BELLCOMM, INC.
955 L'ENFANT PLAZA NORTH, S.W. WASHINGTON, D. C. 20024

B70 09063

SUBJECT: The Influence of Thermal Control System Operation and Environmental Parameters on the Skylab Atmospheric Dewpoint Temperatures - Case 620

DATE: September 25, 1970

FROM: D. G. Miller

ABSTRACT

This memorandum presents a transient analysis of Skylab dewpoint temperatures. Crew metabolic rates are tied to sleep and active periods of the daily cycle using different rates for the sleep and active periods.

The purpose of this study was to explore ways of attaining the desired low levels of CO_2 concentration attendant to two molecular sieve, high flow rate operation (each 15 lb/hr). In particular the advantages of shutting down one sieve during sleep periods when the water generation rate is low were explored. The effect of limiting water removal from the condensing heat exchanger was studied. Application of both of these options in operation of the thermal control system/molecular sieve system (TCS/MSS) results in dewpoint levels which meet the Cluster Requirements Specification (CRS) at 70°F ambient temperature. They would not be adequate at an ambient temperature of 60°F. Somewhat higher levels of CO_2 concentration exist with this arrangement since the atmospheric mass throughput is only 83% of the value for continuous operation of both sieves.

Data are given for the transient case for the new system baseline at a sensible temperature of 70°F with one molecular sieve operating at 15 lb/hr. The analysis indicates that this regime meets the dewpoint specification without the injection of additional water from a humidifier. Lower sensible temperatures do require the addition of water for compliance with the CRS.

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MEMORANDUM FOR FILE

I. INTRODUCTION

Previous steady state analyses have shown that operation of two mol sieves, in order to reduce Skylab CO_2 partial pressure, results in atmospheric dewpoint temperatures significantly below the CRS allowable transient minimum.(1, 3) The CRS states "the nominal dewpoint temperature shall be 45°F with short transients to 40°F".(4)

The purpose of this analysis is to re-examine the humidity problem relative to a typical daily non-steady state crew timeline containing both an active and sleep period. Since crewman water production rate is a strong function of both metabolic rate and surrounding sensible temperatures, these parameters are included. The water partial pressure is calculated at the crew location as a function of time for the daily timeline. This approach provides an insight into the sensitivity of the Skylab water partial pressure, as indicated by dewpoint temperature, to varying environmental parameters. In addition, by changing the operation of the TCS/MSS, possible system changes become obvious that are sometimes not apparent from a steady state solution.

A thermodynamic model of the Skylab atmosphere with the TCS/MSS was developed by the author and programmed using the Chrysler Improved Numerical Differencing Analyzer computer program (CINDA).(2) The model has been verified by comparison of dewpoint and sensible atmospheric temperatures calculated from similar computer solutions developed at MSFC and McDonnell Douglas Astronautics Company Eastern Division (MDACED). The basic assumptions in the model pertinent to the calculation of dewpoint temperature are:

1. No atmospheric leakage from the Skylab to space,
2. The crew represent the only water production,
3. Water is removed by only the TCS condensing heat exchangers and mol sieves,

4. Inlet coolant temperature to the condensing heat exchangers is 40°F,
5. Airflow out of the mol sieves is dry,
6. Airflow rates through all heat exchangers and ducting are as given in reference 3 or as indicated in the analysis.

Based on these general assumptions and specific TCS/MSS operation and environmental parameters, dewpoint temperatures are calculated as a function of time and crew location.

II. DEWPOINT TEMPERATURE DEFINITION

Dewpoint temperature relates to atmospheric water partial pressure as being the saturated water vapor temperature for a specific water partial pressure. In atmospheric air, the water present is generally low pressure, superheated steam. Cooling the air at constant total pressure also cools the water until the water saturated temperature is reached. At this point additional heat removal causes water to condense isothermally. This constant temperature is known as the dewpoint,i.e. that temperature at which water vapor in the atmosphere begins to condense. Since the dewpoint temperature is the water saturated vapor temperature for a specific partial pressure it indicates the mass of water in a given volume of air and is independent of total air pressure or sensible temperature. Therefore, dewpoint temperature becomes a convenient reference for establishing the atmospheric water content as well as indicating the sensible temperature at, or below, which moisture will form.

III. DEWPOINT TEMPERATURE RESPONSE IN THE WORKSHOP (WS)

Based on medical requirements pertinent to minimum water content in the Skylab atmosphere, the CRS specifies a 45°F nominal dewpoint with short transients to 40°F permissible(4). The water production rates necessary to meet this minimum dewpoint requirement were explored by parametrically varying the water production rates in the crew compartment, assuming initial conditions in the Skylab to be 1)no water vapor present and 2)water vapor present corresponding to a 70°F dewpoint. For water production rates $\geq$0.564 lb/hr the crewmen were located in the experiment area and for a rate = 0.1405 lb/hr they were located in the sleep areas. Figure (1) shows the response of the crew compartment to the water production and indicates a fairly long time to reach equilibrium, particularly at rates <<.564 lb/hr. From these data it appears that at relatively high water production rates, as one might expect during the active period of a typical day, the crew compartment should reach the equilibrium dewpoint. However, dewpoints at the low rate for inactive periods would be far from the equilibrium value. In order to better define a minimum dewpoint it was obvious a typical variable water production rate timeline was required.

IV. CREW METABOLIC AND WATER PRODUCTION RATES

A major parameter controlling water production rate is the crew metabolic load. Once this load is defined, the water production rate can be determined as influenced by the crewmen's surrounding environment. MSFC(5) recommends for Skylab use a design daily average crewman metabolic rate of 500 btu/hr-man. However, this same reference indicates the majority of daily averages for the timeline to be only slightly greater than 400 btu/hr-man. For Apollo a design metabolic of 460 btu/hr-man was specified(6). Estimates of the crew metabolic load from Apollo flight data indicate an average 374 btu/hr-man(7). Assuming a similar ratio between design and actual metabolic loads from Apollo for the Skylab program, the actual load could be slightly greater than 400 btu/hr-man. However, this assumption is probably poor based on the Skylab's greater size and more varied crew activities. Therefore, in line with the MSFC recommended design metabolic rate and giving some weight to Apollo experience, it was decided to use 500 btu/hr-man, 450 btu/hr-man, and 400 btu/hr-man as the respective daily average maximum, nominal and minimum metabolic rates.

Water is transferred to the Skylab atmosphere by evaporation from the crewman's skin and by respiration. The evaporation requires latent heat which the body metabolism supplies. Therefore, a portion of the crewman's metabolic rate is latent heat and the remainder is sensible. The latent heat loss, for a fixed metabolic rate, is determined by the surrounding ambient temperature. As the ambient temperature rises, less sensible heat is lost by the body, and the latent heat loss increases through loss of moisture from the body. For example, at 70°F, 300 btu/hr sensible and 100 btu/hr latent heat are lost. At 80°F the sensible heat loss drops to 225 btu/hr but the latent heat increases 75% of what it was at 70°F to 175 btu/hr. In both cases, the total heat loss is the same - 400 btu/hr. This strong function of latent heat or body moisture loss to surrounding temperatures points to the necessity of including Skylab sensible temperature as a parameter controlling dewpoint temperature.

Figure 2 shows the relationship of metabolic rates to latent heat rates and the ambient temperature. These data are plotted from reference 8 along with MSFC data taken from reference 9. For our range of metabolic rates the MSFC data correlate well with reference 8. Additionally, data from reference 10 give an excellent correlation at a 75°F air-wall temperature for a metabolic rate of 450 btu/hr. The dashed lines in Figure 2 represent an extrapolation of the data to lower metabolic rates. This was necessary initially to determine latent heat rates for metabolic rates occuring during crew sleep periods. After obtaining more refined data it was found the extrapolation was poor, resulting in too low a latent heat rate. However, a majority of the dewpoint temperature calculations during the crew sleep period are with these low rates and, hence, are very conservative with respect to minimum dewpoint temperatures. The effect of the higher latent heat rate is discussed and computer results are compared in the succeeding sections.

Assumptions pertinent to the crewman water production rates are:

1. At metabolic rates between 400 and 500 btu/hr, the moisture lost by a crewman to the atmosphere includes sweating, diffusion, and respiration,
2. At assumed sleep metabolic rates of 280 btu/hr - 320 btu/hr the crewman moisture loss is only respiration and skin diffusion,
3. Based on data in reference 11, the effect of pressure was ignored (3.5 psia - 14.7 psia) on latent heat rates for metabolic rates up to 500 btu/hr,
4. Dewpoint temperatures approximately 50°F, (except where specified),
5. Clothing value comparable to men in shorts(10).

In the author's judgment the above water production rates for a given metabolic rate are somewhat low, particularly because of the relatively high assumed dewpoint temperature and light clothing. The respiratory and diffusion losses vary inversely with dewpoint temperature. Additionally, since the crew will be better clothed, sweating will increase with more clothing, which will increase the moisture load to the atmosphere if the clothing acts as an effective wick. Also, all of these factors are time dependent and in the final analysis a realistic crew timeline and location model are required to determine actual water production rates.

V. TIMELINE AND LOCATION MODEL

A Skylab timeline and location model for metabolic rates has been presented(5). However, input of these data to our existing basic atmosphere model would be time consuming as well as costly in computer time. Since the nature of the present work is basically exploratory, rather than design orientated, a representative timeline was assumed. This timeline lumped a day's activity for a given daily average metabolic rate into two constant metabolic rates, one for a 16 hour active period and another for an 8 hour sleep period. Since most of the crew time will be spent in the crew compartment it was assumed the crew were in the experiment area and sleep areas corresponding respectively to active and sleep periods.

The objective of this analysis is to examine the factors affecting the Skylab dewpoint temperature in relation to the minimum dewpoint. Therefore, typical days should be analyzed which are most likely to result in low dewpoint temperatures. Certainly the most obvious time of low dewpoint temperatures would be the period just after WS activation, hence this period was included in the analysis. A representative timeline was constructed starting with crew entry at the beginning of the 16 hour active period with the WS at 0 psia water partial pressure. For any set of conditions, environmental or TCS/MSS operation, this mode of timelining produces the lowest dewpoint temperatures. The timeline was run from these initial conditions over a three day period to allow the dewpoint temperatures to establish daily equilibrium values. This technique was employed to investigate the effects of crew metabolic rates, TCS/MSS operation, WS sensible temperatures, and crew location on dewpoint temperatures.

Once equilibrium dewpoint temperatures were established the timeline was extended for another three days to determine the effect of a day to day variation of the average metabolic rate. For this case an inactive day having an average metabolic rate of 450 btu/hr-man was followed by an active day average rate of 500 btu/hr-man. This second timeline contained the same daily active-sleep constraints as the first and simply represented an extension of the WS initial three day dewpoint history.

VI. TCS/MSS DEWPOINT TEMPERATURE CONTROL

The WS dewpoint history was calculated for the initial WS entry timeline assuming two mol sieves operating at 15 lb/hr-sieve air flow with normal TCS operation of two coolant loops with one pump per loop and a daily average metabolic rate of 450 btu/hr-man. It was assumed the 8 hour sleep period metabolic rate was 320 btu/hr-man, which resulted in a metabolic rate of 515 btu/hr-man for the active period. For these rates the latent heat was determined from Figure 2 for 60°F and 70°F ambient WS temperatures. The water production rate per crewman was determined using a water heat of vaporization equal to 1066 btu/lb as:

$$\dot{W}_{H_2O} = \frac{Q_L}{1066}$$

where $\dot{W}_{H_2O}$ = water production rate lb/hr-man

and Q_L = latent heat rate btu/hr-man

Input of these data to the atmospheric model computer program gave the results in Figure 3. Here the dewpoint temperature is plotted versus time after crew entry into the WS for conditions of the crew sleeping in the WS sleep areas and working in the experiment area. For the 70°F ambient temperature, cyclic equilibrium conditions are essentially established during the second day and repeat through the third day. The CRS dewpoint requirements are not met and dewpoint temperatures range between 42.5°F - 30.0°F.

For the 60°F ambient WS, extremely low dewpoint temperatures are noted due to the low water production rates and it is doubtful equilibrium conditions are reached even in the third day. This serves to illustrate the effect of ambient temperature on dewpoint temperature.

Both curves show that the initial period for low dewpoint temperatures is through the sleep period and several hours thereafter. Since the water production is low during the sleep periods and, correspondingly, CO_2 production is minimal, it was assumed one of the mol sieves could be turned off during sleep without seriously increasing overall CO_2 levels. This operational change to only one sieve during sleep resulted in significantly increasing the minimum sleep dewpoint temperature for the 70°F ambient WS, as shown in Figure 4. The maximum active dewpoint temperature was not affected but, in comparing Figure 3 and 4, a significantly higher average dewpoint temperature is noted during the active period in Figure 4. Also during this active period the maximum dewpoint is at an equilibrium value $>$ 40°F for the majority of the period. Since this temperature is above the coolant inlet temperature to the TCS condensing heat exchangers, these heat exchangers are removing water and impacting WS dewpoint temperatures.

Figure 5 shows the relationship of the condensing heat exchangers to the mol sieves. The present design requires that the air flow through the condensing heat exchangers reduce the dewpoint to a value slightly above 40°F before entering the sieves. This provides low water content air to the sieves and increases the effectiveness of the sieves from the standpoint of CO_2 removal and recycle time. As shown in Figure 5, only ∿1/4 of the air flowing through the condensing heat exchanger goes through the sieves. Therefore, in order to decrease the water removal capability of the TCS/MSS, a possible solution may be to bypass that air not required for the sieves around the condensing heat exchangers. This would be done only during periods of low water production in the WS, i.e., low metabolic rates and ambient temperatures. Assuming this change could be implemented in the present TCS/MSS, calculations were made for the same conditions as presented in Figure 3 but with only one mol sieve operated during sleep and bypassing the airflow around the condensing heat exchangers. Figure 6 gives the results for this TCS/MSS operational change. For the 70°F ambient WS both the maximum and minimum dewpoints increased to 45.1 and 40.2°F respectively. These temperatures are between the overall limits established by the CRS but still are short of meeting the CRS nominal dewpoint limit. For the 60°F ambient temperature, the water production rate is so low that dewpoint temperatures never exceed 40°F, regardless of the TCS/MSS changes. The importance of maintaining at least a 70°F WS ambient with the TCS/MSS operation is dramatically displayed in Figure 6. To further emphasize the significance of ambient temperature, the old baseline using one mol sieve at the lower airflow rate of 10 lb/hr was run for the 60°F WS ambient. As shown in Figure 6, this case also failed to meet the CRS requirement and, in fact, showed poorer performance than the 70°F ambient WS with the assumed TCS/MSS operational constraints.

The influence of metabolic rate on WS dewpoint temperature can be shown by comparing Figure 7 for a daily average metabolic rate of 500 btu/hr-man with Figure 3. Both cases are with the two mol sieve operation and, although the higher metabolic rate increases dewpoint temperatures, the CRS requirements are not met. Applying the TCS/MSS constraints of one mol sieve on during the sleep period, condensing heat exchanger airflow bypassed, and a WS ambient of 70°F, a significant increase is noted in dewpoint temperatures as shown in Figure 8. This case meets all of the CRS requirements after the first day. The equilibrium dewpoint temperatures for the third day fall between 44.8°F - 51.4°F with the dewpoint temperature well above the CRS nominal dewpoint. Since this case meets the CRS requirements, it was decided to continue the calculation assuming the initial 500 btu/hr-man average metabolic rate was followed by several days of varying average metabolic rates of alternate 450 btu/hr-man and 500 btu/hr-man. This case is shown in Figure 9 which starts referenced to Figure 8, at 3840 minutes. This start is shown as 0 time in Figure 9 and is for a daily metabolic average of 450 btu/man-hr followed by 500 btu/man-hr and finally 450 btu/man-hr. Results of the calculation show that the CRS nominal dewpoint temperature requirement is met; however, a period is noted of approximately 10.5 hours in which the dewpoint is below 45°F. Whether this period is too long with respect to CRS durational requirements at the lower dewpoint is unknown, but the period represents less than 15% of the three day cycle.

The effect of a 60°F WS ambient temperature was next calculated by assuming the same daily varying timeline metabolic rate but assuming the WS temperature was 60°F for the 450 btu/hr-man metabolic rate. Again the importance of ambient temperature is reflected in this calculation, since the case failed to meet the CRS dewpoint temperature requirements.

As mentioned in the preceding section, more refined data were found on sleep metabolic rate water production. Based on data provided in references 11 and 12, estimates were made for water production at 320 btu/hr-man and 280 btu/hr-man at 5 psia and sensible temperatures ∿70°F and a dewpoint temperature of 40°F. It was assumed at these low rates there would be no sweating and the entire water production was due to skin water diffusion and respiratory process. The table below gives the results of this work and compares these data with the initial values extrapolated from Figure 2:

METABOLIC RATE btu/hr-man	TOTAL LATENT HEAT btu/hr-man	WATER GENERATION RATE lb/hr-man
320 (refined) } (∿70°F) (Ref 11 or 12)	74.5	.0699
280 (refined)	69.5	.0653
320 (initial) (60°F) (Ref 8)	20	.0188
320 (initial) (70°F) (Ref 8)	40	.0376
320 (initial) (70°F) (Ref 9)	45	.0422

Since the new water production rates for the sleep period were significantly higher, one of the earlier cases was rerun with the new rates. Figure 10 shows the results of rerunning the 450 btu/hr-man metabolic rate @ 70°F ambient, one sieve on during sleep and the condensing heat exchanger flow bypassed. The effect of the higher sleep water production rate was to take the initial case, (Figure 6) which failed to meet the CRS requirement, and raise it to a marginal condition. However, based on the general conservatism of all the water production rates, this case should meet the CRS requirements. Since data are available which indicate that average metabolic rates may only be slightly greater than 400 btu/hr-man, a case was run at that level for a 70°F ambient, and plotted in Figure 10. This case assumes the same TCS/MSS operation as the previous case and the refined sleep water production rate for 280 btu/hr-man metabolic. As indicated in Figure 10, after the second day the dew point temperatures stabilize >40°F with an average daily dewpoint of approximately 40.5°F. Unless more recent data are available indicating average daily metabolic rates <400 btu/hr-man this last case would represent a lower limit for estimated minimum dewpoint temperatures for a 70°F WS.

A case was run in which only one mol sieve was operated continuously at a flow rate of 15 lb/hr for a 450 btu/hr-man daily average metabolic rate with the WS at 70°F. Results of this calculation are presented in Figure 11 and show that the CRS dewpoint requirement is met. However, since only one mol sieve is operating the Skylab resulting CO_2 partial pressures should be higher than those cases in which the mol sieves are cycled through the active-sleep periods.

VII. CO_2 PARTIAL PRESSURE CONSIDERATIONS

The continuous operation of two molecular sieves at the high flow rate of 15 lbs/hr each is designed to reduce the CO_2 average concentration to as low a value as possible. Dr. C. A. Berry has estimated the equilibrium level at 3.5 mmHg.(13) There is a transient component of CO_2 concentration resulting from the sleep-activity cycle. Preliminary MSFC analysis for one molecular sieve operating at 10 lbs/hr gave a transient component of approximately 0.5 mmHg on an average level of 5.0 mmHg. Turning off one molecular sieve for the eight hour sleep period will raise the average CO_2 concentration. Assuming molecular sieve performance is linear in terms of total atmospheric throughput, one would expect the average CO_2 concentration to rise by approximately 20%. Sufficient data for refining this estimate are not at hand. A specification value of average CO_2 concentration has not been formulated corresponding to the dewpoint specification. It is on this fact that the tradeoff of higher CO_2 concentration in favor of higher dewpoint temperatures ultimately rests.

VIII. SUMMARY AND CONCLUSIONS

A parametric analysis was made of the Skylab dewpoint temperature history for a wide range of crew water production rates and selective operation of the TCS/MSS. The crew water production rates were based on metabolic loads for both sleep and higher rate activities within a 60°F to 70°F sensible temperature range. The daily average metabolic load was assumed to be either 400 btu/hr-man, 450 btu/hr-man or 500 btu/hr-man. TCS/MSS operation was with:

1. One pump in each coolant loop and two mol sieves continuously operating at an air flow of 15 lb/hr each,
2. Two sieves on during the active period, one on during sleep at an air flow of 15 lb/hr each,
3. Same as 2 above, but air flow bypassed around the condensing heat exchangers except that flow required for the sieves,
4. One sieve operating at an air flow of 10 lb/hr.
5. One sieve operating at an air flow of 15 lb/hr.

Based on this parametric analysis it appears that operation of the TCS/MSS with two sieves on during the active period, one sieve on during sleep and bypassing that flow not required by the mol sieves around the condensing heat exchangers may result in acceptable Skylab CO_2 partial pressure while meeting the CRS dewpoint requirements. If, in conjunction with these modifications, the TCS (active/passive) can maintain sensible WS temperatures $\geq$70°F, then the CRS dewpoint temperature requirements should be met for crew average daily metabolic rates $\geq$450 btu/hr-man. This investigation also indicates that even the lowest anticipated daily average metabolic rate of 400 btu/hr-man produces an average dewpoint temperature in excess of 40°F.

Operation of only 1 mol sieve at 15 lb/hr in a 70°F sensible ambient and for a daily average metabolic rate $\geq$450 btu/hr-man will also meet the CRS dewpoint requirements without the addition of water by means of a humidifier, but at a higher CO_2 partial pressure.

ACKNOWLEDGMENT

The author wishes to thank Mr. T. A. Bottomley for his help in determining water production rates.

D. G. Miller

1022-DGM-mef D. G. Miller

Attachments
  Figures 1-10
  References

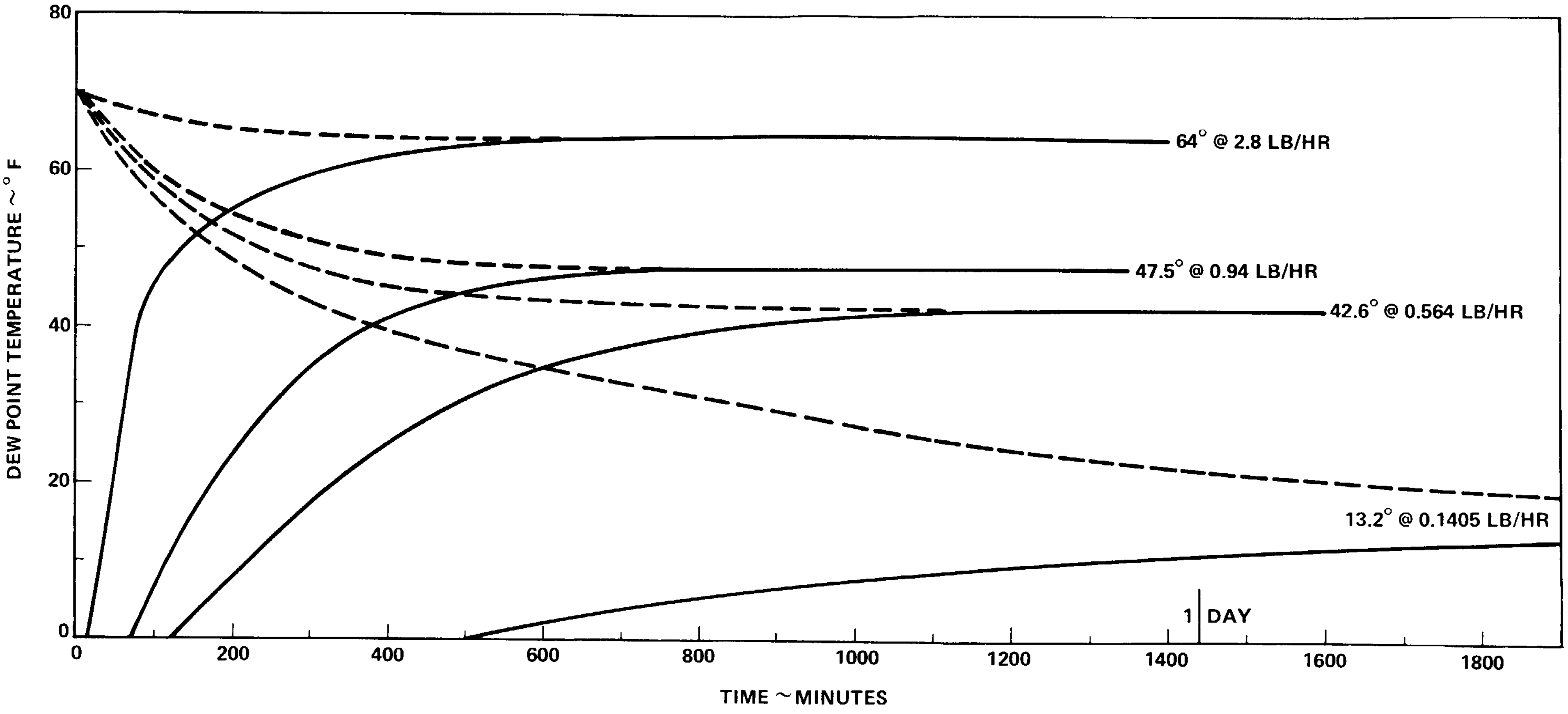

FIGURE 1 - WS CREW COMPARTMENT DEWPOINT TEMPERATURE HISTORY AS FUNCTION OF H_2O GENERATION RATE FOR 3 CREWMEN.

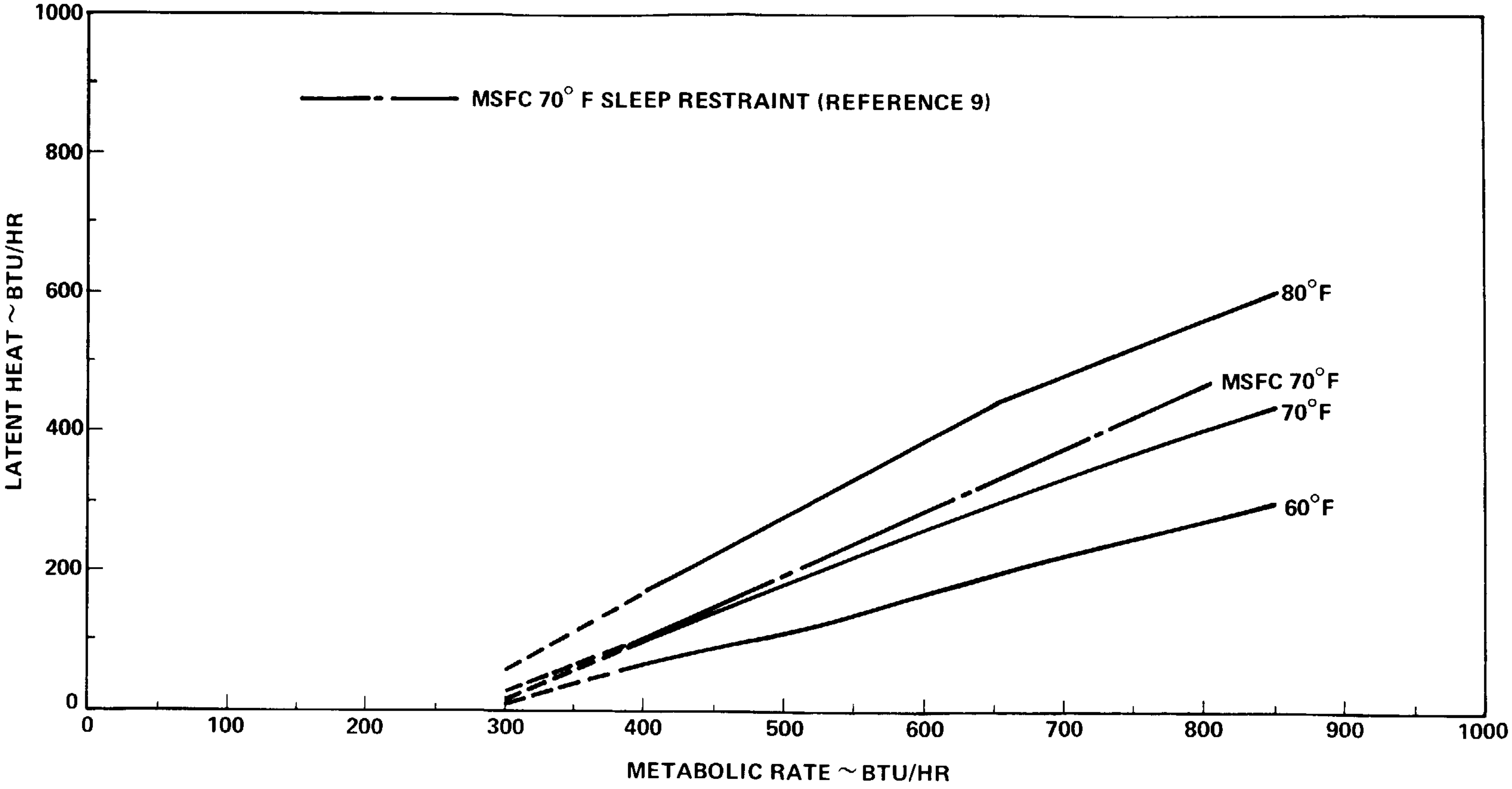

FIGURE 2 - LATENT VS. METABOLIC HEAT RATES FOR VARIOUS SURROUNDING TEMPERATURES (REFERENCES 8 & 9)

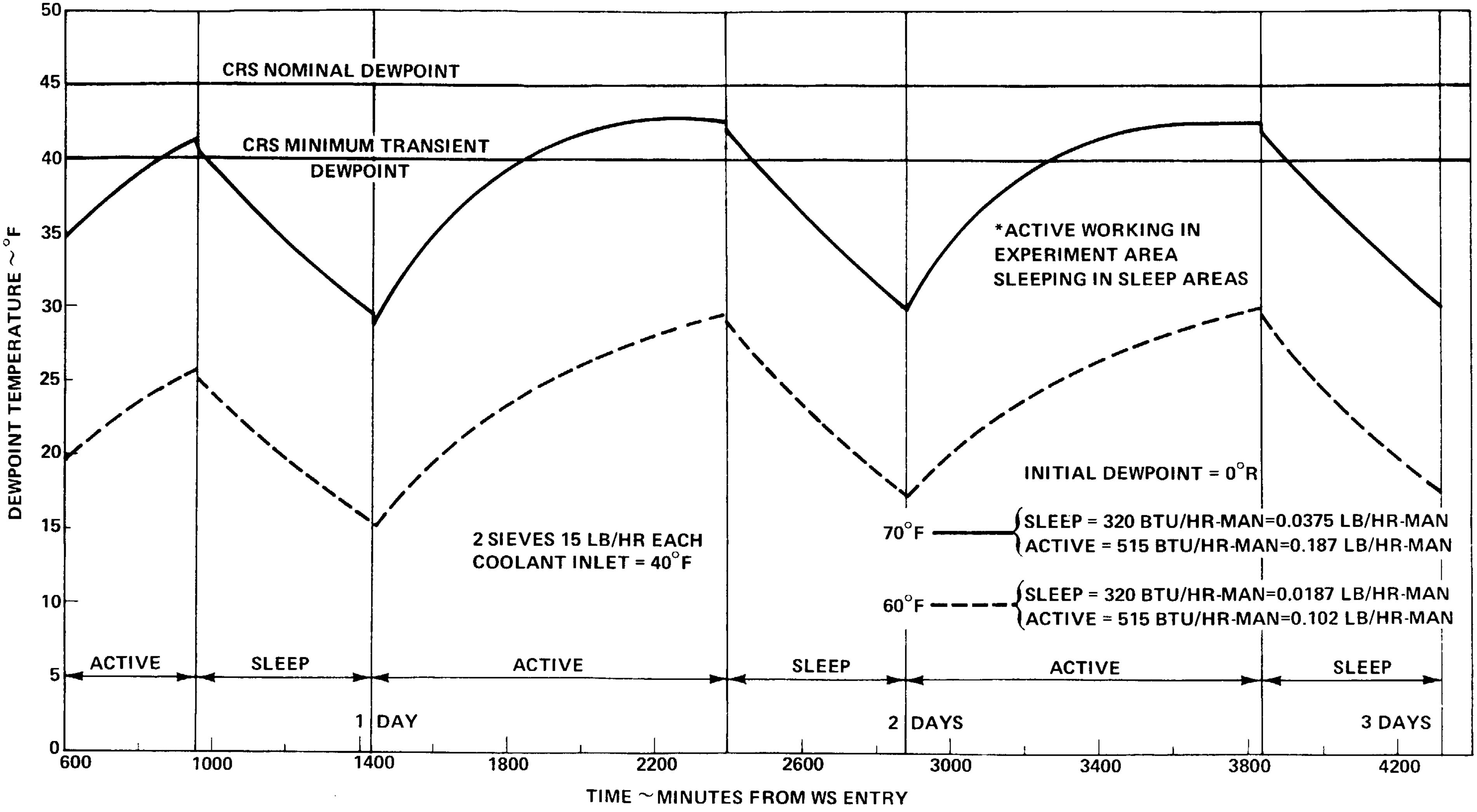

FIGURE 3 - WS DEWPOINT HISTORY, 450 BTU/HR-MAN AVG METABOLIC LOAD AFTER ENTRY*

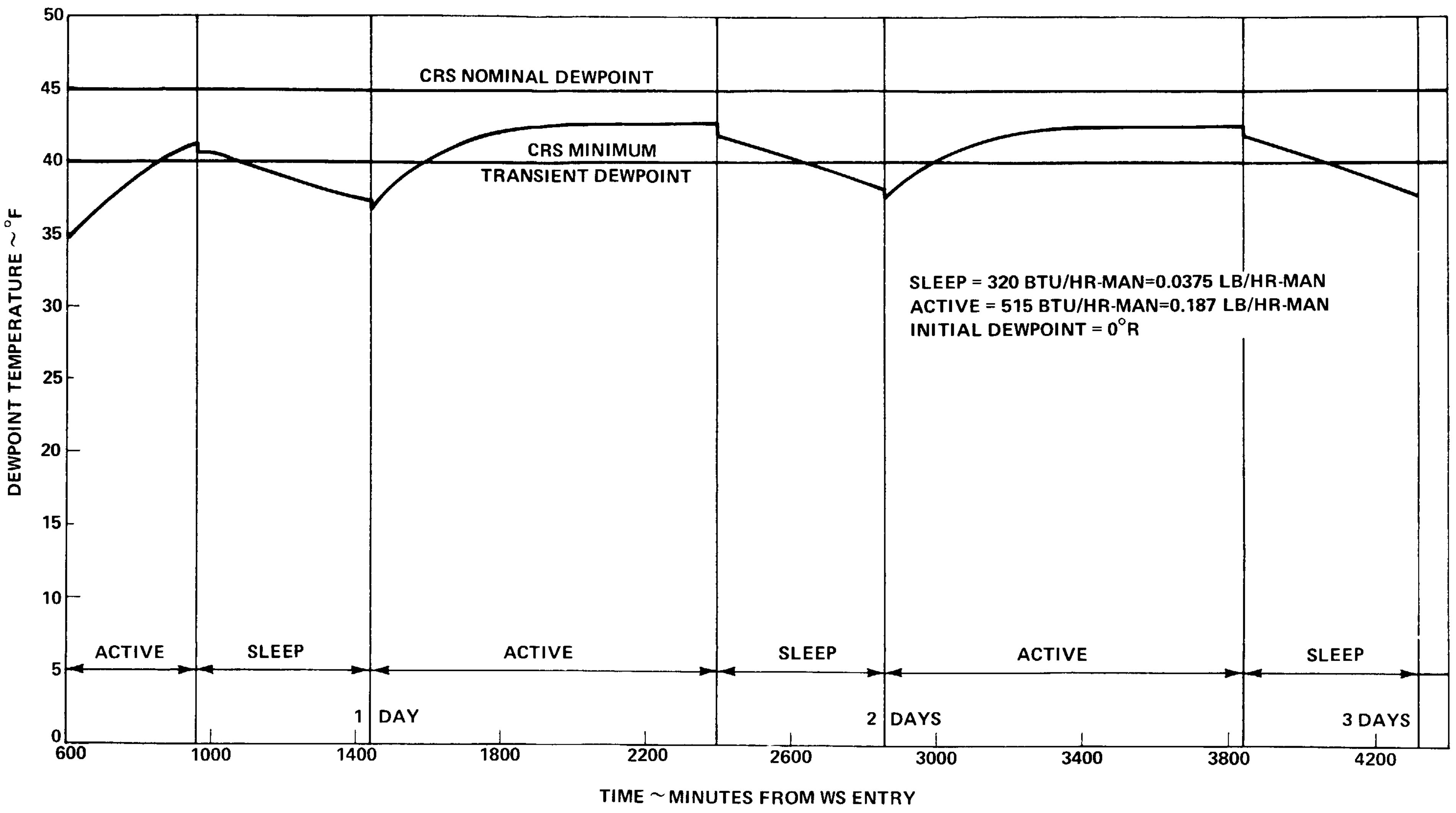

FIGURE 4 - WS DEWPOINT HISTORY, 2 SIEVES ON ACTIVE 1 SIEVE ON SLEEP (15 LB/HR EA.), 450 BTU/HR-MAN AVG (@ 70°F SENSIBLE) METABOLIC LOAD AFTER ENTRY

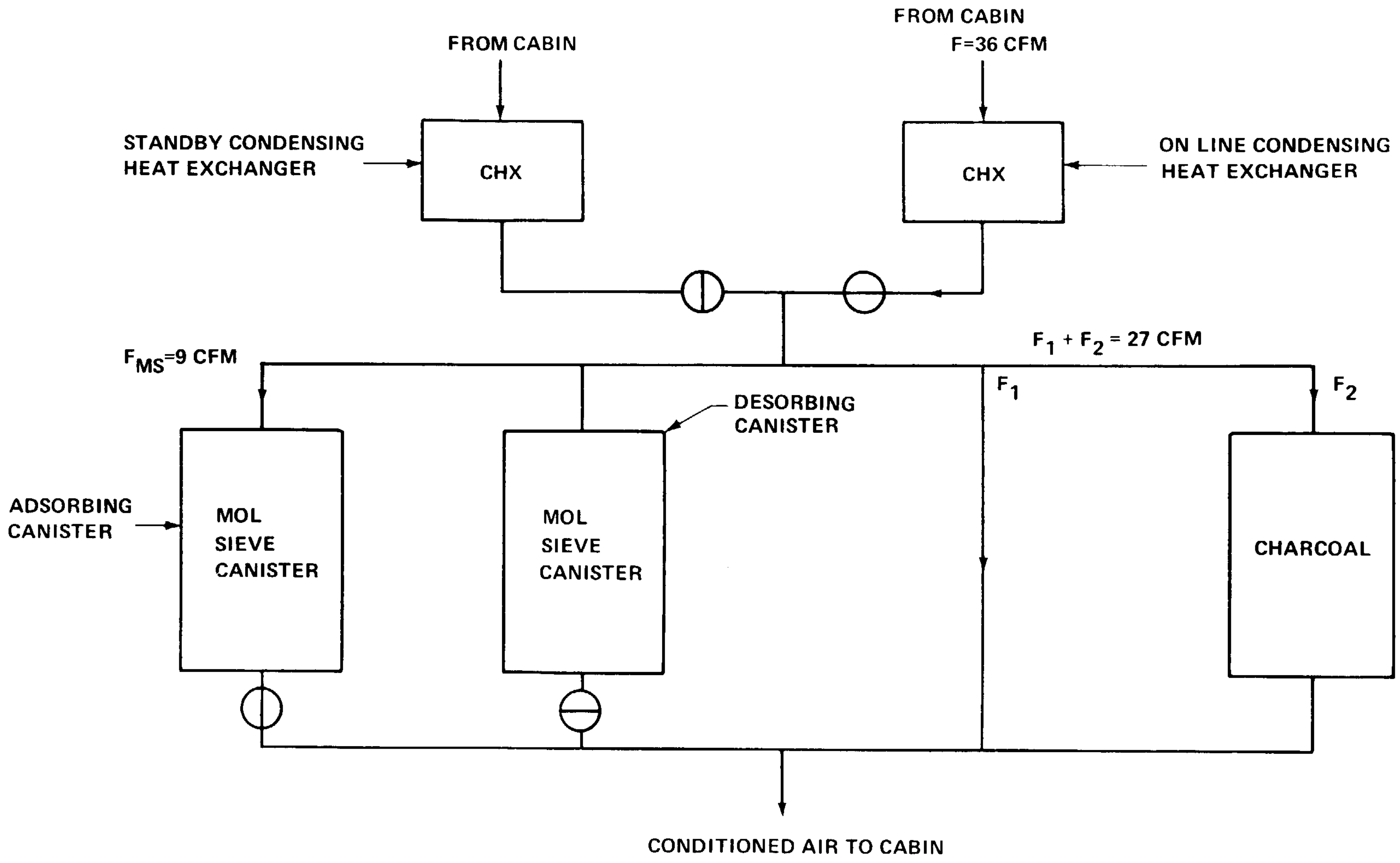

FIGURE 5 - FLOW SCHEMATIC FOR EACH CONDENSING HEAT EXCHANGER/MOLECULAR SIEVE SYSTEM

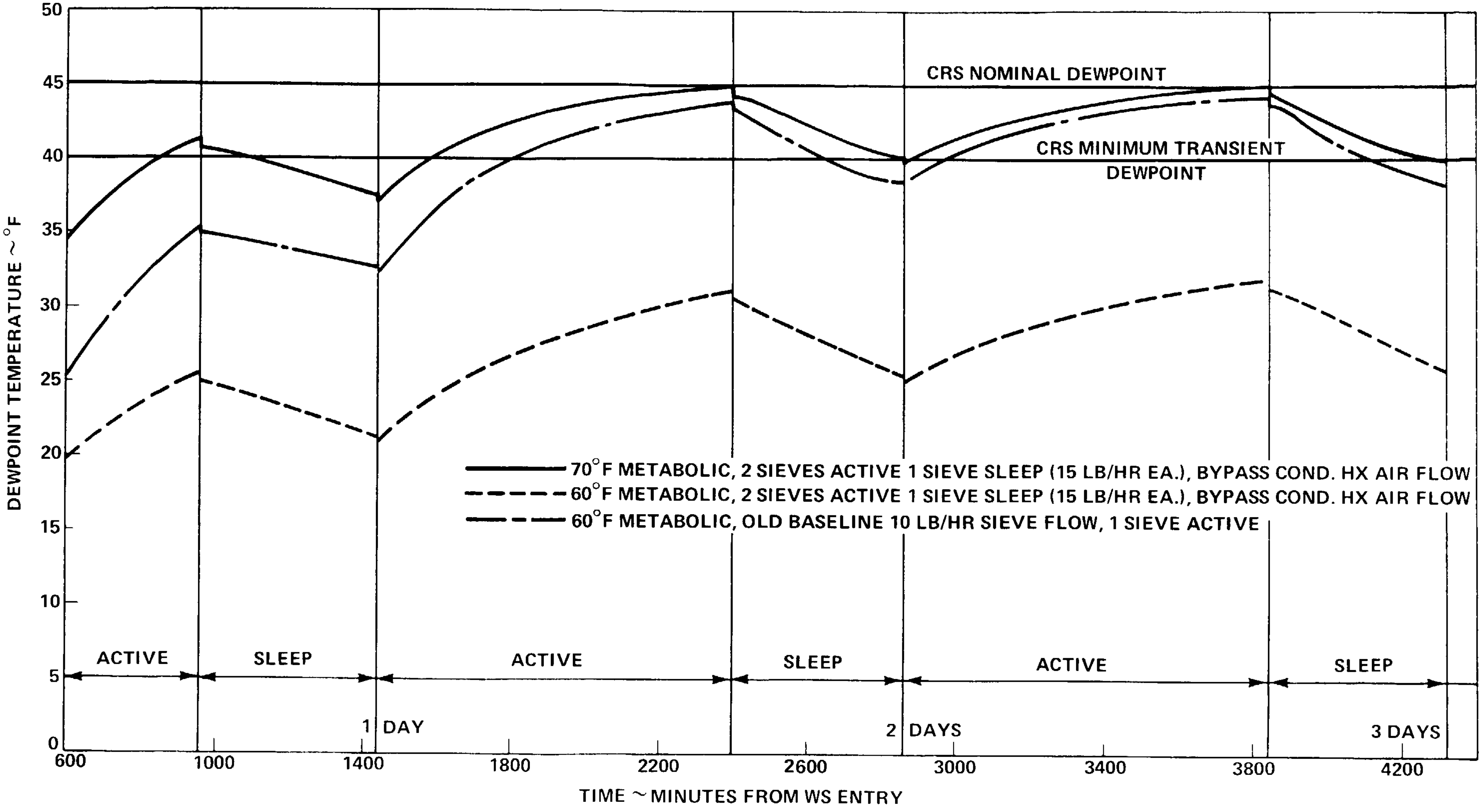

FIGURE 6 - WS DEWPOINT HISTORY, 450 BTU/HR-MAN AVG METABOLIC LOAD AFTER ENTRY

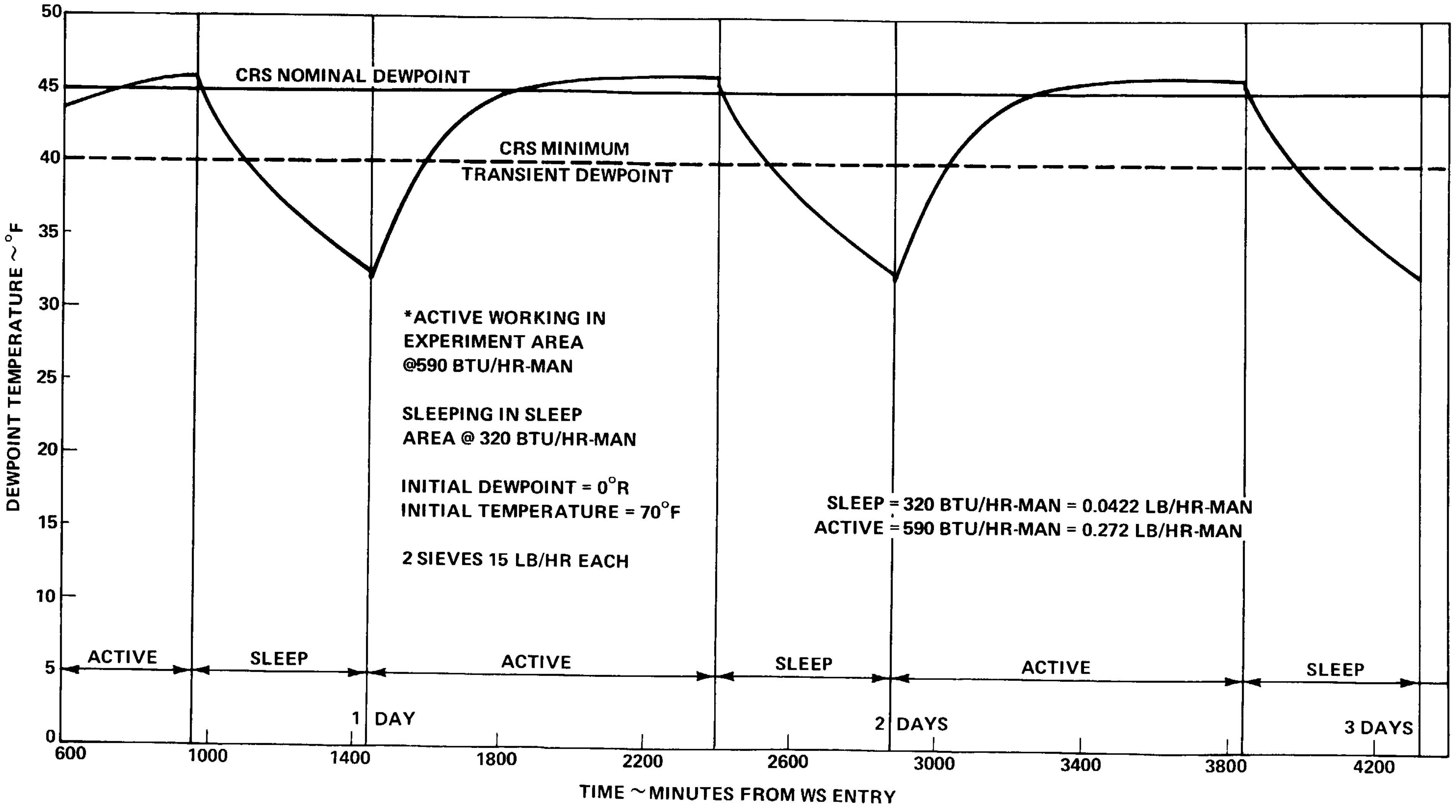

FIGURE 7 - WS DEWPOINT HISTORY, 500 BTU/HR-MAN AVG METABOLIC LOAD AFTER ENTRY*

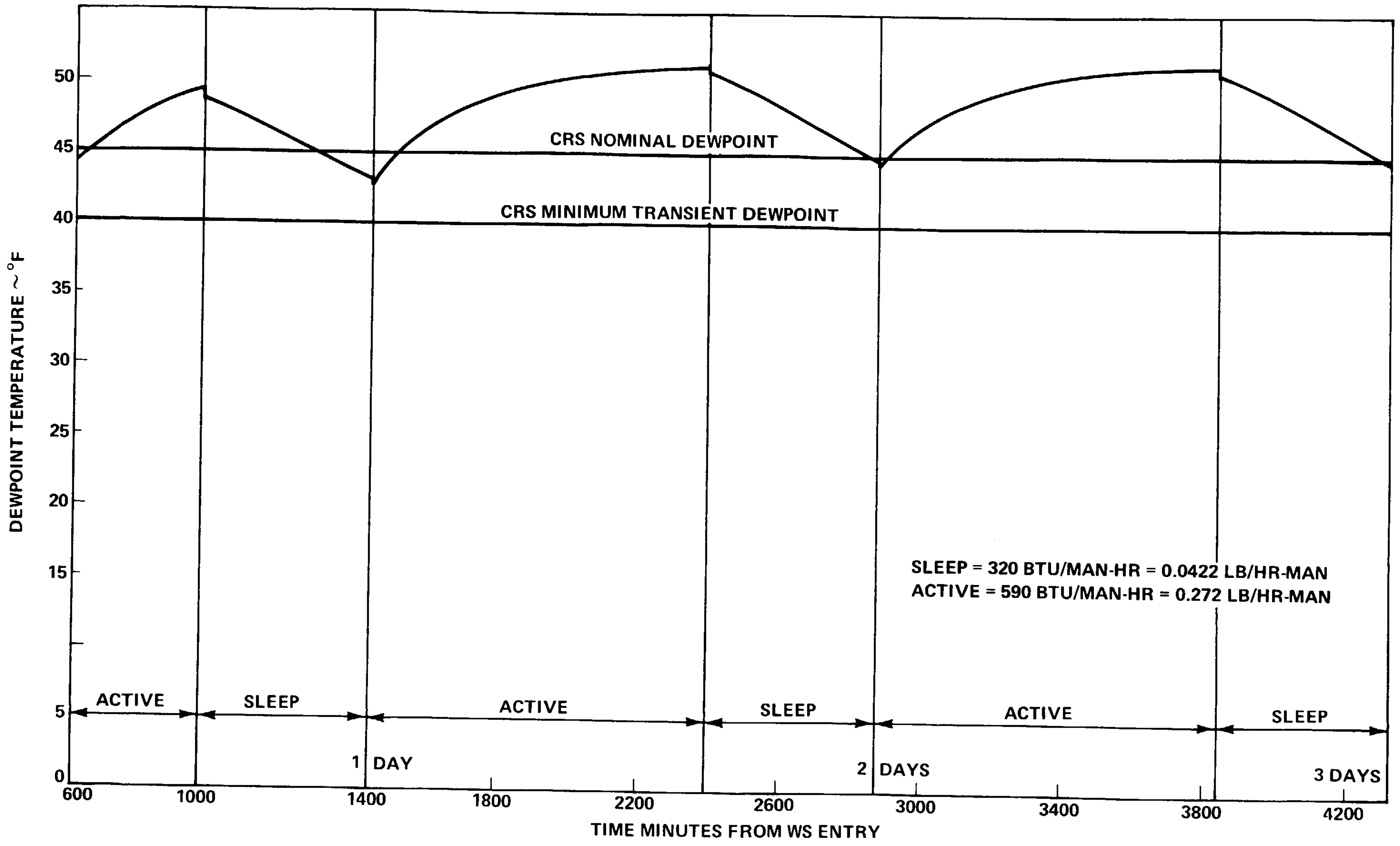

FIGURE 8 - WS DEWPOINT HISTORY, 2 SIEVES ON ACTIVE 1 SIEVE ON SLEEP (15 LB/HR EA.), 500 BTU/HR-MAN AVG (70°F SENSIBLE) METABOLIC LOAD AFTER ENTRY (AIRFLOW BYPASSED COND. HXS)

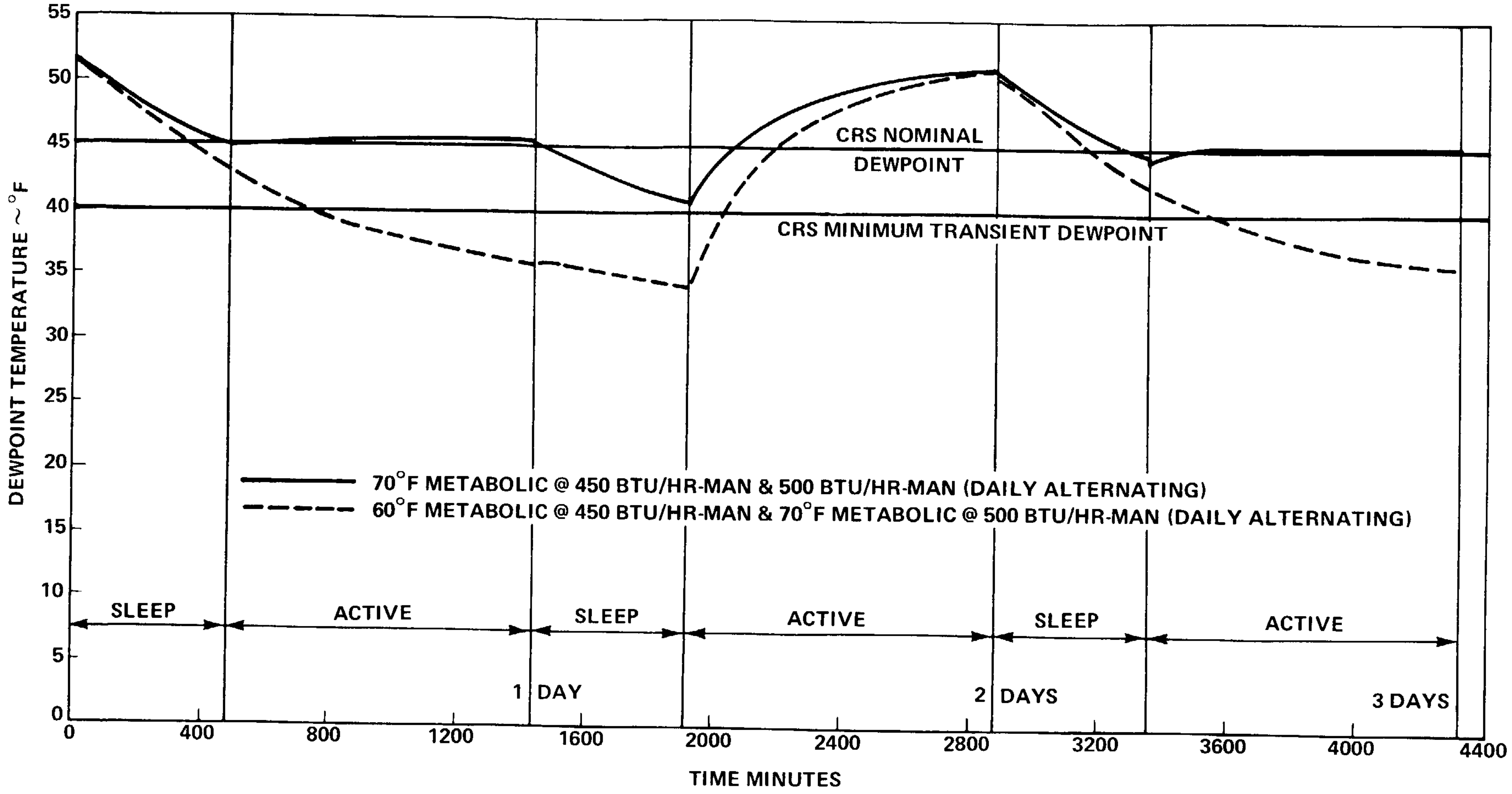

FIGURE 9 - WS DEWPOINT HISTORY, 2 SIEVES ON ACTIVE 1 SLEEP (15 LB/HR EA.), INITIAL DEWPOINT = 51.4°F (COND. BYPASSED)

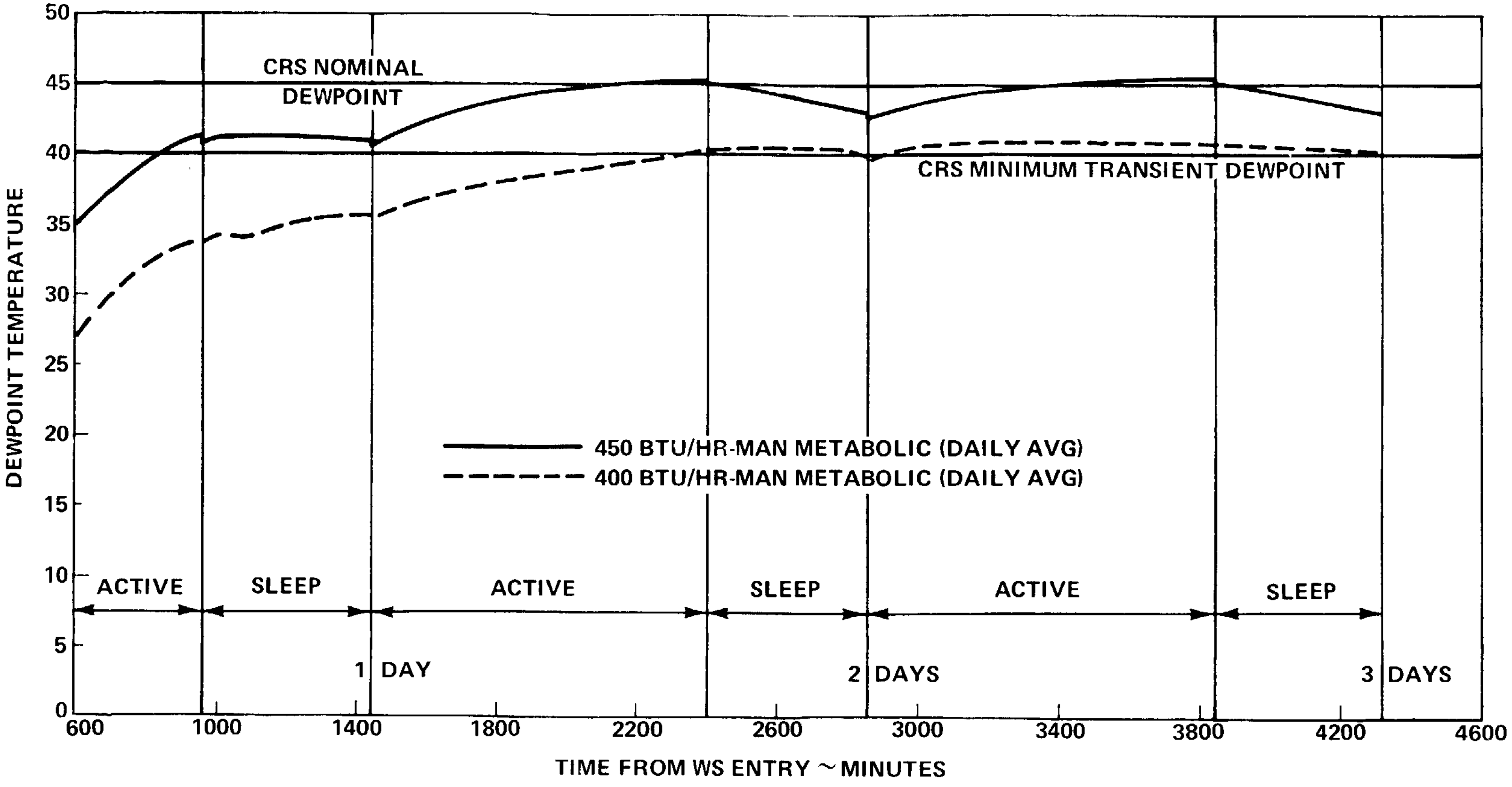

FIGURE 10 - WS DEWPOINT HISTORY, REFINED SLEEP H_2O PRODUCTION DATA,
2 SIEVES ACTIVE 1 SIEVE SLEEP (15 LB/HR EA.), BYPASS COND. HX
AIR FLOW AMBIENT = 70° F

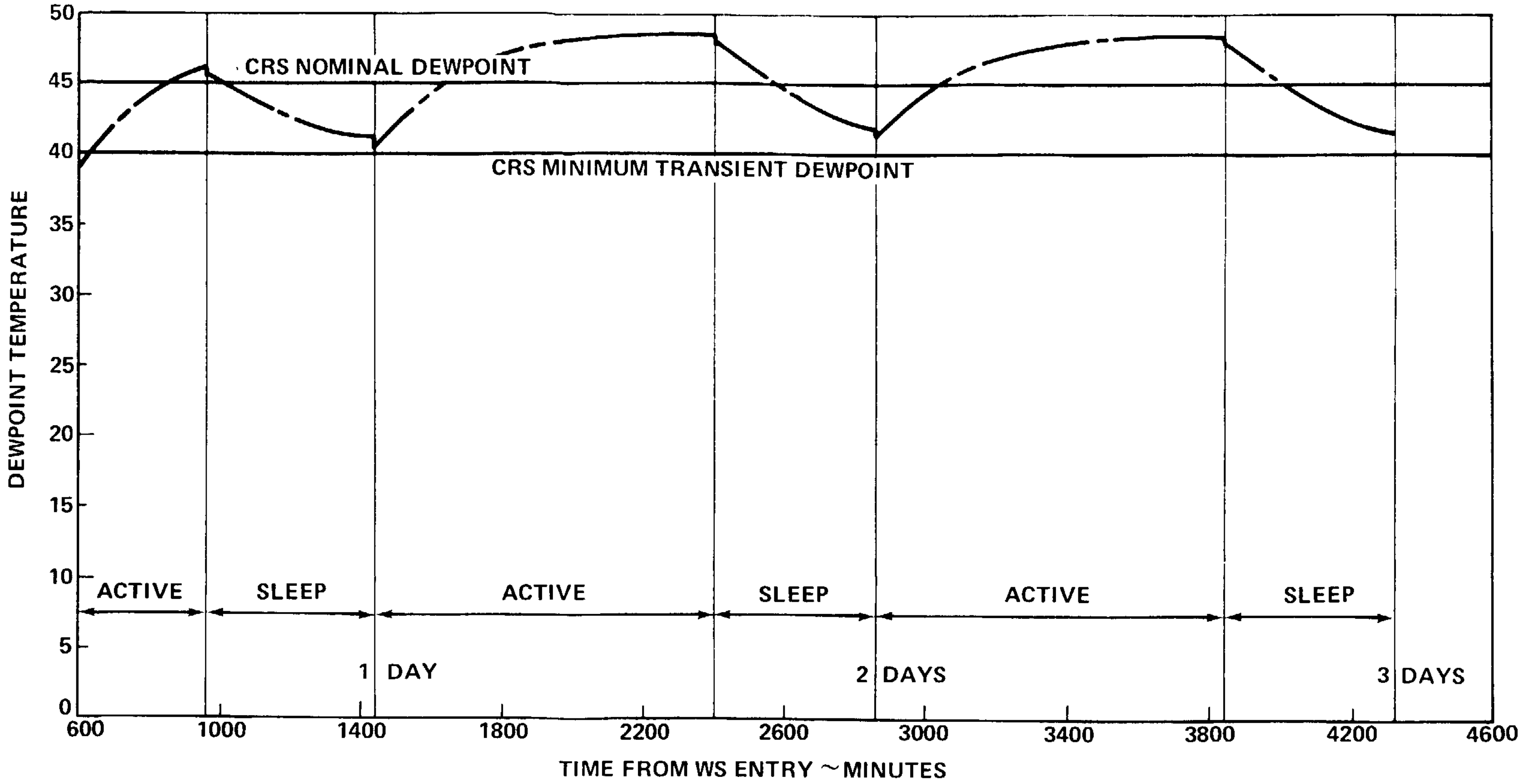

FIGURE 11 - WS DEWPOINT HISTORY, REFINED SLEEP H_2O PRODUCTION DATA, 450 BTU/HR-MAN METABOLIC (DAILY AVG), ONE SIEVE @ 15 LB/HR AMBIENT = 70°F

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Bellcomm

T. A. Bottomley
A. P. Boysen
J. P. Downs
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W. G. Heffron
J. Z. Menard
I. M. Ross
P. F. Sennewald
J. W. Timko
R. L. Wagner
M. P. Wilson
Departments 2031, 2034 Supervision
Division 101 Supervision
Department 1024 File
Division 102
Central File
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MSC

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