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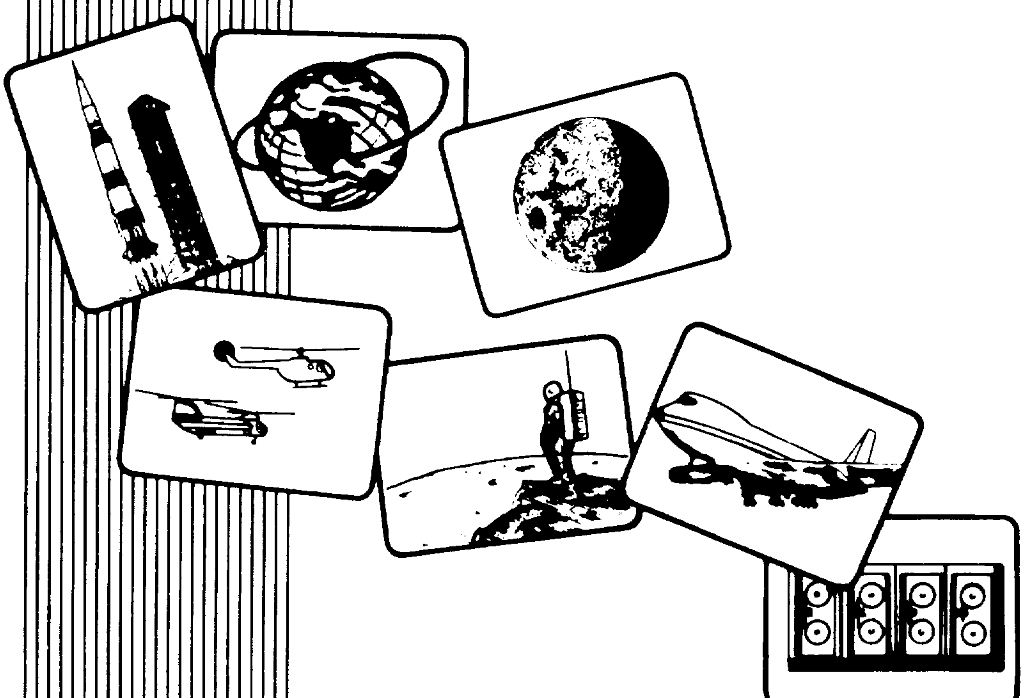
APOLLO OXYGEN TANK STRATIFICATION ANALYSIS

FINAL REPORT

VOLUME II OF II



THE BOEING COMPANY
HOUSTON, TEXAS

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FINAL REPORT
VOLUME II OF II

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Prepared by:

Propulsion and Power Systems
5-2921

Prepared for:

National Aeronautics and Space Administration
Manned Spacecraft Center
Houston, Texas

January 31, 1972

Prepared by: J. E. Barton
H. W. Patterson

Approved by: R. K. Nuno
R. K. Nuno 5-2921
Program Manager

THE BOEING COMPANY HOUSTON, TEXAS

REVISIONS

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ABSTRACT

An analysis of flight performance of the Apollo 15 cryogenic oxygen tanks was conducted with the variable grid stratification math model developed earlier in the program. Flight conditions investigated were the CMP-EVA and one Passive Thermal Control period which exhibited heater temperature characteristics not previously observed. Heater temperatures for these periods were simulated with the math model using flight acceleration data. Simulation results (heater temperature and tank pressure) compared favorably with the Apollo 15 flight data, and it was concluded that tank performance was nominal. Math model modifications were also made to improve the simulation accuracy. The modifications included the addition of the effects of the tank wall thermal mass and an improved system flow distribution model. The modifications improved the accuracy of simulated pressure response based on comparisons with flight data.

KEY WORDS

Apollo
Convection
Cryogenic
Heat Transfer
Heater Cycles
Heater Temperatures
Oxygen
Pressure Decay
Pressurization
Radiation
Stratification
Thermodynamics

ACKNOWLEDGEMENTS

The stratification model used for the oxygen tank analysis was developed by Mr. C. K. Forester, Boeing/Seattle. During the period of performance covered in this report, Mr. Forester modified the math model to include pressure vessel thermal mass, developed methods for establishing model parameters, and made other contributions to the program which are sincerely appreciated.

Special tanks are extended to Mr. R. R. Rice, NASA-MSC, for his many useful suggestions and help in acquiring and interpreting the flight data necessary for the analysis.

TABLE OF CONTENTS

ILLUSTRATIONS AND TABLES

LIST OF ILLUSTRATIONS

LIST OF TABLES

REFERENCES

1. NASA-MSC Contract No. NAS 9-11576, Apollo Oxygen Tank Stratification Analysis, dated November 2, 1970.

2. J. E. Barton, H. W. Patterson, and D. D. Rule, APOLLO OXYGEN TANK STRATIFICATION ANALYSIS FINAL REPORT, Boeing Document D2-118406-1, Volume I of II, August 31, 1971.

3. NASA-MSC Contract No. NAS 9-11576, Apollo Oxygen Tank Stratification Analysis Supplemental Agreement, dated August 10, 1971.

4. "Study Program Plan Amendment - Apollo Oxygen Tank Stratification Analysis - Contract NAS 9-11576," Boeing Memo 5-2940-HOU-1440, September 17, 1971.

5. J. E. Barton and H. W. Patterson, POSTFLIGHT ANALYSIS OF THE APOLLO 15 CRYOGENIC SYSTEM, Boeing Document D2-118422-1, December 15, 1971.

6. J. E. Barton, G. I. Bultman, C. K. Forester, J. B. Urquhart, and H. W. Patterson, COMPUTER PROGRAM MANUAL - APOLLO OXYGEN TANK STRATIFICATION ANALYSIS, Boeing Document D2-118407-1A, January 12, 1972.

7. J. E. Barton, H. W. Patterson, and D. D. Rule, POSTFLIGHT ANALYSIS OF THE APOLLO 14 CRYOGENIC OXYGEN SYSTEM, Boeing Document D2-118405-1, July 14, 1971.

1.0 INTRODUCTION

1.1 PURPOSE

The primary purpose of the Apollo oxygen tank stratification analysis was to evaluate the oxygen tank flight performance. The purpose of the program phase presented in this document was to evaluate the Apollo 15 tank performance and to improve the utility of the variable grid math model. Specific objectives chosen to achieve the program purpose were:

1. Determine the cause of any tank performance difference between Apollo 14 and Apollo 15 which is related to stratification.

2. Modify the variable grid math model to improve flexibility and simulation capability, and determine the maximum acceleration conditions which can be adequately simulated.

1.2 BACKGROUND

The effort initiated November 1, 1970, as originally defined in Contract NAS 9-11576, Apollo Oxygen Tank Stratification Analysis (Reference 1), was completed with the Final Report delivered on August 31, 1971 (Reference 2). The objective of this effort, evaluation of tank flight performance, was successfully achieved. The evaluation based primarily on Apollo 14 flight data did not, however, include all flight conditions expected during later missions. The CMP-EVA condition, for example, could not be thoroughly evaluated since the Apollo 14 mission merely simulated the EVA conditions. Such flight data limitations resulted in a requirement for additional analysis for complete confidence in the tank performance evaluation.

The simulation capability of the stratification math model developed as part of the Contract NAS 9-11576 was also verified with the Apollo 14 flight data. The model accuracy was generally satisfactory; however, modifications to improve the simulation accuracy and increase the model utility were identified.

1.2 Continued

A Contract Supplemental Agreement (Reference 3), which extended the period of performance from August, 1971, through January, 1972, was executed to accomplish a more complete tank performance evaluation and to develop desirable math model modifications. The contract period was extended through January, 1972, in order to evaluate the tank on the basis of Apollo 15 flight data.

1.3 SCOPE

The current analysis effort included only flight conditions that were significantly different from any previously investigated as part of the original contract effort. Math model modifications identified by the earlier analyses to improve the model utility were also included in this final phase of the program. The analytical effort was conducted in the framework of the original contract tasks. The extended tasks were:

Task 1 - Math Model Improvement

Task 3 - Apollo Flight Predictions and Analyses

These tasks are the complete effort defined in the Contract NAS 9-11576, Apollo Oxygen Tank Supplemental Agreement (References 3 and 4). The results of the postflight analysis were included in a task report (Reference 5) delivered to NASA-MSC immediately after task completion. The math model improvements were incorporated in a revised computer program manual (Reference 6) delivered after model changes were verified.

2.0 SUMMARY

The redesigned Apollo oxygen tank flight performance was evaluated by the effort originally defined by Contract NAS 9-11576, Apollo Oxygen Tank Stratification Analysis. This effort, completed August 31, 1971, found the tank adequate for known mission requirements based on analysis of Apollo 14 flight data. The evaluation was not, however, entirely adequate for CMP-EVA conditions which were only simulated by Apollo 14. The math model developed and used for the Apollo 14 analysis provided good performance simulations but some modifications were needed to improve its utility. A Contract Supplemental Agreement was executed to extend the period of performance through January 1972 in order to evaluate Apollo 15 tank performance and to develop identified math model improvements.

The tank evaluation basis was extended by postflight analysis of two Apollo 15 periods exhibiting heater temperatures not completely understood from the Apollo 14 data base. The heater temperature during the Apollo 15 CMP-EVA dropped rapidly while the heaters were on. The cause of the temperature drop was unknown and no similar temperature change occurred during the Apollo 14 tests which simulated the EVA conditions. The heater temperature difference between tanks #1 and #2 of Apollo 15 was also greater than anticipated. The tank #1 heater temperature was expected to be 30°F above the tank #2 temperature during Passive Thermal Control (PTC) due to centrifugal acceleration differences between the tanks. These situations could not be completely understood from the Apollo 14 experience.

The postflight analysis of tank accelerations during the Apollo 15 CMP-EVA identified sudden increases in tank acceleration when the heater temperature dropped. Rapid increases in acceleration from the range of 10^{-7} to 10^{-4} "G" were caused by venting of the cabin atmosphere. The two CMP-EVA heater cycles were simulated with the stratification math model using flight acceleration data to confirm that the acceleration

2.0 Continued

transients caused the heater temperature drops. The simulated heater temperatures and tank pressures were in good agrement with flight data. The good simulation of flight data confirmed that the tank and heater performances were normal for the imposed acceleration conditions.

The analysis of the PTC period included simulation of one heater cycle in each of tanks #1 and #2 using flight acceleration data. The simulated heater temperature difference between the two tanks was 31°F which is less than the 63°F difference shown by flight data. The discrepancy between the simulation result and flight data was attributed to differences in convection inside the heater tube caused by acceleration differences between the tanks. The math model does not include the heater geometry but simulates the heater as an equivalent flat plate with an area based on comparisons with Apollo 14 data. The effect of small accleration changes on the equivalent heater area is unknown. It is evident that the area assumed for this simulation was slightly in error. The simulated peak heater temperatures were, however, within 32°F of flight data. This accuracy is acceptable for flight predictions and the agreement obtained confirmed normal heater operation.

The math model modifications made to improve the program utility included flow distribution analysis and modeling of the pressure vessel thermal mass. The modifications were satisfactorily checked out by simulation of Apollo 14 and Apollo 15 flight data. Methods and criteria for using the model to simulate conditions not previously analyzed, including 1.0 "g" conditions, were developed to increase the capability for future applications.

It was concluded from the analyses conducted that the current Apollo oxygen tanks are adequate for all known Apollo mission requirements. The math model accurately simulates tank performance and should be used for flight predictions, assuming that the most accurate estimates will be required. The model is adequate for use on all Apollo applications.

3.0 PROGRAM TASKS

The program tasks continued by the Contract NAS 9-11576 Supplemental Agreement were intended to provide a more complete evaluation of tank performance and to increase the utility of the variable grid math model. The program tasks were:

Task 1 - Math Model Improvement

Task 3 - Apollo Flight Predictions and Analysis (original title, Apollo 14 Predictions and Analysis)

The significant results of each task are summarized in this section. Detailed results, conclusions and recommendations for Task 3 are included in Reference 5. The Computer Program Manual (Reference 6) was revised to include the Task 1 math model modifications and results.

3.1 TASK 1 - MATH MODEL IMPROVEMENT

The variable grid math model was modified to improve simulation accuracy and the utility of the model. A complete flow distribution model subroutine capable of analyzing all operating modes for two and three tank systems was developed replacing the previous model of the Apollo 14 system. The tank wall thermal mass was added into the tank energy balance to improve the accuracy of the tank pressure response when radiation from the heater to the wall is significant. The effective use of the math model requires proper selection of the finite difference grid network. Grid selection criteria and methods were, therefore, developed to improve the utility of the program. This effort also provided a base for applying the model to conditions outside the range of conditions previously investigated.

3.1.1 Tank Flow Rate

A subroutine capable of analyzing two and three tank systems was developed and used for the Apollo 15 postflight analysis. The subroutine uses

3.1.1 Continued

equilibrium thermodynamics to ratio the total oxygen tank flow (which consists of the ECS flow plus the fuel cell flow) between each of the oxygen tanks. It can analyze both the three tank configurations of the type used in Apollo 15 and the proposed two-tank Skylab system. In each system, the individual tank quantities are assumed to be arbitrary, and any combination of heaters on or off is allowed.

A subroutine logic adjusts the equilibrium pressures derived within the subroutine to allow for the effect of stratification on tank pressurization. The difference between the subroutine equilibrium pressure and the pressure derived by the main program is added to each of the active tank equilibrium pressures. Thus, the subroutine tank pressurization rates are forced to stay in step with the pressure derived in the main program.

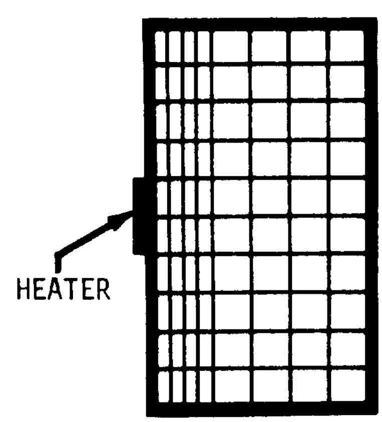
The revised program also eliminates the tank flow rate oscillations which caused difficulty during the earlier simulation of Apollo 14 low quantity conditions (Reference 7). The flow rate oscillation occurred when the heat input to the fluid was sufficient to increase pressure with zero flow but not sufficient to maintain pressure with the active tank supplying the system flow. The flow system logic (check valve status) was determined from the individual tank pressures and the flow was based on the system logic. The pressure relationship with heat input and flow rate caused the system logic to set the tank flow alternately to zero and a maximum flow on successive time steps. The flow oscillation caused some instability in the main stratification program until the heat input to the fluid was sufficient to sustain pressure at the maximum flow. The instability only occurred in a limited range of heater temperature and heat input conditions, but simulation results were not valid while the conditions existed.

3.1.1 Continued

The new flow rate subroutine eliminates the flow oscillation instability by subdividing each program time step into 20 intervals to determine the flow rate for the main program. The flow in each of the subdivision intervals is determined from the system logic, and the average flow for the 20 intervals establishes the proper active tank flow rate without significant oscillation. Satisfactory operation of the new flow distri-btuion subroutine was demonstrated by simulation of the same Apollo 14 heater cycle which caused instability in the earlier model. The flow distributions obtained with the revised model (Figure 3-1) were satis-factory with no severe oscillations and the total flow demand shifted gradually to the active tank (tank 3) as expected.

3.1.2 Tank Wall Mass

The variable grid math model developed earlier in the program determines the tank pressure and heater temperature by simulating the fluid flow field in a rectangle representing the symmetrical half tank (see Figure). The original model treated the heat leak and energy radiated by the heater as a heat flux at the bottom, top, and right hand boundaries. This approach resulted in the radiant and heat leak energy being immediately convected into the fluid. The energy is not, in fact, imme-diately transferred to the fluid because the pressure vessel (tank wall) absorbing the energy must be warmed before heat transfer to the fluid can occur. This heat transfer delay mechanism significantly affects the tank pressurization rate when the radiated energy is a significant fraction of heater power.



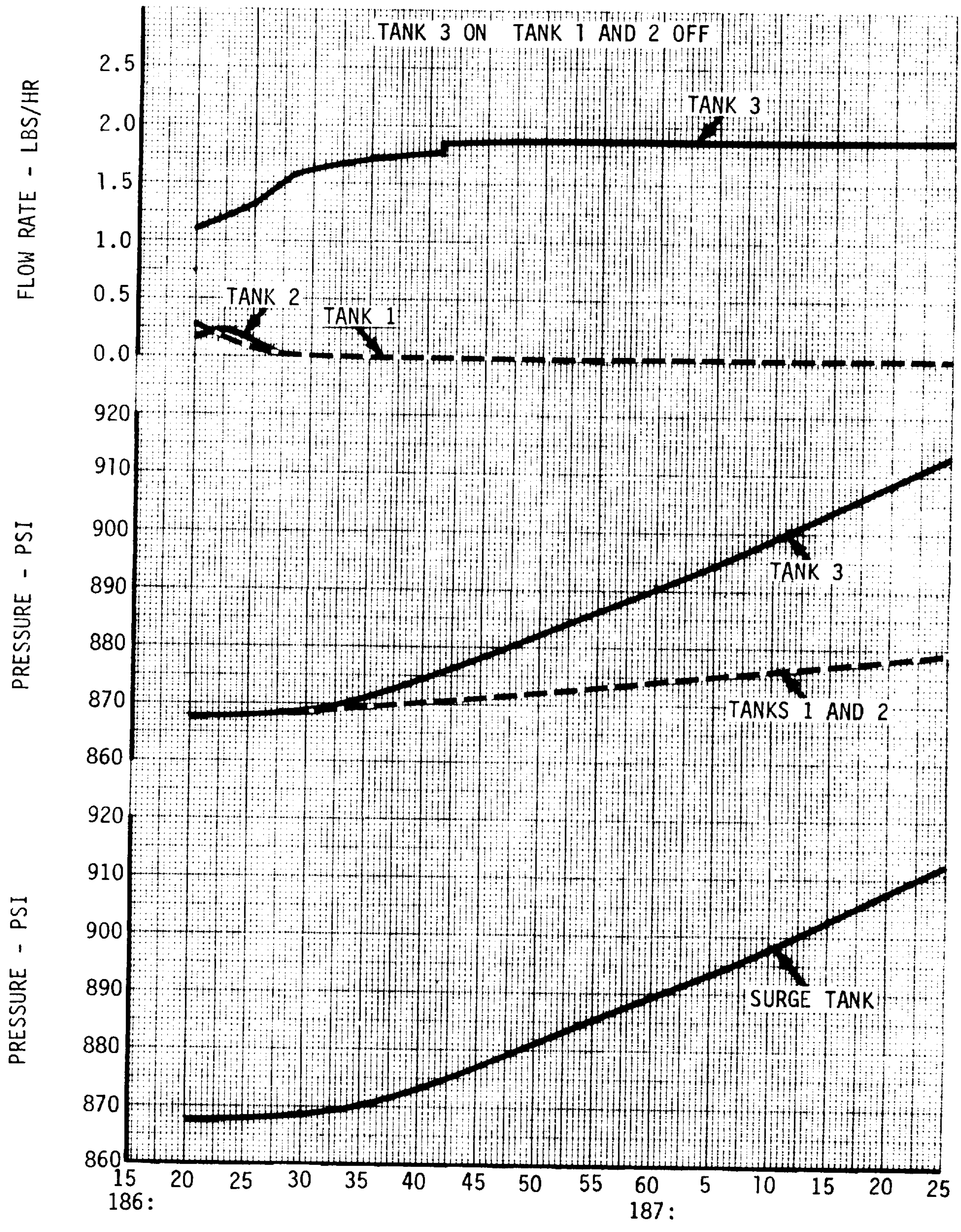


FIGURE 3-1 TYPICAL MODEL FLOW DISTRIBUTION

3.1.2 Continued

The low quantity heater cycle at AET 186:00 examined in the Apollo 14 postflight analysis (Reference 7) was also used to evaluate the effect of the addition to the math model of tank wall thermal mass. The simulation of this period in the Apollo 14 analysis yielded a pressurization rate significantly greater than observed in flight (Reference 7). The math model at the time of this simulation did not include the tank wall mass effects, but convected the heater radiant energy directly into the fluid. It was estimated that, if the heater radiant energy had been deposited instead in the tank wall mass, the tank pressure rise rate would have been in good agreement with the flight data.

The simulation of this heater cycle was repeated using the new math model which included tank wall thermal mass (Reference 6). The results of this simulation (Figure 3-2) show a maximum pressure rise rate of .86 psi/min versus the .78 psi/min rise rate observed in flight. The rise rate calculated in the earlier simulation which neglected wall thermal mass was much higher, 1.3 psi/min. The good agreement with flight pressure data indicates that the math model accuracy was significantly improved by the addition of tank wall thermal mass.

3.1.3 Convergence Limitations

The variable grid math model solves the compressible viscous flow equations in a two-dimensional rectangular region. Governing partial differential equations are approximated by difference equations to obtain the numerical solution. The cell sizes (grids) used for the difference equations are input data for the program. Program solutions depend on the cell sizes because the difference equations are approximations of the partial differential flow equations. The solution of the difference equations approaches or converges to the solution of the differential equations as the cell sizes are reduced or the number of cells increased.

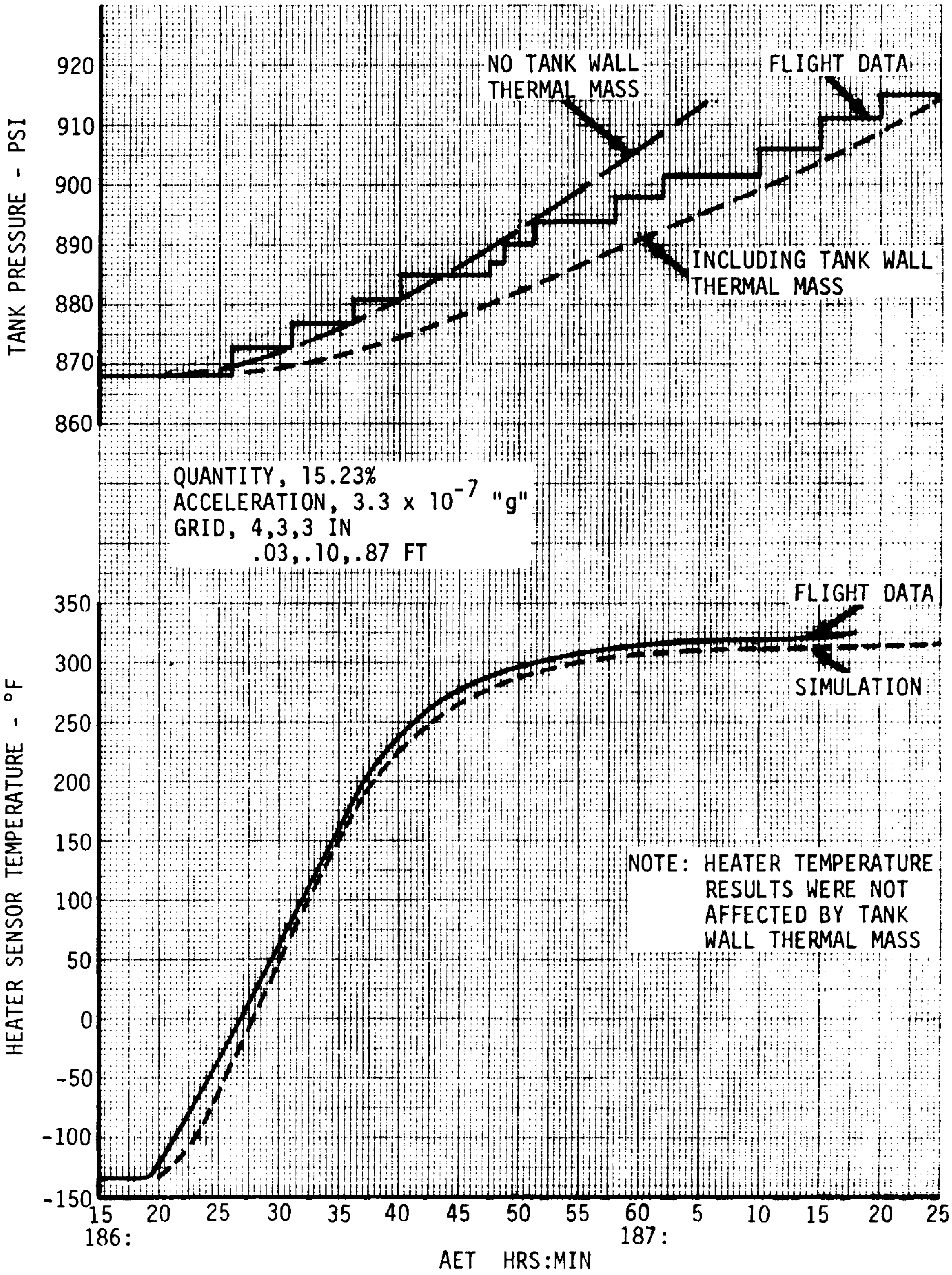


FIGURE 3-2 TANK WALL THERMAL MASS SIMULATION RESULTS

3.1.3 Continued

Therefore, convergence relationships with cell size must be investigated for each simulated condition to assure accurate results for tank performance variables. General methods for performing convergence studies were developed and criteria established for determining the adequacy of the convergence analysis. Errors resulting from the finite cell sizes and size distributions were also evaluated to assure the validity of the convergence study.

The basic approach for the convergence study is to determine the effect of cell size on the dependent variables by performing several simulations with systematically varied cell sizes. A plot of the dependent variable versus cell size or number of cells will approach an asymptote as the cell size is reduced and the number of cells increased. The difference between successive points of this convergence plot will normally form a geometric series; therefore, series relationships can be used to extrapolate to the asymptote. If successive points do not form a convergent series, the flow field has not been adequately resolved, and the cell sizes must be reduced until a convergent set of points is obtained. A complete convergence study requires investigation of both the X and Y cell dimensions. The convergence in the X direction should be investigated first with a Y cell dimension expected to produce fairly accurate results. The X direction convergence should be repeated, and the asymptotic limit found for each of a set of Y cell dimensions. The X direction asymptotic values are used with the Y cell dimensions for the Y direction convergence plot. Simulations with 10 Y cells in 2 feet are usually adequate; therefore, one simulation with 20 Y cells may complete the Y direction study.

The variable grid model will normally be used with different cell sizes in several regions. The convergence should be investigated for each region which includes temperature or velocity gradients which affect significant results. If heater temperature only is of interest, only the region near

3.1.3 Continued

the heater requires investigation. If pressure data are desired, all regions which include heated fluid will require complete analysis. The requirement for analysis of regions remote from the heater can be determined by examination of the temperature and velocity field data.

The convergence study can be efficiently conducted if the initial cell sizes and distributions are properly selected. The cell sizes in the vicinity of the heater can be set based on an estimated boundary layer thickness. Methods for estimating the boundary layer thickness are included in the Computer Program Manual (Reference 2, paragraph 3.5). Two or three cells between the boundary layer peak velocity and the heater surface will provide results near the convergence limit. The effects of the cell size adjacent to the heater must, however, be determined to estimate the accuracy of the simulation.

If the full boundary layer is adequately resolved, very large cells may be used for the remainder of the model regions. The only requirement for the cell size distribution is adequate resolution of velocity and temperature gradients. The cell size outside the gradient region may be suddenly and arbitrarily increased without affecting any results. The changes in cell size will not affect results since the difference equations always conserve mass and thermal energy.

The difference equations do not conserve momentum and kinetic energy. The equations used produce a loss of momentum causing fluid motion to decay. The effect can be described by an artificial kinematic viscosity which has a maximum value of $U\Delta X/4$ or $V\Delta Y/4$ where U and V are fluid velocity and ΔX and ΔY are cell dimensions. The momentum loss is caused by the cross derivative momentum convection term and attains its maximum value in flow turning regions. The effect is proportional to cell size; therefore, the error is essentially eliminated by the convergence study.

3.1.3 Continued

The momentum error is not significant in the simulation of convection at constant accleration because buoyant forces are dominant. The error does affect the flows after an acceleration spike or during periods of fluid rotation caused by vehicle rotation. Reformulation of the the difference equations to conserve momentum would improve coarse grid simulations of these effects. This program revision is recommended only for the analysis of inertially driven flows and is not warranted for convection analysis.

The analyses and simulations conducted indicated that the variable grid model was applicable for any acceleration level or heating rate. This hypothesis was verified by simulating a 1.0 "g" condition at 53% quantity. The results indicated that the heater temperature reached steady-state in about 20 seconds (Figure 3-3). The steady heater temperature was 3.7°F above the fluid temperature. This result is consistent with the fact that a heater temperature change is usually not observed on the ground since the measurement bit value is 3.6°F. The simulated temperature would also be expected to be slightly higher than the actual value since a complete convergence study was not performed. The boundary layer resolution for this simulation (Figure 3-4) was adequate to provide a fairly good approximation of the actual temperature.

The 1.0 "g" simulation confirmed the modeling capability at high accelerations. Approximately 1.0 hour of SRU-1108 time was required to simulate 1.0 minute at this acceleration. The cell sizes selected by the methods described in Reference 2 provided useable results for the condition analyzed. The simulation of high acceleration conditions is feasible. The problems to be analyzed and the grids to be used must be carefully selected to avoid using large amounts of computer time without useful results.

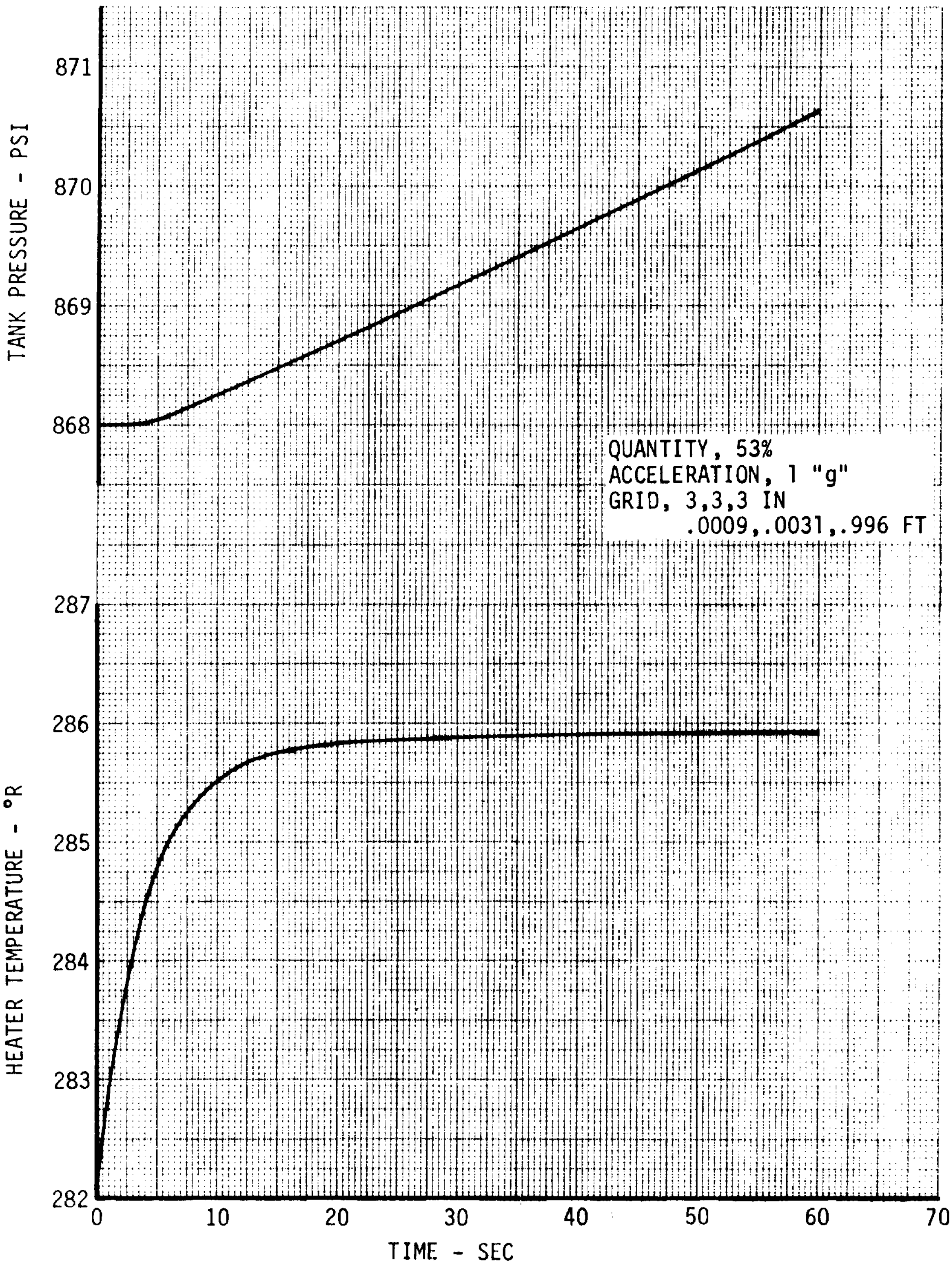


FIGURE 3-3 SIMULATION RESULTS AT 1 "G" ACCELERATION

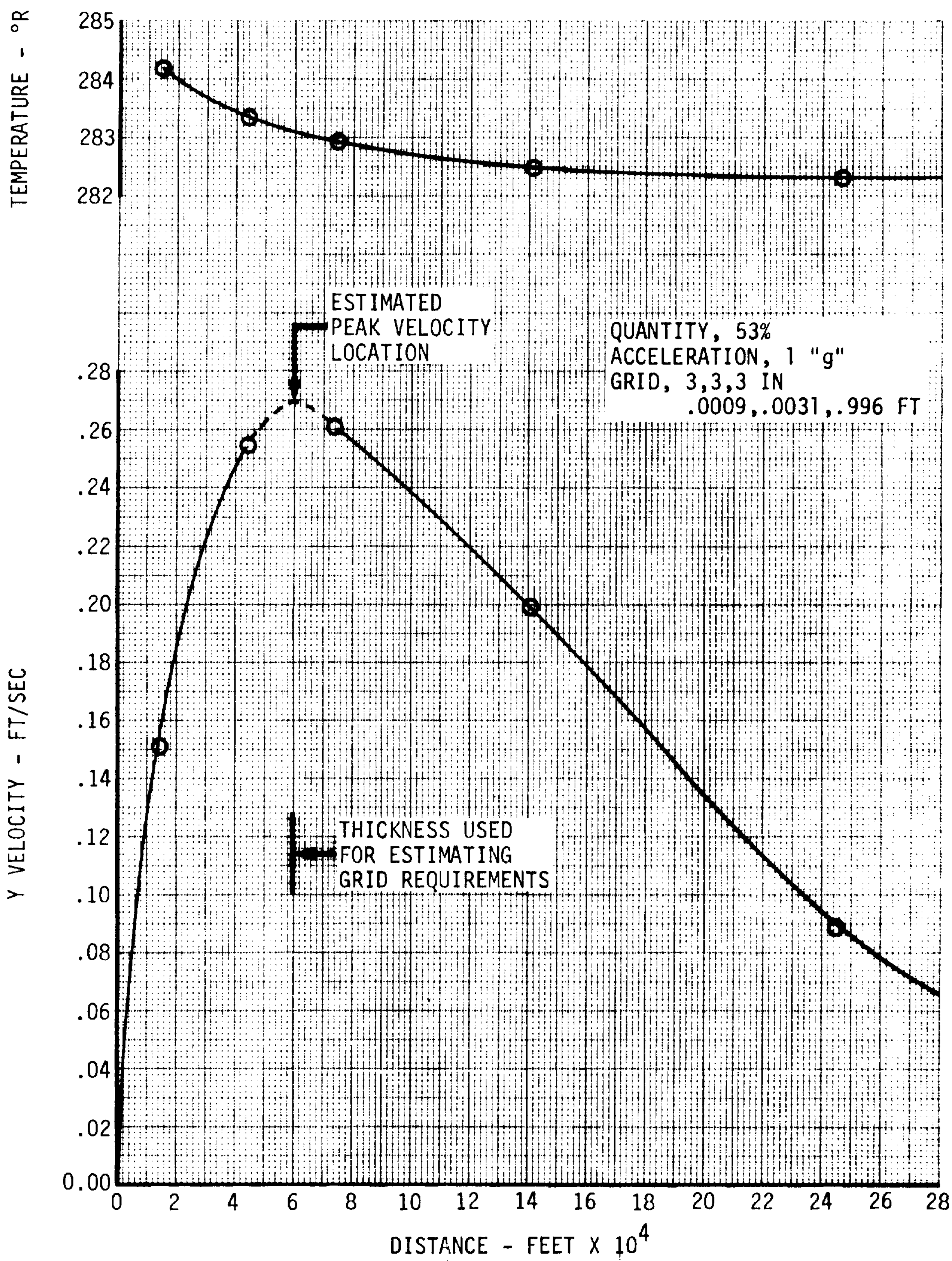


FIGURE 3-4 BOUNDARY LAYER RESOLUTION AT 1 "G" ACCELERATION

3.2 TASK 3 - APOLLO FLIGHT PREDICTIONS AND ANALYSES

The Apollo 15 postflight analysis was conducted to evaluate the oxygen tank performance in flight conditions not encountered during the Apollo 14 mission. The most significant mission difference affecting the tank performance was the Apollo 15 CMP-EVA which was merely simulated during the Apollo 14 mission. The Apollo 14 test simulating EVA conditions was not at the same acceleration as experienced during Apollo 15, resulting in different tank performances. The heater temperature difference between tanks #1 and #2 during Apollo 15 PTC flight modes was greater than expected on the basis of prior data and analysis. A typical PTC flight period was, therefore, included in the Apollo 15 postflight analysis to investigate the unexpected temperature difference.

3.2.1 Tank Response During Extravehicular Activity

Significant temperature drops during the first and second EVA heater cycles occurred at GET 241:52 and GET 242:45 when large accelerations were caused by fluid venting. Simulations of the two heater cycles were performed with the math model to determine if the temperature drops were caused by the acceleration transients and if the tank performance was nominal. The simulations were based on accelerations determined from the RCS bi-level events firing data. Also considered in the acceleration analysis were the cabin pressure data, cabin vent thrust, and astronaut movement. The flow rate through the restrictors was taken as 11.5 LBS/HR while flow was provided to the astronaut life support equipment (GET 241:30 to 242:44).

Initial attempts to simulate the first heater cycle with a heater area of .475 ft^2 did not agree with flight data. Since an acceleration peak at GET 241:33 could have produced flow through the heater tube, the effective heater area was increased to .95 ft^2 for subsequent simulations. Simulations with the large (0.95 ft^2) heater area provided fair agreement with the flight heater temperature data across the acceleration peaks at GET 241:37-241:42. The math model with 6, 3 and 3 cells in 3%, 10% and 87% regions

3.2.1 Continued

of the model width (1 foot) provided simulated temperatures that were near the converged limit pased on the boundary layer resolution obtained. While the resulting temperatures were in fair agreement with the flight data, it appeared that the agreement would be improved if accelerations were increased to reduce overshoot of the peak temperature.

The accelerations used for the analysis were calculated from the Reaction Control System (RCS) firing rate data. It was necessary to use these data since the guidance telemetry data used by the NASA-MSC acceleration program (SVCSRS, #Q581) did not provide adequate time resolution. The guidance data at 2 seconds per sample were completely inadequate for this period when the RCS firing rates were as high as 4 pulses per second. The NASA-MSC acceleration program results were also unrealistic due to high noise content and neglect of significant translation accelerations. The approach developed to determine the flight accelerations used in this study was to evaluate centrifugal contributions from the RCS firing times at the dead band limits and to estimate translation terms from vent flows and RCS average firing rates. Only the most significant centrifugal term (about the X axis) was included and the rotational accelerations were neglected. Even this method is not completely adequate.

The accelerations calculated from the RCS data were low estimates since angular accelerations and other contributions were neglected. The actual accelerations may have been a factor of two greater than the values calculated. The simulation of the first heater cycle was, therefore, repeated with the lowest accelerations increased by a factor of two. The peak simulated heater sensor temperature was only 12°F higher than the observed peak temperature (Figure 3-5). The simulation temperature overshoot was accumulated between GET 241:50 and 241:52:30 while the flight heater temperature sensor was nearly constant. The simulated

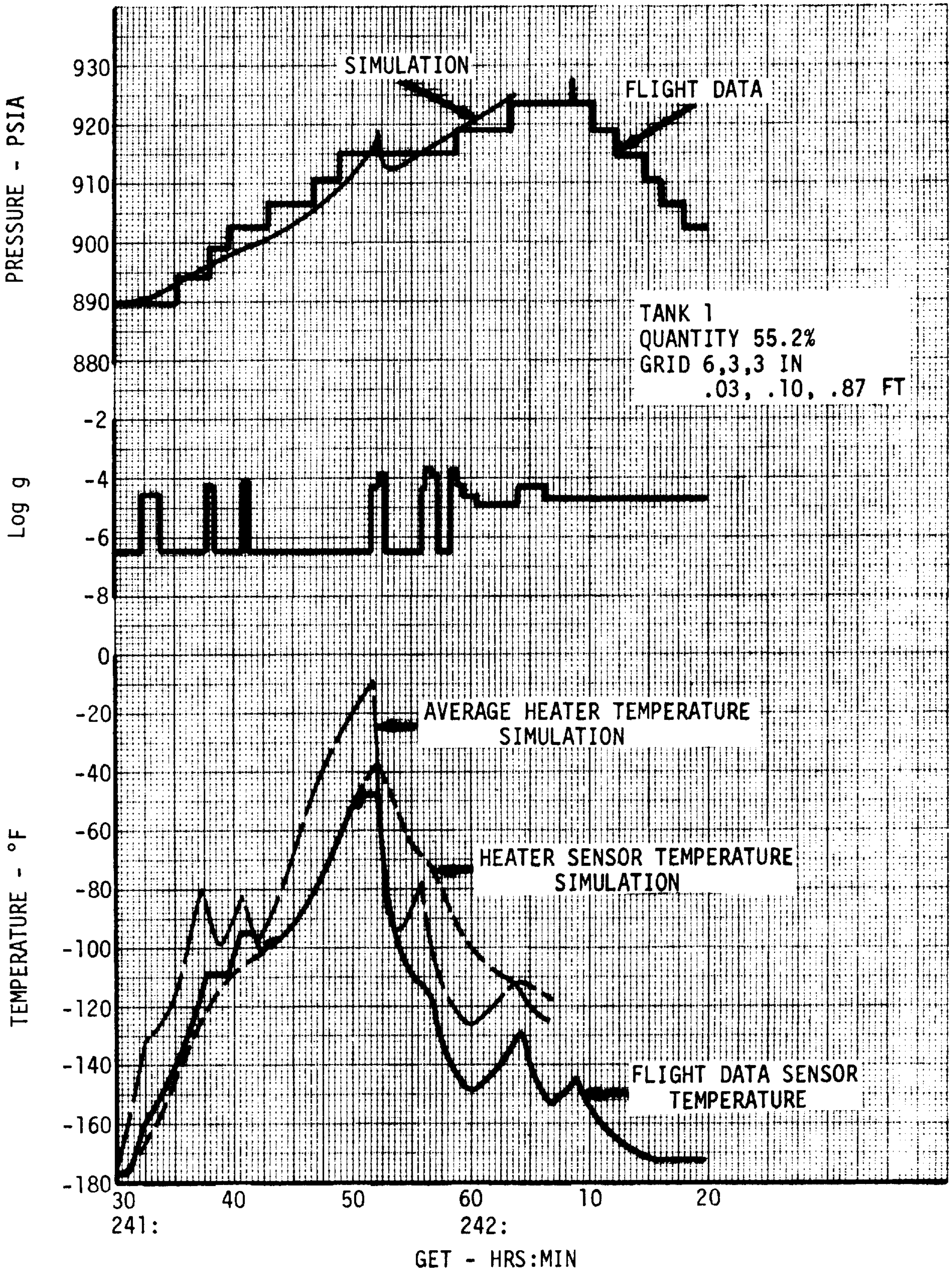


FIGURE 3-5 SIMULATION OF FIRST APOLLO 15 CMP - EVA HEATER CYCLE

3.2.1 Continued

temperature drop of 85°F after GET 241:52 compares favorably with the flight temperature drop of 102°F. The simulated temperature drop, however, required 18 minutes compared with 8 minutes for the flight data.

The error in the simulated temperature decrease rate was partially due to temperature overshoot. This error was probably caused by an acceleration increase at GET 241:50. However, no acceleration increase could be identified at this time. The error in the temperature decrease rate was also partially due to the grid size which did not provide adequate resolution at the high accelerations after GET 241:52. The simulations performed conclusively demonstrated that the temperature drops were caused by acceleration transients and fair agreement between simulation results and flight data obtained.

The second heater cycle was simulated with the heater area and grid size found to be adequate for the first heater cycle. The simulation of the second heater cycle with the calculated accelerations resulted in a temperature peak significantly higher than flight data. Increasing the lower acceleration levels by a factor of two, as before, produced peak heater sensor temperatures near the flight data (Figure 3-6). The simulation temperature drop of 60°F in 8 minutes compares favorably with the actual temperature drop of 85°F in 6 minutes. The simulated tank pressure was in good agreement with the flight data both before and after the acceleration transient which reduced the pressure rise rate.

From the simulation results (Figures 3-5 and 3-6) it is apparent that the heater temperature decreases that occurred during the EVA were caused by acceleration transients. The agreement between the simulation results and the flight heater temperature and tank pressure data conclusively proved that the tank performance was nominal for the actual flight acceleration environment.

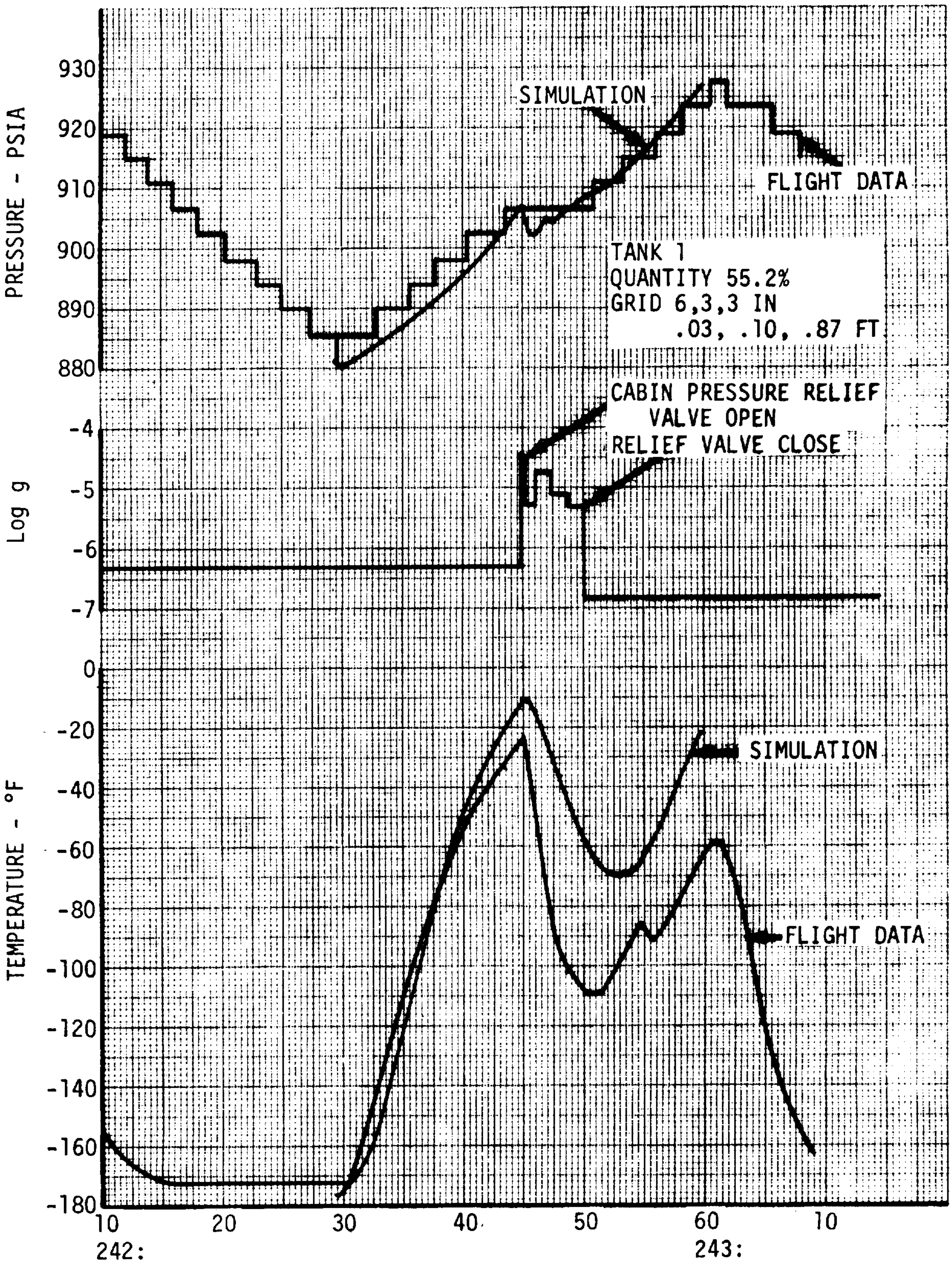


FIGURE 3-6 SIMULATION OF SECOND APOLLO 15 CMP - EVA HEATER CYCLE

3.2.2 Heater Temperature During Vehicle Passive Thermal Control

During the Apollo 15 flight a 63°F temperature difference was noted between the tanks #1 and #2 heater sensors at GET 249:00. This cycle was analyzed to determine if the tank heater performance was nominal. The spacecraft rotation in the PTC flight mode during this period produced a 1.58×10^{-6} "g" acceleration in tank #1 and a 2.87×10^{-6} "g" acceleration in tank #2.

The heater temperature and tank pressure results of math model simulations are compared to flight data for tanks #1 and #2 in Figure 3-7 and 3-8. The pressure curves for each of the model grid distributions (4, 3, 3 x 10; 5, 3, 3 x 10; and 6, 3, 3 x 10) agreed within 1 psi; therefore, only one curve was plotted on each figure. The temperature simulations with the different grids compare to within 8°F and indicate that the 6, 3, 3 x 10 grid adequately resolved the heater boundary layer and represents the converged solution.

The temperature results of the analysis account for 31°F temperature difference between the tanks. The tank #1 simulation peaks at 22°F which is 32°F below flight data, while the peak of the tank #2 simulation is within 1°F of the -9°F peak observed in flight.

Even though these results are within the expected accuracy of the math model, they do not indicate as large a difference between the tanks as the 63°F observed during flight. Several possible causes of the observed temperature difference were investigated (Table 3-1), and it was concluded that the most likely cause of the large temperature difference was a change in the effective heater area. The determination of the effective heater area is highly dependent on tank quantity, "g" level, and tank fluid velocity. The arbitrary selection of .475 ft^2 heater area used in the simulations might have been slightly in error. Further, since tank #2 was at a significantly higher "g" level than tank #1, probably a larger

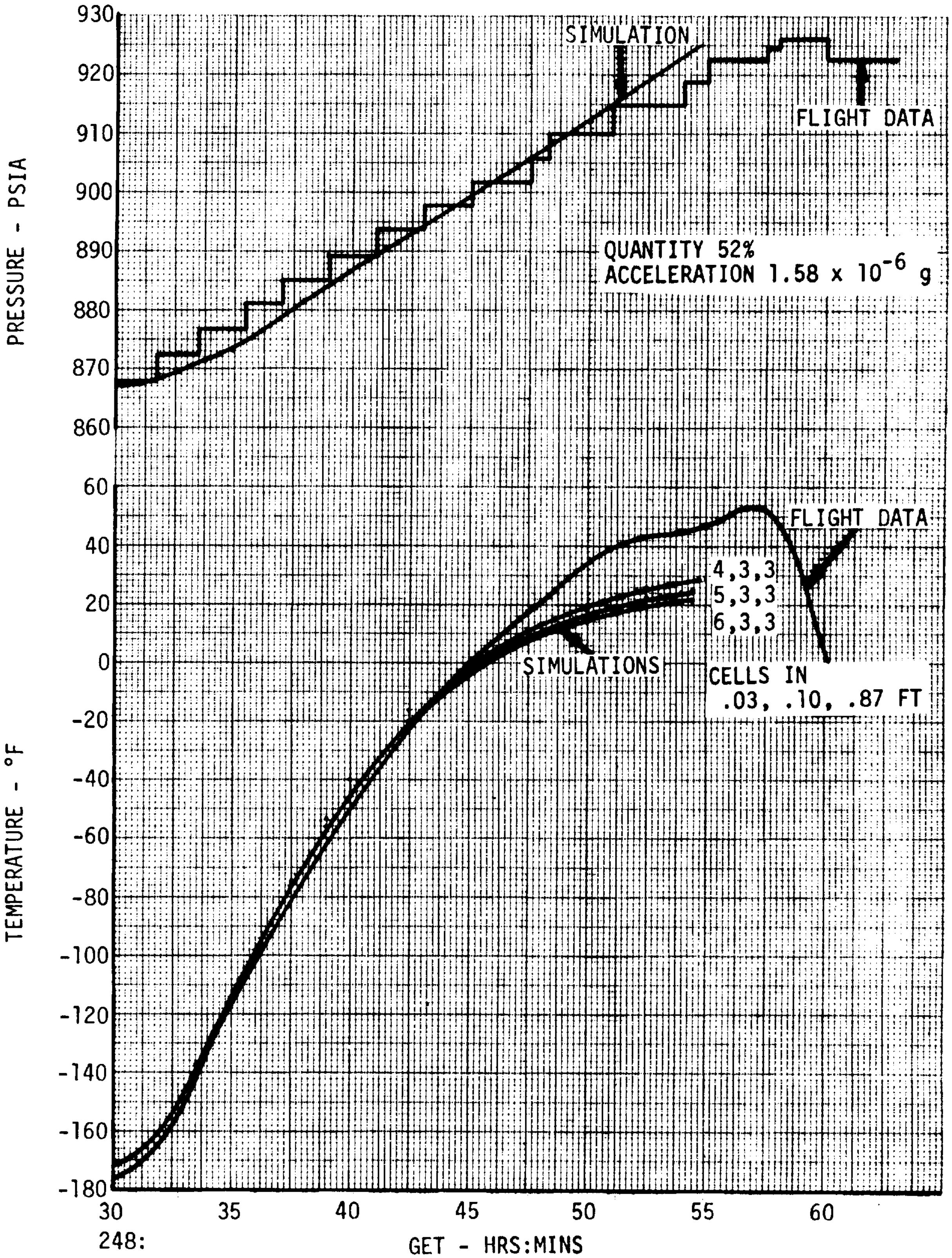


FIGURE 3-7 SIMULATION OF TANK 1 APOLLO 15 PTC HEATER CYCLE

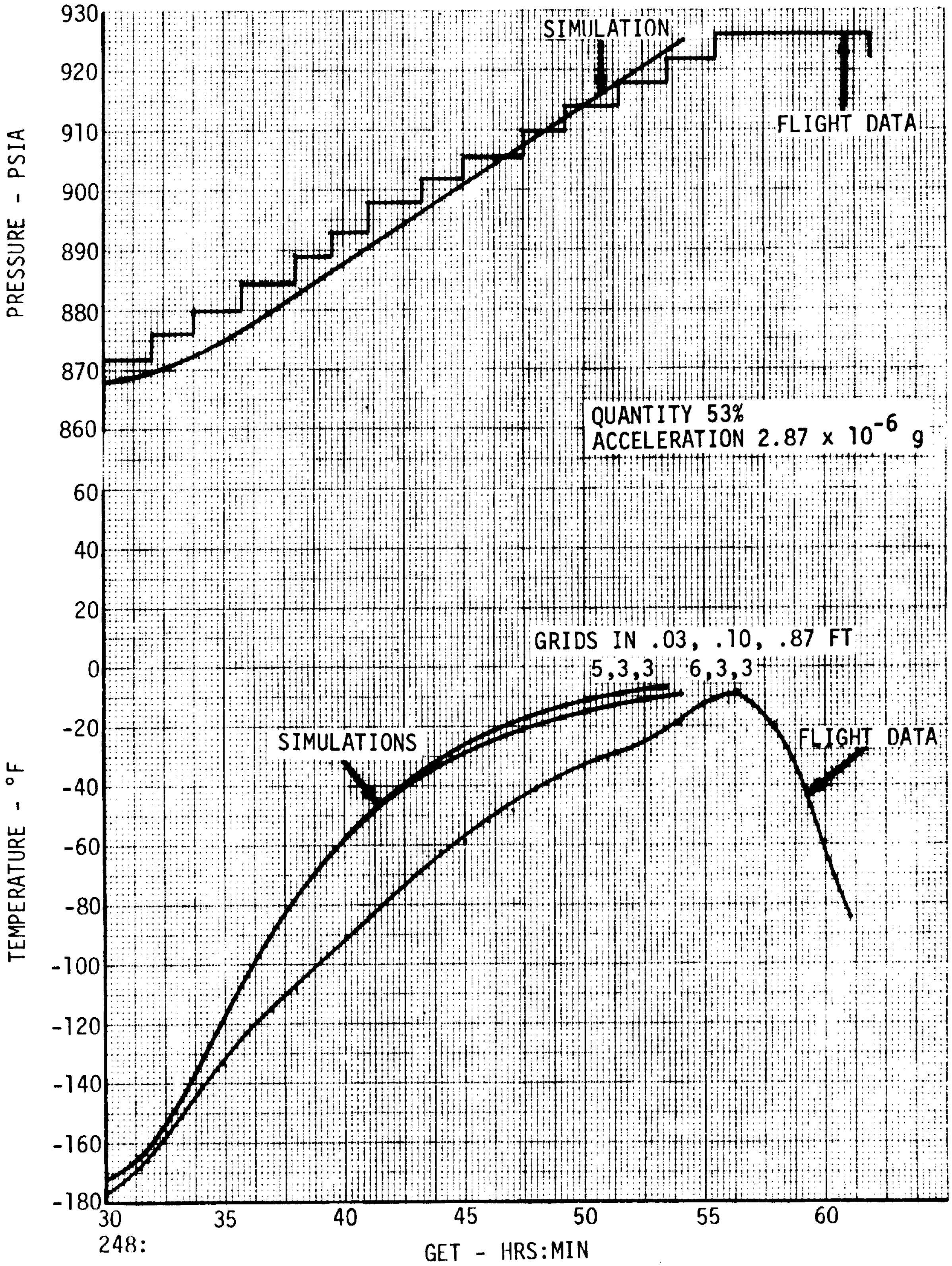


FIGURE 3-8 SIMULATION OF TANK 2 APOLLO 15 PTC HEATER CYCLE

3.2.2 Continued

heater area should have been used for tank #2 than for tank #1. A heater area of approximately .41 ft^2 for tank #1 would reproduce the flight data.

The simulations and analyses conducted accounted for only part of the heater temperature difference between tank #1 and tank #2. The performance of both tanks was nominal, and the 32°F temperature difference not accounted for by the analysis was not caused by any hardware malfunction or tolerance problem. The 32°F discrepancy is within the expected model accuracy and may be due to an inaccuracy in determining the effective heater area in the flight environment. A more accurate determination of heater temperature would require analysis of a large number of heater cycles to determine the effective area to be used for arbitrary accelerations and quantities.

TABLE 4-1 SUMMARY OF HEATER TEMPERATURE DIFFERENCE CAUSES

POSSIBLE CAUSE	INVESTIGATION - RATIONALE	CONCLUSION
Heater Power Difference	Heater and circuit resistance variation between tank 1 and tank 2 was negligible. 10 watts difference required to match temperatures would cause quantity unbalance. No unbalance was observed.	No cause
Heater Location Relative to Vehicle Center of Mass Causing Acceleration Error	Heater location was very near location used for acceleration calculation. Required distance error is about 1.5 ft to cause tank 1 temperature change.	No cause
Sensor Calibration Error	Sensors in tanks 1 and 2 were in agreement at bulk temperature with heater off. Nonlinearity of 30°F is unlikely.	No cause
Sensor Location Relative to Acceleration	Sensor angle with flow was only 12° arc different in tank 1 and tank 2. Cooler sensor, relative to simulation, was in warmer region.	No cause
Abnormal Acceleration Caused by Propellant Sloshing, Vehicle Nutation, etc.	Temperature difference observed during different mission phases. Similar abnormality during different mission phases is very unlikely.	No cause
Fluid Rotation Effects	Rotation should show same effect for both tanks. Effect should diminish with time after PTC initiation. No change with time observed.	No cause
Heater Emissivity Different in Two Tanks	Tank 1 emissivity change from 0.2 to 0.1 would raise temperature only 4°F.	No cause

TABLE 4-1 SUMMARY OF HEATER TEMPERATURE DIFFERENCE CAUSES (Continued)

POSSIBLE CAUSE	INVESTIGATION - RATIONALE	CONCLUSION
Flow through Heater Tube	Some flow through tube apparent from Apollo 14 postflight analysis. Flow increases effective heater area. Effective area 0.475 ft^2 for outer surface only was arbitrarily established. An effective heater area of 0.41 ft^2 for tank 1 and 0.475 ft^2 for tank 2 would simulate the observed temperatures.	**Probable Cause**

4.0 CONCLUSIONS AND RECOMMENDATIONS

4.1 CONCLUSIONS

Conclusions drawn from the analysis of the Apollo cryogenic tank flight performance were:

1. The current design Apollo cryogenic oxygen tank is adequate for known future Apollo mission requirements.

2. Unpredictable tank accelerations produced by fluid venting or other flight events can cause heater temperatures to deviate significantly from predictions based on nominal flight accleration.

3. The variable grid stratification math model simulation accuracy is adequate for flight predictions and mission planning purposes.

4. The variable grid math model is capable of simulating any acceleration condition including 1.0 "g". However, much more computer time is required to simulate higher acceleration conditions.

5. The math model simulation of inertially driven flows is less accurate than the simulation of convection flows. The Apollo oxygen tank performance is dominated by convection flows and the inertially driven flow inaccuracy does not significantly affect simulation results.

6. No adequate method for determining tank acceleration in flight is available. The NASA-MSC acceleration program provides valid results only for a limited range of flight conditions when vehicle rotation rates are nearly constant and no fluids are vented.

4.2 RECOMMENDATIONS

No hardware or operational changes are recommended for the Apollo oxygen tanks. These were found to be adequate for all known Apollo mission requirements. Recommendations related to use and additional development of the math model are:

1. Math model simulations using conservative estimates for tank acceleration should be used to establish heater management requirements. Selection of heater management on the basis of flight data that has not been thoroughly analyzed can result in serious errors due to acceleration differences between the data base and the planned condition.

2. Modify the math model to improve the simulation accuracy for inertially driven flows. This modification is not needed for analysis of the convection dominated Apollo oxygen tank but is recommended to improve the capability for analysis of other systems as, for example, externally pressurized tanks.

3. Develop an improved method for determining tank acceleration during flight to increase the accuracy of postflight analysis and to provide a firm base for flight predictions.