BIOGRAPHICAL SKETCH

ALAN SUPPLEE

Alan Supplee was educated in Washington as a Mechanical Engineer. For eight years he worked with Magnaflux followed by five years with Aero-Jet and three years as president of International Technology. Working in a consultant's capacity, he then worked with Varian Associates and the Cryodry Corporation. Mr. Supplee has now joined the staff of Cryodry on a full-time basis.

Preliminary Technical Feasibility Study on the Use of Microwaves for the Drying of Redwood Lumber

by

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Introduction

This report presents the results of a preliminary study of the technical feasibility of employing a microwave system developed by the Cryodry Corporation for the drying of redwood lumber. The study was undertaken as a cooperative venture by the Cryodry Corporation, (Alan Supplee), the California Redwood Association (Lee Rappleyea), and the Forest Products Laboratory (Helmuth Resch) of the University of California. The Cryodry Corporation made their equipment and facilities available; the California Redwood Association provided the necessary lumber and was instrumental in defining the study objectives and in helping conduct the drying runs; and the Forest Products Laboratory aided in the planning and carrying out of this study as well as in obtaining the experimental data.

The study was instigated because it seemed advantageous to develop improved drying techniques that would permit the redwood industry to obtain dry lumber in a short period of time without decreasing the product's quality. At present, the largest portion of all redwood lumber being produced must be dried to a moisture content of 8 to 10 per cent, based on the oven dry weight of wood. This is accomplished by grouping lumber of similar drying rates, then either drying the stock from its green state in a convention type lumber dry kiln or first air drying it in a seasoning yard to moisture contents approaching the fiber saturation point followed by dry kilning. This procedure to maintain lumber quality and prevent drying defects, requires drying times which may vary with dimension and type of lumber between 10 days and 2 years.

Drying with microwave energy has been suggested by Alan E. Supplee, Cryodry Corporation, as a possible means of reaching low wood moisture contents in relatively short time periods. After discussion with other representatives of the redwood industry, Peter Johnson and Lee Rappleyea of the California Redwood Association agreed to conduct a cooperative preliminary feasibility evaluation of microwave drying of redwood lumber. The writer of this report was invited by the Cryodry Corporation to help in the planning and conduction of this study.

Scope

The main objective of this study was to determine whether redwood lumber can be dried from its green condition, or after air drying to a desired final moisture content of 8 per cent, without the development of drying defects.

The scope of the work was:

1) To determine whether defects may result in redwood lumber when it is dried in a microwave system provided by the Cryodry Corporation

2) If defects should develop, to possibly determine their cause and the means to prevent their occurrence

3) To determine drying rates obtained under conditions which will not lead to the development of defects

4) To obtain an indication whether microwave drying may reduce the strength of wood

5) To determine the approximate power consumption per pound of evaporated water for a number of moisture content levels.

Materials and procedure

The microwave drying unit employed operated 915 megacycles per second and permitted the operator to vary the power input from 1 to 25 KW and the belt speed from 0 to 80 feet per minute.

The material to be dried was purchased from the Union Lumber Company, Fort Bragg, California, and consisted of 1-inch and 2-inch thick, 8 inches wide and 6 feet long redwood boards of the heavy (designated by H), medium (M) and light (L) drying segregation in their "green" condition and of air dried boards (AD) of equal dimension. Those boards dried to date were of the "clear all heart" and "A" grade. The lumber was wrapped in waxed paper before shipping in order to prevent moisture loss during transportation and storage.

Among the large number of variables that could influence the drying behavior of the material, were dimension, sort, grade, and grain direction of the boards, frequency and power output per unit exposure time in the microwave unit, and the velocity and air temperature passing over the boards during drying. Because of the limited time available and the possibility of confounding influences of the various factors mentioned, 1-inch thick lumber and a few 2-inch boards of the top grades and all drying sorts were dried in the microwave unit without the use of forced air. The belt speed was adjusted so that individual boards were exposed to microwaves for 20 or 10 seconds per pass through the unit. Attempts were made to adjust the power level to prevent the occurrence of defects. After a number of passes through the drying unit, the boards were weighed and, if defects developed, allowed to cool for a necessary time period.

Before drying, one 12-1/2-inch long end piece was cut from each board and dried in a air convection kiln at 150° F dry bulb temperature and 128° F wet bulb temperature. A complementary piece of the same length was cut from the remaining board after microwave drying, and conditioned to the same moisture content as the first sample. Then matching toughness test specimens were cut from both pieces and tested according to ASTM standard D143-52.

During the drying runs, the boards were frequently inspected for drying defects and their approximate surface temperature determined by means of "thermopaper." At the end of the microwave drying, a cross section 3 inches long in the grain direction and a matched 2 inches long sample were cut from each board. The current weights and, after drying in a vacuum oven, the oven dry weights were obtained of the first sample and of shell and core slices of the second sample. These weights were used to determine the final moisture contents of boards and recalculate the moisture content loss during drying. Also a prong was cut from every board to obtain an indication whether "case hardening," (an internal stress condition) had developed.

toughness samples kiln drying	toughness samples microwave dr.	moisture content	shell & core	stress	

All boards were inspected for drying defects after microwave drying and some of them were planed and reinspected.

Results

The results are listed in the chronological order of tests conducted. The most pertinent data are shown in the summary table which contains information on the type of boards that were dried, their original weights and moisture contents, weight and moisture content losses, exposure time to microwaves, total drying ti e and electrical energy expended. Drying rates of individual boards are graphed and are shown in figures number 1 through 10. In brief, the following observations have been made:

April 4 (figure 1): Two 1-inch thick boards which had previously been air dried for an undetermined time period were repeatedly passed through the drying unit at a power level of 5 KW. These boards were at initial moisture contents of 18 and 21 per cent -- much drier by far than the air dried stock brought to dry kilns of the redwood mills and whose initial moisture usually ranges between 40 and 60 per cent. The tested boards also contained a number of fine seasoning checks. Drying was rapid and after about 12 minutes the surface temperature of the wood reached 170° F. One check opened in AD-1 after 18 minutes and another in AD-2 after 32 minutes. Both boards reached 8-1/2 per cent moisture content after 45 minutes at which time the power level was raised to 7.5 KW. This heated the wood to between 220° and 230°F. Drying was discontinued when the boards reached 3 and 1-1/2 per cent moisture contents, respectively. The boards were free of casehardening stresses.

April 4 (figure 2): Subsequently two green boards of the light segregation were dried at the same power level of 5 KW. Slight cracking became audible after the surface temperature of the pieces exceeded 170°F. Cooling periods and spraying water on the surface seemingly reduced the temperature of the wood. However, half way through drying an endcheck and a surface check developed in L-10. Collapse and slight cupping degraded L-9 sufficiently to conclude that the power level had been set too high and drying was too rapid. After termination of drying, different moisture gradients existed in the two boards:

	Shell	Core
	per cent MC	
L-9	54	118
L-10	97	68

The amount of electrical power used per lbs of evaporated water was only one-third of that expended for drying the air dried pieces.

April 12 (figure 3): Two other air dried boards with initial low moisture contents were dried at a power level of 4 KW. Only one endcheck developed in AD-3 when it reached 14 per cent moisture content. After its development water spray was used three times to prevent further defects. The power level was increased first to 5 KW then to 6 KW when the wood reached 11 per cent and 5 per cent moisture content; respectively. A slightly higher moisture content in the shell than in the core of both boards resulted.

	Shell	Core
	per cent MC	
AD-3	5	3
AD-4	3	2

The boards were free of casehardening stresses.

April 13 (figure 4): A pair of 1-inch thick and a pair of 2-inch thick air dried boards, all containing a certain amount of surface checks, were first exposed to microwaves at the 3 KW level. While the 1-inch thick boards dried without any defects, a large check developed in one 2-inch thick board at 20% moisture content although its surface temperature was only between 130° and 150°F. After the 1-inch boards reached 10 and 12 per cent moisture content, respectively, the power level was increased to 4 KW which contributed to faster drying. The 1-inch boards remained without defects, however, AD-9-2" developed some internal checking. At the end of drying the moisture was fairly uniformly distributed throughout the boards.

	Shell % MC	Intermediate % MC	Core % MC
AD-8-1"	6	-	5
AD-9-1"	7	-	5
AD-9-2"	14	18	16
AD-10-2"	11	14	14

The efficiency with which water was evaporated from the pieces was, of course, twice as great for the 2-inch thick pieces.

April 15 (figure 5): Slightly drier 1-inch and 2-inch thick pieces than in the previous run could be successfully dried at 3 KW power level. It was felt that air dried lumber could be dried without the danger of defects occurring if reasonably low power levels were employed.

April 15 (figure 6): A pair of light segregation and a pair of medium segregation boards were slightly degraded by internal and surface checks when subjected to microwaves at 2 KW without long air cooling periods. The light segregation boards reached a surface temperature about 170°F first and cracking became immediately audible when the temperature rose to 190°F. A temporary reduction of power to 1 KW after 33 minutes of drying time stopped further surface checking, however, even then birdseye in the "medium" boards checked slightly. The power level was raised again at 63 minutes drying time and surface checking resulted in M-9 at 107 minutes. Seemingly, the boards had been overheated again. The high efficiency with which the moisture evaporated was noticeable.

April 18 (figure 7): A repetition of the previous test was made with two 1-inch thick medium segregation and four heavy segregation boards at a power level of 2.5 KW. Fewer defects resulted, of which "popped" birdseye were the most obvious. Collapse, usually developing in heavy segregation lumber when it is dried too rapidly in air convection kilns, was not observed. The drying rate of this heavy lumber was not as great as one might have expected from the high initial moisture content of H-1, H-2, and H-3. Because only two boards were passed through the drying unit at one time, the efficiency of water evaporation was relatively low. The test was terminated because of time deficiency.

April 19, 20 and 21 (figure 8): In previous tests, the position of the boards relative to each other was changed from pass to pass through the drying unit because it was observed that the boards closest to the entering wave guide would heat up faster than the other pieces. In this test run the order of boards remained the same with M-5 being closest to the entering wave guide followed by M-6, H-8, and H-9. All four boards were passed through the system at the same time and the power level was frequently checked on an especially installed microwave power meter and recorded. The power level was kept close to about 2.2 KW during the most of the run, however, during a warm-up period 4.9 KW were used. During this warm-up period the surface temperature level of M-5 already exceeded 170^{o}F and checking developed, while all the other boards remained below 150^{o}F. Further checking developed in M-5 after 150 minutes of drying time when the board's surface temperature exceeded first 190^{o}F and then 210^{o}F. One check and one end split developed also in H-9, while a small number of dark birdseye opened in all boards. Besides this, boards M-6 and M-9 dried without damage. The test was terminated when M-5 reached 10 per cent moisture content. It was obvious that an excessively large portion of the microwave energy was attenuated in the first board (M-5) closest to the entering wave guide and therefore was overheated and damaged. It was thought that a better distribution of energy at this power level and exposure time and with somewhat longer cooling periods between, may have produced satisfactorily dried lumber. In addition, the efficiency of water evaporation was the highest recorded for all tests.

April 22 (figures 9 and 10): A final test was conducted by passing two sets of four boards, one set at the time, through the drying system at twice the speed and twice the power level (4.44 KW) of previous tests. The position of boards to each other was altered from pass to pass in order to prevent overheating of any single board. It was found that the cooling time in relation to exposure time was too short, because most of the boards reached surface temperatures above 170^{o}F and, in one instance, above 190^{o}F at various times. Invariably the development of checking in H-6, H-10, M-4 and M-1 and of collapse in H-6 resulted. The other undamaged boards showed a few popped birdseye. The exposure time to microwaves was extremely short (56 minutes) considering that all the light and medium segregation boards closely approached the desired final moisture content at the end of the drying run. The ratio of water evaporated to energy expended was quite satisfactory. The moisture distribution was uniform in those boards which had dried to below 14 per cent moisture content and only one pronge showed very slight casehardening while all others were free of stresses.

The ASTM toughness test carried out on 121 matched pairs of clear specimens (tangential and radial grain combined) and cut from kiln dried and microwave dried pieces did not show any statistically significant difference. The average toughness values were 92-inch-pounds for kiln dried specimens and 98-inch-pounds for microwave dried specimens all tested at or near 7.5 per cent moisture content.

Conclusions

As a result of this preliminary technical feasibility study on the use of microwaves for the seasoning of redwood lumber, the following conclusions were reached:

1. One-inch thick redwood lumber may be dried in several hours by microwave energy of 915 megacycles per second frequency from its green condition to moisture contents desired for final use.

2. The required drying time varies with certain wood characteristics, especially with the initial moisture content. The segregation of redwood boards into the common drying sorts of "heavy", "medium", and "light" appears to be very much suitable for microwave drying.

3. Too rapid drying, i.e., most likely heating the wood above a critical temperature level, will cause surface and end-checking, "popping" of birdseye (adventitious branch buds) and, less frequently, collapse in already checked areas. This checking does not result from shrinkage stresses common in wood when it is dried with air convection only, but from too great an internal water vapor pressure. Such checks start in the interior of boards at moisture contents always above the fiber saturation point (below which shrinkage occurs), and through them water vapor surges at temperatures higher than the surface temperature of the undamaged wood. The formation of checks is often accompanied by audible cracking. A definite explanation for the occurrence of collapse cannot be given.

4. The time required to heat wood from ambient temperatures to between 150^{o} to 212^{o}F by exposure to microwaves even at low energy levels of 1 to 3 KW is much shorter than the time required to evaporate the moisture from the wood. Thus an intermittent heating of wood with microwaves, followed by longer evaporation and cooling periods, seems mandatory for the drying of redwood if the development of defects is to be prevented. The optimum ratio of exposure time to microwaves to the time for moisture evaporation is not known; however, it may be expected to change with a change in the moisture content of wood.

5. During microwave drying a moisture gradient exists from the inside to the surface of boards, with higher moisture concentrations in the interior. This condition exists as long as the overall moisture content is above 25 to 40 per cent. Below this level, the moisture becomes more evenly distributed over the entire cross section. In some pieces a higher moisture concentration may be found in the surface layers than in the interior of boards when they are dried to low overall moisture contents. Dry boards are, in most cases, free of internal stresses or may exhibit only slight case-hardening.

6. Microwave drying *per se* does not bring wood to a predetermined moisture content, but evaporates moisture from the material as long as moisture is present. This indicates that a microwave drying system would have to be used either in conjunction with a moisture meter that would indicate those boards that have reached the desired final moisture content level and should be removed from the drying system, or in conjunction with a moisture equalizing system in which the relative humidity is controlled.

7. A strength reduction by microwave drying over conventional kiln drying may not be expected, as far as toughness tests are indicative for other strength values.

8. The microwave unit employed for the trial runs heated the board closest to the entering wave guide to a proportionally higher temperature than the boards at a greater distance from the entering wave guide. This greater microwave attenuation may result in overheating of the first board, and therefore in faster drying and even in the development of defects while other boards will dry at a much slower rate.

9. The largest portion of the microwave energy supplied to the drying unit is attenuated when four 1-inch thick boards of high moisture content are loaded into it. The same volume of wood at lower moisture contents (between 10 and 20 per cent moisture content) will attenuate much less energy. In the first case approximately 2.49 lbs of water can be evaporated per KWh while in the second case an evaporation may be expected of only 1.28 lbs. of water per KWh.

Recommendations

For any future experimentation in respect to the drying of redwood lumber, or lumber of any other species, it is recommended to:

1. Determine the exact exposure level to microwaves below which defects of any kind will not develop. One possible way to accomplish this may be to find a correlation between the surface temperature of boards and defect occurrence. It must be expected that such indicating surface temperatures may be lower for 2-inch thick lumber and for boards containing knots than for 1-inch thick clear material.

2. Determine whether the microwave drying system could be modified in order to distribute the microwave energy uniformly over all the material being dried.

3. Determine the influence of various air velocities and temperatures of forced air to be used in conjunction with the microwave drying.

4. Determine total exposure time to microwaves and overall drying time for 1,000 bd. ft. of 1-inch and 2-inch thick lumber of all drying segregations under optimum conditions established under the points listed above.

5. Evaluate the power consumption for drying redwood lumber over a wide range of moisture content values.

6. Establish economic criteria for the use of microwaves in a lumber drying system.

SUMMARY TABLE

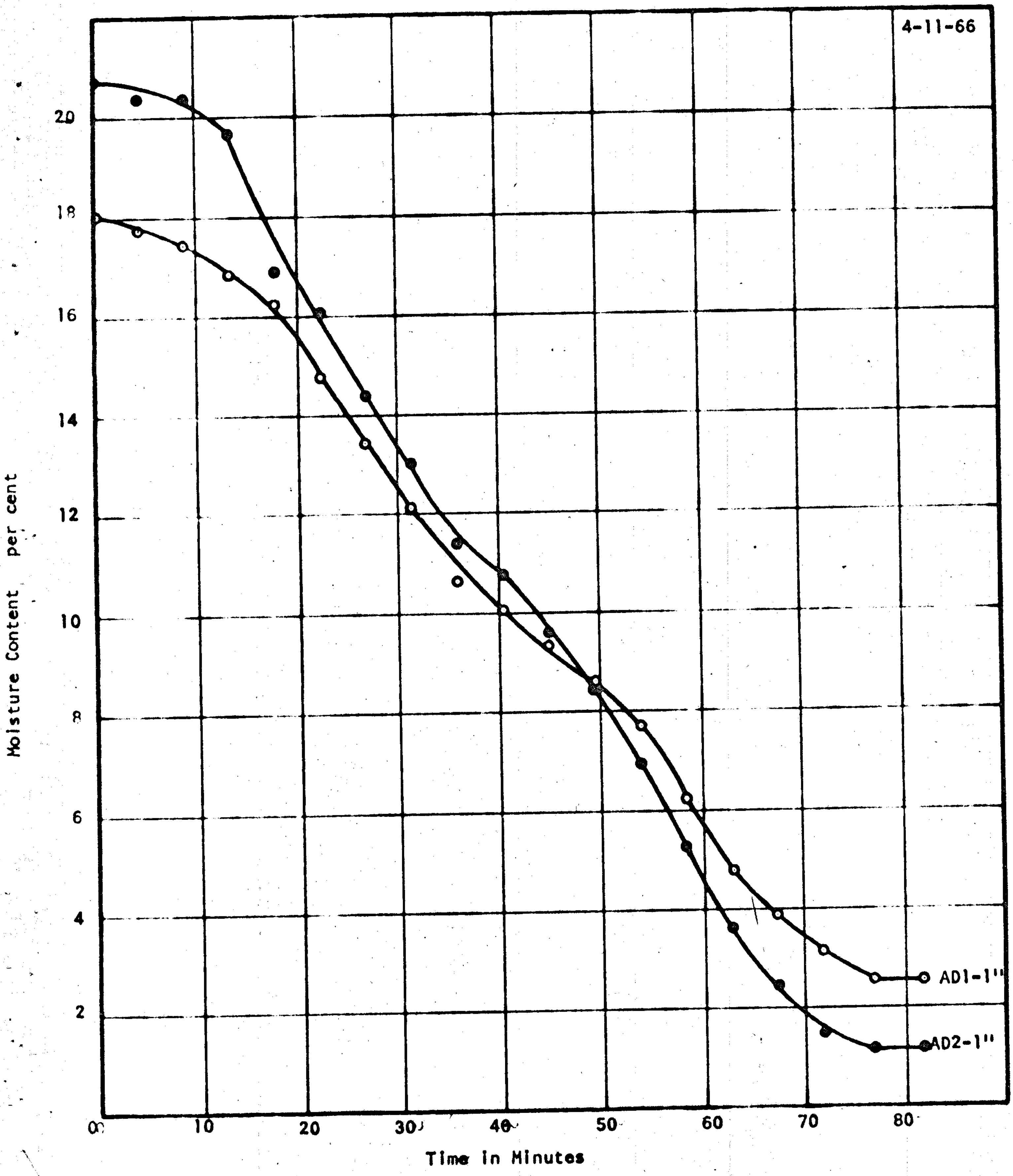
Type of Board				Moisture Content			Weight		Time			Electrical energy expended	
	Thickness	Sort & No.*	Date	Initial	Final	Loss	Initial	Loss	Total	exposed	exp./tot.	MC loss per KWh	Water evaporated per KWh
Corresp. figure	inches				per cent		lbs.			minutes		%	lbs.
1	1	AD1	4-11	18.00	2.50	15.5	8.00	1.05	84.0	52.0	1/1.62	7.0	.449
	1	AD2		20.70	1.10	19.6	7.28	1.18					
2	1	L9	4-11	175.50	115.30	60.2	18.40	4.02	88.0	46.9	1/1.88	22.3	1.525
	1	L10		78.20	47.70	30.5	12.85	2.20					
3	1	AD3	4-12	15.78	3.50	12.3	9.90	1.05	208.2	56.6	1/3.68	6.4	0.538
	1	AD4		18.64	2.65	16.0	9.94	1.34					
4	1	AD8	4-13	12.02	5.76	6.3	8.05	.45	82.3	26.7	1/3.08	7.3	0.519
	1	AD9		12.15	7.76	4.4	7.15	.30					
	2	AD10		20.86	16.80	4.1	19.30	.65	"	"	"	6.2	1.046
	2	AD10		18.49	13.64	4.9	21.00	.86					
5	1	AD7	4-15	14.31	11.88	2.4	7.96	.14	45.8	20.0	1/2.29	5.3	0.338
	1	AD10		6.91	4.40	2.5	7.24	.17					
	2	AD7		16.39	10.45	5.9	19.20	.98	"	"	"	9.1	1.538
	2	AD8		14.02	11.59	2.4	20.12	.43					
6	1	L7	4-15	43.01	22.59	20.4	10.15	1.45	129.3	40.0	1/3.23	34.5	2.478
	1	L8		45.14	25.18	20.0	10.61	1.46					
	1	M9		97.35	75.15	22.2	17.69	1.99	"	"	"	32.2	2.572
	1	M10		49.80	34.32	15.5	9.87	1.02					
7	1	M7	4-18	107.40	81.19	26.2	16.60	2.10	149.0	71.3	1/2.09	27.9	1.750
	1	M8		142.50	84.17	58.3	13.30	3.20					
	1	H1		107.25	88.79	18.5	17.40	1.55	"	"	"	14.5	1.172
	1	H2		141.89	116.44	25.5	19.00	2.00					
	1	H3		137.36	115.07	22.3	18.10	1.70	"	"	"	13.1	1.106
	1	H4		99.75	80.32	19.4	18.70	1.65					

SUMMARY TABLE (Continued)

Type of Board				Moisture Content			Weight			Time		Electrical energy expanded	
	Thickness	Sort & No.*	Date	Initial	Final	Loss	Initial	Loss	Total	exposed	exp./tot.	MC loss per KWh	Water evaporated per KWh
Corresp. figure	inches				per cent			lbs.		minutes		%	lbs.
8	1	M5	4-19&	74.94	9.82	65.1	11.55	4.30		136		40.8	2.767
	1	M6	20&21	104.30	56.56	47.7	13.31	3.11					
	1	H8		108.70	80.25	28.5	17.82	2.43					
	1	H9		189.10	123.20	65.9	18.52	4.22					
9	1	L2	4-22	37.24	10.46	26.8	9.99	1.95	313.0	56.0	1/5.59	33.0	2.121
	1	L6		45.60	13.50	32.1	8.79	1.94					
	1	M3		46.60	13.10	33.5	8.05	1.84					
	1	M4		48.50	13.80	34.7	10.50	2.45					
10	1	H6	4-22	137.60	77.40	60.2	16.42	4.16	319.0	56.0	1/5.69	38.6	2.419
	1	H10		81.50	47.80	33.7	13.71	2.25					
	1	M1		37.70	14.50	23.2	7.63	1.29					
	1	M2		43.00	11.40	31.6	7.38	1.63					

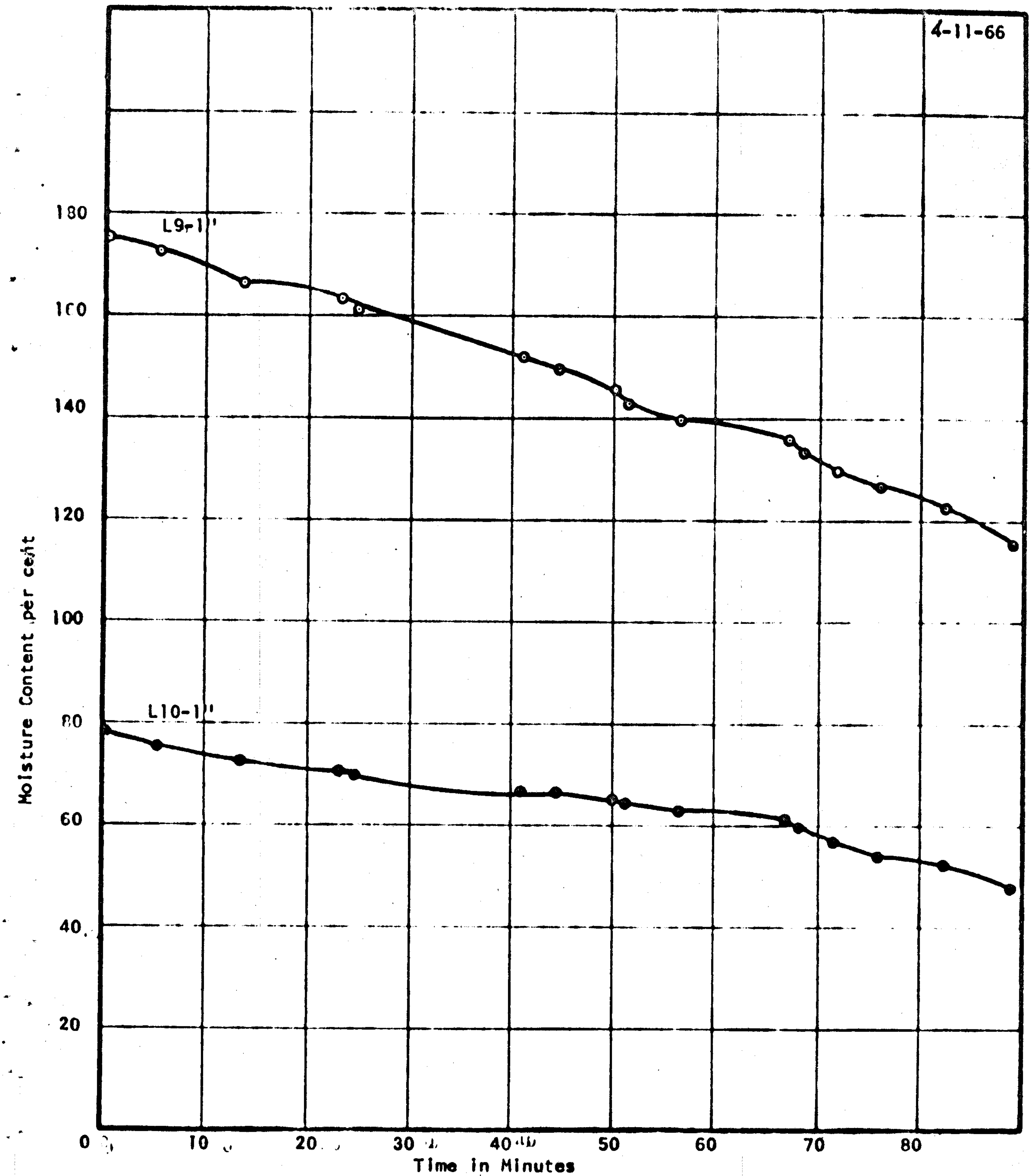
* AD = air dry
L = Light drying segregation
M = Medium " "
H = Heavy " "

Figure 1



Exposure time in drying unit = 52 min
Ave. energy level = 5.78 KW

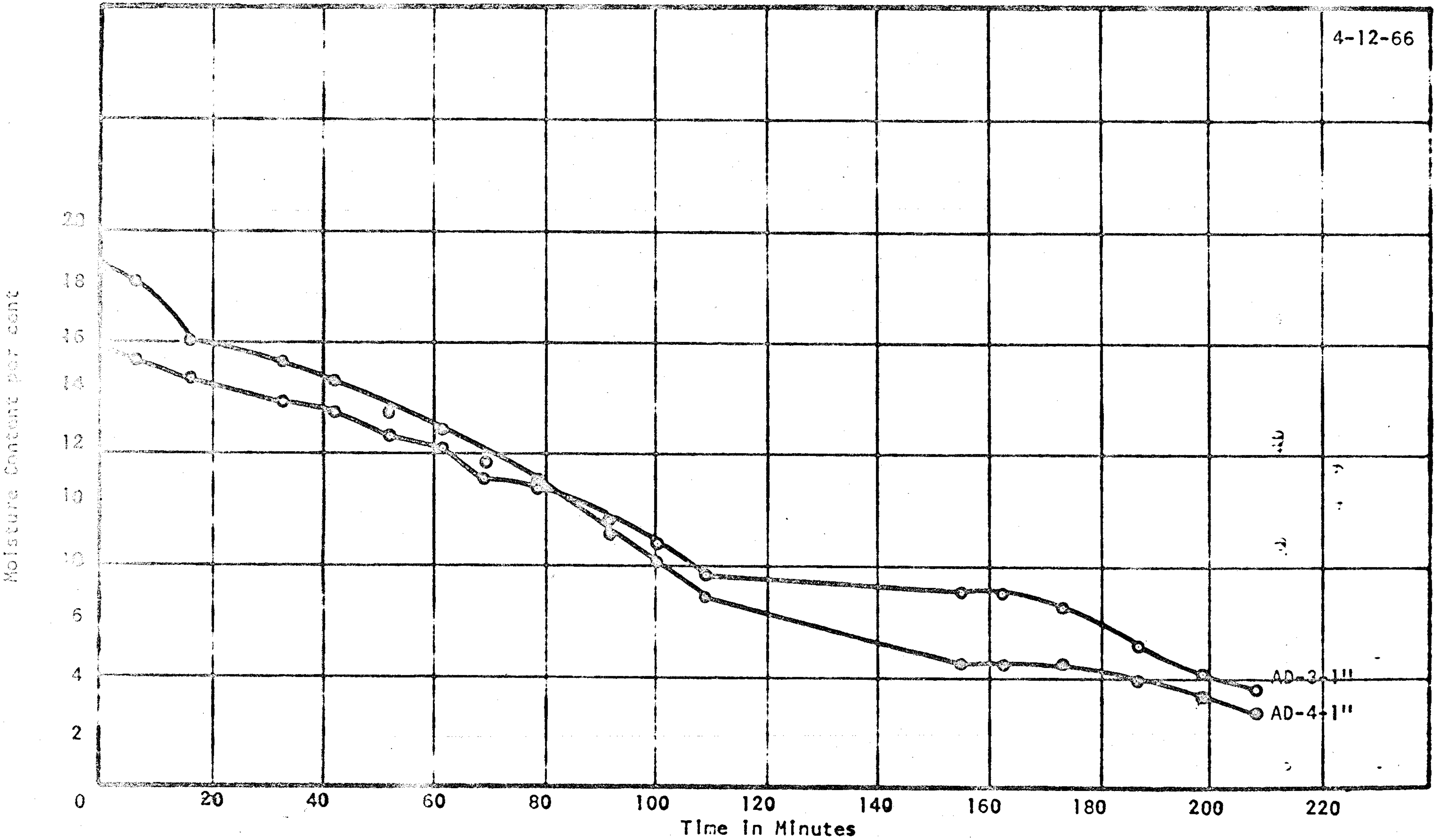
Figuro 2



Exposure time in drying unit = 46.0 min.

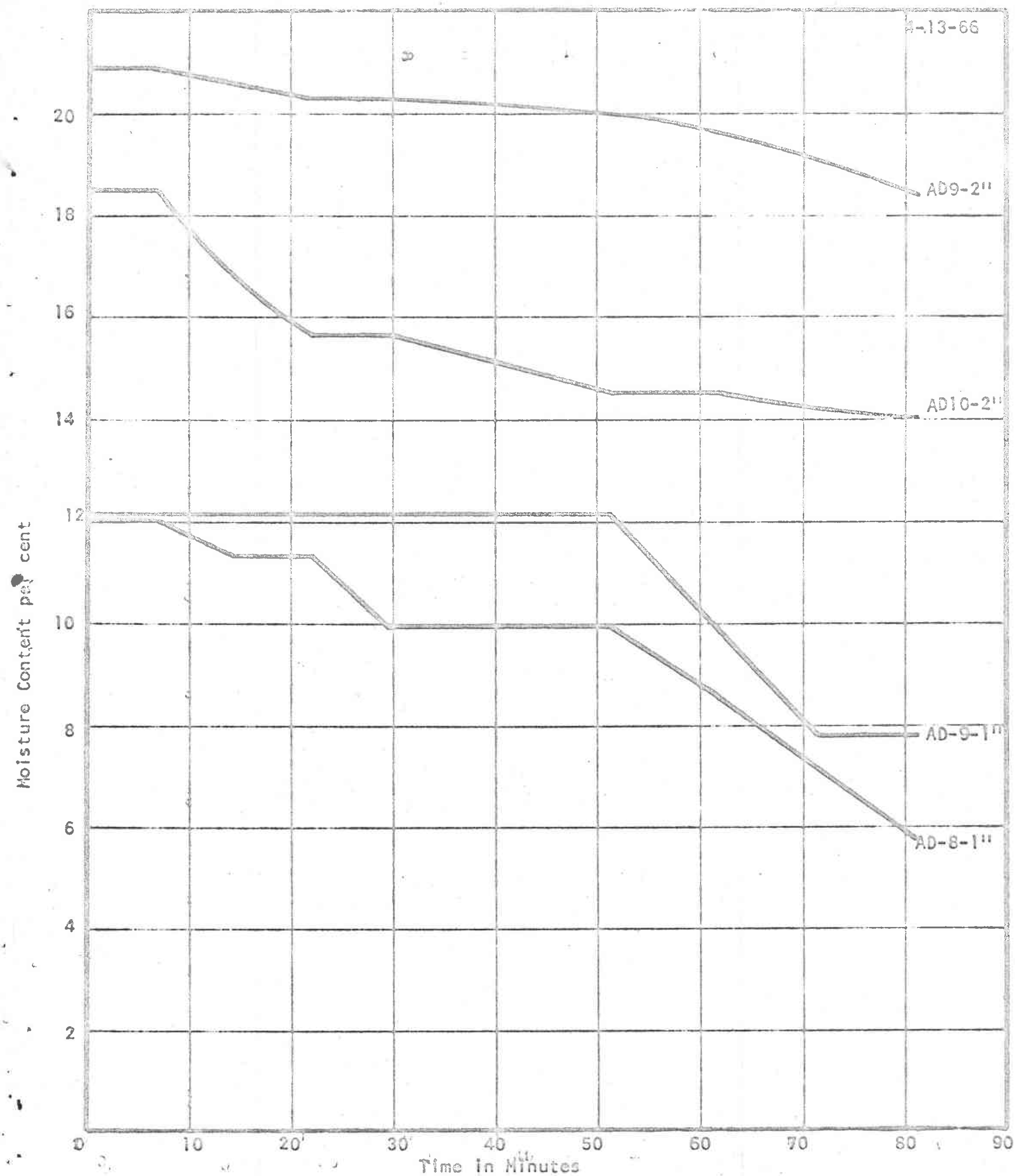
Ave. energy level = 5.21 KW

Figure 3



Exposure time in drying unit = 56.6 min.
Ave. energy level = 4.7 KW

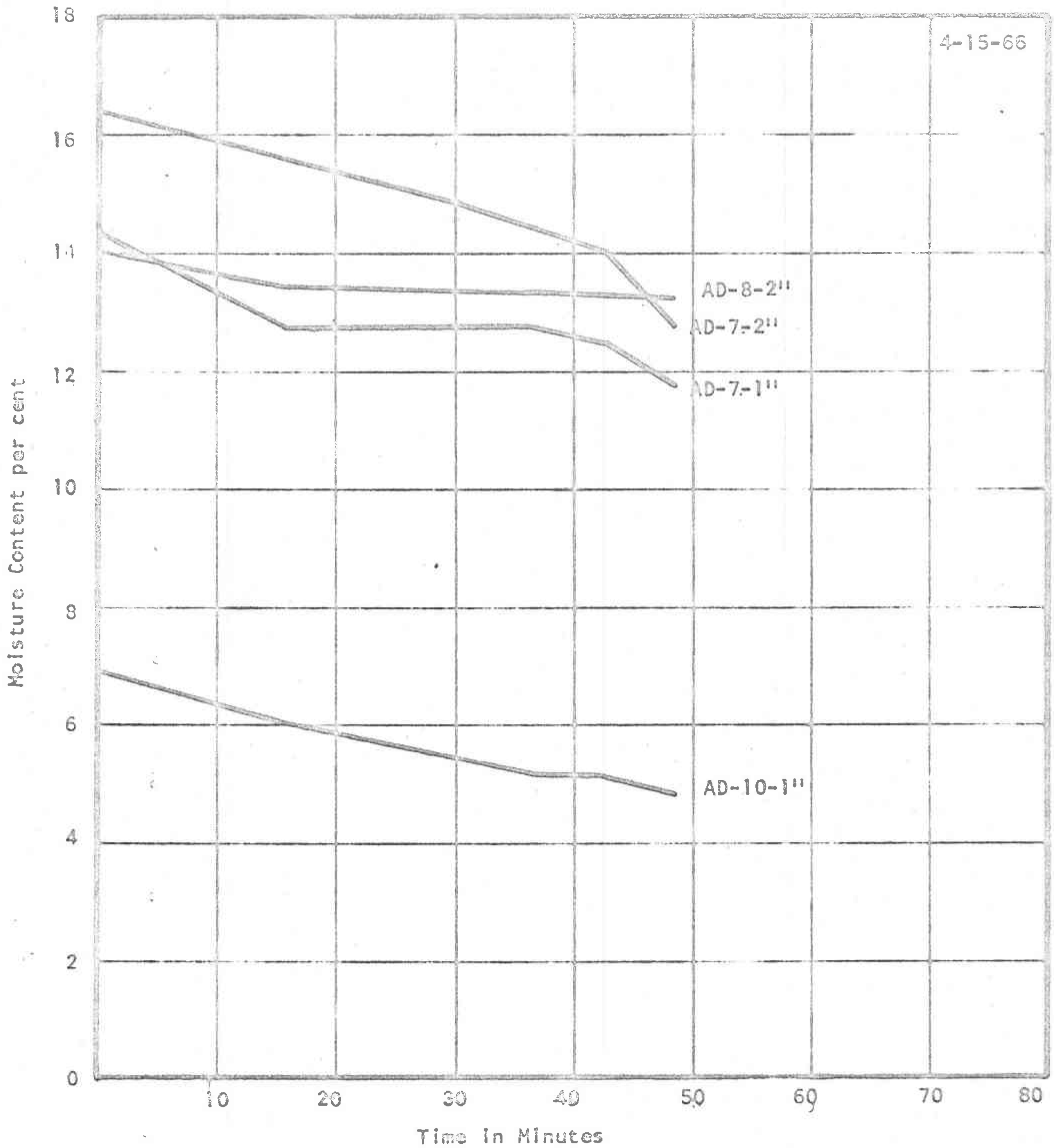
Figure 4



Exposure time in drying unit = 26.7 min.

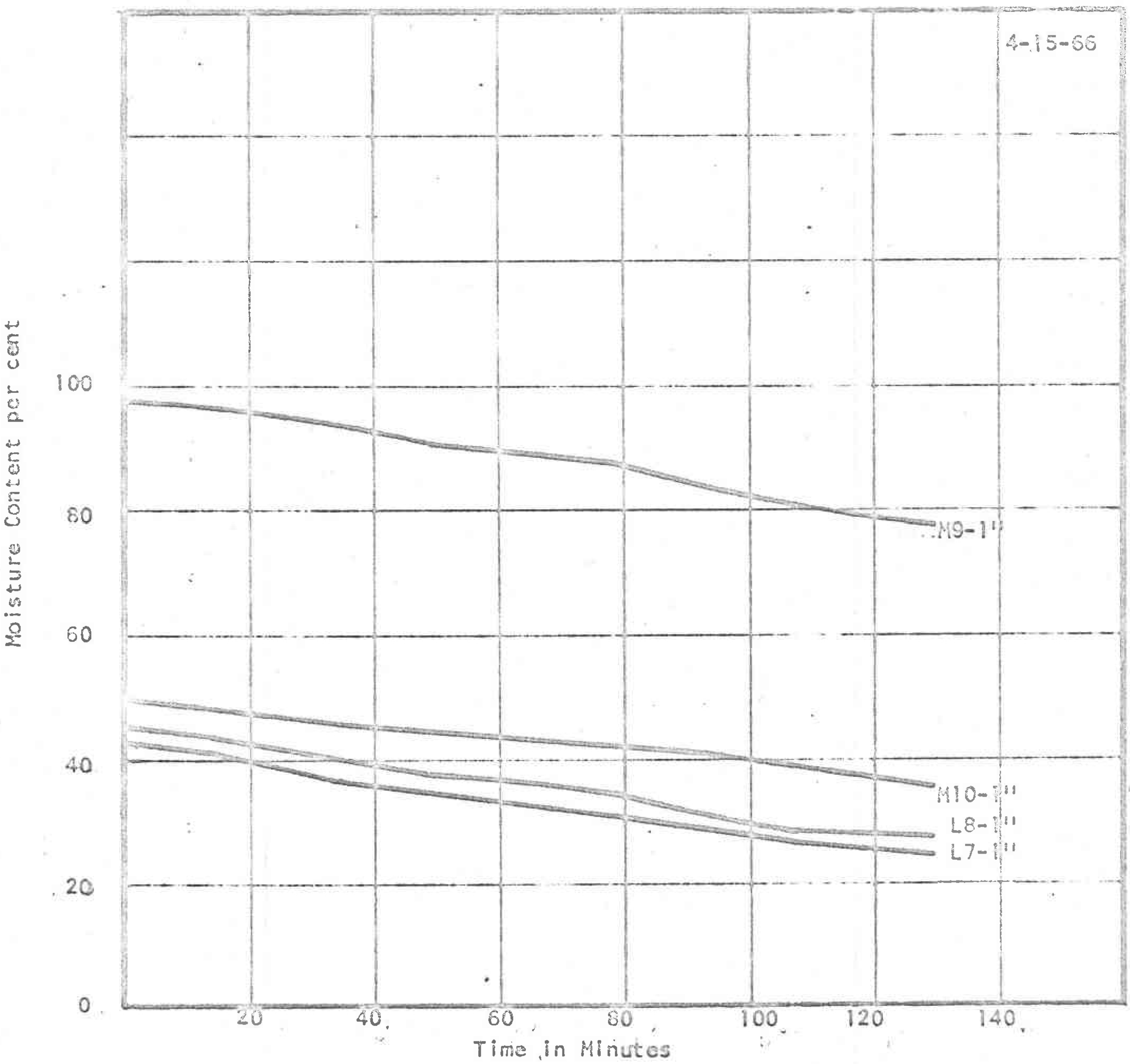
Ave. energy level = 3.25 KW

Figure 5



Exposure time in drying unit = 20 min.
Ave. energy level = 3.50 KW

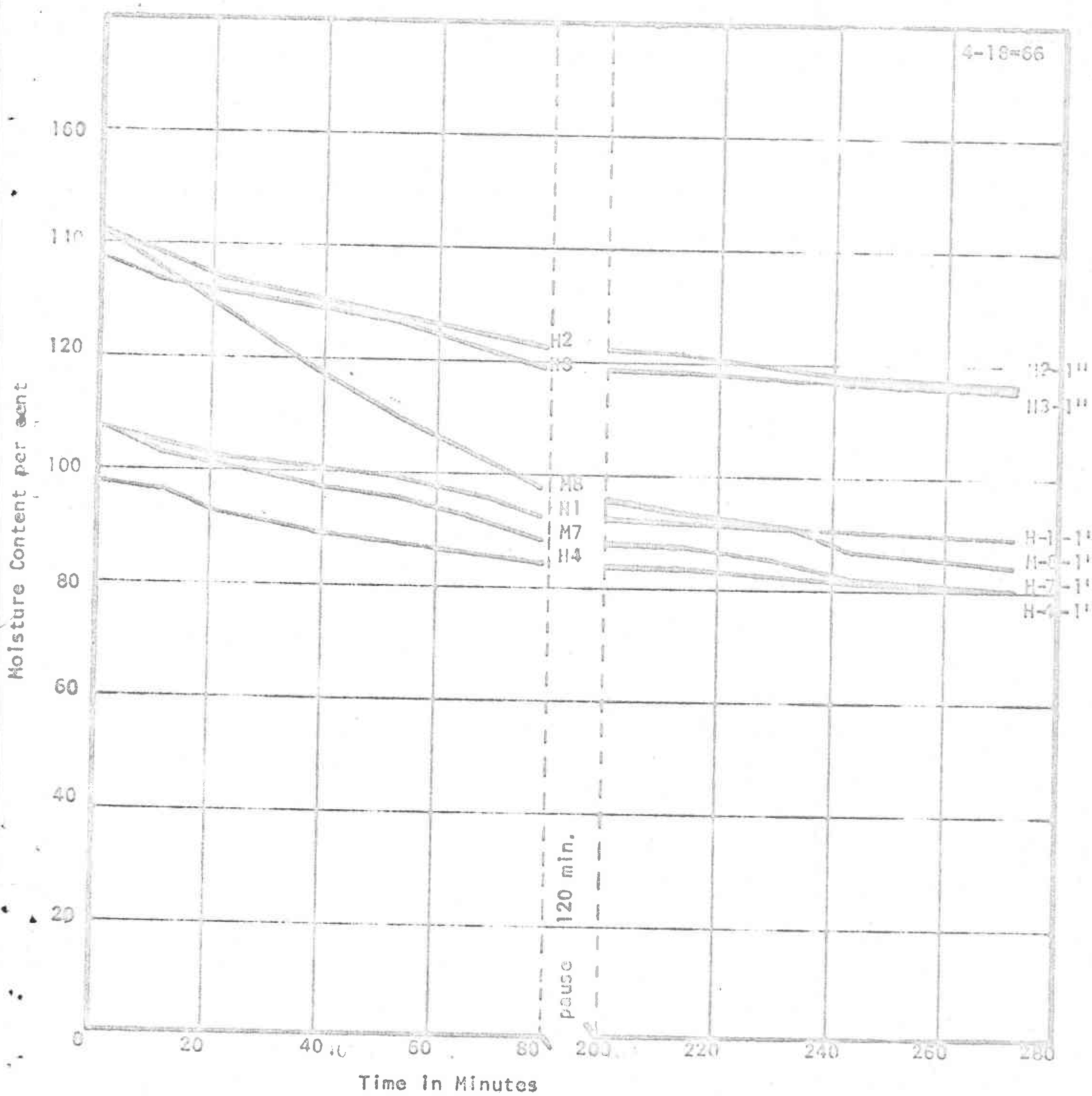
Figure 6



Exposure time in the unit = 40 min.

Ave. energy level = 1.75 KW

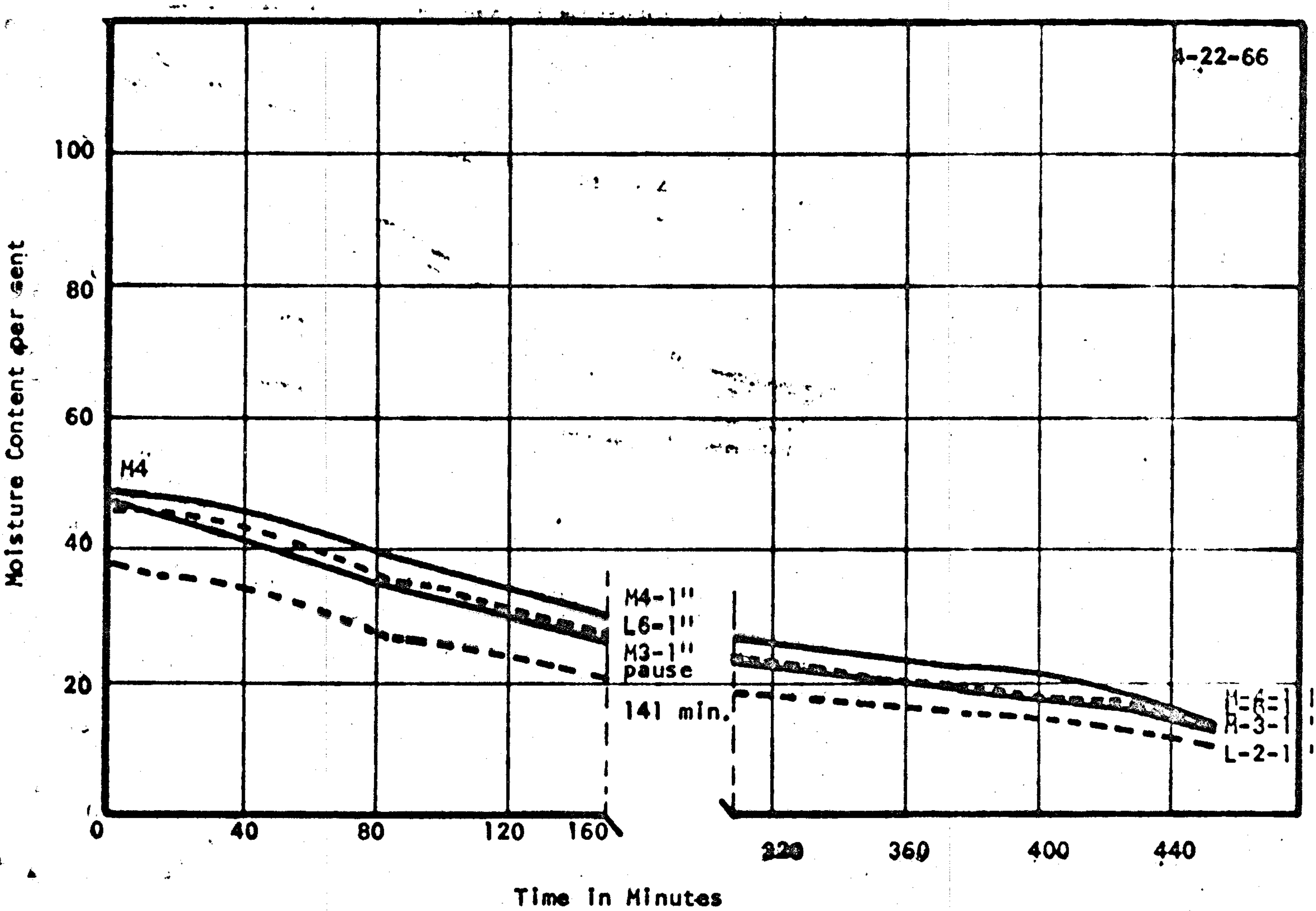
Figure 7



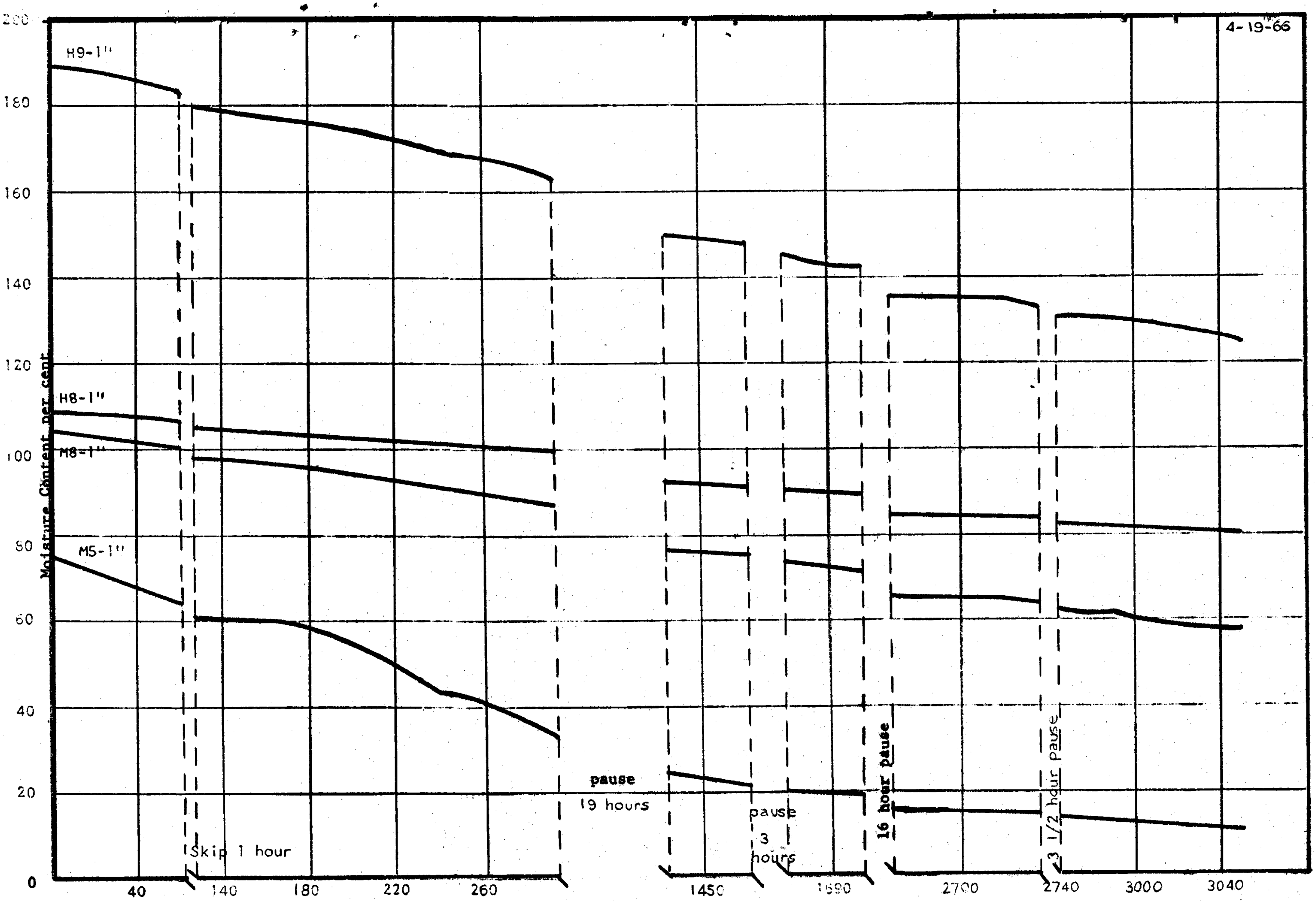
Exposure time in drying unit = 71.3 min.

Ave. energy level = 2.55 KW

Figure 9



Exposure time in drying unit = 56 min.
Average power level = 4.44 KW

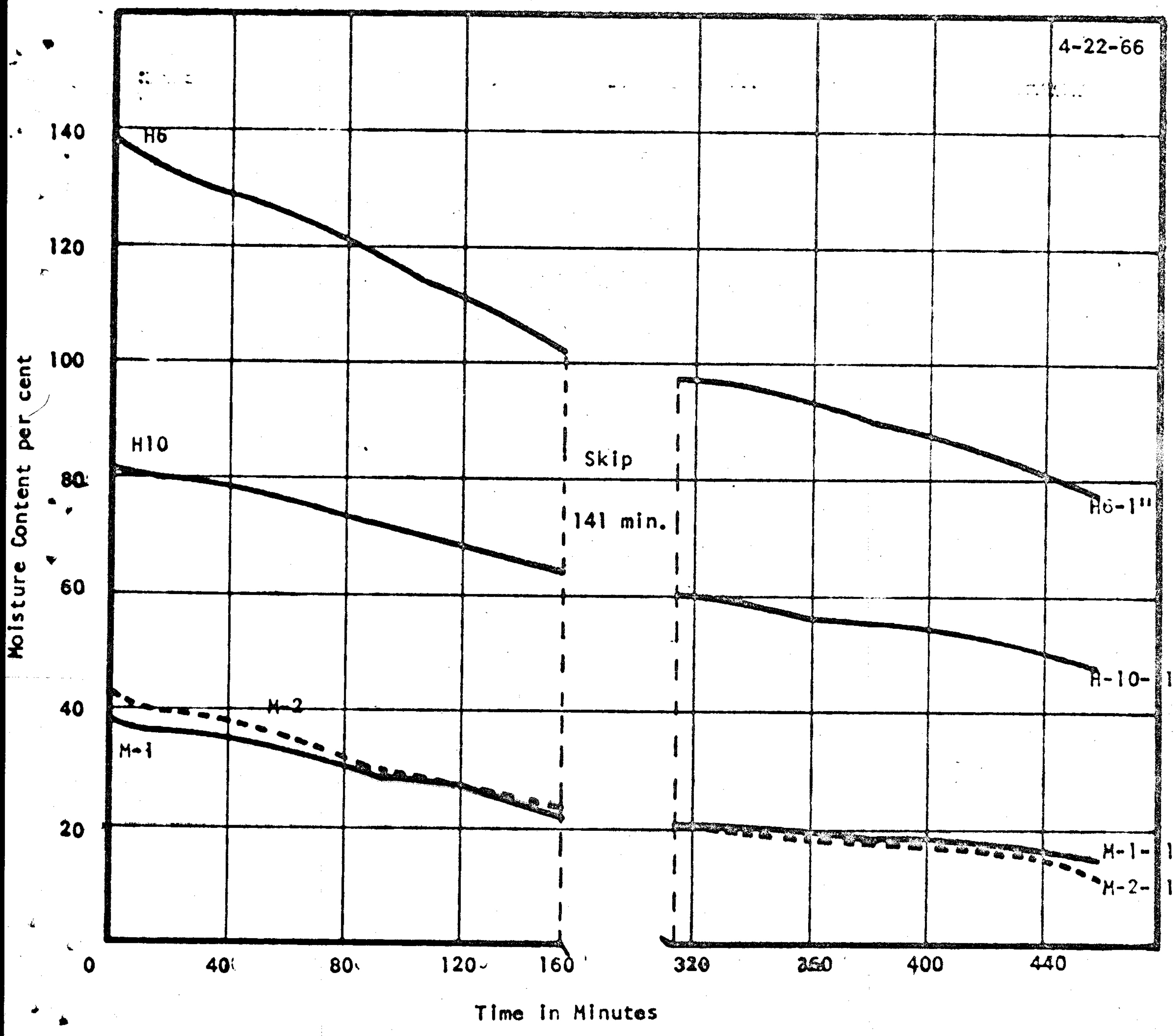


Time in Minutes

Exposure time in drying unit = 136 min.

Average power level = 2.24 KW

Figure 10



Exposure time in drying unit = 56 min.

Average power level = 4.44KW