The sun is an outstanding source of energy for mankind. It is clean and comes to the earth for free. There is no need to drill and refine it or mine it out of the ground. The devices needed to gather its energy are simple, quiet and non-polluting. However, with all its advantages, the sun is not always shining when the users of that energy want it. For solar to be able to fit the needs of the user, the energy must be gathered when it is available and stored until it is needed. The 10 p.m. shower heated by solar energy would be a cold one if it were not for thermal storage.

When the fluid going through a solar collector is air, a common storage method is rock bed storage. When the fluid is water, the energy is typically stored in a water tank: sometimes simply a retrofitted hot water tank from the plumbing shop, and sometimes something much larger. Whatever the size may be, tanks still have their flaws. Tanks can hold the energy gathered by the collector for a while, but do eventually lose their energy to the surroundings. If the hot water is removed from the top of the tank, it is replaced by cold water at the bottom. Ideally, the hot layers on top should stay there and not mix with the cold layers on the bottom. Of course, in reality this is never completely true.

Storage tanks are only one component of several that make up an entire solar system. The collector, pumps, controllers, and pipes also play a role in how a system will perform.
Changing conditions such as day-to-day loads, daily outside temperatures, and yearly variation of the incoming solar radiation also play very important roles in how a solar energy system will perform. With so many variables to consider, and with other energy sources competing very closely with solar, a simple "back of the envelope" calculation will not provide the engineer with a clear-cut winner of which energy system to choose.

To better model systems with properties that vary over time, the University of Wisconsin-Madison has developed TRNSYS [22], a software package that simulates transient thermal systems. TRNSYS allows the engineer to assemble a solar system and allow it to perform for a period of time. At the end of the simulation, the engineer can examine how much energy was used or saved and, if desired, make changes and improvements to the design. By running TRNSYS through a simulation, the engineer can examine how much energy was used (or saved) by each component and then make changes to the design to optimize performance. This dissertation is directed toward describing a tank model to be used for TRNSYS.

1.1 Fundamentals of a Thermal Storage Tank

Figure 1.1.1 shows a simple thermal storage tank. Hot water, having a lower density than cold water, rises to the top of the tank. Assuming the incoming and outgoing flows are not too large to cause mixing, this temperature stratification will generally be maintained. A solar system with a stratified tank will perform better than one with a fully mixed tank [16]. The colder the water is leaving the tank (going to the collector), the better the system performs.
The water will seek out a particular level in the tank, depending on its density. It is also known that the tank fluid will spread out horizontally, thereby maintaining nearly uniform temperature at any level in the tank. A reasonable assumption (in most instances) is that a cross-sectional slice of the tank (of some to be determined thickness) will be at a uniform temperature. Such a volume is often referred to as a node or segment. The tank model described in this dissertation uses from 1 to $N$ isothermal nodes. The temperature distribution in the tank is determined by solving mass and energy balance equations on each node.

If the collector is not delivering enough hot water to the tank, the tank may employ an auxiliary heater to maintain a set temperature. These heaters are typically about 4.5 kW and employ a temperature deadband. The heater is enabled if the temperature of the node containing the thermostat is less than $(T_{set} - \Delta T_{db})$ or if it was on for the previous interval and the thermostat temperature is less than $T_{set}$.

In colder climates, water may not be the fluid used in the collector, but rather some type of antifreeze solution. This fluid must be isolated from the potable water. To transfer the thermal
energy from the collector to the tank, a heat exchanger needs to be used. Some systems employ
the use of a heat exchanger outside the tank (another component separate from the tank), some
systems wrap the heat exchanger around the outside of the tank, and some systems have the heat
exchanger submersed in the tank. This tank model for TRNSYS includes the option for
submersed internal heat exchangers.

1.2 Introduction to TRNSYS

TRNSYS is designed to simulate the performance of thermal systems over time. A
system is simply several components connected together to produce some desired result: hot
water for example. Figure 1.2.1 shows a typical solar water heating system.

Figure 1.2.1 Typical solar water heating system

TRNSYS simulates the process by assembling the components together as they occur in the
physical system. Each component shown in the figure is a subroutine (usually referred to as a
type) in the TRNSYS software. The main TRNSYS program is used to link together all the
component subroutines. For example, the inputs to the Hot Water Storage Tank would be from the outputs of Main Pump, Collector, and Controller.

Once the user has assembled the system in the TRNSYS main program (referred to as the deck), the simulation can be run. The user must specify a starting time, stopping time, and time step. Choosing the proper time step size is an important element in a simulation. If the time steps are too large, TRNSYS may not be able to converge on a solution. Taking time steps that are small will eliminate any convergence problems, but it takes more time to run the simulation.

1.3 Literature Review

There have been many tank models (of varying degrees of complexity) developed in the past. Lightstone [25], Cabelli [5], Issa[18], and Shyu [33], to name a few, have developed two-dimensional (axisymmetric) models of storage tanks. Their papers address one or two phenomena commonly associated with storage tanks such as: inlet mixing, decay of stratification, temperature profiles during charging or discharging, etc. Lightstone [25] stated in his introduction:

"Resolving the behavior of real tanks is not an easy matter. The variable list is long, for example: port locations, nozzle sizes and orientations, tank sizes and shape, wall material, tank insulation and time-profiles of the inlet and outlet stream temperatures and velocities. Experiments are difficult and time-consuming and can only cover a narrow range of conditions."

Not only are there many variables to consider when modeling a tank, but one must also consider the amount of computation time needed for the model. Tank phenomena are typically on the order of minutes. Performing an annual simulation while taking every minute into account will slow the simulation down to a most undesirable speed. For a tank model to be feasible for an application such as TRNSYS, a one-dimensional model must be considered. Zurigat [38] wrote a paper comparing various one-dimensional models (references [1], [8], [24], [29], [35], [36])
and stated in his introduction:

"While two and three-dimensional models are more capable in accounting for different factors affecting the thermal storage tank performance, they are not suitable for use in large energy systems load management programs. Simpler one-dimensional models may be advantageous since they are computationally more efficient. Moreover, the object of any design of a single stratified tank should be the achievement of one-dimensional flow as any motion in the second or third direction would enhance mixing and degrade stratification."

Although the models compared by Zurigat are indeed one-dimensional, they do vary in complexity and, hence, computation time. Moreover, the complex models are used to make an accurate analysis of one or maybe two simple situations. (Inlet mixing, for example). These models may be more accurate for modeling one or two specific conditions, however, they generally lack the versatility to accommodate a multitude of users. This is not to say mixing phenomena is not important in a tank model, but other things such as environment losses, flue losses, auxiliary heat, and internal heat exchangers would probably be rather difficult to incorporate into these models.

Other literature was reviewed to examine the behavior of submersed internal heat exchangers. Blair [4] performed experimental work on transient natural convection from a submersed internal heat exchanger, but the tank size in his work was only 20.7 cm (8.15 in) diameter by 20.7 cm (8.15 in) high. Consequently, the effects of recirculating flows within the small tank tended to produce results that would not necessarily apply to the conditions of a heat exchanger in a large solar storage tank.

Another problem associated with internal heat exchangers is their often complicated shapes. There is much literature available for analytically calculating natural convection from a horizontal cylinder, but nothing for finned, spiraling heat exchangers. Farrington and Bingham [11, 12] performed experiments on several collector-side [11] and load-side [12] heat exchangers which did have widely varying shapes. Much of their work was used to validate the
TRNSYS model. Other literature by Churchill [6, 7] agrees with Farrington and Bingham for computing natural convection heat transfer from a generalized immersed body [7], and provides some correlations for situations when both natural and forced convection are present [6].

1.4 Scope of Study

The current version TRNSYS (version 14) has a tank model, but it is somewhat limited in its applications. As the number of TRNSYS users continues to expand, so do their needs. Some tanks might have only three connections to them. Some tanks may contain one or two or three internal heat exchangers or may not be cylindrical. The goal of this research is to create a more versatile tank model: a model that can accommodate the growing needs of the TRNSYS users, but without the penalties of unreasonable computation time or expecting the user to know the minute details of all the components (especially the internal heat exchangers) in the tank.