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RESIDENTIAL SOLAR HEAT STORAGE WITH ROCKS : A Comparative Study

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GENTLEMEN:

I submit for your consideration a thesis entitled, "Residential Solar Heat Storage With Rocks: A Comparative Study," it is submitted as a requirement of the Bachelor of Technology Degree (Architectural Science).

This report is an examination of the popularity of using rock beds to store energy collected from solar air heaters for residential space heating in Canada. This paper includes a discussion on solar energy as a viable alternative source for heating residential houses and the importance of solar heat storage in this alternate method. A comparative analysis of solar heat storage systems justifies the popularity of rock beds. Attention was then paid to rock bed design factors with parameters such as pressure drop across the bed and temperature stratification within the bed. Finally, a preliminary investigation into alternative storage possibilities such as structured storage assemblies as the packing medium in the beds indicate such alternatives merit future development.

The thesis excludes discussion of solar heat storage systems that might be found in commercial or government buildings. Since emphasis was placed on the performance of the storage systems rather than the cost, excluded is a descriptive cost analysis of the storage media discussed in the report.

The thesis is of great relevance to the architect, builders, and student who may use the report as a design tool or to anyone for the interest sake of solar energy development.

It is hoped that this report is satisfactory in meeting the requirement for a degree. The preparation of this research was both enjoyable and informative and I look forward to further studies in this field.

Respectfully.

ERNEST TAMBURRI

ABSTRACT

This report describes a study which investigated the popularity of using rock beds to store energy collected from solar air heaters used for residential space heating in Canada. In justifying the popularity of rock beds, a comparative analysis of solar heat storage systems was conducted. Attention was then paid to rock beds design factors. Finally, a preliminary investigation into alternative storage possibilities as the packing medium in the beds indicate such alternatives merit future development.

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I wish to recognize the contributions of the solar energy societies and trades for their co-operation in providing me with much of the research information.

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TABLE OF CONTENTS

PART 1

Introduction

1.1 Solar Energy: An Alternative Source	1
1.2 The Need For Storage	1
1.3 Heat Storage With Rocks	2
1.4 History of Rock Storage	3

PART 2

Types of Storage Systems

2.1 Choosing the Storage System	5
2.1.1 Short Term and Long Term Storage	6
2.2 Storage Media : A Comparative Analysis	8
2.2.1 Sensible Heat Storage	8
2.2.1.1 Rock Medium	11
2.2.1.2 Water Medium	13
2.2.2 Latent Heat Storage	15
2.2.2.1 Salt Medium	15
2.2.2.2 Paraffin Medium	17
2.2.3 Chemical Heat Storage	19

PART 3

Air Distribution System with Rock Storage

3.1 Air Distribution System	20
3.1.1 Collector to Storage Mode	21
3.1.2 Air Flow Through Rock Storage	22
3.1.3 Storage to Room Mode	23

PART 4

Rock Storage Design Factors

4.1 Pressure Drop	24
4.2 Temperature Stratification	25
4.3 Rock Shape	27
4.4 Rock Size	29
4.5 Storage Bin Shape and Configuration	31
4.5.1 Aspect Ratio	31
4.6 Storage Bin Size	33
4.7 Location of Storage Bin	35
4.7.1 Underground Storage	36
4.8 Construction of Storage Bin	37
4.8.1 Insulation of Storage Bin	37
4.8.2 Prevention of Heat Loss	39

PART 5

Conclusion

5.1 Design Recommendations	41
5.1.1 Storage Bin Size	41
5.1.2 Container Shape and Configuration	41
5.1.3 Bed Particles	42
5.1.4 Air Flow	42
5.1.5 Insulation	42
6.1.6 Performance of Rock Bed	42
5.2 The Future of Heat Storage	43
5.3 Summary	44

PART 6
Appendix

A - History of Rock Storage	46
A.1 Boulder House	46
A.2 Denver House	48
B - Storage Media	
B.1 Analytic Study of Rock and Water Media	50
B.1.1 Water Example	50
B.1.2 Rock Example	50
B.2 Study : Solution to Problems with Phase Change Materials	52
B.3 Chemical Reactions Used for Heat Storage	54
C - Air Distribution System	55
D - Study on the Effect of Bed Aspect Ratios and Pressure Drop on Flow Distribution in Rock Storage Beds	57
E - Performance Equation	64
F - Bed Simulation Studies	65
F.1.1 Temperature Stratification	65
G - Particle Sizing- Biot Criterion	70
H - Study on Storage Volume to Collector Area Size	72
I - Underground Storage of Heat in Solar Heating Systems	74
J - Solar Energy Trades Literature	78
J.1 Solaron Solar Energy Systems	78
J.2 Watershed Energy Systems Ltd.	80
J.3 Solartech Ltd.	83
References	85
Bibliography	88

LIST OF FIGURES

1.1	Denver House	3
2.1	Rock Contact Points	11
2.2	Heat Exchange	12
3.1	Solar Warm Air Heating System	20
3.2	Storing Heat	21
3.3	Reverse Air Flow Through Rock Storage	22
3.4	Heating From Storage	23
4.1	Temperature Stratification	26
4.2	Rock Resistance to Air Flow	27
4.3	Biot Criterion Plot for Rocks	30
4.4	Proportion of Surface Area to Volume	32
4.5	Optimum Storage Size	34
4.6	Rock Bin Insulation	38
4.7	Prevention of Heat Loss From Storage Bin	40

LIST OF TABLES

2.1	Hours of Bright Sunshine	7
2.2	Properties of Heat Storage Materials	9
2.3	Water and Rock Comparison	13
2.4	Thermal Storage of 10^6 BTU	16

PART 1

Introduction

1.1 - SOLAR ENERGY: AN ALTERNATIVE SOURCE

The supply of Canada's natural resources such as oil, hydro-electricity, and natural gas used for heating purposes is not inexhaustible (ref.39). There is concern for rapidly increasing costs of conventional forms of energy, their decreasing supply, and a need to develop alternate sources of energy before a serious shortage occurs. Solar energy has an abundant supply of potential heat (ref.35) that can be used to provide heat for buildings.

1.2 - THE NEED FOR HEAT STORAGE

Efficient use of solar energy applications for space heating in buildings lies in storage. For the greater part of the heating season the average size collector will provide an excess of heat above the heat demanded by the home during the solar day period (ref.30; p.97). This excess heat must be considered for use during night time periods because of lower ambient temperatures usually prevailing during that period (ref.24). The duration of night hours is also greater than sunlit hours in winter.

Since northerly climates typically experience many consecutive days without sunshine (ref.38; p.76), a solar heated house requires some form of storage to retain excess heat from the sunny days to be used for sun-obscured days.

1.3 - HEAT STORAGE WITH ROCKS

Most Canadian houses have forced air heating systems using conventional fuels (ref.34), therefore, a storage system utilizing air as the transfer medium is assumably preferred. Solar heat collectors are able to heat the storage medium 90°F to 130°F (ref.45; p.91), high enough to be practical with warm air systems.

Presently, rocks are the most popular storage medium for air systems due to their relatively low cost (ref.25), (ref. 33; p.217), and their simple operation (ref.17; p.5). Rocks will be looked at in greater detail and compared to other storage media to justify their popularity.

1.4 - HISTORY OF ROCK STORAGE

In air type collectors and storage systems, air that is heated in the collector is ducted through an insulated storage container filled with rocks. The solar heated air from the collector is cooled in its passage through the rock as it gives up heat and cycled again through the collectors.

FIGURE 1.1 - DENVER HOUSE [ref. 2 : p. 34]

The first analysis of thermal storage for buildings using rock was introduced by Dr. George Löf, a pioneer of solar heating, who first applied a rock storage system in the Boulder House; Boulder, Colorado in 1945 (refer Appendix A.1). The second application was in his own home in Denver, Colorado in 1958. In this design thermal rock storage is contained in two vertical cylinders (fiberboard tubes for concrete formwork), each 3' in diameter and 18' high (figure 1.1), (refer Appendix A.2). The house air return duct is located in the centre of one cylinder. Rocks, approximately 1" in diameter, fill both cylinders except for the lower 2', which contains wire mesh to allow air to pass between the cylinders (ref.45). The cylinders, painted red with hanging plants, is exposed to the living area and is visually pleasing (ref.20).

Since the original Löf installation, operating efficiencies of air systems have been improved with factory produced collectors and rock storages and better air distribution layouts.

PART 2

Types of Storage Systems

2.1 - CHOOSING THE STORAGE SYSTEM

Thermal energy can be stored by three types of storage medium systems:

- 1) Sensible energy stores heat by raising the temperature of the storage medium such as rocks or water.
- 2) Latent heat stores energy in materials such as salts or paraffin when the material changes phase from a solid to a liquid.
- 3) Chemicals are able to store energy by utilizing the heats of chemical reactions.

The storage system is composed of three basic components (ref.37; p.5), the storage medium, energy transfer equipment, and the containment system. The storage medium along with the transfer equipment should be chosen together with the solar collector, which could be a liquid type or air type collector (ref.2; p.188).

Liquid and air collector systems have approximately equal heat transfer characteristics, but air type collectors have the advantage over water type collectors by being simple in operation, lower in first cost (ref.36), and lower in maintenance costs (ref.30; p.101). Air as a transfer medium is not restricted to any temperature range, whereas water boils and freezes (ref.39). Lastly, air can be used as space heat at a lower temperature than water.

2.1.1 - SHORT TERM AND LONG TERM STORAGE

There are two methods of storing the solar energy for use during times when the sun is not shining. The first, short term storage, is collected only during the heating season (winter), with excess heat produced on sunny days stored for a short term, for use in overcast weather (ref.44; p.185). Short term storage does not attempt to store heat for longer periods than a few days (ref.39).

On the other hand, long term or seasonal storage stores heat from summer to winter where solar radiation is collected when the sun is shining in summer with collectors operating at high temperatures. Northern climates generally experience a sustained period of cloudiness during the winter, where November and December have the least amount of sunshine during the year (table 2.1). Designs for annual storage are calculated to store sufficient heating for this period. The result is a storage system that effectively functions for two months of the year while for the other ten months the system is not effectively used.

Long term storage can contribute almost 100% of the home heating demand while short term less than 60%, but to increase the energy efficiency 50% (from 60% to 90%) the cost increases by a factor of 2 (ref.30; p.97). Most experts in Ontario feel that long term storage systems are more suited to larger buildings and multiple housing units which can accommodate the larger storage tanks required (ref.12). For single family

residential houses, short term storage is usually adequate.

City	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
VANCOUVER, B.C	48	80	126	168	226	223	280	254	178	110	53	38
EDMONTON, ALTA.	81	117	168	219	253	251	302	268	188	154	97	75
WINNIPEG, MAN.	100	130	167	204	245	250	294	263	178	133	84	78
TORONTO, ONT.	77	106	149	184	223	263	286	256	201	151	84	67
MONTREAL, QUE.	79	102	145	167	203	222	244	223	170	126	69	61
ST. JOHN'S, Nfld.	66	80	97	101	166	173	232	181	151	106	58	51

TABLE 2.1 - HOURS OF BRIGHT SUNSHINE (ref. 17)

2.2 - STORAGE MEDIA: A COMPARATIVE ANALYSIS

A comparative analysis of rocks and other storage media is required to understand why rocks is the most popular storage medium for air distribution systems. The three methods of storing heat (sensible, latent, and chemical) are discussed.

2.2.1 SENSIBLE HEAT STORAGE

Heat is stored by increasing the storage medium temperature. This is a product of the specific heat, the mass, and the temperature difference (refer Appendix B.1), where the sensible heat results in the internal energy of the system being altered by increasing the kinetic and potential energy of the molecules of the storage substance (ref.39; p.68).

Heat storage capacity is the amount of heat you can store in a cubic foot of material for 1°F temperature rise (ref.2; p.83). Heat energy stored in this way is reclaimed as the temperature of the storage medium falls when used for space heating. The heat storage capacity of different materials varies according to their specific heat (table 2.2), which is the number of BTU required to raise the temperature of one pound of material 1°F.

Material	Specific Heat Btu / lb / °F	Density lb / ft ³	Heat Capacity Btu / ft ³ / °F	
			No voids	30% voids
ROCK	0.21	170	36	25
CONCRETE	0.23	140	32	22
BRICK	0.20	140	28	20
WATER	1.00	62	62	43
SCRAP IRON	0.12	490	59	41
SCRAP ALUMINUM	0.23	170	39	27

TABLE 2.2- PROPERTIES of HEAT STORAGE MATERIALS (ref. 44)

EXAMPLE (ref.15; ch.15)

- 1) specific heat of water = 1.0 BTU/lb.°F
 1 cubic foot of water weighs 62.4 lb
 if the temperature is raised by 1°F
 62.4 BTU would be stored.

- 2) specific heat of rock = 0.20 BTU/lb.° F
 assume 1 cubic foot of rock weighs 100 lb (30%voids)
 if temperature raised by 1 °F
 only 20 BTU would be stored.

Theoretically, water performs much better than rock for the same cubic volume of storage area, since water stores 3.12 times as many BTU for each degree rise in temperature (see above example). Practically, however, rocks are more advantageous than water as the storage medium. A container of water at 50°F may contain more BTU of heat than rocks at 120 °F, but 50°F is useless as house heat while 120°F is quite acceptable, if usable heat storage must be at least 80°F.

Also, water appears advantageous since it holds five times as many BTU per °F rise in storage temperature as the same weight as rock (see above example). On the other hand, water will release five times as many BTU as rocks under the same conditions (ref.22; p.31). So, if equal amounts of water and rock are heated to the same temperature under identical insulated container considerations, the rock will still be warm when the water is cold after a period of time.

2.2.1.1 - ROCK MEDIUM

Heat storage can be accomplished in a bed of loose solids such as rocks. Rocks serve as the heat exchanger (ref.24) due to the large surface area (since a pile of closely packed rocks leaves approximately 1/3 of the volume as void space) and the winding path through the bed ensuring rapid heat exchange (ref. 7; p.50).

The large surface area needed appears to be apparent for heat losses but the loss of heat by conduction to the surrounding walls is limited because the rocks only touch each other in limited areas, at the points of contact (figure 2.1). The slow natural convection of heat through the rocks also offsets this apparent heat loss.

FIGURE 2.1- ROCK CONTACT POINTS

Because of rapid heat exchange, heat is not distributed evenly throughout the bed but only in the area where the heat enters the storage container (figure 2.2). The advantage of this fact is that the air leaving the bed going back to the

collector will be at a relatively cooler temperature. As the sun continues to shine, the collector supplies more hot air to the bed, heating it to a higher temperature. Even if only a small portion of the bed has been heated, hot air from the storage can be blown out to the rooms if needed (ref,44; p.189).

As the hot air enters the bed, the rocks at the top are heated immediately (shaded on figure).

The air leaving the bed, however, is still at the initial temperature of the rocks.

FIGURE 2.2- HEAT EXCHANGE

2.2.1.2 - WATER MEDIUM

Water has the advantage of having the highest specific heat capacity (table 2.2) of any ordinary material on a volume basis. Water, itself is inexpensive and readily available (ref.10; p.21). For solar systems using water as the transfer medium, it is the obvious choice for the storage medium.

Table 2.3 illustrates that water should deliver more energy per cost of storage material alone (column 1) and more heat per volume (column 2) than rocks, but there are many drawbacks. First of all, systems with water as the transfer

STORAGE MATERIAL	QUANTITY OF ENERGY DELIVERED BY STORAGE MATERIAL BTU/\$	TANK VOLUME REQUIRED PER UNIT OF HEAT DELIVERED BTU/FT ³
WATER	2.3×10^6	9,350
ROCKS	1.6×10^4	3,000 (with 30% void volume)

TABLE 2.3- WATER AND ROCK COMPARISON (ref. 23; p.121)

medium are harder to install compared to air systems with rocks (ref.32). So, there are actually higher total system costs using water storage, especially for the storage tank which must be corrosion proof.

Secondly, when solar heated water is fed into the storage tank, convection currents are set up causing heat losses. Also, the temperature of the tank becomes uniform (ref.44; p. 187) and less efficient than rocks because no portion in the storage is hotter than another. Lastly, water is subject to freezing, therefore anti-freeze compounds, such as ethylene glycol must be used (ref.33; p.3) since storage in winter is of primary concern.

Water storage systems are just too complex and filled with associated problems; diversely, rock storage systems are simple in operation and perform at a highly acceptable standard.

2.2.2 - LATENT HEAT STORAGE

Unlike sensible heat storage, the temperature of the phase change medium stays the same during its change from a solid to a liquid. When a solid melts or liquifies a certain number of BTU are stored. When the substance re-solidifies, the stored BTU are released (ref.22; p.33). Some materials are able to melt at temperature not far above room temperature to utilize their heat of fusion properties (table 2.4).

Latent heat storage offers the possibility of storing a great deal of heat in a small volume. Phase change storage is capable of storing up to 9 times more heat for the same volume containment of rocks (table 2.4). This fact is of great importance for retrofits where space might be limited (ref.30; p.104).

Phase change materials are not presently considered for widespread solar space heating applications primarily of the relatively high cost of the storage media (ref.12; p.14), (ref. 34). Also, after years of use the compounds tend to break down and remain in the solid state (ref.32).

2.2.2.1 - SALT MEDIUM

Salt hydrates are among the simplest types of chemicals used for storage. When the temperature of salts is raised to a specific value dependent on the chemical composition, heat is absorbed, releasing water of crystallization which dissolves

Property	Sensible Heat	Material	Latent Heat Material
	Rock	Water	average phase change
SPECIFIC HEAT (BTU/LB/° F)	0.20	1.0	0.5
HEAT OF FUSION (BTU/LB)			100
DENSITY (LB/CF)	140	62	100
Storage of 10^6 BTU			
1 WEIGHT (LB)	250,000	50,000	10,000
2 RELATIVE WEIGHT	25	5	1
3 VOLUME (FT ³)	2,150	1,000	125
4 RELATIVE VOLUME	17	8	1

TABLE 2.4 – THERMAL STORAGE OF 10^6 BTU (ref. 37; p.124)

the salt. When the temperature drops below the crystallization temperature the stored heat is released (ref.1; p.30).

The most common phase change material is Glauber's Salt, pioneered by Maria Telkes (ref.43). One pound of this salt absorbs 104 BTU as it melts at 91.4°F (ref.46) and then absorbs 21 BTU as its temperature rises another 30°F. To store the same total of BTU in the same temperature difference, 20 pounds of rocks is needed.

Many problems are associated with salts as the storage medium. Although the material is able to hold a relatively large amount of heat in a small volume, the surface area of the container must be about 25 times as great as the cubic volume contained in the storage tank (ref.22; p.34). This suggests that a long tubular container be used which imposes an expensive tank. Furthermore, salt hydrates break down after many phase change cycles thus discontinuing their heat - evolving crystallization (ref.1; p.30). Possible solutions to these problems are being developed (ref.22; p.47), (refer Appendix B.2), but the cost and effectiveness of salts as a storage medium remains to be seen.

2.2.2.2 - PARAFFIN MEDIUM

Paraffin also utilizes its heat of fusion properties. It melts and absorbs 65 BTU per pound (ref.1; p.31), less than Glauber's Salt, but does not have the crystallization problems common with salt hydrates.

Most of the problems with paraffin evolve around the container. Paraffin corrodes plastic containers and some metals, such as copper. The medium expands by 20% when it melts causing problems of containment, then when it solidifies, releasing the stored heat, paraffin shrinks and pulls away from the storage tank walls which drastically slows the transfer of heat out of the container (ref.2; p.191). Finally, unless the container is tightly sealed, paraffin will slowly oxidize and disappear into the atmosphere (ref.4).

One of the greatest problems of using paraffin is its combustability. Most building codes restrict the use of such materials inside buildings.

2.2.3 - CHEMICAL HEAT STORAGE

Chemical storage is a relatively new concept for storing solar heat. It is achieved when energy is stored by utilizing the heats of chemical reactions. For example:

- 1) the dissociation of SO_3 into SO_2 and O_2
- 2) the hydration of MgO to form $\text{Mg}(\text{OH})_2$
- 3) refer to Appendix B.3 - "Chemical Reactions Used for Heat Storage."

Chemical change materials have larger heat storage potential than phase change materials (ref.15). One advantage of chemical storage is its heat collector and delivery over a short period of time. Another is that the delivery from the storage is potentially higher than the collector temperature in principal. It is anticipated that the major cost of a storage system using chemical storage will be associated with the heat exchange equipment and container as is the case with phase change materials (ref.4; p.77).

Presently, there are too many areas of research for chemical storage to be used practically as the medium in solar design. One major area of research is to identify chemical reactions which progress at low temperatures (120°F) to be used usefully for residential buildings. A second area of research lies in controlling these reactions (ref.13).

PART 3

Air Distribution System with Rock Storage

3.1 - AIR DISTRIBUTION SYSTEM

In air systems employing rock storage, the controls perform the sensing, evaluation and response functions required to operate the set up in the desired mode (ref.12; p.14). Blowers are activated by thermostat controls and dampers are used to direct the air flow (figure 3.1), (ref.4). An auxiliary energy system using conventional fuels provides the supply of heat when stored energy is depleted or does not sufficiently meet the space heat need (ref.29; p.2).

FIGURE 3.1 - SOLAR WARM AIR HEATING SYSTEM (ref. 18 ; p. 25)

3.1.1 - COLLECTOR TO STORAGE MODE

Solar collection and delivery of heat to storage (figure 3.2) is achieved whenever a sufficient temperature arises in the air, passing through the collector at approximately 2 cubic feet per minute per square foot of collector (ref.24). As solar intensity on the collector surface increases, mid-day air temperatures from the collector can reach 130°F to 170°F (ref.38, p.77). The collector to storage loop is turned off automatically by a thermostat when the stored heat exceeds the temperature available from the collector.

When the space temperature is satisfied the automatic control system diverts the air into the heat storage unit where the heat is absorbed by the rocks.

The air returns to the collector where it is heated and this cycle is repeated.

FIGURE 3.2 - STORING HEAT [ref. 21; p. 31]

3.1.2 - AIR FLOW THROUGH ROCK STORAGE

Air flow through the rock storage is usually top to bottom while collecting solar heat, and from bottom to top while supplying the heat to the house. In this way stratification allows house air to be heated to the highest possible temperature by the warmest rocks at the top of the storage. Conversely, if solar heated air comes in at the bottom, the heat would transfuse upward distributing itself evenly through the entire storage resulting in a lower temperature throughout the bed (ref.2; p.191). Stratification provides a warmer air supply to the home and cooler air supply to the collector (figure 3.3) increasing the efficiency of home heating and collector.

FIGURE 3.3- REVERSE AIR FLOW THROUGH
ROCK STORAGE (ref. 30; p.108)

3.1.3 - STORAGE TO ROOM MODE

When heat is required in the house and solar collection is not taking place, the room thermostat signals the blower to operate and dampers to move into position such that room air will flow to the cold end of the storage (ref.24). Cold air from the room, drawn in at the bottom of the storage bin, is heated as it rises through the warmer top rocks. The hottest rocks on top transfer heat to the air just before it is sent to the rooms (figure 3.4).

At night or on cloudy days when solar energy is unavailable and when heat is needed in the space, the automatic control system directs the building return air into the bottom of the heat storage unit, up through the pebbles where the air is heated and through the air handling unit and into the space.

When the solar heated air does not maintain the space thermostat setting, the automatic control turns on the auxiliary heater to add to the required heat.

FIGURE 3.4 - HEATING FROM STORAGE [ref. 21 : p. 31]

PART 4

Rock Storage Design Factors

4.1 - PRESSURE DROP

A difference in pressure through the solar system (storage bed, collector, and duct work) causes a resistance to air flow through the system. It is important to keep a pressure drop through the entire solar system equal to or less than 0.5 inches W.G. (125 N/m^2), (ref.4; p.3) in order to ensure that the work spent in passing air through the system is less than that of the solar collected.

The pressure drop through the rock bed is directly proportional to the air velocity through the bed, thus, it is the pressure drop that governs the air flow distribution characteristics (ref.5) To secure proper flow distribution in the bed it is recommended that 0.14 inches W.G. (35 N/m^2) be the accepted pressure drop (refer Appendix D).

Of major concern is the necessity to provide a pressure drop through the storage bed a minimum of 5 times higher than in the plenums leading to the storage; this will ensure good flow distribution through the bed (ref.30; p.104). To overcome the required pressure drop, fans are used to force or draw the air through the bed (ref.46).

4.2 - TEMPERATURE STRATIFICATION

Ideal air systems with rock storage allows the heat to stratify. The hot and cold air is separated as the air passes through the rock storage (ref.38; p.79). As mentioned previously, the air at a high temperature can be used for space heating while the lower temperature return air may be circulated back to the collector (figure 4.1). Heated air should be supplied at the top for minimum loss of temperature stratification (ref.24).

The energy obtained by the solar system is maximized by low return air temperature going back to the collector (ref.21; p.30). Heat losses from the system are at a minimum with low collector inlet temperature because the temperature differences between the collector inlet temperature and ambient air temperature are small. Since the main variable to control for utmost solar efficiency is collector inlet temperature (refer Appendix E), this should be as low as possible with temperature stratification (refer Appendix F.1; F.1.1).

When heat is being stored, the collector air enters the storage unit at one end and leaves the other end at a temperature lower than the mean storage temperature.

A - Heat Into Storage

When heat is being extracted from the storage unit, the return air from the space enters at the cool end. The air heats up during its passage through the storage and leaves at a temperature that is greater than the mean storage temperature.

B - Heat From Storage

FIGURE 4.1- TEMPERATURE STRATIFICATION (ref. 39 ; p.3)

4.3 - ROCK SHAPE

For the storage medium, washed (round) gravel has a resistance to air flow up to 3 times less than crushed stone (ref. 30; p.107). Figure 4.2 illustrates how the irregular shapes of crushed rocks creates more resistance than round rock. Also, washed gravel has dust particles around them that would hinder the passage of air through the storage bed.

FIGURE 4.2- ROCK RESISTANCE TO AIR FLOW (ref. 30; p.107)

The major constraint associated with rock beds is that rocks be uniform in size and shape so large void fractions are present to minimize the pressure drop (ref.12; p.219). Uniformity is accomplished when the rocks are screened.

Although washed (round) rock is preferred, in practical cases the air flow through the rock bed is usually too slow over the rock surface that the velocity lacks the power to dislodge and carry particles. For example, the Solar 1 project at the Massachusetts Institute of Technology (ref.31) has 192 cubic feet of rock with an estimated 62,000 square feet of surface area. The average air flow of 600 cfm through the system produces an average velocity of only .0096 feet per minute over the rock surface.

Conclusively, all the installations with crushed rock thus far have not required a change of air filters (ref.16), (ref.31), (ref.34). This fact suggests that washed rocks are not imperative for rock medium efficiency.

4.4 - ROCK SIZE

Rock sizes can vary from 3/8" to 2" diameter depending upon the size of the storage container and the distance that the air must travel to get through the storage from inlet to outlet (ref. 1 ; p.28), both factors establishing the flow rate. A well designed packed bed should be such that particles are large enough to ensure a reasonably low pressure drop across the bed while at the same time are small enough to ensure that the heat supplied to the surface of each particle reaches the centre of the particle as fast as the rate of heat supply at the surface (ref.4 ; p.16) to fully utilize temperature stratification.

It is believed that the heat transfer considerations are more important in optimizing particle size in view of the fact that the pressure drop is reasonably low over most particle size ranges considered for residential solar heat storages with rocks. To do this, one can use the Biot Criterion (refer Appendix G). Figure 4.3 shows a plot of the maximum allowable particle size, D_p , against the flow rate, G_o . It's obvious that as flow rate increases the maximum permissible size of the particles decreases. In optimizing the particle size it must be remembered that a decrease in pebble size increases the air resistance and pressure drop through the storage bin which may affect the blower size and air distribution efficiency of the total solar storage system.

Most residential heat storage systems use 3/4" to 1-1/4"

diameter rocks to obtain the desired pressure drop and heat transfer considerations since washed rounds are readily available in this size (ref. 11).

Assume bed of cross-sectional area 8 square feet
and void fraction of 0.5.

FIGURE 4.3 - BIOT CRITERION PLOT
FOR ROCK (ref. 4 ; p.18)

4.5 - STORAGE BIN SHAPE AND CONFIGURATION

Storage configuration is designed on the basis of a geometry that allows for a high proportion of volume to surface area of containment (ref.30; p.106). In heat storages, an increase in surface area produces a corresponding increase in heat loss, therefore, heat retention will be enhanced by keeping the surface area of the storage to a minimum.

As the configuration of the rock store approaches a sphere, the heat retention efficiency increases due to the increased ratio of volume to surface area (figure 4.4). Less surface area for a given volume allows for less heat loss or longer heat storage capacity (ref.31).

Although spherical shapes provides the maximum volume with minimum surface area exposed to potential heat losses, spheres are difficult to construct on a cost effective basis (ref.32; p.5-7). Financial constraints dictate that a cubical configuration be considered the optimal choice for a heat storage bin.

4.5.1 - ASPECT RATIO

The aspect ratio, length to diameter, of the storage bin affects the performance of the store. Too high an aspect (deep beds) produces a high pressure drop across the storage bed resulting with increased blower requirements. Too low an aspect ratio (shallow beds) produces a low pressure drop that

will yield maldistributed air flow in the bed (ref.4; p.8) and poor usage of the storage volume (ref.43; p.4).

Experiments were conducted to determine the optimum aspect ratio (refer Appendix D). The results indicated that aspect ratios approaching a value of "1" (cubical) are desired so that the rate through the bed will produce the recommended pressure drop value of at least 0.14 inches W.G (35 N/m^2) to ensure even air flow distribution (ref.5; p.2). Hence, the cubical configuration has a twofold advantage, minimum heat loss and optimum air flow distribution within the storage.

RECTANGLE

Surface : 175 SF

Volume : 125 CF

CUBE

Surface : 150 SF

Volume : 125 CF

SPHERE

Surface : 138 SF

Volume : 125 CF

FIGURE 4.4- PROPORTION OF SURFACE AREA
TO VOLUME (ref. 30; p.108)

4.6 - STORAGE BIN SIZE

The optimum capacity of a solar heat storage system depends on the amount of solar radiation available over a certain period of time, the manner in which auxiliary energy is supplied, and how much of the total heat loads should be carried by solar energy source and how much by the auxiliary source (ref.12; p.215).

The discussion on 2.1.1 "Short Term and Long Term Storage," illustrates the necessity to determine which storage system to use in order to analyze data for the coldest and least sunny months. If storage will supply heat during the longest period of overcast weather, the system will be over-designed for the remaining months of the heating season (ref. 44; p.193). The amount of heat stored is only what the solar collectors gathers and not used during the day. For example, a storage large enough for 5 days is of no use if the collector is not large enough to collect 5 days worth of heat (ref.21; p.32). The heat storage ability is only useful if the solar collector capacity is sized amply to bring the storage unit up to its data (longest period of overcast weather) analyzed capacity (ref.7; p.55).

Consequently, the storage unit should not solely be sized for a certain number of "days of storage " (ref.21; p.31) which would incorrectly assume storage container can be filled with heat no matter how much or how little collector area is used. The optimum size of rock storage to use is between 1/2 to 3/4

cubic feet of collector (figure 4.5). Similarly, studies for Toronto determined the optimum ratio to be 0.66 of storage volume to collector area (ref.17; p.86), (refer Appendix H).

The storage temperature is linked to the collector efficiency. For example, if the storage temperature is 120°F, air will not be circulated to the storage until the collector reaches a temperature over 120°F. Therefore, the collector efficiency falls as the temperature of its absorber rises (ref.2; p.195). In conclusion, to increase the storage temperature and to keep storage size to a minimum, use collectors that are efficient at high temperatures.

FIGURE 4.5 - OPTIMUM STORAGE SIZE (ref. 8)

4.7 - LOCATION OF STORAGE BIN

The rock storage does not necessarily have to be located in close proximity to collector, but as the distance increases the heat transfer losses between the heated air and the rocks also increases. Correspondingly, larger air ducts and more electrical power for blowers are required for moving air between the collector, storage, and heated spaces (ref.1; p.28).

The location of the rock storage must take into account its great volume, which could incur into expensive living space, and its great weight, which requires strong foundations. There are three basic types of foundation construction where the rock storage could be located (ref.33; p.5), full or partial basement, crawl space, and slab on grade. One unique rock storage location is found in the "Denver House" by Dr. George Löf at his residence (ref.1.3- "History of Rock Storage and Appendix A.2). The design allowed the rock storage to be directly viewed in the living space. However, it is usually more difficult and expensive since it is a waste of space.

Generally, heat stores should be located conveniently to the collector and care should be taken for the interference with interior living spaces.

4.7.1 - UNDERGROUND STORAGE

Heat storage with rocks is often located below ground level for convenient mechanical support supplied by the ground itself and ideal evasion of living space. The heat conductivity through the earth is usually low, especially if the earth is dry (ref.7; p.53), (refer Appendix 1; table 1.2). The heat taken up by the surrounding earth can be recovered when colder air is passed through the storage unit.

Large scale rock storage units are feasible to be located underground but in small storage units the fraction of heat absorbed by the ground is too large (ref.40). Even underground storage without insulation is feasible since the heat loss to the ground is rather small for systems of a size appropriate for large solar assisted space heating (refer Appendix 1, table I.1). On the other hand, the ground surrounding a typical underground rock storage facility contributes very little to the systems' storage capacity on a daily or seasonal time scale (refer Appendix 1; figures I.1 and I.2).

Practical problems for underground heat storage with rocks involves water fluxes around the storage area, estimating thermal conductivity and capacity of the ground, and determining the ease of either using or suppressing the heat loss upwards from the storage (typically to a basement or crawl space), (ref.40).

4.8 - CONSTRUCTION OF STORAGE BIN

The material used for the storage container is not as critical with rocks as it is with water or phase change chemicals (ref.4; p.23). The construction materials of the bin could be poured concrete, block, or wood (ref.21; p.32), (ref.11), (ref.16), (ref.34), (ref.36), (refer Appendix J).

There is special consideration for the method of supporting the packed rocks and the plenums so that air can be circulated within the storage bin. The plenum at the bottom of the bed must be constructed to carry the weight of the storage medium and to allow air to pass through it (ref.5), (refer Appendix D). Ultimately, there is particular consideration for insulation in the construction of the storage bin.

4.8.1 - INSULATION OF STORAGE BIN

It is not usually desirable to allow heat to escape from the storage container, even if heat is released to a living space it might not be needed at the time so it is important to retain all the heat within the storage by using insulation completely around the bin.

The amount of insulation required depends on the design temperature of the heat store and the temperature difference between the heat store and ambient, which is dependent on the location and construction of the bin walls. For example, a bin next to an exterior wall requires more insulation than a

wall next to a living space. Figure 4.6 gives possible R-values for a type of storage location.

Insulation should be placed on the inside of the bin construction so that the heat flow can be controlled. If insulation is on the outside of the bin walls, heat will be stored in the walls rather than the rocks where it is easily removed when needed (ref. 28). Since rocks stratify the heat stored, more insulation would be required at the hot end than

FIGURE 4.6 - ROCK BIN INSULATION

the cold end, therefore, to utilize the stratification effect tapered insulation could be used to minimize heat losses from the storage bin and to optimize insulation considerations.

Insulation materials suitable for heat storage bins with rocks should not shrink or produce holes at maximum temperatures of 180°F to 200°F (ref.21 ; p.32) and should not crush from the weight of rocks (refer Appendix J for insulation materials used by manufacturers of heat storage containers).

4.8.2 - PREVENTION OF HEAT LOSS FROM STORAGE BIN

There should be provision in the design of the storage bin construction for damping the convection of air through the top of the bed. Since heat always rises in free convection, heat could come in at the bottom so that heat is contained here rather than at the top where "thermal syphonage" would occur (ref.28). If hot air does travel up to the top of the storage bin, a hot water tank could be placed in the rock storage to serve as a pre-heater to save on fuel costs (ref. 26; p.66), (refer figure 4.7). The objective is to provide a portion of the energy needs for domestic hot water without significant reduction in the solar energy supply for space heating (ref.30 ; p.109).

FIGURE 4.7 - PREVENTION OF HEAT LOSS
FROM STORAGE BIN (ref. 28)

PART 5

Conclusion

5.1 - DESIGN RECOMMENDATIONS

Heat storage is essential for solar energy to be a viable alternative source to provide heat for residential buildings. A comparative analysis of the different types of heat storage systems disclosed sensible heat storage with rocks to be the most advantageous for air distribution systems. The simple operation of rocks brings about minimum maintenance but is able to store heat quite efficiently. Consequently, rocks are the most popular storage medium for residential solar heated buildings. From the earlier sections, it is now possible to set up practical recommendations for designing packed bed storage systems.

5.1.1 - STORAGE BIN SIZE

The first design guideline to consider is to determine the size of the bed which is $0.66 \text{ ft}^3/\text{ft}^2$ of collector area for residential homes in Toronto that would supply 50% to 60% solar contribution.

5.1.2 - CONTAINER SHAPE AND CONFIGURATION

A cubical shape with an aspect ratio value of one is recommended to be used for optimum pressure drop and air flow distribution considerations. The advantage of the square cross-section is that it fits conveniently into a basement corner.

5.1.3 - BED PARTICLES

It is suggested that washed gravel be used as the bed material since it is readily available in the accepted particle size range of 3/4" to 1-1/4".

5.1.4 - AIR FLOW

The air flow should be in the opposite direction during the discharging mode from the direction followed during charging. Otherwise, the air flow will tend to destroy the temperature stratification and little heat will be supplied by the storage.

5.1.5 - INSULATION

The location of the storage bin governs the amount of insulation required. Tapered insulation could be used to utilize temperature stratification within the bed and optimize the insulation. The insulation material must be placed on the inside of the bin walls and must be suitable for high temperatures.

5.1.6 - PERFORMANCE OF ROCK BED

The rock bed can be charged and the heat stored for not usually longer than 2 days or the temperature stratification

shows a tendency to get destroyed.

5.2 - THE FUTURE OF HEAT STORAGE

The future of heat storage relies upon the development of storage assemblies that utilize the simplistic behavior and performance of rock beds. Two storage assemblies utilizing the packed bed sensible heat system are monolithic or structured storage assemblies and a packed bed of silica gel (ref.4; p.36), both merit future development.

5.3 - SUMMARY

A review of sensible heat storage systems, latent heat storage systems, and chemical energy storage systems has been completed. A summary of each system type, complete with advantages and disadvantages has been included in the individual sections.

A closer, detailed look of packed bed energy storage with rocks was emphasized since they, at least in the immediate future, appear to be the best alternative for solar energy storage based on reliability, simplicity, expected life, and cost considerations. Very little practical experience has been gained in the use of phase changes materials and chemical energy storage systems.

This report recommends suitable design guidelines to allow one to make necessary estimates to ensure an effective rock storage subsystem using short term storage and an air collector that is able to supply 50% to 60% of residential building's heating demand.

Since sensible heat storage with rocks is the best practical alternative for solar energy storage, the immediate future relies upon the utilization of their performance (ref. 34), (ref.36). Future work considers various alternative materials which can be used in a packed bed as well as the commonly used material, rocks.

PART 6

Appendix

APPENDIX A

History of Rock Storage

A.1 - BOULDER HOUSE (ref.2; pp.22.23)

In 1945 Dr. George Löf designed a collector and installed it on an existing house in Boulder, Colorado. The primary objective in his design was simplicity and economy in construction.

The solar collector consisted of a sheet metal trough containing a series of overlapping glass plates arrayed in stair-step fashion (figure A.1). A pane of glass was blackened on one third of its area. The glass was arranged so that each black surface was beneath two clear surfaces and separated from them by a 1/4" air gap. Sunlight penetrated the transparent surfaces and was absorbed in the black area, raising their temperature to between 150°F and 250°F. Warmed air from the roof-mounted collector was gathered in a duct at the roof ridge and transported to the gravel heat storage bed in the basement. This air returned to the collector after transferring most of its heat to the gravel bed to bring heat to the house. Warm air also circulated to the rooms from the collector.

The primary significance of this project was its successful integration of a functioning solar system with a conventional gas furnace heating unit.

Boulder House
 Boulder, Colorado (42°N)
 Lof, 1945-47
 Heated floor area: 1000 ft²
 Collector - type: air
 area: 463 ft²
 tilt: 27° S
 Storage - type: gravel
 volume: 180 ft³
 Heat distribution: warm air
 Auxiliary heating: gas furnace
 Percent solar heated: 26%

The Boulder House.

Overlapping-plate collector.

FIGURE A.1 - BOULDER HOUSE (ref. 2: p.22)

A.2 - DENVER HOUSE

After his experience with the Boulder House , Dr. George Löf designed a single storey contemporary home in Denver, Colorado with a solar heating system that added an appliance rather than being made an integral part of the house. The following diagrams illustrate the different operation modes of the solar system.

House Heating from Collectors. Hot air is supplied directly from the collectors to the rooms of the house when heat is demanded and when adequate solar energy is being received. Cold air from the house enters the cold air return duct and is distributed to the solar collectors. The air is heated and delivered to the rooms via the hot air manifold and distribution ducts. When required, gas heat may be supplied to the warm solar air to boost it to useful temperatures.

A- HOUSE HEATING FROM COLLECTORS

FIGURE A.2 - DENVER HOUSE (ref.38; p.93)

Storing Heat from Collectors. This cycle operates when the house does not need heat and the intensity of solar radiation is great enough to justify collection. Cold air from the storage tubes enters the cold air manifold and is distributed to the solar collectors. The heated air moves down the vertical duct, through the hot water preheater and into the rock storage bins. The air loses its heat to the rocks as it is passed through the storage tubes, and thus cooled, returns to the collectors.

B - STORING HEAT FROM COLLECTORS

House Heating from Storage. This cycle operates intermittently, usually during evening or night hours. Cold air enters the cold air return duct. The air passes through the storage bins absorbing heat. If temperatures are too low, gas heat is added to the air before distribution in the house. Air is circulated through the storage unit even if it contains little or no heat, thereby ensuring its full utilization but at greater pumping costs.

C - HOUSE HEATING FROM STORAGE

FIGURE A.2 - DENVER HOUSE (ref.38; p.93)

APPENDIX B

Storage Media

B.1 - ANALYTIC STUDY OF ROCK AND WATER MEDIA (ref.42; pp.38, 39)

B.1.1 - WATER EXAMPLE

If water is the storage medium, the storage capacity will be the product of the volume, specific heat of water, and the operating temperature range. Assume volume specific heat of water as 1.16 Wh/litre deg C.

highest temperature obtained	65°C
lowest useful temperature	30°C
operating range	35 deg C

1 m³ of water would give a storage capacity of:

$$1000 \times 1.16 \times 35 = 40,000 \text{ Wh}$$

$$= 40.6 \text{ (KWh)}$$

If the daily heat required of a house is 40 KWh and 2 days heat is to be stored, the volume required will be:

$$\frac{40 \times 2}{40.6} = 1.97 \text{ say } 2 \text{ m}^3$$

B.1.2- ROCK EXAMPLE

If the storage medium is crushed rock, the heat storage capacity can be established as the product of the volume of container, the solidity ratio (% void), the density and specific heat of the storage, and the operating temperature range.

solidity ratio	= 0.70 (30% void)
density of stones	= 2,400 to 3,000 Kg/m ³
specific heat	= 0.30 to 0.32 Wh/Kg deg C

So, if 2m^2 from the water example is filled with crushed rock instead, the storage capacity would be:

$$\begin{aligned} 2\text{m}^3 \times 0.7 \times 2,800 \times 0.30 \times 35 &= 41,160 \text{ Wh} \\ &= 41.16 \text{ KWh} \end{aligned}$$

41.16 KWh is about half of the storage capacity of an identical volume (1m^3) of water.

B.2 - STUDY: SOLUTION TO PROBLEMS WITH PHASE CHANGE MATERIALS
(ref.3; pp.47,48)

Scientists at General Electric Research and Development Centre have developed a solution to the problems associated with phase change materials. The solution promises to be compact enough to fit conveniently in the basement of most homes, since size of the storage is a great disadvantage of rocks and water storage.

The scientist came up with an experimental rolling cylinder device (figure B.1) designed to accomodate any of a number of heat storage materials that have high latent heats of fusion. Their efforts focused on Glauber's Salt. Until now, there have been problems with the "encapsulation effect" of salts that prevented complete solidification of the material after 5 to 10 freeze-thaw cycles, which decrease the ability to store heat. Also previously, freeze-melt storage materials saw a salt build up on the walls of the container during the freeze cycle.

The solution is to stir the heat storage material very gently (3 rpm) with the invention of the rolling cylinder system which has just enough stirring action to keep the temperature of the Glauber's Salt uniform. Under these conditions, the material crystallizes on nuclei in the liquid and not on the cylinder walls.

A thin tubular device, called a "nucleator" plays a key role in the liquid to solid phase change. Inserted through

one end of the rotating vessel, the nucleator contains seed crystals of Glauber's Salt that ensures initiation of the crystallization process when the temperature of the liquid salt drops below its freezing point.

This solution is only in the experimental stage so the cost and effectiveness of the unit remains to be seen for practical purposes.

The GE rolling cylinder heat-storage concept. Though there are many possibilities, this artist's rendering shows one method in which the GE developmental rolling cylinder heat-storage device might be employed in a solar home. On sunny days, air heated by rooftop solar collectors would enter the system and be drawn around the heat-storage cylinder in the basement. The solar-heated air would then be blown through the system to warm the rooms in the house. In the evening—or on sunless days—flaps in the ducts to the solar collectors would close automatically, disconnecting the collectors from the balance of the system. Cut off from a supply of collector-heated air, the heat-storage material inside the cylinder would begin to solidify, gradually releasing its stored heat. Air passing around the cylinder would be warmed by this released heat, then circulated throughout the house.

FIGURE B.1 - ROLLING CYLINDER SYSTEM (ref.3; p.47)

B.3 - CHEMICAL REACTIONS USED FOR HEAT STORAGE (ref.4; p.78)

The following are candidate reactions involving dehydration - hydration:

- 1) $\text{Ca SO}_4 \cdot \text{H}_2\text{O (solid)} + 150 \text{ cal/g} =$
 $\text{Ca SO}_4 \cdot \text{(solid)} + 2 \text{ H}_2\text{O (gas)}$
- 2) $\text{Ca Cl}_2 \cdot 2 \text{ H}_2\text{(solid)} + 86 \text{ cal/g} =$
 $\text{Ca Cl}_2 \cdot \text{H}_2\text{(solid)} + \text{H}_2\text{O (gas)}$
- 3) $\text{Ca (OH)}_2 \text{(solid)} + 200 \text{ cal/g} =$
 $\text{Ca O (solid)} + \text{(liquid)}$

In the above 3 reactions the product, water, can be vented to the atmosphere or alternately retrieved from the atmosphere when reverse reaction is required. Relatively high temperatures are required for these reactions unless vacuums are used.

APPENDIX C

Air Distribution System

FIGURE C.1 - HEAT SPACE FROM STORAGE (ref.18; p.26)

FIGURE C.2 - STORING HEAT FROM COLLECTOR (ref.18; p.27)

Rock Bed Temperature Distribution as a Function of Time and Distance from Heat Inlet. Assume the bed is cold in the morning. As the day progresses, air temperature from the collector rises, peaking at noon, and decreasing in the afternoon. The resulting air temperature distributions in the rock bed are shown at different times during the day. Note that the exit air from the bed is always cold and therefore the collector operates at peak efficiency all day. In the evening, when the collector is off and the building needs heat, air flow direction through the bed is reversed so that the air exits from the hottest part of the bed. (If flow were not reversed, one would have to wait hours to wash the heat through the bed and even then would get only moderately warm air.) As evening progresses, temperature out of the bed rises until 8 o'clock and then falls, resembling the time profile of the inlet temperature during the day, but in reverse. (Source: Los Alamos Scientific Laboratory Report LA-5967)

FIGURE C.3 - ROCK BED DISTRIBUTION AS A FUNCTION OF TIME AND DISTANCE FROM HEAT INLET (ref.38: p.79)

APPENDIX D

Study on the Effect of Bed Aspect Ratios and Pressure Drop on Air Flow Distribution in Rock Storage

D - STUDY ON THE EFFECT OF BED ASPECT RATIOS AND PRESSURE DROP ON FLOW DISTRIBUTION IN ROCK STORAGE BEDS. (ref.5; pp.1-11)

Experiments were conducted by the Energy Resource Group at the University of Waterloo to study the flow distribution characteristics across any plane normal to the direction of flow and factors that influence them. The purpose of the study was to determine the importance of insuring even or uniform flow distribution to avoid any adverse affect on the thermal performance of the rock bed.

The set-up included a container 6'x 6' x 6' with rock 3/4" diameter rounds (all rocks will pass through a 3/4" screen). Plenums were located at the top and bottom of the container for air distribution.

FIGURE D.1 - Shows the ducting system used to convey air to and from the rock bed storage which is capable of reversing air through the storage container for a discharge mode.

FIGURE D.2 - The side view of the container shows the fine mesh at the bottom plenum used to prevent the smaller rocks from falling into the lower plenum. The metal grid provides strength to hold up the rocks.

FIGURE D.3 - The blocks used to support the metal grid has two channels in them that run parallel to each other in such a manner that the flow channels are in the same direction as the

FIGURE D.1 - DUCTING ARRANGEMENT FOR STORAGE BED (ref.5; p.7)
(arrows indicate charging mode)

FIGURE D.2 - SIDE VIEW OF CONTAINER (ref.5; p.7)

FIGURE D.3 - BOND BEAM BLOCK (ref.5; p.8)

ducting to and from the lower plenums.

FIGURE D.4 - The velocity distributions in the bed are shown on the 3 graphs, with the height of the rocks at 3' and the flow rate at 330 Kg/hr.m^2 . The 3 graphs indicate that the velocity distribution along 3 different diameters, AB, CD, and EF, in the square bed.

NOTE: V/V_o is the recorded velocity to the centre-line velocity in the bed.

OBSERVATIONS OF FIGURE D.4

- i) A and B, which are at the far corners of the bed, are almost 2.75 times lower than the air velocity at the centre, V_o .
- ii) C and D, which are at the sides of the bed, are approximately 2 times lower than the air velocity at the centre, V_o .
- iii) E and F, which are at the sides of the bed, are approximately 2.5 times lower than the air velocity at the centre, V_o .

FIGURE D.5 - As in the previous set-up, the velocity distributions in the bed are shown on the 3 graphs with the same height of the rocks at 3' but the flow rate increased from 330 to 516 Kg/hr.m^2 .

FIGURE D.4 - VELOCITY DISTRIBUTION (ref.5; p.9)

FIGURE D.5 - VELOCITY DISTRIBUTION (ref.5; p.10)

OBSERVATIONS OF FIGURE D.5

It can immediately be seen on all 3 graphs that the flow distribution in the bed is much more uniform since a substantial portion of the bed at the centre being subject to a flat velocity profile.

NOTE: The measured pressure drop was 23.4 N/m^2 which is closer to the accepted value of 35 N/m^2 (ref.32; p.1).

D.1 - RESULTS

A dramatic improvement in the flow distribution is evident from an increased in the pressure drop through the bed. This reveals the importance of an acceptable pressure drop of 35 N/m^2 to ensure proper flow distribution in the rock bed.

Similar data was obtained at bed heights increased to 4', 5' and 6'. The minimum optimum flow distribution was found to be between 5' and 6', where the pressure drop was close to 35 N/m^2 , since the improvement in flow distribution was more dramatic to 5' and less dramatic after 6'. This fact suggests that the optimum bed aspect ratio to be approaching a value of "one" (6' x 6' x 6' cubical).

FIGURE D.6 - Effect of Bed Aspect Ratio on the Particle Size

The volume of the bed was maintained at 6m^3 with the flow rate at 1632 Kg/hr . The graph indicates the maximum particle size necessary for a given aspect ratio if a pressure drop of at least 35 N/m^2 is to be maintained for the flow rate and bed volume specified. The result is that for shallow beds, much smaller particles are required.

D.2 - CONCLUSIONS

- 1) Beds of low aspect ratio (shallow beds) are not recommended since there is a fear that flow maldistribution would occur.
- 2) It is the pressure drop that governs the flow distribution characteristics.

Aspect Ratio Effects

Volume of bed = 6 m^3

Flow rate = 1632 kg/hr [800 scfm]

Pressure Drop = 35 N/m^2

FIGURE D.6 - EFFECT OF BED ASPECT RATIO ON PARTICLE SIZE
(ref.5; p.11)

APPENDIX E

Performance Equation

In the Hottle and Woertz performance equation below, the solar gains depend on the radiation intensity and the optical properties of the transmitting and absorbing surfaces. The values of F_R , τ and α are constant for a given collector. Therefore, in order to maximize solar system output the thermal losses must be minimized. The value of U_L is constant for a given system and T_a cannot be controlled. Therefore, the main variable to control in order to maximize solar output is T_i , collector inlet temperature.

$$\frac{Q_u}{A_c} = [F_R H_T \tau \alpha] - [U_L F_R (T_i - T_a)] = \frac{\text{Btu}}{\text{HR ft}^2}$$

$$= [\text{solar gains}] - [\text{system losses}]$$

Q_u	= energy collected	τ	= cover transmittance
A_c	= collector area	α	= plate absorptance
F_R	= heat removal factor	U_L	= overall loss coefficient
H_T	= solar energy available	T_i	= collector inlet temperature
		T_a	= ambient air temperature

SOLAR SYSTEM PERFORMANCE COMPARISON

Comparison of various types of solar heating systems can only be done properly if the entire solar system is evaluated over an *entire heating season*. Collector efficiency is an instantaneous point in time measurement and is not a valid parameter to evaluate the solar system performance. The ideal situation for a solar system is to keep the fluid inlet temperature to the collector as low as possible and have a high usable temperature for space heating. Therefore, the ideal solar system has heat stratified in the storage unit. An air solar system using rocks as the thermal storage provides this stratification. Therefore, the inlet temperature to an air collector is typically 70° F where the liquid collector inlet temperature is 130° F.

$\frac{Q_u}{A_c} = F_R [H_T \tau \alpha - U_L (T_i - T_a)] = \frac{\text{BTU}}{\text{ft}^2 \text{ Hr.}}$			
output	gains	losses	output

Two collectors of similar construction can be compared using the performance equation shown above. When the average liquid collector inlet temperature (T_i) is used, the liquid systems produce less heat output than the air system.

$$\text{AIR: } \frac{Q_u}{A_c} = 0.64[(300)(0.77) - (1.3)(70^\circ - 40^\circ)] = 123 \frac{\text{BTU}}{\text{ft}^2 \text{ Hr.}}$$

$$\text{LIQUID: } \frac{Q_u}{A_c} = 0.90[(300)(0.77) - (1.3)(130^\circ - 40^\circ)] = 103 \frac{\text{BTU}}{\text{ft}^2 \text{ Hr.}}$$

However, this is still an instantaneous point in time measurement which doesn't take into account the fact that the air system will typically collect for longer periods of time and therefore deliver more total heat output. When these systems are evaluated over an *entire season*, the results are as reported by the C.S.U. report #COO-2868-1. "... Because of the stratification, the temperature of the air returning to the collector from the bottom of storage is always near room temperature. Thus, the air collector can deliver useful heat from early morning to late afternoon: the liquid system starts up later in the morning and shuts off earlier in the afternoon. ... Therefore, when system performance is evaluated over an *entire season* it shows that *AIR solar systems actually produce more usable energy than liquid systems of the same size.*

E - PERFORMANCE EQUATION (ref.19)

APPENDIX F

Bed Simulation Studies

F.1 - BED SIMULATION STUDIES (DYNAMIC BEHAVIOR)
(ref.4; pp.20-26)

The heating or cooling mode of packed bed rocks is a time dependent process. A simple way of predicting the storage system dynamic behavior was done by Mumma and Martin (ref.27) using a numerical computer technique. The results are shown on figures F.1, F.2, F.3, and F.4.

F.1.1 - TEMPERATURE STRATIFICATION (ref.4; p.27)

As demonstrated in the preceding study on the dynamic behavior of a packed bed, there is a temperature wave front which moves through the bed in either direction depending on whether the bed is in the charging mode or discharging mode. On each side of this wave front there is either a high temperature region or a low temperature region as seen on figures F.1 to F.4.

Inlet Air Temperature: 65.5°C
Initial Bed Temperature: 21°C

FIGURE F.1 - BED TEMPERATURE PROFILE DURING CHARGING MODE (ref.4; p.22)

Initial Bed Temperature Distribution: 21°C Uniform
Air Inlet Temperature = 65.5° Constant
Bed Operating Mode: Charging

FIGURE F.2 - OUTLET AIR TEMPERATURE OF BED WHILE CHARGING (ref.4; p.23)

FIGURE F.3 - TEMPERATURE PROFILES IN BED DURING CHARGING (ref.;p.25)

Inlet Air Temperature: 21°C

Initial Bed Temperature: Profile obtained when a 21°C (uniform) bed is heated for 5 hours with 65.5°C air

Bed Operating Mode: Discharging

FIGURE F.4 - TEMPERATURE OF AIR SUPPLIED BY STORAGE BED (ref.4;p.26)

APPENDIX G

Particle Size - Biot Criterion

G - PARTICLE SIZING - BIOT CRITERION
(ref.12; pp.221-222) , (ref.4; pp.16-19)

In optimizing particle size, it is important to ensure the rate of conduction through the solid particle is as fast as (or faster) than the rate of convection between the fluid phase and the particle surface to fully utilize the sensible energy heat capacity of the bed.

The Biot number is defined as :

$$Bi = \frac{h_{fp} \cdot a}{K_s} \quad , \quad \text{where :}$$

h_{fp} : Fluid-particle convection heat transfer co-efficient
($W/m^2 \cdot K$)

a : Effective radius of packing particle (m).

K_s : Thermal conductivity of the packing material (W/m.K)

It is important to keep the Biot number as low as possible ; ie K_s should be much larger than $h_{fp} \cdot a$ to ensure that the heat transferred by convection does not accumulate at the surface of the particle owing to the slower conduction into the bulk of the particle while heating or causing a depletion of heat near the surface while cooling. The accepted (ref. 12). criterion is that the Biot number should be equal to or less than 0.1 to avoid thermal gradients within the particles. For a given bed material, K_s the solid thermal conductivity is fixed (provided the temperature does not vary too much) and once the flow rate is established h_{fp} is also fixed.

The flow rate is established by the size and aspect ratio of the bed. The size is fixed at about $0.66 \text{ ft}^3/\text{ft}^2$ of collector area (ref.17) and the aspect ratio from pressure drop considerations discussed in Appendix D. Therefore, the only parameter which can be adjusted to give a low Biot modulus is the particle size. Figure G.1 shows the plots of maximum particle size allowable against the flow rate (h_{fp} in the Biot number varies with the flow rate, G_o , and therefore the particle size, D_p , varies with G_o to keep Bi at a constant value of 0.1). Biot criterion plots were obtained for rocks, brick, and alumina particles. For the three materials D_p was obtained at a void fraction of 0.5. For example, a flow rate of $277 \text{ kg/m}^2 \text{ hr}$ which corresponds to 750 cfm in a bed of cross-sectional area of 6 m^2 (approximately 8 ft. square) the maximum size of rock particles is 2.5 cm.

FIGURE G.1 - BIOT CRITERION PLOT (ref.4;p.18)

APPENDIX H

Storage Volume / Collector Area

H - STUDY ON STORAGE VOLUME TO COLLECTOR AREA RATIO (ref.17)

The ratio of storage volume to collector area considered for an air base system with rock storage was examined. The study was based on flat plate collectors whose performance and cost parameters were described. The effect of this ratio on solar contribution to the energy demand for a single family dwelling located in Toronto is shown on figure H.1. The optimum ratio is in the order of 0.66 cubic feet per square foot of collector area.

The tendency for the solar contribution to be reduced for large ratios is due to the fact that larger storage systems store heat at a lower temperature, thus reducing the efficient use of such heat in an air heating system which has a minimum temperature requirement (90°F), (ref.38; p.76) to ensure thermal comfort.

LOCATION: TORONTO

BUILDING TYPE: SINGLE FAMILY DWELLING "A"

SOLAR SYSTEM TYPE: AIR-BASED SYSTEM

SHORT TERM STORAGE

FIGURE H.1 - EFFECT OF STORAGE VOLUME ON THE PERFORMANCE OF AN AIR SYSTEM (ref.17; p.87).

APPENDIX I

Underground Heat Storage

I - UNDERGROUND STORAGE OF HEAT IN SOLAR HEATING SYSTEMS (ref.40)

This study examines to what extent the ground itself contributes to storage capacity without insulation.

FIGURE I.1 - Typical example of the assumed storage geometry and temperature profiles in the initial analytical portion of this study.

The upward heat loss is easy to minimize, the heat that does move upwards contributes to the heating needs of the building (as long as it is needed at the time).

Of particular interest is the rate of heat loss compared to the total heat stored, as this is a measure of the characteristic time for the stored heat to leak out to the surrounding soil and have bearing on the possible need for added insulation. The heat loss is proportional to the perimeter of storage region and therefore to its radius (figure I.1).

The total stored heat at any given temperature is proportional to the storage region's volume and therefore to the cube of the radius.

$$\frac{\text{heat loss rate to soil}}{\text{heat storage capacity}} \propto \frac{r}{r^3} = \frac{1}{r^2}$$

So, the relative importance of losses decreases very noticeably as the size of the facility increases (see last column, TABLE I.1)

FIGURE I.1 - ASSUMED STORAGE GEOMETRY AND TEMPERATURE PROFILES (ref.40)

Radius of hemispherical storage region, r , in ft	Heat-storage capacity in 10^6 Btu (a)	U-factor for surrounding soil, k/r , in Btu/hr-ft ² -°F (b)	Heat-loss rate per unit temperature difference, 2°rk, in Btu/hr-°F	Daily heat loss as percent of storage capacity (c)
1	0.011	0.50	3.1	80
3	0.30	0.17	9.4	9.0
4.6	1.0	0.12	14	4.1
6	2.4	0.083	19	2.3
10	11	0.050	31	0.89
30	300	0.017	94	0.090
100	11,000	0.0050	310	0.0080

(a) Assuming water as storage medium (volume specific heat, 62.3 Btu/ft³-°F) operating over a temperature difference of 85°F.

(b) Assuming a ground conductivity, k , of 0.5 Btu/hr ft²-°F/ft.

(c) Assuming 120°F temperature difference between the storage region and the soil at large distances ($r = \infty$), which is generous.

TABLE I.1 - STEADY STATE CHARACTERISTICS OF HEAT LOSS TO THE GROUND (ref.40)

Soil Description	k Btu/hr ft ² °F/ft	$\alpha (=k/C_p)$ ft ² /hr °F	C_p Btu/ft ³	ρ lb/ft ³	Authority
very dry soil	0.1-0.2				Munn
wet soil	0.7-2.8				"
dry sand	0.1	0.0054	19		Geiger
wet sand	1	0.042	25		"
sandy clay (15% moisture)	0.6	0.015	37		Letkov.
concrete	1.6	0.046	34		"
organic soil	0.8	0.021	36		Geiger
wet marshy soil	0.7	0.012	54		"
granite rock	0.26	0.008	31		"
concrete	0.54	0.025	22	144	ASHRAE
dry earth, packed	0.037			95	"
sand	0.19	0.011	18	95	"
moist high-conductivity soil	1.2	0.026	46	102	Ingersoll
moist medium-low conductivity soil	0.4	0.013	30	100	"
assorted soils	0.3-1.3			90-110	ASHRAE

TABLE I.2 - THERMAL PROPERTIES OF SOILS (ref.40)

FIGURE I.2 - RATE OF HEAT TRANSFER FROM GROUND TO STORAGE (ref.40)

FIGURE I.3 - CUMULATIVE HEAT GAIN FROM GROUND (ref.40)

CONCLUSION

- 1) The average daily net heat loss into the surrounding ground from uninsulated underground heat storage is estimated to be only a few % of the heat capacity for typical home size units (refer TABLE I.1) in low-conductivity ground in the absence of liquid-water flow. The economics of added insulation under these circumstances appears to be critically dependent on the specialized site and system.
- 2) The ground surrounding a typical heat storage facility contributes very little to the system's storage capacity on a daily or seasonal time scale (figures I.2 and I.3).

APPENDIX J

Solar Energy Trades Literature

GENERAL SYSTEM DESCRIPTION

A drawing of a typical installation is shown to the left. The collectors can be grouped as shown or in any of the configurations shown on page 2, Typical Collector Arrays. Due to the Solaron internal manifolding technique (i.e., air flows from one panel to another internally) the external duct connections are minimized as shown (i.e., one inlet and one outlet for 30 panels, 563 ft.²). This technique reduces field labor and air leaks and leads to an economical installation.

Contact Solaron to obtain system schematics showing how to combine solar heating with:

- Air conditioning
- Heat pumps
- V.A.V. systems
- Multiple zones
- Process water heating
- Make-up air heating
- Process air htg.-drying
- Swim pool water heating
- Industrial and agricultural heating

SOLARON SYSTEM SIZING CRITERIA

Solaron provides the designer with a complete solar system sizing procedure for approximately 250 locations in the U.S. and Canada. The procedure is summarized below:

1. Solar Collector Area: The collector area can be determined by using the Solaron Conversion Factors (SCF) which are available from the Solaron Distributors and Dealers. The collector area is determined by dividing the building UA (i.e. building design heat loss ÷ the design temperature difference = BTU per hour°F) by the Solaron Conversion Factor. This provides the solar collector area required for a given annual fuel savings percentage.
2. Air Flow Rate: 2 SCFM to 3 SCFM per ft.² of solar collector area. Contact Solaron for special applications such as makeup air heating, outside air heating for drying or industrial or agricultural process heating.
3. Heat Storage Size: $\frac{1}{2}$ to $\frac{3}{4}$ ft.³ rock per ft.² of solar collector area. Rock size $\frac{3}{4}$ " to 1 $\frac{1}{2}$ " dia.

PEBBLE-BED HEAT STORAGE UNIT

The pebble bed allows heat to be stored at nearly the outlet temperature of the collector. This is possible because of the high degree of stratification exhibited by the pebble bed and the flow direction reversal between "storing heat" and "heating from storage."

When "storing heat," the high temperature air from the collector outlet enters the top of the pebble bed where it gives up its heat to the pebbles and returns to the collector as cool air. This allows the collector to operate at the highest possible efficiency.

Selection Example:

1. Assume that the S.C.F. have been used to determine that a specific project requires 1000 ft.² of collector.
2. Flow rate = (2 SCFM per ft.²) x (collector area)
= (2) x (1000) = 2000 SCFM
3. Heat storage unit = ($\frac{1}{2}$ ft.³ rock per ft.²) x (collector area)
= ($\frac{1}{2}$) x (1000) = 500 ft.³ rock volume

This can be obtained with a storage unit having inside dimensions of 10' W. x 10' L. x 5' rock depth. The air plenums on top of the rock make the box about 7 ft. high inside.

SOLARON®

SOLAR ENERGY SYSTEMS

300 GALLERIA TOWER • 720 SOUTH COLORADO BLVD.
DENVER, CO 80222 • (303) 759-0101 • TWX 910-931-2580

Model No.	Air Handling Unit (in.)				Dampers & Coil			C.F.M. Range at 1.2" S.P.
	A	B	C	D	E	F	G	
AU—0400	42	20	18	14	16	16	8	300 to 1400
AU—0500	51	24	22	18	20	20	10	1200 to 2400

Larger, custom built air handlers are also available.

AIR HANDLING UNIT

Solaron provides standard factory pre-assembled air handling units including blowers and motor driven dampers. A separate backdraft damper pair is furnished for mounting in the duct system.

A typical installation for the air handling unit, near the auxiliary heater and heat storage, is shown in the General System Description (upper left). The air handler can be mounted either vertically or horizontally with proper orientation and clearance to receive all connecting ducts without interference.

SOLARON AUTOMATIC CONTROL UNIT

The automatic temperature control unit is included as part of the Solaron system. The controller handles all of the operational modes which are shown in the schematics on page 2. The controller operates the solar side of the system and ties into a 2-stage thermostat to provide solar and/or auxiliary heat to the space as required. A standard Solaron controller is available to interface with heat pumps or other types of auxiliary heating systems. Solaron can provide technical assistance to design special controllers for large projects or unique applications.

1. Inlet Air.
2. Air going to adjacent internal manifold.
3. Air entering absorber duct.
4. Air flowing under selective absorber.
5. Air flowing to next series 3000 collector.

Panel Dimensions:
35" W x 77" L x 8 1/4" H
Weight 135 lbs.

THE PATENTED SOLARON 3000 COLLECTOR PANEL

Protected by Patent 4,073,283

Completely modular, the 3000 is the most advanced air heating flat plate collector in the industry. Expanded internal manifold distributes the air flow, minimizes heat transfer loss and requires only minimal ducting. Other installation simplifications include mounted silicone gaskets for between-collector sealing and attractive capping and perimeter strips for weathertight security, simplified collector hold-down.

Solaron Series 3000 features:

- Collector Glazing—single, lightly textured, 1/4" thick, low iron tempered glass.
Easily removable for replacement
- Absorber Coating—black chrome over nickel.
Absorptivity—0.95 minimum
Emissivity—0.15 maximum
- Pan—20-gauge steel.
- Insulation—2.5 inches of glass batt plus 0.5 inch semi-rigid foil backed; R-13 insulation value.
- Connection Ports—unique flange configuration gives automatic airtight seal as modules are installed.
- Cap Strip—aluminum with high quality porcelain enamel finish provides weather sealing between panels.

WATERSHED STORAGE SUB-SYSTEM

Above ground storage (typical section)

Section 'a'
(pattern of
first layer
of blocks)
 $\frac{1}{2}$ " screen

Section 'b'
(pattern of
first and
second
layer of
blocks)
 $\frac{1}{2}$ " screen

The system consists of four major parts:

1. The honeycomb panels, with mounting brackets and glazing caps.
2. The sheet metal ducting.
3. The air handling unit complete with temperature sensors, dampers, motors and controls.
4. The thermal storage tank.

THE WATERSHED SYSTEM

A properly installed system will supply 100% of the heat for a house during spring and fall, when sunshine is abundant, and about 20% in midwinter (December, January). Over a complete heating season, a system will supply 50% to 60% of the building heat requirements. The rock pile storage will provide about one day's storage in the dead of winter, and a week's storage during the early (October) and late (March) winter.

J.2 - WATERSHED ENERGY SYSTEMS LTD.

Solartech Limited

207 Queen's Quay West, Toronto M5J 1A7 Tel: (416) 863-0525

1. GENERAL

The Gravel Bed Heat Storage Unit is not supplied by Solartech because the unit is site constructed from common construction materials. However, the heat storage unit must conform to Solartech approved design. While the general formula for heat storage unit sizing is given here, exact sizing is a function of the relationship between anticipated collector performance and building heat loss. Mechanical and structural consultants are required to consult with Solartech for details of sizing and loading. The following information is provided for general guidance.

Related Work

Heat Storage is part of a complete solar system. See also Solartech specifications for Air Collectors and Solar Air Mover. Forced air ducting connecting these components is specific to each installation site. Standard duct sizing formulas and materials are used.

Quality Assurance

Working drawings for heat storage unit are provided as part of the Solartech contract. Solartech approvals are required for final plans incorporating its product and for plans of certain related work not specified by Solartech but connecting its components, e.g. ducting.

2. PRODUCT

Materials:

See drawing for general arrangement.

DIMENSIONS — Sized according to collector area and building heat load. Sizing Formula: Inside volume, approximately $.15\text{m}^3$ per m^2 of collector ($.5\text{ft}^3/\text{ft}^2$). Typically, heat storage chamber will be between 1.5m and 1.8m (5' to 6') in depth. Plenums: Top and bottom are 200mm (8") deep. Duct Connections: Sized at 250m/min (800 fpm).

GRAVEL — Washed round aggregate, not more than 35% crushed. Size: 20mm ($3/4$ ") nominal. Weight: $1600\text{kg}/\text{m}^3$ ($100\text{lb}/\text{ft}^3$) approx.

INSULATION — High density fibre glass. Indoor Storage: walls and bottom of container, R-12 min.; lid, R-20 min. Outdoor Buried Storage: walls and lid, R-20 min.; bottom of container, R-12 min.

STEEL MESH — Expanded metal wire mesh, 11mm ($1/2$ ") No. 18.

BEAM BLOCK — Concrete bond beam blocks 200 x 200 x 400mm (8 x 8 x 16").

WALLS — Typically 200mm (8") concrete block wall, grouted in all cells, and No. 4 rebar on 1.2m (4') centres, or equivalent poured concrete construction.

FLOOR — Concrete slab, 160mm (6") min. thickness, incorporating 160 x 160mm (6" x 6") 10/10 mesh, horizontal reinforcing.

LID — Timber frame, with 12.7mm ($1/2$ ") exterior grade plywood top and bottom, covered again on bottom with 12.7mm ($1/2$ ") moisture resistant drywall. Fibre glass insulation inside framework.

Operating Conditions

Pressure Drop: typically 37.3Pa ($.15\text{H}_2\text{O}$).

Gross Face Velocity: 0.1m/sec. (20 fpm) typically.

Air Flow Direction: design is for vertical flows only.

Solartech

Gravel Bed Heat Storage Unit

J.3 - SOLARTECH LTD.

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