TECHNICAL REPORT

FEASIBILITY STUDY OF AUTOMATIC CONTROL OF CREW COMFORT IN THE SHUTTLE EXTRAVEHICULAR MOBILITY UNIT (EMU)

Job Order 81-107

Prepared By
Lockheed Electronics Company, Inc.
Aerospace Systems Division
Houston, Texas

Contract NAS 9-15200

For
CREW SYSTEMS DIVISION

National Aeronautics and Space Administration
LYNDON B. JOHNSON SPACE CENTER
Houston, Texas
February 22, 1977

LEC 9980
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1. INTRODUCTION

During the Apollo project, crew comfort in the Apollo Extravehicular Mobility Unit (EMU) was maintained by manual manipulation of a valve that controlled the inlet coolant temperature to the liquid cooled garment (LCG). Four inlet temperature selections were possible ranging approximately from 45°F to 80°F. During Skylab, similar comfort control was achieved by manually operating a valve which varied LCG coolant flow rate.

The Shuttle EMU design proposal includes an 11-position manual valve to vary inlet coolant temperature similar to the method used in Apollo. Eleven inlet temperatures would be available for selection vs. the four previously available.

Apollo experience indicates that some training is necessary to enhance the crewman's comfort and optimize his ability to carry a workload. Several tendencies were noted during lunar and Skylab extravehicular activities (EVA's):

a. Some crewmen precooled themselves in anticipation of a high activity level and left the valve in the valve position selected prior to the activity. A high level of training is needed for such anticipation.

b. Some crewmen tended to work at rates that were conducive to their comfort at some intermediate cooling level. They would slow down or stop and rest if they became too hot, or they would speed up or hurry to the next activity if they were too cool.

c. At times, preoccupation with a task would cause a crewman to forget comfort until excessive sweating or fatigue became imminent, and ground controllers would suggest valve changes.

It was proposed that the manual control valve be replaced with an automatic one as a product improvement item for the Shuttle program. The automatic valve proposed would sense the normally measured parameters of LCG inlet coolant temperature and LCG coolant inlet and outlet temperature difference (LCG AT) for use in controlling comfort. It was further proposed that if computer
simulations gave encouraging results, that tests would be run on Apollo hard-
ware in which the controller logic was simulated by real-time calculations.

LEC/ASD was tasked with determining the feasibility of such a controller
using Program J196 on the 1110 computer and to develop suggested control
logic for testing. This memorandum contains the results of that effort.

This concludes the requirements outlined by Action Item 46, Project 3030.
The study was conducted by LEC/ASD, Dept. 641-11.
2. DISCUSSION

2.1 CONTROLLER LOGIC

2.1.1 GENERAL

Using Program J196, the 41-node man program (ref. 1), a map of comfort can be plotted at steady state. Heat stored at steady state can be calculated for a grid of metabolic rates and inlet coolant temperatures at a given inlet gas dry bulb temperature, dewpoint temperature, and flow rate, and at a given suit heat leak. LCG coolant temperature difference (LCG ΔT) as calculated at steady state by the program can be plotted vs. metabolic rate for constant inlet coolant temperatures. At each plotted point, the heat stored at steady state can be noted. When the grid is completed, comfort boundaries can be interpolated between the heat storage value as follows:

\[ \text{Stored heat at comfort (Btu)} = \text{Metabolic rate (Btu/hr)} - \frac{278 \pm 65}{13.2} \]

A series of these comfort maps have been plotted. An example of such a study is found in reference 2. An example of this type of plot is shown in figure 1.

From plots such as figure 1, a relationship between inlet coolant temperature and LCG ΔT at steady-state comfort is established (figure 2). It was established by averaging together results from several comfort curves such as in figure 1 and modifying them to get better results while developing the controller logic.

To develop logic for this controller, however, some transient data was needed in order to input to the controller how much variation in LCG ΔT was due to previous inlet temperature adjustments and how much was due to changes in the activity level of the crewman (metabolic rate). Therefore, a controller was simulated on the 41-node man program which adjusted inlet LCG temperature by the heat storage of the body. This would be the ideal controller, but the hardware is not practical. Changes in ΔT vs. changes in inlet temperature
were determined as the simulated man remained at perfect comfort while being stepped from one metabolic rate to another. These points were then plotted and an average curve drawn through the points (fig. 3). This curve represents the expected changes in ΔΤ for every change in inlet temperature if the controller is perfectly tracking comfort during a transient in metabolic rate.

2.1.2 METHOD 1 - USE OF FIGURE 2

The logic of the controller using figure 2 was developed as follows:

\[ ΔΤ_{in_1} = K_1 \left( T_{in} - T_{in_{1}} \right) \]  \hspace{1cm} (1)

where \( ΔΤ_{in_1} \) = the adjustment signal to the final control element, \( T_{in} \) (set point for the inlet coolant temperature to the LCG), calculated from the method using figure 2.

\( K_1 \) = The proportional gain constant for the method using figure 2.

\( T_{in} \) = The current inlet temperature to the LCG.

\( T_{in_{1}} \) = The inlet temperature at steady state comfort read off figure 2 as a function of the currently measured ΔΤ.

2.1.3 METHOD 2 - USE OF FIGURE 3

The logic of the controller using figure 3 was as follows:

\[ ΔΤ_{in_2} = K_2 \left( \Delta T_{in_2} \right) \]  \hspace{1cm} (2)

where

\( ΔΤ_{in_2} \) = The adjustment signal to the final control element \( T_{in} \) calculated from the method using figure 2.

\( K_2 \) = The proportional gain constant for this method.

\( \Delta T_{in_2} \) = The changes in the inlet temperature based on figure 3.
\[ \Delta T_{in2} \] is read from figure 3 in the following manner. \( dT_{in}/dt \) is calculated (the changes in inlet temperature with time). \( d\Delta T/dt \) is read from figure 3 as the expected change in \( \Delta T \) (\( \Delta \Delta T \)) during the same period of time. Since the same period of time is used, \( \Delta \Delta T \) is read as a function of \( \Delta T_{in} \). The actual change in \( \Delta T \) (\( \Delta \Delta T \)) from the expected \( \Delta \Delta T \) is then calculated. A calculation of the deviation (\( \delta \Delta \Delta T \)) of the actual \( \Delta \Delta T \) from the expected \( \Delta \Delta T \) is made as follows:

\[ \delta \Delta \Delta T = \Delta \Delta T - \Delta \Delta T \]  

(3)

\( \delta \Delta \Delta T \) is the main error signal for this method. Error derivative and error integral compensation were also added:

\[ \delta \Delta \Delta T = (\Delta \Delta T - \Delta \Delta T) + K_3 \frac{d(\delta \Delta \Delta T)}{dt} + K_4 \int \delta \Delta \Delta T \, dt \]  

(4)

where

\[ \delta \Delta \Delta T = \Delta \Delta T - \Delta \Delta T \]  

(eq. (3)).

\( K_3 \) = the gain constant for error derivative compensation.

\( \frac{d(\delta \Delta \Delta T)}{dt} \) = the error derivative compensation.

\( K_4 \) = the gain constant for the error integral compensation.

\( \delta \Delta \Delta T \, dt \) = the error integral compensation.

The total error signal \( \delta \Delta \Delta T \) is then used on the \( \Delta \Delta T/\Delta T \) curve (fig. 3) to determine the adjustment to the final control element, \( T_{in} \), by reading \( \Delta T_{in2} \). \( \Delta T_{in2} \) is then applied in eq. (2) to determine the adjustment to the final control element supplied by this method.

2.5.4 FINAL TOTAL CONTROLLER SIGNAL COMBINED FROM FIGURE 2 AND FIGURE 3 METHODS

The two methods described in eqs. (1) and (2) are then combined to give a final calculated value to the final control element, \( T_{in} \):
\[ T_{in} = T_{in}^* + \left( \frac{\Delta T_{in1} + \Delta T_{in2}}{2} \right) \]

where \( T_{in}^* \) is the current value of the final control element, the inlet LCG coolant temperature set point.

2.1.5 NEGLECTED CONTROLLER CONSIDERATIONS

Sensor response times, controller deadband, and speed of the final control element were neglected. It should be pointed out that the final control element is the set point for the inlet temperature to the LCG. Another controller would be required to operate the diverter valve bypassing coolant flow around the sublimator in the portable life support system (PLSS) to control the actual LCG inlet temperature. The delay and logic of this controller was neglected in the program and the inlet temperature of the LCG was set instantly to the set point required.

Output differential and integral compensation were attempted in both methods (eqs. 1 and 2). Lack of time prevented the development of gain constants that would improve controller results and these items were not incorporated into the test logic. Error differential and integral compensation in method 1 was never tried for lack of time.

Controller logic was based on Reference 3, pages 6-SERVO-1 through 6-SERVO-20.

2.1.6 PROGRAM CODE AND SAMPLE INPUT

Appendix A shows the program edits used to add the controller logic to Program J196. A nomenclature list is included.

Appendix B shows the input used to develop the necessary calculations from program J196 to do the required pretest predictions.
2.2 CONTROLLER LOGIC VERIFICATION AND PRETEST PREDICTIONS

A 40-hour metabolic profile was run on the J196 program, and values for the gain constants $K_1$, $K_2$, $K_3$ and $K_4$ were varied to obtain optimum controller action. Figures 4 and 5 show the best results that were obtained before an actual hardware test of a simulated controller was run. Figure 4 shows the metabolic profile vs. time. On the same graph, the controller selected inlet temperature and the resulting LCG AT are plotted. Figure 5 shows the resulting heat stored vs. time and how it compares to the comfort limits. On the same graph, controller action is shown by a plot of LCG inlet temperature vs. time.

The best values for the controller parameters resulting from these computer runs were as follows:

a. Values for the inlet temperature vs. LCG AT at steady state comfort were taken from figure 2.

b. Values for $\Delta AT$ vs. $\Delta T$ while tracking perfect comfort were taken from figure 3.

c. Values for $K_1$, $K_2$, $K_3$ and $K_4$ were set at 0.085, 2.6, 0.0000001, and 0.01, respectively.

Pretest predictions of the controller test profile were run using the best controller logic achieved to that point. Metabolic rate levels were proposed to be 15 minutes each of 800, 2000, 400, and 1600 Btu/hr. Results are shown in figure 6. This graph shows heat stored vs. comfort limits. Valve action is shown by plotting inlet LCG temperature for expected test conditions. Recommendations for the test simulated controller included the following:

a. Set point values for the two curves were set at the figure 2 and 3 values as before.

b. $K_1$, $K_2$, $K_3$, and $K_4$ values were set at 0.0952, 2.912, 0.0000001, and 0.01, respectively.
3. CONCLUSIONS AND RECOMMENDATIONS

3.1 CONCLUSIONS

It can be concluded from computer simulation that crewman comfort can be assured by using automatic control of the inlet temperature of the coolant into the LCG when input to the controller consists of measurements of the LCG inlet temperature and ΔT. Subsequent tests using a facsimile of the control logic developed in the computer program confirmed the feasibility of such a design scheme.

Automatic comfort control has been demonstrated as a desirable product improvement. It is not a design requirement.

3.2 RECOMMENDATIONS

This controller should be fabricated and tested if funds can be made available for product improvement or if some reason is discovered that makes the inclusion of the device mandatory.

Design of the controller should include manual adjustment for shifting the curves from figures 2 and 3 to conform to physical changes such as a heat leak or inlet suit ventilation conditions and to compensate for personal preferences in comfort level. Design provisions should also be included in the PLSS hardware to allow that the controller be bypassed and that manual control of the diverter valve be available.

Final values of $K_1$, $K_2$, $K_3$, and $K_4$ should be determined by test. Final values for curves 2 and 3 can also be fine-tuned in testing. Output differential and integral compensation should be tested on both methods and error differential and integral compensation tried on method 1.

Recommendations for controller logic considerations were taken from reference 3, pages 6-SERVO-1 through 6-SERVO-20.
FIGURE 1 - DRY BULB TEMP. - 50
DEWPOINT TEMP. - 50
HEAT LEAK - 0
LCG INLET TEMPERATURE vs ΔT AT COMFORT

The reproduction of the original print is poor.
CHANGE IN LCG ΔT VS CHANGE IN LCG INLET TEMPERATURE WHILE TRACKING COMFORT

CHANGE IN LCG ΔT (°F)

CHANGE IN LCG INLET T (°F)

DWC
12/4/17
FIGURE 5

40 HR. PROFILE

HEAT STORED (Btu)

INLET COOLANT T (°F)

TIME (HRS)

Comfort Boundaries

FIGURE 5
Shuttle EMU Simulated Controller Test

FIGURE 6
REFERENCES


APPENDIX A

PROGRAM EDITS TO MODEL THE PROPOSED CONTROLLER
(NOMENCLATURE LIST IS INCLUDED)
C SO THAT CRANE CAN STEP MORE ACCURATELY
CALL DISCON
C
245 CONTINUE
LHDX = TRUE.
JIC = JT+1
XHATAR(JT) = SETI/60.
IF(JJ =4, INO TO 247
J = JT+1
C PUT THE XHAT VALUES IN ASCENDING ORDER
C
247 CONTINUE
XHAT = XHATAR(1)
JX = 1
IF(JX GT. 247 TO 24)
JT = JT+1
IF(JT GT. 11 TO 26)
CALL ASCEND(JHATAR, JT)
C
837 CONTINUE
I = 0
INIT = 0
NEW = 0
AP = .F.
IF(IPODE .GT. 0) AR = AC
IF(IPODE = 121, 2, 23)
21 WRITE(6, 117)
117 FORMAT(1X, 7SHIRTSLEVES MODE/)
GO TO 26
WRITE(6, 118)
118 FORMAT(1X, 8HNORMAL SUITED MODE/)
GO TO 26
WRITE(6, 119)
119 FORMAT(1X, 8HHEVA MODE/)
GO TO 26
WRITE(6, 120)
120 FORMAT(1X, 7HSUITED WITH HELMET OFF MODE/)
IF(IPRO) WRITE(6, 1101)
1101 FORMAT(1X, 1HPOST LANDING)
IF(NEW) WRITE(6, 1102)
1102 FORMAT(4HSTANDARD, VOLCAR, PD2A, PD2, CP, NUMFR, PA, AREAW,)
2, * TIC#*CPNC
* TIC#*CPNC
170. FORMAT(* ATOMIC GAS CONSTANT, LBF-FT/(LBM-DEG R)) ---- F9.3/
NOMENCLATURE OF VARIABLES APPEARING IN CONTROLLER EDITS

<table>
<thead>
<tr>
<th>Program name</th>
<th>Document engineering symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CCDELT</td>
<td>Figure 2</td>
<td>Curve of LCG $\Delta T$ vs. inlet temperature at comfort (both in $^\circ F$).</td>
</tr>
<tr>
<td>CCDLDL</td>
<td>Figure 3</td>
<td>Curve of change in LCG $\Delta T$ vs. change in LCG inlet temperature while tracking perfect comfort with the change in inlet temperature as the dependent variable (all $^\circ F$).</td>
</tr>
<tr>
<td>CCDLDP</td>
<td></td>
<td>not currently used.</td>
</tr>
<tr>
<td>CCDT WI</td>
<td>Figure 3</td>
<td>Curve of change in LCG $\Delta T$ vs. change in LCG inlet temperature while tracking perfect comfort with the change in LCG $\Delta T$ as the dependent variable (all $^\circ F$).</td>
</tr>
<tr>
<td>DELTAT</td>
<td>LCG $\Delta T$</td>
<td>Difference in the liquid cooled garment inlet and outlet coolant temperature ($^\circ F$).</td>
</tr>
<tr>
<td>DDL DL DT</td>
<td>$d\Delta T/dt$</td>
<td>Error differential compensation ($^\circ F$/hr).</td>
</tr>
<tr>
<td>DLDL DT</td>
<td>$\Delta T$ or $d\Delta T/dt$</td>
<td>Change in LCG $\Delta T$ with respect to time. (Time cancels out on the $\Delta \Delta T$ vs. $\Delta T$ curve) $^1$ ($^\circ F$/hr or $^\circ F$).</td>
</tr>
<tr>
<td>DLTAT I</td>
<td>-----</td>
<td>Difference in the liquid cooled garment inlet and outlet coolant temperatures calculated in previous time step ($^\circ F$).</td>
</tr>
<tr>
<td>DTWI</td>
<td>$\Delta T_{in2}$</td>
<td>The adjustment signal to the final control element using method 2, figure 3, eq. (2).</td>
</tr>
<tr>
<td>(first appearance)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DTWI</td>
<td>-----</td>
<td>Final complete adjustment signal to the final control element, $T_{in}$.</td>
</tr>
<tr>
<td>(second appearance)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
NOMENCLATURE OF VARIABLES APPEARING IN CONTROLLER EDITS (Continued)

<table>
<thead>
<tr>
<th>Program name</th>
<th>Document engineering symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>DTWI (second</td>
<td>dT&lt;sub&gt;in&lt;/sub&gt;/dt</td>
<td>Changes in LCG inlet temperature between current time increment and last (°F/hr).</td>
</tr>
<tr>
<td>appearance)</td>
<td></td>
<td>(Continued)</td>
</tr>
<tr>
<td>EDLDLT</td>
<td>ΔΔT</td>
<td>Expected change in LCG ΔT (dΔT/dt) that would accompany a change in LCG inlet temperature if perfect comfort were being tracked (°F/hr).</td>
</tr>
<tr>
<td>H</td>
<td>dt</td>
<td>Current time increment (hr).</td>
</tr>
<tr>
<td>HO</td>
<td>----</td>
<td>Previous time increment (hr).</td>
</tr>
<tr>
<td>RDLDLT</td>
<td>∫ΔΔT dt</td>
<td>Summation of ΔΔT times the time increment (°F/hr).</td>
</tr>
<tr>
<td>TWI (first</td>
<td>---</td>
<td>New position of the final control element as calculated by method 2, figure 3, eq. (2) (°F).</td>
</tr>
<tr>
<td>appearance)</td>
<td></td>
<td>(Continued)</td>
</tr>
<tr>
<td>TWI (second</td>
<td>T&lt;sub&gt;in&lt;/sub&gt;</td>
<td>New position of the final control element (°F).</td>
</tr>
<tr>
<td>appearance)</td>
<td></td>
<td>(Continued)</td>
</tr>
<tr>
<td>TWI1</td>
<td>---</td>
<td>Position of the final control element at the previous time increment (°F).</td>
</tr>
<tr>
<td>TWI2</td>
<td>---</td>
<td>Position of the final control element as calculated by method 1, figure 2, eq. (1).</td>
</tr>
<tr>
<td>WDLDLT</td>
<td>ΔΔT</td>
<td>Deviation of the actual change in LCG ΔT from the expected change in LCG ΔT.</td>
</tr>
<tr>
<td>WILDLT</td>
<td>----</td>
<td>WDLDLT at the previous time increment.</td>
</tr>
</tbody>
</table>
APPENDIX B

INPUT TO PROGRAM J196 TO BRING ABOUT
THE NECESSARY CONTROLLER PRETEST PREDICTIONS
AND EVALUATIONS