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ENGINEERING SAFETY INTO MISSILE-SPACE SYSTEMS

by

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Presented at the

SAE-ASME-AIAA Aerospace Reliability

and Maintainability Conference, Washington, D. C.,

29 June - 1 July, 1964

ABSTRACT

Safety Engineering, as applied to complex missile and space systems, has developed a new methodology referred to as "System Safety Engineering." The requirement for a comprehensive approach to safety which is included as a contractually covered adjunct to the design, development, and operational phases of a systems life cycle has become apparent from costly missile mishap experience. The general concepts and accomplishments of this new engineering discipline are described along with possible beneficial relationships with Reliability and other recognized organizational elements engaged in safety related activities.

During the past few years a remarkable change in a concept normally associated with safety engineering has been taking place through the missile-space industry. This new concept is referred to as "system safety" to distinguish it from the more familiar and traditional "industrial safety." The prime mover in formalizing this new concept of safety has been the major user of large missile weapon systems, the Air Force. The Air Force has found, through unpleasant experience, that while no one intentionally designs a safety deficiency into a missile component, system, or procedures, some operational systems are less safe than they should be.

As was once the case with reliability, the customer procured weapon systems with the hope safety would be delivered along with the hardware. It was assumed that through some magical process operational systems would not have safety deficiencies built into them. In some cases this was realized, but more often than not the customer accepted safety problems because it was too late to do anything about them (1)*. And, as became the practice in ensuring reliability, the customer determined that safety needed to be engineered into the product, and that the contractor's engineering section should be the prime target of any effort to improve inherent product safety. To make the contractor a member of the SPO/designer/user safety team, USAF concluded that a Military Specification covering safety should be made a part of weapon-system procurement contracts.

After considerable discussion and review, MIL-S-38130 (USAF) "Safety Engineering of Systems and Associated Subsystems and Equipment, General Requirements for," was published on 30 September 1963. Surprising as

*Numbers in parentheses designate References at end of paper.

it may seem in view of the extensive safety considerations associated with missile systems, until this document was developed, no general Military Specification on safety existed. The argument that there has never really been a need for specific safety requirements in missile procurement contracts (since safety has always been a major consideration of the missile designer and development engineer) fails to be convincing when compared to some published Air Force statistics.

In 1962, there were 458 missile mishaps (unexpected events causing material damage or personal injury) recorded by the Air Force's Aerospace Safety Division. Missile weapon systems currently assigned to operational units accounted for 421 of these mishaps. Of this number, 47 percent were caused by material failure, and 15 percent involved designed-in safety dificiencies. Several of these mishaps cost several million dollars each, while at least one caused the loss of a ballistic missile and property damage costing well over $10 million (2). All of these categories of mishaps are targets of system engineering.

That many of these mishaps might have been prevented through a strong design-oriented safety-engineering program is increasingly evident if one begins to analyze the causes. Many volumes have been published detailing results of missile accident investigations painstakingly assembled by teams of expert investigators. But how many designers and engineers not directly concerned have the opportunity, or take the time, to study these reports? How many valuable object-lessons on designing for safety are missed, and mistakes repeated? How can we expect designers and engineers to be knowledgeable about all potential hazards of the component or subsystem they are developing, so that they can ensure that safety deficiencies will not result during the life span of the missile system?

It must be remembered that safety is only one of many requirements placed on a given item of hardware. The designer must consider performance, weight, stress, value, and reliability and many other factors. Safety can be inadvertently overlooked when unequal emphasis is placed on some other requirements because of tight specification requirements in these areas.

In case there are some who still think adequate safety is being provided through existing engineering, quality assurance, and reliability programs and techniques, it might be well to briefly describe several incidents which may illustrate, better than statistics alone, what has been occurring at operational and training missile sites:

1. While performing a Time Compliance Technical Order (TCTO) at an operational ICBM site, the launch platform (LP) was raised approximately 4 feet as called for in the procedure. However, when the LP was raised, 2 wires in the remote control panel of the facility which had been inadvertently disconnected, caused the blast closures to activate. The crew commander feeling the safest position for the missile would be in the down position, directed the LP be lowered. Since certain necessary pressurization lines had been disconnected before raising the bird, when the missile reached the down position, the tank pressure was lost, and a multi-million dollar missile collapsed (2).

   Investigation revealed numerous personnel errors and lack of emergency training had compounded themselves into this major mishap. For example, a simple interlock switch installed to prevent lowering of LP until pressure lines were replaced would have made this TCTO a more fail-safe operation and prevented human-initiated failure from occurring.

2. During a silo missile accident, approximately 18,000 gallons of diesel fuel were gravity fed into the silo and became the main source of fuel for a follow-on 18-hour fire. There was no way to shut off the main feed line, since no one had provided an emergency cut-off valve for this auxiliary system (3).

3. Technicans attempting to remove pyrophoric igniter cartridges from missile engine systems were forced to take off their gloves in order to remove cover plate from the igniter receptacle. Protection of the hands against accidental leakage of the pyrophoric mixture was absent during the most hazardous part of the operation. Investigation revealed the protective clothing equipment listing for this operation in the technical manual was made without any attempt to first verify usability or compatibility with the operational requirements (4).

During an extensive 2-year study on the operational Atlas Missile, Rocketdyne Human Factors specialists were able to identify and categorize 303 problem areas involving some 1500 incidents which could have adversely affected the Rocketdyne engine system with respect to safety, system effectiveness, and operational capability (5). Approximately 1 out of every 5 of these problems directly involved safety, i.e., created a potential personnel or equipment hazard. The detailed descriptions of each of the 60 safety problems provided in that study clearly illustrated the need for a systematic approach for creating a before-the-fact, safety-in-design type program to complement existing systems engineering and support activities.

Confronted with data of these disturbing experiences, the Safety Engineering staff at the Air Force's Ballistic Missile Division (BSD) Headquarters developed and obtained command approval and support for BSD Exhibit 62-41, the forerunner of MIL-S-38130. The system safety engineering requirements contained in BSD Exhibit 62-41 have been incorporated into the Minuteman and Mobile Medium Range Ballistic Missile (MMRBM) weapon system program contracts. When the Air Force Space Systems Division (SSD) separated from BSD, the system safety engineering concept went with it as manifested in SSD Exhibit 62-161, dated 1 November 1963. This placed similar system safety requirements on all major contractors in the Titan III Program.

Before reviewing the manner by which compliance with these system safety documents is being provided, it would appear desirable to discuss in general terms some of the underlying concepts and principles which make system safety engineering distinct from previously existing functions.

Although each aerospace contractor has its own unique organizational structure, nearly all have functional activities which have certain overlapping responsibilities in the area of safety. These include Reliability, Maintainability, Human Factors, and Industrial Safety. Of course, nearly every activity within a company can be logically connected in some manner with safety, but the above-mentioned 4 appear to be the most directly related.

Reliability, as an engineering discipline, has in many ways been the forerunner and guiding light for official system safety engineering documentation that currently exists. This may easily lead to a misconception that since the documentation and approach is so similar, system safety is basically synonymous with reliability, and that sufficient achievement in meeting reliability goals will automatically ensure adequate safety of the product.

The affirmative argument to this correlation between product safety and reliability has been advanced by contractor management genuinely concerned about unjustifiable costs and poor management practices associated with establishing a separate activity to provide an apparently redundant function. A counter to this argument is being advanced mostly by persons having safety responsibility within user organizations. An example of this is found in the following quotations from remarks made by Admiral Edward C. Outlaw, Commander of the Naval Aviation Safety Center at the International Air Safety Seminar held in Athens, Greece, in November 1963.

"...there are two facets of reliability that need further emphasis in order to improve our safety programs. The first of these can be called the "non-failure" mode. This alludes to the part, or system which has had no unpredicted failures, but yet is a potential accident causative factor. This mode involves human factors, under-design, and faults of omission. Increased efforts must be made to reduce the human factors problems before the system gets to the operational stage. Here is where we find a sharp division between reliability and safety...

"A cotter pin, properly installed, is a very reliable mechanism. But, a fail-safe fastener that is designed with full knowledge of the frailties of human competance is more than reliable, it is safe...

"The second facet of reliability needing increased emphasis is even more insidious. Let us call this the "failure mode." Here is a situation where malfunction is anticipated and perhaps even accurately predicted, but since the failure will occur only once every million cycles, the system is considered reliable from a statistical standpoint...

"The point is this: if this statistically reliable system has its "once-in-a-million" failure, and this single malfunction results in a catastrophe, the system is irrevocably unsatisfactory...

"There are many reasons why we do not now get coordinated safety engineering into design. Contractors can list a host of reasons, among them being: lack of adequate specifications, procurement policies, sub-contracted equipment, and the like.

"There is a tendency to believe that present efforts to write firm reliability and inspection requirements will solve many of these problems. (I want to add my support to these efforts, because reliability requirements are paying dividends already, notably in the avionics field.) But more severe reliability requirements alone will not serve to ensure design safety. The difficult problem, of how much reliability is enough for safety in critical systems, is the province of system-safety engineering... Not only will system safety engineering pay its own way, but it may well serve as a lever to get reliability engineering up on both feet."

It should not be concluded from these arguments that there is no common ground between reliability and system safety. To the contrary, in aerospace firms such as Rocketdyne, where Reliability Engineering has both a positive influence in system design and development and a comprehensive program encompassing many related engineering disciplines of product effectiveness. System-safety engineering can, and should, function in close coordination with the reliability activities.

The prime purpose in presenting these comments is to illustrate the potential pitfalls that can occur when management instinctively attempts to interchange the term "reliability" with the term "safety." Experience has shown that once project management is exposed to effective real life, day-to-day system safety engineering activity, the question of overlap and redundant function with reliability soon passes, and a mutually beneficial working arrangement develops. The reliability engineer begins to broaden the scope of his thinking, and the system safety engineer can utilize reliability techniques and data for many of his analysis and design surveillance activities.

Various forms of SSE analysis reports have been prepared. Some of these are primarily for the purpose of discussing safety considerations involved in various operations during ground handling phase of a missile system. No attempt to systematically quantify potential hazardous situations is provided, but the emphasis is on bringing out problem areas which must have attention during both development and deployment phases of the product. Other types of SSE analysis efforts have been directed more toward quantification of the safety status of the design. For example, to determine if necessary assurance against inadvertent launch of the Minuteman missile has been achieved in design, a technique referred to as "fault-tree analysis" has been developed and incorporated into system safety contractual requirements by BSD (6).

Briefly, fault-tree analysis is performed by first selecting an undesirable, unsafe event, such as inadvertent ignition of a rocket motor. Based upon the conceptual design, all events or combinations of events which could cause this mishap are diagrammed to illustrate logical "AND" relations, and logical "OR" relationships. These can then be reduced into Boolean Algebra form for computer analysis. Each event is further analyzed to determine what "sub-event" or combination of "sub-events" is prerequisite. A value is assigned to the probability of occurrence of each event, sub-event, sub-sub-event, etc., and the probability of the occurrence of the fault is computed from this. By this technique, sensitive elements, which should be investigated for potential improvement susceptibility are timely identified.

The similarity between this form of safety analysis and the usual failure-effect analysis performed by most reliability groups is fairly obvious or so it might appear. Both utilize the same probability of failure numbers, which are obtained from reliability analysis of previous hardware component experience. Both analyze causal effects of normal and abnormal component operating modes. Both attempt to forecast problem areas rather than only collect after-the-fact failure data. Where then, are the differences?

In the first place, system-safety engineering is primarily concerned with a certain type of mishap, one which can cause inadvertent destruction or injury. Its concerns are not limited by arbitrary boundaries of jurisdiction, and include all possible, "...hazardous interactions of facilities, equipment, procedures, and personnel, either singly or in combination." (7). For this reason, a system safety analysis usually begins by identifying undesirable events and proceeds to investigate potential causes; the reverse direction of that usually taken in reliability analysis methods.

Secondly, since system safety is primarily concerned with the "effects" of failures rather than the detailed statistical evaluation of their probability (the acknowledged province of reliability analysis), greater emphasis is being placed on criticality indexing of potential failure modes than is normally found in reliability analysis. The proper weighing of the over-all hazardous consequences of a given failure event requires an understanding of the total operational environment which is beyond the scope of the average reliability analyst. The follow-up effort required to ensure that all necessary safety considerations have been included in interface areas between subsystems, facilities, and procedures is also a basically system safety concern.

It is in that grey area which lies between assuring inherent component and sub-system hardware reliability and effective over-all system operation that system safety engineering appears to have its major contribution. It cannot be effective in this essential roll if its efforts are restricted to only the component and sub-system level of design and development. It must have access to the total picture to ensure a logical and consistent continuum of safety throughout the entire life span of a missile or space systems. System safety engineering must properly utilize the data and techniques of reliability analysis, while avoiding the limiting restrictions reliability activities sometimes must place on themselves because of statistical considerations.

A prime example of this is human-initiated error or human reliability. It has been well documented (5, 8, 9) both by objective and subjective experience that the performance of personnel is an essential component of, and input to, over-all system reliability. As indicated earlier, human error is one of the major causes of missile accidents. While "goof-proofing" is recognized as a desirable design requirement, a great deal more usable information is needed on this extremely complex subject of human error if significant achievements in missile-space safety is to be realized.

Human error analysis and reduction usually falls into the province of human factors engineering in most aerospace firms and customer documents. A close working relationship between human factors and system safety personnel assigned to a given missile project can become mutually beneficial. Not only will overlap of effort be avoided, but both can gain a better understanding of the total interrelationships existing between man, machine, and hazards.

However, to say that the human factors specialist is already performing adequate system safety engineering in the normal couse of his effort, is again too closely narrowing the scope of the term "safety." It must be remembered that safety is only one of a large number of objectives to be considered by the human factors engineer to improve operational effectiveness of missile systems. It is usually impossible to allocate enough time and effort to deal with more than the obvious potentially hazardous problems in the man/machine interface area. Thus, while system safety and human factors may find common problems in some areas, both activities have far wider interests and responsibilities which lay outside rather than inside this overlap area.

System Safety has many areas where the benefit of its specialized technical experience can be used with Maintainability (M) activities. These include:

1. Assist M engineers in identifying potential hazards involved in performing required maintenance tasks
2. Evaluating the relative significance of these hazards to pinpoint areas where hazard reduction effort is needed at the earliest possible time during conceptual design phase
3. Provide follow-up surveillance to ensure necessary safety equipment, protective clothing, procedures and training is being provided in a systematic manner
4. Analyze malfunction modes which could be caused by personnel error or unpredicable accidents which could cause missile hazards during its pre-flight life span to ensure that the M concept and plan is adequate in these areas

Industrial health and safety activities are specifically excluded in Air Force documents on system safety engineering contractual requirements. In many missile-space contractor organizations, industrial safety is located in the industrial relations of the personnel department (10). Although the specific organizational relationships may vary from company to company, in nearly all cases industrial safety is an overhead function whose primary purpose is to administer the inplant employee-injury-prevention program.

Responsibility for the inherent safety designed into a delivered product has usually not been considered a function of industrial safety. Even though the prime purposes and responsibilities of industrial safety and system safety are fairly distinct and clear cut, there often develops in actual practice areas of mutual concerns, such as during the development testing of missile propulsion systems.

Being primarily project oriented, the system safety engineer has the opportunity to review and influence development test plans during their formative period. Through functional flow diagrams and other techniques, the system safety engineer can often identify potentially hazardous situations long before they become real-life problems. When these hazardous situations are such that employee injury potential is involved, industrial safety can be made aware of the situation and coordinated effort can be taken to reduce the hazard through both design and operational planning. Through mutual cooperation, industrial safety and system safety can complement each other's activities in an effective manner to reduce accidents and promote safety which could never be achieved independently.

An extensive and penetrating discussion of the possible relationships between system safety, reliability, human factors, and industrial safety is given in Rocketdyne Report R-5135, entitled "Missile System Safety, an Evaluation of System Test Data," dated 1 March 1963 (5). Incidentally, this report, as well as 14 other technical reports on subjects of missile system safety, is indexed and available to all participating contractors and agencies in the Interservice Data Exchange Program, more commonly referred to as IDEP. Although primarily oriented toward reliability test reports on "off-the-shelf" hardware, IDEP is expanding into broader general technical data of a nonproprietary nature. During the past year, at the request of Rocketdyne and with concurrence of sponsoring agencies, category 347.97, entitled "Safety Engineering," has been established in the IDEP code numbering system.

To establish this means for better exchange of safety information among the various missile contractors and government agencies, Rocketdyne has submitted 12 reports on safety to IDEP. To date, 3 additional reports have been contributed by other firms. Many advantages could be realized through the use of IDEP for exchange of up-to-date safety engineering data, if all participants cooperate in the matter of submitting their reports pertinent to safety engineering to the IDEP program.

To illustrate how a relatively low level of expediture of effort specifically oriented to safety can prove to be highly beneficial when incorporated into a program at the appropriate engineering level, some examples are taken from a current missile program under development at Rocketdyne. This program involves the design and development of a ground-to-ground tactical missile of a highly mobile type. To meet the customers requirements, a prepackage, storable liquid propellant system was proposed and accepted.

A significant departure from most previous storable liquid propellant missiles was involved since extended direct personnel handling of this missile, loaded with hypergolic propellants, would be involved under all types of environmental conditions. Potential hazard to personnel involved in storage, transportation, maintenance and operation of this missile exist from accidental liquid propellant leakage, both external and internal.

To help minimize this and other potential hazard of both the development and tactical phases of this program, an experienced system safety engineer was assigned to work in a part-time staff capacity jointly to both the Chief Project Engineer and responsible Reliability Engineer.

Although this program is still in the early R&D phase, the following positive safety features have already resulted from this effort, budgeted at a slightly more than 0.5 man-months per month rate:

1. A comprehensive system safety analysis was prepared and published which clearly identifies all potential hazardous situations which might be encountered during the use phase. This report also provides the basic technical information needed for developing specific safety procedures and operating manuals to reduce these hazards. Safety considerations involved in various emergency and malfunction modes were discussed.

   The release of this 50-page report before completion of even prototype design, enabled effective comments and recommendations during formal design review audits on the matter of safety. However, due to the close working relationship between the system safety engineer and the design group, most critical safety deficiencies in design were resolved prior to formal review.

2. Specific problem areas in design that have been corrected through the help of the system safety engineer have included:

   a. Provisions for emergency field detanking of propellants

   b. Provisions for continuous monitoring of critical internal leaks of propellants

   c. Provisions for decreasing the probability of communication of hypergolic propellants and vapors which could cause catastrophic failure during both ground and flight phases

   d. Provisions for increasing the integrity of the system when subjected to unexpected environmental stress and shocks

3. In support early-development testing activities, a safety-verification test program has been developed which will demonstrate the capability of the prototype system to safely perform all required tests without undue hazard to test personnel or equipment. The safety testing will be accomplished utilizing inert propellants, prior to operations involving hazardous materials, wherever remote operations cannot be performed. This program has been expended to include safety consideration during initial flight testing as well.

4. Safety problems involved with shipment of fully loaded propulsion systems from the manufacturing plant to the flight range have also been investigated, and a detailed plan of action has been developed in conjunction with customer safety representatives.

5. Positive support to logistics activities preparing operational manuals and training classes has been accomplished. Although this particular program is too early in its development cycle to adequately evaluate the effectiveness of these system safety

activities, it is reasonable to state that the probability of a serious accident occurring because of engineering oversight or poor judgement has been significantly reduced. It must be remembered that the prevention of only one serious accident would save the program many times the cost being expended on the system safety effort. It is further conceivable that a few catastrophic accidents during the initial flight testing phase of this program would result in potential delays in the schedule. This factor re-emphasizes the critical importance of the system safety role in missile and space programs, where accidents and unsafe conditions must be prevented, not corrected from criteria based on accident investigation reports.

To obtain some objective data about the current scope of system safety engineering activity in other areas of the missile-space industry this writer submitted an informal questionnaire to a select group of system safety engineers contractually involved with Air Force Safety Exhibit requirements. Although response to this inquiry was less than originally hoped, some pertinent (though admittedly incomplete) information can be summarized.

As stipulated in BSD Exhibit 62-41 and SSD Exhibit 62-161, the prime or integration contractor for each system program is responsible for implementing and administering the Integrated System Safety Engineering Plan (ISSEP) which is to be "...a coordinated and comprehensive safety plan containing procedures to ensure identification, evaluation, and resolution of missile-weapon system safety problems. It will define tasks, responsibilities, procedures, and milestones for the appropriate contractor..." (7). Each associate contractor is to provide independent SSE plans for developing the ISSEP. These exhibits also stipulate that periodic system safety review conferences will be held to explore and obtain resolution of interface safety problems. A notable benefit of this comprehensive safety review provided for in the ISSEP has been the development of better training and operational procedures on safety.

With this brief background, a general review of the status of system safety effort in the 3 programs previously mentioned is as follows:

MINUTEMAN--A comprehensive SSE effort has been underway for approximately 3 years with over-all administration provided by the weapon system safety manager of the integrating assembly and checkout contractor (IACC). Numerous documents have been prepared and released for this effort, including a safety analysis of each major item or subassembly of the Minuteman weapon system. This analysis has been prepared in the following seven volumes: I-Special Analyses, II-Engines (Motors), III-Missile-Borne Equipment, IV-Re-Entry Vehicle, V-Operational Ground Equipment, VI-Maintenance Ground Equipment, Including Transportation and Handling Equipment, and VII-Facilities and Remote Bases (11).

In addition to the IACC, 6 associate contractors, which provide the 3 propulsion stages, guidance and control, re-entry vehicle, and GSE, have prepared and are implementing their specific SSEP's. The System Program Office (SPO) at BSD has an officer assigned specifically to monitor and direct the Minuteman system safety effort.

MMRBM--The SSE activities in the MMRBM program were patterned after those established in Minuteman. Prime effort at this time is being directed at formalizing and implementing the ISSEP. In addition to the IACC, there are 5 associate contractors providing propulsion, ground transport equipment, re-entry vehicle, command and control, and guidance and control.

TITAN III--This program, administered by AFSSD, has a system safety engineering requirement (SSD Exhibit 62-161) included in contracts similar to those stipulated in BSD Exhibit 62-41. The first difficulty in the SSE activity was delay in establishing the ISSEP because of contractual negotiations between the SPO and the IACC. This problem is being resolved, and Titan III Interface Safety Conferences are being scheduled. In addition to the IACC, the liquid propulsion, solid propulsion, and control guidance associate contractors have established system safety functions to comply with their individually-submitted and SPO-approved SSEP's.

From the findings of the questionnairs submitted, a few generalities about form and organization of SSE activity in the various aerospace firms can be drawn. Of course, this varies from company to company because of differences in organizational structure, product line, and contractual requirements.

Of 8 companies from which information was obtained, 3 had associated SSE with the industrial safety and security organization, 3 had placed it within program engineering and 2 within reliability organization. Each firm could support the reasons and list the advantages of their particular arrangement. Propulsion system contractors generally find a greater relationship between industrial safety and system safety. This is because the testing and ground-life phase of a propulsion system often has many handling and maintenance hazards not found in other subsystems, particularly in the tactical missiles.

Concerning the number of engineers who are specifically identified with strictly SSE activity, the range ran from 1 to 4 per program having SSE contractual commitments by the associate contractors, and 10 to 30 for the integrating contractors. The primary function of these individuals is coordination and monitoring, since the majority of actual effort is performed by direct-line engineering personnel and specialists in various support areas.

Among the significant accomplishments of SSE as reported by contributors to this survey were:

> "Financial savings realized through reduction of catastrophic incidents when compared to previous weapon system programs"
>
> "Increased acceptance of safety engineering principles by other functional organizations"
>
> "Change in mental attitude of design engineers toward need for original design safety and thorough safety review of all designed assemblies and/or components"
>
> "Up-grading total engineering effort through top management acceptance and support of system safety practices"

In summary, a positive, before-the-fact, systematic engineering approach to safety in the missile-space program field is being advanced by the Air Force through various contractual requirements. Generally, industry has found implementation of these requirements advantageous as a result of improvement in overall product effectiveness. Although structured differently within the various contractor organizations, SSE is basically a coordinating and implementing activity, relying primarily on technical support from other groups for the majority of its actual detailed work. Full support of top management is an essential ingredient of this approach and a factor which cannot be over-emphasized.

There are indications that the other military services are considering adopting system safety specifications similar to that of the Air Force. The attitude and plans of NASA for incorporating the system safety engineering concept into these programs were not defined in any references available to this writer. This is somewhat surprising, since it would appear that current and future NASA programs provide unequaled opportunity for realization of benefits from the application of system safety engineering concepts and techniques.

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