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Apollo 14 Flight Support and System Performance

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Abstract

The Apollo 13 incident and subsequent oxygen tank redesign for Apollo 14 placed unique requirements on the flight support activity. A major part of this activity was the integration of the various analytical efforts into a single team function. Additionally, the first flight of the redesigned system without an orbital test required an extensive analytical base.

The support team philosophy, objectives, and organization are presented. Various analytical tools that were used during the flight are discussed. Investigations made during the post-flight period are considered and their impact upon subsequent flights shown.

Introduction

There are three major phases of work involved in any flight: preflight, real-time, and post-flight. Because of the cryogenic oxygen system redesign required, those three phases all had their own unique situations and problems which tended to impact each other in more than a normal manner. For this reason, all three phases will be discussed herein--with the preflight discussions being limited to a functional relationship. The paragraphs following introduce the phases.

During the Apollo 14 redesign effort, large contingents of analytical resources were applied to the problem of designing, fabricating, and testing a new cryogenic oxygen system. To provide for adequate communications between the various analytical groups involved, a team approach was thus used. Informal meetings were held during this period so that the team members could present the results of their work and receive feedback to apply to their analyses. As in all flight related programs, the major problem encountered during this effort was the integration of the analyses into the hardware and operational areas. The solutions to this problem are discussed herein and the various end items are presented.

In general, the end result of the analysis effort was a flight support team trained and equipped to respond to the real-time needs of the flight. For example, during the flight, there were several real-time problems that were faced and solved by the team members. Obviously, the training and tools that were used during this time had to be developed prior to the flight. These problems and the methods of solution used will also be discussed.

Once the flight was over, the last phase of work was started--post-flight analysis. For Apollo 14, this was a major task since it basically became a new system evaluation. Therefore, the various items analyzed during this portion of the work are presented to illustrate the requirements for basic system understanding.

The conclusions reached from the three phases of work are presented as concluding remarks to this paper.

Support Team

Pre-Flight

During this effort, there were some twelve identifiable organizational elements involved on the analysis team. The overall coordination of the team was the responsibility of the Power Generation Branch of the Propulsion and Power Division. The major problem faced by the team was that of communications; as mentioned earlier, periodic team meetings were held to facilitate the necessary cross-fertilization between the various efforts.

Since the fan-motors were deleted from the oxygen tanks, the thermal performance of the heater depends to a large extent on the net gravity level. Even though the artificial gravity levels are normally extremely low, natural convection is the predominant mode of heat transfer from the heater to the fluid. Obviously the conditions that dominate these convective processes could not be duplicated in a terrestrial environment; therefore, the adequacy of the design had to be certified by analysis. This then became the major activity of the team: that of insuring that the proposed system would be adequate for the Apollo 14 mission.

There were two main items of interest with respect to the thermal performance of the heater:

1. Maximum temperature reached by the structure (i.e., pressure vessel and heater) during the mission.

2. Maximum expected pressure drop created by stratification effects during the mission.

These items were formally closed prior to the mission with a certification document which contained a condensation of the Analysis Team's findings.

Flight Support

The end result of the analytical effort was to equip the flight support team with the knowledge and resources to make real-time inputs. Figure 1 presents the overall organization that the team functioned under, and as can be seen these activities were concentrated in a support building complex adjacent to the Mission Control Center.

The purpose of the cryogenic support team was to provide a continuous monitoring, analysis, and reporting activity of the cryogenic system. The prime objective of this team was the early detection, evaluation, and reporting of problems or potential problems. A secondary objective was the continuous monitoring, analysis, and reporting of routine system performance.

The general philosophy that was used during the organization of this team was that only those problems that were amenable to rapid solutions could be worked. This restriction had to be observed since a large scale investigation by this team would have destroyed the monitoring capability and left the system vulnerable to additional failures. When problems arose that required large scale efforts, separate teams were called to supply the manpower. In general, the location and organization of these teams were functions of the nature of the particular problem that had to be solved.

The detailed organization of the support team is shown in Figure 2. As can be seen in this figure, the flow of information was basically through the Subsystem Manager's position in the Mission Evaluation Room (MER). As was mentioned earlier, the prime function of the team located in the Backup Support Room (BSR) was that of system monitoring. The procedure used to insure that this was done was to manually plot some thirteen parameters from the real-time displays. This then became the prime data source for the real-time analytical support effort. The required frequency of plotting depended largely upon the system performance. During early parts of the mission, heater cycles occurred at rates of three to four per hour and thus virtually continuous plots were required. Later, when the cycles lengthened, the data points were plotted in about ten minute intervals. This plotting served two purposes:

1. Provided a continuous record of flight performance.

2. Forced an individual to examine the system trends on a rather continuous basis.

As backups to the real-time data, the following items were available to the team:

1. TWX summaries of the flight data on irregular intervals.

2. Polaroid pictures of the displays on ten minute intervals.

3. Tab outputs and plots available on about a twelve-hour turn around basis.

The performance of this support system was such that many real-time inputs were made to the operations team. This type of support team activity was found to be a good solution to the problems of fast response and continuous system surveillance.

In-Flight Analysis

Check Valve Leakage

The first problem noted during the flight was that of a check valve leaking into tank number two. As can be seen in Figure 3, when tank number three's pressure rose, tank number two's pressure would track it. This meant that fluid from tank three was being forced back into tank two. This problem did not affect the overall mission since no fluid was being lost; however, it did affect the cryogenic management and the eventual conduct of the Detailed Test Objective (DTO).

The problem was that as the fluid was forced into tank two, heat energy was also transmitted--thus changing the effective thermal performance of the tank. This would in time affect the individual tank quantity schedule that had been planned prior to flight.

In order to solve this problem, the team members of the Mission Performance and Analysis Division (MPAD) were called upon. The program that they had written prior to flight was modified to include this additional heat and mass transfer into tank two, and the mission quantity schedules were recomputed. As can be seen in Figure 4, the resulting predictions came very close to the actual flight quantities.

It was concluded from this analysis that the leaking check valve would cause no problems during the remainder of the flight and that the DTO could be conducted without modifying the cryo schedule.

Heater Temperatures

The second problem found early in the flight was that the heater temperatures recorded were consistently higher than expected. In order to solve this problem, team members from the Boeing Company, TRW Incorporated, Lockheed Aircraft Corporation, North American Rockwell, Structures and Mechanics Division (SMC), and MPAD were called upon.

The temperature limit of the components inside the pressure vessel was set prior to flight to be 500°F based upon the autoignition temperature of teflon of 700°F. This margin is consistent with margins on flammable materials used in the Command Module. The pressure vessel itself is limited to 200°F based upon fracture mechanics considerations. Preflight analysis indicated that with a maximum heater temperature of 500°F the pressure vessel wall never exceeds this limit. It was known prior to flight that there would be large temperature gradients along the heater and it was felt that the temperature sensor would reflect the temperature of one of the cooler areas of the heater. Using this rationale a limit of 200°F was placed upon the heater sensor indication.

Due to drawing and design changes, the temperature sensor was mislocated in the model by 1.0 to 2.0 inches. This position error occurred at a location where the temperature gradients were as large as 100°F to 300°F per inch. After this was discovered, it was noted that the sensor should and did reflect close to the maximum temperature on the heater. This is shown in Figure 5.

Next, it was found that at various times the heater temperature could lead the sensor indication by as much as 50°F. This was determined by performing a transient analysis of the sensor and heater system.

Using these analyses, it was determined that a safe heater temperature limit could be established as follows:

1.	Heater upper limit	500°F
2.	ΔT between sensor and maximum point	-50°F
3.	Sensor Lag	-50°F
4.	Contingency for instrumentation and analytical errors	-50°F
5.	Final Redline Limit	350°F

Using this rationale, a corrected maximum temperature limit of 350°F was established for the remaining portion of the mission.

Detailed Test Objective Simulation

In view of the new heater temperature work that was done, it was decided to perform the high flow rate test using two heater elements in tank number three (the low density tank). Since all the prior analysis had been performed using three heater elements, the team members of The Boeing Company were called upon to recompute the high flow test predictions. This work was completed prior to the time that the test was to be run, and formed a complete basis for the test monitoring.

The predictions for tank number three along with the test data are shown in Figure 6. As can be seen, the data fell close to the trends predicted. In general, these predictions were such that the support team was able to distinguish between two heater element and three heater element operation.

Real Time Calculations

During the flight, there were many calculations made in an effort to ensure satisfactory system operation. The majority of these calculations involved various methods of establishing the system's thermal performance. Heat leaks were calculated using flow rate averages with the heater off, pressure change rate with the heaters off, and pressure change rate with the heaters on. In general, very little success was obtained using any of these methods to calculate the heat leak. Some of the problems involved with these calculations are as follows:

1. Flow Rate Determination - Since the system does not have individual flow meters for each tank, the flow sharing characteristics must be implied using pressure data, thermal data, and intuition. These methods all leak to large errors when using the resultant flows to calculate heat leaks.

2. Pressure Change Rate - The major problem with this calculation is that the pressure data has a 4 psi bit granularity. This means that a given value of pressure may be as much as 4 psi in error. If the total span of a given cycle is 30 psi, it can be seen that this pressure error represents a very large deviation.

3. System Equilibrium - Since these systems are vapor cooled the thermal performance is a strong function of the flow rate demanded and therefore the flow-sharing characteristics. If a tank has been supplying a large part of the load (i.e., high flow), its vapor cooled shield will be colder than normal. The calculated heat leak into the pressure vessel will then be abnormally low while at the same time another tank will appear abnormally high.

4. Quantity Balance - Finally, with the three tank system, the quantities may be separated by 30% to 40% and each tank will have a different performance based upon its particular fluid state. These heat leaks might at any one time range from 45 Btu/Hr to 20 Btu/Hr.

Post-Flight Analysis

The prime objective of a post-flight analysis is to establish the limits of system performance and to apply these limits to the future Apollo flights. A secondary objective is to reexamine the flight data in detail to insure that no unexplained events go undetected. This type of analysis is done on each flight; however, on Apollo 14, a more detailed analysis than normal was required.

One major decision that had to be made using post-flight analysis was whether or not to install an external recirculation pump on Apollo 15. The various issues involved in this analysis were stratification, quantity gauging accuracy, pressure decay due to stratification, heater temperature limits, crew activity, and extra vehicular activity capability. The data indicated that the quantity gauging accuracy and pressure decays were about the same as those observed on prior flights. As shown in Figure 7, all the observed heater temperatures were within the expected bounds while achieving the demands of Apollo 14. Also, it can be seen that by observing the limits established by this figure, the crew work load could be minimized. Prior ground testing indicated that the system could be operated in the blow-down mode below 20% quantity. Using this data, it was decided that the pumps would not be installed on Apollo 15.

The next major task that was undertaken was to compile a set of data on magnetic computer tapes so that the data could be accessed, used, and plotted. Some thirty-four parameters were stored on these tapes. These included five tank quantities, five tank pressures, five fluid temperatures, three heater temperatures, two bus voltages, three fuel cell currents, six fuel cell flow rates, one environmental control system flow rate, one surge tank pressure, one cabin regulated supply pressure, one cabin pressure, and one oxygen tank manifold pressure. These data were plotted in one second intervals on the Cal-Comp plotter and then distributed to the various team members.

Finally, there were several short studies performed to make sure that the system had performed properly. These studies and their purposes are as follows:

1. Calculated vs Measured Quantities - Using the observed fluid temperatures and pressures in combination with thermodynamic data, densities were calculated. These densities were then used to calculate quantities which are shown compared to the indicated quantities in Figure 8. It should be noted that as the critical region is approached (30% to 50%), this method becomes more inaccurate; however, at the extremes, the method is consistent. This method of quantity determination is shown to be an acceptable backup if it is needed. Also, as part of this effort, these values were compared with Apollo's 11, 12, and 13 to establish the performance of the redesigned sensor. As can be seen in Figure 9, the new sensors are not as accurate as those that were on the old tanks. This was anticipated since the new location of the sensor removes it from initmate contact with the fluid.

2. Tank Energy Balance - This study was performed to establish the overall system energy balance at various times during the mission. This was done to establish whether or not stratification would affect the thermal efficiency of the system. Figure 10 presents the data calculated at various points in the mission. It should be noted that nearly all the data falls within a ten percent band. This is felt to be a remarkable accuracy, considering all of the variables that affect the problem. Also, it is seen that the scatter is random in nature--indicating little or no loss in overall thermal efficiency.

3. Pressure Response Study - This work was performed so that the control characteristics could be established. This information will be used on future flights to aid in system monitoring. During this effort, there were two types of curves developed: heater on time and total cycle time. The results of the tabulation for heater on time are shown in Figure 11. As can be seen in this illustration, exact trends are difficult to observe. Again, this is indicative of a system with many operational variables. The total cycle times are shown in Figure 12; again, exact trends are hard to establish. But, the ranges of times that can be expected for future flights can be observed and also the variation of trend with quantity can be roughed out.

For Apollo 14, there are other analysis efforts that have been done or are in progress. These efforts are very detailed in nature and were in part reported in the other papers. Specifically, these include studies of the "g" levels during various portions of the flight, the heat transfer characteristics of the heater under a variety of conditions, and detailed stratification studies. These studies are not part of normal post-flight evaluation but are typical of those studies that are performed to evaluate specific events of interest.

Conclusions

The system performed basically as was predicted prior to flight and the analytical modes were verified in real-time. In the one case of error--heater temperature--the problem was found to be primarily erroneous heater temperature location input to the model.

It can be concluded that a support team can be organized to respond to real-time flight problems if the members are (1) operationally checked-out and (2) analytical tools are prepared in advance. A corollary to this is that such a large and rather complex team is necessary and can be organized and successfully managed to solve problems of the magnitude of the Apollo 14 cryo system redesign--all in a relatively short time period. Also, it was noted that the parallel nature of many of the studies provided a cross-check of the analytical methods used.

From a technical standpoint, the conclusions are specific and are as follows:

1. The leaking check valve on tank two had little effect on system performance.

2. Large thermal gradients exist on the heater--with the specific temperature profiles being a strong function of gravity level.

3. The location of heater temperature sensors is a critical item on flight systems.

4. The system successfully passed the high-flow test (DTO).

5. The tank quantities can be reasonably calculated from temperature and pressure readings and can be used as a backup to direct quantity readout.

6. Stratification does not affect the thermal efficiency (energy balance) of the system.

7. Tank heat leaks cannot be calculated using present in-flight data.

8. External pumps are not required on Apollo 15.

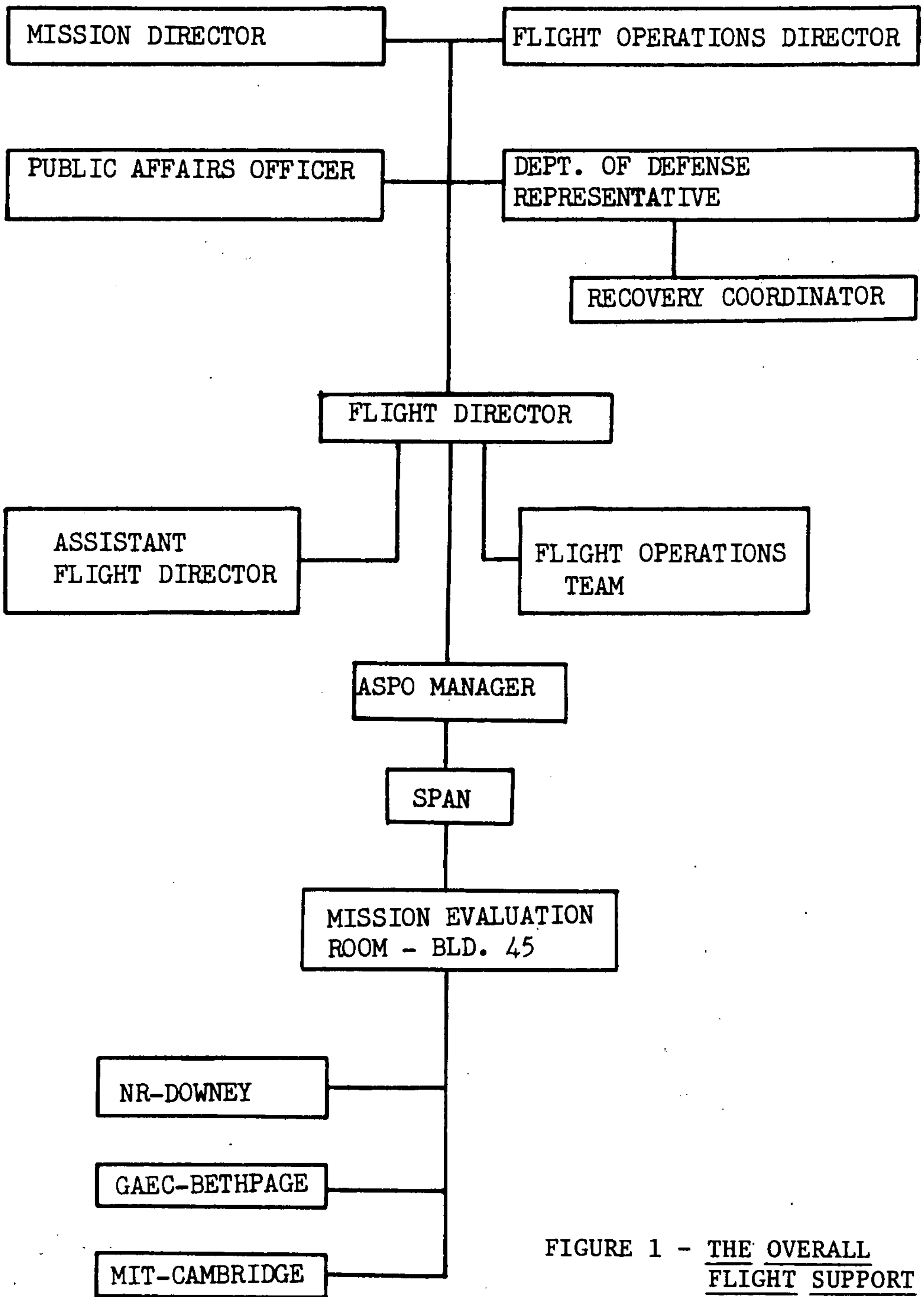

FIGURE 1 - THE OVERALL FLIGHT SUPPORT ORGANIZATION

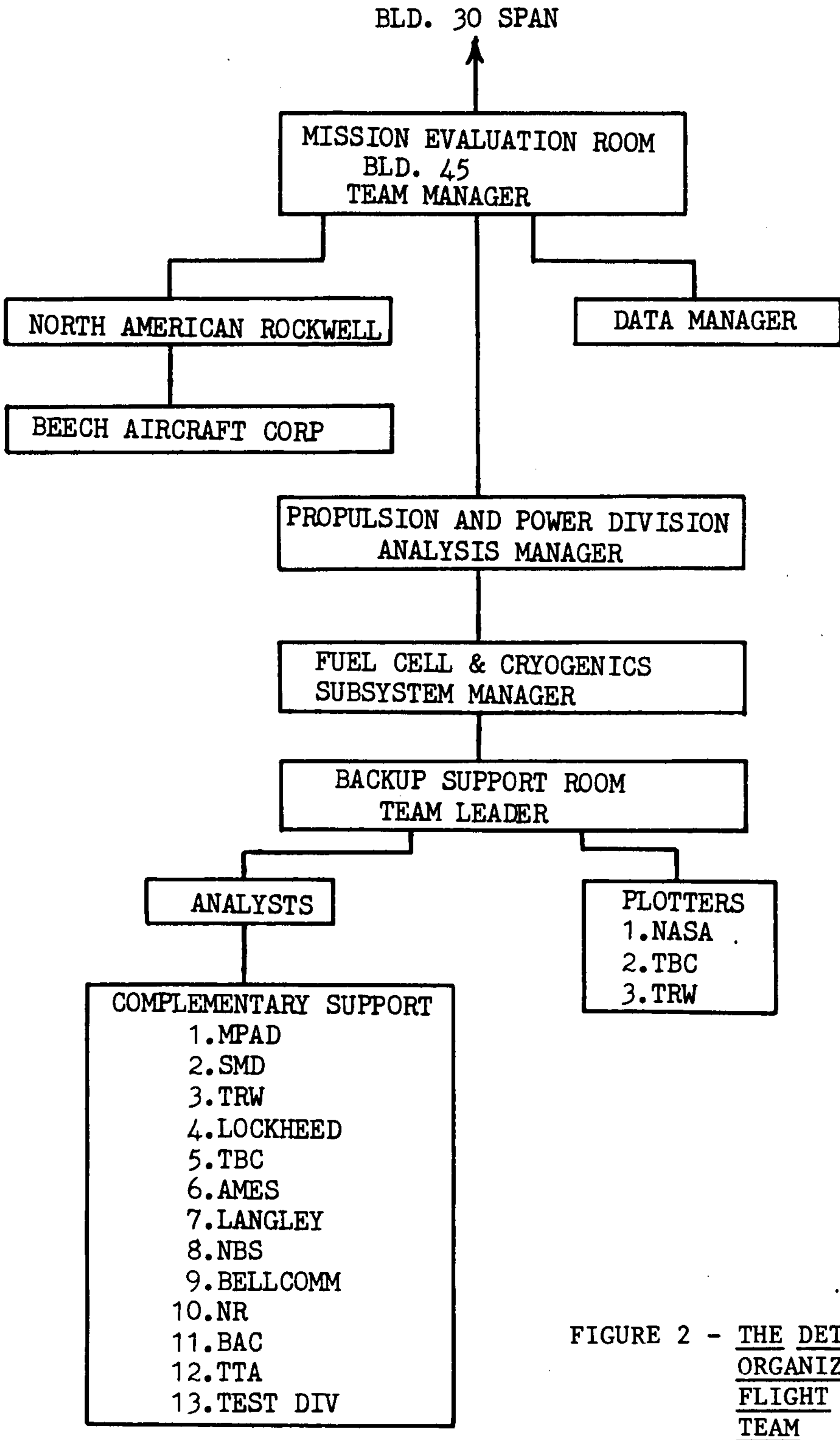

FIGURE 2 - <u>THE DETAILED ORGANIZATION OF THE FLIGHT SUPPORT TEAM</u>

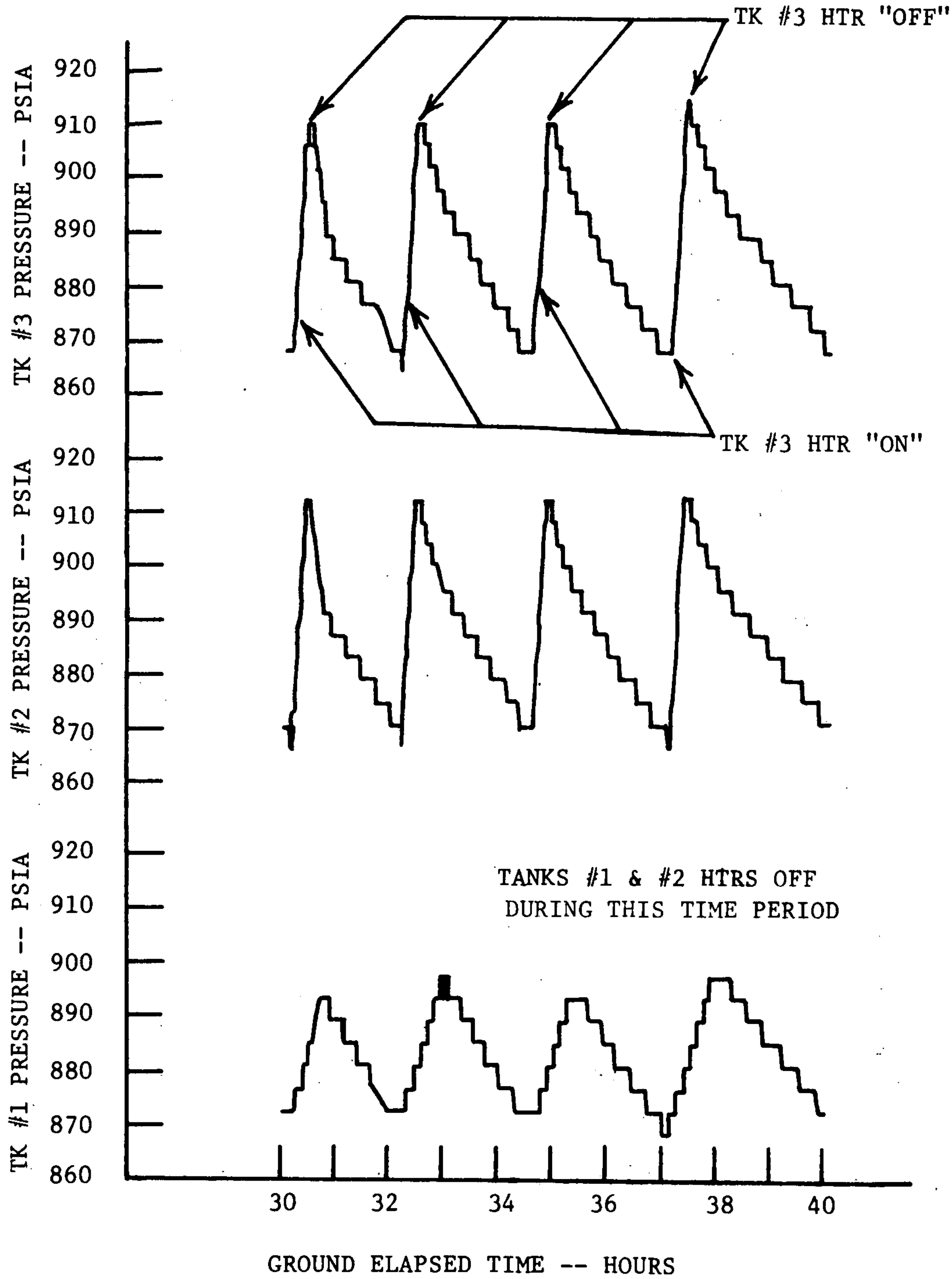

FIGURE 3 - FLIGHT DATA WITH A LEAKING CHECK VALVE

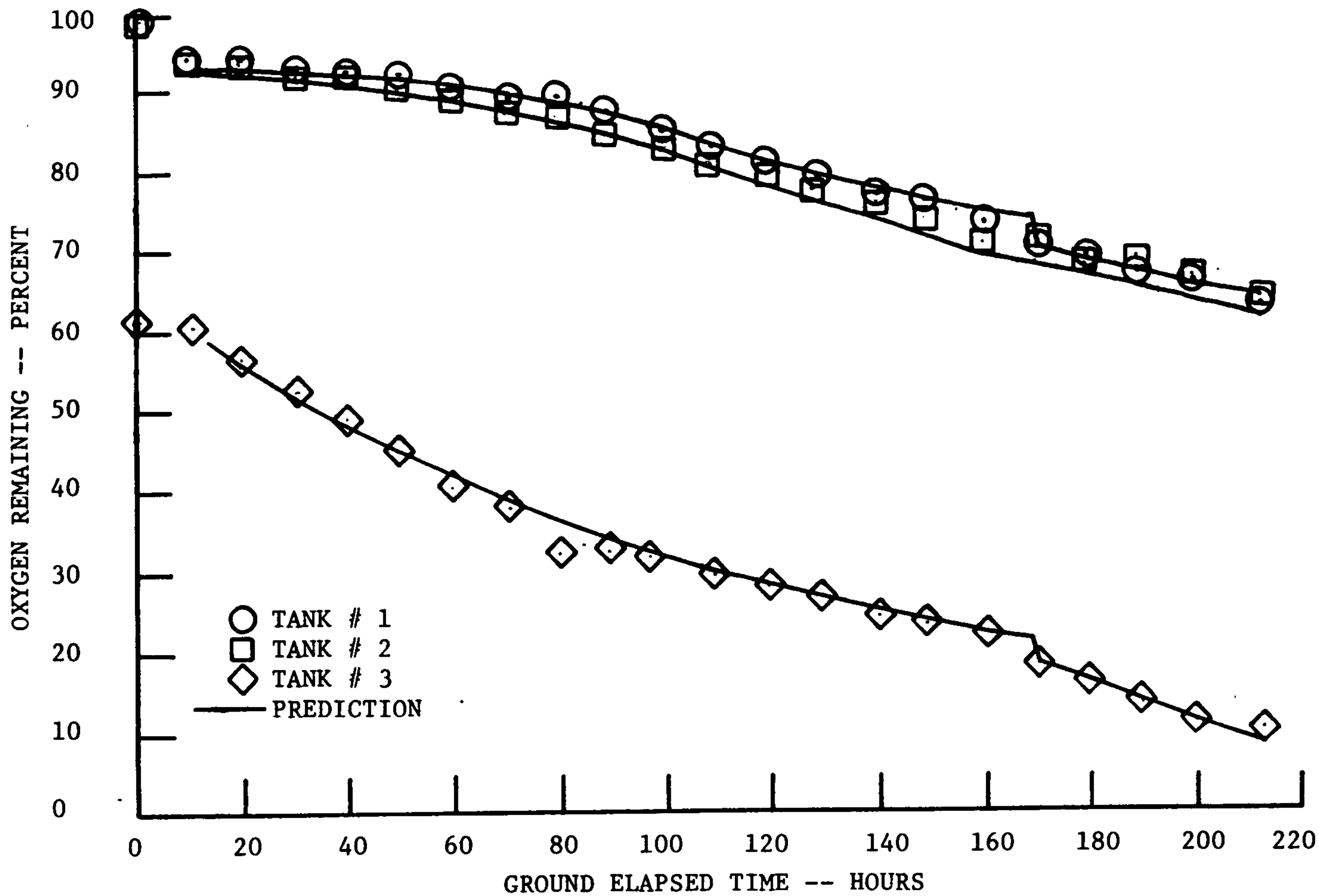

FIGURE 4 - FLIGHT QUANTITY PROFILES COMPARED TO THE PREDICTIONS

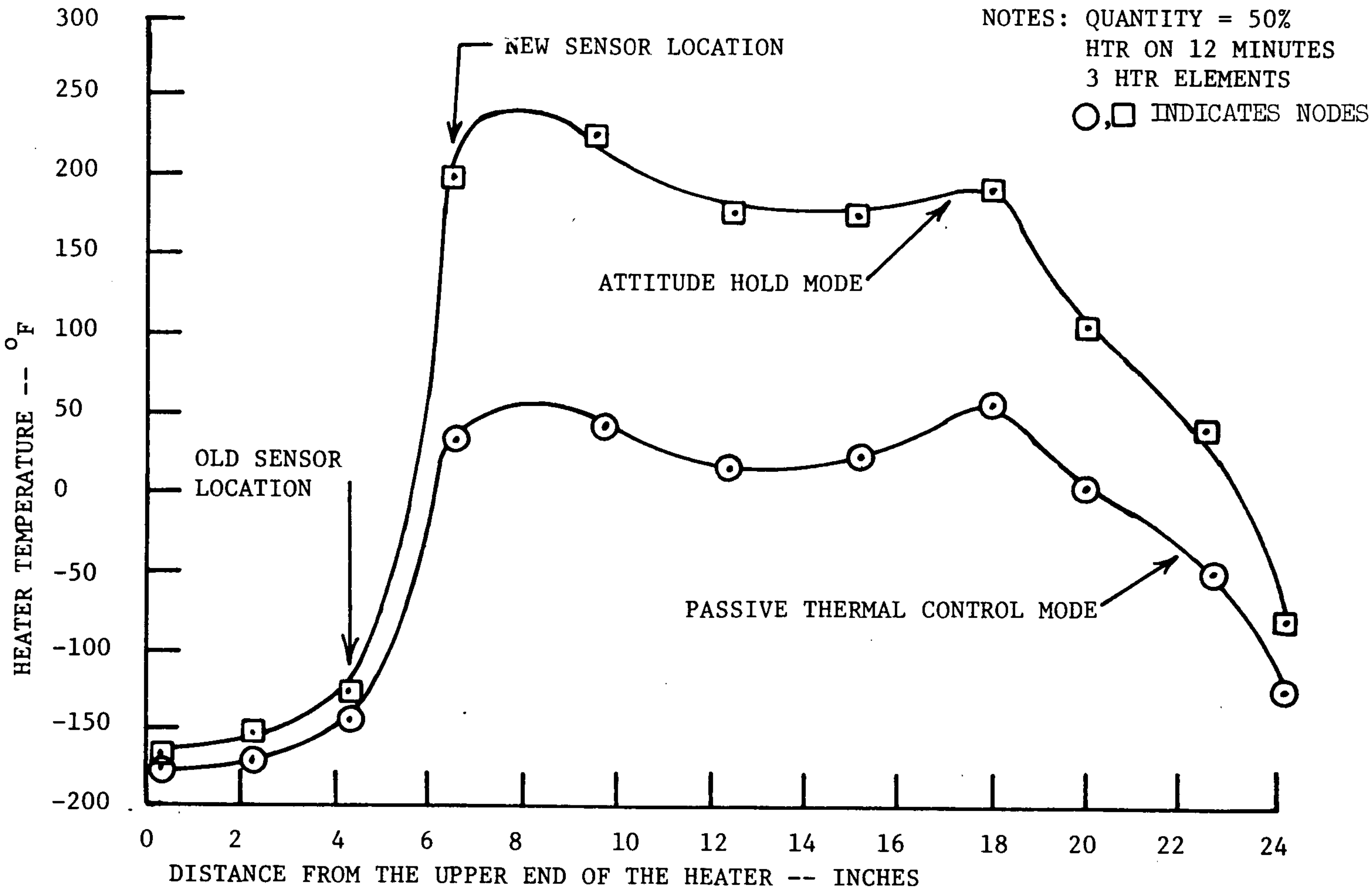

FIGURE 5 - HEATER TEMPERATURE PROFILES

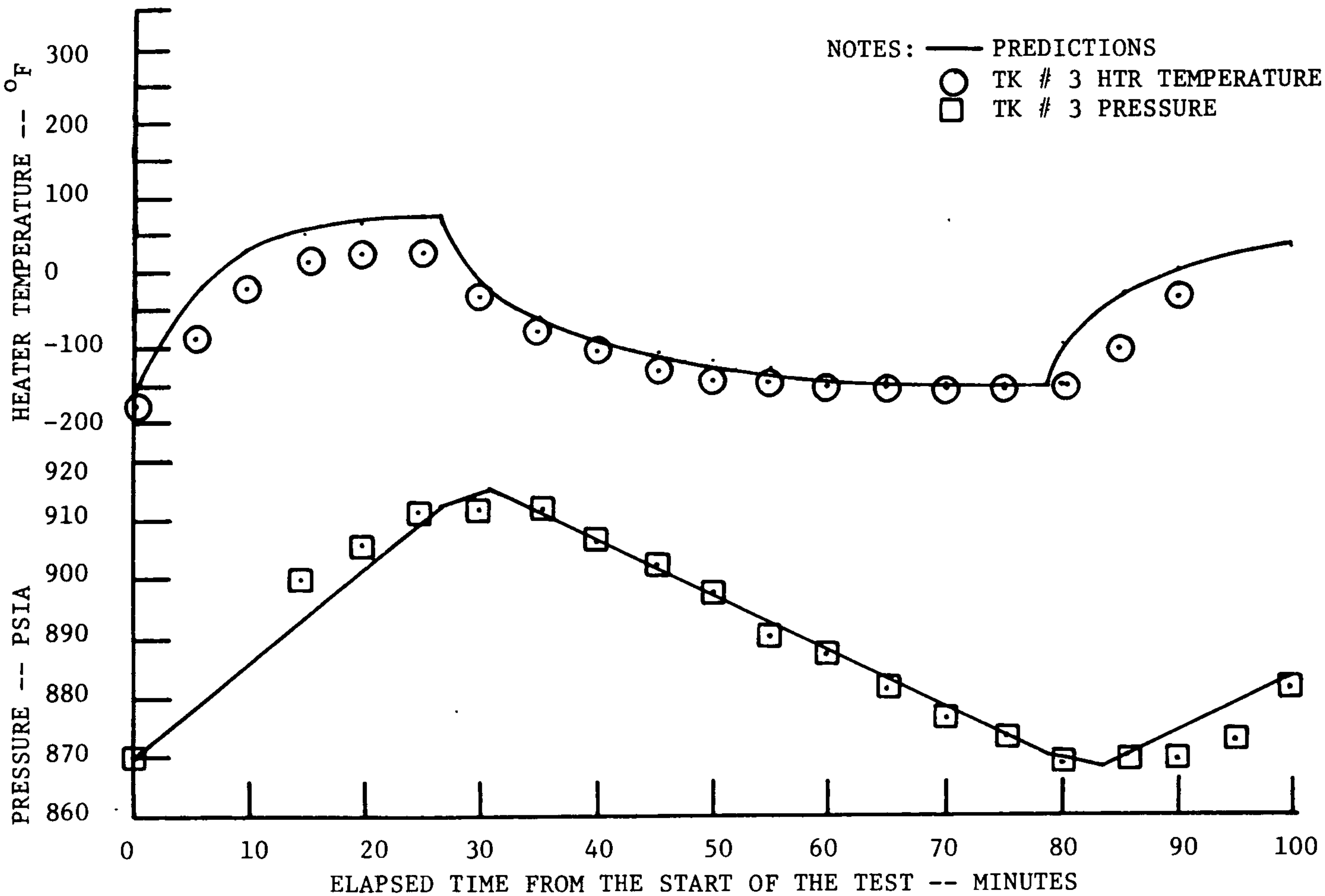

FIGURE 6 - DETAILED TEST OBJECTIVE SIMULATION AND FLIGHT DATA FOR TANK # 3

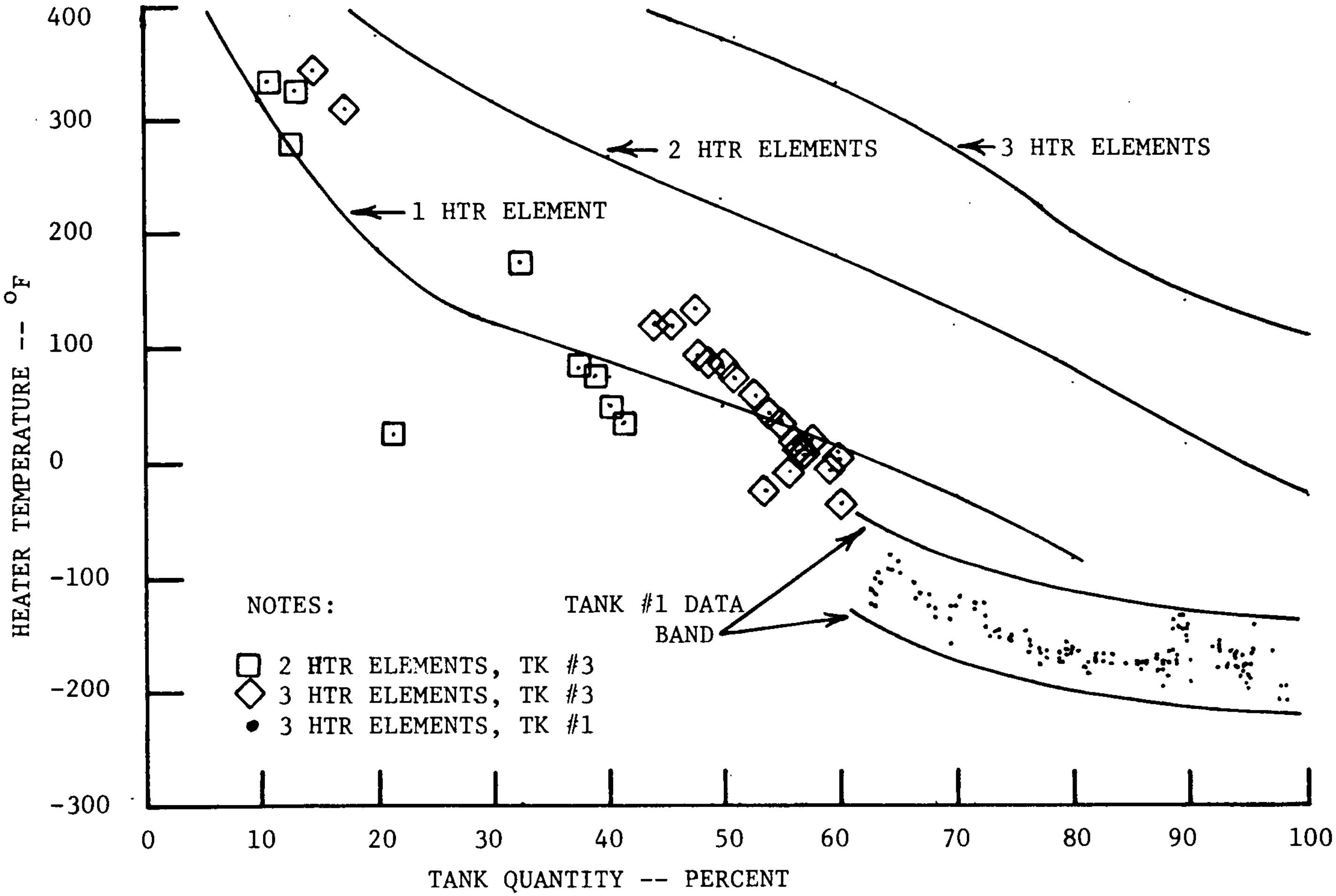

FIGURE 7 - HEATER TEMPERATURES OBSERVED DURING THE FLIGHT COMPARED TO THE MAXIMUM PREDICTED VALUES

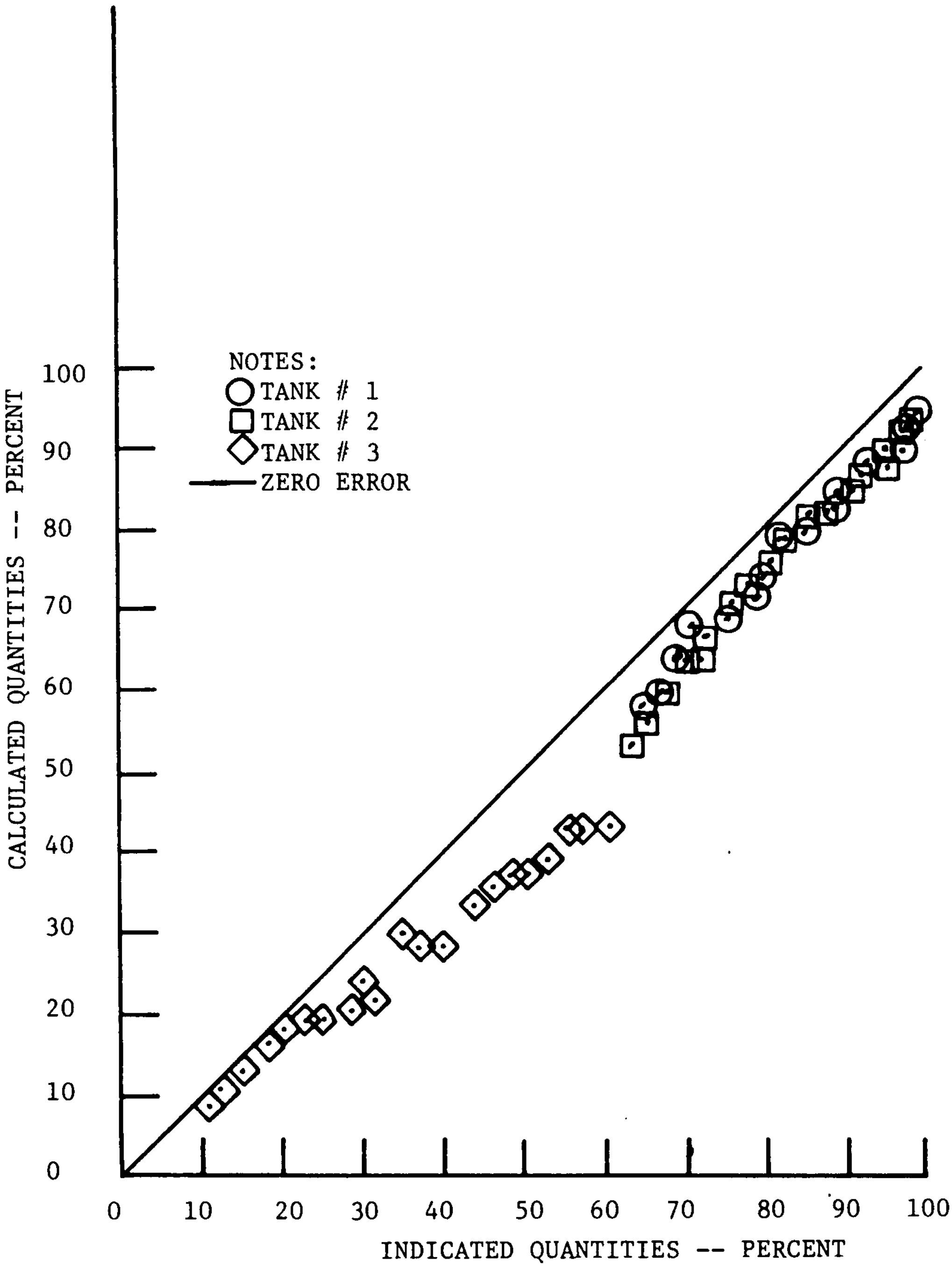

FIGURE 8 - A COMPARISON OF THE CALCULATED AND THE INDICATED QUANTITIES

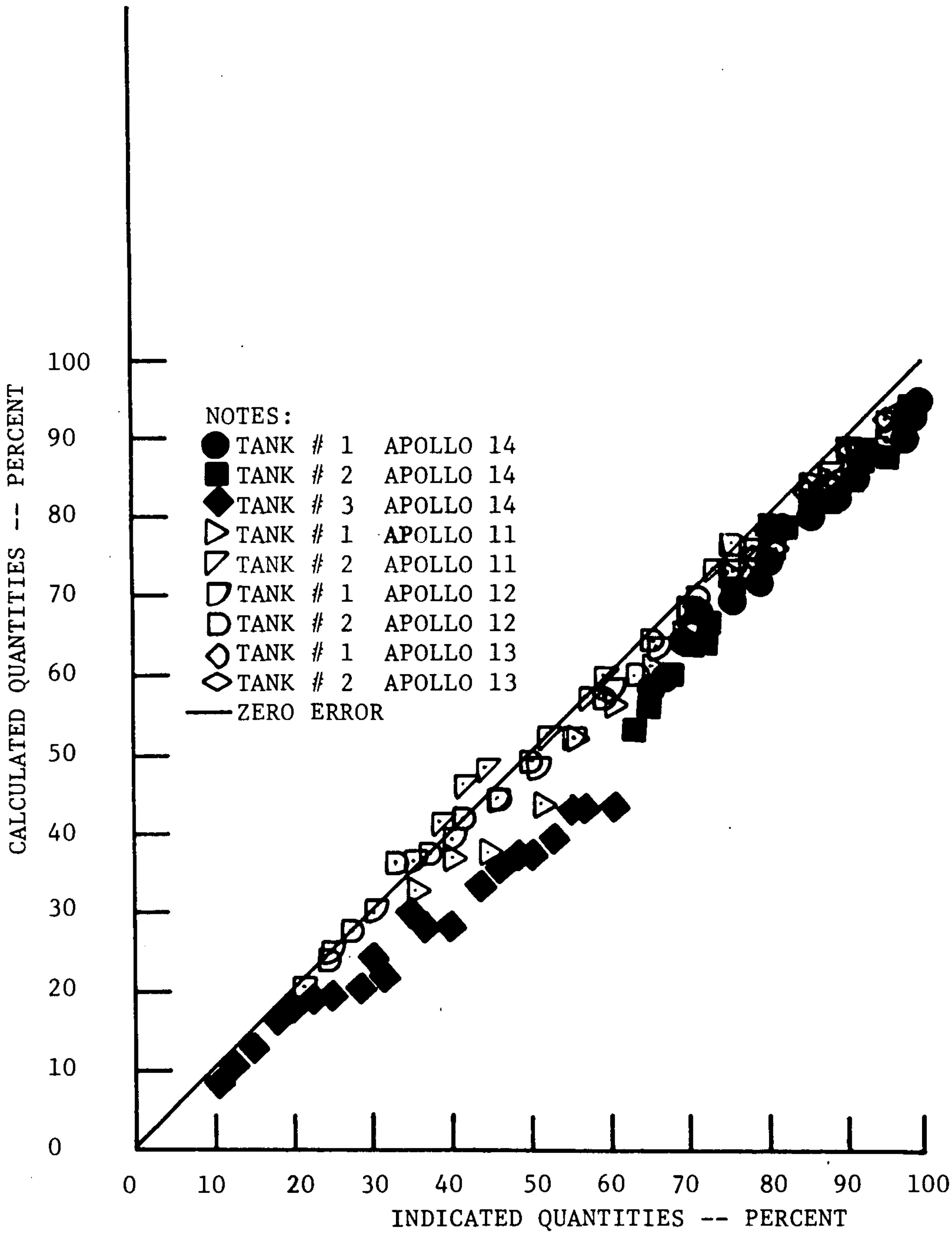

FIGURE 9 - A COMPARISON OF THE CALCULATED AND INDICATED QUANTITIES FROM FOUR APOLLO FLIGHTS

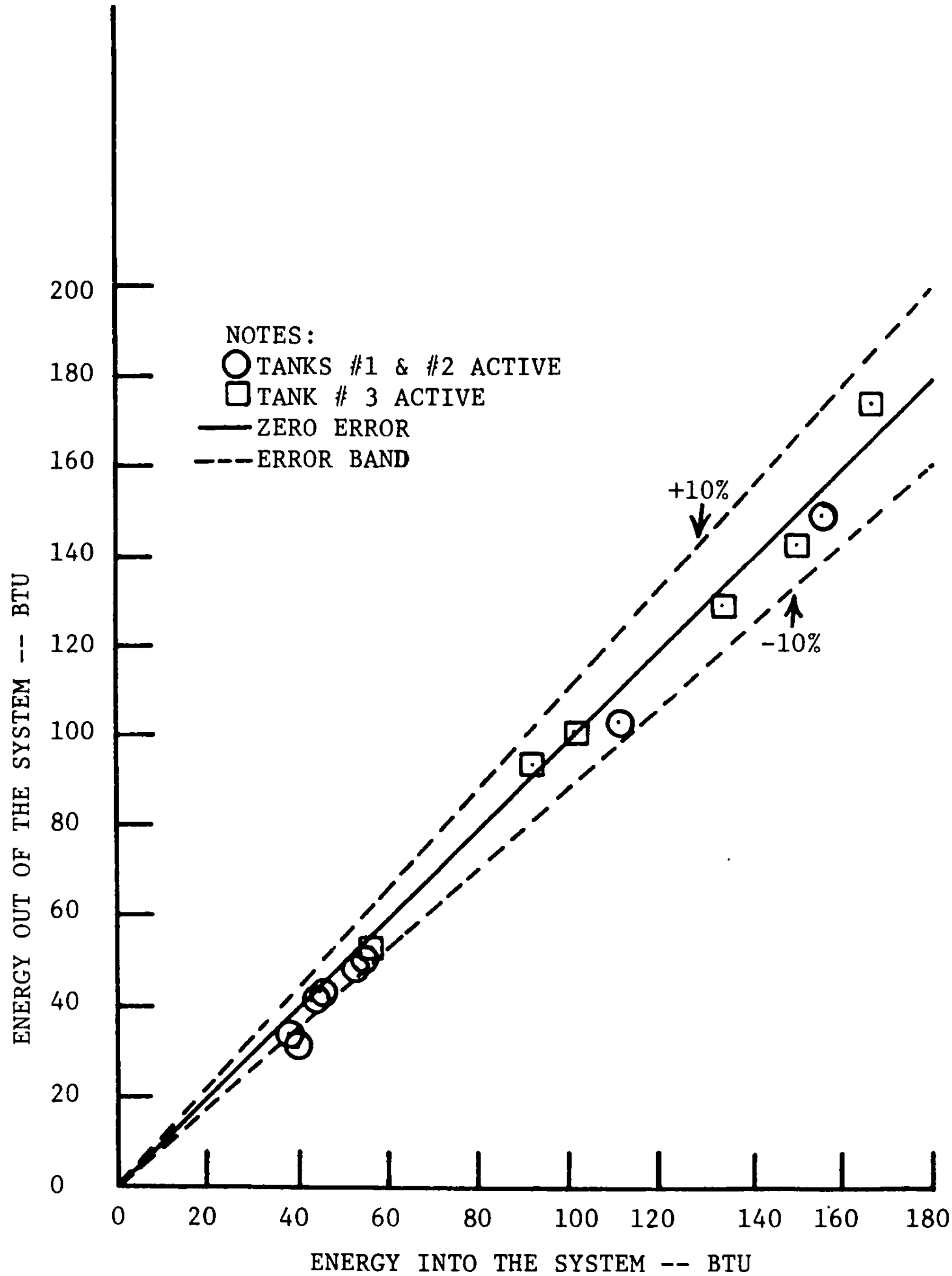

FIGURE 10 - OXYGEN TANK ENERGY BALANCE STUDY

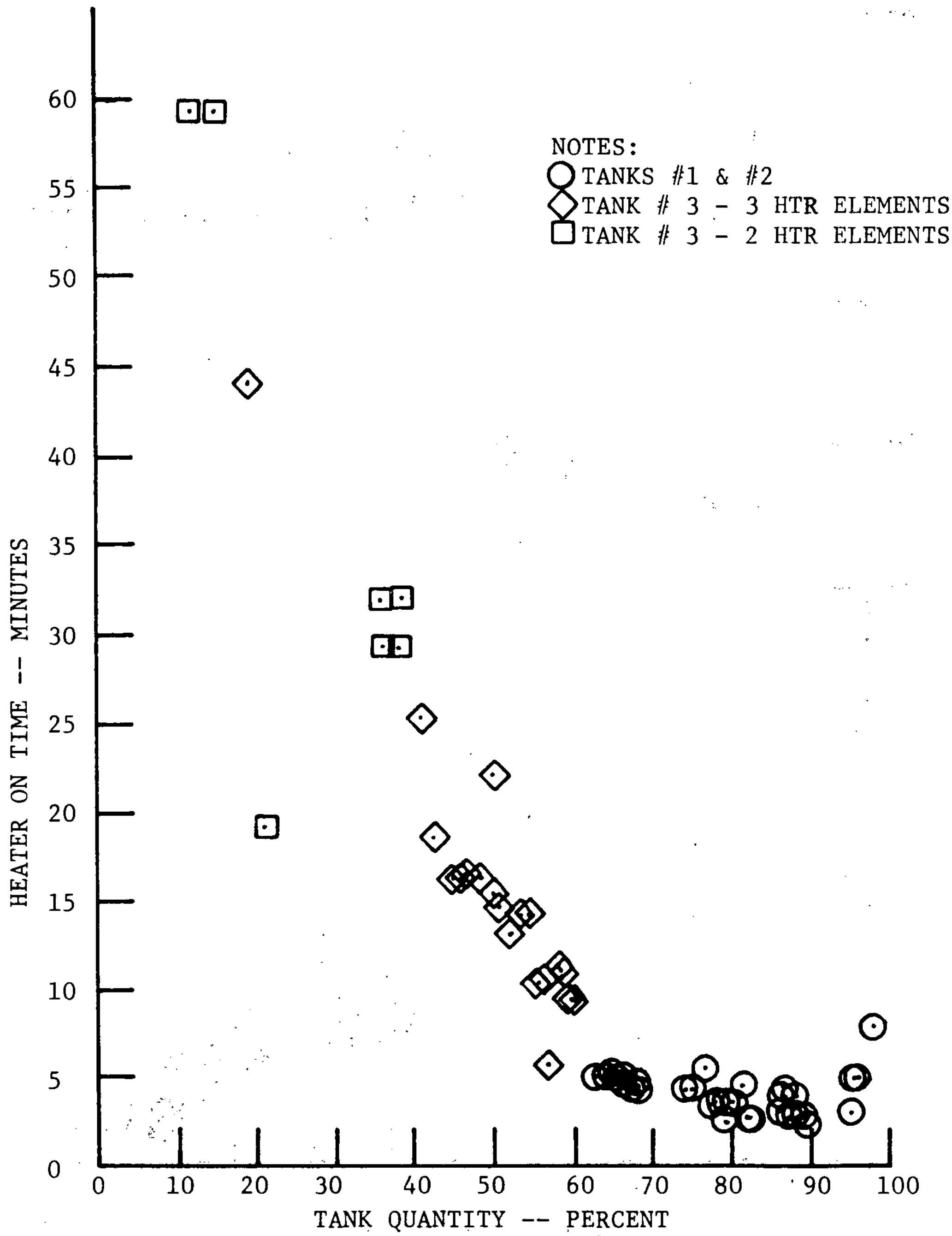

FIGURE 11 - HEATER "ON" TIMES DURING THE MISSION

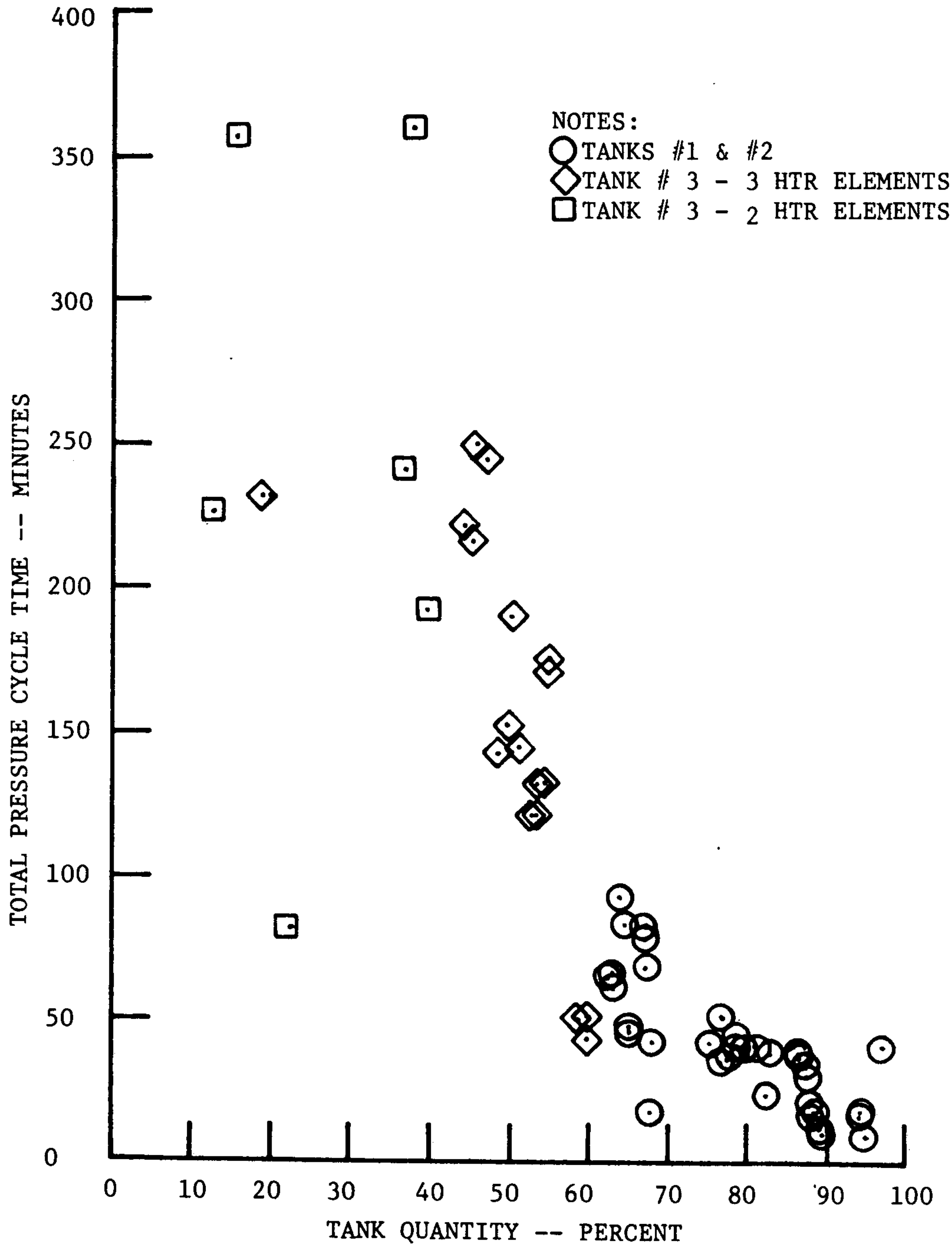

FIGURE 12 - PRESSURE CYCLE TIMES DURING THE MISSION

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