N O T I C E

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FINAL REPORT

PHASE II

PARAMETRIC STUDY OF THERMAL STORAGE CONTAINING ROCKS OR FLUID FILLED CANS FOR SOLAR HEATING AND COOLING

FEBRUARY 1981

Principal Investigator:

Hrishikesh Saha

Prepared For

National Aeronautics and Space Administration

George C. Marshall Space Flight Center

Technical Monitor: Dr. W.R. Humphries

Grant No. NSG-8041

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Alabama Agricultural and Mechanical University

SCHOOL OF TECHNOLOGY

HUNTSVILLE, ALABAMA

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Huntsville, Alabama 35762

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FOREWORD

This report describes the work done for the NASA/MSFC Grant No. NSG-8041, "Parametric Study of Thermal Storage Containing Rocks or Fluid Filled Cans for Solar Heating and Cooling". This report includes literature survey, description of a thermal storage test facility with test data acquisition instrumentation, a test plan for the parametric study of tin cans filled with water and of standard bricks as thermal storage mediums, and final test data with an analysis of the data.

This experimental research program was a continuation of the previous NASA/MSFC Grant No.NSG 8041, "Parametric Study of Rockpile Thermal Storage for Solar Heating and Cooling". The first phase of this project contained the design and initial implementation of the test facility and some test results (27). This second phase completes the proposed objectives.

This research program contributed extensively to improve faculty and student-research capability at the Alabama A & M University. The author appreciates the help received from the school of Technology faculty and staff. A special recognition is due to the graduate assistants (Cephas Agola, Edward Woods, Seyed A. Alavi, John Y. Wu, Falamarz Baiat, Hwai-Tsu Wang, Shu-Jung Wang, Hor-Ching Peter Wang) and Mrs. Debra Hundley, secretary, those who supported the tests, analysis and report preparation activities for this project during the last three years.

The author wishes to acknowledge the helpful assistance and advice received from NASA specialists--Dr. W.R. Humphries, Mr. Sam E. Clonts, Mr. Fred Zur Burg, and his associates, Mr. Juan E. Maldonado, Mr. Olin K. Duren, and Mr. Joe E. Zimmerman and his associates. The author would also like to express his appreciation to Mr. Marion I. Kent, Assistant for University Relations, NASA/MSFC, for his effort in making this grant possible. Hope, this type of basic research will be supported by NASA in the future.

A special thanks to General Shale Products, Corporation Huntsville Brick and Tile Div., for providing this project with bricks, free of charge, which were tested as solar thermal storage medium.

PARAMETRIC STUDY OF THERMAL STORAGE CONTAINING ROCKS OR FLUID FILLED CANS FOR SOLAR HEATING AND COOLING

ABSTRACT

The primary objective of this investigation is to present the test data and an analysis of the heat transfer characteristics of a solar thermal energy storage bed utilizing water filled cans and standard bricks as energy storage medium. This experimental investigation was initiated to find new usable heat intensive solar thermal storage device other than rock storage and water tank which have been the basic storage used thus far. Four different sizes of soup cans were stacked in a chamber in three different arrangements-vertical, horizontal, and random. Air is used as transfer medium for charging and discharge modes at three different mass flow rates and inlet air temperatures respectively. These results were analyzed and compared, which show that a vertical stacking and medium size cans with Length/Diameter (L/D) ratio close to one have better average characteristics of heat transfer and pressure drop. The containerization process can be made economically acceptable if it is produced commercially in large quantities. Due to the internal anti-rusting coating of metal cans and very small corrosivity of water, the containers will be usable for fifteen to twenty years. Outside moisture rusting can be prevented by dipping the containers in an appropriate

paint vat. These types of containerized fluid and salt thermal storage medium have a lower pressure drop, lower volume requirements and higher heat transfer and heat content values than other usual types; also these do not need any special type of storage chamber or heat exchange device. This containerization allows the storage chamber to be horizontal or vertical with respect to the air flow. A second set of tests were conducted using different types of standard bricks with various arrays of holes in horizontal and random arrangements. These results were then compared with those of water filled cans. Standard bricks with ten holes make excellent storage medium instead of rocks since bricks are easily available. The test results and analysis thus far show that these types of storage devices will be well suited for use with solar air systems for space and hot water heating in both active and passive systems.

INTRODUCTION

The literature survey (1) through (20) revealed that there was a need for basic experimental study on heat transfer and content characteristics, pressure loss, flow channelling, temperature stratification, and other properties of advanced solar thermal storage mediums and storage beds. For this purpose of an extensive parametric study to investigate the efficiencies of different thermal storage beds containing rocks, bricks, other solids, and containerized liquid and PCM, a multi-flow cycles storage test facility was designed during the first phase of this project (27) and a series of tests were conducted. The intent of the test series is to find the influences of the various parameters on the performance of the storage beds; size, type, and orientation of stacking of mediums; area and height of the storage unit; air flow rate; pressure drop across the test bed; inlet and outlet temperature of air; and temperature distribution in the test bed.

These objectives are served by following the steps outlined below.

a) A literature survey update of experimental and theoretical studies on solar thermal storage systems.

b) Descriptions of test facility and two types of thermal storage mediums (water filled soup cans and standard ten hole bricks).

c) Test plans

d) Results and discussions of the findings.

e) Conclusions and general comments.

LITERATURE SURVEY

A detailed literature survey of rockpile thermal storage application and analysis was given in the first phase report to NASA/MSFC {27}. The references {1-20} describes different types of thermal storages (Rockpile, Water filled glass jars. containerized PCM, etc.). References {21-23} demonstrates brick thermal characteristics which are useful as thermal storage mediums. References {24-26} represent some of the many recent developments in area of PCM as thermal storage medium. The remaining references list some of the papers and reports presented by the author during this project period.

TEST FACILITY

For the purpose of an extensive parametric study of heat transfer characteristics of rocks/bricks, of other solids, and of different shapes and sizes of containers filled with fluid/PCM, a multi-flow cycle storage test facility was designed and built (27). The general design information of the test facility is given in Fig. 1. A temperature controller regulate the four resistance heating elements of 5 KW each respectively. The electric blower with variable speeds can reach an air mass flow rate of 800-1600 cfm (0.377-0.755 cu.m.s.) for a 1.0 inch (2.54 cm) of water pressure drop. The inlet temperature range of the test section is 70° - 200°F (21.1° - 93.3°C). The storage test section height can be varied from 2 ft. to 8 ft. (0.6-2.4m). Integration of the above using ducts, turning vanes, dampers, intake and outlet valves, etc., forms an air tight and thermally insulated system. Temperature measurements of air, water, brick, and surfaces at various points are taken by using copper-constantan thermocouples (type T) with a tape driven multi-point data logging system and a thermocouple reference junction. The reference (27) contains further detailed design and instrumentation information of the test facility. This design enables four different types of charge and discharge flow cycles in vertical storage mode (Fig. 2,3,4 & 5).

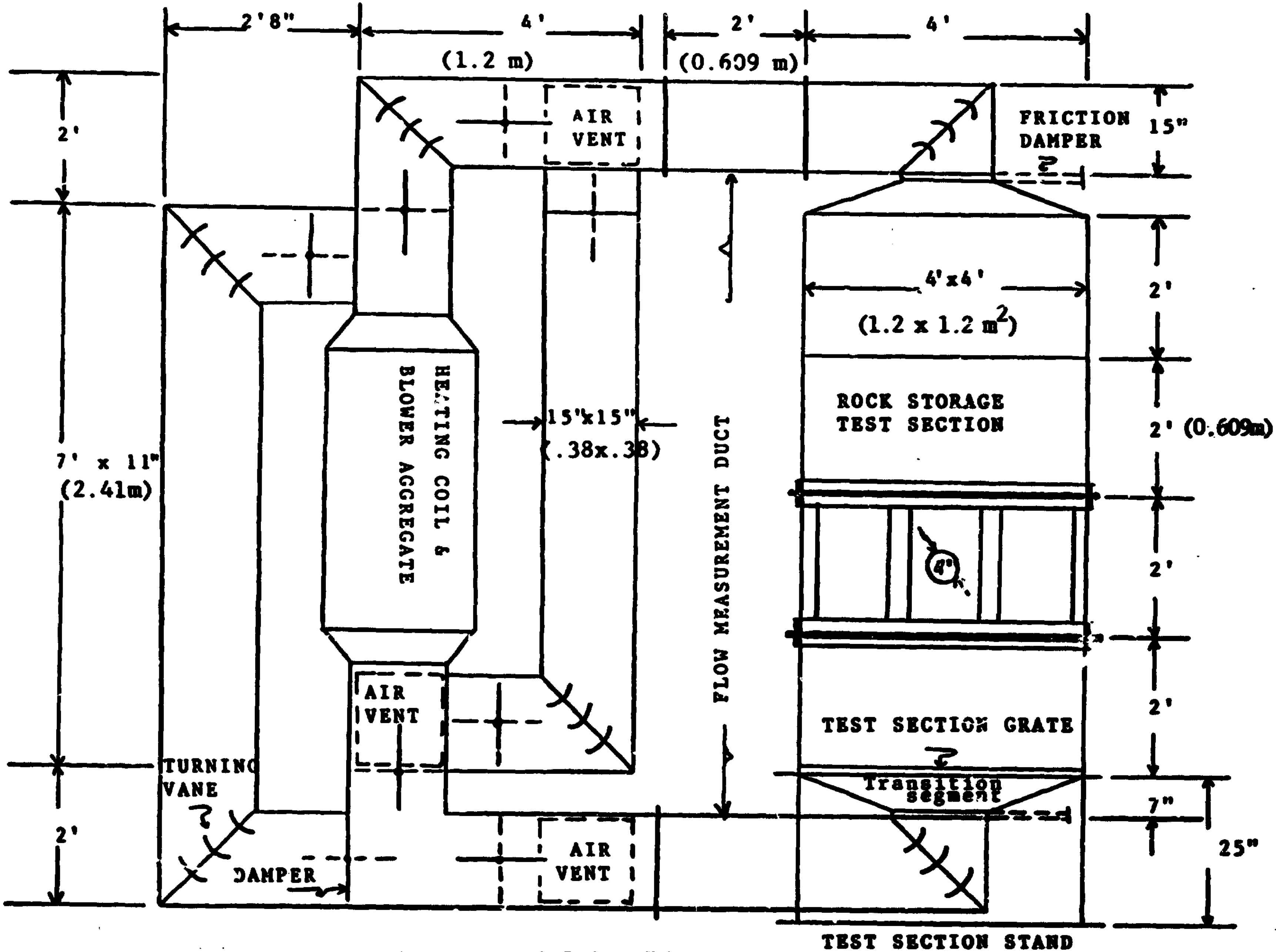


FIG. 1 ROCK STORAGE TEST FACILITY

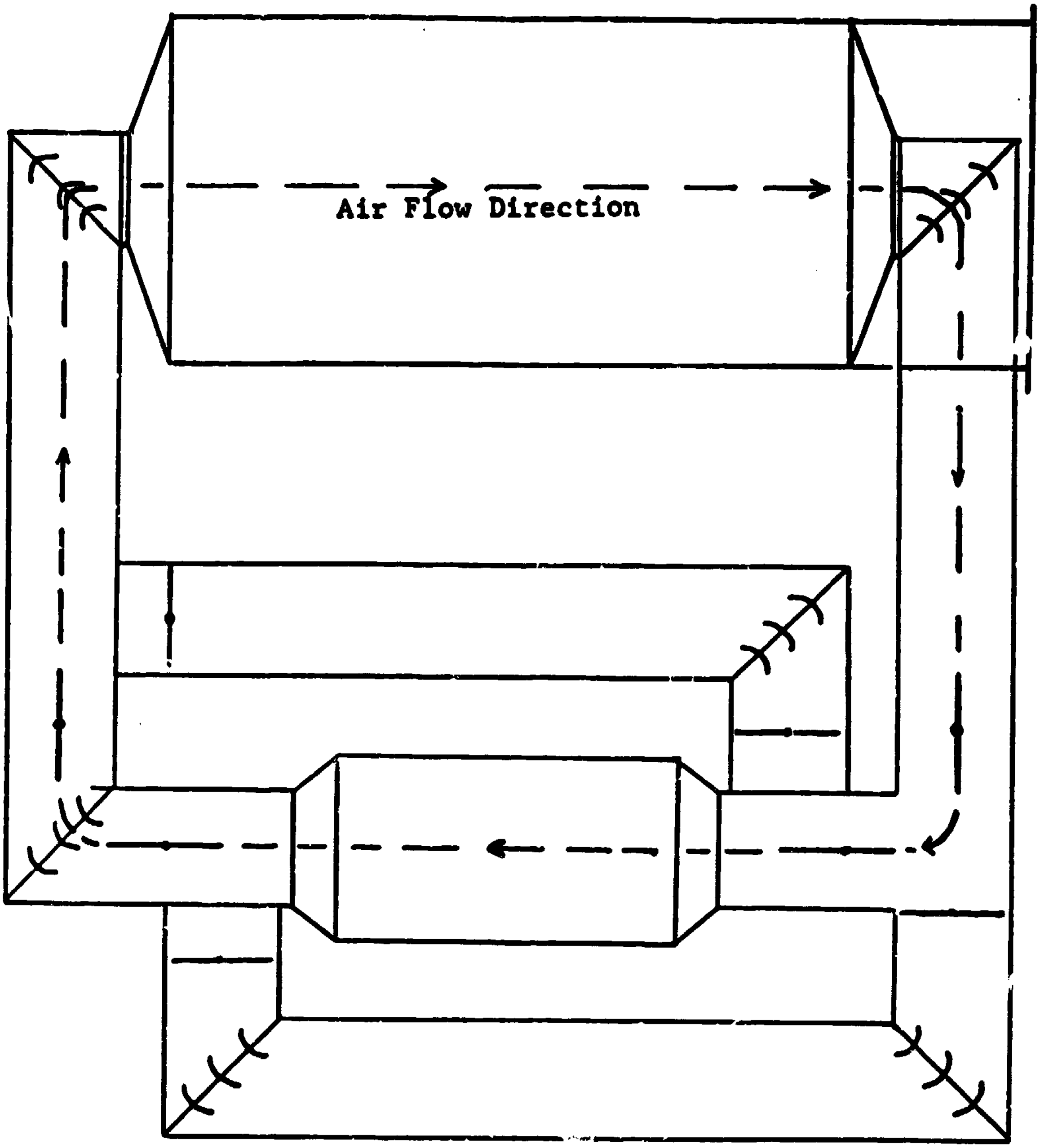


FIG. 2 CHARGING MODE 1

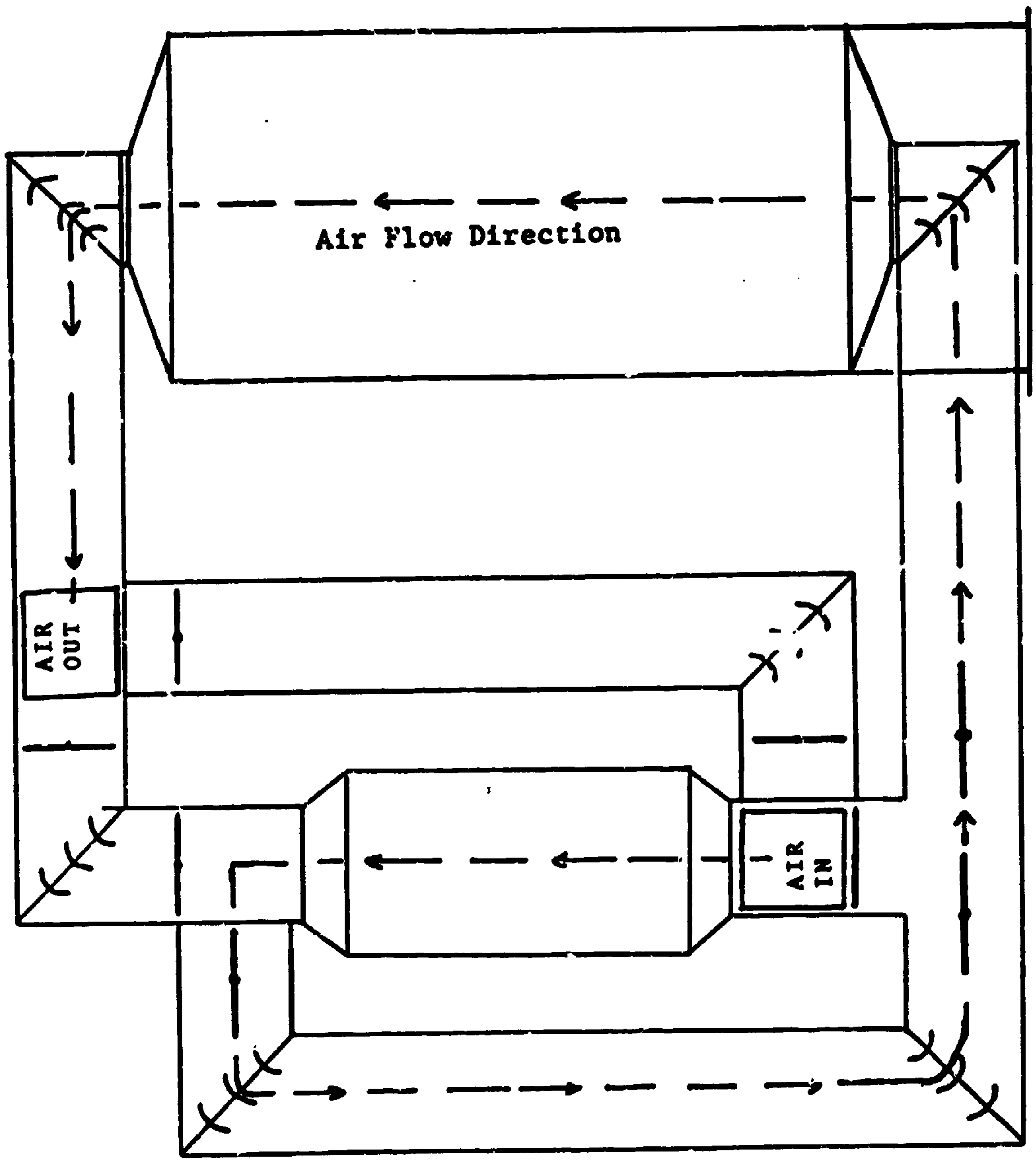


FIG. 3 DISCHARGING MODE 1

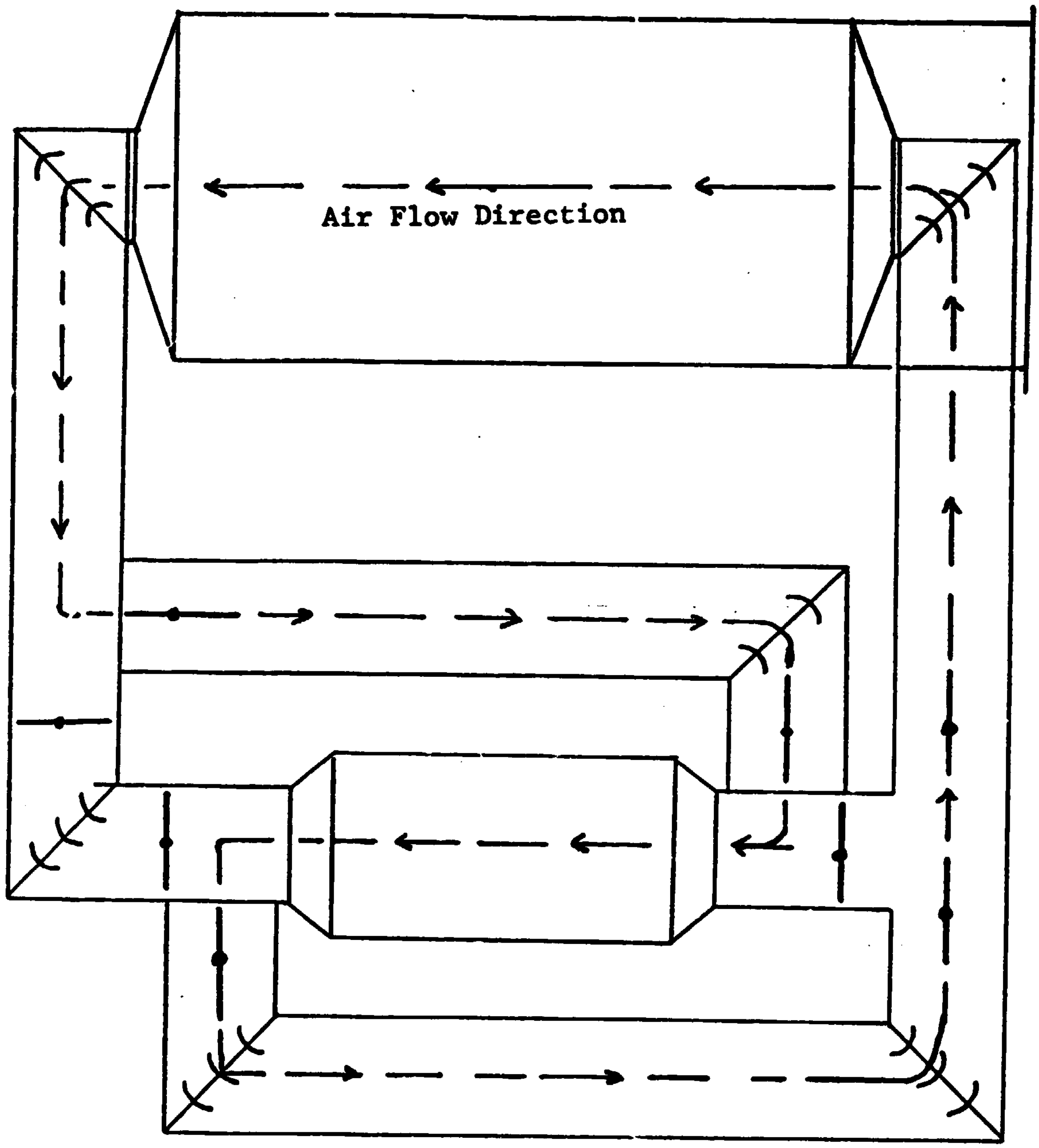


FIG. 4 CHARGING MODE 2

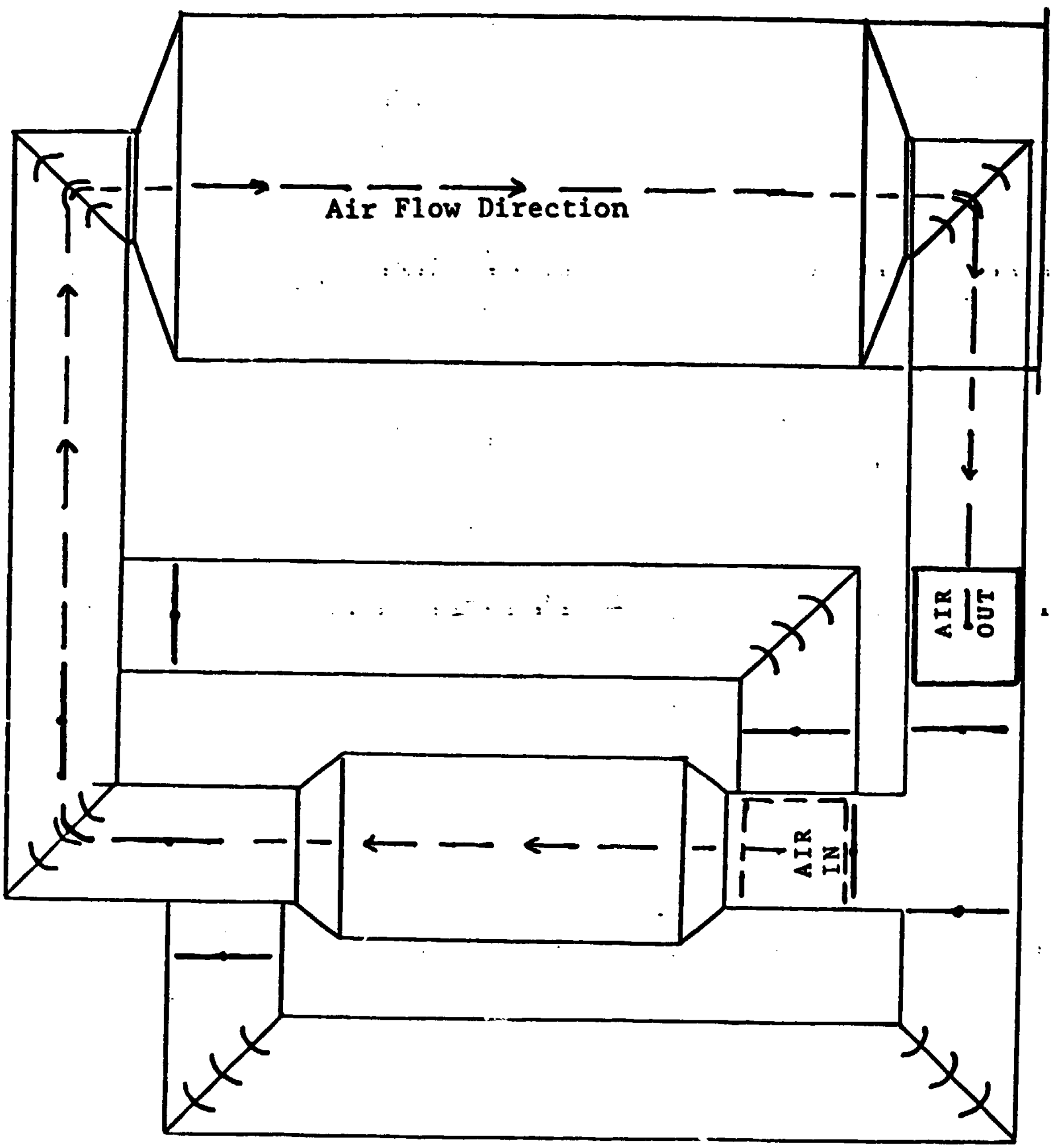


FIG. 5 DISCHARGING MODE 2

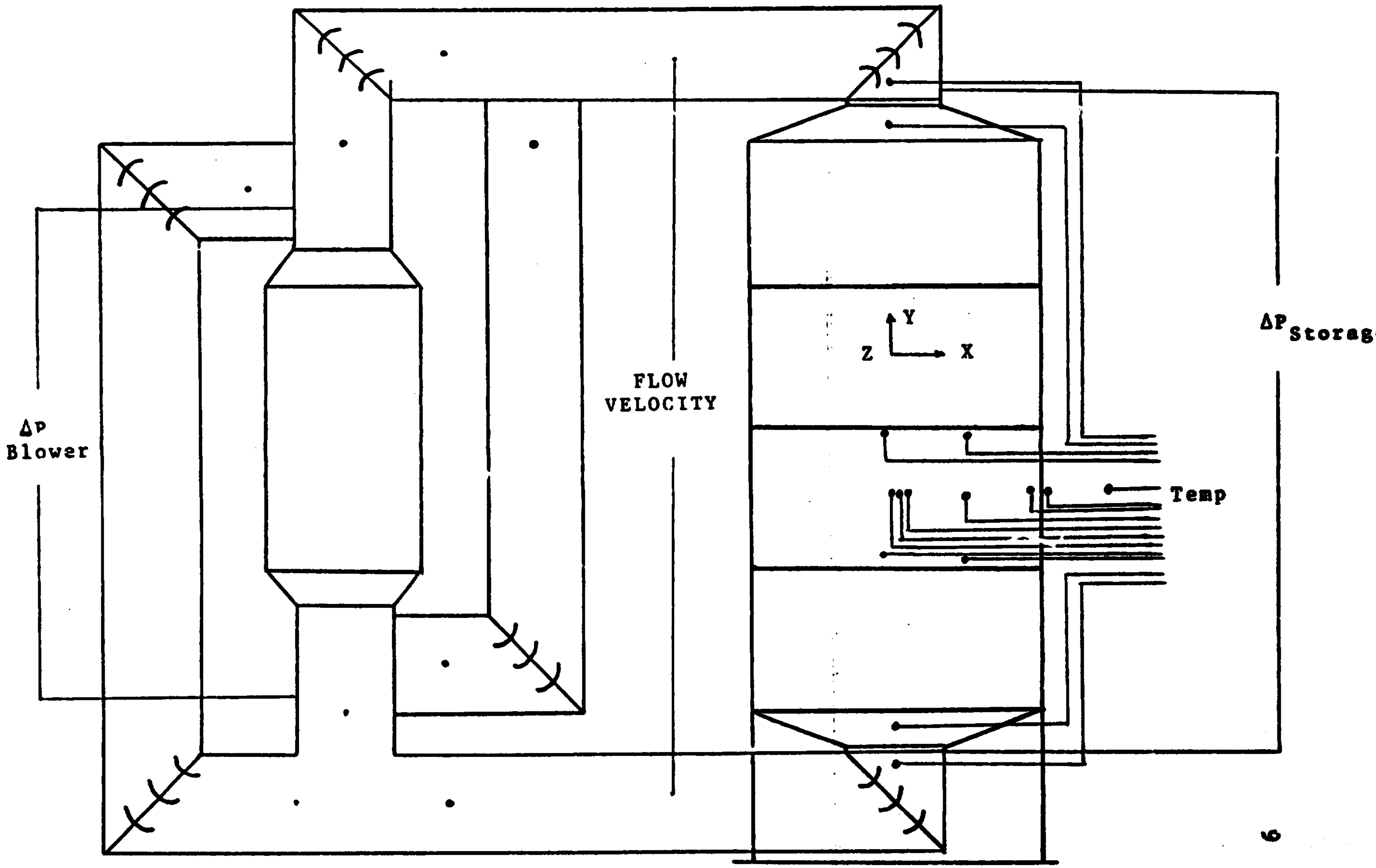


FIG. 6. GENERAL INSTRUMENTATION

TEST PLAN

The Tables 1,2, & 3 show the test specifications and storage medium properties. The test was conducted in a storage bed of 2 ft (0.61 m) height and 4 ft x 4 ft (1.2m x 1.2 m) square. The water filled metal soup can sizes tested were, L/D = 1.09, 1.45, 0.807, and 159. Cans were stacked in random, vertical, and horizontal arrangements (Fig. 7). Standard ten hole bricks of 7.9 in x 3.6 in x 2.3 in (20 cm x 9.2 cm x 5.7 cm) size were also tested in horizontal and random arrangements. Inlet air temperature for charging mode 100°F (37°C), and 160°F (71°C) and inlet air velocities were 500 (2.54), 600 (3.05), 700 (3.56) fpm (mps). During the charging mode, the hot air is blown from the top to the bottom of the storage bed. During the storage mode, the storage bed is isolated by shutting down the inlet and outlet dampers to measure the heat storage characteristics of the medium and the bed. During the discharge mode constant temperature room air is blown through the bottom to the top of the storage bed to determine the heat releasing mechanism of the cans. The air velocities of discharge were 300 (1.52), 400 (2.32), and 500 (2.54) fpm (mps) respectively.

Table 1. Properties of Water Filled Cans

TEST STORAGE SPECIFICATIONS AND PROPERTIES				
Property \ Can Type	I	II	III	IV
Length (L) (cm)	10.16	17.78	8.89	7.62
Diameter (D) (cm)	6.985	11.176	11.176	6.985
L/D	1.45	1.59	0.80	1.09
Surface Area (m^2)	0.029	0.082	0.051	0.024
Water Wt./can (kg)	0.292	1.418	0.680	0.198
Empty Wt./can (kg)	0.056	0.170	0.113	0.043
Volume/can (m^3)	0.388×10^{-3}	0.173×10^{-2}	0.877×10^{-3}	0.292×10^{-3}
Water Wt./Surface Area (kg/m^2)	9.741	17.275	13.371	8.145
Total cans	1310	270	563	1928
Void Fraction	0.44	0.48	0.45	0.37
Apparent Specific Heat of Can & Water (J/kg ^oc)	3587.83	3784.60	3654.81	3529.22

Storage bed Height = 0.6096 m.
Storage bed and plenum volume = 1.132 m^3.
Air Mass Flow Rates: cu. ms/sec (M/S).
Charging Mode - 0.368 (2.54), 0.442 (3.048), 0.516 (3.556).
Discharge Mode - 0.221 (1.524), 0.295 (2.032), 0.369 (2.54).
Can Storage Orientation = Randome, Vertical, and Horizontal.
Inlet Air Temperature range = 32.2 ^oc - 93.3 ^oc.
Specific Heat of Water = 4186.5 (J/kg ^oc).
Specific Heat of Can = 460.52 (J/kg ^oc).

Table 2. Properties of Water Filled Cans {BTU}

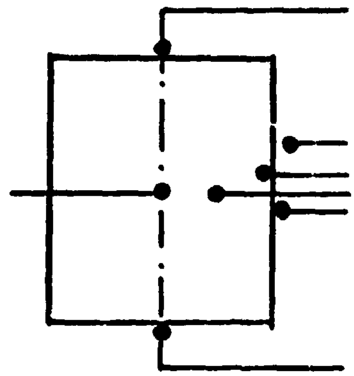
TEST STORAGE SPECIFICATIONS AND PROPERTIES				
Property \ Can Type	I	II	III	IV
Length (L) (in.)	4.0	7.0	3.5	3.0
Diameter (D) (in.)	2.75	4.4	4.4	2.75
L/D	1.45	1.59	0.80	1.09
Surface Area ($ft.^2$)	0.322	0.883	0.547	0.262
Water Wt./can (lb.)	0.644	3.125	1.5	0.437
Empty Wt./can (lb.)	0.123	0.375	0.25	0.0937
Volume/can ($ft.^3$)	0.0137	0.061	0.031	0.0103
Water Wt./Surface Area (lb./$ft.^2$)	1.996	3.54	2.74	1.669
Total cans	1310	270	563	1928
Void Fraction	0.44	0.48	0.45	0.37
Apparent Specific Heat of Can & Water (Btu/(lb. ^{o}F.))	0.857	0.904	0.873	0.843

Storage bed Height = 2 ft.
Storage bed plenum volume = 40 $ft.^3$
Air Mass Flow Rates: cfm (fpm).
Charging Mode - 781 (500), 937 (600), and 1093 (700).
Discharge Mode - 469 (300), 625 (400), and 781 (500).
Can Storage Orientation = Randome, Vertical, and Horizontal.
Inlet Air Temperature range = 90-200 ^{o}F.
Specific Heat of Water = 1 Btu/(lb. ^{o}F).
Specific Heat of Can = 0.11 Btu/(lb. ^{o}F).

Table 3. Properties of brick

Length	7.975 in.	20 cm.
Width	3.625 in.	9.2 cm.
Height	2.25 in.	5.7 cm.
Surface Area	1.117 $ft.^2$	.104 m^2
Weight	3.87 lb.	1.76 kg.
Volume	.027 $ft.^3$	$.762 \times 10^{-3} m^3$
Weight/Surface	3.465 $lb/ft.^2$	16.92 kg/m^2
Volume of Each Hole	$7.5 \times 10^{-4} ft.^3$	$2.12 \times 10^{-6} m^3$
Number of Hole in One Brick	10	10
Volume Ratio: Holes/Brick	.22	.22
Number of Bricks	504	504
Void Fraction	.575	.575
Specific Heat	.193 BTU/lb$^{\circ}$F	807.99 J/kg.$^{\circ}$C
Thermal Conductivity	.25 BTU/hr.ft.$^{\circ}$F	4.327 J/s.m.$^{\circ}$C

TEMPERATURE MEASUREMENTS IN AND AROUND
A CAN FILLED WITH LIQUID



CAN STORAGE TEST ARRANGEMENT

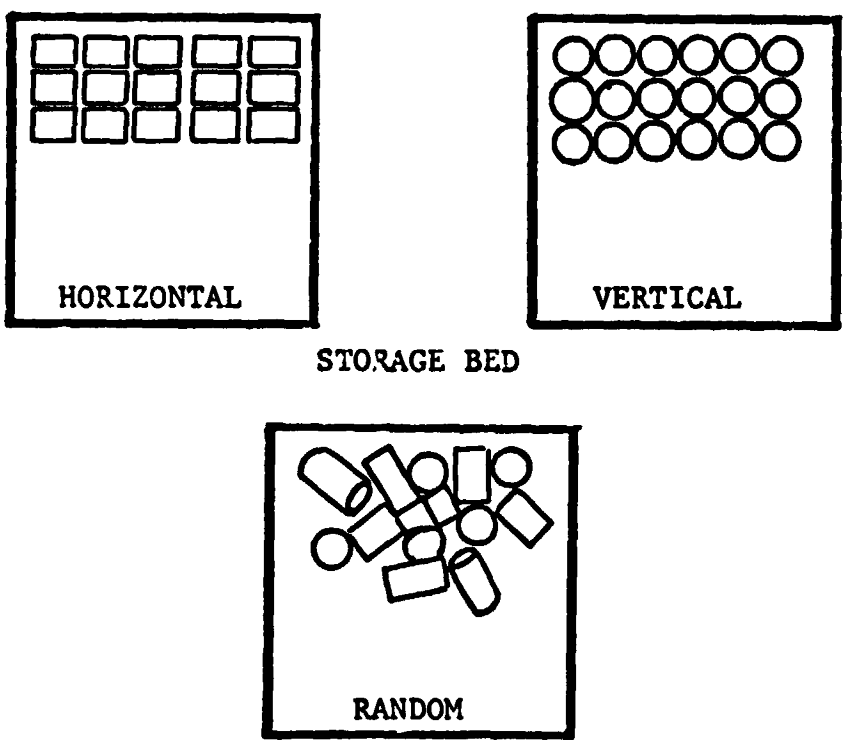


Fig. 7. STORAGE CONFIGURATIONS AND TEMPERATURE MEASUREMENTS

RESULTS AND DISCUSSIONS

To compare the heat transfer and heat content characteristics of the four sizes of cans several tests with similar conditions (mass flow rate, maximum inlet temperature, total mass of H_2O, and can arrangements) were performed. The figures 8 through 25 give the general trend of the results. The figures 8 and 9 show the charging and discharge mode air temperatures across storage bed with time respectively. The storage bed was heated in a closed loop to gradually heat the medium up to a present inlet temperature of 130 ^oF (54.4 ^oC) and then this temperature was kept constant for a period of time until a preset outlet air temperature of 125 ^oF (61.66 ^oC) was reached. The figure 9 shows the air heat gain from the cans in a reversed flow direction. A similar charge and discharge air temperature distributions with time in the storage bed containing bricks as storage medium are shown in figures 10 and 11. The pressure drop across bed (Fig. 12.) for various flow velocities, can/brick arrangements, and sizes. In all three cases, the vertical arrangement of cans (Fig. 7.) seems to have the lowest of all pressure losses. The horizontal arrangement for bricks has the lowest pressure drop (Fig. 12.). Pressure loss increases with increasing flow velocity. Figures 13. & 14. represent the temperature gradients between air flow and the can surface and between can surface and water in a can located at the center of the storage bed. Figure 15 shows the temperature gradients between air and brick surface and between brick surface and brick inner core (average) of a brick located at the center of the storage bed. Cans and bricks with smaller mass/surface area ratio have better heat acceptance characteristics. From these measurements the can internal film coefficient h_i and the outside film coefficient h_o are computed. An apparent thermal transmittance U for the storage system is derived using experimental data for each configuration and the coefficients as computed above, $U = 1/(h_o + 1/h_i)$. The variations of U-factor with time during charging mode for three different are velocities are showned in figure 16. This figure also contains water temperature variations of the center can with time. Fig. 17. through Fig. 23. record the maximum usable energy stored in the storage bed during charging mode with respect to various parameters. This energy was computed by $Q_{total} = \bar{C}_p \cdot M \cdot \Delta T$, where Q_{total} = maximum usable energy, $\bar{C}_p$ = apparent specific heat of the thermal storage medium, and ΔT = bed temperature increment. The cans with smaller mass/surface area store more heat than the larger ones during charging mode for a given time. The figures also show that where as, a smaller mass/surface area cans store more heat in vertical arrangement mode, the larger ones favour random arrangement. Figure 25. shows the charging and discharge mode total heat gain and heat release with time for three air flow rates. A few cases were run where the storage bed areas charged from the bottom through the top and kept for several hours in storage mode to see the effect of heat rise due to conduction and convection in the bed. The temperature stratification upwards was found to be very insignificant. From the measurements as shown in figure 15., an average brick conductivity k_i and the outside film coefficient h_o are computed. An apparent thermal transmittance U for the storage system is derived using experimental data for each configuration and material. The variations of U-factor with time during charging mode for two arrangements of brick are given in figure 24. This figure also shows the total heat storage characteristics of bricks. These figures show that horizontal arrangements with smaller mass/surface area bricks store more heat than other arrangements and types.

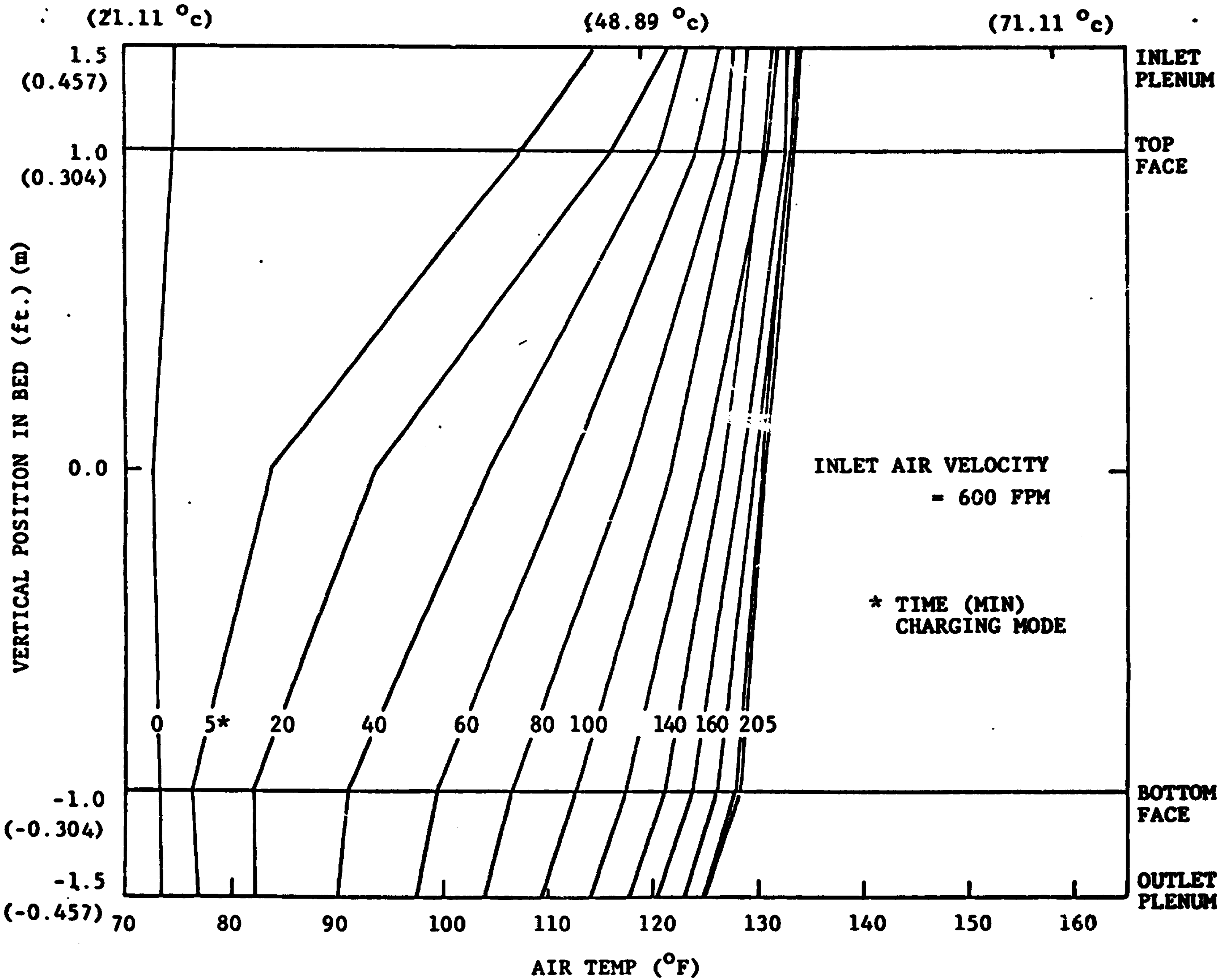


Fig. 8. AIR TEMPERATURE PROFILE IN BED DURING CHARGING MODE.

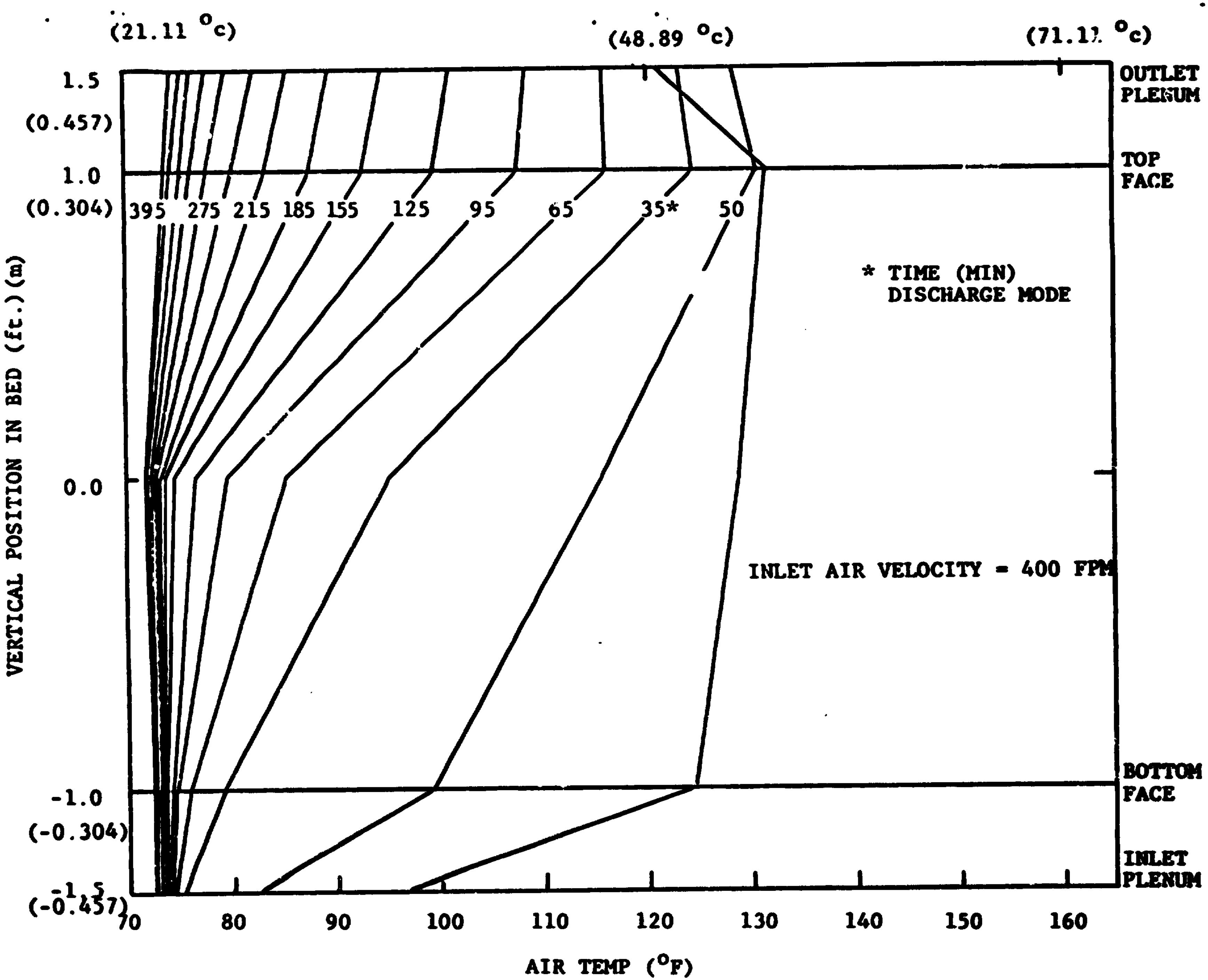


Fig. 9. AIR TEMPERATURE PROFILE IN BED DURING DISCHARGE MODE.

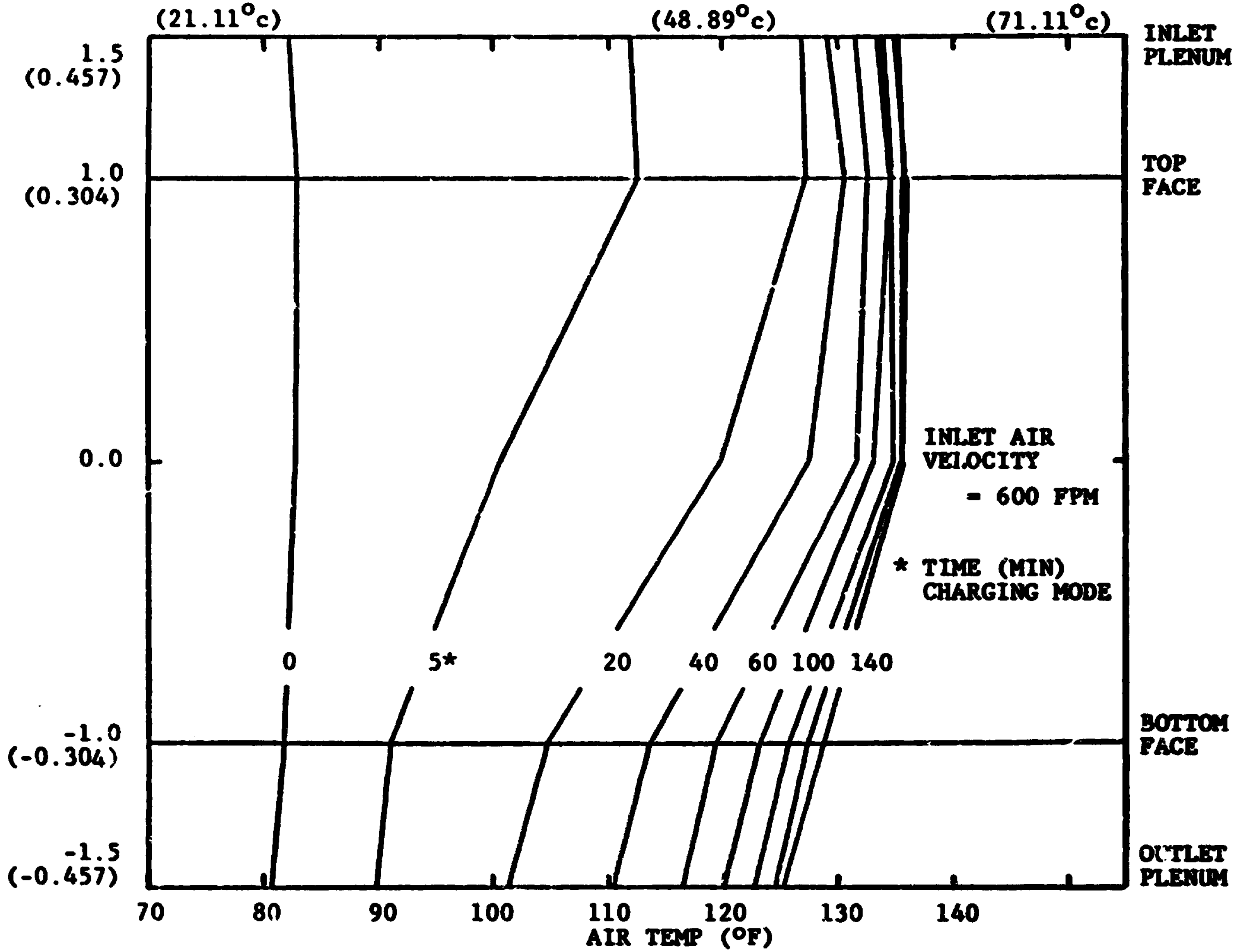


FIG. 10. AIR TEMPERATURE PROFILE IN BED DURING CHARGIFG MODE (BRICK).

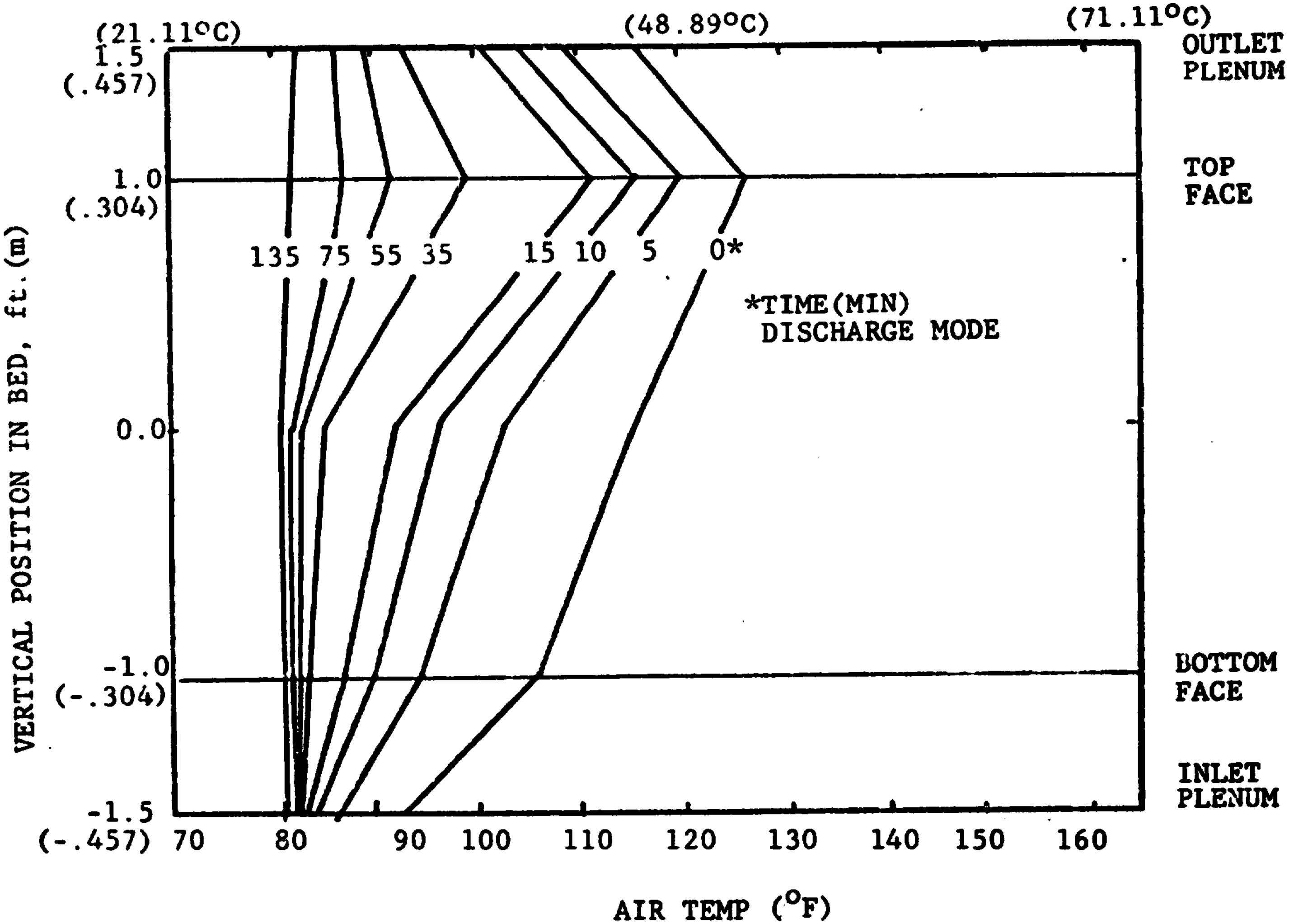


FIG. 11. AIR TEMPERATURE PROFILE IN BED DURING DISCHARGE MODE (BRICK)

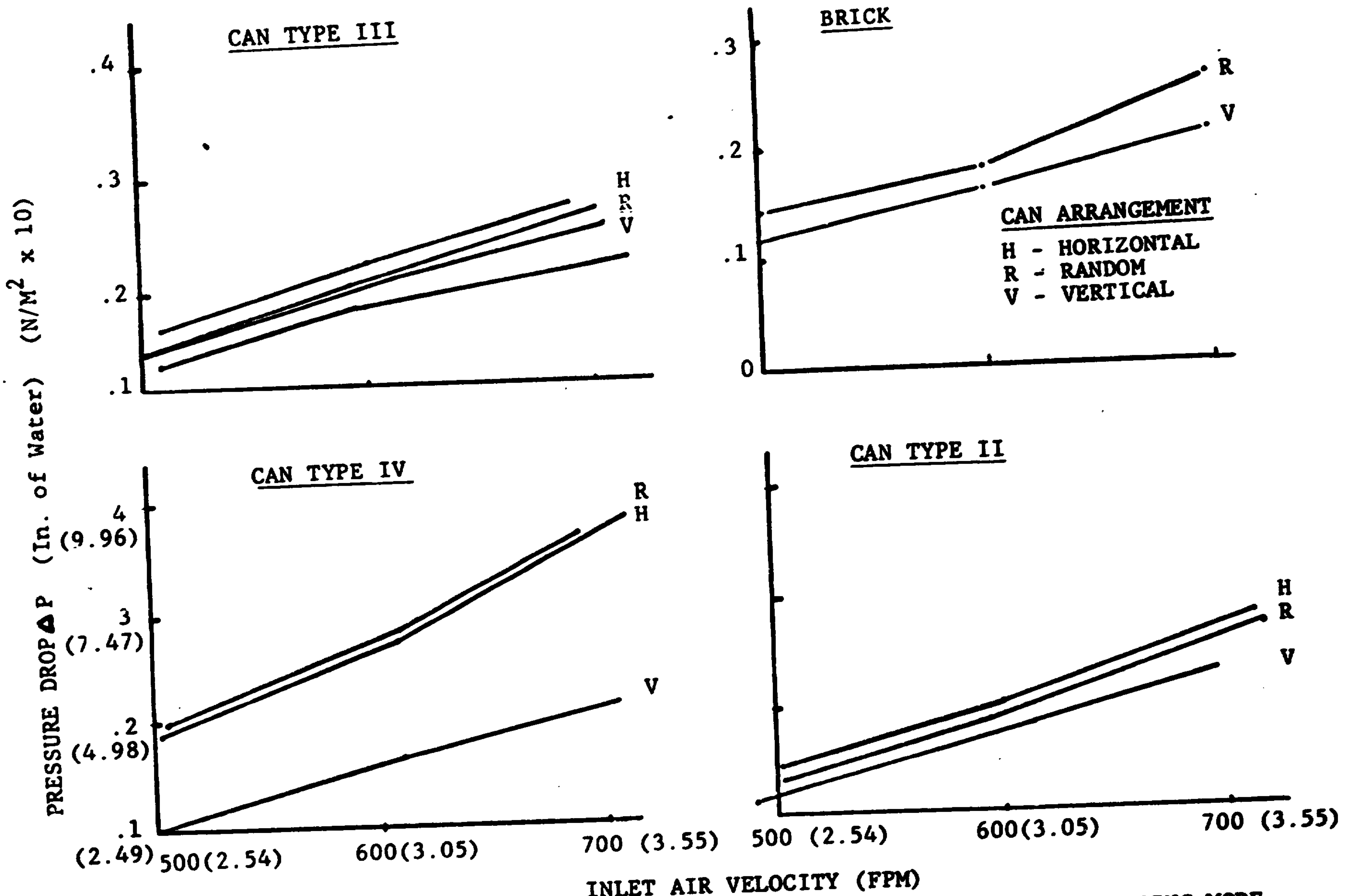


Fig. 12. PRESSURE LOSS CHARACTERISTICS ACROSS STORAGE BED DURING CHARGING MODE.

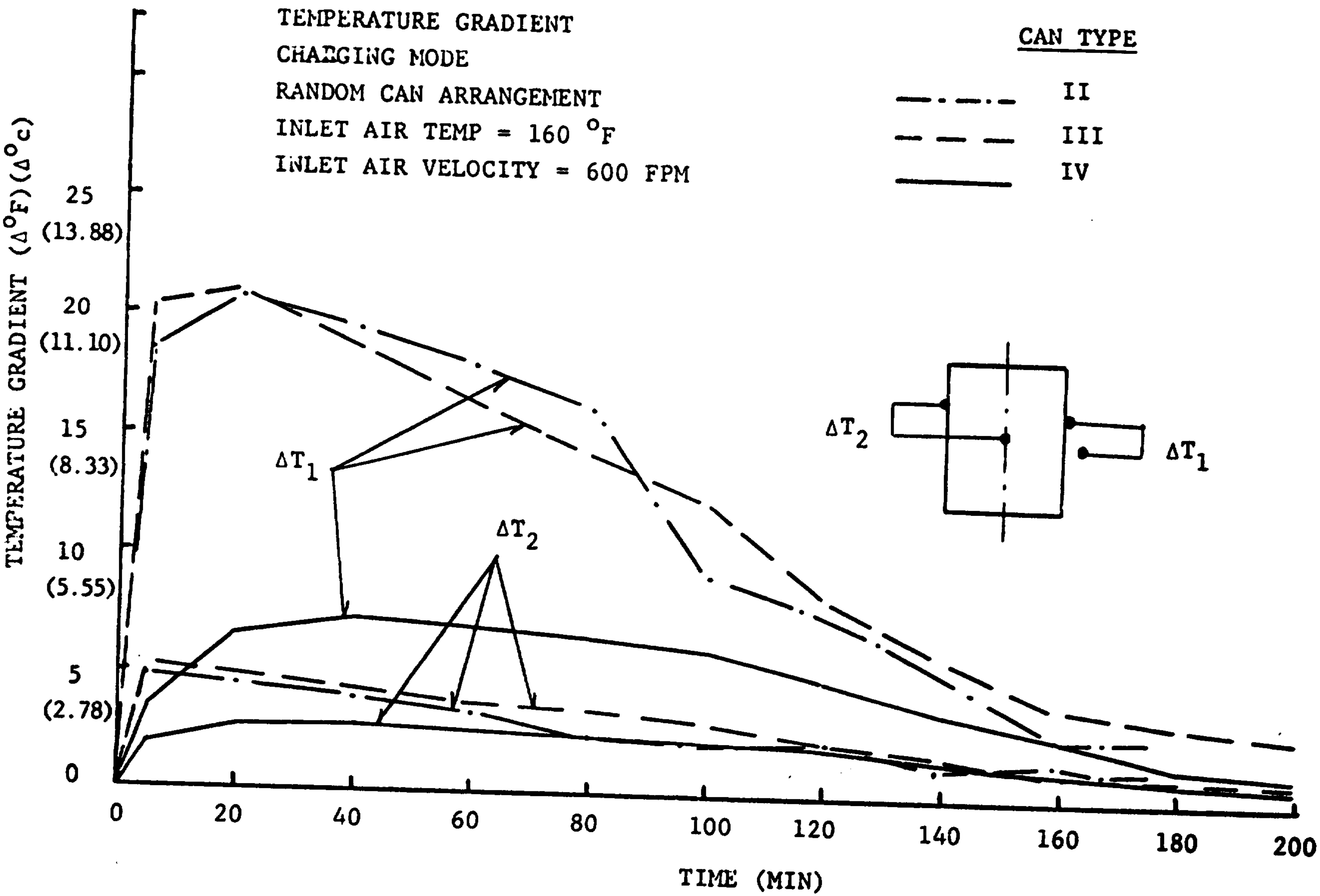


FIG. 13. TEMPERATURE GRADIENTS DURING CHARGING MODE.

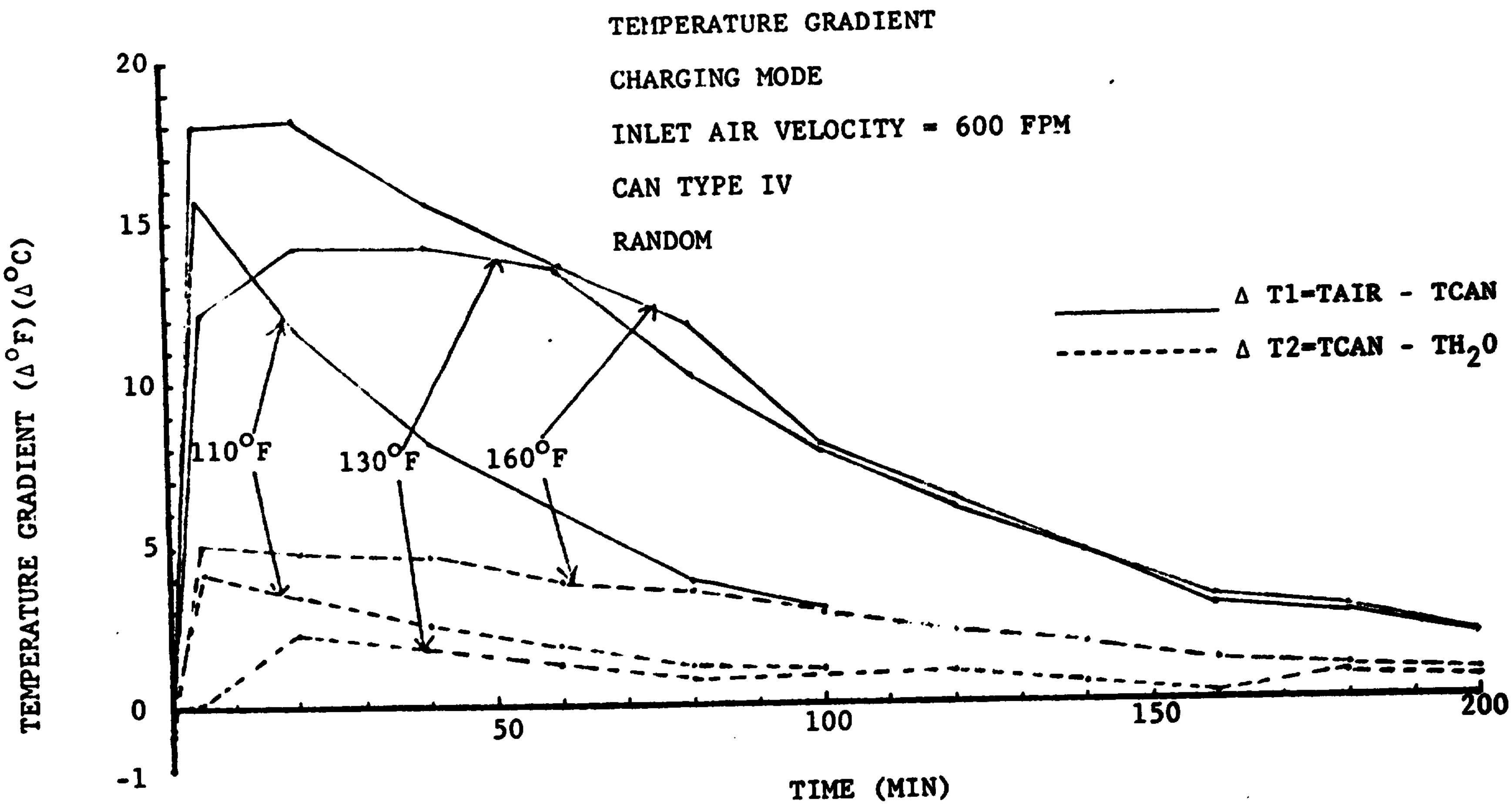


FIG. 14. TEMPERATURE GRADIENTS DURING CHARGING MODE

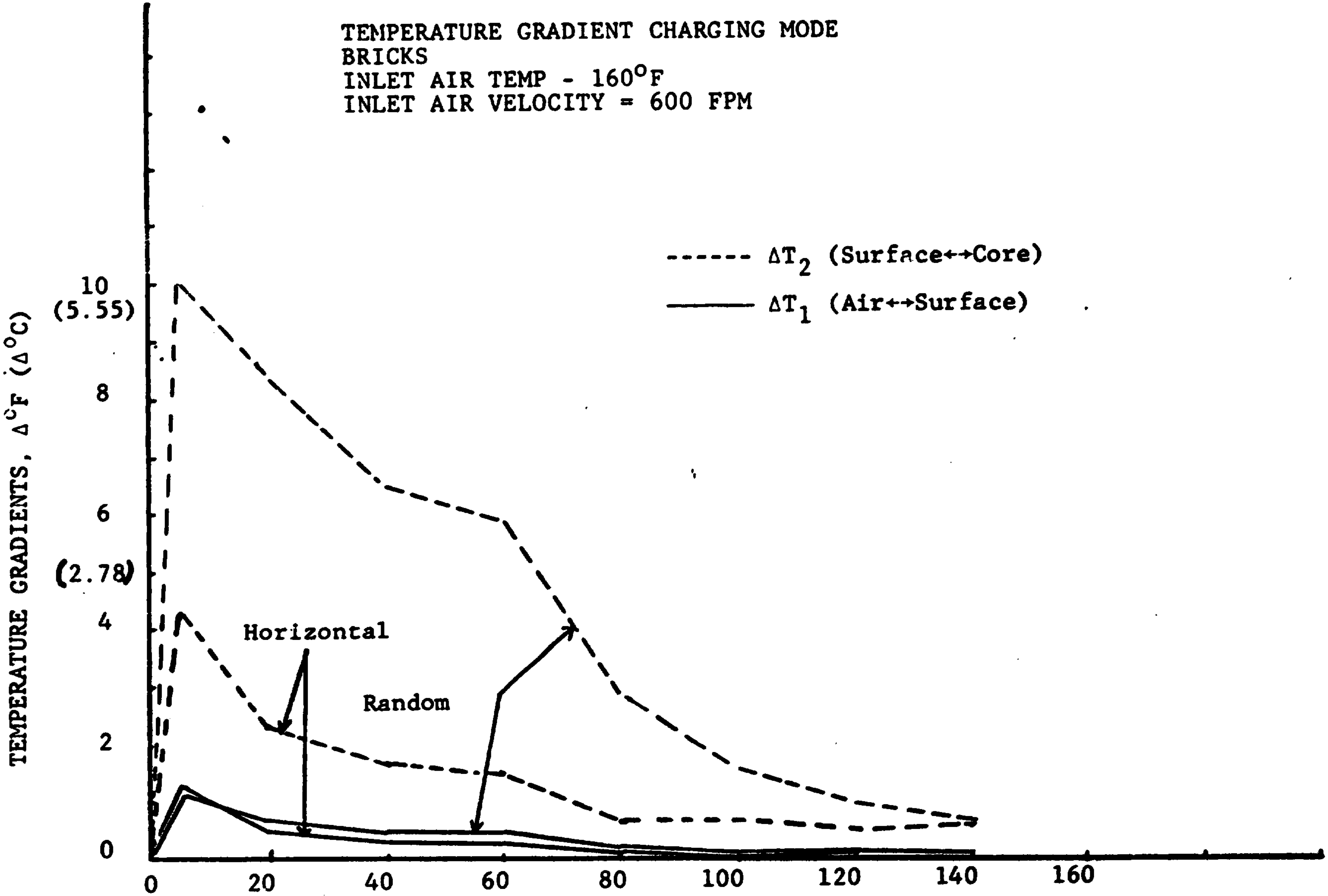


Fig. 15. TEMPERATURE GRADIENTS DURING CHARGING MODE

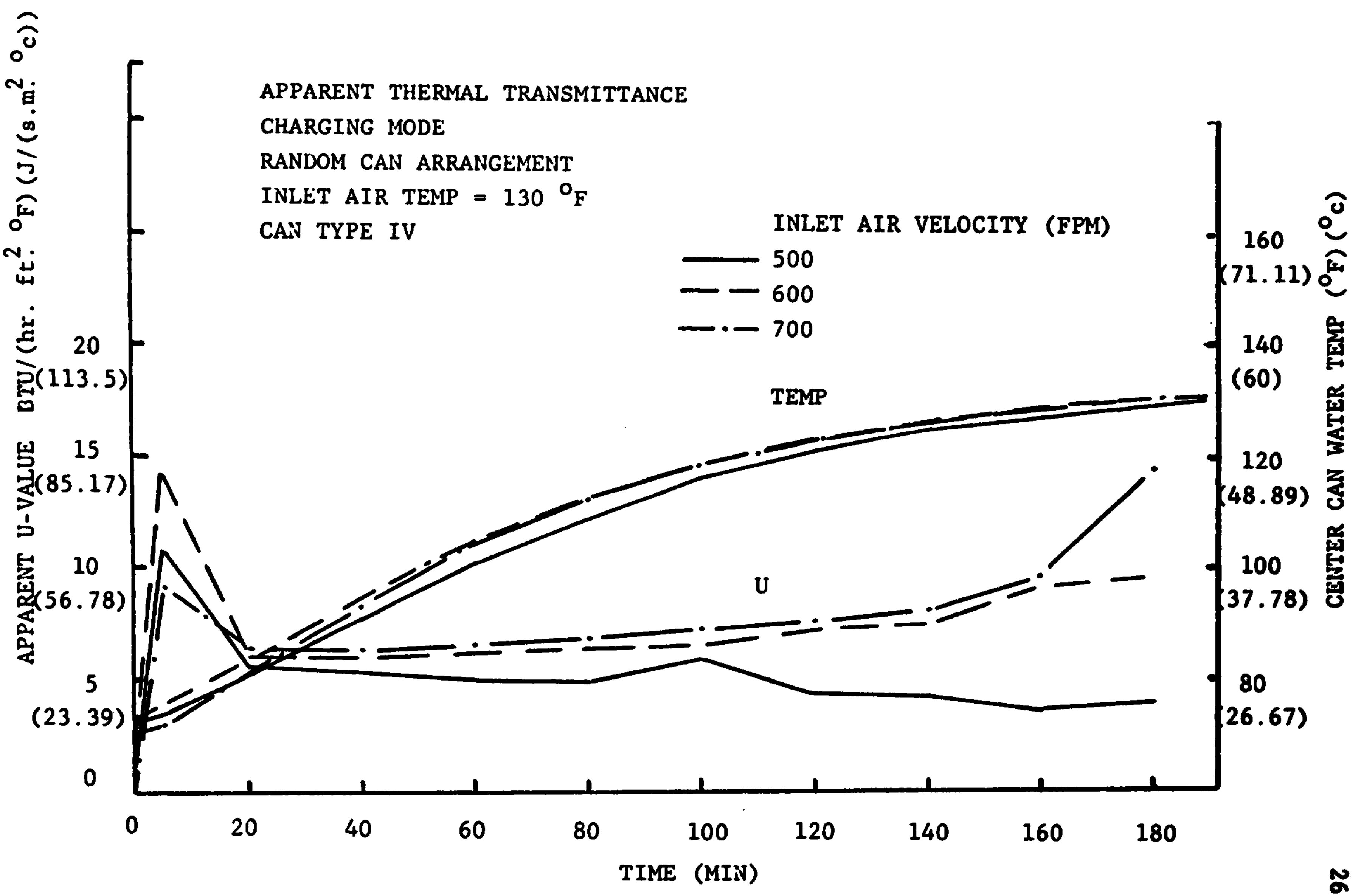


Fig. 16. APPARENT THERMAL TRANSMITTANCE OF THE STORAGE SYSTEM DURING CHARGING MODE.

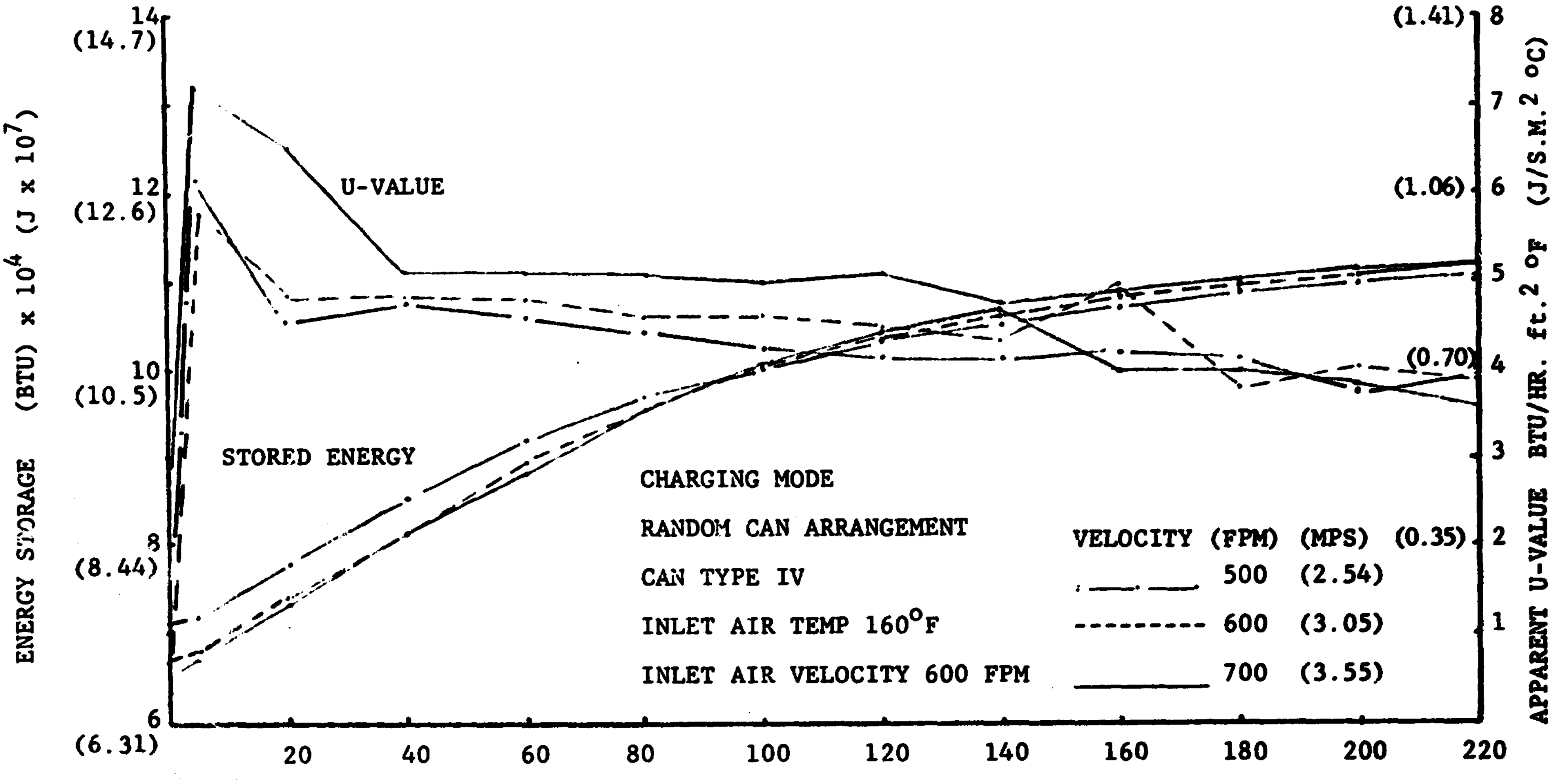


FIG. 17. ENERGY STORAGE AND APPARENT THERMAL TRANSMITTANCE

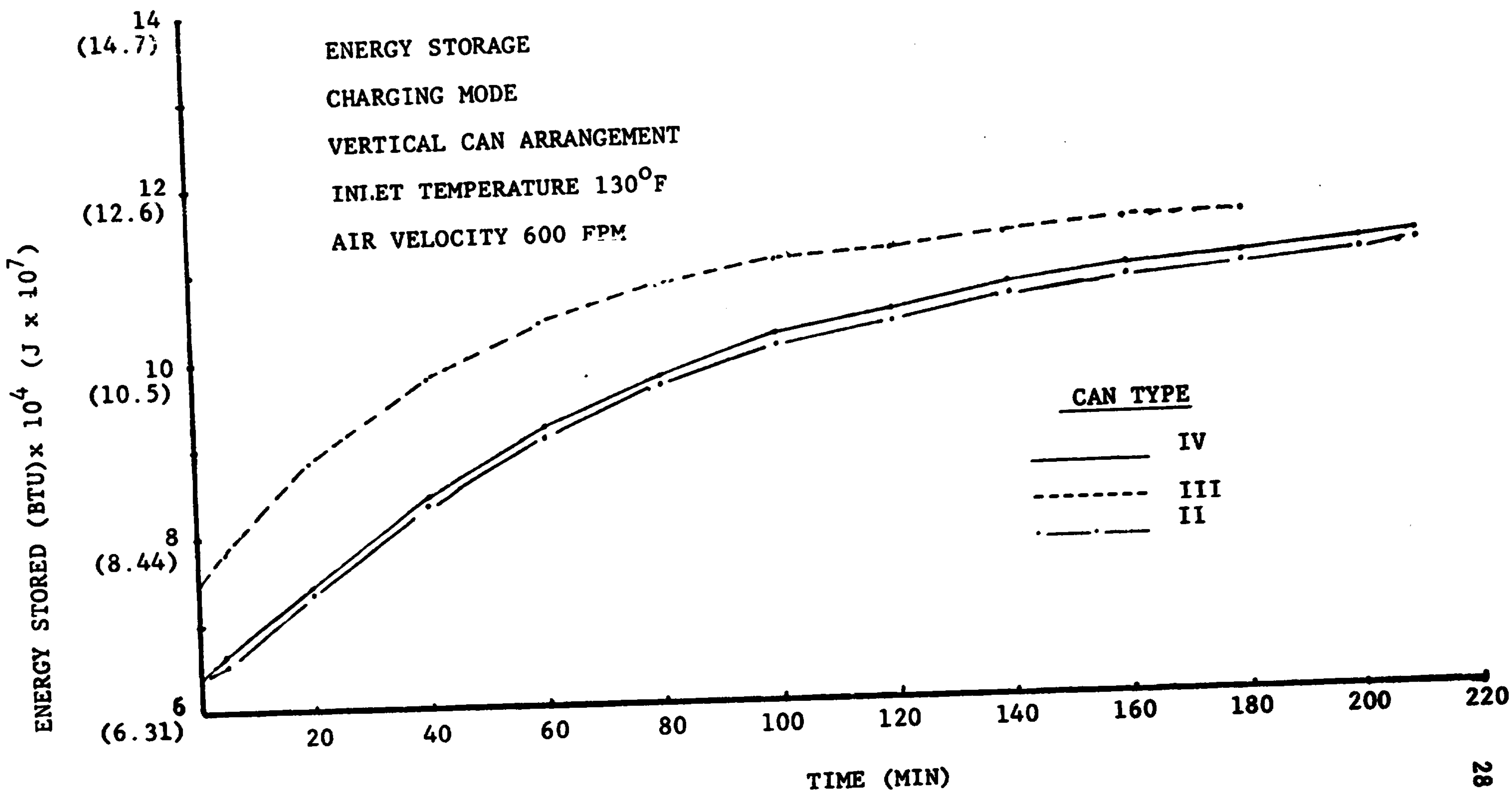


FIG. 18. ENERGY STORAGE DURING CHARGING MODE WITH VERTICAL CAN ARRANGEMENT

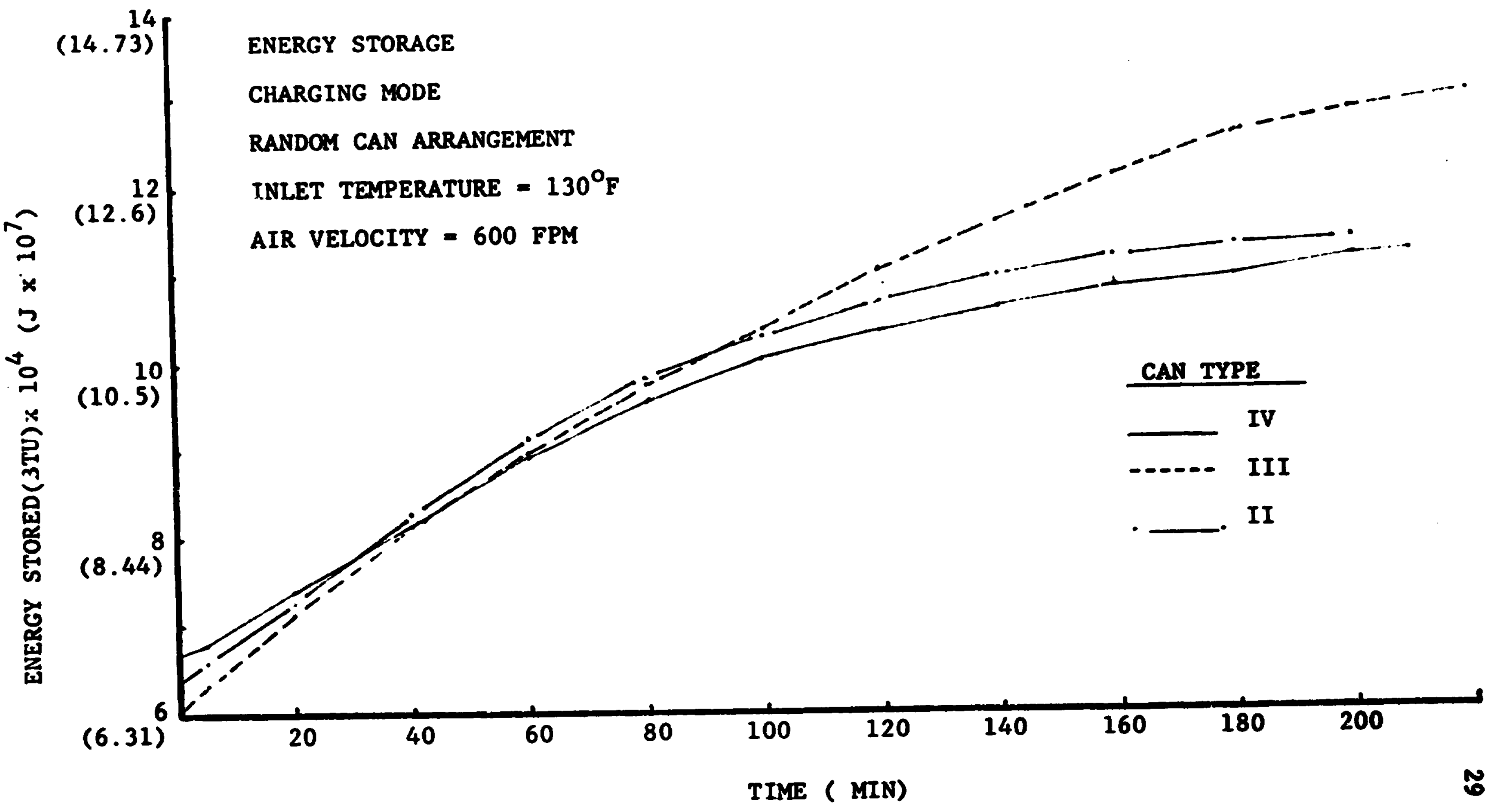


FIG. 19. ENERGY STORAGE DURING CHARGING MODE WITH RANDOM CAN ARRANGEMENT

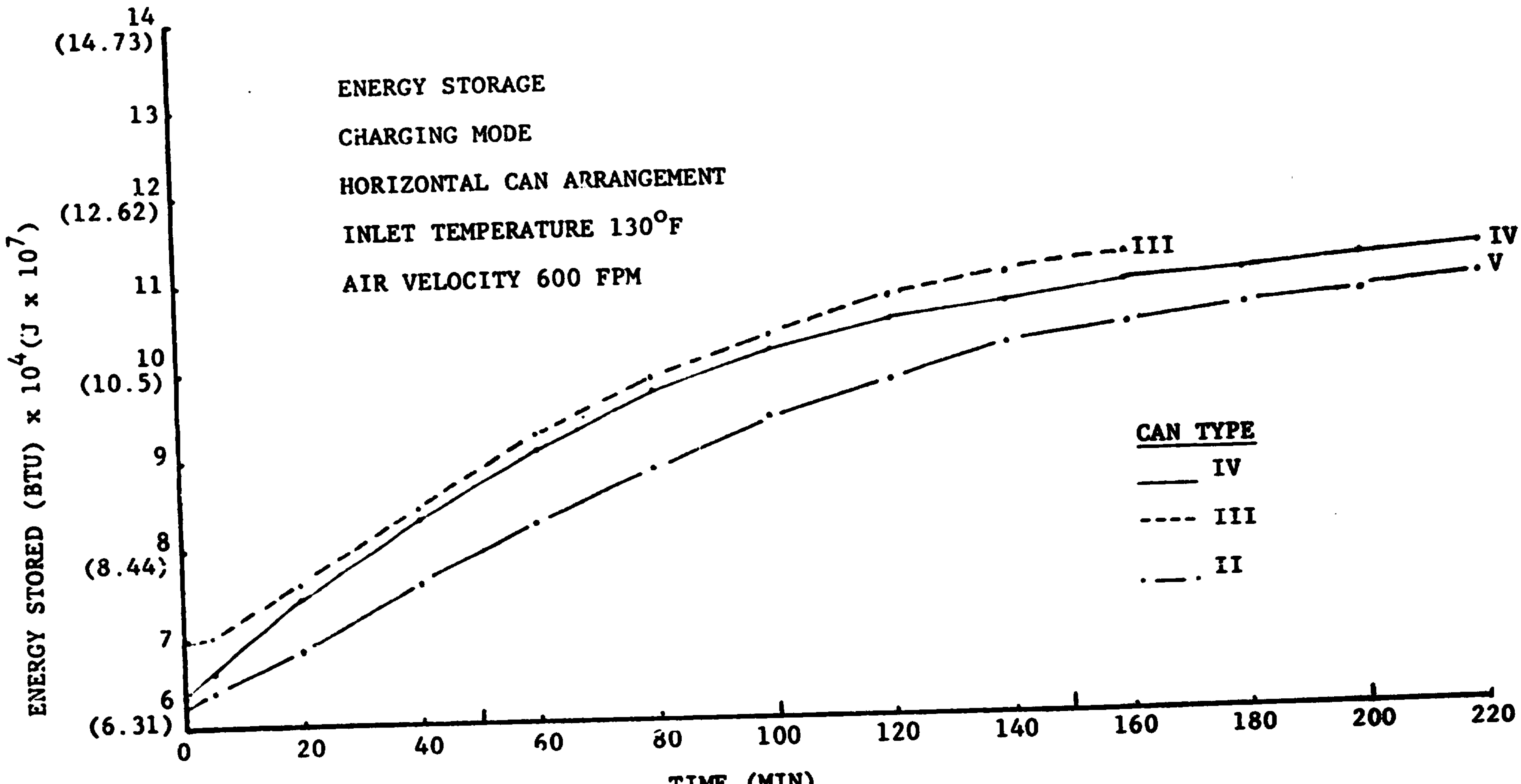


FIG.20. ENERGY STORAGE DURING CHARGING MODE WITH HORIZONTAL CAN ARRANGEMENT

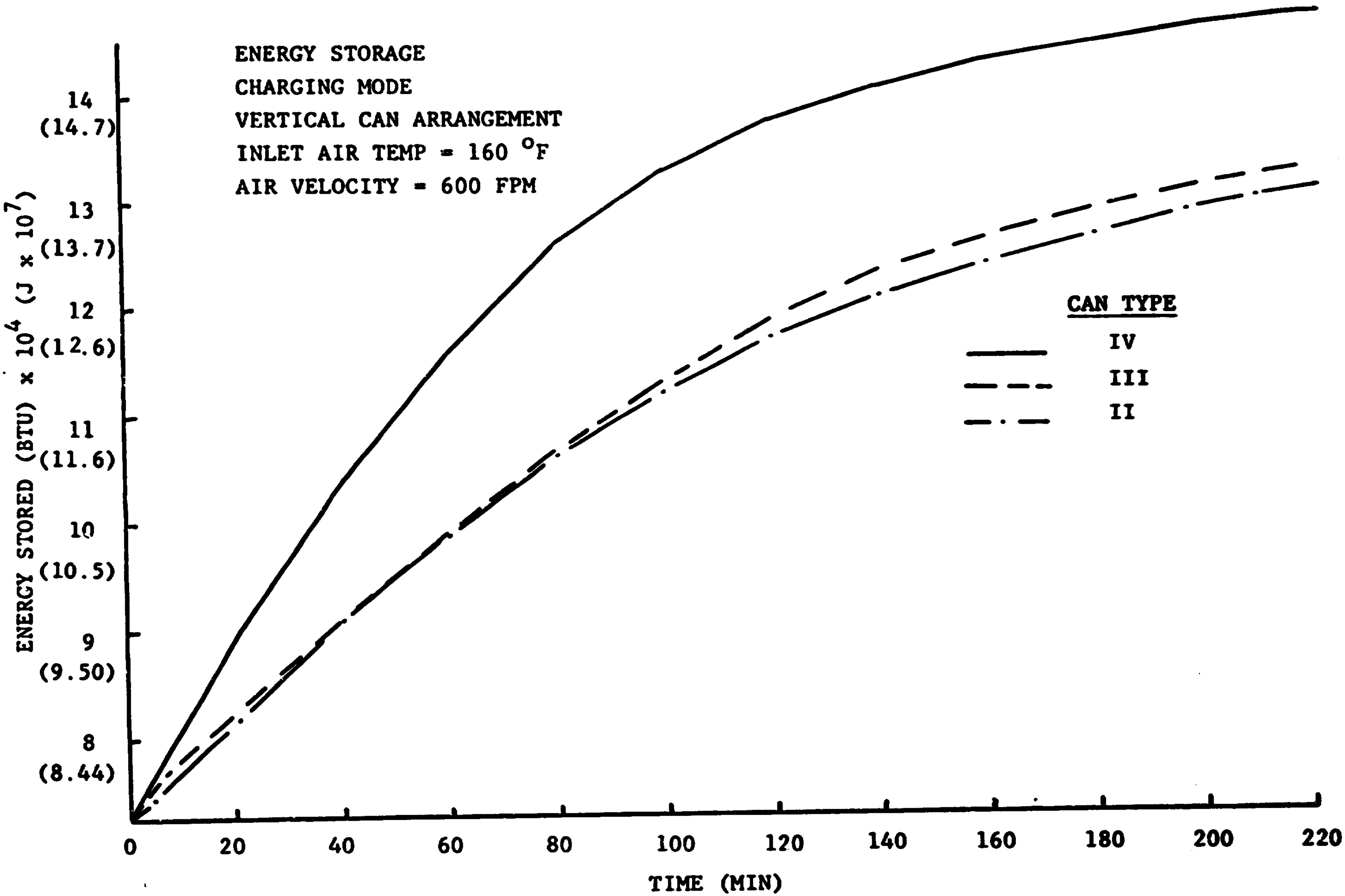


Fig. 21. ENERGY STORAGE DURING CHARGING MODE WITH VERTICAL CAN ARRANGEMENT.

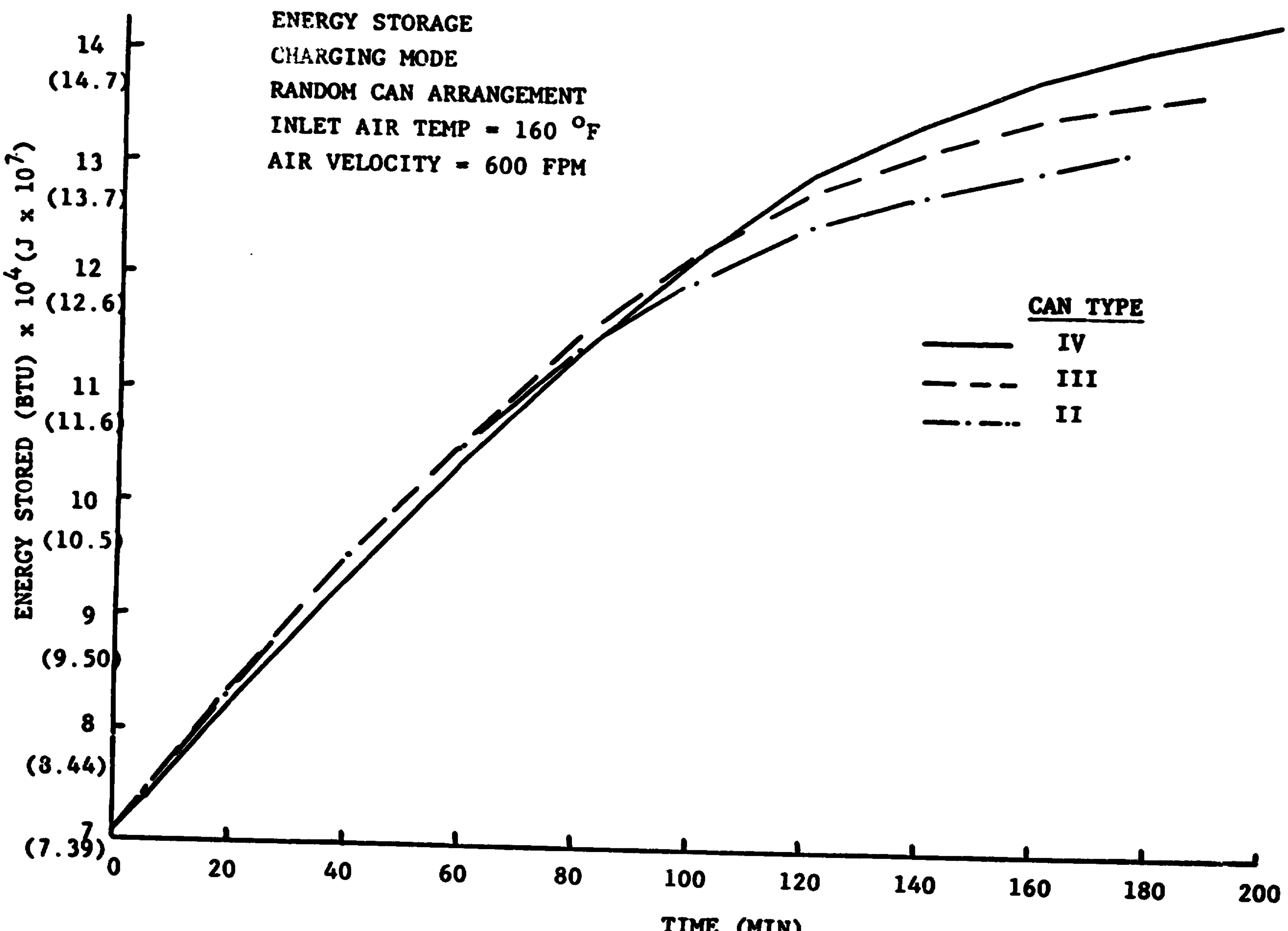


Fig. 22. ENERGY STORAGE CHARGING MODE WITH RANDOM CAN ARRANGEMENT.

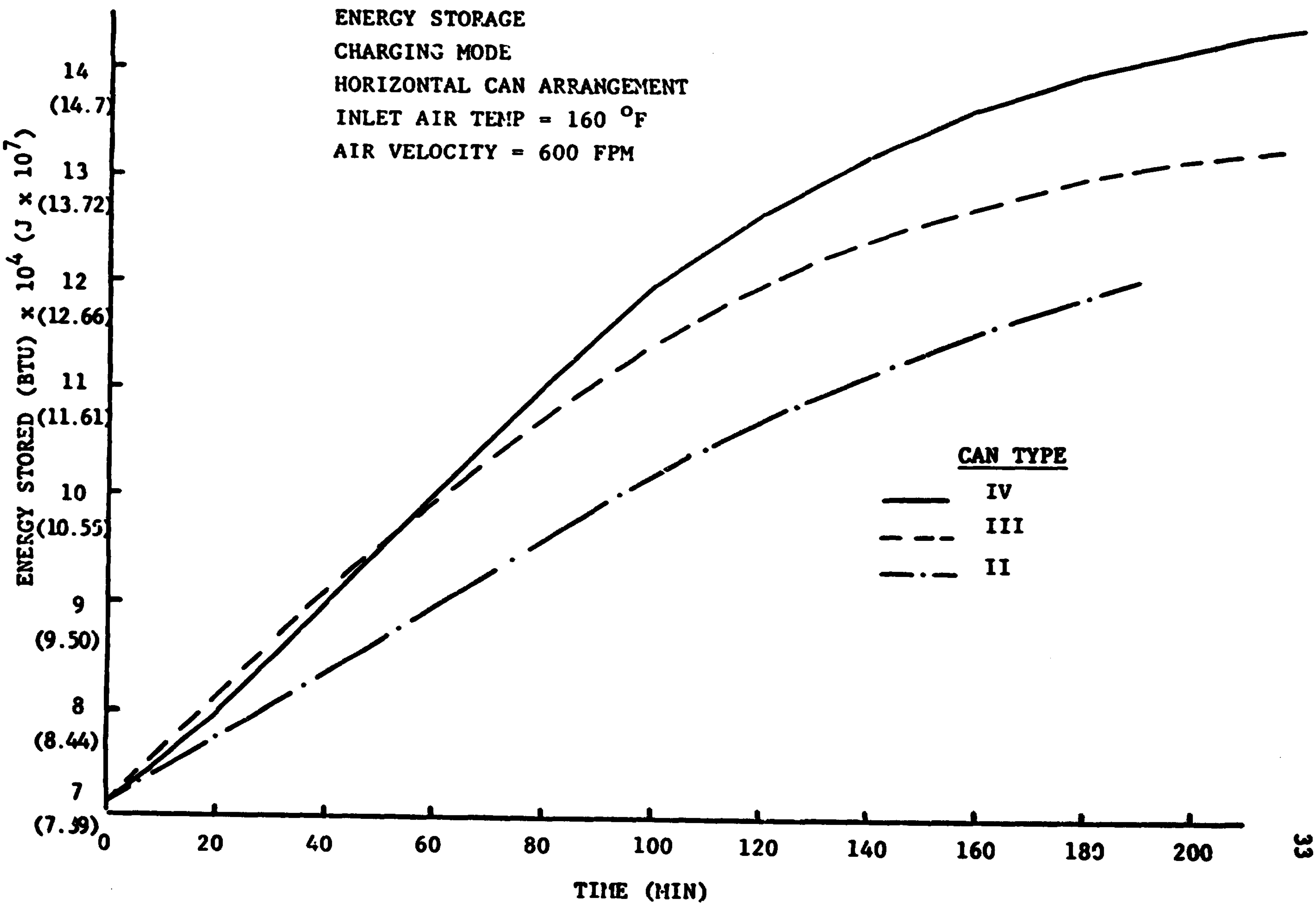


Fig. 23. ENERGY STORAGE DURING CHARGING MODE WITH HORIZONTAL CAN ARRANGEMENT

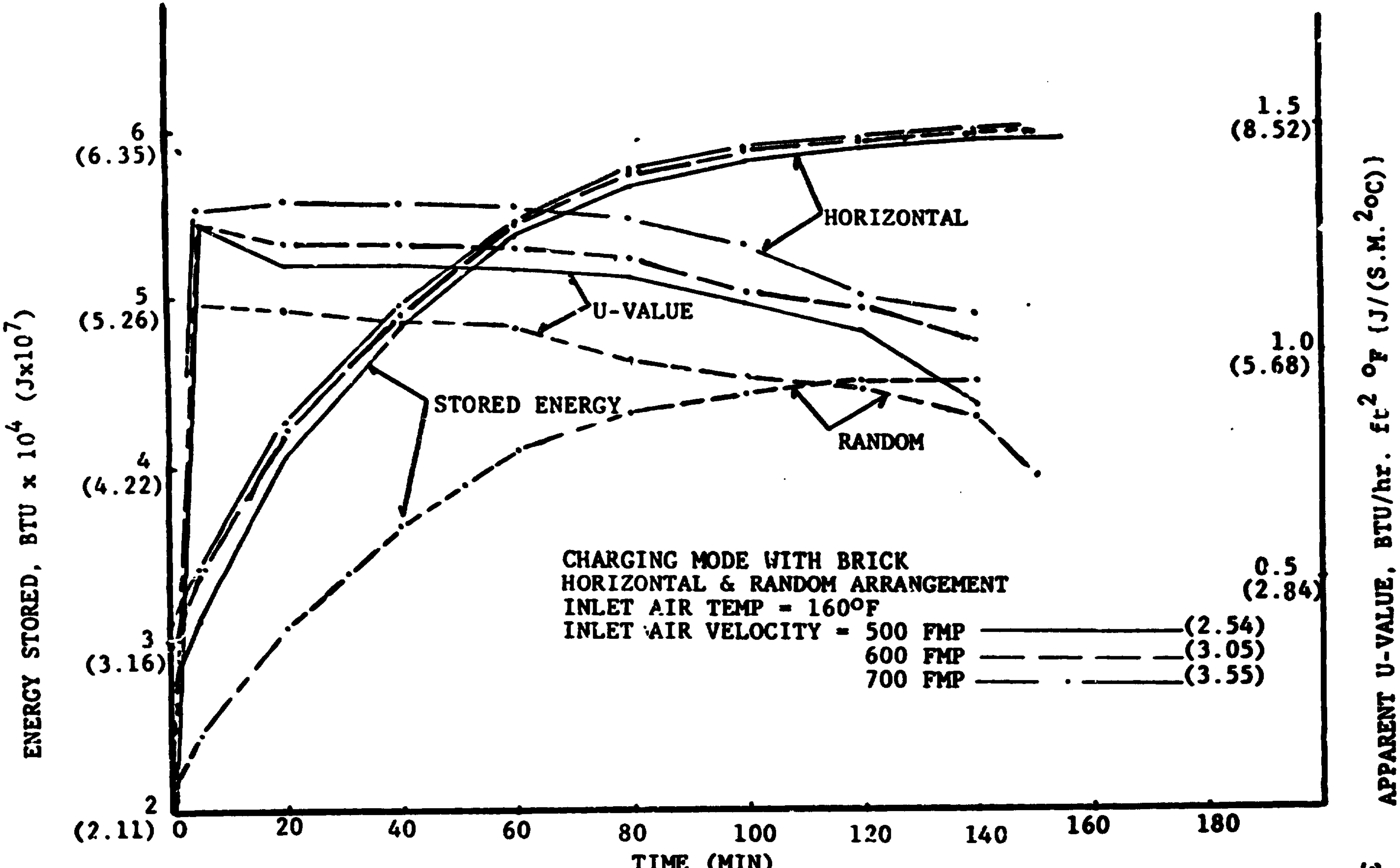


Fig. 24. ENERGY STORAGE AND APPARENT THERMAL TRANSMITTANCE

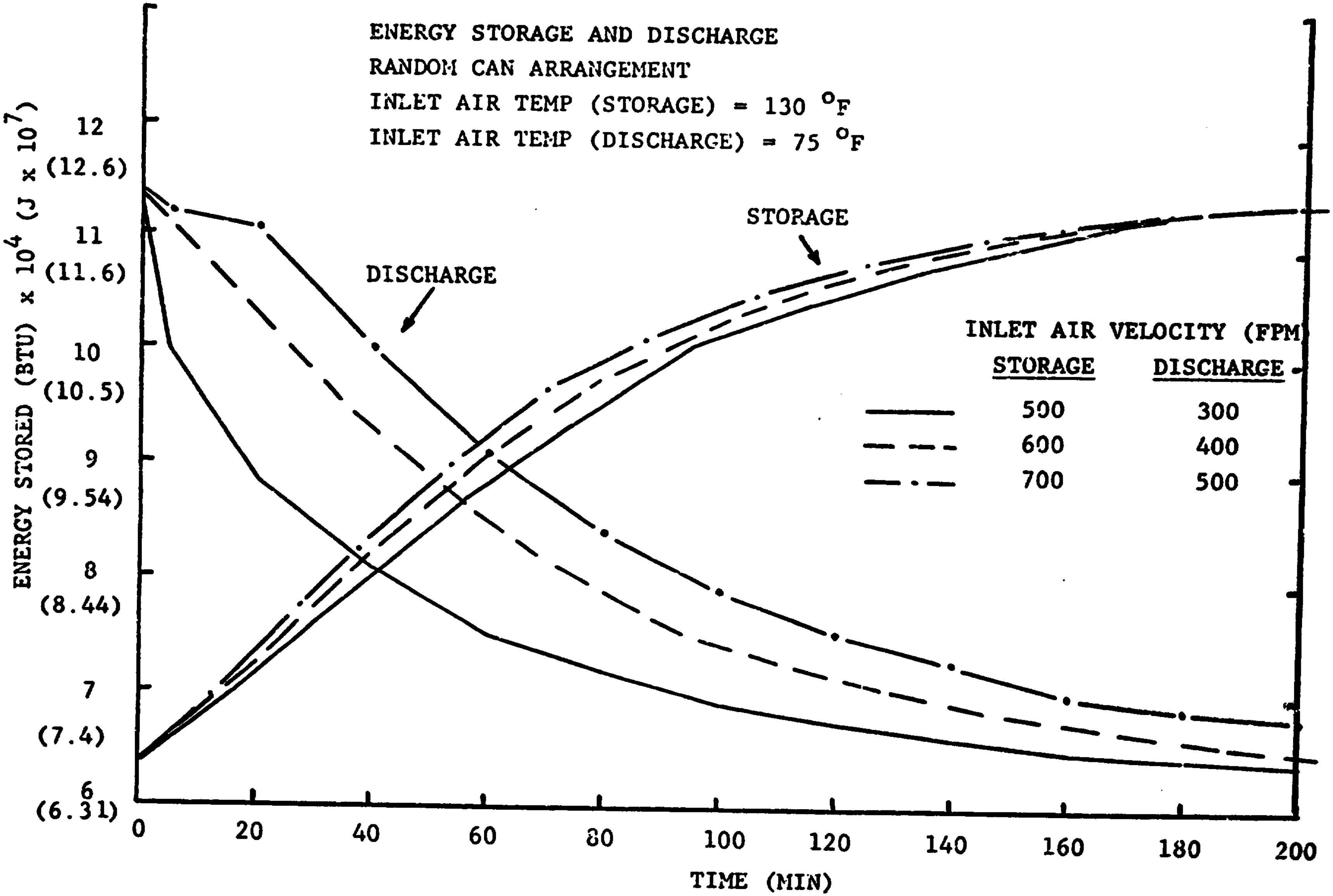


Fig. 25. ENERGY STORAGE AND RELEASE DURING CHARGING AND DISCHARGE MODE.

CONCLUSIONS

The test data analysis for a parametric study to determine the optimum size of cans/bricks and arrangement with respect to heat storage, heat transfer, and pressure drop reveals the following;

a) The size L/D = 0.80 with mass/surface area of 2.74 in random stacking arrangement has better heat transfer characteristics, and

b) the vertical stacking has the least pressure drop across the test bed compared to random and horizontal - stacking arrangement.

c) The standard bricks with 10 holes with mass/surface area of 3.4 in a horizontal stacking arrangement has better heat transfer characteristics.

Since the internal and external film coefficient of containers packed with thermal storage medium can be computed from the test data, an apparent U-factor, representative of heat transfer characteristics, of different types of storage mediums can be easily evaluated. The containerization process can be made economically acceptable if it is produced commercially in large quantities. The problems of container leakage and rusting can be controlled by selecting metal cans with anti-rust coated inner lining (soup cans) and/or high density plastic containers. The external moisture rusting of metal cans can be prevented by dipping them in an appropriate paint solution. These types of containerized fluid and PCM have a lower pressure drop across storage bed, lower volume requirements; due to uniformity of containers thermal channelling does not occur; these do not need any special type of storage chamber or heat exchange device.

Since bricks with different arrangements of voids are easily available, these make excellent thermal storage medium. Due to the holes the apparent diameter, the surface to volume ratio, and the void fraction of this type storage system can perform better than rock storage. Bricks can be used for both horizontal and vertical flow storage system and with appropriate stacking flow channelling can be minimized.

The test results and analysis thus far show that this type of thermal storage device will be well suited for use with solar air systems for space and hot water heating in both active and passive systems.

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