NASA TM-82415

DOE/NASA TECHNICAL MEMORANDUM

DOE/NASA TM-82415

DEVELOPMENT AND TESTING OF THERMAL ENERGY STORAGE MODULES FOR USE IN ACTIVE SOLAR HEATING AND COOLING SYSTEMS (Final Report)

By John C. Parker
Solar Energy Applications Project Office
George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812

April 1981

For the U. S. Department of Energy

U.S. Department of Energy

Solar Energy

TECHNICAL REPORT STANDARD TITLE PAGE

1. REPORT NO. DOE/NASA TM-82415	2. GOVERNMENT ACCESSION NO.	3. RECIPIENT'S CATALOG NO.
4. TITLE AND SUBTITLE Development And Testing Of Thermal Energy Storage Modules For Use In Active Solar Heating and Cooling Systems - Final Report		5. REPORT DATE April 1981
		6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) John C. Parker		8. PERFORMING ORGANIZATION REPORT #
9. PERFORMING ORGANIZATION NAME AND ADDRESS George C. Marshall Space Flight Center Marshall Space Flight Center, AL 35812		10. WORK UNIT NO.
		11. CONTRACT OR GRANT NO.
		13. TYPE OF REPORT & PERIOD COVERED Technical Memorandum
12. SPONSORING AGENCY NAME AND ADDRESS National Aeronautics and Space Administration Washington, DC 20546		14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES

Prepared by Solar Energy Applications Projects Office

16. ABSTRACT

This Document summarizes the final results of contract NAS8-32254 with Artech Corporation, Falls Church, Virginia, for the additional development work on thermal energy storage modules for use with active solar heating and cooling systems. It discusses the intended use of the final report, describes the deliverable end items, lists program objectives, relates how they were accomplished and deals with problems encountered and their solutions.

The report shows that the product developed and tested is marketable and is recommended as being suitable for public use.

17. KEY WORDS Solar, Container, Salt, Eutectics, Chamber, Plastic, Test, Phase Change, Molded, Polyethylene	18. DISTRIBUTION STATEMENT UC59c Unclassified-Unlimited

19. SECURITY CLASSIF. (of this report) Unclassified	20. SECURITY CLASSIF. (of this page) Unclassified	21. NO. OF PAGES 34	22. PRICE NTIS

MSFC - Form 3292 (Rev. December 1972)

For sale by National Technical Information Service, Springfield, Virginia 22151

N81-23604#

TABLE OF CONTENTS

LIST OF FIGURES

TECHNICAL MEMORANDUM

DEVELOPMENT AND TESTING OF THERMAL ENERGY STORAGE MODULES FOR USE IN ACTIVE SOLAR HEATING AND COOLING SYSTEMS - FINAL REPORT

SUMMARY

The intended use for this report is to provide product development information as an aid to the solar heating and cooling systems manufacturing industry in their effort to determine the products suitability for use in active solar heating and/or cooling systems for residential and commercial applications.

This report will also serve as an aid to those who desire to remain abreast of the state-of-the-art of solar energy heating and cooling projects.

In October of 1976, Artech Corp. entered into a contract with the National Aeronautics and Space Administration (NASA)/ Marshall Space Flight Center (MSFC) for the additional development and testing and subsequent delivery of thermal energy storage modules consisting of sealed containers filled with salt hydrates or eutectics which can provide latent heat or coolness at certain desired temperatures, after being thermally charged from an outside heat or cooling source.

The deliverable end item under this contract was to be three identical subsystems. Each subsystem was to consist of modules which when combined would constitute a volume of approximately 6' x 6' x 6'. However, in mid 1977 the contractor began experiencing fabrication problems. Numerous pin holes were found in the air passages of the plastic containers. The container was redesigned and certain improvements made in the molding techniques. This resulted in added costs; and to maintain the funding limitation as established at contract implementation the scope of work was adjusted by changing the number of products to be delivered from three identical subsystems to one subsystem. The one subsystem consists of modules which when combined constitutes a volume of approximately 2' x 2' x 6'.

The thermal capacity was also changed as a result of the reduced volume of the containers. Initially, the thermal energy storage subsystem was to be able to store 700,000 Btu's of heat under certain temperature conditions. The smaller volume subsystem can store approximately 100,000 Btu's of heat under the same temperature conditions.

At contract completion (over a 48-month period), the 2' x 2' x 6' thermal energy storage modules were delivered to the Marshall Space Flight Center, Huntsville, Alabama.

These modules, containing the phase change material, have a specific storage capacity of approximately 70 Btu/lb versus 6 Btu/lb for rocks, masonry, concrete or other heavy solid material. Thus, for the same storage capacity, only 1/12 as much storage material is required, resulting in reduced space which is a big factor in building costs.

INTRODUCTION

PROGRAM BACKGROUND AND GOALS

The problems of energy availability and increasing cost have led to a major national effort to develop alternate energy sources. One such source is the energy in solar radiation, which can be used for heating and cooling buildings, domestic hot water, and other applications. The National Energy Policy, as established in the Solar Heating and Cooling Demonstration Act of 1974 (PL 93-409), of which the effort described in this final report is a part, provided for the demonstration within a three-year period of the practical use of solar heating technology, and demonstration within a five-year period of the practical use of combined heating and cooling technology. Responsibility for implementing the Demonstration Act was given to the Energy Research and Development Administration (now the Department of Energy). NASA/MSFC manages a large part of this work.

PURPOSE OF THIS PRODUCT DEVELOPMENT CONTRACT

The purpose of this contract was to provide funding to Artech Corp. for further development of an existing thermal energy storage subsystem (Figure 1) for solar heating or combined heating and cooling subsystem to make a marketable product and for the procurement of the developed subsystem.

CONTRACT

Contract performance period was from October 1, 1976, through September 30, 1980.

DESCRIPTION

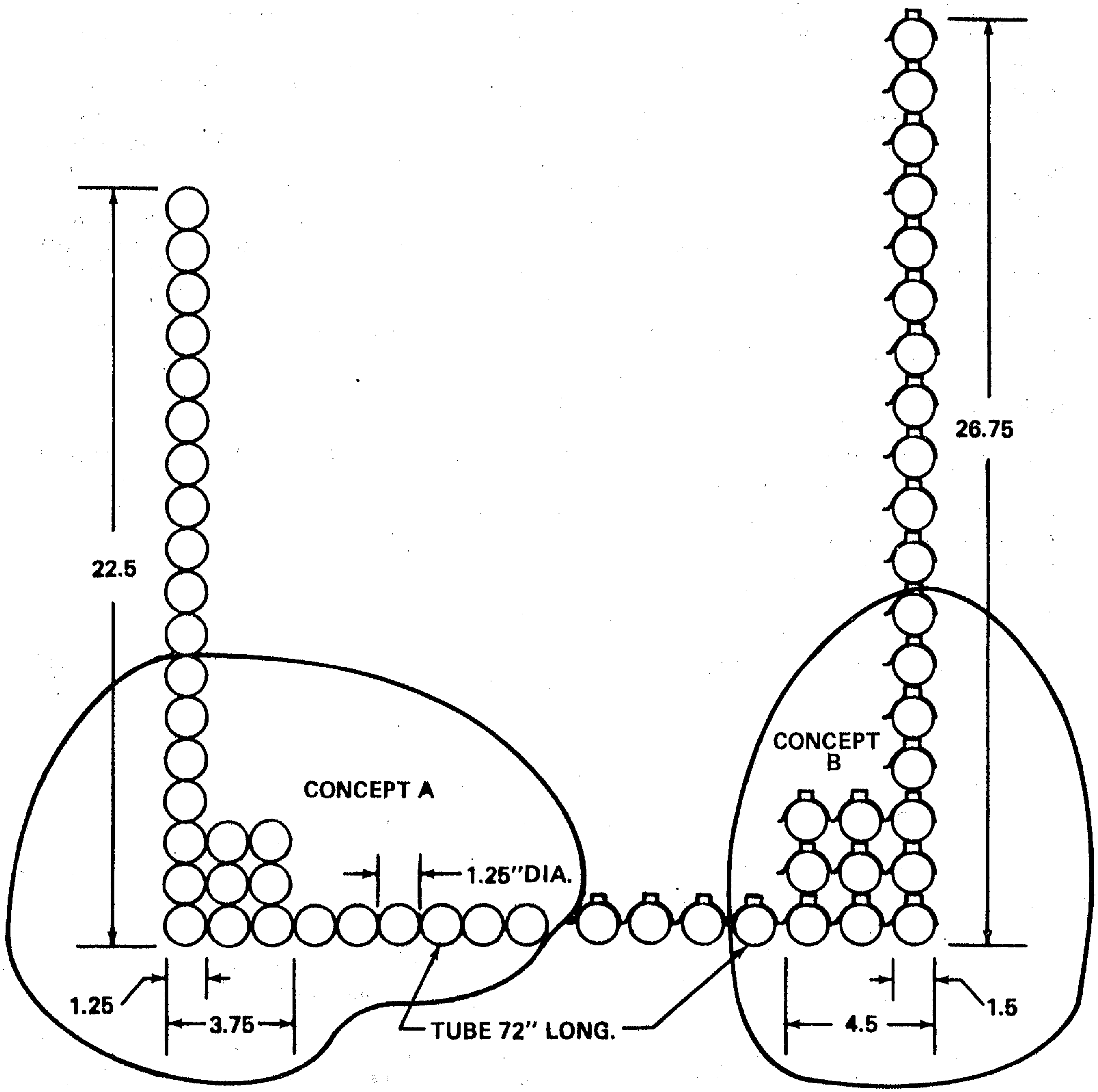
PROJECT DEVELOPMENT REQUIREMENTS AND CRITERIA

During the development of the thermal energy storage subsystem, the contractor was required to:

A) Meet, to the greatest extent possible, the parts of the interim performance criteria for solar heating and cooling systems, as specified in the contract.

B) Meet, to the greatest extent possible, the Subsystem Performance Specifications, as specified in the contract.

C) Provide test data/analyses to verify that hardware, to the greatest extent possible, meets the Subsystem Performance Specifications.



TUBULAR CONCEPT (IN DIRECTION OF AIR FLOW)
PRIOR TO CONTRACT IMPLEMENTATION

NO-SCALE

FIG. 1

D) Provide drawings and specifications in sufficient detail to define the configuration and to ensure manufacturing repeatability.

E) Have provisions to monitor performance.

F) Provide Installation, Operation and Maintenance Manual(s).

G) Provide, to the greatest extent possible, subsystem and/or component hardware certified by independent test laboratory (such as Underwriters Laboratory and American Gas Association) to meet nationally recognized standards and codes (such as American Society of Heating, Refrigeration and Air Conditioning Engineers; American Society of Mechanical Engineers; American National Standards Institute and American Refrigeration Institute).

DEVELOPMENT OF THE THERMAL ENERGY STORAGE MODULES

TESmod™ is ARTECH's trademark for a series of modular thermal energy storage units that make use of the phase change principle for storing heat by melting the storage material. When the module is charged with thermal energy, the material melts. It solidfies again as the energy is removed from storage. The phase change enables the material to store much more heat than a similar quantity of an inert material. The phase change material is a proprietary salt hydrate mixture based on ordinary Glauber's salt, sodium sulfate decahydrate or $Na_2SO_4 \cdot 10H_2O$, which melts at about 90°F. The mixture contains special additives to insure nucleation and prevent segregation, and had been tested for the equivalent of many years of actual use. The salt hydrate mixture is permanently sealed in specially designed containers molded of high-density polyethylene. Each container is designed with ribs or air passages for maximum heat transfer to or from the air flowing through the system. (See Figure 7).

Artech Corp. was originally contracted to develop, fabricate, and deliver three identical thermal energy storage subsystems. Each subsystem was to consist of modules which when combined would constitute a volume of approximately 6' x 6' x 6'. Each module was to be composed of sealed trays filled with salt hydrates, which provide latent and sensible heat or coolness at desirable temperatures and temperature ranges.

Initially, the thermal energy storage subsystem was to be able to store 700,000 Btu (36 percent of theoretical) of heat above a minimum temperature of 70°F and not to exceed a temperature of 126°F. A minimum of 60,000 Btu's per hour would be accumulated with a constant source flow of 3,000 cfm at a temperature not to exceed 150°F.

In July of 1977, the contractor began experiencing problems in fabricating the plastic containers required for the thermal energy storage modules. (The rotational molding technique was used to fabricate the containers). Numerous pin holes were found in the air passages of the plastic containers. Figures 2, 3, and 4 show 3 different air passage configurations. All three had 18 air passages. All three had the same "pin hole" problem.

Finally, Artech Corp. consulted the McNeil-Akron Company, manufacturers of molding machinery, and several producers of molds for the rotational process, and then redesigned the container to meet the requirements of all aspects of the production sequence. Figure 5 shows the redesign. Essentially, it involved reducing the number of air passages from 18 to 10 and increasing the "air passages" radii. Artech then conducted a new design analysis on the redesigned thermal energy storage containers. A summary of the results follows:

This change and other necessary dimensional changes reduced the ratio of heat transfer area to cross-sectional air flow area from 250 to about 190. This ratio is an important parameter governing the heat transfer rate. For a 500-cfm air flow, the calculated heat transfer efficiency dropped, reducing the calculated rate of heat accumulation to 81,000 Btu. This is somewhat lower than the target of 100,000 Btu stated in the Subsystem Performance Specification, but the widening of the fins and the reduction in the number of air passages led to a compensating increase in the volume of salt hydrate mixture in each container. This increased the calculated thermal capacity of the subsystem to slightly more than 130,000 Btu, somewhat higher than the 100,000 Btu called for in the Subsystem Performance Specification.

The added cost of this design change, together with the costs inherent in the delays, required an adjusted scope of work, so that the funding could remain the same. This was done by changing the number of products to be delivered from three identical subsystems to one subsystem. The one subsystem consists of modules which when combined constitute a volume of approximately 2' x 2' x 6'.

After the changes, the subsystem was designed to store 100,000 Btu of heat above a minimum temperature of 70°F and not to exceed a temperature of 126°F, and a minimum of 10,000 Btu per hour was to be accumulated with a constant air flow of 500 cfm at a temperature not to exceed 150°F.

The convenient two-foot cube modules were found in the standard ASHRAE 94-77 test to have a storage capacity of a minimum of 27,000 Btu each. They can be assembled in parallel to increase storage capacity, and in series to increase heat transfer efficiency, in any suitable insulated enclosure connected to a horizontal air circulating system.

TECHNICAL DATA FOR THE THERMAL ENERGY STORAGE MODULES

(See "Installation, Operation, and Maintenance Instructions" on page 20).

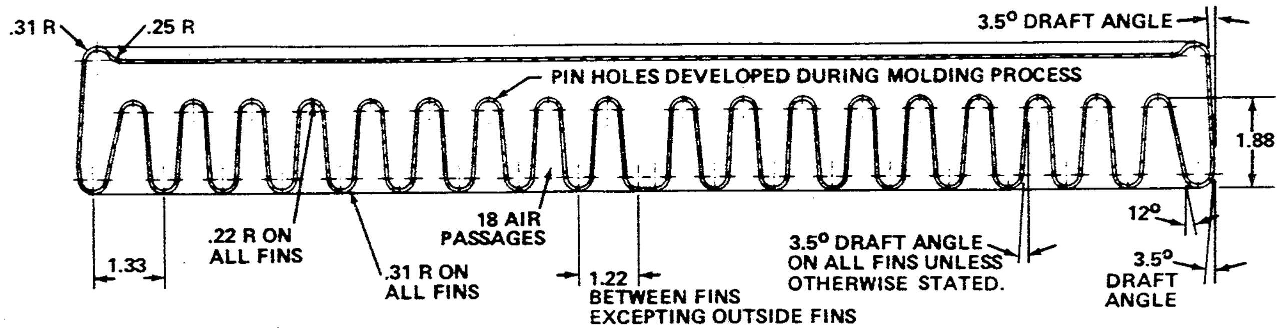


FIG. 2

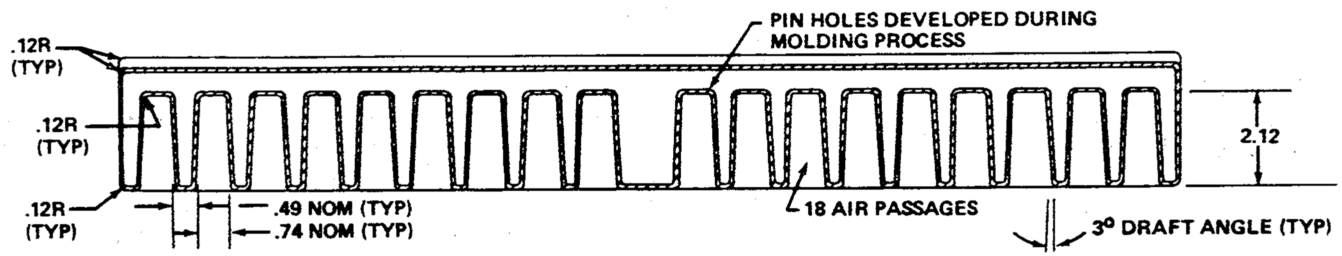


FIG. 3

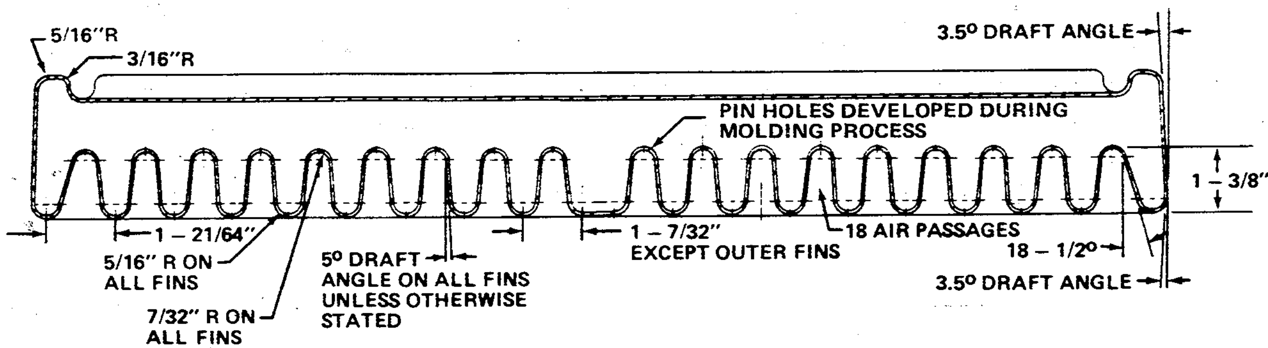
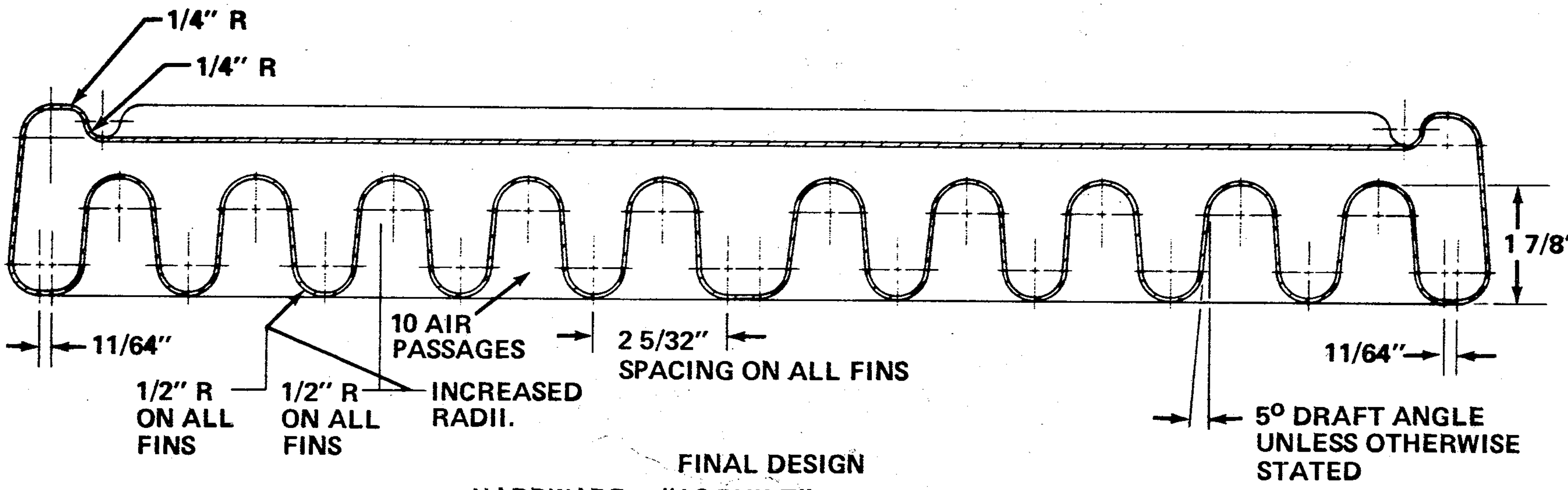


FIG. 4

NOTE: CONTAINERS MADE FROM MOLDS IN ACCORDANCE WITH THESE THREE (3) CONFIGURATIONS ALL HAD PIN HOLES AND POROSITY IN THE RADII AND CORNERS OF THE AIR PASSAGES.



FINAL DESIGN
HARDWARE – "AS BUILT" – CONFIGURATION
FIG. 5

PERFORMANCE TEST

THERMAL ENERGY STORAGE ASSEMBLY

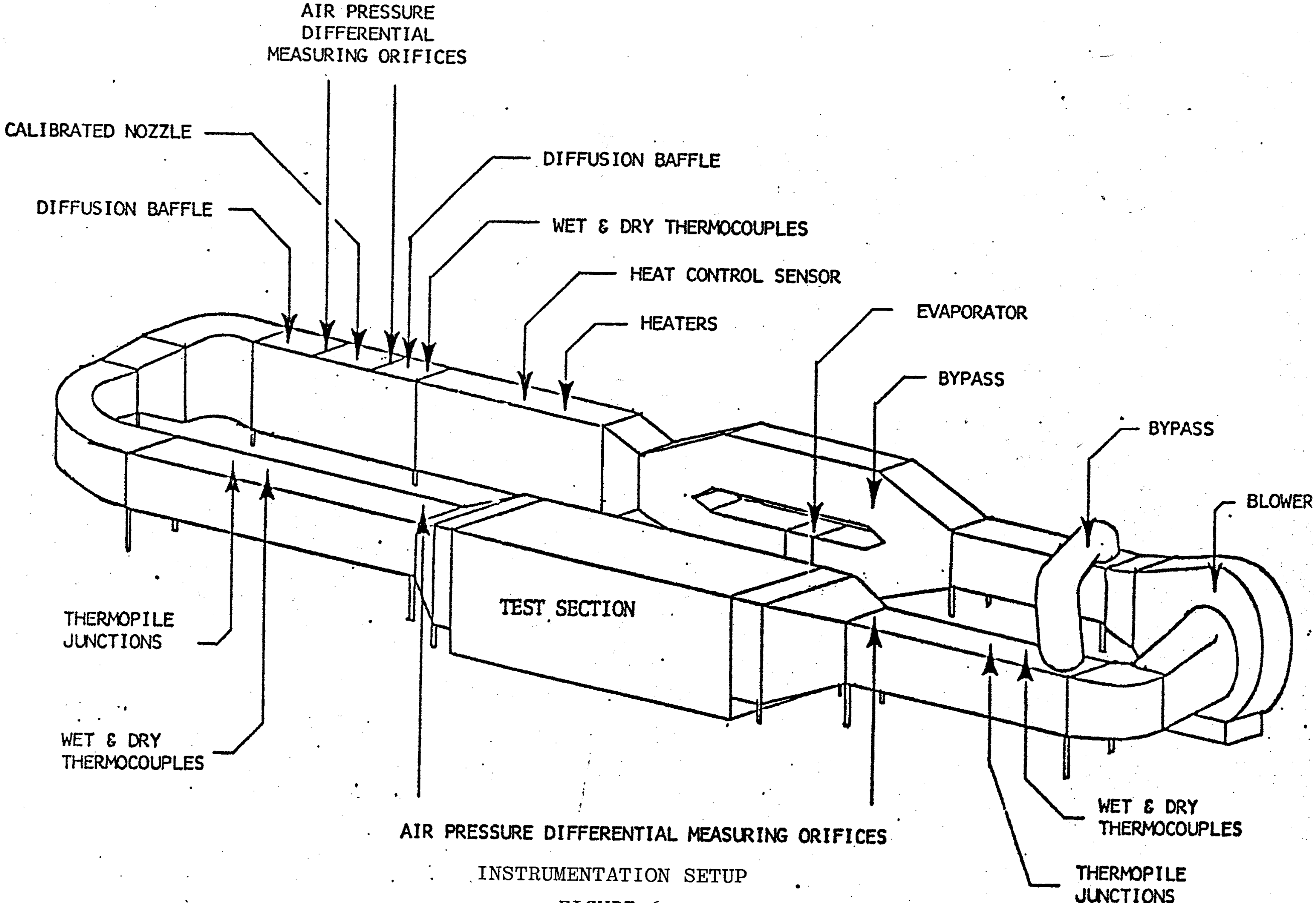
Tests were performed on an assembly of three 2x2x2-ft modules in series, having an area at the air entry and exit faces of 2x2 ft and a length in the air flow direction of 6 ft. This assembly, with duct transitions to 1x1 ft at the inlet and exit ends, is termed the TES unit in the following discussion. It was enclosed in an insulated chamber designed to prevent short-circuiting flow around the modules. Test procedures essentially conformed to the recommendations of ASHRAE Standard 94-77.

To determine the heat transfer rate in flowing air, the TES unit was monitored with thermocouples in a closed heating and cooling loop instrumented according to the requirements of ASHRAE 94-77 (See Figure 6). The air flowing in the loop was heated to 128^{o}F for charging the heat storage material and cooled to 65^{o} for discharging. The flow rate and the difference between inlet and outlet air temperatures were recorded. Tests were to be performed with a step increase and decrease of inlet air temperature, but the step changes were not achieved in practice owing to inadequacy of the heating and cooling capacity of the air reconditioning system. In a significant portion of each test, the heat exchange rate was impaired by this inability to reach the desired incoming air temperature. In Charge Test No. 2, the incoming air did not reach the desired temperature until after the two-hour test period specified by ASHRAE 94-77 was over.

The heat transfer rate was determined by multiplying the change in temperature by the mass flow rate and the specific heat of air. The heat transfer rate was integrated over the charge and discharge periods to obtain the storage capacity. Correction was made in the manner specified by ASHRAE 94-77 for heat flow through the walls of the storage chamber.

DUCTING

The test loop specifications called for an air inlet test duct, between the air flow measuring apparatus and the TES unit; and an outlet test duct, between the TES unit and the air reconditioning apparatus, to have the same cross-sectional dimensions as the outlet of the TES unit. The test section ducting satisfied this requirement.



INSTRUMENTATION SETUP

FIGURE 6

TEMPERATURE, PRESSURE AND AIR FLOW MEASUREMENTS

All temperature measurements were made with thermocouples or a thermopile constructed from calibrated type J (copper-constantan) thermocouple wire. No extension wires of other materials were used in the fabrication or installation. The wire diameter was no larger than 0.51 mm (No. 24 AWG).

Temperatures indicated by thermocouples, and the millivolt output of the thermopile, were recorded on strip chart recorders during the tests. The thermocouple-recorder combination was calibrated with an ice bath and a hot water bath, the temperature of the latter being measured by a calibrated thermometer.

DRY AND WET BULB TEMPERATURE

The air flow temperature was determined with thermocouples located at the air inlet and at the outlet of the TES modules in the test loop. A wet-bulb thermocouple, whose reservior was kept filled with distilled water by a siphon arrangement, was in close proximity to each of the dry-bulb thermocouples.

TES MATERIAL TEMPERATURE

Two spaced thermocouples were provided near the trailing edge of the stack of containers in each of the three modules.

TEMPERATURE DIFFERENCE MEASUREMENT ACROSS THE TES UNIT

The temperature difference across the TES unit was determined by a thermopile whose nine junctions on each side were located at the centers of equal cross sectional areas in the inlet and outlet ducts. These junctions were located at the inlet and outlet of the TES unit.

DUCT PRESSURE MEASUREMENTS

The static pressure drop across the TES module was measured at 500 cfm using a manometer with a measuring sensitivity of 0.005 inches of water. Each side of the manometer was connected to four pressure taps on the air inlet or outlet duct via an external manifold. The pressure taps were 6.4-mm (1/4-inch) nipples soldered to the duct and centered over 1-mm (0.040-inch) holes. All inside duct surfaces were free of surface irregularities and hole burrs. The pressure drop at 1000 cfm was estimated from the 500 cfm value.

AIR FLOW MEASURING APPARATUS

The air flow rate was determined by measuring the pressure drop across a calibrated nozzle as specified by ASHRAE Standard 37-69.

AIR RECONDITIONING APPARATUS

The reconditioning apparatus, within the limits of its heating capacity of 9 kW and cooling capacity of 27,000 Btu/hr, was capable of controlling the dry bulb temperature of the air entering the TES module to within $\pm 1.0^{\circ}C$ ($\pm 1.8^{\circ}F$) of the desired test value during the tests.

PERFORMANCE TEST RESULTS

Tests were run at air flow rates of 500 and 1000 cfm, for four and two hour charge and discharge periods respectively, as specified by ASHRAE 94-77. In addition, each charge or discharge test was continued until the system reached essentially a steady state, as required in preparation for a subsequent test, and the temperature difference representing heat input or output was integrated over the entire period (5-16 hr) to determine the total storage capacity of the heat storage unit.

Results of the two-and four-hour tests are summarized on the data sheets, prescribed by ASHRAE 94-77, which follow.

General Information

Manufacturer	ARTECH CORP.
Model Number	TES 90-2 (quantity - 3 in series)
Serial Number	1, 2, & 3
Storage Medium	ARTECH TES-90 (Sodium sulfate decahydrate with proprietary additives)
Transfer Fluid	Air
Container Material	High density polyethylene
Length	6 ft
Width	2 ft
Height	2 ft, plus 5-1/8 in. dolly height
Weight of Storage Device, W	4305 lb
Volume of Storage Device, V	24 ft^3
Normal Operating Temperature Range	50 - 150°F
Minimum Transfer Fluid Flow Rate	250 cfm
Maximum Transfer Fluid Flow Rate	1000 cfm
Maximum Operating Pressure	N/A
Flow Configuration Tested	see sketch (Figure 6) (picture or diagram)

Heat Loss Rate Test

t_a	75.7°F
TSC_L	123,000 BTU
Average of ($t_{in} - t_{out}$)	2.4°F
w_L	1911 lb_m/hr
c_{tf}	0.240 BTU/(lb_m-°F)
L	24.4 BTU/(°F-hr)

Transient Tests

t_a	77°F
t_i	65°F
Δt	63°F
τ_c	4hr 20 min
w_c	1899 lb_m/hr (500 cfm)
Δp	0.048 in. H_2O
c_{tf}	0.240 BTU/(lb_m·°F)
TSC	136,700 BTU
C_c	55,100 BTU
τ_d	4 hr 20 min
w_d	2230 lb_m/hr (500 cfm)
C_d	42,400 BTU

General Information

Manufacturer	ARTECH CORP.
Model Number	TES 90-2 (quantity - 3 in series)
Serial Number	1, 2, & 3
Storage Medium	ARTECH TES-90 (Sodium sulfate decahydrate with proprietary additives)
Transfer Fluid	Air
Container Material	High density polyethylene
Length	6 ft
Width	2 ft
Height	2 ft, plus 5-1/8 in. dolly height
Weight of Storage Device, W	4305 lb
Volume of Storage Device, V	24 ft^3
Normal Operating Temperature Range	50 - 150°F
Minimum Transfer Fluid Flow Rate	250 cfm
Maximum Transfer Fluid Flow Rate	1000 cfm
Maximum Operating Pressure	N/A
Flow Configuration Tested	see sketch (Figure 6) (picture or diagram)

Heat Loss Rate Test

t_a	75.7°F
TSC_L	123,000 BTU
Average of $(t_{in} - t_{out})$	2.4°F
w_L	1911 lb_m/hr
c_{tf}	0.240 BTU/(lb_m-°F)
L	24.4 BTU/(°F-hr)

Transient Tests

t_a	73°F
t_i	65°F
Δt	63°F
τ_c	2 hr 10 min
w_c	3922 lb_m/hr (1000 cfm)
Δp	0.18 in. H_2O (est.)
c_{tf}	0.240 BTU/(lb_m·°F)
TSC	136,700 BTU
C_c	41,700 BTU
τ_d	2 hr 10 min
w_d	4444 lb_m/hr (1000 cfm)
C_d	35,300 BTU

The essential results of all these tests are as follows:

Test performed at an air flow rate of	500 cfm	1000 cfm
ASHRAE Test duration	4 hr	2 hr
Charging rate	13,800 Btu/hr	20,800 Btu/hr
Capacity	55,100 Btu	41,700 Btu
Discharging rate	10,600 Btu/hr	17,600 Btu/hr
Capacity	42,400 Btu	35,300 Btu
Ultimate capacity, charging	80,000 Btu	76,700 Btu
Time allowed for equilibration	12 hr	5 hr
Ultimate capacity, discharging	81,600 Btu	69,400 Btu
Time allowed for equilibration	16 hr	5 hr

Thus the subsystem achieved 81% of the target value of 100,000 Btu for ultimate storage capacity and an average of 122% of the target value of 10,000 Btu/hr for heat transfer rate during the ASHRAE test period at a flow rate of 500 cfm.

INDUSTRIAL

Air Conditioning Company

September 24, 1980

Dr. Fred Ordway
Artech Corporation
2901 Telstar Court
Falls Church, Va. 22042

Subject: TES Test

Dear Dr. Ordway:

The undersigned, having been "certified" by the National Environmental Balancing Bureau (NEBB) for the testing, balancing and adjusting of heating, ventilating and air conditioning systems, both as a technician and a supervisor, you recently requested that I examine your current TES testing and report to you accordingly.

NEBB standards encompass five major categories, as follows:

1. Instruments and measurement accuracy.
2. Preliminary procedures.
3. Equipment and system checks.
4. Testing, balancing and adjusting procedures.
5. Test reporting.

Having examined the TES test setup on two occasions, on September 10, 1980, prior to the actual testing but with instrumentation complete, and on September 25, 1980, during the actual testing, I am pleased to report that the testing equals or surpasses all NEBB standards in my judgment.

Very truly yours,

George R. Smith

George R. Smith, P.E.

GRS:mk

P.O. BOX 2076 2824 FALLFAX DRIVE (703) 573-7700 FALLS CHURCH, VIRGINIA 22042

PROBLEMS ENCOUNTERED AND THEIR SOLUTIONS

Initially, the period of performance of this contract was from October 1, 1976, through September 30, 1977. Around mid 1977, problems were encountered in fabricating the plastic containers. This problem continued for the best part of three years. Finally, after resolving the difficulties, the period of performance was extended through September 30, 1980, at no cost to the Government.

The plastic containers for this project were fabricated using the rotational molding technique. This method is commonly used in the plastic industry, but its use is limited to the fabrication of parts that are regular in shape such as hollow cylinders, hollow spheres, or hollow containers that have generous radii in the corners, ends or sides.

As can be seen from Figures 2, 3, and 4, the original containers have rather sharp radii in the fin areas, and the fins are close together. It was found that this configuration was "pushing" the state-of-the-art, as it were.

After several attempts at molding containers by changing fin radii and the distance between them, a product with uniform wall thickness and free of porosity was finally achieved (see Figure 5). The end item delivered has this configuration and is satisfactory.

CONCLUSIONS

A common alternate to the thermal energy storage module for heat storage in an air circulating system is a large mass of rocks, masonry, concrete, or similar heavy, inexpensive solid material. These materials store only sensible heat--that is, the temperature goes up as heat is added, and goes back down as heat is recovered. It can't go too far down or there won't be any heat transfer into the circulating air. It can't go too far up because the solar collectors become less and less efficient as their outlet temperature increases. For a reasonable operating temperature range of 30°F and a typical specific heat figure of 0.2 Btu/lb.°F, the specific storage capacity is 0.2 x 30 = 6 Btu/lb.

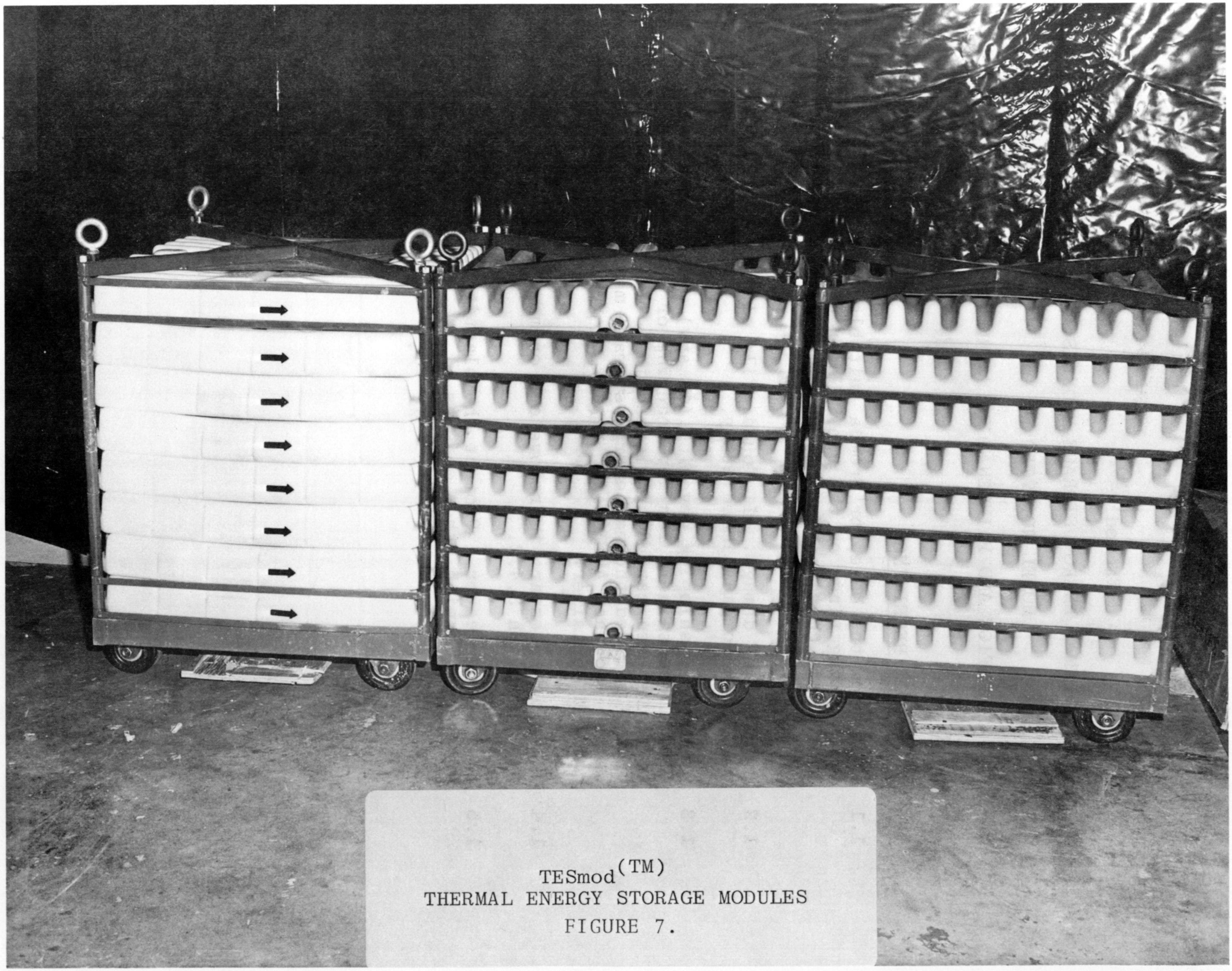
The phase change material in the thermal energy storage module, on the other hand, stores energy mostly as latent heat--that is, the heat can be put into storage and recovered without any significant change in temperature. The material stays near its melting point of 90°F. The specific storage capacity in this case is 70 Btu/lb. Therefore for the same storage capacity only 1/12 as much material is required.

This size reduction factor means that a typical storage capacity of 300,000 Btu can fit in a closet-size space, anywhere the designer finds convenient, rather than in a whole basement filled with 25 tons of rocks. Saving space is saving money. Further, adding solar heat to an existing building by this method may be the only heat storage system that space will allow.

It has been determined that the product developed under this contract is marketable and suitable for public use.

RECOMMENDATIONS

For this type of thermal energy storage, an immediate application and one requiring a minimum of retrofit installation effort, could be in existing greenhouses, both domestic and commercial.



TESmod(TM)
THERMAL ENERGY STORAGE MODULES
FIGURE 7.

GENERAL

TESmod(TM)

THERMAL ENERGY STORAGE MODULES

MODEL NO. 7750

INSTALLATION, OPERATION AND MAINTENANCE INSTRUCTIONS

IMPORTANT

1. IMMEDIATELY ON RECEIVING

1.1 Lift from the base, or from a suitable sling through the lifting rings on the top. Never pick up module by plastic containers or steel cross pieces. FRAGILE. DO NOT DROP.

1.2 Examine for damage. If found, file claim with transportation company immediately.

1.3 Remove the shipping covering (if any). Check the plastic containers for any cracking or leakage that may have been caused by mishandling. If found, mop up any spilled thermal energy storage material with water. Contact ARTECH for repair or replacement of damaged container.

1.4 If it is necessary to remove one or more containers, see paragraph 3.4.2.

1.5 Store under cover. Protect the plastic containers from contact with other objects.

2. DESCRIPTION

2.1 Each thermal energy storage module is composed of high density polyethylene plastic containers filled with thermal energy storage material. Each container is supported by a steel frame unit 24 in. (610 mm) square and 3 in. (76 mm) high. The frame units are joined to make a module two feet high by means of vertical connecting rods through the four corners of the frame units. The standard 2x2x2-ft (0.6x0.6x0.6-m) module consists of eight frame units and containers. The corner rods are attached to a steel base having four dolly wheels. At the top, the corner rods are attached to a lifting frame provided with eye-bolts so that the module can be lifted by means of a chain or cable sling. The module should be lifted only (1) by a sling attached to all four eyebolts, or to a pair of them on opposite corners, so that the module remains vertical when lifted, or (2) by a fork lift or similar equipment under the steel base.

2.2 The containers can be removed and reinstalled by disassembling the module. See paragraph 3.4.2 for disassembly procedure.

2.3 The thermal energy storage material in the plastic containers absorbs latent heat, and melts, at approximately 90°F (32°C). The module must not be subjected to a temperature greater than 150°F (65°C).

2.4 Each module is shipped assembled on its steel base. The base has four heavy-duty wheels, two in swivel mounts and two in rigid mounts. For flexibility in installation, one-third of the modules are assembled with the two swivel wheels on one side, and the remainder with the swivel wheels on one end, unless otherwise specified by the customer.

2.5 The eye bolts may be removed from the lifting frame to facilitate a close fit between the module and the enclosure.

3. INSTALLATION

3.1 DUCTWORK

3.1.1 The module is designed to be placed with its base horizontal and the ribs on the plastic containers in the direction of air flow, inside a close fitting, insulated plenum designed as part of the heating/cooling system. The module can be placed alone, or with other modules in parallel and/or in series (tandem), to provide the combination of storage capacity and heat transfer efficiency desired by the designer.

3.1.2 External dimensions of the module are 2x2 ft (0.6x0.6 m) in plan and 2 ft (0.6 m) in height, plus the depth of the dolly (5-1/8 in. or 130 mm) and the height of the lifting frame (3-3/8 in. or 86 mm). See figure 9 on page 27 of these instructions. Plenum dimensions should allow no more then 1/8 in. (3 mm) laterally between modules, or between an outside module and the enclosure, to ensure proper air flow through the modules. Suitable spacer material must be provided to prevent air flow past the dolly wheels and lifting frame, if these are present in the installation. If any air spaces exist between the sides of parallel modules, or between modules and plenum, they must be closed at intervals of 2 feet (0.6 m) or less with a suitable material.

3.1.3 Ductwork and plenum should be in accordance with good design practice, and should provide for uniform distribution of the inlet air flow over the cross section of the module assembly. Uneven air flow distribution will result in decreased thermal charging and discharging rates. Plenum and ductwork should be air-tight for efficiency.

3.1.4 The modules, like any heat exchange device, must be accessible for periodic inspection and cleaning. If the temperature of the module may be below the dew point of the incoming air at times, provision for collecting and removing the condensate must be incorporated in the plenum. The containers are designed so that any condensate will drip from their inlet and outlet faces.

3.1.5 The inlet air temperature must not exceed 150°F (65°C).

3.2 SUPPORTING STRUCTURE

3.2.1 The plenum must be supported or suspended in a manner consistent with the weight of the modules. Each 2x2x2-foot (0.6x0.6x0.6-m) module weighs 470 lb (213 kg), plus 12 lb (5.5 kg) if equipped with dolly wheels and 16 lb (7.3 kg) if equipped with a lifting frame.

3.2.2 Each module must be placed horizontally and level within 1/4 in. per foot (20 mm per meter).

3.2.3 Each module must be oriented with the indicator arrows pointing in the direction of the air flow during the discharge (i.e., freezing of the thermal energy storage material) part of the operating cycle. Air flow during charging may be in either direction.

3.3 INSULATION

3.3.1 This discussion is based on the physical units customary in the U.S. air conditioning trade. Conversions to other units will be supplied by ARTECH on request.

3.3.2 The following quantity depends on the materials used in the storage plenum:

R = insulation value of plenum walls, top, bottom and sides ($ft^2 \cdot hr \cdot °F/Btu$)

The R value is usually obtainable from the maker of the insulating material or from handbooks.

3.3.3 The following quantities depend on the arrangement of modules:

s = number of modules in series (tandem)

p = number of these tandem groups in parallel

h = number of series-parallel groups stacked vertically

3.3.4 To compute the area to be insulated, calculate

$$A = 8(sp + sh) = 8s(p + h)$$

This is the area around the top, sides, and bottom of the enclosure. The inlet and outlet ends are presumably occupied by the duct connections.

3.3.5 To compute the temperature differential, subtract the average ambient temperature outside the plenum from 90°F:

$$T = 90 - T_A \qquad (°F)$$

3.3.6 The rate of heat loss from the storage plenum is approximately

$$Q = AT/R = 8s(p + h)T/R \text{ (Btu/hr)}$$

3.3.7 The total storage capacity is approximately

$$C = 27{,}000sph \text{ (Btu)}$$

3.3.8 The half-retention time (i.e., the time required for half the stored heat to be lost) is

$$t_{hr} = C/(2Q) = 13{,}500sphR/[8s(p + h)T]$$
$$= 1687phR/[(p + h)T]$$

3.3.9 The required R value of the insulation is

$$R = t_{hr}\ (p + h)\ T/(1687ph) \quad (ft^2 \cdot hr \cdot °F/Btu)$$

3.3.10 EXAMPLES

3.3.10.1 A small heat storage unit in a basement space maintained at 65°F, has three 2x2x2-ft modules in series. What insulation value is required to retain half the stored heat for seven days? The numerical values are

t_{hr} = 168 hr

p = 1 module (width of array)

h = 1 module (height of array)

T = 90° - 65° = 25°F

The calculated insulation value is

$$R = 168\ (1 + 1)25/(1687 \cdot 1 \cdot 1)$$
$$= 5.0\ (ft^2 \cdot hr \cdot °F/Btu)$$

3.3.10.2 A heat storage unit for a home, consisting of three parallel sets each having nine modules in series, is exposed to outside air at an average temperature of 30°F and is required to retain at least half of its stored heat for four days. What insulation value is required?

t_{hr} = 96 hr

p = 3 modules in parallel

h = 1 module high

T = 90° - 30° = 60°F

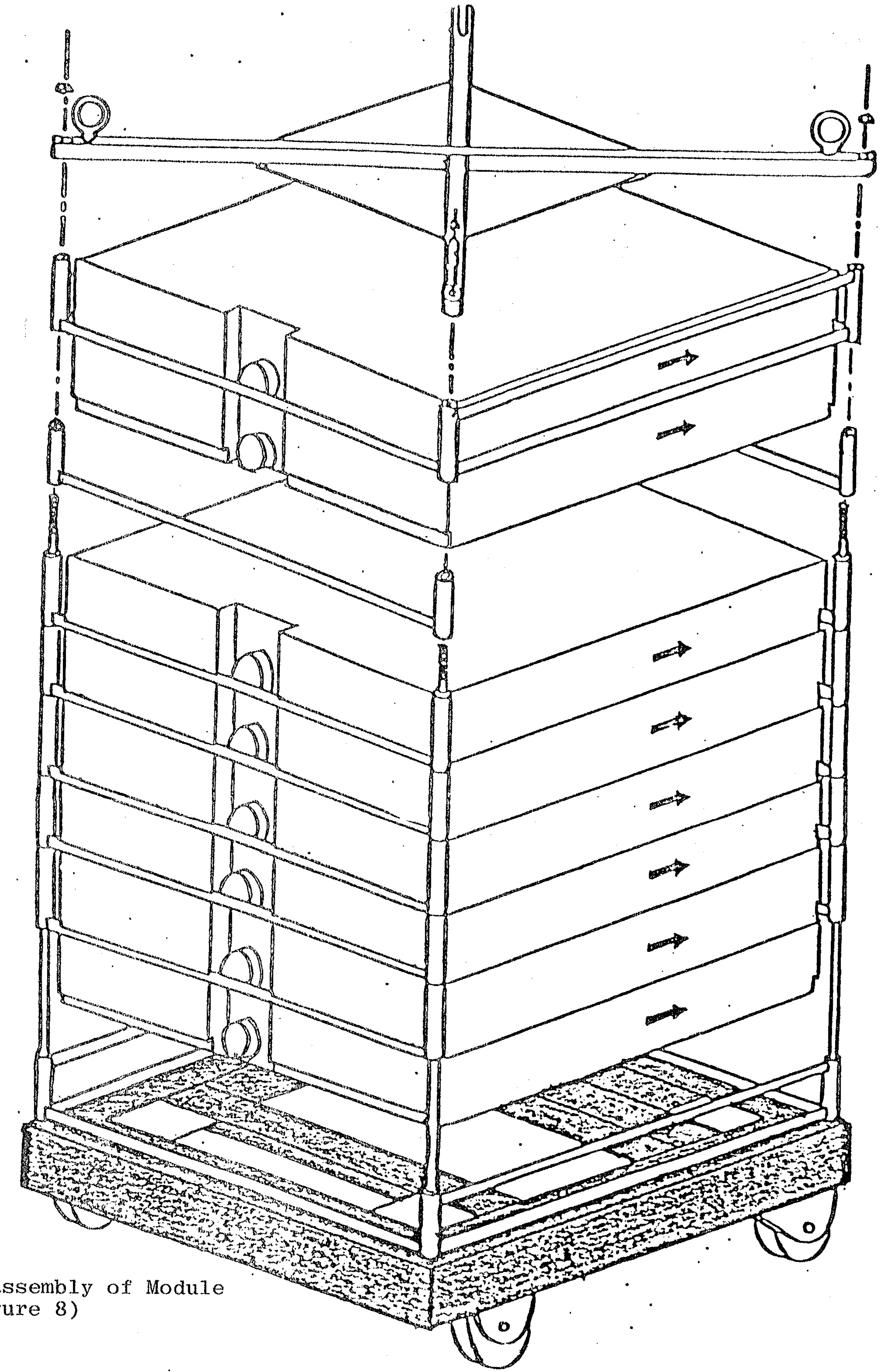
The calculated insulation value is

$$R = 96(3 + 1)60/(1687 \cdot 3 \cdot 1)$$
$$= 4.6(ft^2 \cdot hr \cdot °F/Btu)$$

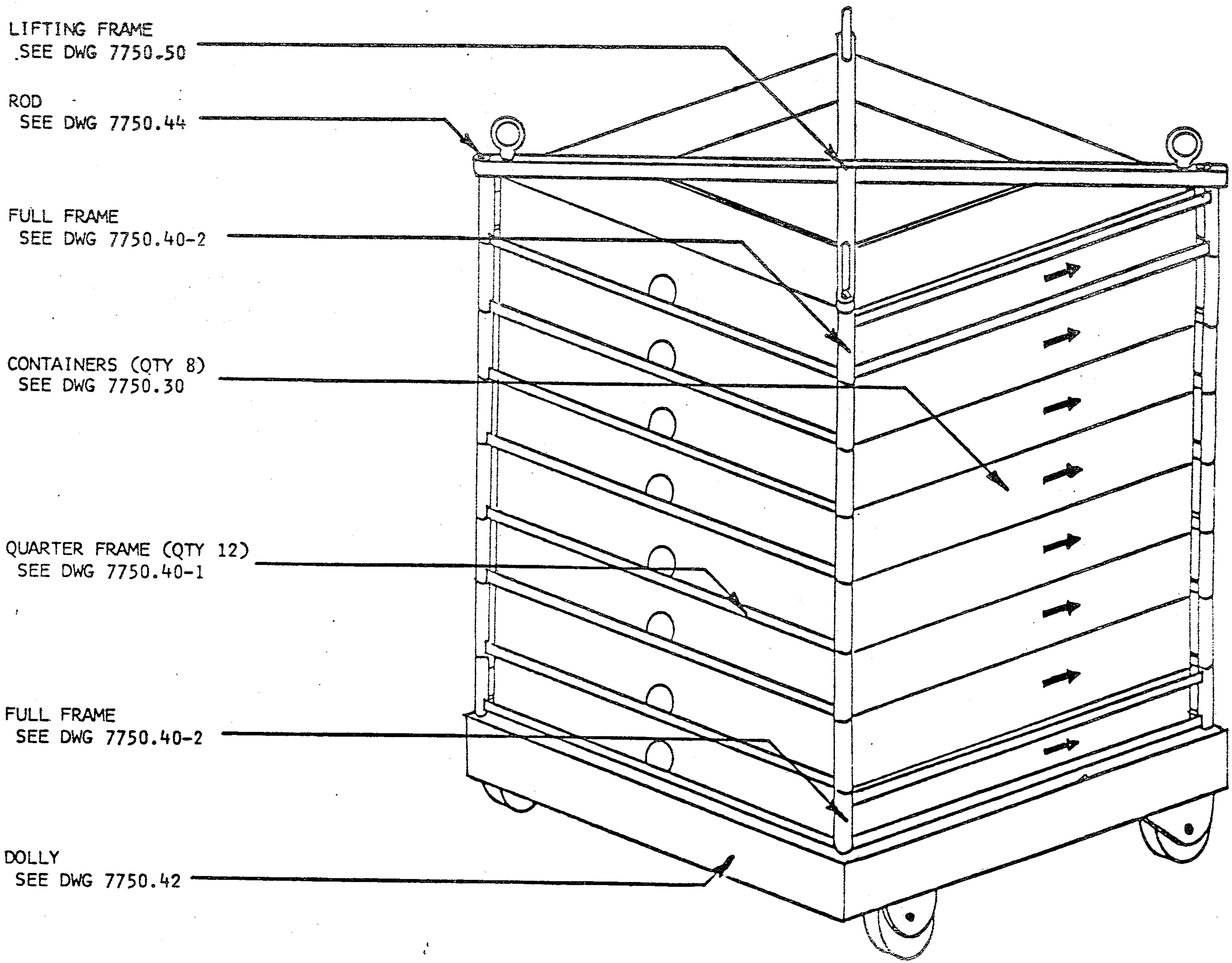
3.4 SETTING THE MODULE IN PLACE

3.4.1 DO NOT lift module by the containers or the frame elements around them. Lift by the eye-bolts on the lifting frame (with a suitable sling so the module remains horizontal) or by the base or dolly.

3.4.2 If necessary, some or all of the containers may be removed to facilitate moving the module into position. To remove the containers, remove the four nuts at the top corners and lift off the lifting frame. Then remove each plastic container, followed by the frame elements that supported it. Note carefully the position of each component as you remove it. DO NOT DROP THE PLASTIC CONTAINERS. In reassembling the module, make sure that the plastic containers are correctly oriented with respect to the dolly wheels and that each container is supported at the inlet and outlet ends by its frame elements. The arrows on all containers should point in the same direction. When all parts have been replaced, tighten the nuts on the corner rods to a torque of approximately 15 lbf·ft. (20 N·m). (See figure 8.)



Disassembly of Module
(Figure 8)



(Figure 9)
Parts Identification

4. OPERATING INSTRUCTIONS

4.1 INITIAL CHECK

4.1.1 Inspect for leaks of thermal energy storage material or damage to the plastic containers.

4.1.2 Verify that the position of the module(s) is horizontal and level.

4.1.3 Verify that each module is oriented with the caps of the plastic containers toward the entering air during the discharge (i.e., freezing of the thermal energy storage material) part of the operating cycle.

4.1.4 Verify that any air spaces between the sides of parallel modules, between module(s) and plenum, or below the module base have been blocked off at the inlet and outlet of each module.

4.1.5 Verify the presence and operation of system controls to prevent the air inlet temperature from exceeding 150°F (65°C).

4.2 AIR FLOW RATE

4.2.1 Determine the desired air flow rate from system design calculations. The rate will normally be between 300 and 1000 cubic feet per minute (0.15 and 0.5 m^3/s) for each 2x2x2-ft (0.6x0.6x0.6-m) module.

4.2.2 Check actual flow rate with suitable instruments such as a flow meter and stop watch.

4.2.3 If actual flow rate differs from required flow rate, make necessary adjustments of fan(s) and/or damper(s).

5. MAINTENANCE

5.1 Inspect module(s) after every three to six months of operation for container leaks and cleanliness. If a leak is found, mop up with water and contact ARTECH regarding repair or replacement of the leaking container assembly. If dust has accumulated in the container air passages sufficiently to impair heat transfer, remove it with a vacuum cleaner, water spray, or compressed air.

5.2 If provision for condensation in the storage plenum is required, make certain that the condensate drain is not clogged. Verify that the provisions for control of the air flow, listed under "INSTALLATION, DUCT WORK", are still effective.

5.3 Check that system controls prevent the inlet air temperature from rising above 150°F (65°C).

TESMOD™ LIMITED WARRANTY

The thermal energy storage modules used for residential or commercial heating and/or cooling shall be warranted against defective materials and workmanship for a period of five years. Replacements will be made FOB the contractor's plant, subject to receipt of defective items, shipment prepaid, and the contractor's examination confirming the defect. This warranty specifically excludes failure due to overheating or mechanical damage, usage in research or experimental applications, or installations other than those made under the supervision of an authorized representative of ARTECH CORP. This limited warranty supersedes any other warranty, express or implied.

☆ U.S. GOVERNMENT PRINTING OFFICE 1981—740-006/407 REGION NO. 4

APPROVAL

DEVELOPMENT AND TESTING OF THERMAL ENERGY STORAGE MODULES FOR USE IN ACTIVE SOLAR HEATING AND COOLING SYSTEMS

FINAL REPORT

By John C. Parker

The information in this report has been reviewed for technical content. Review of any information concerning Department of Defense or nuclear energy activities or programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

William A. Brooksbank, Jr.

WILLIAM A. BROOKSBANK, JR.
Manager, Solar Energy Applications Projects