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# TEST AND CHECKOUT CONCEPT FOR SPACE TRANSPORTATION SYSTEMS

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## Summary

Current space vehicles and missions are characterized by almost complete dependence upon ground support equipment and facilities for determination of vehicle status. For the manned missions of the post Apollo era, this dependence will degrade the probability of mission success. Achievement of autonomous space vehicles is necessary for the successful accomplishment of advanced manned missions.

The development of an on-board test and checkout concept and the design, fabrication and test of a major hardware element of the concept is described.

The integration of functions into an overall data management system for future vehicles, with the flight crew assuming the role of ultimate decision maker for resolution of non-nominal occurences is a logical and obvious extrapolation of current technological developments, and will yield the autonomy required for tomorrows manned missions.

## Introduction

Just as air and surface transportation systems have achieved the ability to move vast quantities of equipment and supplies, as well as whole populations, rapidly, safely, simply, and consistently over and on the earth's surface, so eventually will the space-ways of the solar system be plied by transportation systems carrying man, his equipment, and his supplies. The achievement of such space transportation systems will not come easily, quickly, nor cheaply, but it will come.

A necessary step along this difficult road is the elimination of the current, almost complete, dependence upon ground based equipment and facilities to achieve accomplishment of the mission.

This elimination must, of course, be selective and must proceed first to those elements which, if not eliminated, would mitigate against the optimum accomplishment of missions which we can now identify as having a high probability of occurrence in the post Apollo era - missions such as rescue, un-scheduled re-supply and orbital assembly. The rescue and un-scheduled re-supply mission will not permit lengthy pre-launch checkout prior to launch but must exhibit the type of "instant" response currently characterized by our emplaced ICBM's. The orbital assembly mission simply does not permit the utilization of large ground complexes to verify proper assembly and operational readiness of the assembled vehicle or space craft.

A prime element to be considered for early elimination, then, is dependence of the vehicle on that portion of the Ground Support Equipment devoted to vehicle post-assembly and prelaunch checkout.

## Background

The evolution of, and dependence on, Ground Support Equipment for checkout of launch vehicles and payloads is completely logical and has provided the United States with an enviable success ratio in both manned and unmanned launches.

Since the first vehicles able to consistently leave the sensible atmosphere were developed as unmanned weapon delivery systems, and as such represented an extension - albeit by an order of magnitude - of artillery, no requirement existed, nor could any be logically postulated, which would have lead to any approach to their post assembly and prelaunch checkout than by the use of ground support equipment.

The logic of this approach, for the missions and vehicles of yesterday and today cannot be seriously challenged. It is to the vehicles and missions of tomorrow that we address ourselves.

## Missions And Vehicles

The missions of tomorrow, using the visibility of today, will fall within the broad categories of exploration, logistics and utility. The vehicles will surely include, in addition to the Saturn family, a reusuable shuttle and an orbital launch vehicle capable of accommodating a variety of payloads. The orbital launch vehicle may well include one or more nuclear stages and will, of course, require assembly, checkout servicing, pre-launch and launch from earth orbit.

## Man In The Loop

These missions and vehicles will all be characterized by one overriding factor. A factor which, of necessity, has not been "designed in" to today's missions and vehicles. The missions of tomorrow will utilize to the utmost the manifest capabilities of man on-board the vehicle to enhance the probabilities of success of the mission. The role of man - flight crew member -

in our space activity to date has, with one exception, been three-fold.

He has acted as a back-up for a ground controlled or automatic system; he has been used as the subject for extensive bio-medical investigation and data gathering; and he has been used to obtain records - over a wide range of wave lengths - of the earth's radiation signature, as well as targets of opportunity selected by the crew. The exception to these roles, was, of course, the final stages of the Gemini 6-7 rendezvous mission when command pilot Shirra accomplished the final closing maneuver on GT-7 by classical pilotage of the GT-6 space craft, using visual cues and responses finely honed by years of experience in highly maneuverable aircraft.

Tomorrow's space vehicles will not be adaptations of previously developed weapon delivery systems but will, like the Saturns, be designed for manned missions and will, therefore, be more capable of permitting man to truly be "in the loop".

## Roles

What, then, will be the crew members' function in tommorrow's space mission? It will be the flight crew that must make the decisions that will mean success or failure to the mission. These on-board, real time decisions will be made based upon data requested, obtained and meaningfully presented to the flight crew by means of on-board systems. These data will provide information necessary to establish the operational readiness of the vehicle or space craft to undertake the next portion of the mission, or will clearly indicate a malfunctioned or marginal subsystem and will identify the options available to the crew in resolving such problems. Such resolution may require inflight maintenance, selection of alternate missions, or mission abort.

The necessity for on-board decision making and its reliance on on-board checkout for the manned missions of tomorrow becomes overriding when the manned Mars flyby or landing mission is examined. The two way transit time for data or commands at the Martian encounter distance is on the order of twenty-four minutes. This "dead" time is simply incompatible with the exigencies of manned planetary encounter.

Even at so relatively close a body as our own moon the dead time for round trip communications of almost three seconds may well be longer than can be tolerated. During the second launch attempt of the GT-6 mission, considerably less than three seconds occurred between engine ignition, engine shut-down, and Command Pilot Shirra's decision not to eject.

## Implementation

What type of on-board system, then, will be required for tomorrow's vehicles and missions to provide the required performance? In general, the on-board system must be capable of enhancing realization of the inherent reliability of the flight systems. This enhancement may be obtained by increasing the options available to the flight crew in the event of a simple malfunction and could not be feasibly obtained without maximizing man's role on board in a real-time decision making capacity.

The on-board system must be versatile. If a sufficiently high probability of completely nominal operation of all flight functional systems could realistically be obtained prior to the conduct of the mission, the case for on-board checkout would vanish. It is directly because of our collective experience in the non-nominal mission and because of the relationship between mission elapsed time and probability of malfunction that we consider the requirements for an on-board checkout system.

Versatility. The versatility we require in an on-board checkout system must be such that no reasonable malfunction which could occur cannot be identified by the flight crew and an assessment of their options made. It should be immediately recognized that no reasonable computer program of and by itself can be expected to accomplish this requirement. The power of today's computers and available programming is formidable, but the restrictions imposed by the flight regime in the forseeable future preclude the use of a completely computerized on-board checkout system. These restrictions, in addition to the evident size, weight, and power consumption limitation, occur primarily in the man/machine interface area.

Integration. The on-board systems must be truly integrated into the space craft or the vehicle. This integration, ideally, will occur during design and fabrication of the flight systems. Thus, when the flight equipment leaves the factory, it will proceed through its various test cycles, at a variety of locations, not using dissimilar, nor even similar, test equipment, but with each test, at each level, at each location being conducted with the same equipment. The benefits to be derived from this approach are substantial.

Consistency of test results, regardless of test level or location.

Accumulation of parametric test data for application to long term failure prediction.

Elimination of the historical time lag between design changes to the functional system and its test equipment.

Increased confidence in the flight crew.

Permance of functional system/test system interconnections.

Elimination of "carry-on equipment".

Reduction in ground complex and vehicle/ ground interconnects.

Convenience In Operation. Finally, an on-board system must be characterized by convenience in operation. This convenience must be manifested by rapid operation, totally integrated system checkout, accurate fault isolation, and a confidence inspiring man/machine interface.

The keys to rapid operation appear to be utilization of digital processor technology combined with simultaneous checkout of different functional systems.

Totally integrated system checkout utilizes "end-to-end" testing of a system with all subsystems interconnected and operating in their normal functional manner. If the end-to-end test gives a "go" for the system, no further testing is required, although the past history of the system may be called up for presentation along with the current test results to assess whether or not a long-term trend is evident.

If a "no-go" occurs, the on-board system must be capable of providing accurate fault isolation to a pre-determined level. Upon isolating the fault, the on-board system must present the flight crew with available options. These options will, of course, have been pre-determined prior to flight by extensive tests, analyses and simulations and will be stored on-board for either automatic or manual retrieval by the flight crew.

Attainment of a confidence inspiring man/ machine interface will, without question, be one of the more difficult tasks in achieving the system we seek. For to achieve the true realization of man's capability in tomorrow's missions, man and machine must be totally complementary - each doing that which it can best do - with no unduly restrictive barriers to maintenance of a meaningful "dialogue" between them.

We have attempted to identify broad requirements for the establishment of a test and checkout concept for tomorrow's space transportation systems. The full realization of this concept will not come in one giant step, rising, like the Phoenix, from the ashes of today's complex, far-reaching and proven ground facilities, but will evolve step by logical step as a demonstrated need can more optimally be satisfied by the transfer of more and more of mission checkout functions from the ground complex to the vehicle.

## On-Board Test Set

The Boeing Company, has over a period of years, conducted company sponsored research programs covering many of the elements of the concept herein developed.

Many of these research programs are devoted to analytical solutions to tomorrow's identifiable problems. Others attempt to extend the technological base from which solutions to the, as yet undefined, problems of tomorrow may be obtained. Yet others are used to hone existing skills on the stone of developmental hardware.

The remainder of this paper describes one of the latter type company sponsored research programs which has yielded a major hardware element for the type of on-board checkout concept we have been discussing. The developed hardware does not reflect "tailoring" to any specific vehicle or space craft, but serves as a center line design implementation from which specific applications may be adapted.

The developed hardware is but a step toward achievement of the total concept, but the step it represents may well be a necessary one in the evolution of the autonomous space transportation system.

## Computer Control

The developed hardware is intended for use with a remotely located computer. This digital processor, ideally, would also be on board the vehicle and could perhaps serve the dual purpose of guidance and test control. However, many of today's on-board computers are special purpose guidance machines which may not be sufficiently versatile to achieve maximum utilization from the combined system. Since the advent of an on-board test control computer has not yet occurred, the developed test set may at first work with a computer external to the flight vehicle. This external test control computer could be located in a ground complex or, later, in an orbital way station.

Implementation of a first generation on-board checkout concept using the Boeing-developed remote computer controlled test set would utilize several of the test sets physically located in proximity to the system or systems to be tested and all interconnected with the remote test control computer. Figure I is a schematic representation of this concept.

## Modes Of Operation

In order to obtain the flexibility and versatility necessary for real time operation, the test set has been designed to operate in any one of three principal modes; automatic, single step, and new test. In addition, a self check mode is provided to verify the functional integrity of the test set, and a repetitive single step mode for continuous evaluation of a selected test measurement.

In each of the modes the computer serves as a translator between the test set and the test conductor.

Table I describes the system in each of its three principal modes, identifying the roles of the test conductor and the test set. Recognize the continuing role of the computer as the language translator between these two system elements.

| Test Conductor | Test Set |
|---|---|
| Automatic Mode | |
| Requests a block of tests for a particular system. | Provides detailed programming (including fault isolation) for all test steps within the requested block. Implements the testing and proceeds to the end of the block or until a sequence hold is obtained. |
| Single Step Mode | |
| Requests conduct of a single test measurement within a system. | Provides programming necessary to establish the proper conditions for obtaining the requested measurement, makes and presents the value of the measurement. |
| New Test Mode | |
| Requests tests to be conducted by providing detailed set-up and measurement instructions to the test set. | Presents available test set capability options, performs each requested step and reports back status of set-up and measured results. |

Table I

The primary mode of operation for the system is the automatic mode. Use of this mode relieves the computer memory of the thousands of detailed instructions that can be pre-determined by the design specialists and test system engineers, and permits the computer to perform time sharing functions, data reduction, and data formatting for display.

The choice of automatic as the primary mode was influenced by recognition of the present non-availability of a separate test control computer for this generation of space vehicles.

The test set, as we have developed it, is an automatic programmer-evaluator. It utilizes locally stored instructions to select and route stimuli, select test points, select measurement and evaluation modes, and evaluate the measurements against stored limits. The stored instructions also provide sub-routine programming for fault isolation.

The selection of locally stored programming at each test set was made to:

Reduce the on-board computer memory requirements, and

Permit each test set to operate autonomously for the majority of its operation.

Secondary benefits, derived from the local programming concept include the ability to accommodate program changes to individual systems with absolutely no effect on other systems, other test sets, or the central computer.

## Functional Description

The test set has been developed to conform to the building block principle. Functional elements may be added or deleted to an individual test set to accommodate a specific application.

The functional building blocks we have used in our developmental model include signal conditioners, evaluators, switching matrices, memories, logic, control and response elements.

In order to verify the physical as well as the functional capability of the test set and to exercise our design capability for space packaging, we have provided a package design for the test set. Figure 2 depicts the packaged test set.

The microcircuits in the test set are mounted on six layer etched circuit boards. Each of the 35 2.25 by 4.85 inch boards in the set can mount up to 48 microcircuit devices - 24 on each side in a three by eight arrangement. Two of the six layers of each board are used for power distribution to and heat transfer from the devices. Simple conductive cooling to a standard thermal panel represents adequate environmental control for the test set.

## Test Set Operation

Operation of the test set will be initialed by a twenty-four bit command word from the computer. This command word will be decoded by the test set. Based upon the decoded word, the test set will either switch its main gate to its local programmer (for the automatic and the single step mode) or will keep its main gate latched awaiting further instructions from the computer (new test mode).

The flow of data from the computer or local programmer occurs in twenty-four bit, parallel words, each having a cycle time of 13 microseconds. The words are checked for parity and then loaded into a "universal" memory. The universal memory is one of the functional building blocks of the test set.

Each memory consists of a single etched card which is addressable by the test set and which may be physically located external to the test set with its associated stimulus equipment or other building blocks. When the necessary memories have been loaded and the loaded words checked for agreement with the command words, the execute bit of the last command word will instruct the response section of the test set that a measurement is to begin. This will cause the memories to begin an evaluation delay, switch stimulus and response matrices, program the stimulus generator, set up the signal conditions and program the counters and tolerance comparator. The measurement itself takes place after the programmed evaluation delay.

The measured value is then compared to programmed limits, and the result used to initiate the next test step, to drop into a fault isolation sub-routine, to re-evaluate, or simply to notify the computer of the measured value, depending upon the selected operating mode and the test results.

The test set, then, is able to perform the necessary function of programming, test point connection, stimuli activation, measurement and reporting. These functions have been placed into a small, light weight package that can be judiciously placed throughout a large vehicle or space craft and under the general supervisory control of a computer, can provide necessary test and checkout results on the vehicle systems to the flight crew.

## Performance Specification

The performance specifications for the control and response section of the test set are shown in Table 2.

| Parameter | Specification |
|---|---|
| Input word rate, computer to test set | 75 KC max. |
| Input bit rate, test set to universal memory | 1.2 megabits/sec |
| Memory cycle time | 13 microseconds |
| Number base | Binary |
| Work length | 24 bits |
| Checking | 24 bits parity; 16 bits equality |
| Output | Test result or test number; Go, No-Go High Limit, No-Go Low Limit; Polarity; Test Set Address; Parity |
| Evaluation Modes | Frequency; ac-dc peak or average voltage; time interval; period count (EPUT); Ratio; Difference; Sum |
| Accuracies, Frequency | ≤10KC, ± 1 count<br>>10KC, ± 0.01% |
| Voltage | DC, ± 0.1%<br>AC, ± 0.5%, 50cps-100 KC<br>± 1.0%, 30cps-200 KC |
| Period | 100 sec ± 1 count |
| Input Impedance | <0.1V, 100K ohm<br>≥0.1V, 1 megohm |

Table 2

The minor weight penalty incurred by installation of test sets onto the vehicle may be partially offset by a reduction in, or even elimination of, many of the umbilical connectors which presently fly with the vehicle. The present S-IVB stage and Instrument Unit for the Saturn IB vehicle carry into orbit more than twenty-five connectors to which are soldered over eight hundred and fifty individual analog and bi-level commands and measured values used during ground test.

## Control Language

One of the major elements required for the checkout concept developed earlier in this paper was that for a "confidence inspiring man-machine interface". Recognizing this paramount requirement to attaining an autonomous space transportation system, our development of the described on-board test set was paralled by the development of a test language for the control of the test set. The language is characterized as an on-line query, wherein the human operator communicates with the test set, via the computer, with a series of questions, with a list of alternatives for selection by the operator, or by requesting numerical information.

The language has been coded for execution in Boeing's Simulation Center at our Huntsville facility and is currently operational with an IBM 7044 computer acting as the language translator. The 7044 represents substantially more capability than is being used in our program. We presently have available 7000 words of core storage and are using an additional 150,000 words of tape storage. This memory is sufficient to perform in excess of 14,000 individual tests. In this context, a test is defined as all of the steps necessary for obtaining a defined measurement under specified conditions, evaluating it and, based upon the result obtained, identifying the next test.

No attempt has been made in our current research effort to develop a flight prototype control and display system for the test set. Entry into the system as we are currently using it is by means of an IBM 1014 Remote Inquiry Station and the responses of both the test set and the operator are recorded by the station's print-out equipment as depicted in Figure 3. The test language has been designed, however, for use with a simple thirteen position entry keyboard and an alpha numeric cathode ray tube display.

Figure 4 is a sample print-out of dialogue between the test operator and the test set. It will be noted that the operator, at his option, may select both a description of the test set and a glossary of terms as well as the desired operating mode.

It will also be noted that the sample print-out was obtained on a time sharing basis - each test set response preceeded by the computer time. All of the operator's inputs are preceded by an H. The thirteen position entry key-board with which the language has been designed to work would contain push buttons for the digits 0 through 9, "yes", "no", and "execute".

## Growth Features

Adaptations and extensions of the described system come easily to mind. The crew will doubtless be provided with a microfilm reference library with detailed instructions, options, or emergency procedures for almost any conceivable malfunction that the test set may uncover. The required reference would, of course, be selected by the computer and displayed to the test conductor.

The functions of the test set may be integrated into the operational systems in such a way that no discrete black box labled "Test Set" could be identified.

Since the test sets have a command capability and are so intimately associated with the vehicle systems, over-all command system capability is enhanced and the possibility of using the test set/computer capability to provide an alternate mode of operation for a malfunctioned subsystem is not beyond reach.

Since the test set has the capability to continuously monitor vehicle discretes and provide an alarm in the event of signal failure the traditional emergency or malfunction detection function is enhanced.

Recognizing these growth features and the seemingly constant decrease in size, weight, and power consumption of available circuitry, a marriage of the functions presently performed by discrete checkout, command, telemetry, launch control, and malfunction detection system may confidently be predicted. This unified data management system will enable tomorrow's flight crew to obtain complete information on the status of every part of their vehicle, to make the necessary decisions concerning each phase of their mission, from pre-launch to re-entry, to accommodate a wide spectrum of unplanned events which, while neither desired nor anticipated will surely occur, and will, finally, permit man to achieve the role in space transportation systems that he has long held in surface systems.

## Conclusion

Achievement of a space transportation system will require, as a necessary step, the incorporation of vehicle test and checkout functions on-board the vehicle. The role of the flight crew as decision makers for the conduct of the mission must be enhanced by providing the crew with the necessary data to assess a non-nominal situation and arrive at an optimal course of action.

A step along this path has been accomplished by the development, on a Boeing sponsored program, of a space packaged, on-board test set, and a test control language. This program has provided the hardware for accomplishing the test functions on-board and the software for implementation of meaningful, real time, on-board assessment of vehicle system status.

As we become more sophisticated in our technology, the union of functions of traditionally separate systems, will provide further autonomy to the vehicles and crews required for a space transportation system.

Figure 1 Remote Computer Controlled On-Board Test Set Concept

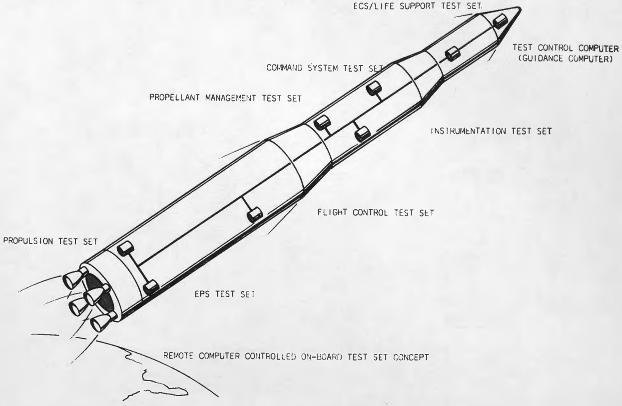
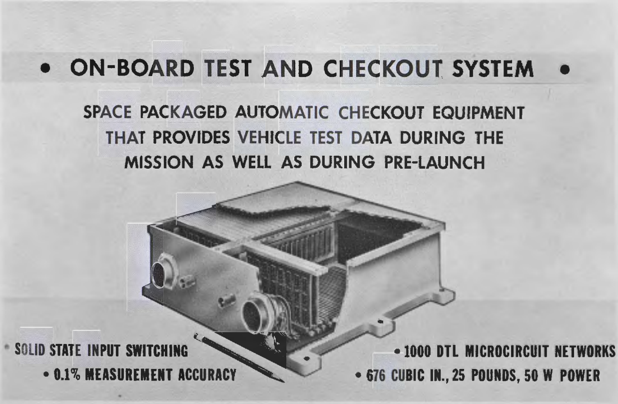


Figure 2 On-Board Test And Checkout System



• ON-BOARD TEST AND CHECKOUT SYSTEM •

SPACE PACKAGED AUTOMATIC CHECKOUT EQUIPMENT THAT PROVIDES VEHICLE TEST DATA DURING THE MISSION AS WELL AS DURING PRE-LAUNCH

- SOLID STATE INPUT SWITCHING
- 0.1% MEASUREMENT ACCURACY
- 1000 DTL MICROCIRCUIT NETWORKS
- 676 CUBIC IN., 25 POUNDS, 50 W POWER

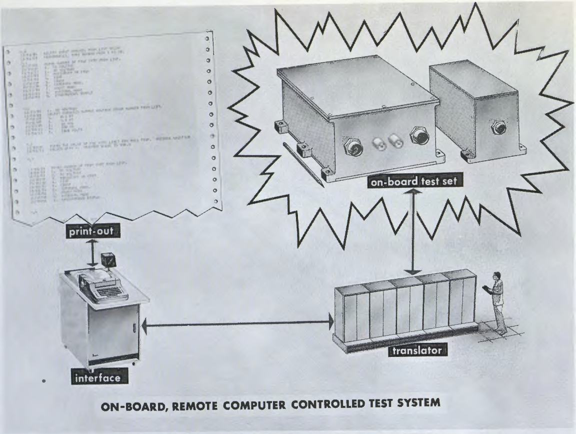
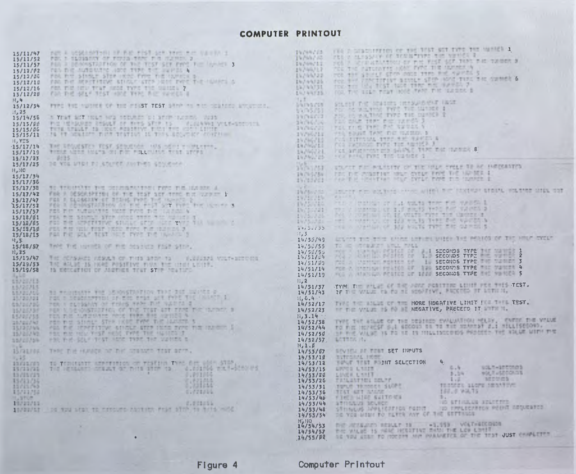


Figure 3 On-Board, Remote Computer Controlled Test System



COMPUTER PRINTOUT

Figure 4 Computer Printout