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Undergraduate Final Year Project Report
Tim Helweg-Larsen, April 2001

fighting

ICE with ICE

Design, construction and reliability testing
of an
Automatic Draindown Mechanism
to
prevent frost damage
to
Passive, Thermosyphoning Solar Water Heaters
In
High Altitude Regions.

CONTENTS

ABSTRACT

This project covers the design, construction, testing and evaluation of a simple and dependable auto-draindown mechanism for use with solar water heaters to prevent frost damage.

This is considered a key link in making thermosyphoning solar water heaters economically and practically feasible for Himalayan regions lying above the snowline. Solar water heaters can make a significant contribution to reducing a household's reliance on purchased or laboriously collected fuels.

In its simplest form, the proposed mechanism consists of two valves and a thermally controlled actuator. One valve isolates the water tank, the second drains the solar panel. Both are operated by the actuator. The actuator consists of a car thermostat whose reservoir of wax has been replaced with water. When temperatures drop to zero, the water freezes, expanding into ice and driving forward an actuator rod to operate the valves. The next day the mechanism resets itself and the water heater can continue to operate.

Figure 1 Leh Old Town

1 INTRODUCTION

1.1 Defining the project

The project started before the formalisation of its title. The overall objective was to make a useful contribution to living standards through the development of appropriate technologies. While the greatest benefits may come from work in agriculture and solar architecture, for a manageable piece of work the development of solar water heaters was chosen. The aim is to bring solar water heaters to the rural population of the Ladakh. With this as the start to the project, development of objectives began first by looking at the different solar water heating technologies available.

The systems considered included:- low cost oil-filled heat-exchange thermosyphons, and various simple devices for heating a batch of water. These might be as simple as a blackened can.

For the system to receive wide-scale adoption it should compete with the convenience of heating water indoors on a fire, it was decided that the system should therefore be piped.

The simplest and most appropriate piped system for Ladakh was considered to be a water filled thermosyphon as these have become popular in parts of Nepal. However even with the system's water tank located inside the house, this design is traditionally prone to frost damage in the collector panel and external pipe work. Consequently it must be drained before freezing.

The most common means of adapting thermosyphons to frosty conditions is to use a two-stage system. An antifreeze filled thermosyphon heats water via a heat exchanger. Such systems are inevitably more expensive due to their increased complexity and antifreeze requirements. Further, many of the more efficient antifreeze liquids are toxic and to reduce the risk of contaminating the drinking water adds further to the costs of the system.

There are modifications that can be made to thermosyphoning solar water heaters to help them withstand extreme cold temperatures. They have generally been developed in wealthy Western countries and are too expensive for domestic use in the Himalayas
They are listed bellow along with the reasons why they are not appropriate.

	Method	Associated Problems
1	Heat tape on tubes and collector panels	Requires reliable electricity and significant extra cost
2	Reversing the pumps of an active system at night to supply pipes with flow of warm water from the storage tank	Requires a pump system which in turn means reliable electricity, extra areas for maintenance, less efficiency as heat is lost in warming pipes, consequently extra cost
3	Pump drain down. With a suitable valve placement, a pumped system can reverse the flow and drain down the water contained in the collector panel and associated pipework.	Requires a pump system which in turn means reliable electricity, extra areas for maintenance and extra cost
5	(Just) Manual drain down	With no automatic safety valve, freeze damage will occur if the user forgets to drain down the system

One way that the system could be made useable and still remain affordable is if a low cost mechanical solution could be developed. It is to this end that the project is committed.

2 BACKGROUND

2.1 Background

Thermosyphoning solar water heaters have become popular in the lower altitudes of Nepal. This is due in part to their low cost, ease of maintenance and the economic advantage they deliver over alternative water heating methods. Solar water heating has experienced much less popularity in other Himalayan regions which find themselves at a greater altitude and prone to frost. This project sets out to define a low cost approach to bringing solar water heaters to high altitude areas.
In particular the Region of Ladakh in the Indian Himalayas has been chosen as the specific area of application. This location was chosen as the author had spent some time in the region however it is hoped that outputs of the project would also be applicable in other areas.

2.2 Ladakh

Ladakh lies in the Indian Himalayas at latitude 35° North. It has borders with both China and Pakistan and consequently a large military presence. The mountainous geography puts most of inhabited altitudes between 2,500m and 4,500m. Ladakh lies in the rain-shadow of the Himalayas and although there are indications that this might be changing, it presently receives only 30mm or so of annual precipitation. Most of this comes in the form of snow which landing over the large mountainous areas melts in the summer to provide running water for settlements lying in the valleys.

The region is predominantly rural, with larger villages lying along the main road that comes up from the plains to Leh, Ladakhs' principal town. This road is blocked off by snow for almost six months of the year, leaving the region inaccessible except by air.

Winter in Ladakh is long and night temperatures drop to between –10°C and -20°C. Despite this, the area still receives a lot of sun with more than 300 clear days a year. Low ambient temperatures during the day are made quite tolerable by the sun's intensity.

Extended families live together in quite spacious homes that grow with each passing generation. In the winter the family all moves into a single winter living room where they will cook, sleep and spend much of the day though the coldest months of the year.

Figure 2 Winter living room / kitchen, Photocsar Village, Zanskar, Ladakh

An open fire will often be used to provide heat to the room. The smoke, although unpleasant and injurious to health, is felt to keep the occupants warmer and will exit through an opening in the roof. In some homes a closed room with a chimneyed stove will be used. This is becoming more popular and is promoted by several local NGOs.

Water is collected by hand even in Leh and is heated on the fire. Because of the lack of rain, Ladakh can accurately be described as a high altitude desert. Consequently nothing larger than low grasses and shrubs grow without irrigation. Fuel wood must therefore be grown for the purpose and is supplemented by dried dung and shrubs. In villages above the tree line, the latter are used almost exclusively. Most homes will also keep a supply of kerosene, although this is usually used for lighting. In wealthier households kerosene and LPG are used for cooking and heating water.

Most households grow their own food and supplement it with purchased supplies. There are few opportunities for jobs in the formal sector, families make money trading surplus stocks. There are fewer men in the villages to help with chores and farm work, as children spend time in school, and men try to get jobs in the towns or in the army. Tourism is a major source of income for the economy, but not much of this trickles down to the individual household. This is easier for villages with easy access to Leh.

2.3 Thermosyphoning Solar Water Heaters

A brief outline of the workings of a thermosyphon may be useful to the general reader.

In its simplest form a Thermosyphoning solar water heater has two main components; a water storage tank and a collector panel that uses the sun’s radiation to heat the water

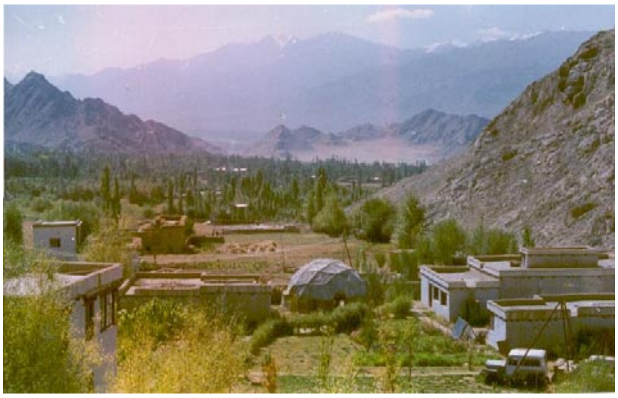
These two components are joined by one pipe allowing water to flow between the bottom of the tank and the bottom of the collector panel, and a second pipe connecting the top of the collector panel to a point near the top of the tank.

The tank, the pipes and the underside of the collector panel are all thickly insulated. The top of the collector panel is painted black to help absorb heat, and is glazed to retain that heat.

For the system to work it must be filled with water and exposed to the sun.

The collector panel heats up and warms the water contained within it. As the water warms, it expands becoming less dense, and floats out of the panel and up to the top of the water tank. The arrival of warm, low density water at the top of the tank displaces the colder denser water at the bottom which sinks down to enter the bottom of the collector panel. This new water is heated and so the cycle continues.

2.4 Solar Water Heaters in Ladakh



Ladakh has seen various appropriate technology initiatives over the last 20 years. LEDeG (Ladakh Ecological Development Group) has an appropriate technology workshop which manufactures patch solar water heaters, and has experimented with and tested antifreeze thermosyphoning systems.

LEDeG, Leh, Ladakh

The Leh branch of SWRC (Social Work Research Centre) has trained engineers in the construction of oil filled solar water heaters.

SECMOL has investigated innovative pipeless water heaters, such as plastic bags of water on the roof.

The Indian Government has a ministry for renewable energies, and the Ladakh department is involved in a small Photovoltaic power station for a remote community.

The author first became interested in the possibility of a draindown mechanism while working as an intern at LEDeG.

2.5 Existing Designs for Autodrain Valves

A search was made for existing designs that would meet the functional aims of the project. While no designs were mentioned in any of the literature on solar water heaters, a number of designs were found through a patent search.

Most of these patented designs come from the U.S. They were found to meet some but not all of the prioritised aims of this project.

All of the designs were highly engineered. The simplest of them opened a valve at freezing and had to be reset manually. Some of them were able to self-reset. Some of the designs were able to automatically isolate one element of a system and drain off another, which would most completely fulfil the aims of this project. However they were triggered electronically and were prohibitively complex for inexpensive local manufacture.

See Bibliography for a full list of sources including books, periodicals, patents and internet sites.

2.6 Scenario Planning

During warm summer months, temperatures rarely drop to freezing. The problem arises during the long winter, and it is for this period that the new design becomes necessary.

Various scenarios will be described through this report, which put increasing demands and constraints on the design. To begin, the basic pattern of usage as described in this chapter and an associated Base Climatic Scenario. Further scenarios will be introduced later as the design develops.

2.6.1 Basic pattern of usage

The water tank is filled by hand on a daily basis. Few families have access to plumbed water and those that do, have to drain their pipes over winter. Water is fetched by hand, often from some distance, as small streams that flow close to houses in summer freeze and dry up in winter.

Families carry water often with plastic or military Gerry cans, and will keep a store of 70 or 100 litres in the kitchen / winter living space.

The day starts with breakfast and washing and a likely pattern of use for the system would be to use the hot water remaining from the previous day first, then fill up the water tank so that it is ready for heating as the sun grows in intensity. Hot water will be drawn at various times in the day. The cycle will repeat itself the next morning.

Hot water from the solar water heated will be used for cooking and making tea. Fuel load can be reduced through shorter cooking times. Water for washing can be made up by mixing hot and cold.

2.6.2 Base Climate Scenario

The base scenario that the auto-drain mechanism must deal with the following sequence:

A warm day , strong sun and positive air temperatures thought the day.

Cold night , as night falls, air and sky temperatures drop below zero, and remain so until daybreak.

Second warm day.

In this scenario, the collector panel remains hot during the day as it thermosyphons. As the sun goes down and air temperatures drop, the collector panel temperature drops below the water temperature at the top of the tank and tries to reverse siphon. (The design should prevent this, in order to stop the associated heat loss).

As temperatures drop to zero, ice would start to form in the collector panel, which due to its design is a very efficient radiator. (The design should prevent this, and any associated frost damage).

3 AIMS / SPECIFICATION

Of those aspects listed below, the design must fulfil the Primary Function, satisfying the Conditions of Use and the Other Factors. It should aim also to fulfil as many of the Secondary Functions as possible.

3.1 Primary Function

To prevent frost damage to a thermosyphoning solar water heater by draining the exposed elements in good time.

3.2 Other Factors

Low Cost:	(< 20% of the total cost of the water heater)
Simple to construct, using;	(commonly available tools, low tolerances, few component parts, available manufacturing skills)
Cheap to maintain:	(< 5% of the cost of the mechanism per year)
Easy to maintain:	(serviceable by unskilled owner, reparable by trained plumber)
Durable:	(useful life > 20 years)

3.3 Secondary Functions

To be reusable (doesn't require replacement of parts each time it is used)
To keep the water in the water tank, when the rest of the system is drained
To prevent the water heater from reverse siphoning and consequently cooling the stored water
To refill the exposed components of the system when they are warm enough
To fulfil all of the above secondary functions automatically (to be self setting)
The design must fail-safe

4 PROJECT APPROACH

The project as stated in the title covers design, construction, and testing of the mechanism.
Necessarily, these three aspects build one upon the other, and have, as might be expected, gone through several iterations. At each level, new understanding is gained as different avenues are explored. This structure has led to most of the project time being devoted to design; thought experiments, sketches and research in the literature. The outcome of this

design work has been an increased understanding of the problem, and at various points has provided inputs to construction.

Time spent on construction has been comparatively brief, and of the items built only a few aspects have been tested.

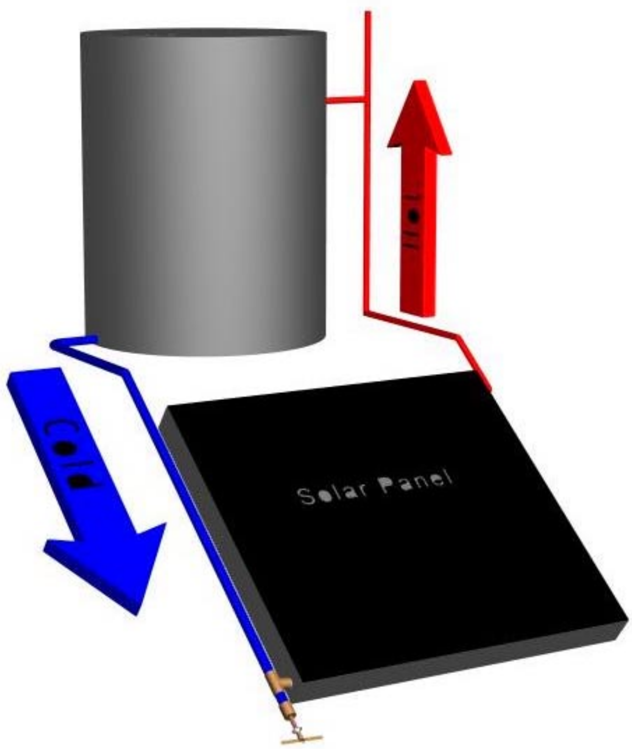
This three-tiered pyramid is just as it should be, and is significantly quicker at developing a winning solution than blindly going into construction and testing.

To detail the entire train of thoughts and ideas that have occupied this project would be a drawn out and clumsy exercise indeed. Instead the development will be narrated only in so much as it relates to the chosen final design. Promising alternatives to design features will be included as cursory notes. Major avenues for future development are highlighted at the end of this report.

5 Chosen Design

This chapter briefly outlines the final design. This should help the reader to follow the development that led to it, as described in the next chapter.

5.1 Overall system



Thermosiphoning solar water heater

The water tank is located inside the building and the collector outside on the South face.

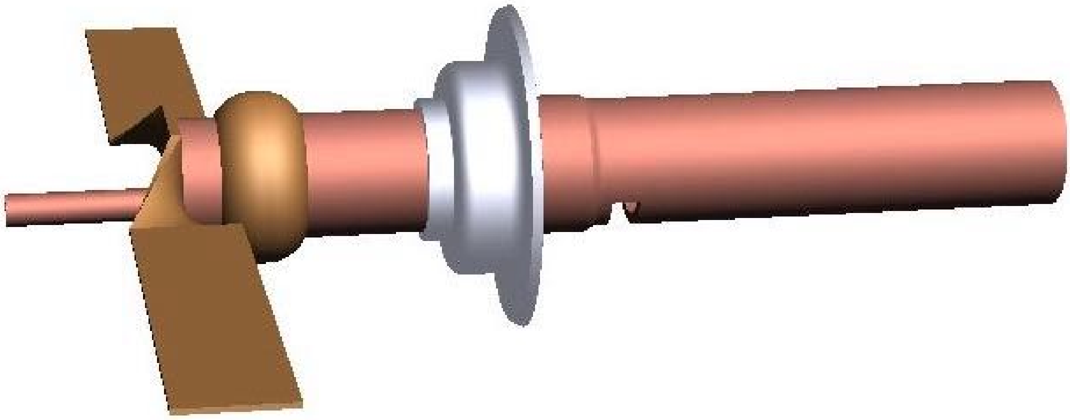
A non-return valve is placed at the top of the hot water pipe. This prevents reverse siphoning. It also stops the water in the tank from leaving when the collector is drained.

The collector panel is tilted gently so that one of its bottom corners is higher than the other. This allows complete gravity drainage.

A ventilation pipe rises up from the top of the hot water pipe, above the level of the tank, to allow the system to pull in air when it drains down.

The key to the system is the Auto-drain assembly. This is a twin valve unit, located at the lowest corner of the collector panel. It is temperature sensitive, and drains the collector panel and hot water pipe, but not the tank, before frost damage can occur.

5.2 The Autodrain Assembly



Auto-Draindown Mechanism 1

Two valves are placed in series at the bottom of the cold water pipe, just next to the lowest corner of the solar panel. The valves run along a single actuator rod. When this rod advances, it locates the first valve (shutting off the cold water pipe and the tank). The rod then continues to advance opening the second valve to drain the solar panel.

The actuator rod is driven by an ice actuator. This essentially comprises a modified car thermostat.

The thermostat has had its reservoir drained of wax and filled with water. The reservoir has been enlarged, and has brass cooling fins soldered to it. These are painted black and insulated on their underside.

Everything but the top of the finned reservoir is insulated. When ambient and sky temperatures drop, the reservoir of the ice actuator loses heat dramatically faster than does the collector panel. The water in the reservoir therefore freezes before the panel does, and on freezing it expands and drives forward the actuator rod.

The collector panel then drains before it can be damaged by ice.

The action of the actuator rod advancing, also compresses a strong spring. In the morning, the actuator thaws and the valves are returned to their original positions by the spring.

6 PRODUCT DEVELOPMENT

6.1 An Evolving Understanding of Water and Ice

As this project developed so an understanding of the properties of ice became necessary. The project aims to prevent ice formation, or more specifically, the problems that this ice can cause:

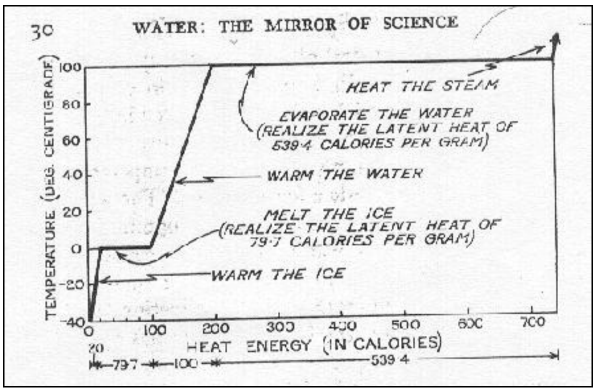
1. Bursting of pipes
2. Blockages rendered to the system, which present an additional heating load to be overcome before thermosyphoning can resume the next morning.

During the course of the design process, it was noted that the expanding volume of water during solidification could be used to generate the movement for operating valves. This made necessary a further understanding of the dynamics of ice and its transition with water.

Water has unique properties many of which are essential for the operation of a thermosyphoning solar water heater.

1. Liquid water can be safely consumed.
2. It has a high specific heat, which contributes to an efficient thermal flow.
3. It changes density significantly with temperature, which is observed in the thermosyphon effect.
4. It expands by 10% on freezing.

This project has become an exercise in further exploring the phases and properties of water and applying them to advantage.



Water the mirror of science

Ice grows in tendril like crystal formations. Ice is a superior heat conductor to still water, and in the case of freezing in a pipe, the formation of tendrils allow heat to be drawn out from the core of the water to the chilled pipe wall. This effect is less pronounced with the freezing of cool water than with hot, and is the reason that Ice cream can be made faster if the mix is warmed before it is put in the freezer.

There is a significant body of literature describing the formation of ice on a microscopic level and its manner of progress along capillaries is well documented. Little is available however on the macroscopic growth, particularly in pipes. For the purposes of this project, Ice formation in a pipe has been considered to approximate a growing layer on the inside walls of the pipe. Convection has largely been ignored as it is expected that, at the temperatures and component sizes considered, it has much less effect than conduction.

6.1.1 How do pipes burst?

Tests or literature review have not been conclusive, but it is thought that pipes do not burst at localised points of freezing, but rather they burst as the result of constrained freezing. If a length of pipe freezes solid at two points some distance apart, the water between these points is trapped. If this trapped water subsequently freezes, then the expanding ice must either push the blockage along the pipe, or if there is too much resistance, escape by bursting a hole in the pipe wall. The freezing point of water is depressed by pressure (10mK/bar) however very high pressures indeed would be required to move it from zero by even a fraction of a ^{o}C. The drop in atmospheric pressure experienced at high altitude of Ladakh will have negligible effect on melting freezing points. Standard plumbing pipes will burst if filled with water and subjected to freezing temperatures.

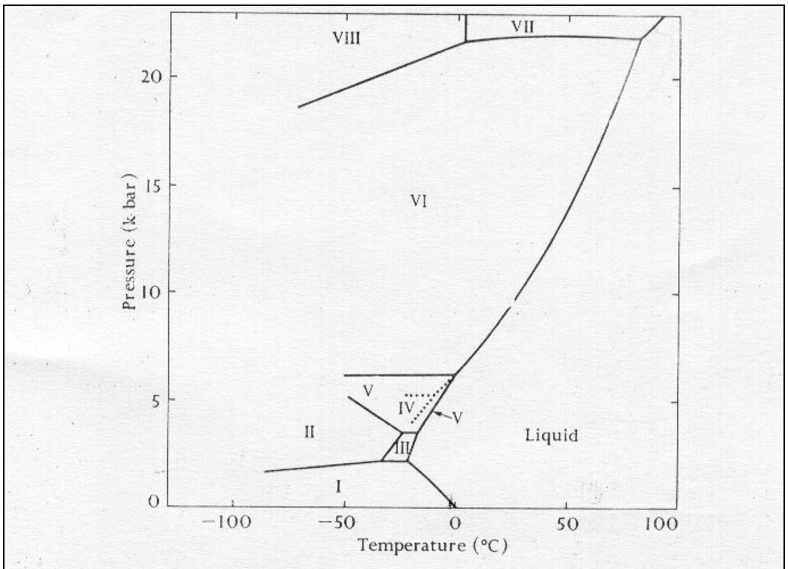


FIG. 3.11. Phase diagram of H_2O, based on data of Bridgman (1912, 1935, 1937) and Brown and Whalley (1966). The field of metastable ice IV is shown by dashed lines; it should be noted that this field was actually mapped by Bridgman only for D_2O. Adapted with changes from Kamb (1965 *a*).

The diagram above shows the nine phases of H_2O. Under normal atmospheric conditions we only ever observe water and Ice 1. Of particular interest is the angle with which the phase boundary between liquid and Phase 1 meet, this gives the pressure – temperature relationship stated above.

6.2 Configuration

The overall system configuration is necessarily determined by the design of the Valve Linkage, Actuator and Heat Exchanger described later in this chapter. The design process was an iterative one. The design of the system's configuration can be described here, but the reasons for particular design choices often lie in the details of its component parts.

The primary function of the design as described in the Aims / Specification is to:

> "Prevent frost damage to a thermosyphoning solar water heater by draining the exposed elements in time"

The configuration used to achieve this objective varied and necessarily increased with complexity as Secondary Functions were incorporated.

6.2.1 Revised Component Specification (Configuration)

In order to fulfil all the secondary functions a revised specification can be arrived at for the configuration in general.

1. To prevent the critical components (collector panel and water pipes) from freezing, they are required to be drained.
2. To retain the bulk of the heated water, the storage tank must be isolated so that it does not drain.
3. To prevent leakage, the sequence of isolating and draining the respective components is critical. In the evening the tank must be isolated before the panel is drained. In the morning, the panel must be closed before the tank can be reopened.

6.2.2 Design

The configuration design will be related over the following sections as the Valve linkage and Actuator are developed.

6.3 Valve Linkage

This section covers the development of the linkage and general arrangement of the valves, looking at how they need to operate to fulfil the criteria established in the previous section "Configuration".

As stated, there are three valve operations required.

1. To close the cold water pipe (preferably as it leaves the tank)
2. To close the hot water pipe (preferably as it enters the tank)
3. To open the collector panel to drain (necessarily at the lowest point on the system)

It would be desirable to have a single valve unit that could fulfil all three operations. This would alleviate any problems of operating different, independent valves in the correct order.

The first problem with this however is that the obvious positions of these three operations are all physically distant from one another.

It would be possible to do away with the valve returning the hot water to the tank and allow a certain amount of water to drain from the tank until it reached the level of the hot water pipe. This might be quite a tolerable loss as it would be at the end of the day when some of the heated water had already been used. Further, it would be possible to catch the drained water in a bucket and every few days it could be emptied back into the water tank. The only drawback is that it would not start thermosyphoning automatically the next day.

An alternative is to use a simple non-return valve on the hot water pipe. This would need to have a very light action so as not to cause significant resistance on the flow of thermosyphoning water. Options have yet to be tested but it is hoped that a collapsible plastic tube as used in the cistern of a western style toilet could be employed.

One of the primary benefits of using a non-return valve is that it is operated by flow rather than temperature and will be triggered by the action of the drain down valve. This removes problems of sequencing. It is open when there is positive flow, and it closes when the flow reverses either due to draindown, or more likely due first to reverse siphoning.

A notable benefit here is that reverse siphoning would be eliminated. Reverse siphoning occurs when the solar panel drops below the temperature of the tank. When this arises, water in the panel is cooled and sinks, drawing warm water down from the top of the tank and cooling it. The thermosyphoning system, upon which the solar water heater relies, is reversed and progressively cools the water in the tank.

With the valve at the top of the hot pipe dealt with, two more valves remain.

After much thought it seemed that the design would be significantly less complex if it used two valves rather than a single two-way valve. Various routes were considered and it again became apparent that it would be better to operate both valves from the same actuator to avoid problems of sequencing. This would be easier to do if the valves were located close to one another. Two main approaches were considered: one was to move the valve on the cold water pipe to the bottom of the pipe, where it would be close to the lowest part of the system, a suitable place for the drain-down valve. This would make the cold water pipe susceptible to frost and it would need to be protected with insulation, and possibly even a compressible closed-cell foam-strip insert. The other option considered was to bring the drain-down valve up to the level of the cold water pipe's top, and drain the water by siphonic action. Not surprisingly, this second route had numerous complications and was dropped in favour of the first approach.

6.3.1 Component Specification

1. Two valves operated by a single actuator rod.[1] (The rod will advance as zero temperatures begin, and retreat when temperatures rise.)
2. One valve (tank isolation) must close off the bottom of the cold water pipe.
3. The other valve must open a drainage outlet.
4. The drainage valve must open 2nd and shut 1st , with respect to the tank isolation valve.

Both valves consist of a washer reducing the diameter of the pipe, against which a rubber pad is pushed, blocking water flow.

The valves are operated in sequence, one closes and then the other opens. It is important that the first operation is completed before the second begins. Were this not the case, water could drain away from the tank during the time that both valves are open.

The time taken for the valves to operate may be quite long (if surroundings cool slowly) this would mean a large amount of hot water would drain away. Further, allowing hot water to drain at all could bring enough heat energy to the area of the freezing ice actuator that it warmed and stalled.

6.3.2 Pipe and fittings

In many ways the design is not tied to any particular type of pipe. However it is assumed in this project that the water heater is probably made from copper piping. Assuming that copper is used, it would be desirable to use copper or brass for any additions such as the drain-down mechanism. Joining and working techniques will be consistent and there would be few problems of corrosion, which might develop with steels or other electrically contradictory materials.

For a domestic solar water heater, pipes will likely be of the standard sizes (15mm, 22mm and 28mm OD), to mitigate against frost damage in the cold water pipe it has been oversized to accommodate a compressible insert. 28mm has been used for this design although it would be easy to size it up or down a size.

Fittings can be soldered, and to minimise the stroke length, the drainage outlet will be made short but wide and will take the form of a slot filed through the bottom of the pipe.

6.3.3 Threaded rod

A threaded rod will be used to transfer movement from the ice actuator through to the valve components. This has been chosen as they are readily available in brass (non-corrosive) and will allow the simple and adjustable positioning of the valve components along its length. Locked nuts are used to hold elements in position.

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[1] This constraint is fed in from the next section concerning the actuator

The rod will run along the centre of the pipe and valve components, keeping everything symmetrical.

6.3.4 Valve seals

The valve seals are constructed from circular pads of closed cell foam. They serve the dual purposes of forming a good seal and absorbing extra travel from the actuator rod. The pads are supported by 25 Paise Indian coins and are held on the thread by locked nuts.

6.3.5 Springs

The movement generated by the actuator is used to compress a spring, which in the morning returns the valve components to their original position ready for thermosyphoning. Thermosyphoning will only begin when the panel is raised to a higher temperature than the coldest water in the tank and can set up a positive thermosyphon past the non-return valve.

The spring from the car thermostat is used for this purpose and conveniently fits neatly inside 28mm OD copper pipe.

A second, smaller spring is required to take up the 5mm or so travel as the actuator rod closes the isolation valve before opening the drainage valve. A suitable spring was made by coiling a 2mm brazing rod around a pencil. This provides a low stiffness spring which won't corrode.

6.3.6 Insulation

All pipes on the solar water heater need to be thickly insulated and this is true also of those used in the valve arrangement.[2]

6.4 Actuator

6.4.1 Component Specification

1. Must generate enough travel to operate the valves
2. This movement must be generated before 15% of the water in the panel has turned to ice[3]
3. The mechanism must either be fail-safe, or so reliable as to virtually guarantee uninterrupted performance

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[2] The actuator needs a comparative advantage in loosing heat over the pipes.

[3] See Apendix for calculation

4. The movement generated must be forceful enough to overcome the pressure of 2m head of water on the valves.

6.4.2 Principals for Generating movement?

Different methods were considered, bearing in mind that movement must be generated without electronics, a bimetallic actuator was considered as were various thermally expanding metals and liquids.

The result of these investigations was that there is nothing to be found that expands as much as Ice at exactly freezing point.

If a small body of water could be placed in a more exposed spot than the comparatively large collector panel, it would be possible to freeze one before the other.

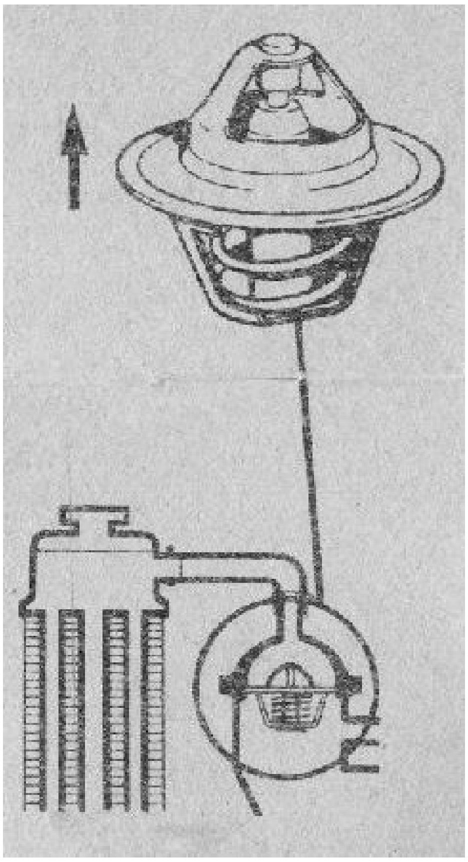
On further thought, it became apparent that this theory relied on both the actuator and the panel to start at some positive temperature and then for the actuator to cool faster and freeze before the panel. As this theory is played through with lower and lower starting temperatures, it is found that the actuator will need to be increasingly rapid at loosing heat. Ultimately if both components have a starting temperature of zero but have not yet begun to lose their specific energy of fusion, then the actuator will have to generate ice infinitely fast in order to drain the panel before any ice forms in it.

This impasse is relieved when we permit a tolerable amount of ice to form in the panel. Ice forming in the panel is not a problem per se. It is the threat of constrained expansion and subsequent damage to pipes that is the primary concern. A small amount of ice is tolerable if the water it displaces is unconstrained, and the total quantity of ice formed does not place a significant additional heating load on the system in the morning.

A figure of 15% has been arrived at as a tolerable amount of ice to allow to form.

If a domestic water heater has a $1m^2$ collector panel, with 10 vertical pipes and two fatter (3 times larger cross-sectional area) horizontal pipes linking the tops and bottoms. Low density ice is likely to form at the top of the system, i.e. along the top horizontal pipe. If we permit this pipe to ice up entirely it would constitute 17% of the internal volume of the collector panel. This figure has been rounded down to 15%. It is assumed that the 10 vertical pipes would provide ample opportunity for displaced water to escape through. Further, this would be only a small thermal load for the system to overcome as it starts up in the morning. It is imagined that the by blocking the tops of the pipes and preventing thermosyphoning, the water in the panel would rise fast to higher temperatures than it normally operates at, and this will accelerate the melting of the ice.

6.4.3 Capturing the expansion



Many approaches were considered, from rolling socks to bellows. The design now rests on the use of a car thermostat, a commonly available and relatively inexpensive item in Leh.

The thermostat as it stands, contains a reservoir of wax. When this wax reaches its melting temperature it expands, forcing a plunger forward by around 8mm.

The Drain-down mechanism is a modification of the thermostat, its reservoir is enlarged, cooling fins are added and the wax is changed to water. The Enlargement is necessary to provide sufficient initial volume of water to generate the full stroke length as it freezes.

The cooling fins, the subject of the next section, will increase the rate of heat loss as the actuator cools

6.5 Heat Exchanger

The heat exchanger describes the thermal conscious design of the actuator reservoir and more prominently its fins. These will hasten the rapid transfer of heat to or from the water or ice contained in the reservoir.

6.5.1 Component Specification

1. Heat must be lost fast enough to generate 100% freezing of the actuator before the panel has reached 15% freezing (under any climatic conditions)
2. Heat must be gained to melt the actuator (thus re-setting the system) before too much of the day's sun is wasted. This must be true for most days, i.e. the commonest climatic conditions.

6.5.2 Heat Exchange

In order to meet the criteria of operating properly under any climatic conditions, it is essential that the heat exchanger should gain and lose heat in the same manner as the collector panel.

The difference comes in that the heat exchanger should guarantee to lose heat at a faster rate.

The collector panel loses heat in different ways under different conditions, and consequently will freeze in different times. If the draindown mechanism is to be effective it has to adjust its freezing times accordingly. The heat exchanger should be insulated, orientated and free from shade in the same way that the panel is.

The collector panel loses heat through radiation and convection. Given the thick insulation on the underside and sides of the panel, it can be considered as losing heat only off the top surface.

Further, the glazing on the surface, while transparent to visible light, can be simplified in a heat loss model, since at infrared frequencies no radiation will pass through it directly, but will rather land, be conducted through and then re-radiated. By considering the collector as just a hot piece of glass, it loses heat by conduction and radiation just the same as the fins of the heat exchanger. The heat exchanger must be insulated on the bottom, and given the negligible thickness of its fins, has no need to protect the sides.

6.5.3 Freezing Times

Heat loss equations were used to calculate the rate of heat loss from the collector panel and from the heat exchanger.

These equations were then transferred to a spreadsheet which allowed the input variables, particularly fin size, to be altered until satisfactory outcomes were achieved.

The spreadsheet (see appendices) calculates the thermal masses of the panel and the heat exchanger, it then gives the time taken for the heat exchanger to achieve 100% freezing and for the panel to achieve 15 % freezing.

The example figures are for a previous design but the principle is the same. By altering the fin dimensions, the rate of heat loss for the heat exchanger can be increased until its 100% freeze time matches the panels' 15% freeze time.

By altering the fin sizes it is not just the nominal time to freeze that is adjusted, but something akin to a cooling ratio. Both the temperature that the heat exchanger and panel start at and are chilled to can be set to any figure and the two freezing times will always remain equal to one another.

The heat exchanger has a higher ratio of surface area (cooling area) to water volume than the solar panel.

7 ASSESSMENT AND TESTING

7.1 Cost – Benefit Analysis

Rather than a straight comparison, this section provides a discussion of the costs and benefits of solar water heaters. While reasonable estimates can be arrived at for the costs components and labour time, the benefits of the system require a more detailed social and economic analysis than is available to the author.

7.1.1 THE COSTS

Assessing the costs of the system includes both the Autodrain mechanism and also the solar water heater it is to be used with as well as any small maintenance costs. Not all items costed bellow lend themselves to a monetary analysis. It is simplicity, that they have been converted into Rs. (prices are estimates and have not been verified)

• **System Costs:**	150 lpd solar water heater	15,000
	Installation time	2 days
	Installation cost (2 engineers x 400 Rs./day)	1,600
	Sub Total	**17,100 (£ 285)**
• **Additional Costs of Auto-Draindown Mechanism**:		
	1 man-day of skilled craftsperson (plumber)	200
	Car Thermostat	300
	1 x 28mm straight compression fitting	150
	1 x 28,22,28mm Yorkshire T	100
	1m 28mm pipe, short length 3mm pipe	50
	200mm of brazing rod	20
	200mm threaded rod and nuts	50
	2, 25 Paise Indian coins	.5
	Sub Total	**870.5 (£14)**
	TOTAL	**17,970.5**

60Rs =£1

7.1.2 THE BENEFITS

The expected benefits of a solar water heater would be realised in both time and money saved and hopefully also health and hygiene aspects that would linked to improved access to hot water.

As explained in the opening chapters, the target beneficiaries are poor households. The benefits of solar water heaters are not as clear-cut as one might hope. The cost of a solar water heater, even a simple thermosyphoning one, is considerable in local terms. Even in Nepal where they have seen wide-scale adoption, it has largely been guesthouses that can afford the initial cost, and who are encouraged to purchase because their fuel costs are both significant and entirely monetary.

Fuel Collection

The further a family is from the cash economy, the harder it is to see clearly the benefits of a solar water heater. A rural household will get its fuel from a number of sources. They will purchase some Kerosene, mostly for lighting and perhaps for starting fires. They may also grow fuel wood if they are below the tree-line. These sources incur a direct cost of time or money to the family.

Dung and shrubs are also collected, either deliberately or as a retr-fit exercise to some other activity. A shepherd will pick up dry dung as she walks her goats, filling a wicker basket on her back. In the Winter, animals are brought in from grazing and are kept close to or in the house. The animals will be fed straw and their dung can easily be collected by the household. In this way fuel in the form of dung can be collected will little extra effort to rearing the animals and could be considered as free or concessionary fuel.

Cooking

Energy can be saved by cooking with preheated water. This is more apparent with tea and hot drinks than solid foods. The benefits are actually greater in Summer than in Winter. During Winter, cooking can be viewed in part, as a by-product of heating the living/kitchen space. The stove burns for much of the day keeping the rooms occupants warm. A pot of water sits on the fire and is always ready for tea making or cooking. Here we can see that the use of fuel for heating water is again partly free or concessional.

The benefits would be more fully realised in a home that has been built or retrofitted with energy conserving and passive solar principals in mind. Work is being done by a number of NGOs in Ladakh to promote greenhouses, double-glazing, draft exclusion and basic principles of designing rooms with insulation and heat gain in mind.

For a family whose house already benefits from these techniques, and needs little or no fuel to keep the living space warm through Winter, a solar water heater would be the next step to reducing fuel consumption.

Washing

Washing is a very flexible activity, the easier and more pleasant it becomes the more washing is likely to be done. Not surprisingly, more washing goes on in Summer than winter, clothes can be taken to the stream and people can bathe there also. In winter this becomes much less pleasant if not impossible when streams freeze up. Washing is preferably taken indoors, but that requires carrying and heating of water. Various approaches are taken through the winter months, clothes can be washed indoors with hot water from the stove and then taken outside for rinsing (a more water intensive activity). An ingenious approach that is employed, is to beat clothes against the ice of a lake or stream, the dust and dirt sticks to the ice, and it has much the same effect as vacuuming the garments.

It is hoped that personal hygiene would improve with a greater availability of hot water, bathing could be more frequent and washing hands more pleasant.

7.2 Initial Tests

There were a number of things that needed to be known about the formation of ice in pipes. These included;

- Verification that water would expand by 10% into ice
- Weather expansion would or could be restricted by the strength of a pipe
- How long a pipe needed to be to burst
- Weather an ice plug could be formed at the open end of a pipe and successfully block the water behind it.

Some simple tests were done involving placing lengths of different steel and copper pipe in a home freezer at -15^{o}C and measuring the level of water/ ice in the pipes.

10% growth was observed and in the case of copper pipe, small bulging occurred in the centre of the pipe.

7.3 Prototypes

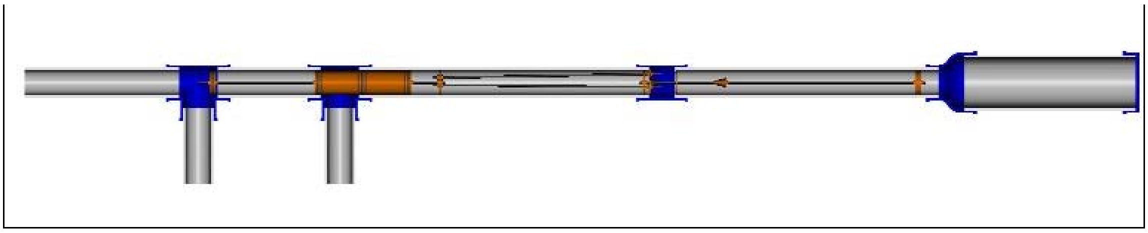
7.3.1 Prototype . Rolling Sock.

This was the first design manufactured. It relied on ice forming in the chamber formed by a rolling sock. This growth operated a single valve seen comprising a rubber covered coin, fitting against a pipe reducer.

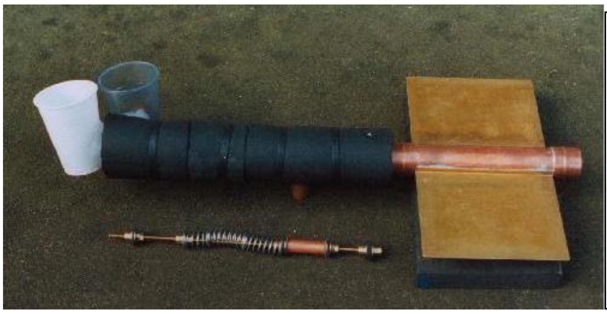
The design was clumsy and the sock, which was made from bicycle inner tube was difficult to manipulate.

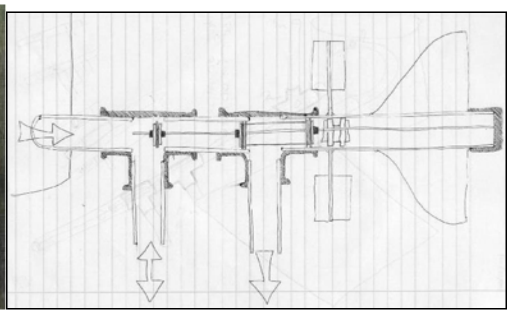
7.3.2 Autodrain Mechanism for Siphonic system

In an effort to drain the cold water pipe, a siphonic system was designed which would drain the solar panel by priming a drainage pipe fixed to the top of the cold pipe. The design was required to operate with a snap action so as to prime the siphon effectively.



7.3.3 Prototype . Ice Plug, with Twin Valves.





The photograph and sketch above show the design of a twin valve arrangement. He large finned pipe at the right of the pictures is the ice chamber in which water freezes to generate the growth.

Just to the left of this an ice plug must form first, the volume of the pipe is filled with a sereies of coins clamped together. Fins on the outside of the pipe (not shown in the photograph)cool the water around these coins and freeze them into an ice plug. This then acts to restrain the freezing water in the ice chamber. As the pressure builds, the ice plug is forced left along the pipe pushing the valve arrangement along with it.

Two valves are placed in series in the mechanism and the whole assembly is located at the bottom of the cold water pipe. They are operated by an actuator rod. When the actuator rod is driven forward, both valves travel up the pipe. First one closes off the cold water pipe. Then as the actuator rod continues to advance, the second valve opens up a drainage pipe.

The water held in the collector panel and hot water pipe then drain down through the drainage pipe.

Problems were encountered in the valves, rubber was used to start with. Circular pads cut from bicycle inner tubes were held between coins. These however stuck to the wals and rolled over the coins, jamming. Oil soaked leather pads were experimented with. A sharpened piece of pipe was used to cut out the circular pads. These leaked and so the assembly was not freezer tested. Improvements on the pads could likely have been made but alternative designs were persued which made them redundant.

The Ice plug has therefore not been tested and its viability is unknown. Problems however were identified with it, through thought experiments and analysing freezing schedules with a spreadsheet.

The problem would arise on days where the temperature moved up and down around freezing point. An example would be a day where ambient temperature was a few degrees below freezing, the sun was strong and clouds were moving in the sky. Under these conditions, the components of the solar water heater and the auto-drain mechanism might thaw in the morning and rise to a few degrees above freezing as a result of the sun falling on them. If however, a cloud obscured the sun after the ice plug had melted (allowing the valves to return to their original positions under the force of the springs), but before all of the ice in the actuator had thawed, a problem would arise. The temperature of all the components would, under the shadow of the cloud, drop once again bellow $0^{o}C$ and the solar panel would begin to freeze. The ice actuator would not be able to develop sufficient movement to open and close the valves because it would only have a fraction of the water required to make enough ice (because some of the water is already frozen but the movement it originally generated has been lost when the springs returned the valves).

While it might be possible, through an elaborate arrangement of shading to allow the ice plug to freeze first and thaw last it was considered an excessive complication and other avenues of design were pursued instead.

7.3.4 "Car Thermostat" Actuator

Other means of containing the water and generating ice were considered. A car thermostat was chosen as an effective way of containing the water to be frozen. Unlike the final design, the ice chamber was capped with a compression fitting and all extra volume was created from the shape of the compression fitting. Fins were soldered to the end-cap and it was experimented with both with and without boss-white sealing paste.

The unit was weighed to determine if water was leaking from it. Experiments were also conducted to measure the movement generated when it froze. Encouragingly, movement was found in the order of 3mm to 5mm. The unit however was found to be leaking, and this persisted even when using boss-white sealant.

7.3.5 Final Design.

In order to ensure against any loss of water a method was devised by which water could be sealed into the thermostat by soldering all joins. This approach proved to be effective.

7.4 Water loss

To ensure that the actuator was not loosing water, it was weighed using precision scales.
The compression fit actuator was found to loose weight quite rapidly. This lead to the move to re-seal it with boss white (a putty like substance) leaking was reduced but still present. Even a very small leak is intolerable because there is only a small volume and finite volume of water to start with. These findings led to a redesign that allowed for the whole unit to be sealed with soldered joints including the point from which water was fed in (see Construction Manual in appendices).
The new soldered design was weighted over a three week period. Losses could not be determined outside the error of the weighing scales

7.5 Actuator Freezing Times

Two lines of experiment were pursued, to gather information about the time taken to freeze the actuator. One to measure the stroke length of the actuator over one freezing cycle. The other was to record the pattern of growth over time.

7.5.1 Measuring Stroke Length

The stainless steel rod was pushed into the actuator, a gentle force was used and the rod was then allowed to return as the rubber diaphragm relaxed. In this starting position the rod was measured to see how far it protruded from the actuator. Vernier callipers were used.
The actuator was placed in a home freezer for a period in excess of 40minutes.

7.5.2 Timing Growth

The actuator was positioned in a home freezer with the stainless steel rod pushing vertically upwards The rods movement was transferred by a short pencil which pushed up against a pivot arm. The vertical motion of the rod was amplified by the pivot and this movement could be read of from a scale fixed into the freezer box.

The open face of the freezer was covered with transparent cling film to prevent the chilled air from falling out when the freezer door was opened.

For each round of experiments, the actuator was left to thaw and take on the temperature of its surroundings. Tests were conducted with the actuator starting variously at room temperature and at the temperature of the fridge (1^oC to 4^oC)

The freezer and the measuring apparatus within, were left to settle their temperature during the same period.

To start the experiment, a flap in the cling-film was peeled back and the actuator placed inside before re-sealing the freezer space. The freezer door was kept closed and opened only to take readings. Each reading took around 15 seconds to perform and they were taken every 2 minutes up to the point were the actuator started to generate movement. From then on readings were taken every minute until no further movement was observed.

Using the relative distances between the pivot point and actuator and pivot point and readout, movement was calculated for the actuator.

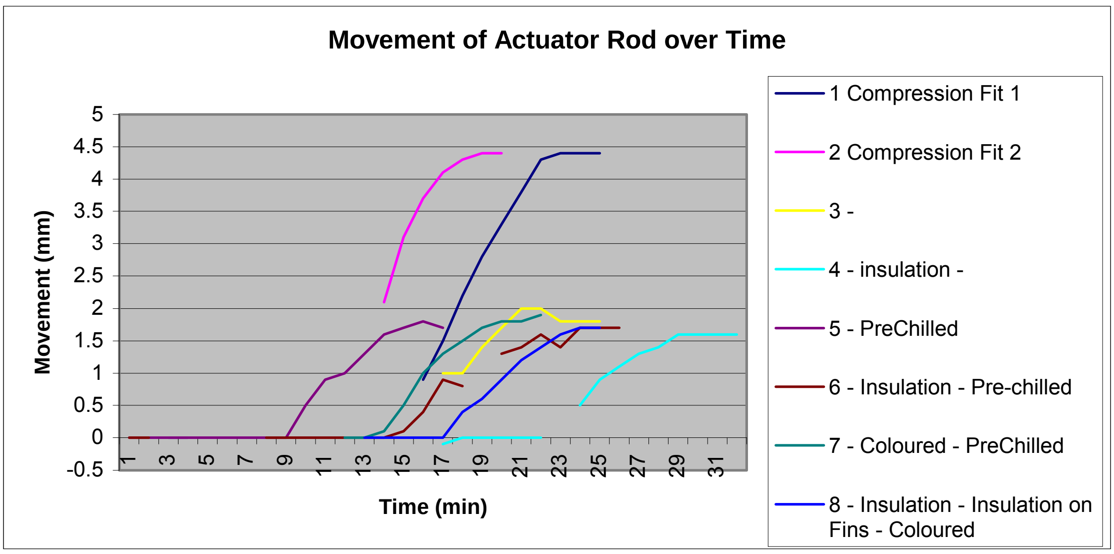
7.6 Results of Stroke Length

	Compression fit	Compression Fit (boss white)	Soldered
	2.6	4.75	3.15
	2.15	4.7	4.42
	2.45	5	3.5
	2.15	3.75	4
	2	4.15	3
	2.4	4.45	3.9
	2.65	4.5	
	2.6	4.5	
	2.35		
Average (mm)	2.4	4.5	3.7

Three sets of data were gathered; The compression fitting, compression fitting with boss white sealant and the soldered item. The volume of water contained in the actuator was determined by the size of the compression fit end-cap and its position in the cases of the first two and in the case of the soldered actuator, the length of the short extension pipe. The volumes contained by these items were estimated before assembly to give growth of 8mm (comparable to movement achieved by the wax filled thermostat).

Once filled it was difficult to change the volume contained within and the results in the table show the extension that was achieved by each item. The second compression fitting gave on average 4.5mm movement rather than the 2.4mm achieved by the first. This increase was due to sliding the end-cap further down the reservoir creating a larger volume inside. Certainly 8mm of movement should be attainable from the soldered design given a suitably sized extension pipe. More than this may be possible and should be investigated.

7.7 Movement of the ice actuator over time



The graph shows the movement recorded by the pivot arm resting on the actuator rod inside the freezer. The figures have not been related back to the actual movement of the rod but are useful in showing the timing of the movement.

The readings from the pivot chart were difficult to take accurately, due to the poor lighting inside the freezer and the cling film in the way. The readings were accurate to + - 0.15 which accounts for the slight wobble at the seen in the graph at the top of some curves

The readings are from two different units the first two readouts are both from the compression fitting sealed with boss white. The remaining readouts are all from the soldered unit which was set up differently for each reading.

While the results are limited in so far as there is only one set of readings for all but the first of the conditions, the following observations might tentatively be made

- By approximating a straight line fit to the curves. The point at which fusion begins can be seen along the x axis. The effect of insulation is evident in the reading "4" shows a delay of perhaps 8 minutes over the uninsulated reading "3". A similar effect can be seen from the insulated and Pre-chilled reading "6" which was delayed by 5 minutes over the uninsulated and pre-chilled reading "5". Further Reading 8 which had the back side of its fins insulated showed even greater delay despite its blackened fin surface.
- The coloured experiment "7" where the fins were blackened shows a one minute head start over the unblackened reading "6".
- Each of the pre-chilled experiments (5, 6 and 7) are quicker to start freezing than those which started at room temperature.

7.8 Predicting Actuator Movement

The Spreadsheet used earlier to help understand the manner in which heat is lost from the actuator was used to attempt to predict the time taken for a: the actuator to achieve full movement and b: to predict the duration of the stroke action. The initial results were seemed promising

Test "3", soldered , no insulation.

	Time to chill water (period of no visible movement)	Time to freeze water (period of movement)
Predicted Result	17min	1min
Experimental Result	15min	6min

However the predictions were wildly inaccurate when made for those that started at lower temperature (4^{o}C rather than 18^{o}C). The equations were analysed and it was seen that the problem lay in the way that the Rayleigh Number was being calculated. The equation was for a steady state and assumed that the temperature of the actuator remained constant (rather than cooling as it does over time). The spreadsheet was not revised for this project but will be recommended for future work.

8 FURTHER AREAS FOR DEVELOPMENT

The project has resulted in a promising design that has been partially tested. Further testing and investigation into other related issues would be useful.

8.1 Current Design – further tests required

- The valve assembly needs to be constructed and tested
- The foam pads should be tested for their durability, in particular how well they stand up to cyclic heating.
- Investigate if the drainage outlet stays clear of ice or is it prone to blocking up
- The non-return valve needs to be constructed and tested
- Further experiments should be conducted with the car thermostat to define its durability, in particular with regard to the rubber diaphragm
- The design should be field tested

8.2 Socio-economic Research

- A number of units of the existing design should be commissioned and installed by different craftsmen and plumbers in Ladakh and their experiences of building them observed.
- A detailed cost benefit analysis of introducing a solar water heater. Assess fuel consumption and water usage in more detail. What benefits would a water heater bring to a family, either on its own or in concert with other technologies such as passive solar architecture. The need for solar water heating needs to be more conclusively verified.
- What is an affordable / attractive cost for a hot water system (with or without access to micro-credit schemes)

8.3 Design Alternatives

- The current design uses a thermostat chosen for its likely availability in Ladakh. A full range of thermostats should be collected, including those for trucks and Other large vehicles. It may be that more movement can be generated from an alternative model.
- The design should be investigated further to see if it can be made safe under all modes of failure (It must “Fail Safely”). Currently it would do so only if the springs break or rusts, but not if the rubber diaphragm or the soldered joints broke.
- During the initial research into alternative designs a Chinese design was found which allowed for the whole of the solar water heater to freeze up by cooling in a suitable sequence. This approach although simple was dismissed at the start because it was

assumed that it would take too long to thaw in the morning. Further reading and investigation would be useful into this. In particular; what is the impact on overall efficiency of the system (by having to thaw itself)? and how long does it take to thaw under different conditions?

9 CONCLUSIONS

The design of the Ice actuator has been manufactured, tested and shown to work under a limited set of likely operational conditions. The valve arrangement used to drain the system has not been tested. The area of the valve has been investigated to the point that it is clearly a soluble problem and while the current design has not been tested, there is good confidence that it would work.

The design, in theory fulfils all of the primary aims set out at the beginning of the project. Essentially that it should prevent frost damage to a simple solar water heater. It also satisfies the secondary aims with the exception that it is not totally fail safe.

The design has proven itself practically to be simple and easy to make. Tolerances were low and each stage of manufacture can be completed with hand tools.

The components of the design are inexpensive, readily available and labour time should be a day or less.

Areas for further work have been highlighted and it is hoped that a working prototype could be fitted and tested within the scope of one further 3rd Year Engineering Project.

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US Patent 4456024 Freeze protection valve assembly
DE 41 04 817 A1 Valve for pressure container – is for filling connection, and has exhaust connection for feedback lines, safety valve as freeze-up protection
US Patent 4438777 Freeze protection valve with improved resetting capability
US Patent 4848389 Freeze protection device
US Patent 4681088 Freeze protection valve for solar water heaters
US Patent 4878512 Valve mechanism
US Patent 4541448 Freeze protection valve with metallic to plastic fitting design
US Patent 4763682 Thermally responsive valve activating assembly

11 LITERATURE REVIEW

Books have provided little information on existing drainage mechanisms but have proved useful in covering solar water heaters generally and the properties of water and ice on a microscopic level.

As an overview of all aspects of solar heating, Duffie and Beckman provide a highly accessible and relevant text. Davis and Day in their shorter work, “Water- the Mirror of Science” give a clear introduction to the workings of water and ice.

Cengel provides an excellent introductory text book. Equations for heat transfer are well explained and easy to navigate. The book also includes useful tables on the thermal properties of materials, liquids and gasses.

The Internet has been notably barren of relevant designs with the notable exception of the patent search engines. This has been one of the most productive avenues of research. Using the online patent database esp@cenet at http://gb.espacenet.com patents were searched by keyword. Keywords used included:

“solar water heater” pipe* valve drain* frost freez* protection passive, NOT active NOT pumped

many designs were found and were in an accessible format, covering; abstract, diagrams and further details in the form of claims.

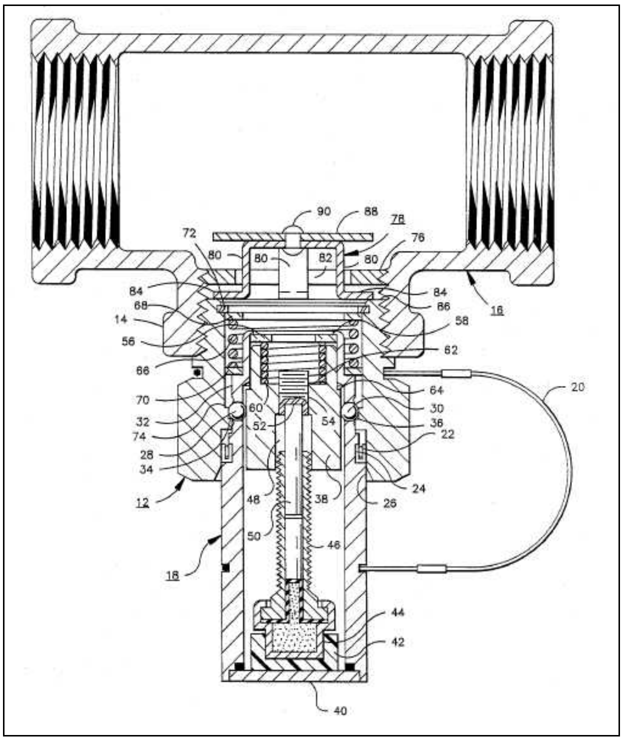
ANNEX 1

Existing Patents and Designs

In searching for existing designs, none were found that could fulfil all of the criteria of the product specification. Those designs that came close were found from patent records rather than literature. Below are brief outlines of several noteworthy designs.

Manually Set Auto-Drain Device

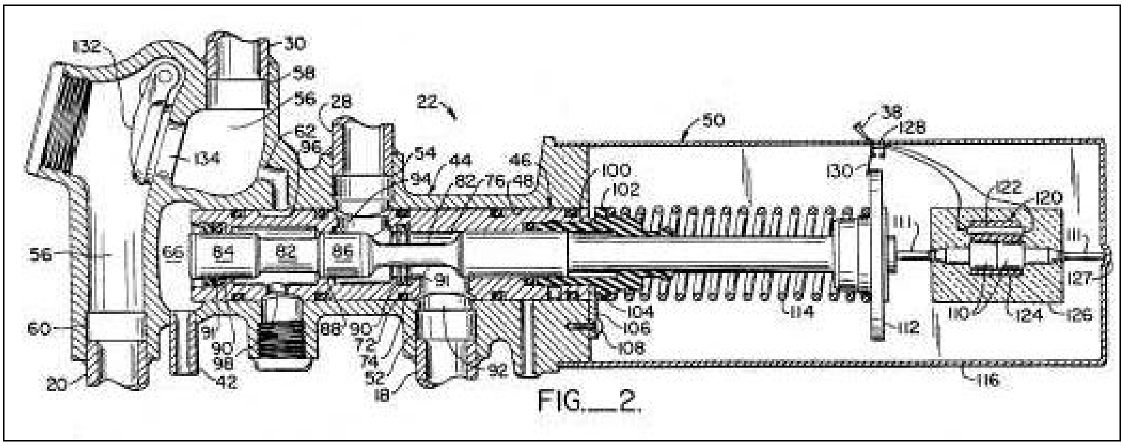
A number of designs were found through patent searches that would open a faucet as temperatures reached zero. This design relies on a small body of water held in a glass vile to freeze and release a catch, allowing the cap to be forced out by the pressure of water behind it. The cap is left hanging on a string (20) while the pipework is drained. The system must be reset manually.



US Patent 4848389

Multi Valve Auto-Drain Device

This design achieves many of the aims of the project. It is designed specifically for solar water heaters and can close of the collector panel and simultaneously isolate the water tank. Unfortunately it is complex design and relies on electronic thermostats to operate it.



US Patent 4450868

Ice Tolerant Solar Water Heater

One of the most interesting pieces of research found was a paper by the Beijing Solar Energy Institute. Only the abstract was available in English, a brief verbal translation of the text was also collected.

The Institute had successfully operated a solar water heater for several years allowing it to freeze and thaw as the weather dictated, suffering no damage. The design of the system was such that the progressive freezing of the water, always allowed a path into which it could escape. The design was put to one side at the beginning of the investigations of this project. It was discarded largely for fear that a fully frozen system would constitute an excessive thermal load to be overcome in the morning by the water heater.

In retrospect this may not be the case and further examination would be useful.

ANNEX 2

Heat Loss Analysis

Variables		Collector Dimensions		Constants	
Fin Length	0.15				
Pipe Length	0.207	Collector Area	1	Specific Heat Capacity (Copper)	381
Pipe Diameter	0.035	Fin width	0.09	Specific Heat Capacity (Water)	4205
Pipe Circumference	0.109935	Vein Diameter	0.01	Fusion Energy of Water	333700
Pipe Wall Thickness	0.0008	Vein Circumference	0.03141	Conductivity of (Copper)	401
Pipe volume (Internal)	0.0001991	Total Vein Length	10	Conductivity of (Ice)	0.564
Pipe Volume (material)	1.821E-05	Total Vein Volume	0.00078525	Density of (Copper)	8900
Fin Width	0.118	Vein and fin thickness	0.0005	Density of (Water)	1000
Fin Surface Area	0.0177	Volume of Vein and fin (Steel)	0.000528525	Gravity	9.8
Fin Thickness	0.001	Mass of (Copper)	4.7038725	Stefan Boltzmans Constant (6)	5.67E-08
Fin Volume	0.0000177	Mass of (Water)	0.78525	Emisivity (E)	0.8
Emisivity of Top Surface	0.8			Thermal Conductivity (k)	0.024
Emisivity of Bottom Surfaces	0.3			Kinematic Viscosity (v)	0.000013
Ambient Temperature	283			Prandtl Number (Pr)	0.719
Initial Temperature	273			Volume Expansivity (top surface) (B)	0.003646308
Tf (ground)	279.25			Volume Expansivity (bottom surface) (B)	0.003581021
Tf (sky)	274.25			Volume Expansivity (top Fin) (B)	0.003613369
Tf (horizon)	276.75			Volume Expansivity (bottom fin) (B)	0.003581021
Mass of (Copper)	0.3195566				
Mass of (Water)	0.0182052			Assumed Rate of cooling of collector (W)	6
Tempertature Drop to Outer Space	10				
Average outside Temperature	278				
Running Temperature	275.5				
Dimensions and emisivity values of the Actuator design are entered. Ambient temperature and temperature diferential to outer space also included. Volumes, masses and different temperatures are calculated. All temperatures are given in degrees Kelvin		Characteristics of the Solar Collector Panel. The assumed rate of cooling in the next collumn has been estimated rather than derived from first principals.		Constants for Water and Copper are entered. Input values for the heat loss eqations are calculated	

	Energy Stored in Actuator	in Collector Panel
Copper	33238.04068	54.97347083
Water	20898.97374	901439.5163
TOTAL	54137.01442	901494.4897
Fusion energy	6075.087253	262037.925
% Freezing	50%	15%
Energy To be removed	3037.54	39305.69

Rates of Heat Loss from Actuator

Convection off Top Surface	
Characteristic length (6)	1.049077491
Rayleigh Number (Ra)	438817905.6
Nusselt Number (Nu)	78.15645363
Convection Heat Transfer C	1.788004131
Area (A)	0.042645
Qcht	0.19062359

Convection off Bottom Surface	
Characteristic length (6)	1.049077491
Rayleigh Number (Ra)	430960825.9
Nusselt Number (Nu)	39.07822681
Convection Heat Transfer C	0.894002065
Area (A)	0.042645
Qcht	-0.667182566

Convection off Top Vertical Fin	
Characteristic length (6)	1.049077491
Rayleigh Number (Ra)	-1304561633
Nusselt Number (Nu)	85.39316229
Convection Heat Transfer C	1.953560069
Area (A)	0.056097
Qcvt	-0.821916444

Convection off Bottom Vertical Fin	
Characteristic length (6)	1.049077491
Rayleigh Number (Ra)	-1304561633
Nusselt Number (Nu)	85.39316229
Convection Heat Transfer C	1.953560069
Area (A)	0.056097
Qcvb	-0.821916444

TOTAL CONVECTION	
Qc total	0.19062359

Radiation off Top Surface	
Qrht	0.399015802
Radiation off Bottom Surface	
Qrhb	-0.473970752
Radiation off Top Fin	
Qrvt	-0.539367073
Radiation off Bottom Fin	
Qrvb	-0.539367073
Total Radiation	
Qr total	0.399015802

TOTAL Heat Loss	
Q total	0.58963939

Freezing Times

Actuator (50
5152
86
1.43
Collector Pa
5241
87
1.46

Energy stored in collector and in actuator are calculated.

% Freezing shows the amount of freezing required to take place in the actuator within the same time as that tollerated in the Solar panel.

"Energy to be Removed" is the energy stored multiplied by the "% Freezing".

The actuator is assumed to comprise a pipe containing water, with 2 horizontal and 2 vertical fins. Heat loss is calculated as convection and radiation of 4 surfaces.

All values except losses from the top surface have been greyed out. This is because they provide heating rather than cooling in warm air.

A greyed out value is assumed to be insulated and have a zero heat transfer value

"Total Heat Loss" shown here includes only losses off the top surface.

Design values for the actuator have been adjusted untill the feezing times above match one another.

Annex 3

Notes on Heat loss equations used in spreadsheet.

Convection

The actuator is considered as a pipe with four fins, the concept is simplified by considering including the pipe surface area as part of the fins.
Consider the fins to be at ½ the temperature of the pipe.

We assume air pressure in to be 1 atmosphere. The properties of air are to be evaluated at the film temperature.

$$\frac{T_F = T_S + T_\infty}{2}$$

T_F = Film Temperature, T_S = Surface Temperature, $T_\infty =$ Visible Temperature of Outer Space

<u>For Vertical fins</u>

The characteristic length in this case is the height of the fin, which is ς. Raleigh Number is:

$$R_a = \frac{g\beta(T_S - T_\infty)\delta^3}{v^2} P_r$$

Natural convection Nusselt number :

$$Nu = 0.59 \times R_a^{1/4}$$

Convection Heat Transfer coefficient:

$$h = \frac{k}{\delta} Nu$$

Area: $A = L_1 L_2$

Convection heat loss from the top vertical fin:

$$Q_{CVT} = hA(T_S - T_\infty)$$

Multiply by 2 for the two sides of the fin

Radiation

The sky is assumed to be 10^o cooler than the air and the ground surface temperature is assumed to be equal to the air temperature. $Q_{RHT} = \varepsilon A \sigma$

ANNEX 4

Water Loss

	Dry Weight	Wet weight	Date	Zero balance
	58.110.	60.057	Tue	0.001
Compression Fit and		60.021	Tue	0.001
BossWhite		59.925	Wed	0.0015
		59.874	Thur	
		59.8325	Fri	
Soldered		57.684	04/04/01	
		57.684	05/04/01	
		57.680	21/04/01	0.005
		57.682	24/04/01	0.0005

ANNEX 5

Growth times for freezing Actuator

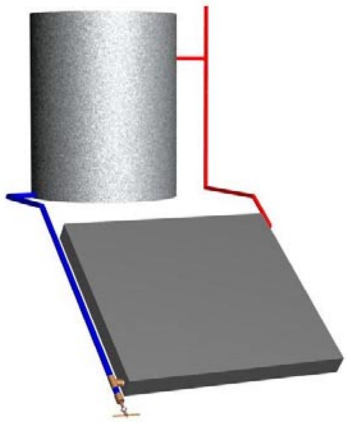
	Compression Fit		Soldered Fit					
			-	- insulation -	- PreChilled	- Insulation - Pre-chilled	- Coloured - PreChilled	- Insulation - Insulation on Fins - Colourec
Time (min)	Length (mm)							
0	6.4	6.1	8	8.5	8.5	8.7	8.4	8.1
1					8.5	8.7		
2	6.4	6.1	8	8.5	8.5			
3	6.4				8.5			
4		6.1	8		8.5			
5	6.4				8.5			
6		6.1	8		8.5			
7	6.4				8.5	8.7		
8		6.1	8		8.5	8.7		
9	6.4				9	8.7		
10		6.1	8		9.4	8.7		
11	6.4				9.5	8.7	8.4	
12		7.7	8	8.4	9.8	8.7	8.4	8.1
13	6.4	8.2			10.1	8.7	8.5	8.1
14		9.2	8	8.4	10.2	8.8	8.9	8.1
15	7.3	9.8			10.3	9.1	9.4	8.1
16	7.9	10.2	9	8.4	10.2	9.6	9.7	8.1
17	8.6	10.4	9	8.5		9.5	9.9	8.5
18	9.2	10.5	9.4	8.5			10.1	8.7
19	9.7	10.5	9.7	8.5		10	10.2	9
20	10.2		10	8.5		10.1	10.2	9.3
21	10.7		10	8.5		10.3	10.3	9.5
22	10.8		9.8			10.1		9.7
23	10.8		9.8	9		10.4		9.8
24	10.8		9.8	9.4		10.4		9.8
25				9.6		10.4		
26				9.8				
27				9.9				
28				10.1				
29				10.1				
30				10.1				
31				10.1				

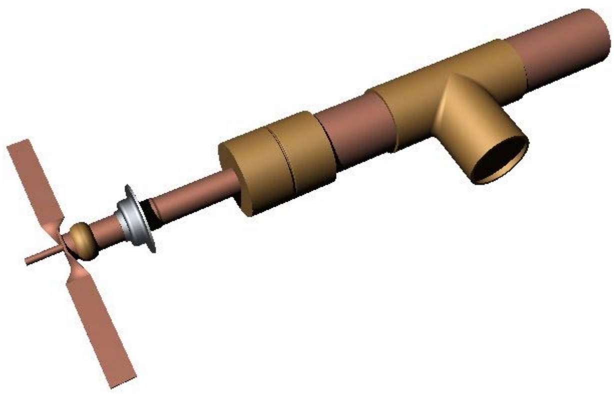
ANNEX 6

Construction Manual

Automatic Drain-Down Mechanism

For Solar Water Heaters





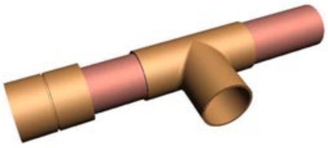
Overview

This short manual gives guidance on how to construct an “ automatic drain-down mechanism” for a solar water heater. The device will provide frost protection to a standard thermosyphoning solar water heater by draining the collector panel when temperatures drop towards freezing.

The design assumes a water heater made from copper piping with external pipework (hot and cold pipes) of 22mm O.D.

The design will require simple plumbers tools, a blowtorch, solder, hacksaw, hammer, file and hand drill. Reasonable proficiency is expected with these tools and the mechanism should not prove difficult for a plumber. The mechanism can be built in a day or less although a first attempt will likely take longer.

Pipe



Parts

[A] Yorkshire T (28mm, 22mm, 28mm)

[B] Straight-fit Compression Fitting (28mm)

[C] Reducer for the Compression Fitting (28mm – 12mm)

[D] 28mm Pipe (50mm)

[E] 28mm Pipe (equal in length to the original 22mm cold pipe)

[F] Valve Shoulder (28mm OD, 16mm ID)

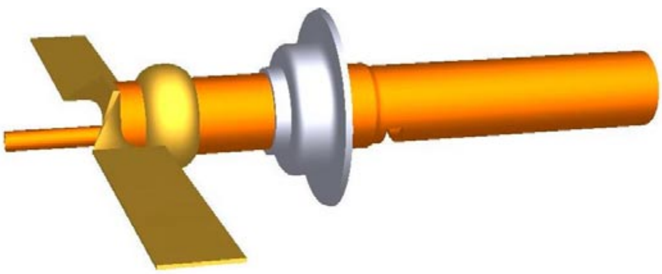
The valve shoulder is made from brass or copper sheet. A piece of pipe can be cut open and flattened to provide the material. Drill or file out the 16mm hole and mark out the 28mm outside diameter using the end of a pipe as a template. Cut out the disk and file it round.

Assembly

1: Solder "Valve Shoulder" [F] to the bottom end of "28mm Pipe" [E]

2: Solder the short "28mm Pipe" [D] into one end of the "Yorkshire T" [A]

Actuator



Parts

[G] 12mm Pipe (8mm length)

[H] 12mm Pipe (70mm length)

Swage out one end to about 11.5mm internal diameter for 5mm, it will need to fit onto the thermostat. Just after the swage, file a hole in the bottom of the pipe, this is the drainage hole for the system.

[I] 12mm Olive (from compression fitting)

[J] 3mm Pipe (30mm length)

[K] Car Thermostat

This design is based on the use of a common thermostat found on many models of Suzuki car. It is expected that Indian made Maruti vehicles will have the same style of thermostat.

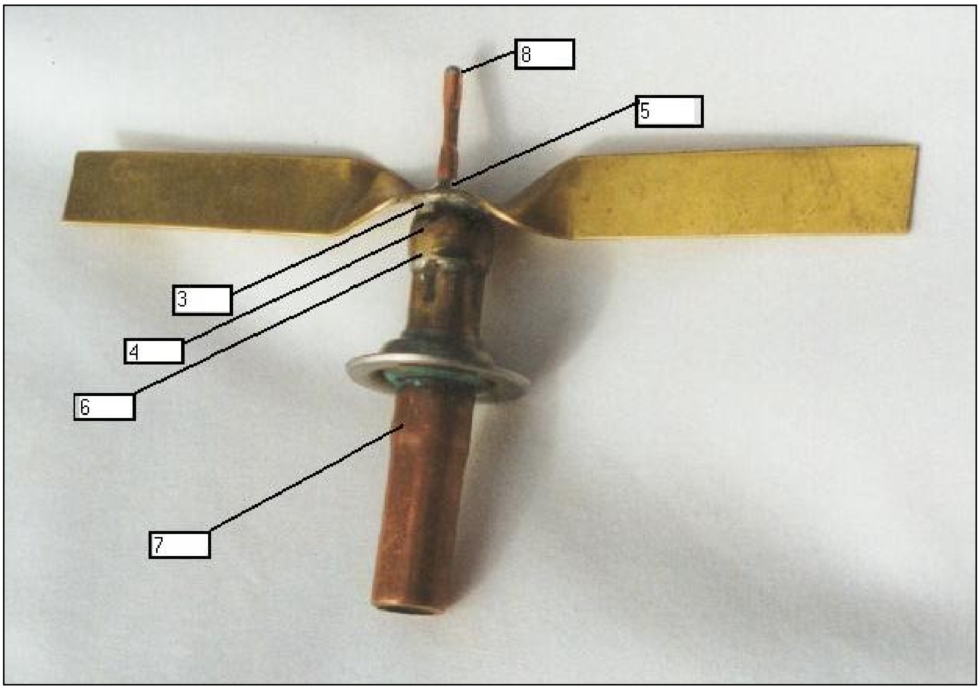
Cut away and discard the outer cage. The spring will be used later. Drill into the base of the wax reservoir, be sure not to damage the rubber diaphragm inside. Heat up the thermostat so that the wax melts and runs out. Now it is ready for use in this design.

[L] Fin

As for piece [F], cut out and flatten a piece of piping. It should form a rectangle 200mm by 12mm. Twist the copper strip into the shape shown by holding the middle with a tightened spanner and hold the arm with another.

Assembly

[NOTE] The sequencing of steps in this assembly should be followed carefully to make good the soldering of each component. Each soldering job requires that the previous jobs do not heat up too much and come undone. Be careful to wrap everything up with wet rags leaving only the current job exposed to heat.



3: Solder the “12mm Pipe” [G] to the centre of the “Fin” [K]

4: Wet the “Fin” and joint form previous step. Solder the “Olive” [I] to the open end of “12mm Pipe” [G], leaving half the “Olive” on and half off the pipe.

5: Drill a 3mm hole in the “Fin” [L] providing access to the “12mm Pipe” [G] chamber bellow just inside the wall i.e. the hole is central on the “Fin” [L] but off centre with the “12mm Pipe” [G]

6: Fit “3mm Pipe” [J] into hole on “Fin” [L]. wet the “12mm Pipe” [G] and solder [J] to [L]

7: Remove the actuator from the thermostat and fill the rubber diaphragm with water (to keep cool). Wet all parts not being soldered. Slide the swaged end of the “12mm Pipe” [H] over the end of the thermostat component (Not the end you drilled). Solder this joint.

8: Wet all parts not being soldered. Slide the open end of the “Olive” [I] onto the drilled end of the “Car Thermostat”. Solder this joint.

9: The above steps work to form a seamless vessel which will form the basis of the ice actuator. All that remains is for the vessel to be filled with water and sealed. Fill the vessel with water by squirting it in through the “3mm Pipe” [J] with a syringe and hypodermic needle. Flick the unit with your fingers or tap it until all bubbles have surfaced an left the vessel, add more water with the syringe, Use settled water, free from air bubbles and be sure to fill the vessel completely.

10: Crimp the “3mm Pipe” [J] with a mole wrench. Grab the pipe half way down, so that the compressed pipe does not damage the solder bellow or the opening above. The ridges in the crimp (formed by the mole wrench) should be at 90^o to the length of the pipe (so as to trap the water effectively).

11: With the mole wrench still clamped firmly to the “3mm Pipe” insert a short length of fluxed solder wire into the open top of the pipe. Wet the mole wrench and all components except the top tip of this pipe. Heat the top so that the solder seals it (you may need to apply a short gentle heat to help moisture around the top evaporate. The job must be done without the water filled vessel heating and boiling, forcing steam out past the clamped portion of the pipe.)

Testing

1st Test : Measure the Movement Generated by the Actuator

It is necessary

Push the stainless rod that form part of the “Car Thermostat” into the diaphragm in which it sits. Not hard, but enough that it can settle at its lowest point. Leave the rubber to relax for a minute. Measure the distance between the top of the stainless steel rod and the top of the “12mm Pipe” [H].

Place the Actuator in the freezer and leave until it has frozen and expelled the stainless steel rod as far as it can.

Re-measure the distance from the top of the rod to the top of [H]. Subtract the second measurement from the first. This is the “Stroke Length” and should be as long as possible, hopefully approaching 8mm.

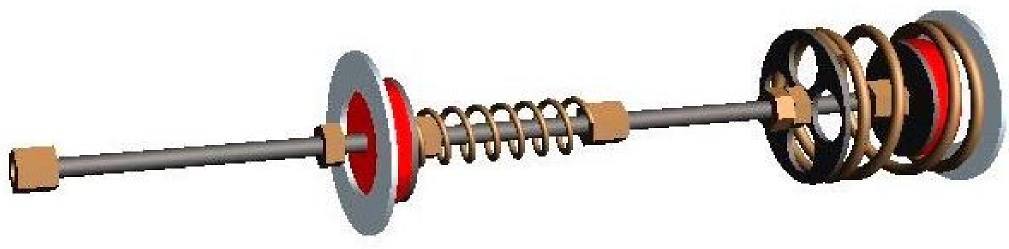
2nd Test : Checking the Actuator for Leakages

It is very important that no water is lost from the ice actuator as this would reduce the amount that ice that can be formed and the movement that can consequently be generated for the actuator rod.

Even a very slow leak would be a problem as the water held in the actuator is very small in quantity and can not easily be replaced. If there is a leak it is unlikely to be visible, water will simply evaporate.

It is necessary to test for small losses in water before the actuator is put into service. To do this, the actuator must be weighed very carefully on the best weighing scales available. There is only about 1.5grammes of water contained in the system, so losses if there are any are likely to be in the order of milligrams or 10s of milligrams. The actuator should be kept in a warm place, perhaps in the sun where evaporation from a crack can be encouraged and it should be weighed on a number of consecutive days. Any measurable loss in mass is unacceptable.

Valve Assembly



Parts

[M] Big Spring (Taken from “Car Thermostat” [K]

[N] Small Spring (50mm length)

Make from a length of brazing rod, by coiling it around a pencil.

[O] Threaded Rod (BS 4, 150mm length)

[P] Nuts (15 x BS 4)

[Q] 25 Paise Indian Coin (x 2)

Drill a 5mm hole in the centre of each coin.

[R] Circular Closed Cell Foam Pads (x 2, approx 2mm-10mm thick)

Cut from foam sheet, use scissors or a razor and cut a 5mm holbe in the centre.

[S] Catch (27mm OD, 5mm ID)

As per “Valve Shoulder” [F], but drill four extra holes, diameter 4mm as per the diagram to allow through flow of water.

Assembly

12: Assemble parts as per diagram

13: Pared nuts are locked against each other (don't tighten them too hard or they will weaken the "Threaded Rod"

14: Springs should be gently compressed by around 3mm from their fullest length

15: The distance between the exposed surfaces of the two foam pads should be 1mm greater than the distance between the facing surfaces of the two "Valve Shoulders"

Final Assembly

Parts

[T] Ice Actuator

[U] Pipe Assembly

[V] Valve Assembly

Assembly

16: Solder the "Yorkshire T" to the bottom of the "28mm Pipe" [E] and to the 22mm pipe at the bottom of the solar panel.

17: Insert the "Valve Assembly" [V] into the "Pipe Assembly" [U]

18: Hold the remaining "Valve Shoulder" [F] against the end of the "28mm Pipe" [D] and fix the "Straight-fit Compression fitting" [B] over the end

19: Connect the "12mm Pipe" [H] of the "Actuator" to the "Pipe Assembly", using the "Reducer for the Compression Fitting" [C]

The System is now fully assembled.

Testing

3rd Test : Final Test of Operation

Use the following test to check the system works, before you install it.

Fill two balloons with water and bind their open ends to the two open ends of the "Yorkshire T". Allow the "Pipe Assembly to fill with water as you do this. Check the balloons do not leak. Place the whole arrangement in a freezer or pack it in ice. Place a cup under the drainage outlet on the "12mm Pipe" [H]. The balloons simulate the water held by the tank and panel.

If the test is successful, the Actuator will freeze and operate the valves, draining the water from one balloon and leaving the other balloon full.

WARNING :

- At the time of writing, this design had not been fully tested
- Not all aspects of the device will fail safe. If the "Automatic Draindown Device" fails, the solar panel is at risk of damage from frost.