb(),Rzone(),Tpipe(),TTmass(),TWin()
ERASE TWout(),Tzone(),UAext(),UAzone(),Waternet()
'-----
'end of initialization section; now get setup information from file
'-----
CLS

```



```

$if %DEBUGMODEOFF
  INPUT "What is the name of the input file? ",ifile$
  INPUT "What is the name of the output file? ",ofile$
  INPUT "What is the number of hours that the program should run?
",maxhours
  INPUT "What print interval do you wish (min)? ",prntint
  INPUT "Do you wish to run the program in STEADY STATE mode?
",SSOP$: SSOP$=UCASE$(SSOP$)
'*****
$ELSE
ifile$="test.dat"
ofile$="test.out"
maxhours=1
prntint=0.5
ssop$="N"
$ENDIF
'*****
  OPEN ifile$ FOR INPUT AS #1
  INPUT #1, dum$,tfile$

  LINE INPUT #1, dum$ 'ignore titles
  LINE INPUT #1, dum$ 'ignore titles
  INPUT #1,dum$,Tzone(1)
  INPUT #1,dum$,Tzone(2)

  LINE INPUT #1, dum$
  LINE INPUT #1, dum$
  FOR i=1 TO 24: INPUT #1,Toutside(i): NEXT i

  LINE INPUT #1, dum$
  LINE INPUT #1, dum$
  FOR i=1 TO 24: INPUT #1,Hloads(i): NEXT i

  LINE INPUT #1, dum$ 'ignore titles
  LINE INPUT #1, dum$ 'ignore titles
  INPUT #1,dum$,ibzone
  INPUT #1,dum$,btmass
  INPUT #1,dum$,bwt11
  INPUT #1,dum$,bwtul
  INPUT #1,dum$,fire
  INPUT #1,dum$,sseff
  INPUT #1,dum$,UAjacket
  INPUT #1,dum$,UAstack

  LINE INPUT #1, dum$ 'ignore titles
  LINE INPUT #1, dum$ 'ignore titles
  INPUT #1,dum$,maxcirc
  INPUT #1,dum$,nsecs
  INPUT #1,dum$,flowrate
  INPUT #1,dum$,pipevol

```

```

LINE INPUT #1, dum$      'ignore titles
LINE INPUT #1, dum$      'ignore titles
LINE INPUT #1, dum$      'ignore titles
FOR i=1 TO nsecs
    INPUT #1,idum,UAzone(i),UAext(i),PTmass(i),IZone(i)
NEXT i

```

```

CLOSE #1
OPEN tfile$ FOR INPUT AS #1
INPUT #1, items
FOR i=1 TO items
    INPUT #1, NTable(i),FTable(i),HLTable(i)
NEXT i
CLOSE #1
OPEN ofile$ FOR OUTPUT AS #1

```

```

'-----
'now calculate the remainder of the variables needed to start
'-----

```

```

prntint=prntint*60
wtmass=rhocp*pipevol
dthx=3600*pipevol/flowrate

```

```

FOR i=1 TO nsecs
    TTmass(i)=PTmass(i)+wtmass
    INCR dummy1,( wtmass*Tzone( IZone(i) ) )
NEXT i

```

```

bwt=(bwtul*btmass + dummy1)/(btmass + nsecs*wtmass)
bwtorig=bwt
FOR i=1 TO nsecs
    twin(i)=bwt
    twout(i)=bwt
    tpipe(i)=bwt
NEXT i

```

```

CALL STEADYSTATE(TWin(),TWout(),Tpipe())

```

```

FOR HOUR=1 TO MAXHOURS
    Nextprint=0
    Rfuel=0: Rjacket=0: Rstack=0: icntcyc=1: Rboiler=0
    ERASE Rzone(),Ramb(),Qzone(),Qamb()
    carryover=0
    time=0
    CALL PRNT2FILE(1)
    CALL PRNT2SCRN
    hload=HLoads(HOUR)
    IF SSOP$="N" THEN
        CALL LOOKUPTBL(hload,ncyc,fracton)
    ELSE
        ncyc=1: fracton=1!
    END IF

```

```

CALL CIRCPROF( ncyc,fraction,Circon(),Circoff() )

FOR time=1 TO 3600 step dthx
  Qjacket=0: Qstack=0: Qfuel=0
  Qboiler=0: Qboiler2=0
  iscircon=0

  IF time>Circoff(icntcyc) AND (time-dthx)<=Circoff(icntcyc)
THEN
    INCR icntcyc,1
  END IF

  IF (time>=Circon(icntcyc) AND time<Circoff(icntcyc)) THEN
    iscircon=1
    CALL PLUGSHIFT( nsecs,Twin(),TWout(),bwt,Qboiler )
  END IF

  FOR i=1 TO nsecs
    dummy1=0: dummy2=0: dummy3=0: dummy4=0
    IF iscircon THEN
      CALL H X O N (
Twin(i),TWout(i),Tpibe(i),dummy1,dummy2,dummy3,dummy4,i,dthx)
    ELSE
      CALL H X O F F (
Twin(i),TWout(i),Tpibe(i),dummy1,dummy2,dummy3,dummy4,i,dthx)
    END IF
    INCR Qzone(i), dummy1
    INCR Qamb(i), dummy2
    INCR Rzone( IZone(i) ),dummy1
    INCR Ramb( IZone(i) ),dummy2
    Waternet(i)=dummy3
    INCR Pipenet(i), dummy4
  NEXT i

  IF SSOP$="N" THEN
    CALL BOILER(dthx,bwt,isboileron,Qfuel,Qjacket,Qstack)
  ELSE
    bwt=bwtorig: Qfuel=0!: Qjacket=0!: Qstack=0!
  END IF
  INCR Rfuel, Qfuel
  INCR Rjacket, Qjacket
  INCR Rstack, Qstack
  INCR Rboiler, Qboiler

  CALL PRNT2SCRN
  IF time>=Nextprint THEN
    INCR Nextprint,Prntint
    CALL PRNT2FILE(1)
  END IF

```

```

        IF SSOP$="N" THEN
            CALL CHECKCIRC((3600-time),hload,isboileron,isdone)
            IF isdone THEN time=3600
        END IF
    NEXT time
    IF isdone=0 THEN
        IF ibzone=2 THEN dummy1=Rjacket ELSE dummy1=0
        carryover=(Rzone(2) + dummy1)-hload
    END IF
    CALL PRNT2FILE(1)
    PRINT #1, USING "CARRYOVER= ###,###.##";carryover
    CALL PRNT2SCRN
    print #1, ""
NEXT Hour
CLOSE #1
END

```

```

-----
$include "hydronic.inc"          'routine library
$include "noises.inc"            'warble & alarm library
-----

```

LOADCURV.BAS

'This program determines the behavior of a hydronic heating system.
 'It acts as a preprocessor for the program hydro. Its main purpose
 'is to generate runtime profile for a given hydronic system and
 'save a table that relates fractional ontime, # of circulator
 'cycles, and heat delivered to the conditioned space (this last
 'value excludes jacket losses). To determine the parameters for
 'the table the program runs in steady state mode, where the boiler
 'water is kept at a constant temperature.

'PROGRAM NOTES:

'1) The variables in the program follow the standard FORTRAN
 'naming conventions: variables beginning with the letters I through
 'N are integers, all others are assumed to be single precision
 'floating point values.

```

-----
CLEAR                                'ZERO OUT MEMORY
DEFINT I-N                          'DEFAULT Integer type
DEFSNG A-H,O-Z                      'DEFAULT Single precision floating point
ISCIRCON=0                          'FLAG: IS THE CIRCULATOR PUMP ON OR NOT
ISBOILERON=IOFF                     'FLAG: IS THE BOILER ON OR OFF
i=0                                  'generic loop counter
icnt=0                               'another generic loop counter
idum=0                               'integer dummy variable
dummy1=0: dummy2=0                  'floating point
dummy3=0: dummy4=0                  'dummy variables
dum$=""                             'dummy string variable
ifile$=""                           'input file name
ofile$=""                           'output file name
A$="ITEM= ## TIME= ####.## NCYC=## FRACTION=#####"
B$="## , ##### , #####.###"

```

```

btmass=0      'Boiler thermal mass      (Btu/F)
bwt=0         'Boiler water temperature  (F)
bwtold=0      'Boiler water temp. (saved value)
bwtorig=0     'Original boiler water temperature (for steady state
only)
bwtll=0       'Boiler water temperature: lower limit (F)
bwtul=0       'Boiler water temperature: upper limit (F)
dthx=0        'Time step: time required to move 1 slug of water 1
section (sec)
fire=0        'Firing rate (Btu/hr)
flowrate=0    'Water flowrate (ft^3/hr)
fracton=0     'Circulator pump fractional ontime (decimal %)
ibzone=1      'Boiler zone (DEFAULT=1)
icntcyc=0     'Counter variable: # of circulator cycles
items=0       'Number of entries within the table
maxcycles=0   'Maximum # of circulator cycles per hour
ncyc=0        'Actual # of circulator cycles expected this hour
nsecs=0       'Total # of pipe sections in the hydronic loop
pipevol=0     'Interior volume of each pipe sections (ft^3)
Qjacket=0     'Jacket losses per time step (Btu)
Qzone=0       'Heat from each pipe section into the zone
rhocp=62.5    'Specific Heat of water (Btu/cu. ft)
Rjacket=0     'Jacket losses (Btu): CUMULATIVE
sseff=0       'Steady state efficiency (0->1)
Tamb=0        'Outdoor air temperature (F)
Texit=0       'Temperature of water as it exits the hydronic loop
(F)
Time=0        'Loop counter
UAjacket=0    'Jacket loss heat transfer coeff. (Btu/hr F)
UAstack=0     'Stack loss heat transfer coeff. (Btu/hr F)
wtmass=0      'Thermal mass of water in each pipe section

DIM Circoff(1:24) 'Time circulator cycle i starts
DIM Circon(1:24)  'Time circulator cycle i stops
DIM FTable(1:50)  'Fractional ontime column in profile table
DIM HLTable(1:50) 'Heating loads column in profile table
DIM HLoads(1:24)  'Hourly heating load data
DIM IZone(1:50)   'Zone section i is located in
DIM NTable(1:50)  '# of cycles column in profile table
DIM PTmass(1:50)  'Pipe thermal mass for section i
DIM Tpipe(1:50)   'Average temperature of the pipe wall in each
section
DIM TTmass(1:50)  'Total thermal mass for section i
DIM TWin(1:50)    'Entering water temperature for each section
DIM TWout(1:50)   'Exiting water temperature for each section
DIM TIstart(1:50) 'Entering water temperature after Steady State
DIM TIend(1:50)   'Exiting water temperature after Steady State
DIM TOutside(1:24) 'Outside ambient temperature (hour by hour)
DIM TPstart(1:50) 'Pipe temperature after Steady State
DIM Tzone(1:2)    'Zone temperature
DIM UAext(1:50)   'Heat trans. coeff. between pipe & ambient
DIM UAzone(1:50)  'Heat trans. coeff. between pipe & zone

```

```

'Clear out random junk
  ERASE Circoff(),Circon(),IZone(),PTmass()
  ERASE Tpipe(),TTmass(),Twin()
  ERASE TWout(),Tzone(),UAext(),UAzone()
/-----
'end of initialization section; now get setup information from file
/-----
CLS
  INPUT "What is the name of the input file? ",ifile$
  OPEN ifile$ FOR INPUT AS #1

  INPUT #1,dum$,ofile$
  LINE INPUT #1, dum$      'ignore titles
  LINE INPUT #1, dum$      'ignore titles
  INPUT #1,dum$,Tzone(1)
  INPUT #1,dum$,Tzone(2)

  LINE INPUT #1, dum$
  LINE INPUT #1, dum$
  FOR i=1 TO 24: INPUT #1,TOutside(i): NEXT i

  FOR i=1 TO 8
    LINE INPUT #1, dum$
  NEXT i
  INPUT #1,dum$,ibzone
  INPUT #1,dum$,btmass
  INPUT #1,dum$,bwtll
  INPUT #1,dum$,bwtul
  INPUT #1,dum$,fire
  INPUT #1,dum$,sseff
  INPUT #1,dum$,UAjacket
  INPUT #1,dum$,Uastack

  LINE INPUT #1, dum$      'ignore titles
  LINE INPUT #1, dum$      'ignore titles
  INPUT #1,dum$,maxcycles
  INPUT #1,dum$,nsecs
  INPUT #1,dum$,flowrate
  INPUT #1,dum$,pipevol

  LINE INPUT #1, dum$      'ignore titles
  LINE INPUT #1, dum$      'ignore titles
  LINE INPUT #1, dum$      'ignore titles
  FOR i=1 TO nsecs
    INPUT #1,idum,UAzone(i),UAext(i),PTmass(i),IZone(i)
  NEXT i

  CLOSE #1
/-----
'now calculate the remainder of the variables needed to start
Tamb=0!: FOR i=1 TO 24: INCR Tamb,TOutside(i): NEXT i:
Tamb=Tamb/24

```

```

wtmass=rhocp*pipevol
dthx=3600*pipevol/flowrate

FOR i=1 TO nsecs
    TTmass(i)=PTmass(i)+wtmass
    INCR dummy1,( wtmass*Tzone( IZone(i) ) )
NEXT i

bwt=(bwtul*btmass + dummy1)/(btmass + nsecs*wtmass)
bwtorig=bwt
FOR i=1 TO nsecs
    twin(i)=bwt
    twout(i)=bwt
    tpipe(i)=bwt
NEXT i

CALL STEADYSTATE(TIstart(),TIend(),TPstart()) 'Run in steady
state
CALL GETCYCLELBL(NTable(),maxcycles,items) 'build column 1 of
profile
CALL GETFRACTIONLBL(FTable(),NTable(),maxcycles,items) 'build
column 2 of profile
/*****
'Below is the code that generates the last column in the hydronic
loop profile
*****/
FOR icnt=1 TO items
    ERASE Circon(),Circoff(),TWin(),TWout()
    Qzone=0: Qjacket=0: icntcyc=1
    FOR i=1 TO nsecs
        TWin(i)=TIstart(i)
        TWout(i)=TIend(i)
        bwt=bwtorig
    NEXT i

    CALL CIRC PROF( NTable(icnt),FTable(icnt),Circon(),Circoff()
)
    FOR time=1 TO 3600 step dthx
        PRINT USING A$; icnt,time,NTable(icnt),FTable(icnt)
        iscircon=0
        IF time>Circoff(icntcyc) AND (time-dthx)<=Circoff(icntcyc)
THEN
            INCR icntcyc,1
        END IF

        IF time>=Circon(icntcyc) AND time<Circoff(icntcyc) THEN
            iscircon=1
            CALL PLUGSHIFT( nsecs, TWin(), TWout(), bwt, dummy1)
        END IF

        FOR i=1 TO nsecs
            dummy1=0: dummy2=0: dummy3=0: dummy4=0

```

```

        IF iscircon THEN
                                C A L L   H X O N   (
Twin(i),TWout(i),Tpipe(i),dummy1,dummy2,dummy3,dummy4,i,dthx)
        ELSE
                                C A L L   H X O F F   (
Twin(i),TWout(i),Tpipe(i),dummy1,dummy2,dummy3,dummy4,i,dthx)
        END IF
        IF IZone(i)=2 THEN INCR QZone,dummy1
    NEXT i
    bwt=bwtorig
    'CALL BOILER(dthx,bwt,isboileron,dummy1,dummy2,dummy3)
    'IF ibzone=2 THEN INCR Qjacket,dummy2
    NEXT time
    HLTable(icnt)=Qzone+Qjacket
    NEXT icnt
    OPEN ofile$ FOR OUTPUT AS #1
    PRINT #1, items
    FOR i=1 TO items
        PRINT #1,USING B$;NTable(i),FTable(i),HLTable(i)
    NEXT i
    CLOSE #1
END

```

```

'-----
$include "hydronic.inc"          'routine library
$include "noises.inc"           'warble & alarm library
'-----

```

HYDRONIC.INC

\$IF 0

This file is hydronic.inc. It is a library file of all the routines that are needed by the hydronic.bas program. The list of routines included is listed below.

CIRCPROF: Determine the circulator pump on-off times from the %ontime & cycle info

PLUGSHIFT: Move the slugs of water forward 1 section & mixes boiler water

HXON: Calculate heat transfer when the circulator is on

HXOFF: Heat transfer when the circulator is off

BOILER: Determine the heat flows for the boiler; "master" routine

BOILERON: Sub routine for BOILER; handles the boiler on period

BOILEROFF: Sub routine for BOILER; handles the burner off period

PRNT2SCRN: Generate Screen Display

PRNT2FILE: Generate output file

\$ENDIF

SUB CIRCPROF(ncyc, fract, circon(1), circoff(1)) LOCAL
LOCAL ontime, offtime, ondur, offdur, i

IF ncyc=0 AND fract=1 THEN circon(1)=0: circoff(1)=3600: EXIT
SUB

IF ncyc=0 AND fract=0 THEN EXIT SUB
ontime=3600*fract 'convert fractional ontime to seconds
ondur=ontime/ncyc 'duration for each circulator on
period
circon(1)=0 'first on period starting time
circoff(1)=ondur 'first on period stop time
offtime=3600-ontime 'total time that the circulator does
not run
offdur=offtime/ncyc 'duration of each "dead" period
FOR i=2 TO ncyc
circon(i)=circoff(i-1)+offdur
circoff(i)=circon(i)+ondur
next i

END SUB 'circprof

SUB PLUGSHIFT (nsecs, twin(1), twout(1), bwt, qboiler) LOCAL
SHARED btmass, wtmass, tpipe(), ptmass(), ttmass()
LOCAL i, bwt1

bwt1=bwt
bwt=(twout(nsecs)*wtmass + bwt*(btmass-wtmass))/btmass
qboiler=wtmass*(bwt1-twout(nsecs))

FOR i=nsecs TO 2 STEP -1
twin(i)=twout(i-1) 'SHIFT PLUGS
twout(i)=twin(i)
NEXT i

twin(1)=bwt1
twout(1)=twin(1)

END SUB 'plugshift


```

SUB HXON (t1,t2,tpold,qz,qa,qw,qp,isec,dt) LOCAL
  SHARED tamb, ttmass(), ize(), uazone(), uaext(), tzone()
  SHARED ptmass(), wtmass
  LOCAL i, iz, uatotal, qt, tz, tpz, denom, tol, tpnew
  LOCAL hai, hao, iflag, dum, tp, tw, twold, ratio

  qz=0!: qa=0!: qw=0!: qp=0!: t2=t1 'initialize return variables
  uatotal=uazone(isec)+uaext(isec) 'overall UA value
  if uatotal<=0 THEN EXIT SUB 'no heat transfer
  tol=0.00001! 'iteration tolerance
  hai=500! 'guess of inside pipe film
coef*area
  hao=(hai*uatotal)/(hai-uatotal) 'guess of external film coef

  twold=0.5*(t1+t2)
  iz=ize(isec) 'zone # (saves typing)
  tz=tzone(iz) 'saves typing
  tpz=tz-(uaext(isec)/uatotal)*(tz-tamb) 'psuedo zone temp
  tp=tpold
  dum=ptmass(isec)+hai+hao

DO
  t2=tp+(t1-tp)/exp(hai*dt/(3600*wtmass)) 'water exit temp.
  tw=0.5*(t1+t2)
  IF t2<>tp THEN
    ratio=(t1-tp)/(t2-tp)
    IF ratio<>1 THEN tw=tp+ (t1-t2)/log(ratio)
  END IF
  tpnew=tp+ dt*( (tw-tp)*hai + (tpz-tp)*hao
)/(3600*ptmass(isec))
  IF ABS((tpnew-tp)/tp)>tol THEN
    iflag=1
    tp=tpnew '0.75*tp+ 0.25*tpnew
  ELSE
    iflag=0
  END IF
  LOOP WHILE(iflag)
  qw=wtmass*(t2-t1) 'total heat change in the
water
  qp=ptmass(isec)*(tpnew-tpold) 'total heat change in the pipe
  qt=-(qw+qp)
  tp=0.5*(tpnew+tpold)
  denom=uazone(isec)*(tp-tz) + uaext(isec)*(tp-tamb)
  qz=qt*(uazone(isec)*(tp-tz)/denom) 'heat trans. to zone
  qa=qt-qz 'heat lost to ambient
  tpold=tpnew

END SUB 'hxon
'*****
*****

```

```

SUB HXOFF (t1,t2,tpold,qz,qa,qw,qp,isec,dt) LOCAL
  SHARED tamb, ize(), uazone(), uaext(), tzone(), wtmass,
  ptmass()
  LOCAL iz, uatotal, qt, tz, twold, twnew, tpnew
  LOCAL hai, hao, tpseudoz, tol, alpha, beta, gamma, dum
  qz=0!: qa=0!: qw=0!: qp=0!: 'initialize return
  values
  uatotal=uazone(isec)+uaext(isec) 'overall UA value
  IF uatotal<=0 THEN EXIT SUB
  tol=0.001!
  hai=2!*uatotal 'must be revisited!!!
  hao=(hai*uatotal)/(hai-uatotal)
  iz=ize(isec) 'zone # (saves typing)
  tz=tzone(iz) 'zone temp. (ditto)

  IF (t1<=tpold OR t2<=tpold OR t1=t2) THEN
    twold=0.5*(t1+t2)
  ELSE
    twold=(t1-t2)/log( (t1-tpold)/(t2-tpold)) + tpold
  END IF

  IF abs(1-twold/tz)< 0.001! AND abs(1-tpold/tz)< 0.001! THEN
    t1=tz: t2=tz: tp=tz
    EXIT SUB
  END IF

  tpz=tz-(uaext(isec)/uatotal)*(tz-tamb) 'psuedo zone temp
  alpha=haidt/( 3600*ptmass(isec) )
  beta=hao*dt/( 3600*ptmass(isec) )
  gamma=haidt/( 3600*wtmass )
  dum=tpold + beta*tpz + (alpha/(1+gamma))*twold
  tpnew=dum/(1+alpha+beta-alpha*gamma/(1+gamma))
  twnew=(gamma*tpnew + twold)/(1+gamma)
  qp=ptmass(isec)*(tpnew-tpold) 'total heat change in the
  pipe
  qw=wtmass*(twnew-twold) 'total heat change in the
  water
  qt=-(qw+qp) 'total heat trans. to zone &
  amb
  tpold=0.5*(tpnew+tpold)
  denom=uazone(isec)*(tpold-tz) + uaext(isec)*(tpold-tamb)
  qz=qt*(uazone(isec)*(tpold-tz)/denom) 'heat trans. to zone
  qa=qt-qz 'heat lost to ambient
  t2=t2+(twnew-twold) 'reflect the relaxation over time dt
  tpold=tpnew 'returned value of pipe temp.
  IF t2<tpnew THEN
    t2=tpnew
    t1=2!*twnew-t2
  ELSE
    t1=t1+(twnew-twold) 'update t1 & t2 to
  END IF
END SUB 'hxoff

```

```

SUB BOILER (duration,bwt,isboileron,qfuel,qjacket,qstack) LOCAL
  SHARED bwtll,bwtul,fire,bwtorig
  LOCAL timeleft,ison,qf,qj,qs

  timeleft=duration      'time left in the current sub call
  Do WHILE (timeleft>0)
    qf=0: qj=0: qs=0
    IF bwt<=bwtll OR (isboileron AND bwt<bwtul) THEN ison=1 ELSE
ison=0
    IF fire=0 THEN ison=0
    IF ison THEN      'the boiler is running
      CALL BOILERON(timeleft,bwt,qf,qj,qs)
    ELSE              'the boiler is not running
      CALL BOILEROFF(timeleft,bwt,qf,qj,qs)
    END IF           'ison if
    INCR qfuel,qf
    INCR qjacket,qj
    INCR qstack,qs
  LOOP 'end timeleft loop
  isboileron=ison
END SUB      'boiler
'*****
*****

```

```

SUB BOILEROFF(time,bwt,qf,qj,qs) LOCAL
  SHARED bwtll,btmass,uastack,uajacket,ibzone,tzone()
  LOCAL time2ll,uatotal,qacc,t2,tz,dumtime

  qf=0: qj=0: qs=0
  tz=tzone(ibzone)
  uatotal=uastack+uajacket

  IF uatotal<=0 THEN
    time=0
    EXIT SUB
  END IF 'uatotal
  IF bwt<tz THEN
    CALL ALARM
    PRINT "ERROR: bwt<tz in boileroff"
    STOP
  END IF 'bwt

  time2ll=3600*(btmass/uatotal)*log( (bwt-tz)/(bwtll-tz) )
  IF bwt<=bwtll THEN time2ll=time+1

  IF time2ll<=time THEN
    t2=bwtll
    dumtime=time2ll
  ELSE
    t2=tz+ (bwt-tz)/exp( uatotal*time/(3600*btmass) )
    dumtime=time
    IF t2<tz THEN

```

```

        CALL ALARM
        PRINT "ERROR: t2<tz in boileroff"
        STOP
    END IF 't2
END IF 'time211

DECR time,dumtime
qacc=btmass*(t2-bwt)          'heat accumulated in the boiler
qs=-qacc*(uastack/uatotal)    'stack losses
qj=-qacc*(uajacket/uatotal)   'jacket losses
bwt=t2

END SUB 'boileroff
*****
*****

SUB BOILERON(time,bwt,qf,qj,qs) LOCAL
    SHARED uajacket,sseff,bwtul,btmass,fire,ibzone,tzone()
    LOCAL tz,t2,dumtime,dum1,time2ul,qin,qacc

    IF fire=0 THEN
        CALL ALARM
        PRINT "ERROR: fire=0 in boileron"
        STOP
    END IF
    tz=tzone(ibzone)
    qin=fire*sseff
    dum1=(bwt-tz-qin/uajacket)/(bwtul-tz-qin/uajacket)
    time2ul=3600*(btmass/uajacket)*log(dum1)
    IF time2ul<=time then
        t2=bwtul
        dumtime=time2ul
    ELSE

t2=tz+(qin/uajacket)+(bwt-tz-qin/uajacket)*exp(-uajacket*time/(36
00*btmass))
        dumtime=time
    END IF
    qacc=btmass*(t2-bwt)          'accumulated in boiler
    qf=dumtime*fire/3600          'amount of fuel used
    qs=qf*(1-sseff)
    qj=qf-qs-qacc
    IF qj<0 THEN
        call warble
    end if
    DECR time,dumtime
    bwt=t2
END SUB 'boileron
*****
*****

```

```

SUB CHECKCIRC( duration,hload,isboileron,ireturnvalue) LOCAL
  SHARED twin(), twout(), nsecs, bwt, ibzone, carryover
  SHARED qfuel, qjacket, qstack, tpipe(), Qzone(), Qamb()
  SHARED izeone(), Rfuel, Rjacket, Rstack, Rboiler, Rzone(), Ramb()

  LOCAL i,bwt2,tl(),tr(),tpw(),qzn(),qloss(),iboiler
  LOCAL qf,qs,qj,d1,d2,d3,d4,zone1,zone2, heat2zone
  DIM tl(1:50), tr(1:50), tpw(1:50), qzn(1:50), qloss(1:50)

  bwt2=bwt
  ireturnvalue=1
  iboiler=isboileron
  FOR i=1 TO nsecs
    tl(i)=twin(i)
    tr(i)=twout(i)
    tpw(i)=tpipe(i)
    CALL HXOFF (tl(i),tr(i),tpw(i),d1,d2,d3,d4,i,duration)
    IF izeone(i)=1 THEN INCR zone1,d1 ELSE INCR zone2,d1
    qzn(i)=d1
    qloss(i)=d2
  NEXT i
  CALL BOILER(duration,bwt,isboileron,qf,qj,qs)
  IF ibzone=2 THEN heat2zone=Rzone(2)+qj+Rjacket
  heat2zone= Rzone(2) + heat2zone + zone2
  IF heat2zone<hload THEN
    bwt=bwt2
    ireturnvalue=0
    isboileron=iboiler
  ELSE
    ireturnvalue=1
    INCR Rzone(1),zone1
    INCR Rzone(2),zone2
    INCR Rfuel, qf
    INCR Rjacket, qj
    INCR Rstack, qs
    INCR Rboiler,Qboiler
    FOR i=1 TO nsecs
      twin(i)=tl(i)
      twout(i)=tr(i)
      tpipe(i)=tpw(i)
      Qzone(i)=qzn(i)
      Qamb(i)=qloss(i)
    NEXT i
    carryover=heat2zone-hload
  END IF
END SUB
'*****
*****

```

```
SUB STEADYSTATE(T1(1),T2(1),TP(1)) SHARED 'DETERMINE STEADY STATE
VALUES
LOCAL i,irun,Textit,d1,d2,d3,d4
```

```
    irun=0
    Textit=TWout(nsecs)
    DO
        CALL PLUGSHIFT( nsecs,TWin(),TWout(),bwt,dummy1)
        FOR i=1 TO nsecs
            dummy1=0: dummy2=0: dummy3=0: dummy4=0
            CALL HXON( TWin(i),TWout(i),Tpipe(i),d1,d2,d3,d4,i,dthx)
        NEXT i
        bwt=bwtorig
        IF ABS(TWout(nsecs)-Textit)<0.0001 THEN
            FOR i=1 TO nsecs
                T1(i)=TWin(i)
                T2(i)=TWout(i)
                TP(i)=TPipe(i)
                irun=1
            NEXT i
        END IF
        Textit=TWout(nsecs)
    LOOP UNTIL irun
```

```
END SUB
```

```
*****
```

```
SUB GETCYCLETBL(NT(1),mc,items) LOCAL
    LOCAL i
    items=2*mc+1
    FOR i=1 TO (mc+1): NT(i)=i-1: NEXT i
    FOR i=(mc+2) TO items: NT(i)=items-i: NEXT i
END SUB
```

```
*****
```

```
SUB GETFRACTIONTBL(FT(),NT(),mc,items) LOCAL
    LOCAL i
    FOR i=1 TO items
        IF (i<=mc) THEN
            FT(i)=0.5*(1! - SQR(1!-NT(i)/mc))
        ELSE
            FT(i)=0.5*(1! + SQR(1!-NT(i)/mc))
        END IF
    NEXT i
END SUB
```

```
*****
```

```
SUB LOOKUPTBL( hl,nc,f) LOCAL
    SHARED FTable(),HLTable(),NTable(),items
    LOCAL i,j
```

```
    IF hl=>HLTable(items) THEN      'load is > than flat out running
        nc=1
```

```

        f=1!
    ELSEIF hl<=HLTable(2) THEN      'HLTable(1)=0
        n=1
        f=(hl/HLTable(1))*FTable(1)
    ELSE
        FOR i=2 to (items-1)
            j=i+1
            nc=-1
            IF hl>=HLTable(i) AND hl<=HLTable(j) THEN
                nc=NTable(i)
            f=FINTERPOLATE(hl,HLTable(i),HLTable(j),FTable(i),FTable(j))
            EXIT FOR
        END IF
    NEXT i
    IF nc=-1 THEN
        CALL ALARM
        PRINT "ERROR IN TABLELOOKUP!! CYCLES NOT SET"
        STOP
    END IF
END IF
END SUB
'*****

FUNCTION FINTERPOLATE(X,X1,X2,Y1,Y2) PUBLIC 'INTERPOLATE BETWEEN 2
DATA POINTS
    FINTERPOLATE=y1+ (X-X1)*(Y2-Y1)/(X2-X1)
END FUNCTION
'*****

SUB PRNT2FILE(IFILENUM) SHARED
    LOCAL i
    PRINT #IFILENUM,USING A$; hour, time/60, bwt, iscircon,
isboileron
    PRINT #IFILENUM,USING B$; Rstack, Rjacket, Rfuel,
Rfuel-Rstack-Rjacket-Rboiler
    PRINT #IFILENUM,USING C$; Rboiler
    PRINT #IFILENUM,USING D$; Rzone(1),Rzone(2),Ramb(1),Ramb(2)
    PRINT #IFILENUM,E$
    FOR i=1 to nsecs
        PRINT #IFILENUM, USING F$; i, TWin(i),
TWout(i),Tpipe(i),Pipenet(i),Waternet(i)
    NEXT i
    PRINT #IFILENUM,""
END SUB
'*****

```


SUB PRNT2SCRN SHARED

LOCAL i

CLS

PRINT USING A\$; hour,time/60, bwt, iscircon, isboileron

PRINT USING B\$; Rstack, Rjacket, Rfuel,
Rfuel-Rstack-Rjacket-Rboiler

PRINT USING C\$; Rboiler

PRINT USING D\$; Rzone(1),Rzone(2),Ramb(1),Ramb(2)

PRINT E\$

FOR i=1 to nsecs

IF i>16 THEN EXIT FOR

PRINT USING F\$; i, TWin(i),
TWout(i),Tpipe(i),Pipenet(i),Waternet(i)

NEXT i

END SUB

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