An Investigation of the Adequacy of Aerospace Vehicle Testing

CHARLES E. CARNAHAN*
Martin Marietta Corporation, Vandenberg Air Force Base, Calif.

IF there is to be a substantial, continuing space effort in this country, it will have to strike a solid and imaginative chord in national interest, and it must be priced to compete successfully for tax dollars with such vital problems as pollution, Viet Nam, and the War on Poverty. We must market good, reliable products that also fit the national pocketbook. Launch operations deserve special attention, because between 20 and 40% of all the so-called recurring expenditures for a typical space program are related to testing and preparation of a completed vehicle for launching. It was the very real possibility that increased flight success could be combined with reduced expenditures as a practical amalgamation that led to my investigation of the adequacy of aerospace vehicle testing.

Security restrictions and divergent configurations tend to befuddle attempts at flight performance authentication. Despite this information gap, some data are available that are useful in projecting the mean probability of success for any given system. Figure 1 was developed from unclassified sources covering some 486 Earth orbital launches over 12 yr.

From this rather large sample base, it can be seen that space launch operations have improved, but the curve begins to flatten markedly in the years 1966 through 1968, at a level near 95%.

Three launch vehicle programs were intensively examined, and from a total of 88 launches and 25 flight failures, we found that:

1) In no case, either at the factory or at the launch complex, was a test performed for the failure which occurred. Although it is true that in some cases components that failed in flight were tested, in every case the mode of testing was insufficient to duplicate the failure environment.

2) Every failure was of the type that could not be detected by any checkout mode then in use, either in the manufacturing facility or at the launch complex.

3) Incorrect launch test procedures did not contribute to any failure.

4) Inadequate logistic support or improper spares control did not contribute to any failure.

5) The Combined Systems Test or Simulated Flight was not capable of detecting any of the types of failure which occurred.

6) No deficiency in the configuration control system was determined to be the cause of failure.

7) No operating trend data system existing either in the manufacturing facility or at the launch complex could have predicted or prevented the failure.

8) Static and sequence compatibility firings did not increase success probability.

It should be made clear that, with the exception of static firings, each of the eight systems test and test support functions discussed may have supported the prevention of additional failures. It was obvious, however, that they did not prevent the 25 failures that did occur. Of those 25 failures, three were attributed to personnel error; the remaining 22 were the result of an anomalous operation of a deficient or defective component that, once it had been assembled in or attached to the completed vehicle, allowed for no testing technique that would provide for malfunction detection. Of the 22, 20 were mechanical in nature. Even the two so-called electrical failures actually appeared in a mechanical mode.

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* Director, Vandenberg Operations, Denver Division. Member AIAA.

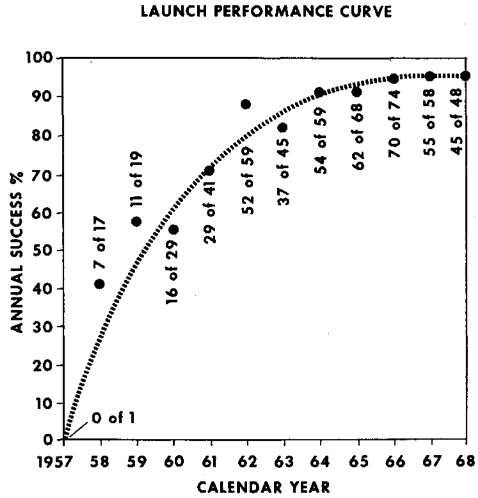

Fig. 1 Launch performance curve.

Thus, the most frequent real cause of flight failure is the malfunctioning, inoperability, or structural separation of a piece of basically mechanical hardware that does not lend itself reasonably, or, in most cases at all, to systems testing.

When one considers that system checking is the only kind of testing, in fact, that the vehicle is normally exposed to once it reaches the point of final assembly on the factory floor, and the only type of testing to which the vehicle can reasonably, economically, and often physically, be subjected in the final cycle that prepares it for launch, the conclusion is evident—realign the test emphasis to the area of component acceptance and development.

New and special importance must be placed on components that cannot be properly exercised and tested at the system level. There is an absolute need to test selected components beyond operating levels to establish performance margins for all dynamic conditions. The most substantial contribution to reducing the launch operation costs and increasing the chance of mission success would be to establish an avowed dogmatic attitude regarding component development and testing. We should adopt a hard clear policy that any component or subassembly or structure that cannot be effectively and completely checked at the system level must either be overdesigned, operated at well under rating, contain redundancies, or be otherwise so thoroughly tested as to pre-

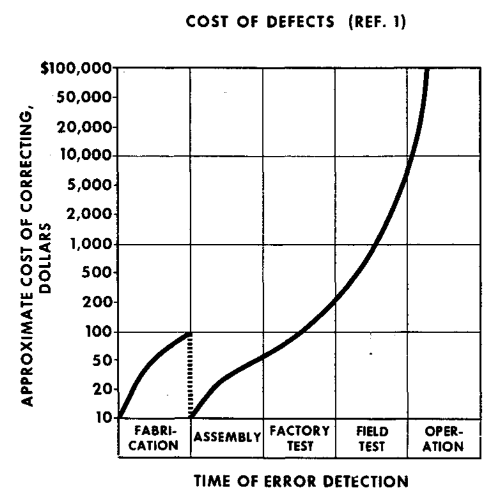

Fig. 2 Cost of defects (from Ref. 1).

clude its chance of failure once it has been installed in the vehicle. This approach is attractive not only because of its technical soundness, but also because of the economically responsible manner in which it can be accomplished.

With respect to the cost of testing, in the erection to launch cycle of 19 vehicles taken in consecutive order from two programs, there were 3693 airborne and ground system components replaced that resulted in 17 successful flights and two catastrophic failures.

Add to the 3693 component replacements the irrefutable fact that they all occurred at the most expensive end of the development to launch sequence, as illustrated in Fig. 2,[1] and you have the premise for the basic conclusion which resulted from this investigation.

Over the past several years, some form of a successful Combined Systems Test or Simulated Flight has attained the status of being almost synonymous with successful flight. In fact, every vehicle that flew successfully was preceded by a successful Combined Systems Test. It is also a fact that every vehicle that failed was preceded by a successful Combined Systems Test.

This type of test is effective for examining the status of electrical components in a nonflight environment and for determining the integrity of system interfaces, but it cannot detect incipient, dynamic failure modes, and it has not proved useful in detecting or preventing the basic cause of flight failure.

An analysis of all of the flight failures included revealed that 90% were mechanical, electro-mechanical, or structural. Of these, some 48% occurred in components involving no moving parts. The remaining 52% involved mechanical or electro-mechanical components that utilized moving parts to perform their function. This ratio points out that the seemingly "simple" mechanical and structural components' relevance to flight failure is equally as significant as the more complicated components with moving parts.

From the flight data, it was determined that mechanical failures usually occur on parts under stress or operating conditions that take place only during the dynamics of flight, and therefore cannot be tested on the assembled static vehicle. Again, the same conclusion is supported. Adequate preflight testing on most mechanical or electro-mechanical components can only be conducted during design development, qualification, and acceptance testing.

Throughout the research that went into the preparation of this study, we were also frequently exposed to discussions and reports dealing with circumstances that ostensibly prohibit the conduct of adequate testing. There were indications that this impossible-to-test situation is sometimes underwritten by economic restraints, by compression of time, by design limitations, or by the very nature of the devices to be tested.

We noted, however, that subsequent to flight failure, no component or system, even those previously labeled "impossible-to-test," escaped exhaustive scrutiny. All systems and all components were suddenly "testable." We found that no impossible-to-test cases existed when: 1) all development failures were treated as though they were flight failures and received the same corrective action that would have been afforded a flight failed component, or 2) testing was done to the flight environment before the failure instead of after, by applying the same foresight to the development and acceptance tests before flights as was done after flight failure.

The economic gains of designing for test are yet to be fully recognized. In the large launch vehicle systems studies, we found many very real limitations still exist in performing checkout operations. Although electrical checkout, in more cases, has been automated to a sophisticated level, there are still mechanical operations which are reminiscent of the white scarf and goggles era. Connectors must be mated and demated; simulators and test tools must be installed and removed; personnel access must be made to various areas of the vehicle with no reasonable provision for such access; facility requirements of a massive and complicated nature result from a reluctance to accommodate vehicle design with simple preparation and checkout provisions. This study disclosed that, conservatively, 30% of launch site test crew effort was expended exclusively on maintenance of facility and ground equipment which had only a secondary relationship to launch vehicle activity.

In our investigations, we found that the test sequence which a component follows from its physical inception to flight is essentially the same for all missile and space systems.

Moreover, elements of development, qualifications, acceptance, subsystem, and then flight simulation are in logical order. The illogic of this scheme stems from a fundamental lack of definition of what each of these basic elements is expected to accomplish; in short, missile test and launch organizations have no clearly defined philosophy behind testing.

The cost of detecting and correcting defects rises sharply as the point of detection moves closer to flight, with the ultimate price being paid when detection occurs during flight itself. On the other hand, there is little understanding, and no clear policy, that launch operations testing can only be economically useful when it is involved in determining system interface integrity and not in weeding out defective components that should have been eliminated prior to the vehicle's arrival at the test range.

The large complements of personnel necessary today to operate and maintain launch operations can be substantially reduced if the test engineer will bring his experience to bear on the design concept. The fundamental responsibility for the serious development of these solutions rests with the test organization itself—and it has, literally, done little to solve them. The course this nation's space effort follows over the next several years may well be affected by the insight, the energy and the shrewdness which launch operations organizations apply to maturing their role in the aerospace community.

Reference

[1] Cornell, C. E., "Minimizing Human Errors," *Space Aeronautics Magazine*, March 1968, pp. 72–81.

Effect of Specific Heat Ratio on Surface Pressure Coefficient for Lifting Cones

D. J. JONES*

National Aeronautical Establishment, Ottawa, Canada

Nomenclature

C_p	= surface pressure coefficient, $2(p - p_\infty)/\gamma p_\infty M^2$
$C_p{}^A, C_p{}^B$	= values of C_p for $\gamma = 7/5$ and $\gamma = 5/3$
$C_p{}^R$	= value of C_p at $\alpha = 0$ with $\gamma = 7/5$ for the same M, θ_c combination for which $C_p{}^A - C_p{}^B$ is being examined; i.e., $C_p{}^R \equiv (C_p{}^A)_{\alpha=0}$
K	= hypersonic similarity parameter, $K \equiv M \sin\theta_c$
M	= freestream Mach number
p, p_∞	= surface pressure and freestream pressure
γ	= ratio of specific heats
θ_c	= cone half-angle
α	= angle of incidence
ϕ	= circumferential angle; $\phi = 0$ is the windward plane of symmetry

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* Mathematician. Member AIAA.