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A MODEL FOR THE MANAGEMENT OF
TECHNICAL RISK IN NEW
TECHNOLOGY DEVELOPMENT
PROGRAMS

THESIS

Peter B. King
Captain, USAF

AFIT/GSM/LSR/89S-22

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IN NEW TECHNOLOGY DEVELOPMENT PROGRAMS

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Presented to the Faculty of the School of Systems and Logistics
of the Air Force Institute of Technology

Air University

In Partial Fulfillment of the
Requirements for the Degree of
Master of Science in Systems Management

Peter B. King, B.S.

Captain, USAF

September 1989

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Acknowledgements

I would like to express my appreciation to my faculty advisor, Capt Carl Davis, for his excellent guidance and candid comments to improve the thesis as each successive version emerged. I also want to thank Maj Larry Emmelhainz for getting me on the right track with the proposed topic of risk management so many months ago when the topic seemed overwhelming.

I also thank the small platoon of people who helped bring the actual document to fruition: the phenomenal contributions of Mrs. Jeryl Cartwright, the great transcribing of Mrs. Lisa Roe, and skillful graphics help from Ms. Kim Ware.

Finally, it is definitely true that without the constant and motivated help of my wife, Kimberly, that this thesis would not have been possible. To her I give my greatest thanks and appreciation.

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Abstract

Inadequately managed technical risks have resulted in setbacks, failures and operational disasters in Department of Defense programs. Therefore, the purpose of this ~~research~~ ^{study} was to synthesize a model that epitomizes a strategy for the management of technical risk. The model was synthesized using the three-pronged effort of: (1) a literature search and review to determine what previous work was done in risk assessment and risk management, (2) case studies of historical, contemporary and prospective new technology development programs, and (3) interviews predominately with Chief Scientists at the Wright Research and Development Center (WRDC) at Wright-Patterson Air Force Base. The model validation was via reviews of the model that were made by the stated interviewees. If the model is used as a technical management guide and decision aid by individual program or project managers at all levels, collective marked improvement in the technical risk management throughout the Department of Defense may be achieved. (L.F.)

A MODEL FOR THE MANAGEMENT OF TECHNICAL RISK IN NEW TECHNOLOGY DEVELOPMENT PROGRAMS

I. Introduction

Overview

Presently, a large number of military and civilian development programs involve new technology. However, the newer the technology that is being introduced into a development project, the greater the risks that may be involved with successfully managing the development program. Future military weapons systems may be even more complex. According to General William Thurman, Commandant of the Defense Military Systems Management College, "These [future weapon] systems will create management problems that far surpass our contemporary management theory and practice" (143:12). This chapter introduces the concept of technical risk and its implications in the development of new technology. The specific problem for this research effort, relevant assumptions, and pertinent definitions are also presented.

Background

At any moment, national defense concerns, or suspected technological breakthroughs by potential adversaries, can mandate that development programs involving new

technologies be undertaken by the United States. For instance, the Manhattan Project was undertaken by the United States during World War II to build an atomic bomb. Albert Einstein's 1939 letter to President Franklin D. Roosevelt (Appendix A) expressed concern over potential German strides toward the first atomic weapon (41:397). Similarly, after the 4 October 1957 launch of the Sputnik I satellite into Earth orbit by the Soviet Union, the United States reacted on 31 January 1958, by launching Explorer I (11:32; 42:91; 145:164). Since new technology is by definition largely unprecedented, new technology programs would incur much more technical risk than even state-of-the-art technology programs. At present, a host of relatively immature, but promising, new technologies and technological opportunities such as, X-ray laser technologies, and optical and neural computers are evident. This suggests that technological breakthroughs by any potential adversary may plunge the United States into a host of new technology weapon system development programs involving unprecedented technical risks (2:88; 21:76). For example, recent Soviet test flights of an experimental aircraft that uses hydrogen fuel, could eventually dictate that the United States undertake an urgent development project in that area. Also, if the Soviets are able to build and deploy an X-ray laser, then "the survivability of American space assets could be questioned" (69:1). Similarly, any advances in neural computers by the Soviets

could theoretically provide them with crucial image and pattern (i.e., target) recognition breakthroughs. Further, with the recent development of the optical equivalent to the transistor, an optical computer is becoming increasingly feasible. Because an optical computer would use beams of light instead of the electron currents that are used at present, an optical computer may be capable of "a trillion operations a second" (1:85) and of parallel processing. The military implications of a successful union of neural and optical computer technologies would be staggering (1:85,93; 2:88,94; 105:52,55; 123:40).

However, urgent new technology development projects could arise from national involvement in, or observation of combat or terrorist incidents anywhere on the globe. For example, the development of more advanced Remotely Piloted Vehicles (RPV) for surveillance and penetration, may eventually be mandated by the effectiveness with which the United States and Israel employed RPVs in the Vietnam War and the 1973 Yom Kippur War, respectively (53:2-18,22,23; 115:89). Also, the rate at which the "Egyptians and Israelis shot down their own aircraft in the 1973 Middle East War" (50:2) and the rate at which the Israelis shot down their own helicopters during the 1982 conflict with Syria, indicated that the technology to identify friend from foe (IFF) is a critical combat requirement. Those observations have prompted the United States to replace the ailing 1950's technology IFF systems with IFF systems that

will be appropriate to the potential 1990's combat environment (50:1-4).

It is clear then that technology breakthroughs by potential United States adversaries in a number of emerging technologies, or international incidents that threaten national security, could necessitate urgent new-technology weapon development programs involving enormous technical risk. Many of these technologies, particularly "directed energy weapons . . . may revolutionize military strategy, tactics and doctrine" (58:120). It is therefore essential that an effective strategy for systematically reducing the technical risk inherent to new technology development projects be available. However significant technical risk is also incurred in performing major modifications to systems. A United States Air Force study concluded that "many modifications are generally as difficult as the original design" (111:116).

Justification

Department of Defense Directive 5000.1, regarding major and non-major weapons acquisition programs, acknowledges that program decisions must be made commensurate with technological risk (31:para 3, para 9a, para 9b), yet it provides no explicit process for systematically minimizing that technical risk. Even Military Standard 499A, Engineering Management, although stressing that technical risks must be assessed and

minimized, provides no explicit strategy for achieving technical risk reduction.

Although a number of studies regarding technical risks in military programs have been done (10; 132; 144), many examine technical risk mainly as a contributor to budget overruns. While a recent defense document (36) provides excellent templates for the management of technical risk in transitioning from development to production, this is only a fraction of the regime wherein technical risk is evident. Still fewer of these documents examine technical risk from a historical perspective for lessons learned in minimizing technical risk when the technology in question is relatively unprecedented.

What appears to be needed is an all-encompassing, high level technical risk strategy that includes the extreme case where the development project involves totally new technology. By addressing this extreme case, the strategy should bound the less extreme cases of development programs that are extensions of more established technologies.

While a number of military documents (25; 27; 39) provide technical checklists for technical risk reduction, they do not outline an explicit management process--a task sequence and priority--to achieve such risk reduction. As a result, the manager is usually left on his or her own when it comes to implementing a technical management strategy and integrating existing technical checklists into that strategy. With no explicit technical management

strategy, each technical manager must "re-invent the wheel" when it comes to technical risk management.

According to Koontz, strategies are so important to success that

. . . the development and communication strategies are among the most important activities of top managers .
. . [the study has shown that most business failures are due] to lack of strategy, or the wrong strategy .
. . without an appropriate strategy, appropriately implemented, failure is a matter of time. (98:281)

Accordingly, a top level management strategy for technical risk reduction, particularly for projects involving unprecedented technology, could be of immense value to Department of Defense weapons acquisition.

Statement of the Problem

At present, it is not well known how to assess and manage the technical risks associated with weapon systems development programs which involve state-of-the-art technology. The technical risks are even greater when the development involves technology that is unprecedented. The question for this research was: How can the technical risks of development projects involving state-of-the-art or unprecedented technologies be minimized? Once this was answered, the researcher developed a strategy for the effective reduction of the technical risk associated with new-technology development projects. A model was synthesized to be used as an effective management strategy

and decision-asking aid for minimizing technical risk in development programs that involve new technology.

Investigative Questions

The research focused on the following investigative questions to answer the stated research question.

1. How is technical risk defined?
2. How is technical risk identified?
3. What are the important factors for the assessment of technical risk?
4. What are the major pitfalls to avoid in assessing or managing technical risk?
5. What criteria are used to determine whether new technology is sufficiently established for incorporation into a development project?
6. How does the Air Force Wright Research and Development Center Laboratories (WRDC) minimize the technical risks associated with new technology?

Scope

The risks in a Department of Defense development program are usually divided into cost, schedule and performance (i.e., technical) risks. This thesis will be concerned only with assessing and minimizing the technical risks connected with the development or incorporation of laboratory-demonstrated technology. Consequently, this thesis will not address the technical risks of achieving basic research objectives. Also, this thesis will not

examine the impact of unstable funding or wavering national or political commitment to an ongoing technical development effort.

Limitations

In keeping with the stated scope and assumptions of this research, a number of factors that have some impact on technical risk have not been addressed. Consequently, the model did not specifically include these factors.

Nevertheless, such factors are important. Two such factors are national commitment and priority. Selected specific examples illustrate the importance of these factors. In September 1955 President Eisenhower assigned "the highest national priority" (42:79) to the research and development of the Intercontinental Ballistic Missile (ICBM).

Similarly, on 25 May 1961, President John F. Kennedy, in announcing the goal of a man on the moon, stated that the decision requires "a national commitment of scientific and technical manpower, materials and facilities" (139:29).

Clearly, the national priority and commitment to a particular technical endeavor will often be a determinant of the resources that are dedicated to. This will in turn hamper or help the risk management effort. Similarly, this research, while acknowledging the eventual effect of schedule and funding limitations on the technical risk of a system under development, did not explore such effects.

The interviews that were done as part of the effort to synthesize the technical risk management model were predominately with Chief Scientists of WRDC Laboratories. Although Mr. Cannon of the ASD Office of Development Planning was interviewed, no other cognizant personnel associated with a Systems Programs Office were interviewed. Therefore the interviews reflect technical risk from a largely laboratory point of view.

Assumptions

A major assumption of this thesis is that the cost and schedule risk of a development project or program are ". . . primarily attributable to the occurrence of unforeseen problems that are usually technical in nature" (99:223). A 1982 Defense Science Board Task Force determined that the "causes of acquisition risk are technical, not managerial" (39:Sec 1,3) since an industrial process, composed of engineering and manufacturing, is involved.

Therefore, a fundamental assumption of this thesis is that if the technical risk in the program is minimized, then the related cost and schedule risk of the program will be likewise minimized. Another assumption is that new technology being introduced into a development program has been proven feasible via laboratory experiments, although techniques for adapting or tailoring the technology to a specific application may not have been investigated in depth. This assumption is important because this thesis

primarily examines the technical risk of the development of new technology and not the risks of attaining basic research objectives.

Further, it is assumed that the user's requirements for the system under development have been clearly and completely communicated to the agency charged with developing the equipment or weapon system in question. Last, but not least, it is assumed that new technology approaches cannot be avoided due to certain specified high performance requirements, or based on defense intelligence threat information.

Acronyms

The acronyms listed below apply to this thesis. Other acronyms are identified in the text as they occur.

ASD	(Air Force) Aeronautical Systems Division at Wright-Patterson Air Force Base, Ohio
DARPA	Defense Advanced Research Projects Agency
DOD	Department of Defense
DOE	Department of Energy
GAO	General Accounting Office
NACA	National Advisory Committee for Aeronautics (predecessor of NASA)
MIT	Massachusetts Institute of Technology
NASA	National Aeronautics and Space Agency
NATO	North Atlantic Treaty Organization
NORAD	North American Air Defense Command
SDI	Strategic Defense Initiative

SPO	System Program Office
SDIO	Strategic Defense Initiative Organization
WRDC	Air Force Wright Research and Development Center (previously Air Force Wright Aeronautical Laboratories)

Definitions

For the purpose of this thesis, the following definitions apply:

1. Modularity--the design practice of grouping hardware or software elements that perform the same particular function into "a self-contained unit" (29:44).
2. Monte Carlo Method--"Any procedure that involves statistical sampling techniques in obtaining a probabilistic approximation to a mathematical or physical problem" (7:69).
3. New Technology--Any significant technical advance, possibly stemming from a scientific breakthrough, that deviates significantly from the established approaches in the field or which represents a marked improvement over the current technical approach or application.
4. Performance Risk--Synonymous with technical risk.
5. Risk--"The probability and consequence of not achieving some defined program goal (such as cost, schedule, or performance)" (24:II-3).
6. Risk Assessment--"The process of examining a situation and identifying the areas of potential risk" (30:Sec 15).

7. Risk Analysis--A detailed, systematic examination of the source of risks, to determine the probability and consequences of adverse events, in order to evaluate or develop alternatives (30:Sec XV,1).

8. State-of-the-Art--Technology that represents the highest current knowledge in a particular technical endeavor. For all practical purposes, this term is synonymous with the term "new technology".

9. Technical Risk--The probability and effect of not attaining a technical (i.e., performance) objective. The term includes the risk of fatal accident or injury to personnel as a result of system malfunction or failure.

10. Technological Risk--Synonymous with technical risk.

11. Work Breakdown Structure--A project development planning, control, and monitoring tool that breaks down a system into its component subsystems, functions (e.g., software, hardware) and indicates the interrelationship among these components (118:23).

Summary

In many cases high technical development risk stems from the newness of the technology or from the particular implementation despite the fact that the feasibility of applying underlying scientific principles may have been successfully demonstrated by laboratory experiments. Chapter I, introduced the concept of technical risk,

defined the problem, and specified the objectives of the research. Chapter II provides the methodology whereby a model for technical risk reduction was synthesized. Chapter III contains the literature search and review regarding risk in general, with the emphasis on technical risk. Chapter III also contains pertinent case studies to this research. Chapter IV provides the analysis considerations for synthesis of the model and then presents the model. Chapter V is the research conclusion with recommendations for further research.

II. Methodology

Introduction

The purpose of this thesis is to synthesize a model for managing technical risks associated with new technology development programs. To develop such a model, a three-pronged research effort was undertaken consisting of: (1) a literature search and review to determine what previous research was done; (2) case studies of selected new technology development projects in order to glean lessons-learned; and (3) model reviews and interviews with Air Force Wright Research Development Center (WRDC) scientists to refine and validate the model. Figure 1 summarizes the three-pronged approach that was taken. The inputs of the scientists to the model synthesis were critical since the laboratories are "the state-of the art experts in many areas" (25:6, Sec 2) and because the model is primarily concerned with the development of state-of-the-art technology. Figure 2 indicates pertinent specific case studies that were selected.

Based on the results of the literature review and the examination of selected case histories, a model was developed of the sequence of steps that should be followed in order to systematically reduce the technical risks involved with the use of new technology in development projects. The primary model objective was to provide a

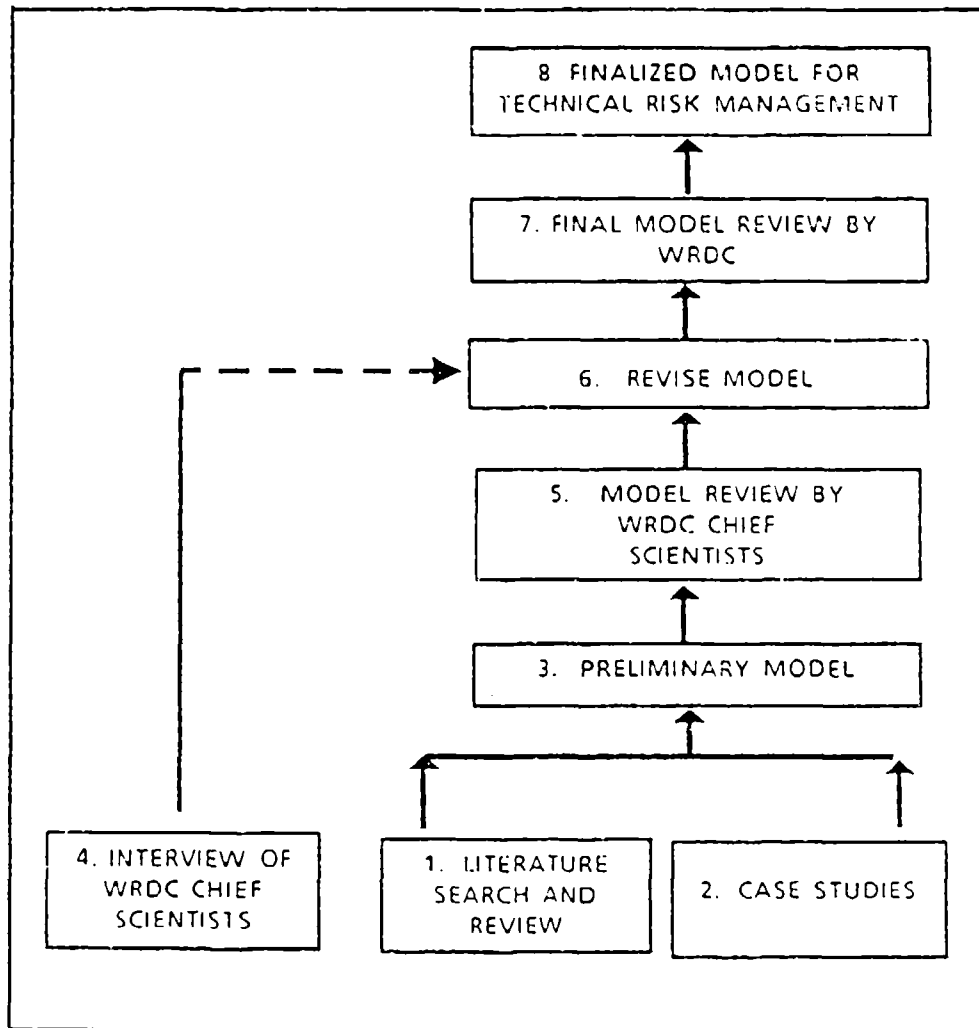


Figure 1. Synthesis of Technical Risk Management Model

useful strategy and process for reducing technical risk. That is, the emphasis in the model was on the macro-level of technical management strategy rather than on the more micro-level of technical principles and concepts, at the electronic or mechanical component level.

Literature Search

As a first step in the research, a literature search was conducted via the Defense Technical Information Center (DTIC) to determine what previous work was done in the area of risk assessment and management. However, the search was supplemented by manual approaches as necessary. The literature review initially covered the established techniques for assessing risk in general. After the general risk management techniques were examined, the focus shifted specifically to the management of technical risk. The emphasis here was on those methods that are used to minimize the risks involved with the development of new technology systems.

Case Studies of New Technology Development Projects

This second part of the thesis research to synthesize a risk management model examined significant major historical new technology development projects. As Figure 2 illustrates, the cases were generally grouped under one of three categories: historical, contemporary and prospective. During the examination of each of these selected cases, the focus was on the technical risk

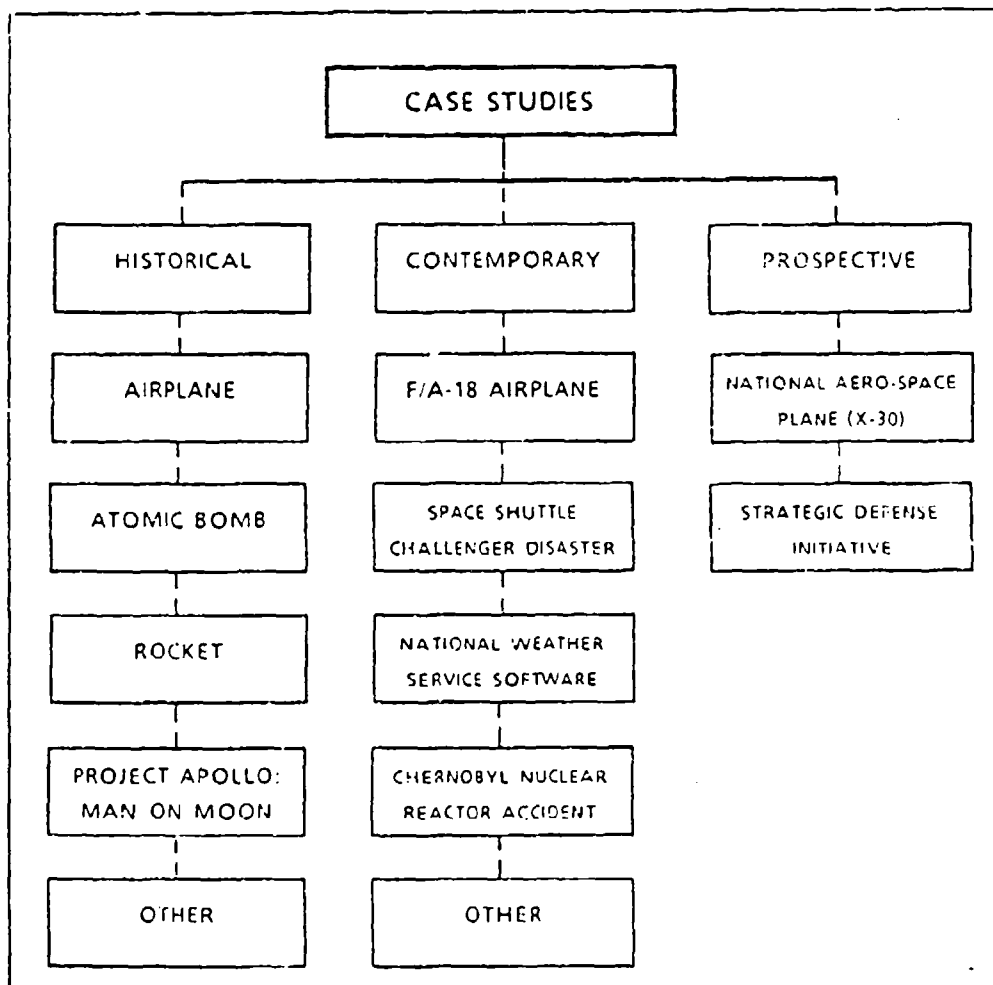


Figure 2. Some of the Selected Case Studies

reduction methods that were required in order to achieve the development program in question. The examination of the selected cases was important in order to highlight those unanticipated pitfalls--and the method of resolution --which can be encountered in new technology development projects. Ultimately, the case studies lead to the formulation of technical management guidelines which constituted a fundamental strategy for the management of technical risk. This resulted, in turn, in the synthesis of a model which epitomized that strategy.

Case Study Selection Criteria. The criteria for selecting the cases to be examined were as follows:

1. The output of the development project must have revolutionized military strategy or tactics or had significant international (i.e., technological) ramifications.
2. The technical principles (i.e., feasibility) of the development project in question must have been demonstrated prior to the start of the the development effort. However, the actual development of the technology must have involved significant technical risk.
3. Ongoing major defense development projects may be selected if sufficient information is available regarding some technical risks inherent to those projects.
4. The case need only meet one of the above criteria to be selected.

For example, the airplane, the atomic bomb and the Intercontinental Ballistic Missile (ICBM) are developments that meet at least one of the stated criteria. Therefore, these three cases were candidate cases to be examined.

In the examination of the selected cases, one emphasis was placed on determining which actions were taken by the technical staff in question to eliminate or minimize the anticipated technical risks during development. In addition, any unanticipated technical problems that surfaced during the analyses or development were given particular scrutiny to determine whether or not such problems are characteristic of new technology development projects, and to determine how such technical problems were overcome in the specific case.

Of particular concern was whether one or more categories of unanticipated technical risk were common to two or more of the selected case histories. Because the emphasis is on lessons-learned, the case history examinations that were conducted were of sufficient detail to elicit the genesis, effect and implications of a technical risk element in question from a management perspective. A detailed technical exposition of a case study was not attempted unless such a discourse was immediately relevant to the synthesis of the technical risk management model or clearly illustrated important technical risk reduction factors.

Technical Risk Management Model

Based on the literature review and the examination of selected case histories, an appropriate model was synthesized for the technical risk assessment and management of new technology development programs.

Groundrules for the Model. The following groundrules governed the model and guided the model synthesis:

1. The model shall be a general technical risk management model; it will be adaptable to development programs involving new technology, as well as to development programs involving older, more mature technology.
2. The model will primarily emphasize the strategy and process for minimizing technical risk rather than the detailed steps for technical activities (e.g., circuit design). However, reference to the documentation containing relevant detail will be provided.
3. The model will indicate applicable military documents, as appropriate, to preclude unnecessary duplication of information contained in such documents.
4. The model will indicate a preferred sequence of management tasks and possible paths to take based on the result of a previous task(s) in the sequence.
5. The model shall indicate and distinguish between mandatory and highly recommended technical risk management tasks.

6. The technical risk management model will indicate priority and precedence (e.g., prerequisites) of the management tasks as well as recommended simultaneous events.

Some examples of formats which were considered for use included: networks, hierarchical block diagrams, decision trees, and flowcharts. However, the model format was not limited to these since formats were selected, combined and supplemented to provide appropriate model detail, clarity and comprehensiveness (per these stated groundrules). The case histories were supplemented in the text with specific examples of technical risk situations, and management techniques elicited from topics other than the selected case histories.

Interviews of Wright Research and Development Center (WRDC) Scientists

The third part of the effort to synthesize a technical risk management model, consisted of structured interviews with the chief scientist at each of the five respective laboratory divisions of the Air Force Wright Research Development Center (WRDC) at Wright Patterson Air Force Base. The interviews were face-to-face and were conducted only after a preliminary model had been synthesized based on the literature review and case studies.

The primary WRDC candidates for the interview was the Chief Scientist in each of the major divisions of AFWAL. If the Chief Scientist was unavailable for the interviews,

then the highest ranking individual, civilian or military having at least a master's degree in a technical discipline (e.g., engineering, science, mathematics) was to be selected for the interview.

Interview Objectives. The primary objective of the interviews was to have the interviewee review and comment on the preliminary technical risk management model. All interviewees were given a minimum of six working days to review the model. A secondary objective of the interviews was to determine what techniques these scientists consider crucial for technical risk reduction in new-technology development projects, and to determine what techniques WRDC uses for managing technical risk. Comments and suggestions of the experts were incorporated into a revised model as necessary.

Interview Questions. For the structured part of the interview, a list of questions were developed which were asked of each chief scientist. The questions asked attempted to elicit the following information:

1. Technical and managerial experience of the person being interviewed.
2. Examples of technical risk arising from new technology.
3. The approach that is used by their laboratory and/or organization to identify technical risk.
4. The approach that is used by their laboratory and/or organization to manage technical risk. This

included a determination of the approach used, if any to monitor the level of risk reduction.

5. Any specific quantitative and qualitative approaches that are being used for technical risk management.

6. Key documents, references or regulations that he/she cites as key guidance for providing risk assessment and risk management procedures.

The unstructured part of the interview consisted of general question to allow the interviewee to comment on relevant technical risk management items that may not have been touched on during the structured interview. The specific questions that were asked on the interview are in Appendix B.

WRDC Review of Preliminary Model.

After the interview, the interviewees were asked to provide their comments on the preliminary technical risk management model. In particular, the interviewees were asked to comment on the adequacy, utility, limitations of the model and to recommend specific ways that the model could be improved. The interviewees were encouraged to indicate the recommended revisions by marking the model. The model revision was then reviewed a second time by the experts to validate the final product.

WRDC Review of Revised Model

The model was revised based on the scientists' review, comments and recommendations. To verify that the interviewees concurred with the revised model, a follow-up visit was conducted to provide the interviewees with one final chance to comment. In the event that the individual who provided a comment was unavailable for the follow-up visit a copy of the revised model was left for review.

In the event that any conflicting comments or recommendations pertaining to the model could not be resolved, the reason for the conflict was so noted and indicated on the model (e.g., by dashed lines).

Model Review and Interviews

An attempt was made to interview each of the Chief Scientists of the Wright Research Development Center Laboratories. Each interviewee also reviewed the preliminary model. The interviewees/model reviewers with their respective position titles indicated, are:

Dr. Keith Richey
x.59400

Technical Director of WRDC

Dr. Harris Burte
x.52738

Chief Scientist, WRDC
Materials Laboratory

Dr. Jim Olsen
x.57239

Chief Scientist, WRDC
Flight Dynamics Laboratory

Dr. Arnold Mayer
x.53311

Chief Assistant for
Research and Technology,
Vehicle Subsystems Division
of WRDC Flight Dynamics
Laboratory

Dr. Squire Brown
x.52377

Chief Scientist, WRDC
Technology Division

Mr. Jack Cannon
x.55877

Technical Director of
Development Planning,
ASD Office of Plans

Dr. Jess Riles
x.53627

Chief Scientist, WRDC
Avionics Laboratory

Mr. C.J. Cosenza
x,55393

Chief, Advanced Development
Division, WRDC Technology
Exploitation Directorate.

The WRDC Laboratory Chief Scientists shown, reviewed the model and provided an interview. For ease of reviewing (or transcribing) the interviews, a tape recorder was used during the interviews with the permission of each interviewee. Dr. Curran, Chief Scientist of the WRDC Aerospace Propulsion and Power Laboratory, was unavailable during the period of the interviews. Dr. Olsen and Dr. Mayer were interviewed jointly. Mr. Cannon and Mr. Cosenza, were interviewed and they also reviewed the model; they were both recommended by one or more chief scientist. The phone extensions shown are those on Wright-Patterson Air Force Base, Ohio.

III. Literature Review

Background

In 1981, US Air Force Brigadier General William Thurman, Commandant of the Defense Systems Military College, stated:

There is an impressive and growing list of failures in large-scale advanced technology programs. Many of these failures involve military programs, but there have also been numerous failures in non-military projects. We know less than we think we do about the management process by which new technology is converted into operating systems. (143:12)

Even though a new technology may have been demonstrated in a laboratory, the risks of failure in developing (i.e., applying) that technology may be high. This is because information on the use and the limitations of the new technology in a particular application, may be inadequate or unavailable. Such limited information imposes uncertainty, and the associated risk of failing the development project in question. Specific steps are required to systematically minimize the attendant technical development risks associated with new technology (80:148; 143:12).

The United States' Manhattan Project is perhaps the premier example of a new technology development program. The Manhattan Project was undertaken during World War II to design and build an atomic bomb based on the principle of

atomic fission that was successfully achieved in the laboratory. The development of an atom bomb involved considerable technical risk (80:180-181). A contemporary example of a major technical undertaking that relies heavily on the state-of-the-art technology, and that involves concomitant high technological risk is the United States' prospective Strategic Defense Initiative (SDI)-- colloquially referred to as the "Star Wars" program. In his SDI announcement on 23 March 1983, President Ronald Reagan challenged the defense technological community to develop the technology which could ". . . intercept and destroy strategic ballistic missiles before they reached our own soil or that of our allies" (97:8). According to Dr. Donald Ulrich, senior program director for the Air Force Office of Scientific Research, a significant amount of the technical risk reduction in the SDI program depends on the availability of advanced materials suitable for the formidable space environment (84:10; 97:8,9).

Another project which would involve considerable technical risk is the transatmospheric flight vehicle, announced in President Reagan's 1986 State of the Union Address. That aircraft, called the National Aero-Space Plane (NASP) may be able to travel from California to the Orient within two hours, have the capability to travel at "speeds (above Mach 6) in the atmosphere" (133:13), enter space, and then re-enter the atmosphere for a runway landing (140:67).

State-of-the-art technologies such as Very-High-Speed-Integrated-Circuits (VHSIC), being pursued by the Air Force and Navy, present significant technical risk--especially where semiconductor material processing and fabrication are concerned. Other high technology development efforts in the areas of high-power lasers and microwave weapon technology also involve high technical risk. Despite the high technical risks, these technologies--and others--are being pursued because they are crucial to a strong national defense (16:50-53; 33:1,2; 34:1,2; 35:1,2).

To underscore the importance of adequately identifying and managing technical risk, and to illustrate that technical risk may also be inherent to established technologies, one can cite two recent false alarms at the North American Air Defense Command (NORAD).

On June 3, 1980, false attack indications were caused by a faulty component in a communications processor computer. On June 6, 1980, false attack indications were once again caused by the faulty component during operational testing. (61:3)

Considering the crucial defense role of NORAD, it is clear that any technical performance deficiencies inherent to NORAD attack warning equipment, including false alarms, jeopardize national defense (61:3,13,22).

Definition of Risk

Webster defines risk as "the possibility of loss, injury, disadvantage or destruction" (146:1961). Still,

other definitions of risk focus on safety considerations. Risk has been defined as "The probability of loss or injury to people and property" (89:9). In fact, risk is often associated with a mathematical probability or a likelihood of occurrence.

However, it is acknowledged that "there is considerable overlap (and often confusion) between the terms Reliability, Safety, Hazard and Risk" (89:9). For instance, the risk of fatal accident in an aircraft was quantified by the early 1960's as being one fatal accident out of every million flights (89:1). This is consistent with the definition that risk is "an expression of the possibility of a mishap in terms of hazard severity and hazard probability" (39:3). In the Department of Defense (DOD) risk has been defined as "a potential occurrence that would be detrimental to plans or programs" (30:1, Sec 15).

Haines distinguishes between risky and uncertain situations as being, respectively, those in which "the potential outcomes can be described by reasonably well known probability distributions" (85:217), and those in which they cannot. Nevertheless Haines acknowledges that the term "risk" can be used to "connote situations of both risk and uncertainty" (85:217). However, Golden and Martin assume that "uncertainty and risk can be treated as synonymous terms" (80:148). However, they have divided risk into the four categories of "environmental, functional, informational and technical risk" (80:148).

These four categories they have subdivided even further to create a hierarchy of risk categorization. A Rand study proposes a similarly structured "hierarchy of uncertainty" (144:24) with a probability distribution associated with the success of each component of each level of the system hierarchy in question. According to the Rand study, the collective probability of system success can then be obtained from these individual system components by using the techniques of Monte Carlo Simulation and Propagation of Error (144:24).

Similarly, in the Department of Defense, weapon system development risk has typically been divided into performance, cost and schedule risks, although these risks are actually interrelated (28:27; 151:97). A Defense Systems Management College handbook on risk assessment techniques defines risk as the "probability and consequence of not achieving some defined program goal (such as cost, schedule, or technical performance)" (24:3, Sec II). In summary, most definitions of risk are centered around the concept of uncertainty since in the presence of certainty, there is no risk (80:148; 143:38).

Technical Risks

Technical risks are "those problems or uncertainties that may hinder the achievement of design and development goals" (58:1) of a weapon system. The technical risk in complex weapon system development stems from unknowns

connected with ". . . inadequate knowledge of the basic technology or its specific implementation" (143:12).

The unknowns in a project may be subdivided into recognized unknowns and unrecognized unknowns. A recognized unknown is an item for which an individual is aware that the present information or knowledge is absent or inadequate. However, an unrecognized unknown is an item of which an individual is not even aware is, or will be, a pertinent factor for technical risk reduction for the project or endeavor in question. Therefore the planning to effectively handle unknowns--information risk--is important for systematic risk reduction (132:38). Indeed, the performance risk associated with new technology stems from uncertainty. Rowe cautions that in addition to unknowns connected with pushing the state-of-the-art, technological risk is also due to ". . . a major gap between an organizations' area of expertise and what is required to perform effectively" (132:40). In fact, Shannon states that actual project failures have usually been traced to either

1. Failure to seek the help of appropriate specialists.
2. Failure to ask the specialists the right questions at the right times.
3. Failure to heed the advice of the specialist after it is given. (137:83)

Any plans therefore should specifically address the availability, access to, and utilization of specified technical experts to minimize technical risk (79:321).

Risk Assessment

Risk assessment is "the process of examining a situation and identifying the areas of potential risk" (30:Sec 15,1). The risk assessment is usually followed by a risk analysis wherein the probabilities and consequences of particular events are examined and quantified. In the 1940's technical risk management focused on the improving reliability through the enhancement of quality with better design and materials (89:2). In 1954, Air Force Brigadier General Bernard A. Schriever was given authority to develop "the free world's first ICBM [Intercontinental Ballistic Missile], an immensely complex technical task" (9:201). However, ICBM accidents drove the formalization of safety studies as part of system design:

The emergence of a Systems Safety Study as an independent separate activity was first mandated by the Air Force in 1962 following disastrous accidents at four ICBM missile/silo complexes. (89:3)

Ultimately, this led in 1969 to MIL-STD-882, System Safety Programs for Systems and Equipment: Requirements for, as a documented safety approach (81:75; 89:4). In the 1960's, due to the development of the Intercontinental Ballistic Missiles and manned rocket programs such as Project Mercury and Project Gemini, there was enormous

emphasis on technical performance and on the reduction of technical risk. This was especially the case because such rocket launches could not be redone once the rocket left the launch pad. It was in 1961 that H. A. Watson of Bell Telephone Laboratories originated the Missile launch control system. Fault Tree Analysis remains an important and widely used technique for technical risk assessment (89:3,45). General William Thurman stated that

Formal recognition of risk and uncertainty analysis in DOD resulted from a 31 July 1969 memorandum from David Packard to the DEP SEC DEF [Deputy Secretary of Defense] identifying problem areas in the weapon system acquisition process. (143:12)

The WASH 1400, A Reactor Safety Study, which was commissioned by the United States Atomic Energy Commission and completed in 1974, was a comprehensive risk assessment of nuclear facilities. That study, led by Professor N. Rasmussen, remains a landmark in risk assessment and risk analysis methodology. Many of the qualitative and quantitative risk assessment techniques used in the WASH 1400 study are widely used today (89:4,19-24). The United States Air Force Systems Command specifies that the general steps for a technical risk analysis are as follows:

1. Form a Risk Analysis Task Force
2. Identify the objective
3. Specify critical events
4. Develop contingencies for each event
5. Construct program network
6. Collect data
7. Evaluate network
8. State conclusions. (25:Sec 8,7)

Henley and Kumamoto outlined a three phase methodology for conducting a technical risk analysis as outlined in Figure 3. Similarly, Haimes has defined risk assessment as a process that includes the five steps of "risk identification, risk quantification, risk evaluation, risk acceptance and risk aversion, and risk management" (85:217).

Qualitative Techniques of Risk Assessment

Qualitative risk assessment techniques are those techniques which rely heavily on opinions and judgements of experts rather than on explicit empirical data. Therefore, the experts must have detailed technical knowledge of the purpose and function of the system in question and of the environment in which the system must operate (141:77). Some clear indications of technical expertise are the holding of positions in national scientific organizations, on editorial boards for key technical journals, and the holding of research contracts awarded by the government (88:3-5). The detailed knowledge of experts is especially important because it is often necessary for trade-off decisions to be made "among conflicting . . . objectives and attributes" (85:217). In particular, appropriate and early laboratory involvement is crucial for accurate assessment of technical risk, since the laboratories are "the state-of-the-art experts in many areas" (25:6, Sec 2).

PHASE I: DEFINE THE SYSTEM

Step 1. IDENTIFY THE HAZARD (Is it toxic release, an explosion, a fire...?)

Step 2. IDENTIFY THE PARTS OF THE SYSTEM WHICH GIVE RISE TO THE HAZARDS. (Does it involve the chemical reactor, the storage tank, the power plant?)

Step 3. BOUND THE STUDY (Will it include detailed studies of risks from sabotage, adversary action, war, public utility failures, lightning, earthquakes...?)

PHASE II: IDENTIFY THE ACCIDENT SEQUENCES, EVENT TREES, FAULT TREES

PHASE III: CONSEQUENCE ANALYSIS

Figure 3. Risk Analysis Methodology (89:19-21,24,29)

Harmon states that the three characteristics of diversity, depth, and breadth of knowledge are important for "a good panel of experts" (88:4). To be diverse the panel should be comprised of multidisciplinary experts (e.g., logistics, engineering, safety, reliability, etc.) in order that multiple aspects of the problem or system in question can be completely examined. For depth, at least one expert should be present with profound knowledge in each major scientific or engineering field (29:58,59; 88:3-5). Finally, for breadth, there should be some "systems experts . . . [since they are] accustomed to thinking . . . in terms of the interactions of various subsystems" (88:4).

Design Reviews. Often, experts are assembled in a conference or committee to collectively assess the technical risks of the system or event in question and to recommend actions to prevent or reduce technical risk by appropriate design. These conferences usually constitute one or more formal design reviews of a system. The conduct and content of design reviews for weapon systems has been formalized in the US Air Force in Technical Reviews and Audits for Systems, Equipments, and Computer Software, MIL-STD-1521B (28:1-123; 38:A-7). The assessment of risk should also include dialogue with the intended users and/or customers of the system in question, to include their attendance at design reviews, since such information could

enhance the technical risk assessment and reduction effort (30:2,Sec XV; 89:19,24).

However, the knowledge of even experts is incomplete therefore "technical errors and inconsistencies" (132:40) are still possible. Fox stresses that technical personnel can be overly optimistic regarding what is within the state of the art and that this over-optimism may indirectly lead to technical risk since immature technological approaches may be pursued (48:128). For example, a GAO evaluation cited that problems in the development of the Inertial Upper Stage used to boost satellites from low earth orbit, were actually due to "the main contractor's underestimating the technical complexity of the Inertial Upper Stage" (49:61). Even experts very close to a prospective technical project may disagree on the technical risks. For instance, Mr. Roy Woodruff allegedly resigned from the Lawrence Livermore National Laboratory late in 1985 because he claimed that "overly optimistic" (69:6) claims were being made by Dr. Edward Teller and Dr. Lowell Wood regarding the development potential for the X-ray laser (69:1-6,10; 100:52). The stated Dr. Teller is the eminent scientist who has been called the "father of the Hydrogen Bomb" (87:7; 100:52).

Delphi Technique. For adequate risk assessment, steps must also be taken to minimize certain negative group processes such as external or internal pressure for a consensus among the experts, in order to ensure

objectivity. Accordingly, the opinions of one or more dissenting experts in such a conference must be given careful consideration. The Delphi technique, whereby expert inputs are obtained in writing without a conference among the experts, may be employed to solicit risk factors or assessments that are almost devoid of group pressure to conform to a particular viewpoints. Instead the Delphi technique arrives at a consensus among the experts by "an anonymous process" (136:643) whereby several cycles of written questions and written summary of anonymous responses (and the accompanying rationale) are presented to each of the experts. Based on the anonymous responses each expert is allowed to modify his/her answer in successive cycles. Ultimately, a consensus of the technical risks are achieved (136:643; 141:77).

To conduct a qualitative risk assessment, the experts must define the system boundaries and broadly identify potential system malfunctions or catastrophic failure (e.g., explosion, fire, toxicity). Then, the respective system components whose failure can ultimately result in a particular hazard or malfunction, are identified. Finally, the scope of the study must be appropriately limited. Checklists providing some possible system hazards and malfunctions for consideration, are often used to facilitate the experts' qualitative risk assessment. A checklist used by Boeing Aircraft Company is presented in Figure 4. If the stated qualitative risk assessment

Hazardous Energy Sources

- | | |
|----------------------------------|--------------------------------|
| 1. Fuels | 11. Gas generators |
| 2. Propellants | 12. Electrical generators |
| 3. Initiators | 13. rf energy sources |
| 4. Explosive charges | 14. Radioactive energy sources |
| 5. Charged electrical capacitors | 15. Falling objects |
| 6. Storage batteries | 16. Catapulted objects |
| 7. Static electrical charges | 17. Heating devices |
| 8. Pressure containers | 18. Pumps, blowers, fans |
| 9. Spring-loaded devices | 19. Rotating machinery |
| 10. Suspension Systems | 20. Actuating devices |
| | 21. Nuclear devices, etc. |

Hazardous Processes and Events

- | | |
|---------------------------|--------------------------|
| 1. Acceleration | 10. Moisture |
| 2. Contamination | high humidity |
| 3. Corrosion | low humidity |
| 4. Chemical dissociation | 11. Oxidation |
| 5. Electrical | 12. Pressure |
| shock | high pressure |
| thermal | low pressure |
| inadvertent activation | rapid pressure changes |
| power source failure | 13. Radiation |
| electromagnetic radiation | thermal |
| 6. Explosion | electromagnetic |
| 7. Fire | ionizing |
| 8. Heat and temperature | ultraviolet |
| high temperature | 14. Chemical replacement |
| low temperature | 15. Mechanical shock, |
| temperature variations | etc. |
| 9. Leakage | |

Figure 4. Checklists of Hazardous Sources (89:20)

process extensively identifies the alternative sequence of events that lead to a particular malfunction or catastrophic failure, as well as possible corrective action for the system in question, then the assessment is called a Preliminary Hazard Analysis (PHA). The PHA usually involves a decision tree which aids in interrelating the potential decisions and corrective actions to prevent a particular system malfunction or catastrophic failure (89:21).

Failure Modes and Effects Analysis. Another risk analysis technique is the Failure Mode and Effects Analysis (FMEA). The FMEA is a systematic examination and analysis of the worst-case impacts on the system due to the failure of each component in a system. As part of the FMEA, the potential failure modes of each component are considered and the applicable corrective action is recommended. Based on the results of the analysis, the components are assigned Criticality 1, 2 ,3 or sometimes 4 (89:31).

Regarding the space shuttle, NASA designates a system component as Criticality 1 if a single failure in a component can result in "loss of life or the vehicle" (67:8). A component is designated as Criticality 2 if a single failure in the component could "cause loss of mission" (67:8). Those components remaining after the Criticality 1 and 2 designations have been completed are designated as Criticality 3. However, NASA also uses a category 1R which indicates that a particular item has one

or more backup (i.e., redundant) item and that failure of the primary as well as all redundant items would cause loss of life or vehicle. Similarly, category 2R indicates that the primary as well as all redundant components must fail in order to cause loss of mission (67:8; 89:31;).

Fault Tree Analysis. This technique involves specifying an undesirable event as a top event and then constructing lower level failures that can lead to the top-level undesirable event. Henley points out that one limitation of fault trees is that as they get very large, "mistakes are difficult to find, and the logic becomes difficult to follow or obscured" (89:48).

Material Risk. The degree of technical risk for a development project can often be assessed by determining whether materials having the required performance characteristics, and the processes for forming these materials are readily available and have been in relatively common use. If present materials are known to be marginal for the performance regime that is anticipated for the new technology system, then it is clear that there will be technical risk connected with the selection and processing of newer materials. For instance, aircraft evolution has been, and continues to be very dependent on the state of materials technology. This is because the greater the speed at which an aircraft flies, the higher is the skin temperature of the aircraft as a result of air friction (140:67,68). Increases in aircraft speed are often due to

improved propulsion technology. Such improvements usually subject the engines to greater internal operating temperatures, thus height ending the technical risk. The technical risks associated with aerospace vehicles is further heightened because "high operating temperatures correspond to [greater] fuel efficiency" (19:52). Further, the need for high strength coupled with light weight in order to increase payload capacity (i.e., number of passengers, instrumentation or warheads), may mean that the use of new or exotic materials are mandatory in order to meet system performance requirements (19:51).

Dr. Robert Barthelemy, manager of the National Aero-Space Plane (NASP), presently in the research phase, says that the availability of the appropriate high technology materials is crucial for reducing the technical risk connected with the NASP vehicle. Significant technical risk arises from the NASP requirements to travel to the edge of space, and to travel faster than Mach 6 in the atmosphere (133:13).

Technical Maturity. According to Major General Thomas R. Ferguson, Deputy Chief of Staff for technology and requirements at Air Force Systems Command, it is necessary to " . . . ensure that the technology is as mature as possible in order to reduce risk when we start a new program" (96:7). Indeed, the maturity of a candidate technology--which he dubs "technology readiness" (96:6)--

actually determines the viability of development alternatives.

Therefore, a technical risk assessment must include an evaluation of whether materials with the required characteristics are available, have been tested, and whether these candidate materials have been previously applied with the required degrees of success (19:52,54; 133:13; 140:68).

Process and Productivity Risks. Technical risk arises also from new processes used to form materials into the respective system components. For instance, the now famous Lockheed "Skunk Works", which built such advanced aircraft like the Mach 3+ SR-71, initially had significant problems working with a particular titanium alloy. In spite of the fact that there were ten years of research on that titanium alloy, there had been no use of the alloy in a development project up to that point. Regarding the titanium alloy, Kelly Johnson, Skunk Works manager, stated that there was ". . . a hell of a gap between the research and the application" (8:256). The crucial nature of new processes as sources of technical risk is also underscored by the initial difficulty of obtaining semiconductor-grade silicon with "parts-per-billion impurity levels" (18:9). Indeed, Mayo has observed that each advancement in electronics, communications and computers has "been associated with new materials or processing methods that are more sophisticated than the past" (107:59). The foregoing examples illustrate

that technical risk often depends on whether or not a particular weapon system or component is producible. In fact a recent General Accounting Office (GAO) report to the Congress (Reference COMP) determined that a smooth transition from weapon system design to manufacture is crucial for low technical risk. As early as possible, the risks attendant to a particular design should be identified. This requires that one determines

. . . how each part will be made, and what it will be made of, identifying necessary production equipment and skills, determining the layout and sizing of the facility, and determining how and when to inspect for quality. (20:2)

The selection of a particular design is a key determinant of the degree of technical risk that is associated with production the weapon system or component in question. Accordingly, design reviews must also include evaluation of factors (20:2,3,9,21,22,27). In addition, frequent revisions to the design of a contemplated weapon system greatly increase the productivity risk because such changes can invalidate previous productivity planning and preparation. This is especially the case if the technology involved is pushing the state-of-the-art or if the design changes are occurring relatively late (20:31-33). All design changes therefore drive updates and reevaluation of previous analyses (28:66).

Quality. However, the technical risk arises not just from whether or not a particular design is producible, but

also from whether or not the item can be produced with the desired level of quality that is required or requested.

For example

. . . missiles are complex systems with numerous components and parts required in their assemblies. Each requires production processes and many thousands of individuals using an array of production and testing equipment, to manufacture and deliver a quality product. The opportunities for defects to occur are immense and one defect can render a missile ineffective. (66:4)

Specifically, defective material and workmanship during the building of a system can contribute markedly to the technical risk. A recent General Accounting Office (GAO) report states that "soldering defects can and have lead to missile failures" (66:28). Further technical risk arises from the long term deleterious environmental effects on the solder joints. This is of special concern since some missiles, such as the Phoenix missile, have over 60,000 solder joints (66:28-30).

Prerequisite Technologies. An adequate technical risk assessment must also take into account whether certain prerequisite technologies required for the success of the project in question are sufficiently well developed. For instance, early computers were built using vacuum tubes. However, more significant computer advances were achieved only with the advent of the transistor (8:253,256,257; 18:6).

Human-Induced Malfunctions

A GAO study emphasized that human factors and reliability concerns are often inadequately considered during the design of a system. In fact, some studies have found that "human errors account for at least 50 percent of the failures of major systems" (54:27). Those errors represent a major source of risk to proper system performance. Because the human is often a component of the system performance, the reliability of the human should be considered as a component of the system technical risk. However a mission or system failure may be caused by a human performing a procedure incorrectly or selecting the wrong procedure although this would not necessarily lead to equipment failures (54:28-30). Human errors fall into the five categories of

1. Failure to follow procedures
2. Incorrect diagnosis of a particular situation
3. Misinterpretation of communication (Written or verbal)
4. Inadequate support, tools, equipment and environment
5. Insufficient attention or caution. (54:30)

For correct system design the designer must take into account certain key characteristics of the personnel that will be operating and maintaining the system. Some of these key human factors are

1. Muscular strength and coordination
2. Body dimension
3. Perception and judgement
4. Sensory capacities

5. Native skills and capacity to learn new skills
6. Optimum workload
7. Basic requirement for comfort, safety, and freedom from environmental stress. (54:29)

Quantitative Techniques of Risk Assessment

As stated above, the opinion of experts is often a critical component of a qualitative risk assessment. Such qualitative assessments are often a prerequisite for follow-on quantitative risk assessments (24:II-1; 89:24; 132:40). The major techniques in use today for quantitatively assessing project risk are:

1. network analysis,
2. the method of moments,
3. decision analysis,
4. Work breakdown system simulation,
5. Graphics,
6. Estimating relationships
7. Risk factors. (24:Sec IV,I)

Although these techniques focus largely on cost and schedule risk, a technical assessment of some sort is normally a component of each of these techniques. Therefore, these techniques will be examined here. Since the techniques are discussed in some detail in Risk Assessment Techniques: A Handbook for Program Management Personnel (24) only a summary description of each will be given here.

Network Analysis. Network analysis gained renown because of its use in the development of the Polaris submarine. A network is composed of a series of lines and circles which are present, respectively, the activities and

the important intermediate objectives which will collectively result in the successful achievement of the project. In particular, such activity lines and objective circles must reflect the interrelationships and the sequence that is required for project success (24:IV-2-5). The Program Evaluation and Review Technique (PERT) is a network technique that was primarily used as a tool for managing project schedule. Time durations for completing each activity, and the respective probabilities for on-time completion of each of the activity are assigned to determine which objective is at risk of being achieved late, and to assess the schedule risk posed to subsequent or interrelated objectives. Computer simulation can then be used to evaluate the pessimistic, most likely, and optimistic completion times for the entire project (124:216-221).

Method of Moments. The method of moments is a program risk assessment method which is primarily concerned with cost risk. This method, unlike the network method just described, does not use a sequence of network relations. Instead, the collective effect of the probability distribution functions associated with program elements in a Work Breakdown Structure, are determined mathematically instead of through simulation (24:IV-10,IV-11).

Decision Analysis. Decision analysis is a risk assessment method whereby decisions are broken down into sequences of constituent and supporting decisions. Such

decisions (i.e., outcomes) are usually represented by a "tree" where the branches from each node represent possible outcomes. Probabilities of each of the outcomes are usually assigned and expected values for each outcome can then be calculated. Specific variations and enhancements allow decision trees to be used for calculating and comparing the expected values for a number of different decision sequences regarding cost and schedule (24:IV-7).

WASH 1400--the landmark risk assessment study mentioned previously--used variations of decision trees to assess the risk of accident whereby a nuclear reactor would release toxic radioactive fission products (89:24).

Work Breakdown Simulation. The work breakdown simulation method is essentially the same as the method of moments except that computer simulation is used to obtain a probability density function (24:IV-13).

Graphic Method. The graphic method is another method that is used to assess the cost risks of a particular program. In this technique, the cumulative distribution functions (CDF) of the individual cost elements (cost versus the probability of that particular cost) is combined to form a collective CDF for the overall program (24:IV-14,15,16,17).

Estimating Relationship Method. The estimating relationship method is a technique that uses appropriate historical cost data to determine the amount of contingency funding that should be reserved to cover the unanticipated

development expense due to the technological risk involved. This technique requires that factors such as "engineering complexity, degree of system definition, contractor proficiency/experience, and multiple users" (24:19) be evaluated (24:18,19).

Risk Factor Method. The risk factor method uses a technical Work Breakdown Structure that assigns relative weighting corresponding to the degree of anticipated technical risk associated with the system components. The weighting allows costs estimates for development costs to be assigned commensurate with technical risk, thereby minimizing the risks that the estimated costs are not realistic (24:IV-21). There are a number of computer programs presently in use in which the appropriate input information results in an output which identifies the cost risk to a project. For instance the Army has developed the Total Risk Assessing Cost Estimates (TRACE) software to identify the cost risks of projects in an entire command and to aid in assigning funds commensurate with the cost risks (24:23; 30:Sec 15,13).

Design Comparisons. One method of assessing technical risk is by comparing the design of an existing or proposed system to the design of a system that has had a performance failure. Such a comparison may be quantitative qualitative or both. This technique has been used to determine the accident risk of a number of United States nuclear reactors by comparing them to the reactor which had an accident near

Chernobyl in the Soviet Union. Refer to the case study on the Chernobyl Nuclear Reactor Accident for an example of how design comparisons are made (62:1-6; 63:1-6). A comparison between an existing and a proposed design or system is also valuable for ascertaining that the time allotted for achieving the proposed design or system is realistic. An unrealistically short time could increase technical risk since some recommended technical tasks could be abridged or eliminated. For example, a GAO report cited that the time scheduled for the development of a particular trainer aircraft was "probably too short given the history of problems with engine development programs" (75:16). Because time is often a factor in technical risk reduction, technical productivity aids should be identified and used. One important class of such productivity aids are design tools which "cover the spectrum from computer simulations supporting design, to computer-integrated manufacturing" (29:82). These tools have been cited for increasing the "capability of engineers [by] 300-3500%" (29:84).

Risk Management

In general, any action which reduces the uncertainties or unknowns associated with achieving a desired outcome is in essence a risk management technique. Accordingly, a risk assessment "is the first step in risk management" (30:Sec I,2). A study sponsored by the Defense Advanced

Research Projects Agency (DARPA) defined risk management, as it regards a project, as a process of evaluating, decreasing or avoiding the uncertainties associated with meeting objectives so that a program will successfully achieve its goals (113:1).

Techniques of Technical Risk Management

Ideally, the best method of managing technical risk is to eliminate risk by use of an appropriate design. This is especially preferred where safety risk (i.e., a hazard) is concerned. However, rarely will all risk be eliminated, therefore some technical risk management will have to be pursued (3:113; 36:6). Incidentally, it is highly important that the key technical criteria and parameters are identified for a system undergoing development that can be used as indicators of system technical health, progress or lack of progress (25:Sec 8,6). The following general types of technical risk reduction techniques have been cited:

1. Test and Evaluation
2. Use of Prototypes and Demonstration
3. Studies and Analyses
4. Development of New Ideas and Concepts. (143:21)

The Air Force MIL-STD-1521B cites the following technical risk reduction techniques:

1. Adequate trade-offs (particularly for sensitive mission requirements versus engineering realism and manufacturing feasibility to satisfy the production capabilities);

2. Subsystem/component hardware;
3. A responsive test program;
4. Implementation of comprehensive engineering disciplines (e.g., worst case analysis, failure mode and effects analysis producibility analysis and standardization). (28:26)

Risk reduction may also be achieved by selectively applying military specifications and standards, when appropriate, since they are a "valuable corporate memory [based on] . . . past experience"(25:Sec 8,8).

Design. A fundamental guideline of risk management by design is simplification. That is, the design of the system should be "no more complex than necessary to perform the function reliably" (29:39). By minimizing the number of parts and interconnections, simplifying the support tools and equipment, and providing easy access to test points, the system will be "simpler to build, operate, support and upgrade" (29:40). Modularity simplifies the system design, troubleshooting, and software and hardware revision. Software modularity also reduces the likelihood of logic errors and aids troubleshooting (29:44,45). For maximum benefit, analyses such as Fault Tree Analyses and Failure Modes and Effects Analyses, should be done early enough so that the results can be used "to influence the design, not just to document it [the design]" (29:67). Since analyses may indicate system deficiencies and inadequate design margins, the timing of analyses are very important for technical risk reduction (29:65-67). One basic risk reduction technique is to incorporate design

margins whereby parts are selected which are rated to withstand much higher loads or capacity, as applicable, then they are expected to encounter when used in the system. This practice in electronic design is called derating, and results in increased reliability (i.e., decreased failure rate) since the parts "experience stress levels below their rated values" (29:78-79).

Testing. Testing has been identified as so crucial to the technical risk reduction process that the Department of Defense position is that: "testing will begin as soon as possible . . . to reduce acquisition risk and to estimate the capability of the system under development". (32:2).

For example, testing revealed that the M-1 tank met such combat requirements as firepower and mobility, but that the tank's power train did not meet the Army's durability goal (59:ii). Similarly, laboratory tests of the Army's Viper--a light anti-tank weapon fired from the shoulder of an infantryman--revealed that "static electricity or radar waves may cause the Viper to accidentally fire" (58:48). Operational tests revealed that "20 of 368 Viper rounds failed to fire on the first attempt . . . [due to] poor quality . . . defective batteries . . . gunner error . . . [or] unknown [causes]" (58:49). For effective testing to be performed, detailed test planning must be completed so that the necessary test resources can be identified or developed, and the critical test issues can be ascertained (52:ii).

It is important that the testing of a system or component be very realistic. Equipment may function well at ambient temperature but may fail to function correctly when subjected to the extremely cold or hot temperatures that the equipment is likely to encounter. For example, the Air Launched Cruise Missiles' (ALCM) Flight Data Transmitters (FDT) were sensitive to cold temperatures. In two different operational launch attempts, an FDT malfunctioned during the pre-launch test due to the effects of cold temperature. Both FDT's appeared to function properly when tested on the ground at ambient temperatures, but, when later chilled in a laboratory, both failed (73:13). The sensitivity of FDT's to cold temperatures was especially important since "SAC bombers, which launch the ALCM, flying at the 32,000-52,000 feet required for strategic missions, could encounter temperatures as low as below [minus] 116 degrees F" (73:13).

A fundamental example of the importance of test realism in reducing technical risk is illustrated by the case of the Army's High Mobility Multipurpose Wheeled Vehicle (HMMWV). Although the HMMWV performed well during development testing, several deficiencies became evident as a result of the more realistic operational testing. During the operational tests it was discovered that the vehicle's radiator "was subject to clogging in dusty and sandy environments" (51:5). Further, the HMMWV's air induction

system allowed "dirt and water to enter the engine" (51:5). This was a serious deficiency since the vehicle would be vulnerable to mud, dust and water during cross-country maneuvers. To resolve the stated deficiencies, and to thereby reduce the technical risks, corrective design modifications were planned for the HMMWV prototype (51:5-8).

The operational testing is normally conducted by an independent organization because one cannot "expect a man or organization who created a system to discover its faults" (125:6). However, the performance of any test does not actually eliminate technical risk. Only the implementation of corrective actions or design modifications that are shown to be necessary by the testing, will actually reduce technical risk (82:258-268).

Simulation and Analysis. Since a test article may not be available at the inception of a new technology development program, there should be heavy emphasis on simulation, modeling and analysis to begin to assess the technical risks and limitations of prospective design approaches (32:7).

However, the deficiencies in a simulation may result in the introduction of additional technical risk. For example, the GAO found that "certain target and simulation shortcomings" (71:3) meant that some specific Anti-Submarine Warfare simulations, being performed by the Navy to test the Advanced Capability and MK-50 torpedoes,

1. Is the system operated by typical units?
2. Operated by typical operating personnel?
3. Supported by typical support units?
4. Equipment put under realistic stress by design?
(e.g. outer envelope of performance requirements tested?)
5. Personnel put under realistic stress by design?
6. Realistic combat tactics?
7. Did the physical environments approximate the intended range of environments (terrain, time of day, weather, sea state, clutter, IFF)?
8. Did target systems approximate actual targets, realistically employed?
9. Did threat systems approximate actual threat, realistically employed?
10. Was the tested system production representative and prepared for the test in a realistic manner?

Figure 5. Framework for Evaluating the Effectiveness of Operational Test and Evaluation (76:34-35)

incompletely represented "important environmental factors . . . and may increase technical risks of weapons not performing as intended" (71:3). Therefore, effective evaluations of test resources are necessary to determine the utility and validity of the test results that are obtained using a particular test resource (71:4).

In particular, certain weapon systems must be tested in the electronic warfare environment since their performance may be markedly degraded in such an environment. Simulated threat environments which are inaccurate could introduce technical risk (52:2). For example,

. . . the Air Force's Sparrow air-to-air missile was tested against aerial targets that did not realistically represent the actual threat. When first used in Vietnam, the Sparrow missile missed its target more than it hit. (52:6)

A relatively new technical and test concern is whether or not the crucial control electronics of a particular system can continue to function when subjected to the electromagnetic pulse radiation from nuclear explosions in air or space (57:21; 110:164).

Goodman points out that it is prudent to be aware that one or more technical approaches may look good on paper but must be tested to ascertain that these contemplated approaches can be reduced to practice. In some cases, he states, analyses are inadvisable for assessing the

technical risk and some sort of test must be implemented to gauge technical risk (38:A-28; 58:258-261).

Detailed Failure Analyses. The availability of facilities to conduct failure analyses on subsystems or components of prototype hardware can also contribute immensely toward risk reduction since the lessons-learned can be used to improve the technical design. For instance the Rome Air Development Center has a Quick Reaction Failure Analysis Laboratory that can conduct detailed analysis of failures in semiconductor devices. Based on the results of failure analyses, appropriate design changes can be made by the DOD program in question. Therefore the reduction in technical risk that may be derived from laboratory support can include the use of sophisticated laboratory instruments (e.g., scanning electron microscope, pattern generators, oscilloscopes, infrared scanners) and non-destructive tests (e.g., X-rays) for electronic microcircuit failure analysis, as well as technical assessments of contemplated design approaches (40:42,43).

Failure analysis personnel may also be employed to prevent certain failures. For example, the growth of "tin whiskers" within some electronic components is an incipient failure mode that can ultimately result in internal shorting in hybrid and integrated circuits. This means that weapon systems that have tested functional before storage could potentially fail those same tests after storage. Fortunately, the Department of Defense has been

alerted of this particular failure mode and can minimize the risk by selecting proper materials. Refer to Appendix C for detailed correspondence on the "tin whisker" failure mode. Similarly, Appendix I outlines the risk of electronic component damage due to electrostatic discharge.

Software Testing. Thorough testing of software, as part of software verification and validation, has been established in numerous technical programs as indispensable for precluding low software reliability and to verify that user requirements have been achieved by a system in question. A GAO report cited that the development of application software is such a laborious "and error prone process, and errors can be made both in deciding what the program should do, and in writing them to do it" (56:1). To enhance the testing objectivity and to increase the chances that user requirements were correctly understood and implemented in the software, independent testing and evaluation of the software should be conducted in addition to in-house testing (56:38,39). Due to the labor intensive nature of software, test tools--such as test data generators--should be used both to increase the software testing effectiveness and the productivity of the software effort. However, manual techniques can be used to supplement the automated testing techniques. Further, adequate personnel and time should be allotted for the software effort (56:10,12).

Contingency Planning. Another method of minimizing risk is to plan for contingencies. This involves looking at possible "what-if" situations and laying out possible courses of action before the particular situation occurs. This contingency planning may be taken further by evaluating the options corresponding to certain worst-case scenarios (28:24; 98:280). Goodman states that as a contingency measure, it is highly important to identify and carry along (i.e., demonstrate) at least one lower technology approach corresponding to each high technology approach in order to have a fallback position if the high technology approach is not achieved (79:262).

Such contingency planning should include a consideration of relatively mundane sources of technical risk. For example, the 21 July 1961 flight of the Mercury capsule into space made Captain Virgil Grissom the second American in space. There had been concern that upon splashdown in the ocean, the space capsule would become submerged (instead of floating on the surface). To allow the astronaut to escape, an innovative explosive cord had been placed around the hatch. However upon splashdown, the hatch apparently blew inadvertently, causing sea water to enter the capsule. To avoid sinking with the capsule, Grissom quickly scrambled out of the open hatch. Grissom's was designed to allow him to float on water, by closing off a "neck dam" (23:XVII). However, in quickly leaving the sinking capsule, Grissom forgot to close off "an intake

port in the center of the suit [and] . . . water began to enter the suit" (23:XVII). Having endured the 6 g force of ascent and the 10.2 g forces of re-entry, it was clear according to one doctor that Grissom came close to drowning during the splashdown (23:XVII,XVIII).

Parallel Effort. To reduce the technical risk, "simultaneous parallel efforts are encouraged [early in a DOD Acquisition process] . . . to reduce the risk from uncertain technology and development" (143:15). Such parallel design efforts pursue the same technical objectives in order that a number of different design approaches are available to be evaluated for superiority (143:15).

For example, on 4 October 1957 the Soviet Union was the first to put a man-made satellite--Sputnik--into orbit. The United States' first attempt to achieve the same feat ended when the Vanguard rocket exploded on the launch pad during the attempted launch on 6 December 1957. However, the United States Army had been building the Explorer I vehicle which was successfully launched on 31 January 1958. The nearly simultaneous availability of both the Vanguard and the Explorer I launch vehicles provided alternatives for achieving the United States launch objective (86:148,160,162).

Incremental Development. The use of an incremental development strategy can greatly reduce technical risk. Under this approach only established technology having

little development risk would be implemented in an ongoing program and each successive version of the hardware could include newly matured, proven technologies and enhancements. A variation of this approach is called Pre-Planned Product Improvement, whereby the option to upgrade the completed or deployed system to higher technology would have been preserved all along by appropriate design and planning. An example of the incremental development approach was the United States Gemini space vehicle series. The Gemini space vehicle "drew heavily on proven Mercury [predecessor program] technology" (92:65), therefore the Gemini space vehicle were much more advanced and versatile (132:33).

Technical Enrichment. Goodman has stated that one of the techniques of minimizing technological risks is to ensure that the technical, human resources involved with the project are continually being enriched by innovative ideas and perspectives. To achieve the said enrichment, new technical personnel can be recruited into the organization, attendance at professional technical meetings can be encouraged, and an appropriate emphasis on training can be employed. However, Goodman repeatedly emphasizes that for risk reduction, "the key management task is to create an early learning path" (82:258). Especially if the staff involved is new or inexperienced, Goodman stresses that it is necessary to "rush-to-prototype" (82:262) to

provide the staff with experience that is specific to the technical endeavor.

Case Studies

A number of case studies of technical risk management have been selected based on the criteria specified in Chapter II. These case studies reveal significant lessons and potential pitfalls in the management of technical risk. Since the case studies encompass past, contemporary and prospective systems, they provide a wide vista for the examination of technical risk management in action.

The F/A-18 Strike Fighter. Designed for Navy and Marine Corps use, has two engines, "redundant flight control computers and a backup mechanical flight control system" (55:1). Such redundancies, besides enhancing reliability, are also intended to enhance the survivability of the aircraft during a combat mission. The software development for the F/A-18 flight control system was behind schedule because Navy and contractor personnel underestimated the amount of work necessary. Also, requirement changes, driven by the need to correct a roll-rate problem, adversely affected the software effort. Further, "almost all of the flight control computer's memory space had been used while demands for additional space continued" (55:8).

The use of composite materials on some F/A-18 surfaces, instead of aluminum and titanium, resulted in

added technical risk. Specifically, poor predictions were made regarding the flexibility of composite structures since the aircraft industry was less familiar with composite structures than with aluminum and titanium (55:8-11). To enhance maintenance, a built-in test system was being developed for the F/A-18, however, as of 1980 a relatively high number of built-in test false alarms had been seen (55:22).

The F/A-18 development and test effort was not without catastrophes because ". . . in September 1980 a development F/A-18 aircraft crashed in England because of a failure in the low pressure turbine [disk] of one of its F404 engines" (55:ii). Also, "on November 14, 1980, during an operational test and evaluation . . . [an F/A-18] aircraft entered into a spin while practicing combat maneuvers, and the pilot was unable to regain control" (55:ii).

Chernobyl Nuclear Reactor Accident. In early 1968, the reactor core of a "graphitemoderated, water-cooled nuclear reactor" (63:2) exploded near Chernobyl in the Soviet Union killing 31 people and spreading deadly radiation. The Chernobyl reactor accident was attributed to "a combination of human error and poor reactor design" (63:8). To assess the risk that some United States reactors could fail the same way, some comparisons were made between some United States reactors and the Chernobyl reactor. In particular, a GAO study found that the Chernobyl reactor and the Fort St. Vrain (United States)

reactor both use "a graphite core to control the rate of fission within the reactor" (63:2). However, the Chernobyl design allowed only seconds of response time to avoid the equivalent accident. This difference in allowable response time is due to the difference in the cooling system design in the two reactors (63:2,3,33; 83:39-42). The Fort St. Vrain reactor was specifically "designed so that the graphite in the reactor core absorbs most of the heat" (63:3). That heat is then transferred to helium gas that circulates through the graphite. However, in the Chernobyl reactor, the graphite was specifically designed only for fission moderation and not especially for heat absorption. Instead, the Chernobyl reactor uses cooling water to absorb the heat. Therefore, "the consequences of a loss-of-coolant accident would be more severe at a Chernobyl-type reactor than at Fort St. Vrain" (63:3). According to a Soviet report, the Chernobyl accident occurred while the reactor operators were conducting a test which required that a number of reactor safety systems be disabled (63:32). However, the Chernobyl reactor

. . . was not designed to withstand loss of coolant without the use of the emergency cooling system. If the cooling is inadequate for a very short period (seconds) . . . the fuel would begin to melt. This would result in over-pressurization of the fuel tubes and explosions. (63:21)

It is very clear that the hazardous events happened with such rapidity that past a certain point the Soviet

technicians could not respond quickly enough because "in less than 20 seconds, the reactor power level increased to 100 times its designated power level" (63:32). In fact, "the power surge was so rapid that neither the control rods nor the coolant could be adjusted fast enough to stop the accident" (63:33).

Airplane Development. On 17 December 1903 at about 10:35 in the morning near Kitty Hawk, North Carolina, Orville Wright--with his brother Wilbur and five witnesses on the ground--successfully flew the first airplane. However Professor John D. Anderson, chairman of the Department of Aerospace Engineering at the University of Maryland, states that

Contrary to some popular belief, the Wright Brothers did not invent the airplane; rather they represent the fruition of a century of prior aeronautical research and development. The time was ripe for the attainment of powered flight . . . The Wright Brothers' ingenuity dedication and persistence . . . [made them] first.
(5:3)

The efforts of the British inventor Sir George Cayley significantly advanced the theoretical understanding of aeronautics and was therefore instrumental in reducing some of the technological risk of attaining the 1903 flight with the Wright Brothers' aircraft. In 1804 Cayley built a revolving-arm mechanism which he used for experimenting with airfoils. Also, in 1804, Cayley built and flew a small (one-meter long) model glider. In 1849 Cayley built and flew a full scale glider that had three wings mounted

above each other. On a number of occasions, a small boy on the glider was lifted several meters into the air when the glider was traveling down a hill (5:8,9,10; 47:219; 109:397).

Other aeronautical experiments, such as the more than 2,500 successful flights that Otto Lillienthal made in his hang gliders, clearly reduced the technical risk. On a 9 August 1896 flight, Lillienthal crashed, broke his back, and died the next day. His last words were (translated from German): "Sacrifices must be made" (142:43). The Wright Brothers followed the Lillienthal hang glider flight experiments intently through written accounts and some of Lillienthal's reports (5:18). It was Lillienthal who first showed that curved wing surfaces were superior to flat wing surfaces for gliding (43:242). Wilbur Wright stated that "It was the death of Lillenthal that brought the subject [the problem of flight] to our attention" (108:7). This spurred the Wright Brothers to write to the Smithsonian Institution in order to obtain books relating to flight. Orville Wright contended that he and his brother Wilbur had determined "that Lillenthal had been killed through his inability to balance his machine in the air" (103:7). Further, the achievements of Samuel Langley and Octave Chanute also advanced the theory of flight (142:46). In fact, the sheer number as well as the content of the letters between the Wright Brothers and Octave Chanute indicates that Chanute was both a consultant mentor and

friend of the Wright Brothers up to his death in 1910 (108:7-537; 109:677-993).

Clearly, many technical risks associated with powered heavier-than-air flight were reduced in the century prior to the successful Wright Brothers flight. However, formidable technical risks remained for the Wright Brothers to solve. The Wright Brothers "took up gliding as a hobby while they were operating a bicycle repair shop in Dayton, Ohio" (46:146). A perusal of the content of the papers (e.g., letters and diaries of the Wright Brothers) reveals that from the beginning that they were meticulous in their study of the available literature relating to flight and in surveying the results of previous flight experiments (108:5, 19, 20-22).

During 1900 and 1901 the Wright Brothers tested gliders in the steady winds of Kittyhawk, North Carolina. At first these gliders were flown like box kites, later they were flown manned--usually pushed from a small hill. Wilbur Wright's notebooks are a testament to the methodical and meticulous nature of the Wright Brothers investigations into flight. His September to October 1900 notebook entries contains detailed observations that he made regarding the flight of birds. In particular, the flight characteristics of different types of birds were compared. Wilbur Wright made the simple observation that "no birds soar in a calm" (108:7) and indicated that he was paying particular attention to the equilibrium (i.e., balance) of

birds in flight (108:34-36). In a letter dated 23 September 1900 to his father Bishop Milton Wright, Wilbur Wright fundamentally outlined the technical risk approach regarding the nearly finished first Wright glider:

My idea is to experiment and practice with a view to solving the problem of equilibrium . . . once a machine is under proper control under all conditions, the motor problem [to obtain true flight] will be quickly solved. (108:26)

That some letters indicated that Wilbur Wright gave priority to equilibrium in flight because once equilibrium was attained "a failure of motor will simply mean a slow descent and safe landing instead of a disastrous fall" (108:26). Further risk reduction was indicated by Wilbur's intention to conduct all experiments relatively close to the ground and to build his plane "to sustain five times my weight and am testing every piece" (108:26). Perhaps the most telling indication of the Wright Brothers' understanding of risk is the statement by Wilbur in that 23 September 1900 letter:

The man who wishes to keep at a problem long enough to really learn anything positively must not take dangerous risks. Carelessness and overconfidence are usually more dangerous than deliberately accepted risks. (108:26)

Therefore, just in case of any potential crash landing Wilbur Wright concluded that landing on the sand near Kitty Hawk would lessen the risk of injury (108:26). Because the gliders initially exhibited little lift, the Wright

Brothers were convinced that the curvature of the wing surfaces was wrong. To address this technical problem they built a six-foot-long wind tunnel to study various curved wing surfaces in moving air. They tested hundreds of glider wings in the wind tunnel and made "the first reliable tables of air pressures on wings" (46:146). This effort along with their quantitative records and analyses of their glides contributed immensely to their airplane design knowledge (108:119-170). In 1902, based on the result of their wind tunnel experiments, the Wright Brothers built a third glider with wings of 32 feet long and approximately 5 feet across. This glider was successful and allowed the Wright Brothers to make over a thousand manned glider flights--some for longer than one minute. At the time there were only crude propellers with efficiencies that were below 50 percent, and no developed theory for the design of an aerodynamic propeller. The Wright Brothers were "the first to recognize that the propeller is basically a rotating wing, made up of airfoil sections" (5:364). This understanding allowed them to design a propeller that was 70 percent efficient, and greatly contributed to the success of their first flight (5:3-23,363,364; 46:146-147).

The development of an efficient propeller was not the only technological risk that the Wright Brothers had to overcome. Because no automobile engine existed that could meet their combined power and weight requirements as a

power plant for their aircraft, they found it necessary to develop their own using an automobile engine as a model to aid their design. The Wright Brothers' mechanic Charles Taylor was responsible for the detail design of the engine (114:56). In February 1903, during the first test of their engine, the aluminum crankcase cracked. Two months later, a replacement crank-case finished casting and in May 1903--roughly 7 months before their historic powered flight--their four cylinder (in-line) engine successfully passed its tests (5:367; 43:237; 114:55).

Rocket Development. In July 1914, Goddard obtained "patents on rocket combustion chambers, nozzles, [and] propellant feed systems" (5:372). In 1915, Robert H. Goddard demonstrated the principles of rocket propulsion in a vacuum at Clark University in Massachusetts. In November of 1923, Goddard achieved successful operation of a rocket motor in a test stand using liquid oxygen and gasoline jointly as the rocket fuel. However, there was clearly technical risk since Goddard's early attempts to launch a liquid-fueled rocket were unsuccessful. Further, it was necessary for Goddard to develop specialized high pressure pumps to force the fuel into the rocket chamber. Finally, on 16 March 1926, Goddard successfully launched the world's first liquid-fueled rocket engine. This success in the field of rocketry was analogous to the Wright Brothers' first successful flight of the airplane at Kittyhawk, North Carolina in December 1903 (5:1,3,372; 42:4,16,17,21;

145:48). Robert H. Goddard's development of the rocket by transforming all the preceding theoretical rocket knowledge into actual practice, has been called "one of the most amazing lone-wolf development programs in the history of technology" (145:48).

Almost continuously from 1930 to 1941, Goddard conducted development and flight tests at Roswell, New Mexico with his wife and four assistants. According to Goddard's wife, the "reliability of propulsion, stability in flight, and recovery, [of the rocket after launch], were the primary aims in the early tests, rather than the attainment of altitude" (145:46). However, to further reduce technical risks connected with rockets, particularly as it regards reliability, extensive mathematical reliability modeling had to be employed.

The early development of mathematical reliability models began during WWII in Germany, where a group led by Werner von Braun was developing the V1 missile. The first series of ten missiles was totally unreliable; they all blew up on the launching pads or fell into the English Channel. (89:1)

This underscores the point that in order to minimize technical risks of new technology development programs, special analytical or mathematical techniques may have to be refined or developed, and then applied (89:2). A brief chronology of the development of the rocket is provided in Appendix D. A detailed chronology of Robert H. Goddard's

flight tests and results can be found in Von Braun and Ordway's History of Rocketry and Space Travel (145:48-52).

Atomic Bomb. The critical impact of experts in the reduction of technical risk is readily apparent in connection with the Manhattan Project--the United States' project that resulted in the world's first atomic bomb. In 1939 Albert Einstein, at the urging of a number of scientists, sent a letter to President Franklin D. Roosevelt which expressed concern that Nazi Germany could be making significant strides towards the development of the first atomic weapon (41:397). President Roosevelt established the Office of Scientific Research and Development, and appointed the United States scientist Vannevar Bush as the director. In December 1941, the United States entered World War II. In May 1942, "The decision [was] made to proceed on all promising production methods" (45:325) for obtaining fissionable materials. Vannevar Bush decided to involve the Army in the construction of the plants that would be used to produce fissionable materials. Therefore in 1942, the Army Corps of Engineer opened a New York City office called the Manhattan Engineer District Office under General Leslie Groves. However, on 1 December 1942, when General Groves signed the contract for the construction of a facility to produce plutonium, there were still many unknowns. Most notably, "the diffusion barrier [used to separate gases] had not yet been proven practical [and] plutonium

chemistry was almost unknown" (45:325). Although a nuclear fission reaction had been achieved on 2 December 1942 in a nuclear reactor at the University of Chicago, formidable technical obstacles remained in the path of atom bomb development. One of the major technical challenges was to produce enough plutonium and to separate Uranium-235 (U-235) from Uranium-238 (U-238). A laboratory at Los Alamos (New Mexico), for exploring the methods of manufacturing the fissionable materials for an atomic bomb was placed under the direction of J. Robert Oppenheimer (46:517; 47:831).

Another major technical concerns regarded the approach that should be pursued in the atom bomb assembly. During the fall and summer of 1943, the "gun" approach was being pursued for the design of a nuclear weapon. Under the gun approach, "a mass of Uranium-235 or (Plutonium 239) would be fired into . . . another piece of Uranium-235" (45:325). When the two pieces joined they would become since "neutrons would be created at a faster rate than they can escape from the assembly" (45:324) resulting in an explosive release of energy (45:324-325). In April 1943, Seth Neddermeyer, a physicist under J. Robert Oppenheimer, "proposed to assemble a supercritical mass from many different directions" (45:325) instead of the two directions used in the gun approach. Neddermeyer's proposal--the implosion method--was supported by United States physicist Edward Teller and United States

mathematician John von Neumann. In July 1944 it was concluded that the implosion method was the appropriate one. However, there were significant technical hurdles to overcome in order to implement the implosion method (45:325). In particular,

The big problem facing the physicists at Los Alamos [New Mexico] was how to produce an extremely fast reaction in a small amount of Uranium isotope, U-235, or of plutonium so that a great amount of energy would be explosively released. (81:180)

John von Neumann, a theoretical mathematician who also had a crucial knowledge of hydrodynamics, was brought in as a consultant to the group at Los Alamos late in 1943. Von Neumann's contributions ultimately resulted in the success of the sophisticated technique of attaining critical mass of the bomb's nuclear material by subjecting such material to a spherical shock wave. Further, von Neumann and James L. Tuck invented "an ingenious type of high explosive lens that could be used to make a spherical wave" (81:181). However, von Neumann's greatest contribution towards reducing the technical risk of atom bomb development was "his showing the theoretical people how to model their phenomena mathematically and then to solve the resulting equations numerically" (81:181) on the computer (42:44; 81:178-181).

Indeed technical risks associated with developing the bomb were also significantly reduced by the emergence of the first electronic computer--the Electronic Numerical

Integrator and Computer (ENIAC). A number of crucial computations for atom bomb development were done with the ENIAC, and other computers, with the aid of von Neumann (81:117,150).

Another project in which von Neumann was involved resulted in the now famous Monte Carlo method. Fundamentally, the Monte Carlo method involves the modeling of a system as a repeated probabilistic experiment in order to evaluate the collective effect of probability distributions of the individual components of the system. Von Neumann used the Monte Carlo Method for studying the diffusion and multiplication of neutrons. This reduction of the complex neutron interaction to a relatively simple Monte Carlo simulation gave the Los Alamos scientists a valuable tool for experimentation (78:652-653; 81:294-296).

The fissionable materials were manufactured mainly at Oak Ridge, Tennessee and at Richland near Hanford, Washington, and then shipped to the Manhattan Project research laboratory at Los Alamos, New Mexico (46:517; 47:831). A brief chronology of events regarding the development of the Atomic Bomb is presented in Appendix E.

Laser Development. In 1917 Albert Einstein recognized the principle of stimulated emission. The principle of microwave amplification by stimulated emission of radiation (MASER) was discovered by Charles H. Townes of Columbia University. In 1954 a working maser device was built by Townes, James P. Gordon and H. J. Zeiger, and subsequent

improved models were built by Bell Laboratories. Since the masers operated at microwave frequencies, Arthur L. Schawlow and Charles H. Townes proposed a technique to obtain a maser-like device which operated at optical frequencies. Assuming that the technical risk could be overcome, the device in question would in actuality be based on light amplification by stimulated emission of radiation (LASER). The first successful construction and operation of a laser was achieved in 1960 by T. H. Maiman of the Hughes Aircraft Company using a ruby crystal (44:686; 134:234; 135:227).

Schawlow states that the building of an optical maser (i.e., a laser) "required preparation of an active medium that would actually display maser action in the optical region of the spectrum" (135:228). One of the major problems in using crystals or glasses as the lasing medium is that they "are usually formed at high temperatures and require considerable effort and expense" (101:255) to free them of optical imperfections. The ruby crystal in Maiman's laser had been machined into a rod whose ends were "polished optically flat and parallel and . . . partially silvered" (135:228). To obtain lasing, the ruby rod was then subjected to light from an electronic flash tube which could attain the necessary critical intensity (44:686). A brief chronology of laser development is presented in Appendix F.

Project Apollo. On 25 May 1961, President John F. Kennedy declared that the United States "should commit itself to achieving the goal, before this decade is out, of landing a man on the moon and returning him safely to earth" (116:736). A prerequisite for achieving the goal was the development of a booster--the Saturn V--capable of the required thrust (91:38).

Saturn V Rocket. The three-stage Saturn V rocket was the product of highly experienced rocket experts who "had lost a number of rockets in earlier development programs and had blown up a few engines" (90:52). The rocket expert Werner von Braun had accumulated data from launching V-2 missiles in the New Mexico desert and then began building improved successors to the V-2. Other engine experts such as David E. Aldrich of Rocketdyne, who "had helped to develop the engine for the X-2 research aircraft" (90:52), provided necessary expertise for the Saturn V development. According to Aldrich, since "the heart of [a jet] engine" (90:53) is the fuel injector, that is the first obstacle to successful engine development. Aldrich was the Rocketdyne program manager for the Saturn V F-1 engine. An early technical problem with the F-1 engine was that the fuel combustion "was so violent that it triggered shock waves producing more heat than the engine's cooling system could handle" (90:53). On 28 June 1962 one F-1 engine was destroyed when to the "fire in the [combustion] chamber burned through the injector" (90:53). Within a

span of one and a half years, thirty different injector designs were tried without success. Finally, the test engineers decided to use explosive charges within the combustion chamber to trigger shock waves when the rocket was firing. It was thereby discovered that when baffles were used to isolate each combustion region, the shock waves in the chamber would die out. Other refinements such as enlarging the diameters of the holes from which the fuel and oxidizer were squirted, finally resulted in a solution (90:52,53).

The size and weight of the Saturn V was a major challenge since it stands "363 feet tall [and when] fully fueled it weighs nearly 6.4 million tons" (145:171). New building techniques had to be used for the Saturn V, and facilities capable of withstanding the weight of the tooling were necessary. One of the major trade-off decisions that had to be made for Project Apollo was that of structure versus weight. The need to reduce the weight became so critical that the second stage of the Saturn V "emerged as the merest eggshell of a rocket" (90:99). This fact contributed to the rupture of two Saturn second stages during test (90:99; 145:170-173).

The first launch of a Saturn V on 9 November 1966 was successful. Due to a decision by George E. Mueller, director of NASA's Office of Manned Space Flight, live upper stages for the Saturn V were used on these unmanned (i.e., test) launches. On the second launch in April 1968,

Two of the J-2 engines in the second stage shut down prematurely. The J-2 engine in the third stage failed to re-start on command, leaving the stage stranded in orbit. (90:60)

These failures during the second Saturn V launch were of major concern because the next launch had been scheduled to be manned. The malfunction investigation of the second flight was confounded by the fact that the failed hardware was inaccessible--either in orbit or burned up upon re-entry. The telemetry (i.e., transmitted data) that had been obtained from the prior to the malfunctions was scanty since there were a relatively small number of Saturn V data channels. Further, these particular in flight failures had never been encountered during ground tests. The program manager Paul Castenholtz and Marshall McClure had been trying to determine why the failures occurred in space but not on the ground. By repeatedly studying movies of J-2 engines firing on the test stands they began to realize that the ice that formed on the fuel and oxygen lines during ground tests was highly significant. The hypothesis was that the ice actually dampened some severe vibrations and thereby prevented the fuel and oxygen lines from rupturing. Using the available telemetry data Castenholtz localized the problem to a special part of the engine. Then, eight of the suspect fuel lines were operated in a special test chamber which duplicated the firing of a J-2 engine in the vacuum of space. All eight fuel lines ruptured. Since the ice that formed on the fuel lines

during ground tests did not form in space, the vibrations were not dampened in space. This was the reason that a fuel line could break "after a few minutes of vibration in space" (90:60). The problem was solved by substituting a "rigid stainless steel pipe" (90:60) for the flexible fuel lines. "Thousands of man-hours" (145:171) were required to identify and correct the stated malfunction. The cause of both J-2 engine failures during the second Saturn V launch was specifically attributed to the "fatigue failure of a small liquid hydrogen line" (145:240).

To reduce the enormous technical risks associated with landing a man on the moon and returning him safely to earth, the United States implemented a series of spaceflights designated as Project Apollo. One of the major technical decisions involved the actual flight path and moon landing technique that would be followed in order to land on the moon and return. It was known that the flight profile, in turn, would govern the "configuration of the entire vehicle" (11:33). There were strong arguments between "NASA and the academic science community" (11:33) regarding this issue of the flight path and the moon landing technique. In late 1962 a technique called the Lunar Orbital Rendezvous (LOR) method was generally accepted. Under the LOR method, the spacecraft would orbit the moon upon arrival. Then, one section would detach from the orbiting spacecraft and land on the moon's surface. For the return, the detached section would blast off from

the moon's surface and rendezvous (join) with the orbiting portion of the spacecraft (11:33,35).

The Apollo spacecraft consisted essentially of three parts. The Command Module (CM) contained crew controls and living space. The Service Module (SM) contained the propulsion system, fuel and other. The Service Module was connected to the Command Module but the SM was jettisoned prior to re-entering the earth. Finally, the Lunar Module (LM) had an ascent and descent stage that was used to carry the astronauts between the CM, which remained in lunar orbit, and the lunar surface. All of this sat atop the Saturn V rocket during launch (91:40).

Due to heavy schedule pressure, NASA management decided to do "all-up" flight testing. Instead of testing component by component, gradually building confidence in the system, the full apparatus would be tested in ready-to-fly configuration. This all up approach was considered to be unorthodox engineering (11:35).

Gemini Space Vehicles. The Apollo program had been preceded by the considerable, but less ambitious, United States space endeavors such as Project Mercury which was the first United States manned space program, and Project Gemini (91:80-82,65-67). Project Gemini was the successor to Project Mercury. The Gemini series of space vehicles (12 in the series) provided the astronauts and ground crew valuable experience in activity (i.e., spacewalks), rendezvous and docking, long duration flights,

and guided re-entry. This experience was to prove invaluable (91:65). In fact, the first in-space emergency occurred during Gemini 8. On 16 March 1966 the Gemini 8 spacecraft with Armstrong and Scott achieved the first in-space docking with an Agena target rocket placed in orbit 101 minutes earlier" (91:66). After linking, the two vehicles started "tumbling and spinning out of control" (91:66) due to a jammed Gemini thruster. Armstrong and Scott "escaped only by firing their retro-rockets" (91:65) and returned to earth two days earlier than planned. Also, tragically, the original crew of the Gemini 9, See and Basset, died while trying to land "a jet fighter in bad weather at McDonnell works" in St. Louis (91:67).

The Apollo program started off with tragedy

. . . when on 27 Jan 1967 a short circuit in the electrical systems set fire to the all-oxygen atmosphere while the crew, Virgil Grissom, Edward White and Roger Chaffee, were carrying out a full launch rehearsal on Pad 34. White, reaching back over his head was unable to open the hatch in the few seconds before the crew was overwhelmed. (92:53)

In the wake of the tragedy, major re-design of the space-craft cabin and marked improvements to the crew operations were undertaken to greatly minimize crew safety risks (77:71,271; 92:53).

Site Selection. To reduce the enormous technical and operational risks involved in achieving a roundtrip manned moon landing, each flight in the Apollo series tackled increasingly difficult technical and operational

milestones. Some highlights of selected Apollo flights are presented below. Technical teams, especially geologists, devoted 5 years looking for a suitable lunar landing site. Several of the flights in the Apollo series, particularly those which orbited the moon, had an objective of observing possible lunar landing sites. Such detailed surveillance and selection of potential lunar landing sites was necessary to curtail the risk that the moon lander would slide off a cliff, or land on uneven ground and overturn. It was further necessary to verify that the surface was firm enough so that the lander would not sink and be swallowed up upon landing. Some of the stated technical risks connected with the lunar surface were addressed by the series of Ranger and Surveyor spacecrafts. Rangers 1 and 2 were orbited around the Earth "to check out instrumentation" (145:191). Rangers 3 through 6, intended to explore the moon, failed, but in 1964 and 1965, Rangers 7, 8 and 9 relayed some 17,000 images" (150:44) of the moon's surface before crash landing onto the moon. The pictures, with resolution of 1 foot, showed rocks on the moon's surface and indicated that the surface could support some heavy objects (145:191; 150:43,44).

However, site selection, had to take into account other risk factors such as "communication, tracking, fuel capacity, rocket performance" (150:44). When the Soviet Union's Luna 9 and the United States' Surveyor I probes both landed on the moon in 1966, the moon's surface was

"barely dented" (150:45). Follow-on Surveyor probes established the properties and chemical composition of the lunar surface. Once it was determined in what areas to concentrate the search for landing sites, a series of five Boeing-built Lunar Orbiters were sent to photograph the lunar surface so that by February 1968, five potential lunar landing sites were selected by relying on the expertise of geologists. The top two candidate sites were then observed by astronauts in Apollo 8 and 10 during lunar orbits as low as 10 miles above the lunar surface. The information obtained from the Surveyor and Orbiter probes was crucial for the planning of the Apollo manned mission (145:193; 150:46,47).

Simulator Training. While the geologists were searching for a safe and suitable landing site, the astronauts were training for the actual moon landing operations. In order that the astronauts could simulate landing on the moon, a Lunar Landing Training Vehicle (LLTV) was built. The LLTV was a truss assembly (no wings) built around a vertically placed jet engine. The thrust allowed vertical takeoff and landing. When the LLTV thrust was adjusted to support five-sixth of the vehicle weight, the LLTV could be used to effectively simulate the effect of landing in lunar gravity from about 500 feet above the moon's surface. "To prepare the astronauts for emergencies, the LLTV was occasionally programmed to fail" (150:44). There were a number of occasions when an LLTV

pilot had to eject from a malfunctioning LLTV. When the attitude control rockets--which kept the flight stable--shut down putting the LLTV into a spin, Neil Armstrong ejected at 200 feet. Another NASA pilot had to eject during another attitude control failure, while yet another pilot ejected from an LLTV that was blown out of control by strong winds (150:44).

Apollo 7. The October 1968 Apollo 7 flight, although confined to Earth orbit, was the first manned flight of the Command and Service vehicles. During Apollo 7, the main propulsion engines of the Service module were fired automatically as well as manually, and the engine performance was evaluated. Further, the heat shield of the vehicle was evaluated during re-entry (92:53).

Apollo 8. While the Apollo 7 operations were confined to Earth orbit, the December 1968 Apollo 8 flight was man's first flight around the moon. In fact, it was the first time that the 3000 ton Saturn 5 rocket had been used to launch men into space. During the 147-hour Apollo 8 mission, the crew achieved the critical lunar orbit insertion. They spent 20 hours circling the moon, and photographed potential landing areas (92:53; 149:1).

Apollo 9. Apollo 9 continued the trend of incrementally reducing the technical risks associated with landing a man on the moon. The March 1969 Apollo 9 flight was confined to Earth orbit, however, it was the first manned flight with the Lunar Module. During the ten day

flight, separation, rendezvous and docking was practiced between the Lunar Module (LM) and the Command Module (CM). Although the flight was confined to earth orbit, some operations were nevertheless performed to simulate a moon lift-off (92:53). Apollo 9 the May 1969 Apollo 10 flight was "a successful dress rehearsal for the Moon landing [that occurred] two months later" (92:53). During the Apollo 10 flight, the entire Apollo spacecraft orbited the moon for the first time. To simulate a moon landing, the Command Module maintained a 111 kilometer orbit around the moon, while the Lunar Module, with Stafford and Cernan on board, separated and descended twice to nearly 14.5 kilometers from the surface of the moon. The Lunar Module then re-docked with the Command Module after a separation of 8 hours (92:53).

Apollo 11. Finally, the July 1969 Apollo 11 flight, with the crew of Neil Armstrong, Edwin Aldrin and Mike Collins, resulted in the first men on the moon (148:1). However, despite the previous Apollo flights, there remained significant sources of risk that were evident during the Apollo 11 flight. For instance, on the way down to the moon in the Lunar Module "Armstrong decided to take over manual control because the spacecraft was approaching an area in the Sea of Tranquility strewn with boulders" (92:54). In fact, "had Armstrong not taken control [the craft] might have overturned or smashed on alighting" (116:765). Other technical risk was evident

since it was confirmed that one of the on-board computers was over-loading. That computer "was a vital part of the radar system which calculated the LM's [Lunar Module's] attitude and rate of descent, and on which the life of the crew depended" (92:54).

Although the Apollo 11 flight put the first men on the moon on 21 July 1969, there were nevertheless near disasters on some of the later moon landing flights. This clearly illustrated that the sources of technical risk were not eliminated. For instance, the November 1969 Apollo 12 mission

. . . started sensationally, for as the launch was being made through a rain squall, the Saturn 5 rocket was struck by lightning. The spacecraft's electrical system was briefly put out of action and for the first time during a manned launch they were very close to an abort. (92:55)

But, the flight was not aborted and the crew members of Apollo 12 went on to complete a mission that resulted in 31.5 hours of walking on the moon (92:55). Appendix G provides a brief chronology of the achievement of a man on the moon.

Apollo 13 Accident. The April 1970 Apollo 13 mission had been planned to be the third moon landing mission. However,

. . . an explosion on board when the spacecraft was 329,915 km from the earth all but cost the lives of the crew and turned the mission into a 3.5 day rescue drama . . . as tens of thousands of technicians worked to bring the crippled spacecraft safely home. (92:56)

Initially, it was determined that due to the explosion only half the power, water, and oxygen that was needed to get the crew home, would be available. However, based on simulations that were done by technicians on the ground, some ways were found to conserve energy by powering down systems. This unfortunately meant that the cabin became increasingly cold and disaster threatened again ". . . when the astronauts, tired and chilled, made mistakes" (92:56). For the journey home, it was necessary for the astronauts to move into the Lunar Module and use it like their "lifeboat [a backup craft for their safe return] . . . using a jury-rigged arrangement . . . to purge carbon dioxide from their atmosphere" (92:56). It was later determined that an oxygen tank had overheated and exploded since some "heater switches had welded shut when subjected to excessive pre-launch electric currents" (92:57). The exploding tank took another oxygen tank out of commission as well. Astronaut Lovell--one of the Apollo 13 crew members--concluded that

. . . warning signs during testing went unheeded, and the tank, damaged from 8 hours of overheating, was a potential bomb the next time it was filled with oxygen. That bomb exploded on 13 April 1970--200,000 miles from Earth. (92:57)

This illustrates that testing--intended to decrease technical risk--if done incorrectly, can actually increase technical risk by causing damage (92:56,57; 147:1).

Space Shuttle Challenger Disaster. Inadequately managed technical risk has resulted in disasters and national defense setbacks. The in-flight explosion of the Space Shuttle Challenger (Flight 51-L) on 28 January 1986, resulted in the death of seven astronauts on board the shuttle, and the concomitant loss of part of the military space operations capability. Investigations revealed that the hot exhaust gases in a solid rocket motor of the space shuttle eroded, and then bypassed two "O-ring" seals. These hot gases eventually ignited the hydrogen in the nearby space shuttle External Tank, thereby causing an explosion. However, the potential for just such a disastrous O-ring sealing failure on the solid rocket motors had been identified as early as 17 December 1982 and the failure potential of the seals was under study at the time of the disaster. Indeed, Morton Thiokol, Inc., producer of the solid rocket motors, had recognized the need for improvement of the field joints as well as the motor case/nozzle joint prior to the accident (68:3; 102:38). In the wake of the Challenger disaster, nearly 220, 155, 31 and 8 modifications were made, respectively, to the Orbiter, solid rocket motors, main engines and external tank. In particular, a third "O-ring" and a metal seal feature was added to the solid rocket motor field joint (12:1; 67:10,11; 93:24; 102:38,39; 103:24-26).

Some of the major changes that were made to the Space Shuttle solid rocket motors to reduce technical risk were

actually quite mundane, yet very important. These included the following:

Heaters to maintain seal temperature at 75 degrees Fahrenheit or above, a weather seal to prevent water entry into the joint and possible freeze-up, longer pins [used to hold the rocket segments together at each joint] and new retention bands, an alternative insulation (J-seal) to eliminate the putty previously used. (67:11)

In addition to the hardware changes that were made, a number of procedural changes were recommended by the Presidential commission that investigated the accident. The commission recommended that detailed testing of the solid rocket motor joint be conducted in the "exact flight configuration in the vertical position" (67:10), and that the National Research Council oversee the NASA re-design of the solid rocket booster or joints (67:10-13).

Other commission recommendations included an increased emphasis on rotating some former astronauts into management positions. Further, the commission recommended that a major effort be undertaken to provide a crew escape capability and an improved in-flight launch abort capability for the space shuttle. Most of the recommended changes were implemented (67:32). Thirty-two months after the Challenger disaster, the shuttle named Discovery, with five astronauts aboard, was flown to a successful mission (93:20).

After the Challenger disaster, NASA intensified their three-step risk analysis effort. The NASA three-step risk

analysis effort consists of a Failure Modes and Effects Analysis (FMEA), a Critical Items List and a Hazard Analysis. The FMEA is conducted to identify hardware that are "critical to performance and safety of the vehicle and mission" (67:8). As the second step, NASA makes a Critical Items List (CIL) which identifies those components whose failure alone (i.e., a single failure) would cause either loss of life, vehicle or mission. The CIL contains the rationale for those specific components in the design that do not have redundancy. Such rationale should provide "information regarding the (1) design, (2) tests accomplished to assure integrity of the hardware, (3) specific inspection points, and (4) operational means to mitigate the failure" (67:8). The CIL is based on the results of the FMEA. As the third step, NASA conducts a Hazard Analysis (HA). The purpose of the HA is to identify and recommend necessary corrective actions for those potential sources of risk that arise during the operation and maintenance of the system hardware and software. The HA also examines sources of risk arising from man/machine interfaces (e.g., the crew), the environment, and mission-related activities (67:7-9).

Inertial Upper Stage Anomaly. Three years before the Challenger disaster, on 5 April 1983, hot exhaust gases were also cited for eroding and thereby bypassing seals on the Solid Rocket Motor #2 (SRM-2) of the Inertial Upper Stage (IUS) booster. This ultimately resulted in a mission

anomaly whereby a NASA satellite--the Tracking Data Relay Satellite (TDRS)--was placed in an incorrect orbit. The combined TDRS satellite and the IUS booster had been released from the payload bay of the Space Shuttle in low Earth orbit (less than 200 miles above Earth). During this sixth space shuttle mission the IUS was supposed to boost the satellite to the much higher geosynchronous orbit. However, the combined satellite and IUS booster began to tumble in space about 83 seconds after the start of the SRM-2 burn. Specifically the Inertial Upper Stage Anomaly Board investigation concluded that the failure resulted in an IUS "nozzle gimble mechanical failure" (4:4) that resulted in the SRM-2 nozzle being jammed in an off-center position. Due to the mechanical failure the nozzle positioning actuators were unable to correctly reposition the nozzle until the SRM-2 motor burned out (i.e., finished thrusting). The author of this thesis was in the Inertial Upper Stage Systems Program Office at the time (4:4). However, the engineers were later able to successfully execute a plan to command the satellite to fire its small rocket thrusters and finally achieve the correct orbit (4:4; 120:116).

In fact, the technical risk from "flame erosion" (66:39) caused by the leakage of hot gases has even been manifest after post-firing inspections of the Phoenix missile in April, 1986 (66:39).

AFOS Software Development. A 1982 GAO report cited that the National Weather Service's automated data processing and telecommunications system was undergoing some major technical, scheduling and managerial problems relating primarily to software development. The system is called the Automation of Field Operations and Services (AFOS). One of the problems cited was that the "AFOS hardware lacks sufficient core memory to accommodate current software or applications initially planned for AFOS; the Weather Service cannot tell how much more memory is needed" (65:ii). In addition, the operating system could not "meet concurrent processing requirements originally specified" (65:ii).

The GAO cited that one of the major problems was that the software was "unnecessarily complex" (65:31). For example, each of the software modules in the AFOS were made so interdependent that even minor changes to one module caused major technical repercussions to the other modules. This module interdependence also complicated the troubleshooting of programs. In addition, the AFOS system would experience "deadlock when the computer [attempted] to process two or more tasks that need the same resources" (65:31). Also, information that was being input would be lost if the system malfunctioned during the inputting (65:31,32). One of the primary causes of problems with the National Weather Service (NWS) software was NWS inexperience with software projects of that magnitude. Due

to inexperience, the NSW had erroneously assigned a higher priority to the data processing hardware than to the software development procedures (65:31). In fact, the GAO found that "development priority was not clearly established and top priorities [were] ignored in favor of low priority work" (65:21).

Changing user requirements meant that completed software work had to be redone. A large amount of technical risk also stemmed from inadequate design specifications. With only ambiguous specifications to guide them, each programmer tended to act independently rather than as part of a coordinated team. An outgrowth of this was that the software documentation so "critical to effective software development and operation" (65:35) was clearly deficient (65:31-35).

Space Defense Initiative (SDI)

The Space Defense Initiative (SDI) is a "program to determine the feasibility of developing and deploying a defense against nuclear ballistic missiles" (72:1). To reduce the inherent technical risks, the SDI organization

has used . . . 3 parallel contractor efforts to analyze technology, propose preliminary system concepts and associated mission performance and interface requirements, define data needs for sensor design, and develop preliminary demonstration plans. (72:4)

The technical risk reduction strategy includes the conduct of some "technology validation experiments" (71:1)

by the Army's Strategic Defense Command. The objective is to demonstrate that issues regarding critical technologies are resolved so that the risks in any ensuing full scale development phase are also reduced. For instance, to ensure that effective sensors for a strategic defense system can in fact be developed, the Army had initially pursued two competing sensor designs. In fact, it has been determined that three types of sensors--corresponding to the three trajectory phases of launch, midcourse and terminal--would be necessary. Technical risk has also been identified in connection with the design of a sophisticated data processor and with the air turbulence expected during airborne tests of sensors (6:94; 71:12). Key technologies have been identified for SDI such as

1. component technologies for long-wave infrared sensors including optics, detectors, signal processors, and cryogenic coolers, technologies for laser
2. technologies for laser radars and space-based radars. (72:3)

However, it is clear that a host of experimental or new technologies may eventually be necessary to achieve an actual strategic defense. As a result, the Livermore National Laboratory is carrying out X-ray laser research in support of SDI (69:1,2). It is possible that space nuclear rocket technology will become very important for SDI applications (64:8,11). The SDI program is also highly reliant on analytical capability consisting of

supercomputers, software and analysts, in order to test and evaluate a number of potential strategic concepts and systems for battle management and command and control. As of early 1988, there was difficulty in achieving a timely, secure (i.e., cryptographic) supercomputer link between three key analytical sites (70:1-5,9).

National Aero-Space Plane

The National Aero-Space Plane (NASP) program was established in December 1985 as a joint Department of Defense and NASA program. The program involves such Department of Defense agencies as the Air Force, Navy, DARPA, and SDIO, (60:1-10) and was established as a "development and demonstration program" (60:22). The NASP has been tentatively designated as the X-30 since it is "an experimental vehicle and not a prototype or operational vehicle" (60:27).

To reduce the technical risks in building the prospective X-30, the technical community has identified "critical or enabling technologies" (60:10) whose availability and maturity should be monitored. Such technologies include advanced strength, refractory (i.e., high melting point) materials. To gauge the technical risk to the NASP, engineers have compared the anticipated flight trajectory of the NASP to that of the Space Shuttle. While the Space Shuttle "reaches orbit very quickly in an almost vertical flight trajectory, the X-30 would achieve speeds

of Mach 25 in the upper atmosphere before [achieving] orbit" (60:13). Further, the X-30 would take off horizontally and be essentially air breathing while the Space Shuttle does neither. However, the re-entry trajectory for the X-30 is expected to be the same as the Space Shuttle (19:67-68; 60:12-15).

The anticipated X-30 trajectory has also been compared to that of existing aircraft. Thus it is expected that the "X-30 must be designed to fly ten times faster and higher than existing air-breathing aircraft" (60:12). The X-30 is therefore expected to spur greater emphasis on hydrogen fuel technology (19:71; 60:12,15,40).

According to NASP and NASA scientists, the greatest technical risk connected with the X-30 is "the development of an air-breathing propulsion system" (60:25). However, the development of suitable materials and the integrating of the X-30's major subsystems such as the thermal control, structures, propulsion and avionics, also provide formidable technical risks. Indications are that the X-30 design and development will require significant computational resources. In particular, there is a known requirement for "computational fluid dynamics to predict the aerodynamic, thermal and propulsion characteristics at . . . (Mach 8 to 25)" (19:71; 60:25; 122:14).

The NASP program office has formulated a strategy for reducing the technical risks. One of their groundrules is that existing national facilities (e.g., wind tunnels and

laboratories) will be used where possible to preclude delays due to construction of new facilities (60:26). Indeed, it has been contemplated that a suitably instrumented space shuttle could be used to aid the X-30 design. Another groundrule is that more than one technical approach will be pursued for high risk components or systems to increase the chances of finding appropriate solutions in a timely manner. Consequently, the NASP program intention is to compete a number of contractors with the expectation that each contractor will pursue different--perhaps even highly different--conceptual approaches. Simultaneously, the NASP program intends to promote efforts to advance those technologies that are critical to the X-30. Additionally, a series of milestones, with corresponding design reviews and key decision points, have been established in order to facilitate the reduction of technical risks (60:26,35-40).

The plan is to minimize safety risks connected with the X-30 by incorporating the appropriate safety features into the design and operation of the vehicle. For example, the X-30's propulsion engine will have at least two engines, and the flight control system is planned to have four backups. Some features of the vehicle's operation would also contribute to safety. The flight trajectory is such that the vehicle would largely fly above adverse weather (60:45-47). In the event of an aborted mission, the vehicle will be able to maneuver and make a powered

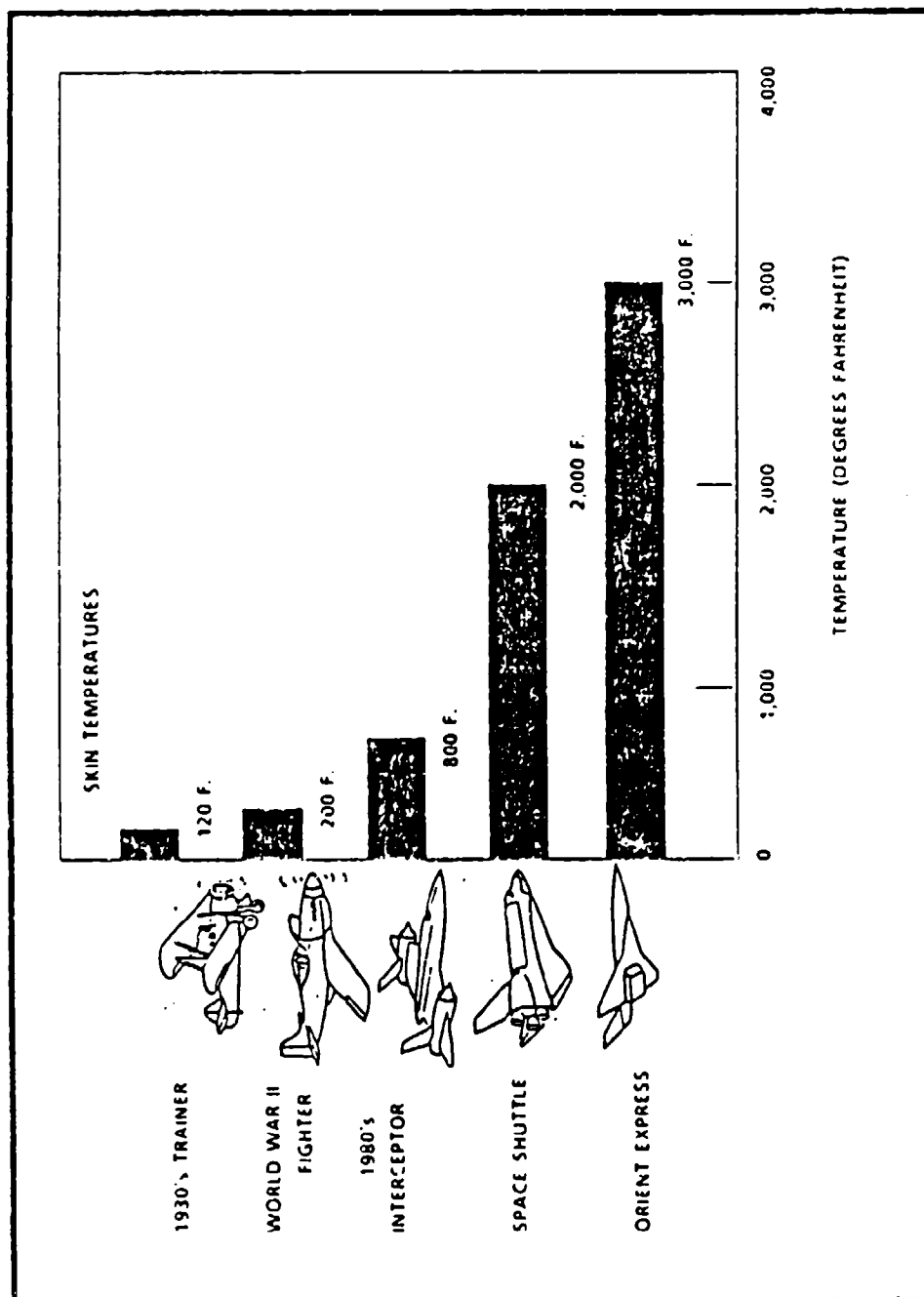


Figure 6. Technological Trend of Increasing Aircraft Skin Temperature (140:68)

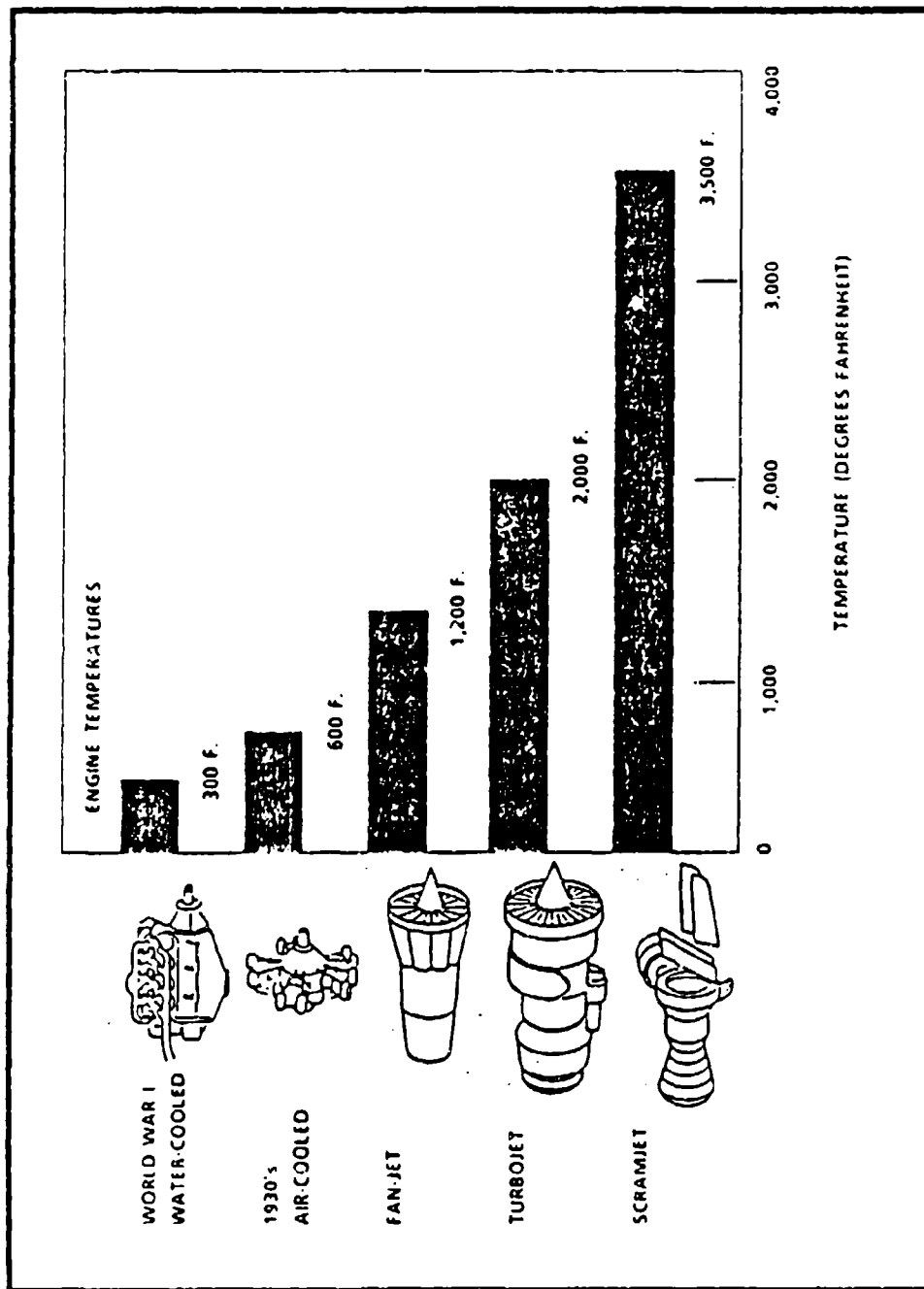


Figure 7. Technological Trend of Increasing Engine Temperature (140:68)

landing. The use of the intended hydrogen fuel has been determined to pose less danger than conventional fuels "since its ignition temperature is 1,065 degrees Fahrenheit or twice that of aviation grade kerosene" (60:46).

However, the technical strategy has taken into account other sources of technical risk. There is a risk of foreign object damage to the X-30 since "small rocks on the runway, hail, ice, rain, or even space debris" (60:46) could pose considerable danger primarily to the X-30's engines and skin. Some peripheral technical concerns have also been considered such as the need for new fuel processing and handling procedures (60:46-48,77,78).

Summary of Case Studies

The case studies reveal that the sources of technical risk vary and may be unanticipated. For the F/A-18 aircraft, the technical risk was due to new materials (composites) that were used, the underestimated need for computer memory capacity, and certain in-flight failures that led to crashes. For the Chernobyl Reactor, human error and poor design introduced technical risk. For airplane development, the Wright Brothers addressed technical risk by carefully determining the cause of Lillienthal's fatal crash and then identifying and concentrating on solving what they determined to be crucial for achieving successful flight. Specifically, the Wright Brothers gave the solving of the flight equilibrium problem

priority over the development of a suitable engine or propeller. To develop the rocket, Robert Goddard worked to first understand such critical rocket components as rocket nozzles, combustion chamber and propellant feed system and then conducted numerous captive and flight tests of rockets. The Atomic Bomb development required not only the achievement of unprecedented production (i.e., separation) techniques for plutonium and uranium isotopes, but also new analytical techniques (e.g., Monte Carlo method) and computational tools (i.e., the electronic digital computer). Laser development required an extrapolation from maser principles and the overcoming of difficulties in the preparation of an appropriate optical material.

The Apollo 11 landing of a man on the moon required that certain formidable prerequisites be satisfied such as the development of a high thrust vehicle (the Saturn V), selection of the flight path and moon landing sites, and astronaut training. The technical risks were fundamentally overcome in stages via successive space flights leading up to the Apollo 11 moon landing. The Apollo 13 Accident, the Space Shuttle Challenger Disaster, the Inertial Upper Stage Anomaly and the AFOS Software problems clearly illustrate how inadequately managed technical risks can result in significant program problems, setbacks or disasters.

The case studies indicate some important potential "unknown unknowns"--factors which constitute unanticipated sources of technical risk. One potential unknown unknown

is the need for one or more secondary development efforts. For example, since no adequate engine or propellor was available to power an airplane the Wright Brothers had to develop both. Similarly, after initial launch failures, Goddard had to develop specialized high pressure pumps to force the fuel into the rocket chamber. The Atomic Bomb case study shows, one unknown unknown is the need for relatively unprecedented analytical techniques and tools. Figure 8 outlines various types of potential "Unknown Unknowns."

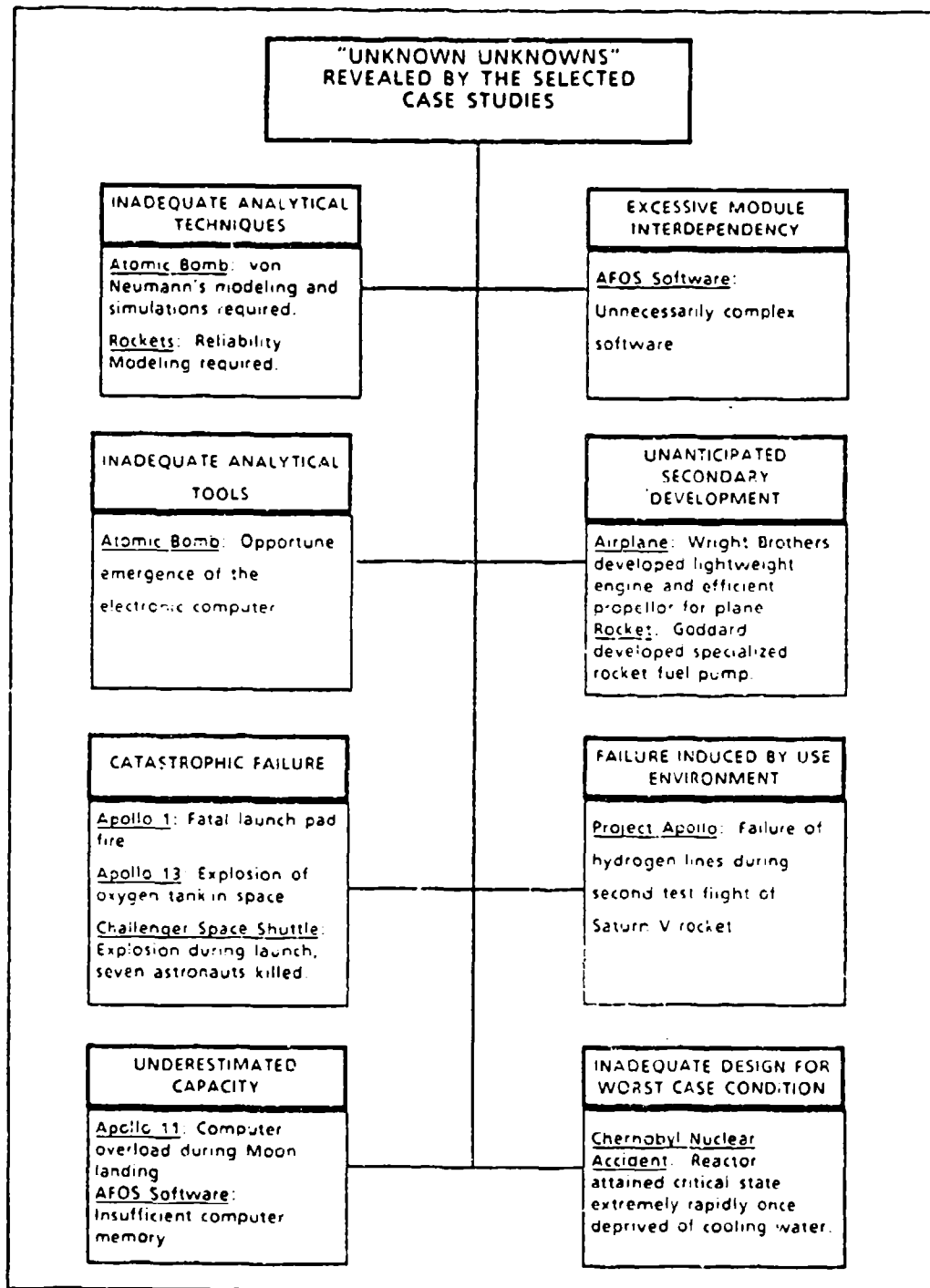


Figure 8. Some Potential Unknown Unknowns

IV. Model Development

Analysis Considerations

Decision making must often be made in the presence of risk. To reduce technical risk, correct and adequate risk assessments must be made by technical experts. Then follow-on risk analyses allow effective decisions to be made by identifying those alternatives that have the highest probability of success. According to Klopp, a successful decision (i.e., risk analysis), requires:

1. A problem to be solved
2. Viable and achievable alternative courses of action
3. Information
4. A decision maker
5. A decision strategy. (95:107)

Timson has presented the general model for system development decision making shown in Figure 9. Timson's model illustrates the potentially cyclical nature of system evaluation and revision. Similarly, General Thurman emphasized that ". . . the planning for uncertainty and risk turns out to be a dynamic and iterative process" (143:15). Further, the technical and performance risk is heightened because ". . . complex performance requirements [of multiple subsystems or components] . . . must interface perfectly. . . ." (143:12).

Prevention. Where possible, technical risk should be prevented. The way to achieve this is to select proven

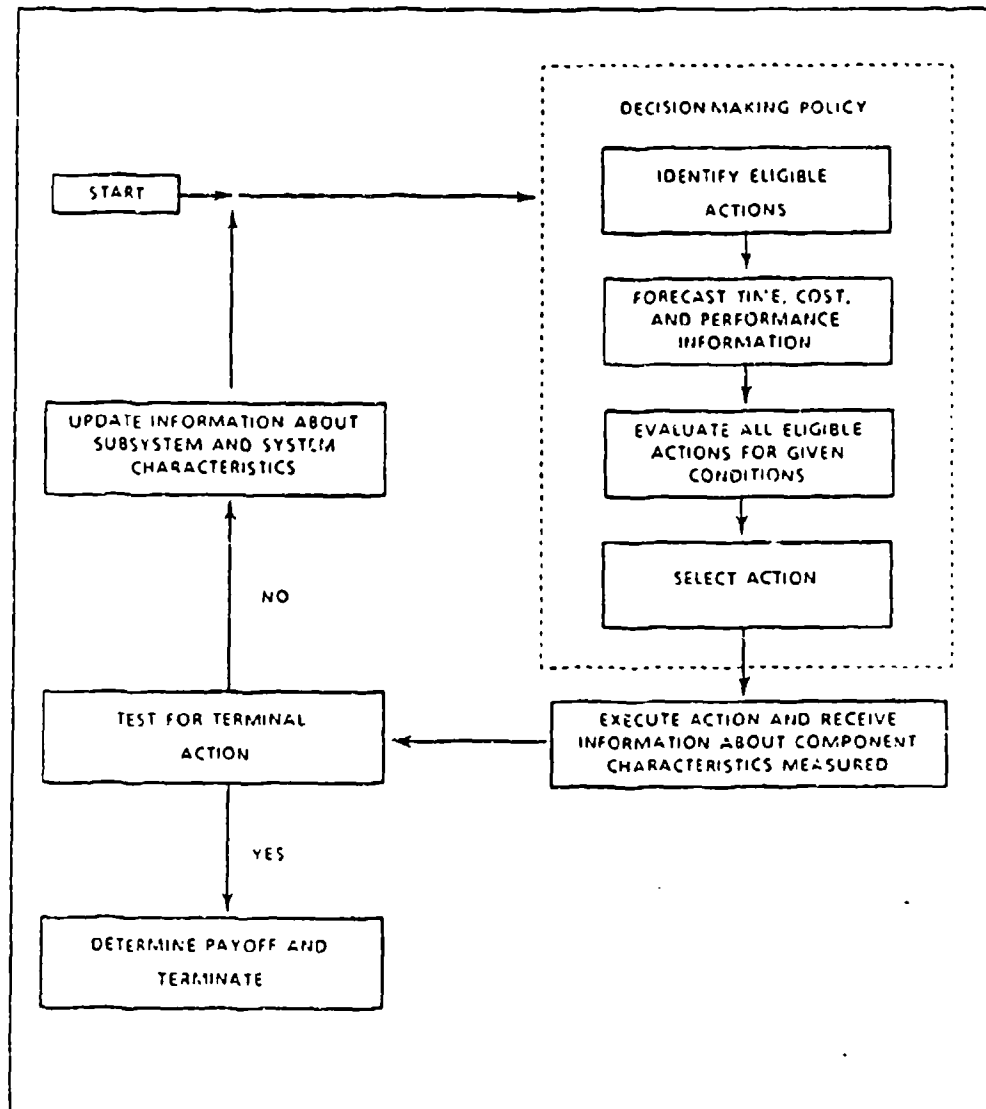


Figure 9. Model of System Development Decision-Making (144:32)

techniques, materials, and designs which involve very little uncertainty. However, a Rand report has stated that Air Force missions often require increasingly higher technology since "the newer systems must perform more functions . . . with greater precision . . . [with] more integration among functions" (129:23). This implies that technical risk is often unavoidable.

The prevention of technical risk is especially crucial where safety is concerned. Accordingly, MIL-STD-882B System Safety Program Requirements states that the first safety precedence is to eliminate hazards by an appropriate design. Thus the first design priority is, if at all possible, to design a system such that technical risk is eliminated. However, the total elimination of all technical risk in a particular system is rarely attainable. Therefore the second design priority is to minimize technical risk by appropriate design practices (3:113; 39:6).

Uncertainty as the Source Risk. Technical risk in complex weapon programs stems from uncertainties connected with ". . . inadequate knowledge of the basic technology or its specific implementation" (143:12). There is the initial pitfall that the actual technical problem being evaluated will be formulated incorrectly and will thereby result in the right answer to the wrong question (126:15). For a risk reduction plan to be effective, it must lead to successively more information which ultimately identifies

and reduces both the anticipated and unanticipated technical unknowns connected with a project. Klopp states that there is a "continuum of knowledge" (80:148) ranging between having no information and total information on the internal and external factors that govern the technical success of a particular system. Clearly, few good decisions will be made when there is no information. Instead, actions are often undertaken to obtain sufficient information prior to a decision. Therefore, the most important task of any decision maker is to identify where there is uncertainty due to incomplete information and attempt to resolve that discrepancy (80:148). Kraemer has proposed the risk assessment model of Figure 10 which results in a quantified risk assessment (i.e., probabilities). In particular, Kraemer has divided problems into "normal risk" and "higher risk" in his model. Henley and Kumamoto proposed the program risk assessment framework of Figure 11 which begins with a qualitative assessment of risk, that is then quantified and ultimately results in a risk management strategy.

Pitfalls. Although the general source of technical risk is uncertainty, more specific factors that contribute to technical risk are

1. Underestimation of the degree of the technological breakthrough required in a state-of-art of product development, while under a fixed and tight time and budget constraint
2. Pushing technology too fast
3. Lack of prototype development

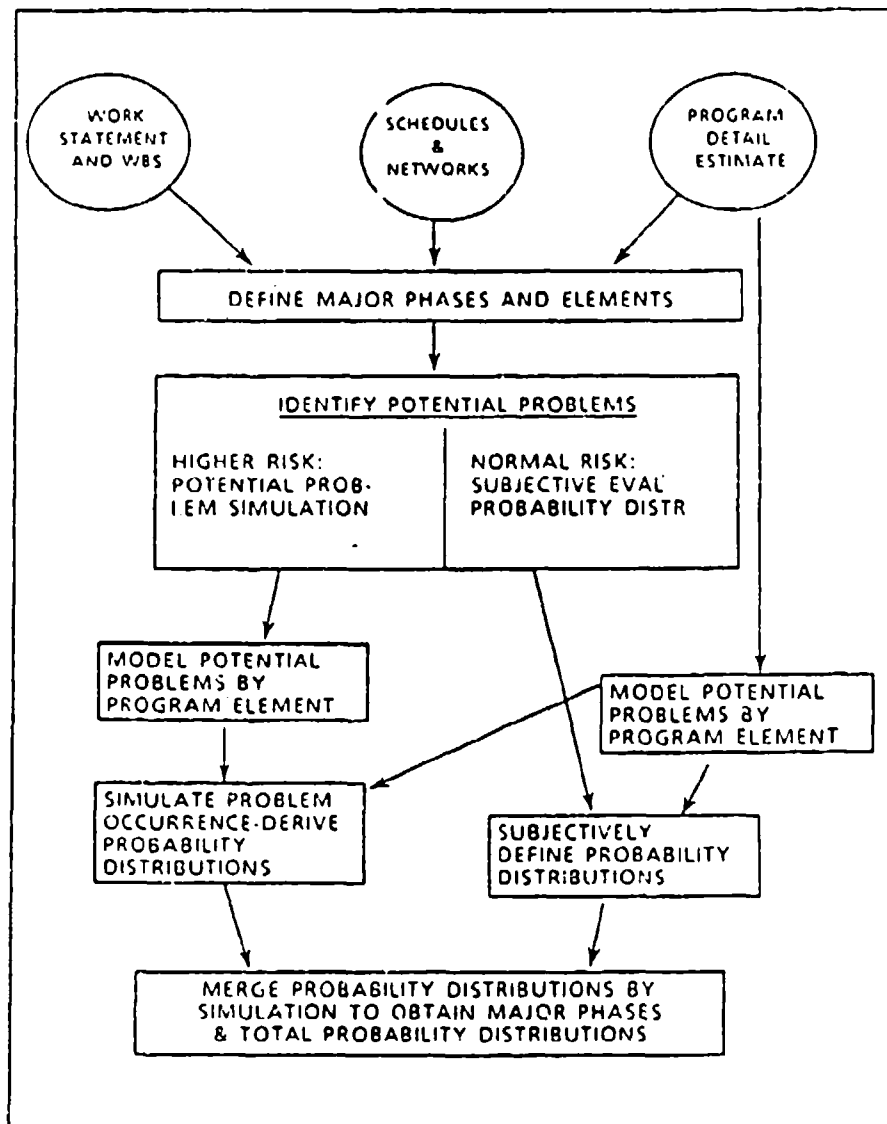


Figure 10. Risk Assessment Flow Diagram (99:224)

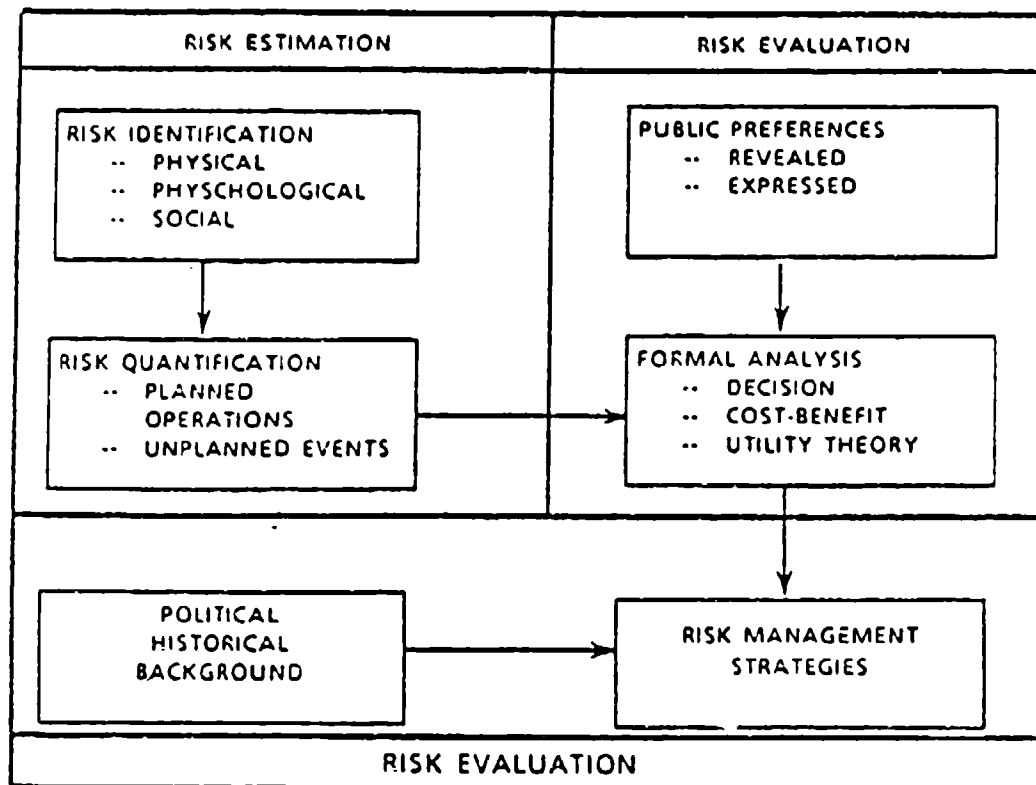


Figure 11. Henley and Kumamoto's Risk Assessment Framework
(89:14)

4. Performance requirements beyond state-of-the-art
5. Inadequate test program
6. Major design or scope changes. (132:35)

These stated factors can become pitfalls if they are overlooked. The case studies of the IUS and the AFOS illustrate that technical over-optimism leads to an underestimation of the technical risks involved. To ensure that the most realistic assessment of the technical risks are obtained as soon as possible, the system should be prototyped as soon as practical. Early prototyping of the system is especially important if the in-house experience level of the technical managers and designers is more theoretical than "hands-on". Early prototyping has been cited.

State-of-the-Art. Because technological risk is determined, in large part by the state-of-the-art, Rowe and Somers have proposed the factors cited in Figure 12 for evaluating the technological state-of-the-art (132). In general, the higher the state-of-the-art (i.e., the newer the technology), the greater is the technological risk involved. Accordingly, greater emphasis must be placed on early accurate risk assessment.

The technical success of certain development efforts often hinges upon advancements in a few critical areas. For instance, advancement in ". . . propulsion has led the way for all major advancements in flight velocities" (5:327). Therefore, accurate and timely identification

1. Size---number of interrelated components, physical volume
2. Complexity---difficulty in meeting performance requirement
3. Newness of technology---experimental state of technology
4. Percent proven technology---degree of newness
5. Experience in the field---work on similar programs
6. Percent new components---test and evaluation requirements
7. Interdependency of subsystems---types of linkages
8. Degree of precision---quality or cleanliness requirements
9. Special resources---testing or tooling requirements
10. Definitive specifications---clarity in meeting requirements
11. Design flexibility---tolerance level, substitutes available
12. Required theoretical analysis---need to support proposed design
13. Degree difference from existing technology---life cycle of technology
14. Available knowledge in the field---amount of experimentation required
15. Infra-structure support required---degree of dependency on vendors

Figure 12. Factors Determining the
State-of-the-Art (132:40)

of those high risk factors and components which are critical to correct system performance is mandatory for reducing technical risk. Once identified, these critical technical risk areas must be prioritized by experts and emphasized accordingly.

However, the technical success of one system may also be dependent upon the technical success of one or more separate, but allied, system or systems. For example, the GAO had determined that the "Anti-Submarine Warfare Standoff Weapon is subject to increased risk due to problems in a related program" (58:8). Technical risk also arises due to excessive interdependency between subsystems. The AFOS case study illustrated that if software modules are made highly interdependent, then a modification to one module will have repercussions to other software module and the system will be immensely complex to modify, troubleshoot or update. Therefore the interdependency of subsystems should be minimized unless absolutely necessary.

Expert Resources. To avoid or reduce technical risk, it is critical "that the proper specialists are asked the right questions at the right time and that their advice is heeded when given" (137:83). Technical development case histories illustrate, and Shannon stresses, that the violation of this fundamental concept in part or in total, is responsible for most technical failures.

Timing. Based on lessons that were learned in DOD acquisition it is well established that

. . . the concept phase is the critical phase for risk and uncertainty analyses; and that an innovative tailored approach is required for each program . . . the analysis at concept phase establishes the basis for the rest of the program by developing system specifications and technology base. (143:21)

Risk assessment and analysis is needed most during the concept definition phase--the earliest phase--of a development program, because it is here that technical uncertainty is greatest. In the concept definition phase, there are usually a number of general technical approaches that appear viable. The correct choice from among these approaches, along with successively correct choices within the selected approaches (e.g., design, materials and electronic components) is significantly aided by performing a risk assessment (24:V-11; 143:21). Further, it is critical that the risk assessment be available for decisions during the concept studies since "by the end of concept studies, 70 percent of the key decisions on the weapon system have been made" (128:138) according to Lt Gen Reynolds, formerly Vice Commander of Air Force Logistics Command.

Technical experts are required as early as possible to identify and select those design alternatives which will preclude as much technical risk as possible. Their expertise then becomes critical for minimizing risk in the design. However, because a "risk assessment is the first of the steps in a risk analysis" (10:12), the risk

assessment must be accurate or all the ensuing effort will be invalid to some degree.

Planning for Technical Contingencies. The technological uncertainty inherent in a new technology development program means that the "real world occurrence of technological breakthroughs, and catastrophes" (144:93), particularly the latter, must be realistically considered. Specifically, the responsible agency must ensure that ". . . historical safety data, including lessons-learned from other systems are considered and used" (39:4) to improve the contemplated or existing design of the system. Such effective design techniques such as simplicity, modularity, redundancy of subsystems, safety and design margins, etc., should be used to minimize the technical risk by design.

Among other things, the case studies illustrate that especially where new technology is involved, established analytical methods, analytical methods, test techniques, and facilities may be wholly or partially inadequate or invalid. Thus the success of the Atomic Bomb development was to a large extent dependent on Dr. John von Neumann's modeling of critical mass phenomena on one of the first electronic computers. It is probable that without either the contributions of Dr. von Neumann or the opportune emergence of the electronic computer, the successful development of the atomic bomb would have been impossible, or severely delayed. Similarly, it has been determined that the design and development of the National Aerospace

Plane (X-30) would require the use of computational fluid dynamics because "wind tunnels are of no use in modeling speeds above Mach 8" (122:14). In general, the case studies show that there are some identifiable categories of technical risk that are usually unanticipated. Some of these unanticipated categories of technical risks--unknown unknowns--were outlined above in Figure 8.

Analysis of Interviews. The interviews were conducted in accordance with the methodology of Chapter II. Appendices K through P contains transcripts of most interviews. The WRDC interviewees were virtually unanimous in stating that technical risk reduction is not the first priority of the laboratories. Rather the primary focus in the laboratories is in exploring the technical possibilities. For example, Dr. Olsen, Chief Scientist of the WRDC Flight Dynamics Laboratory, stated that "Risk is something that I don't think that we [the labs] manage much. We generally work on trying to prove that something is feasible and can be done. . . ." (119). However, the scientists stated that the laboratories are implicitly involved in technical risk reduction every day since the labs must ultimately transition sufficiently mature (i.e., low risk) technologies to the System Program Offices. According to Dr. Keith Richey, the Technical Director of WRDC, the labs ". . . make a conscious decision as to when to turn it [the technology] loose" (130) since they must transition the technologies relatively fast to the Air

Force at sufficiently low technical risk. According to Dr. Richey, there will rarely be zero risk in a technology that is transitioned to the SPOs since the labs cannot examine all possible applications of a particular technology (130).

Dr. Richey stated that acquiring ". . . as much knowledge as you can have on the physical and non-physical phenomena that you are dealing with" (130) is the most important technique for managing technical risk. Similarly Dr. Harris Burte, Chief Scientist of the WRDC Materials Laboratory, emphasized that "it is important to identify what you know and what you don't know and that what is what is not known is probably the most important source of technical risk" (14). According to Dr. Arnold Mayer, Chief Assistant for Research in the Vehicle Subsystems Division, analysis, mathematical and physical models, tests, and demonstrations, are used in the iterative process of investigating feasibility and that this equates to investigating technical risk (106). Mr. Jack Cannon, ASD's Technical Director for Development Planning, stated that "if you had to select one, then certainly prototype testing is the way you reduce risk" (17). Similarly, Dr. Squire Brown, Chief of WRDC's Technology Assessment Division, stated that a suitable demonstration (e.g., flight demonstration) is essential (13). It became very clear from the interviews that in Dr. Olsen's words: ". . . risk in the laboratories is not the same as risk in a SPO" (119).

Model Review Comments

The preliminary model was revised to incorporate comments of the panel of experts. Some specific written comments from their reviews may be found in Appendix J. However, many of the comments that were provided were written on the actual copy of the preliminary model. In addition, information obtained during the interviewing of the experts was also incorporated into the model.

The model had initially indicated that the System Requirements Specification is written just prior to the concept exploration. However, Dr. Squire Brown's comment was that it would most likely be a "needs" statement at that stage. He also indicated in his review that, in his words, "there may be an intermediate stage before prototype--a technical demonstrator like the X-29, followed by the Advanced Tactical prototype." The model was revised to incorporate these comments (under Stage 3 and Stage 7 of the model, respectively). Because Dr. Brown also expressed that some transitions in the model were unclear, he was provided a later subsequent version of the model for an additional review.

Dr. Jess Riles' first model review comment (Appendix I) was the question "Where does cost enter into the model?" Although the scope of this research (as stated under Scope, Limitations, and Assumptions in Chapter I) does not expressly address costs, Dr. Riles' rationale that "Technical feasibility may be demonstrated but may not be

affordable," is compelling. Therefore, a (prerequisite) block was added under Stage 1 of the model that requires that one "Identify and Confirm Funding Constraints." His other two comments were in accord with the research groundrule that some technical feasibility of the development program in question has been demonstrated.

After Dr. Squire Brown's second review of the evolving model, he had some additional comments. Specifically, he recommended that the design priority sequence be corrected to show that the first design priority in Stage 8 is to achieve the primary performance objective of the system and only then is the rest of the design priority sequence valid. These comments were discussed by phone with Dr. Brown and then incorporated into the model.

Model Presentation

The synthesized risk management model is divided into ten stages and can be found later in this chapter beginning on page 131. Citations are provided to document the specific source whereby each respective model component was derived. Many of the model components have multiple citations where necessary to fully document the model synthesis. Some blocks in the model indicate pertinent technical risk management examples. These specific examples are in lower case letters and enclosed within bracket; all other citations pertaining to the block are placed outside the bracket. For example, on the first page

of the model, the Atomic Bomb is listed in lower case as an example in the block entitled "Identification of a Real or Potential Threat." The citation pertaining to the Atom Bomb example is placed within the brackets.

Logic Symbols. The model uses or and and logic symbols or "gates" as shown in Figure 13. For the or gate, a correct output occurs at D only if input A or input B or input C is present, or if all three inputs are present simultaneously as inputs to the or gate.

For the and gate in Figure 13, a correct output is obtained at D only if all inputs to the and gate, inputs A and B and C, are present. If any of the indicated inputs to a particular AND gate are missing then no (valid) output will be obtained at the output of that particular and gate. Thus, the and gate is literally being used as a "gate" in the model that ensures that the correct inputs are obtained before any output is passed on as an input to the next succeeding task.

Main Line. A key feature of the model is the Main Line. This is the thick, black line on the left hand side of every page of the model. The risk management tasks flow along the Main Line subject to the fulfillment of prerequisites. These prerequisites are indicated by blocks that are off of the Main Line but which are generally inputs to AND gates along the Main Line. For ease of reference, all blocks along the Main Line, except those in Stage 8 of the model, are numbered sequentially. The Main

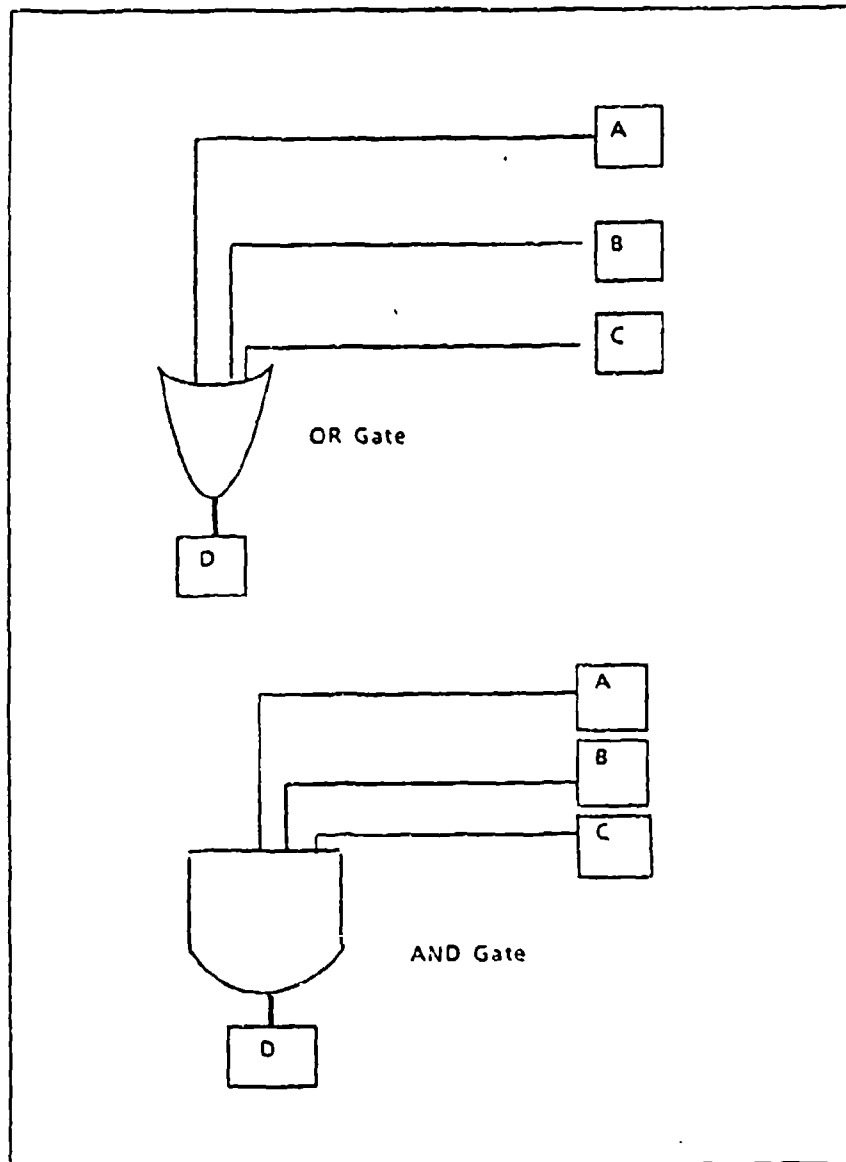


Figure 13. OR and AND Logic Gates

Line blocks in Stage 8 are distinct due to their "priority" assignment.

Design Diamonds. The model contains four diamond-shaped blocks which indicate that specific "Yes/No" question is asked and the corresponding path, analogous to a decision, is then followed in the model.

Requirement Block. The model actually starts with the Requirement Block. The OR gate that precedes the Requirement Block has four inputs: (1) the requirement may be mandated, (2) resulting from a deficiency, (3) stem from a threat, or (4) be due to the decision to pursue a particularly mission-enhancing capability. After the Requirement Block, the model is divided into Stage 1 through Stage 10.

Stage 1. After the requirement has been specified and authorized, we proceed to block 1 where we "Identify Appropriate Technical Disciplines and Experts . . ." that are pertinent to the specific requirement. However, this identification of experts can be correct only if the appropriate representatives from the using organization, and laboratory experts, and individuals with previous experience, that are pertinent to the requirement, have been identified.

Stage 2. Similarly, we should proceed to Stage 2, the Initial Study by Experts, only if the three identified prerequisites for the first step in Stage 2 are satisfied. During this stage the requirement is confirmed and

communicated to the experts) along with any salient priorities within the requirement that the using organization has identified. This way when the cadre of (national) experts--of the correct diversity, depth, and breadth of expertise--have hopefully studied the requirement somewhat prior to their assembly. It is therefore possible that the experts may arrive at the first formal assembly having already identified some of the "Key Variables Governing Successful Achievement of the Requirements" or with an understanding of various technical tradeoffs that may eventually have to be investigated prior to the system design (Blocks 4 and 5). For example, for a rocket booster as the Project Apollo case study made clear, there is a trade-off between the weight (e.g., structural strength) and the payload carrying capability.

At Block 6, the broad technical objectives of the system are initially specified. These objectives should be consistent with the operational requirements from the using organization. At Block 7, the system's technical objectives are initially prioritized although this may have to be revised based on results of forthcoming analyses or prototyping. For an effective prioritization, one prerequisite is specific previous experience, by the individuals doing the prioritization, is mandatory. The other immediate prerequisite shown for Block 7 is a network of the technical tasks (e.g., a PERT network) would be essential for showing the interrelationship among the tasks

and for ultimately determining the potential impact of late completion of technical tasks on the entire system development schedule. At Block 8, a systems requirements statement--much more general than a specification--is written.

Stage 3. During Stage 3, the concept exploration and technical risk assessments are conducted as Blocks 9 and 10 show. The pitfall identified in conjunction with Block 9 is that technical overoptimism must be guarded against to ensure that no potential weaknesses or problems with a contemplated technical concept are overlooked. Eight prerequisite tasks are shown before the Block 10 Technical risk Assessment task can be considered completed. For instance, the "level of the technical expertise that is needed vs available" must be evaluated. In general, the technical risk assessment will have to be done for each concept that is examined. In Block 11, the technical risks corresponding to each concept are prioritized (i.e., rank ordered).

Stage 4. In Stage 4, specifically Block 12, a concerted effort is made to identify and plan to resolve the important unknowns that have a bearing on the outcome of the system development effort. In order to achieve the Block 12 task, one prerequisite is for resolving information uncertainty is to "Identify Relevant National Superlabs, Expertise, ..." and existing simulations or software that can help to resolve any information

uncertainty relevant to the technical effort. This stage is also important because it may prevent unnecessary duplication of tasks that have already been done elsewhere.

Stage 5. In Stage 5, Block 13, there is a concentrated effort to acknowledge a plan for "what-ifs"--to consider courses of action prior to the actual occurrence of technical problems. In Block 14 through 16, criteria for evaluating candidate approaches are identified. The approaches (Alternatives) are then analyzed against the criteria and those approaches that meet or exceed the criteria are selected as candidate technical approaches. Finally, in Block 17, the alternatives which survive the screening are tentatively rank ordered for the most rigorous study in Stage 6.

Stage 6. In Stage 6 there is an intensive effort to ensure that a rapid learning curve is achieved with respect to the surviving technical approaches and the potential technical risks. Per Block 18, the candidate concepts are investigated in detail with respect to the prerequisites identified: "Analytical and Simulation Tools, Math modeling, etc." In Block 19, in-depth simulation or physical models are used. For adequate risk reduction, one cannot proceed past Block 19 unless the applicable "worst case" parameter values as well as "most likely" parameter values have been identified for the design under study. Further, it must be ascertained that the simulation is representative of "real world" conditions in order for the

simulation output to be of value. As part of the learning curve process, the organization's technical knowledge must be continually enriched (Block 20). This enrichment can take the form of recruiting "fresh" technical personnel from time-to-time, training, and attendance at appropriate technical seminars.

Stage 7. In this stage the basic system design corresponding to each candidate approach is outlined (Block 22) and key technical parameters for measuring technical progress of the prospective system are tentatively identified (Block 23). Some experimental prototyping of some components or subsystems that are anticipated to be high risk (Block 23) is pursued in this stage. Assuming that the indicated prerequisites are met, one or more Preliminary Design Reviews (Block 24) are held to select the primary technical approach for the system and/or for the system's key subsystems (Block 25). Block 26 is a decision diamond regarding whether or not the selected primary approach should be pursued solely. If the technical approach selected is not relatively old then we come off the "No" side of the diamond and pursue two or more approaches in parallel. If the technical approach is old then we come off the "Yes" side of the diamond. In either case we go through the OR gate to a decision diamond regarding the experience of the personnel (Block 28) in the selected approach or approaches. If the personnel are not experienced, then we rush to Stage 8, Design of Prototype."

block 29 likewise requires a decision on the technical and operational familiarity with the environments within which the system will operate. This results in selection of the Block 30A or Block 30B tasks to determine how the system will function in the use environment. Block 31 involves the formation of specific strategy to minimize the risks involved with eventually achieving a successfully functioning prototype. Such a strategy can then be applied to actual prototype design (under Stage 8). At Block 32, experimental prototypes can be used in early field tests in order to obtain an early evaluation of suitability to the operational environment.

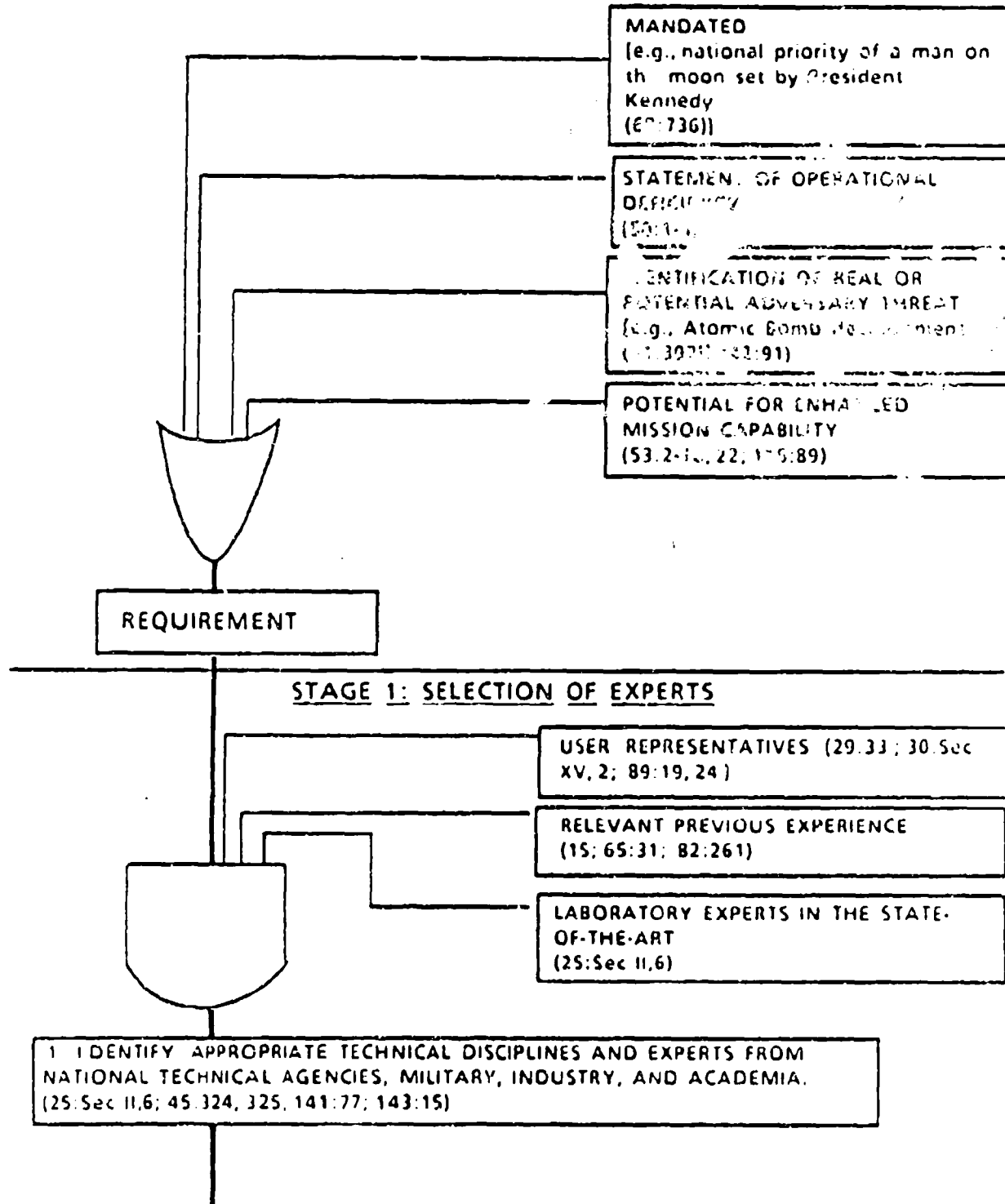
Stage 8. This stage involves the actual design and building of the prototype system. Stage 8 is divided into nine (9) design priorities ranging from designing to meet or exceed the primary performance objectives to designing for easy modification at subsystems. Thus, the highest design priority is Design Priority 1 and the lowest design priority is Design Priority 9. Collectively, these design priorities ensure that the higher priority design task is achieved before a lesser task is given emphasis. In practice these design priorities may be pursued somewhat simultaneously if the indicated prerequisites of each have been met.

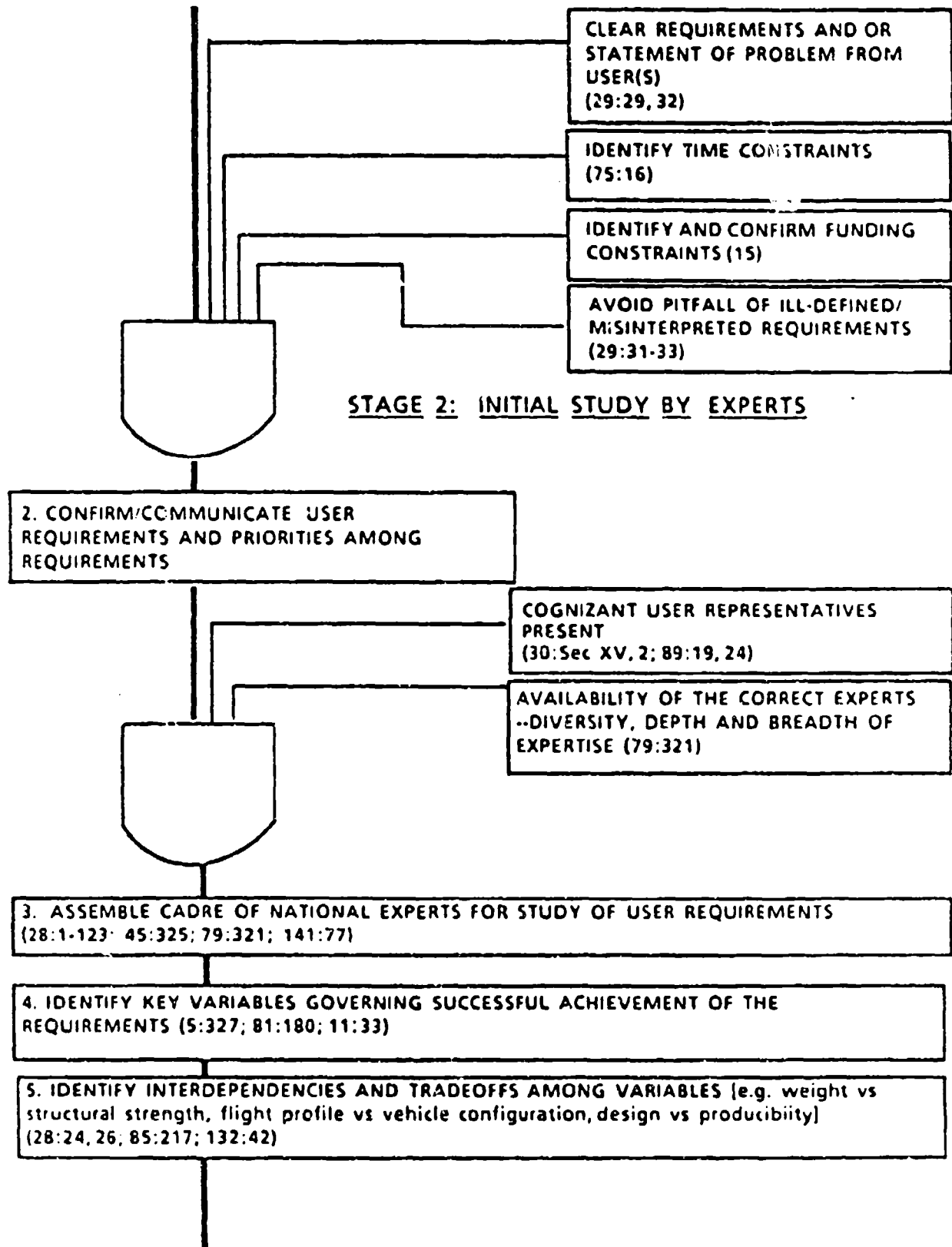
Stage 9. Once the prototype has been designed and built , a technical risk evaluation of the actual system is made. The potential hazards that may arise from the system

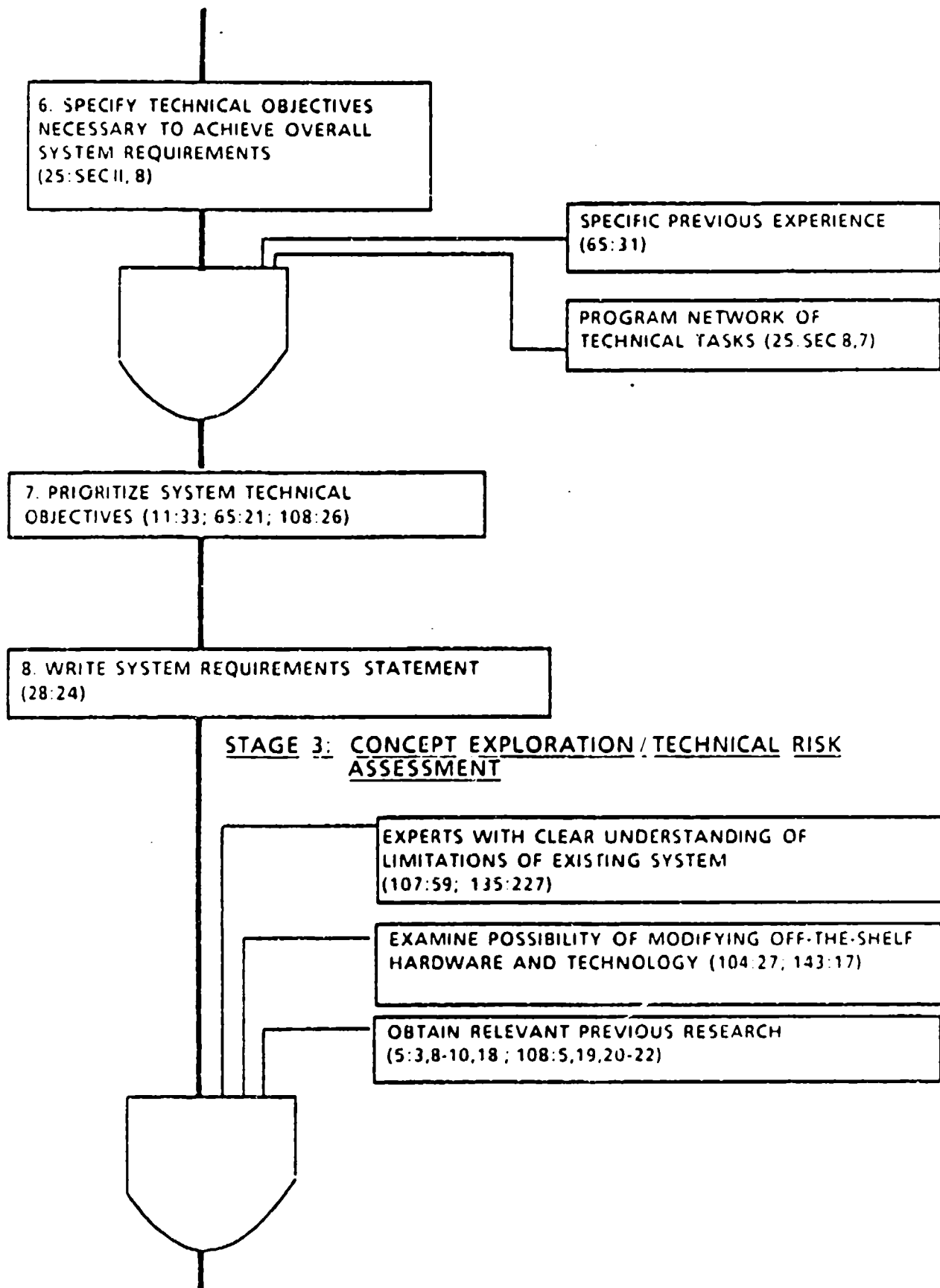
(e.g., explosion, fire) are identified (Block 33). The Boeing checklist in Figure 4 can be used for this. The prototype must then be evaluated for possible failure modes and the consequences of those failures (Blocks 34 through 38). The failure mode analyses along with information derived from testing, will eventually result in the implementation of design improvements. Then more Critical Design Reviews can be held to evaluate the technical progress and to decide on necessary design changes for subsequent (e.g., more mature versions) prototypes. Because the Critical Design Review occurs after a prototype has been designed and built instead of before, more technical information upon which to base a decision regarding necessary design modifications.

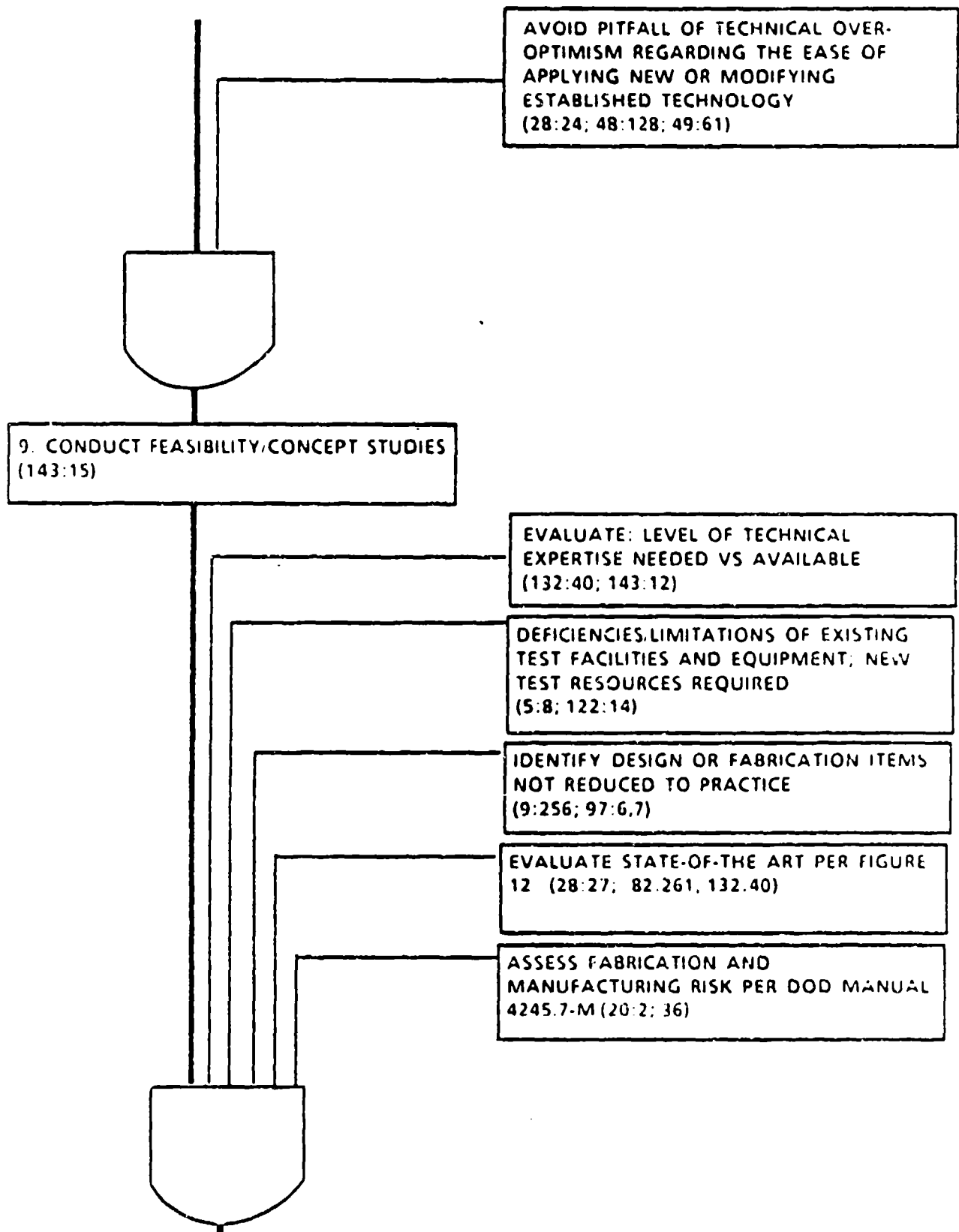
Stage 10. Detailed testing of the prototype (or a later version) is conducted in Stage 10 of the risk management model. "Specific Test Objectives" and "pass/fail criteria," along with the other items shown, are prerequisites for effective testing (block 41). At the decision diamond (Block 42) technical experts must be consulted (Block 43A) if there is a test failure and design changes must be implemented (Block 44). After the design changes there will be a retest. If the system passes, no further design changes are implemented (Block 43) and the readiness for production of the system is evaluated in accordance with Air Force System Command Regulation 84-2 on Production Readiness Reviews.

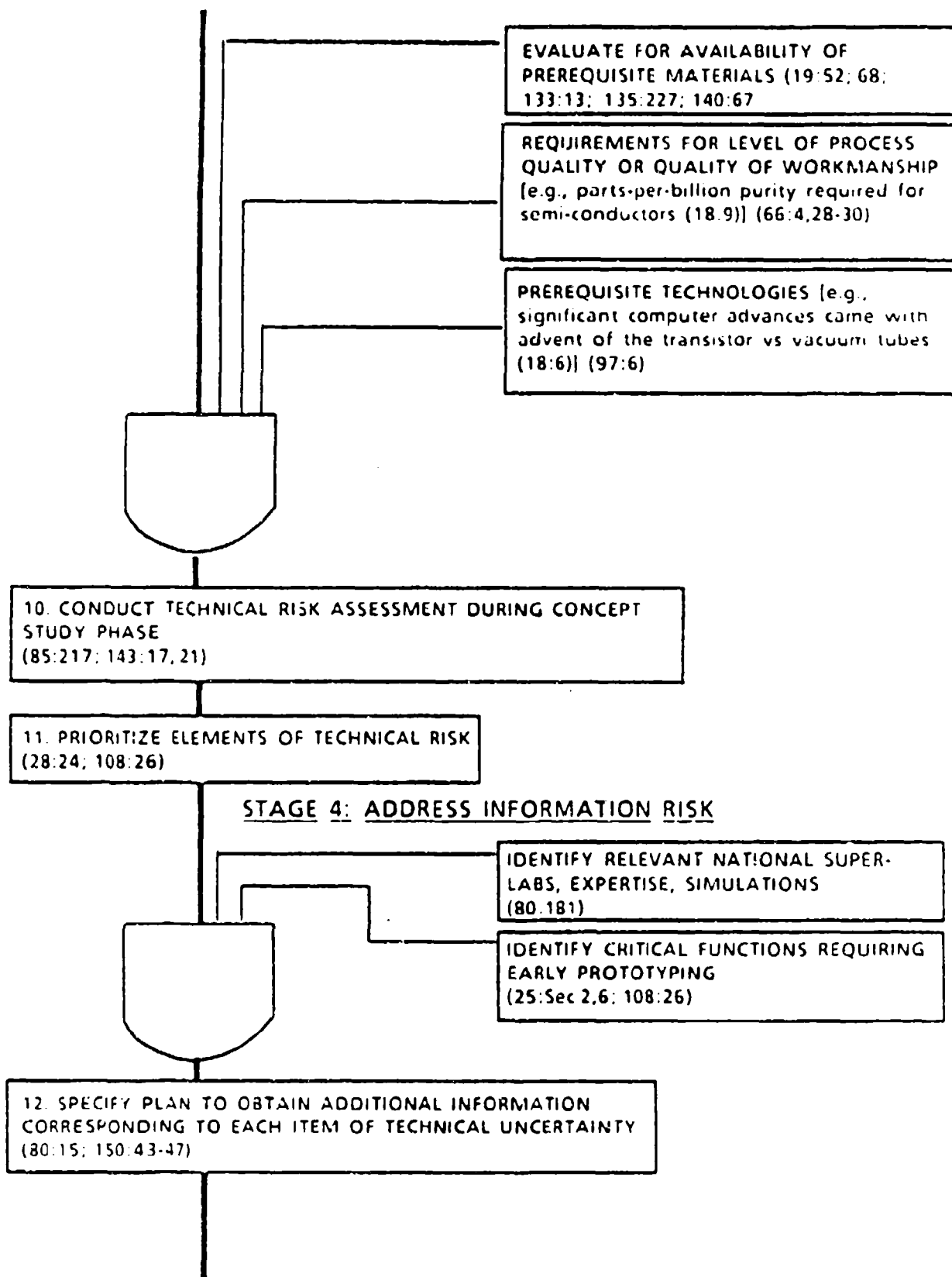
MODEL FOR TECHNICAL RISK MANAGEMENT



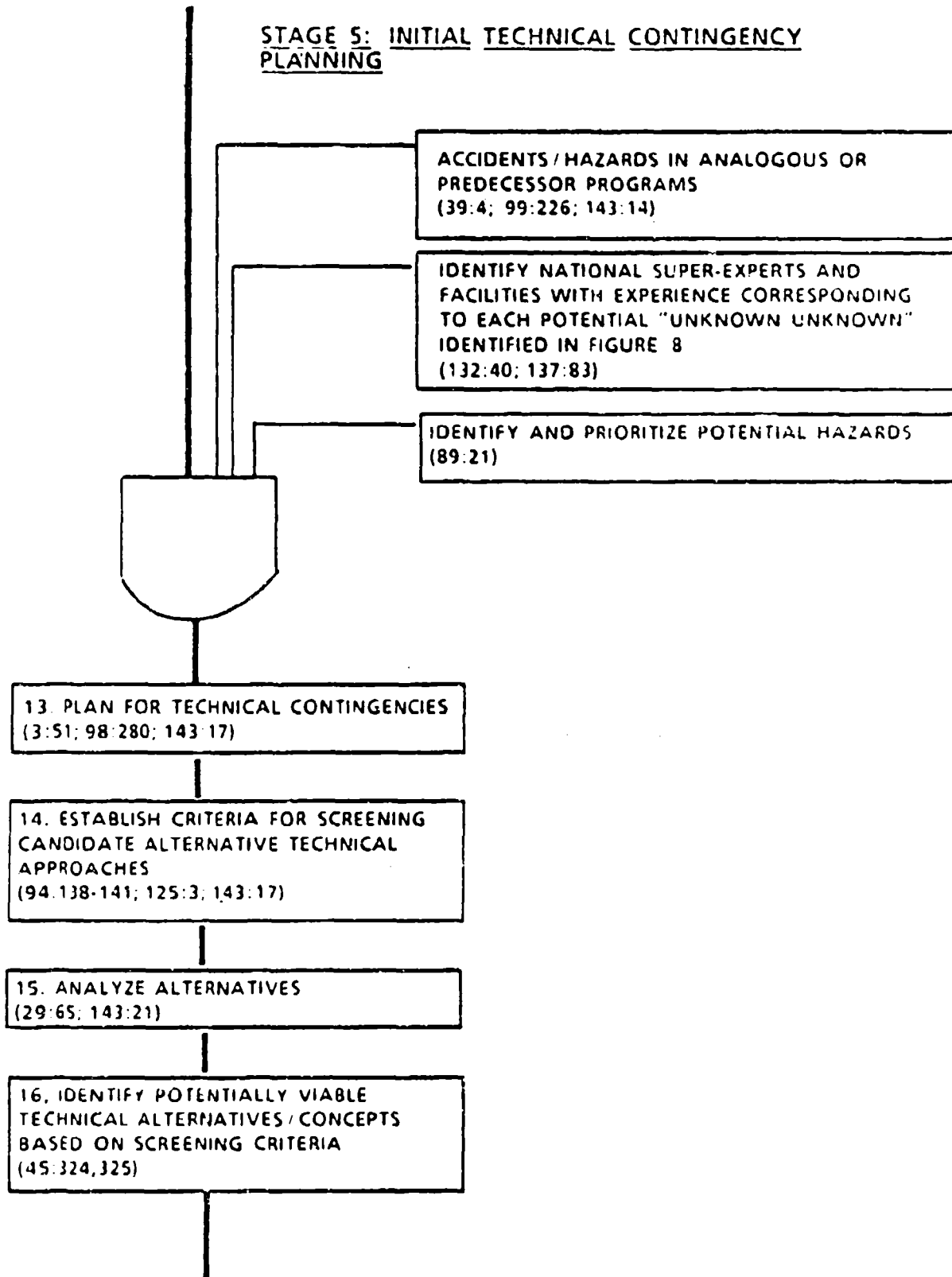








STAGE 5: INITIAL TECHNICAL CONTINGENCY
PLANNING



17. RANK ORDER ALTERNATIVES WHICH
PASS THE SCREENING CRITERIA
(94:142)

STAGE 6: ACHIEVE FAST LEARNING CURVE

ANALYTICAL AND SIMULATION TOOLS
(81:117,150; 143:18)

MATH MODELING OF SYSTEM OF SYSTEM
(81:181; 112:7; 143:18)

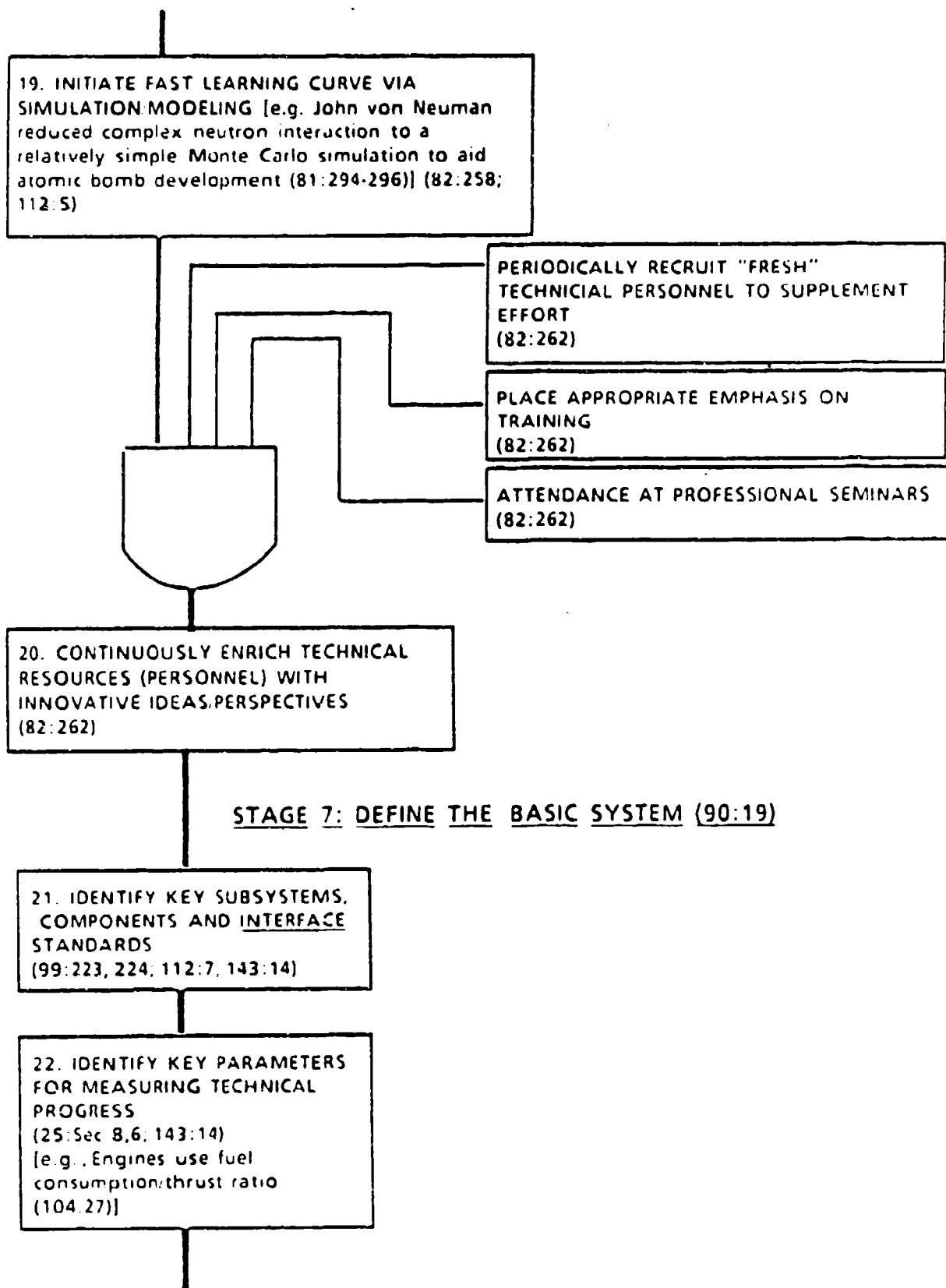
PROBLEMS, LIMITATIONS OF PREDECESSOR OR
ANALOGOUS SYSTEMS
(39:4; 99:226; 108:7)

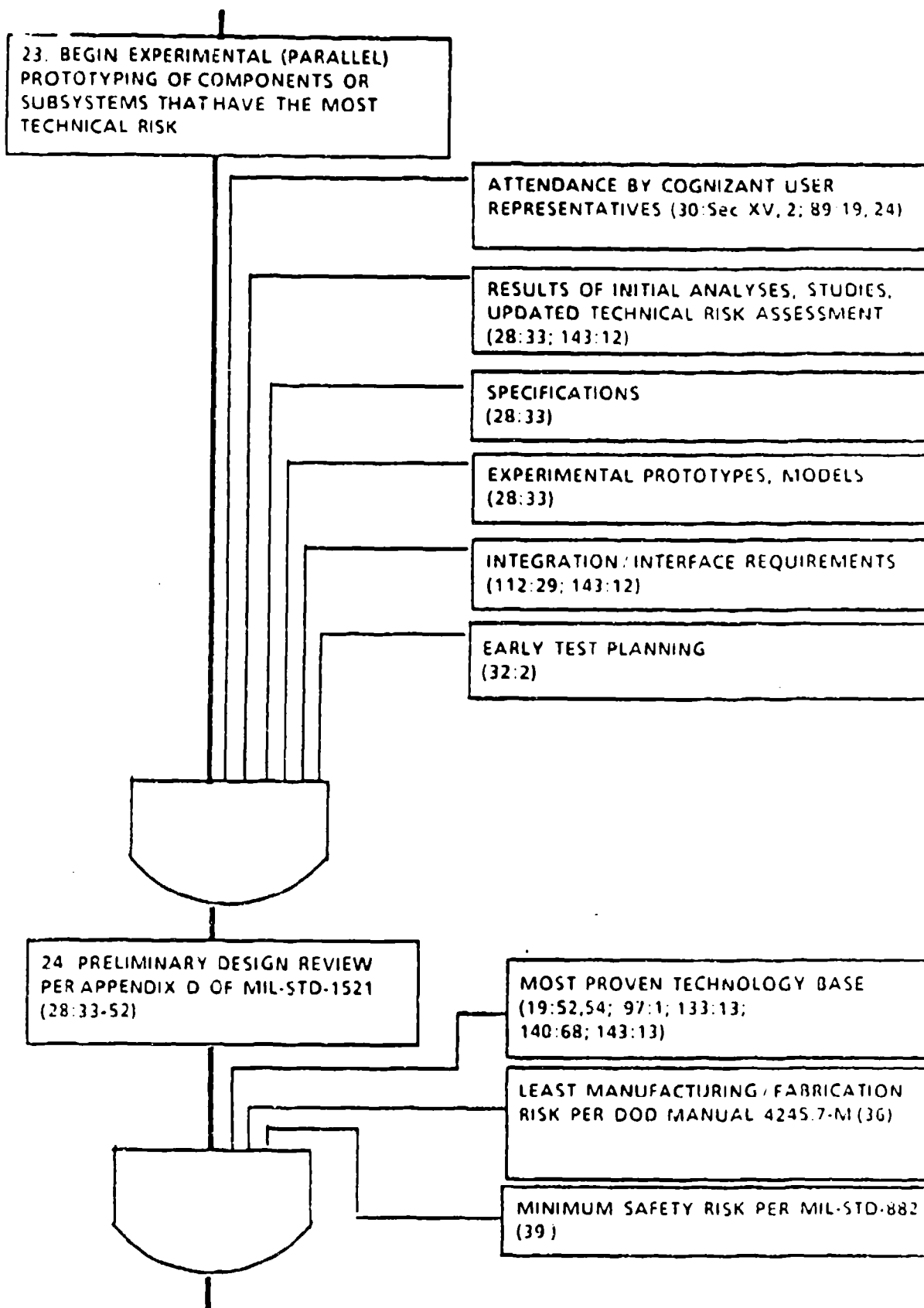
IDENTIFY LIMITATIONS OF AVAILABLE
COMPUTATIONAL TOOLS AND TECHNIQUES
(81:181; 89:1)

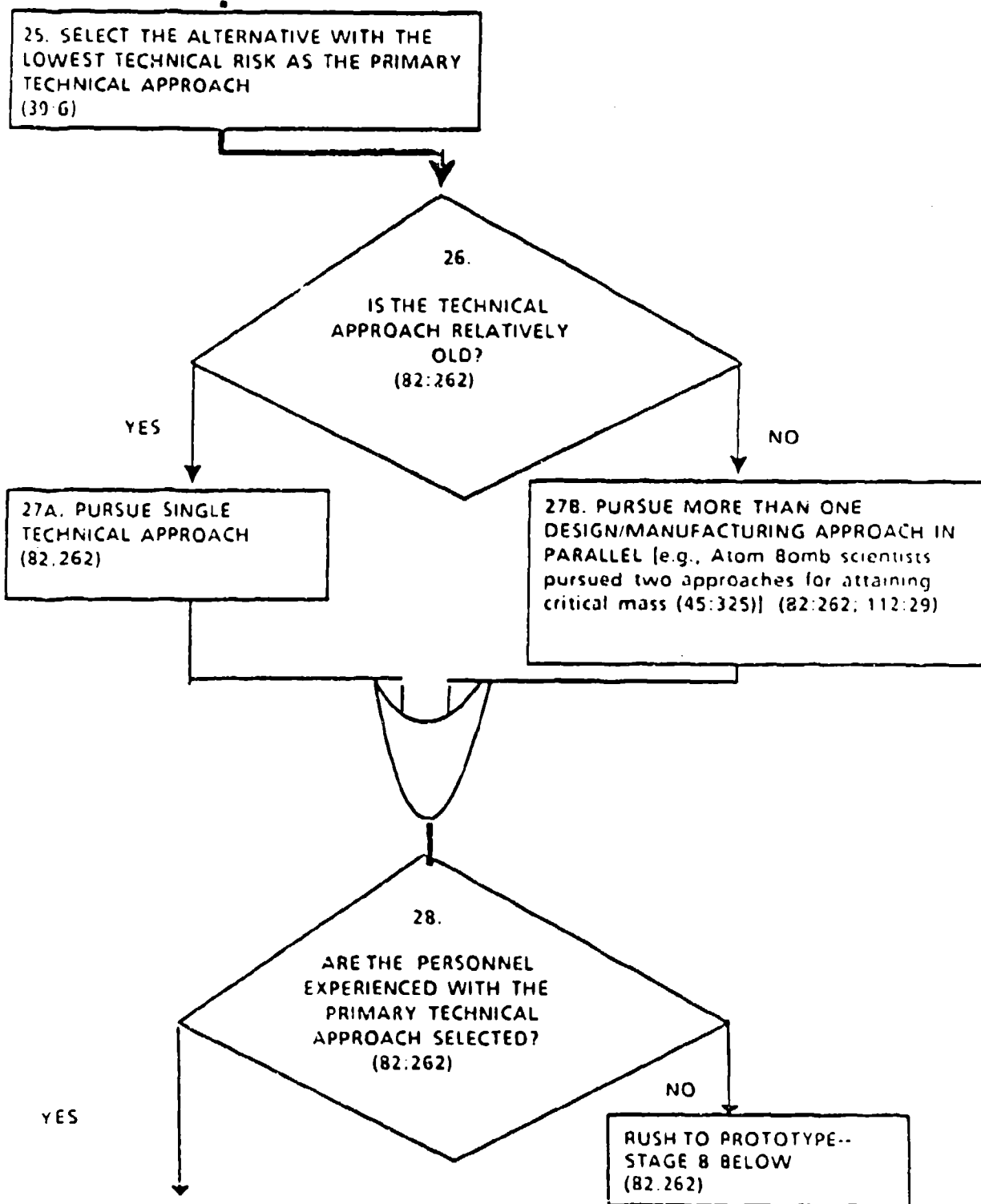
18. ACHIEVE FAST LEARNING CURVE VIA CONCEPT STUDY
(82:258)

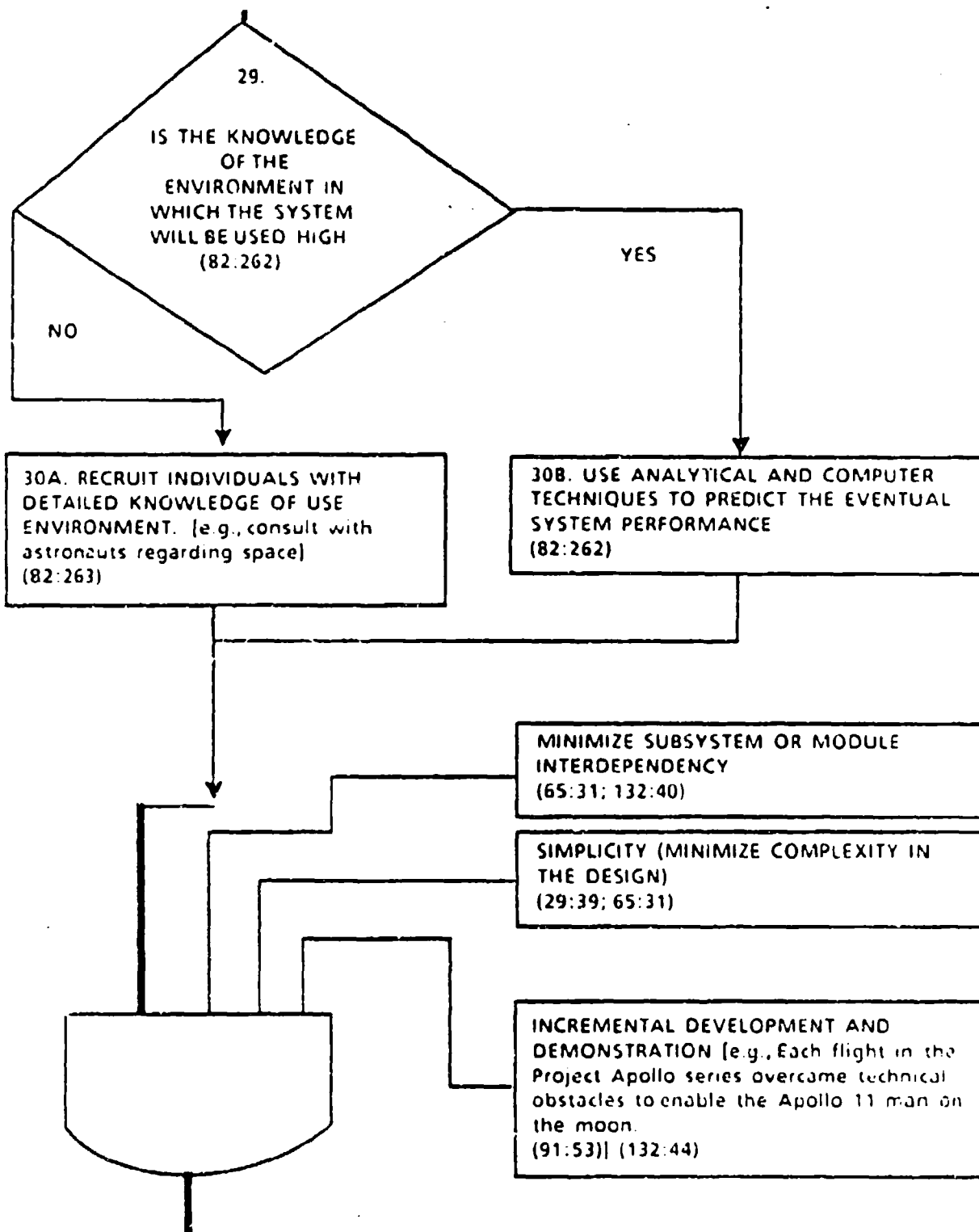
IDENTIFY WORST CASE AND MOST LIKELY
CONDITIONS AS INPUTS TO SIMULATION
(125:8)

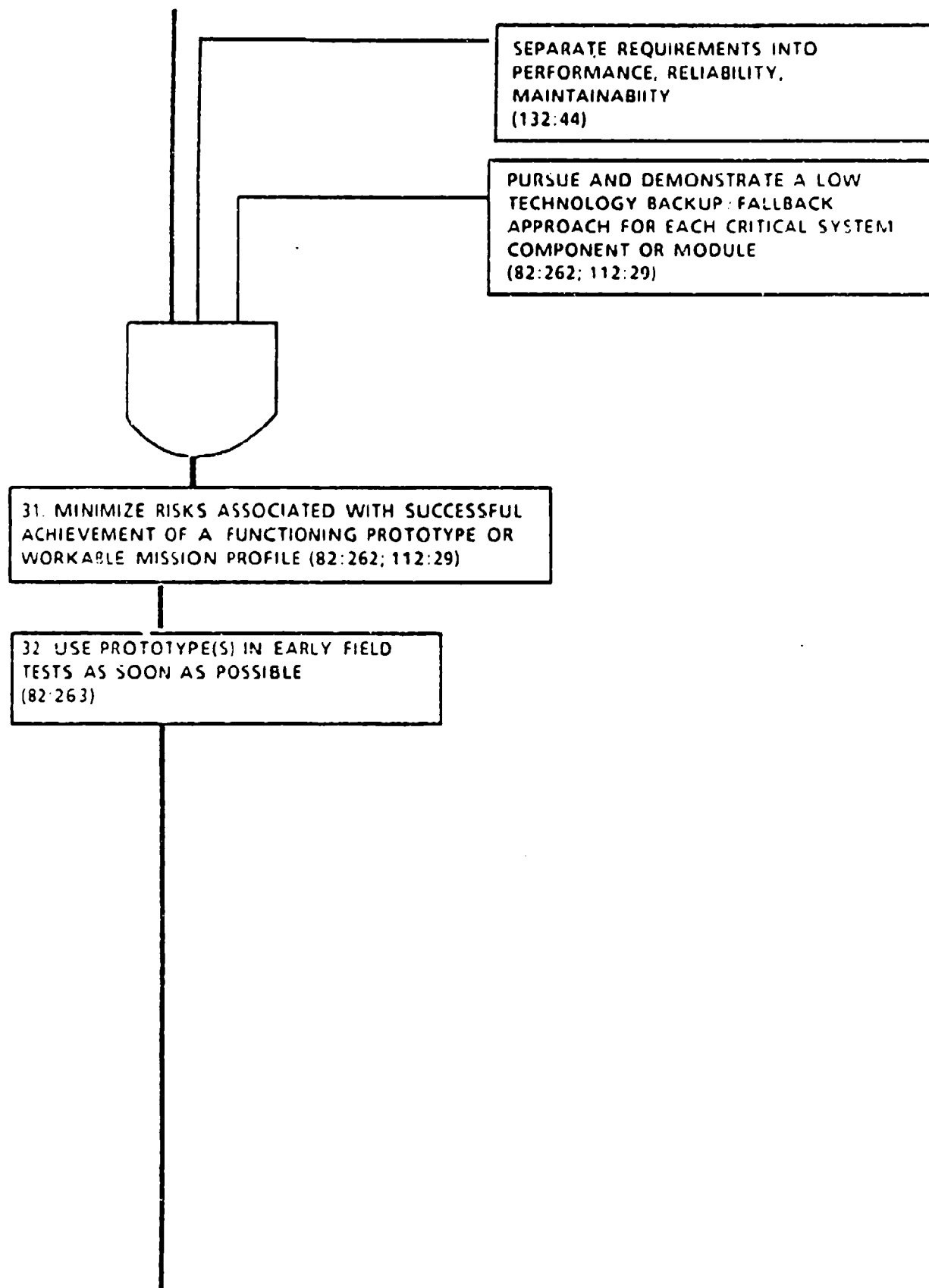
AVOID PITFALL OF UNREALISTIC,
UNREPRESENTATIVE SIMULATION OF THREAT,
ENVIRONMENT
(51:5; 52:6; 71:3; 73:13; 112:3)





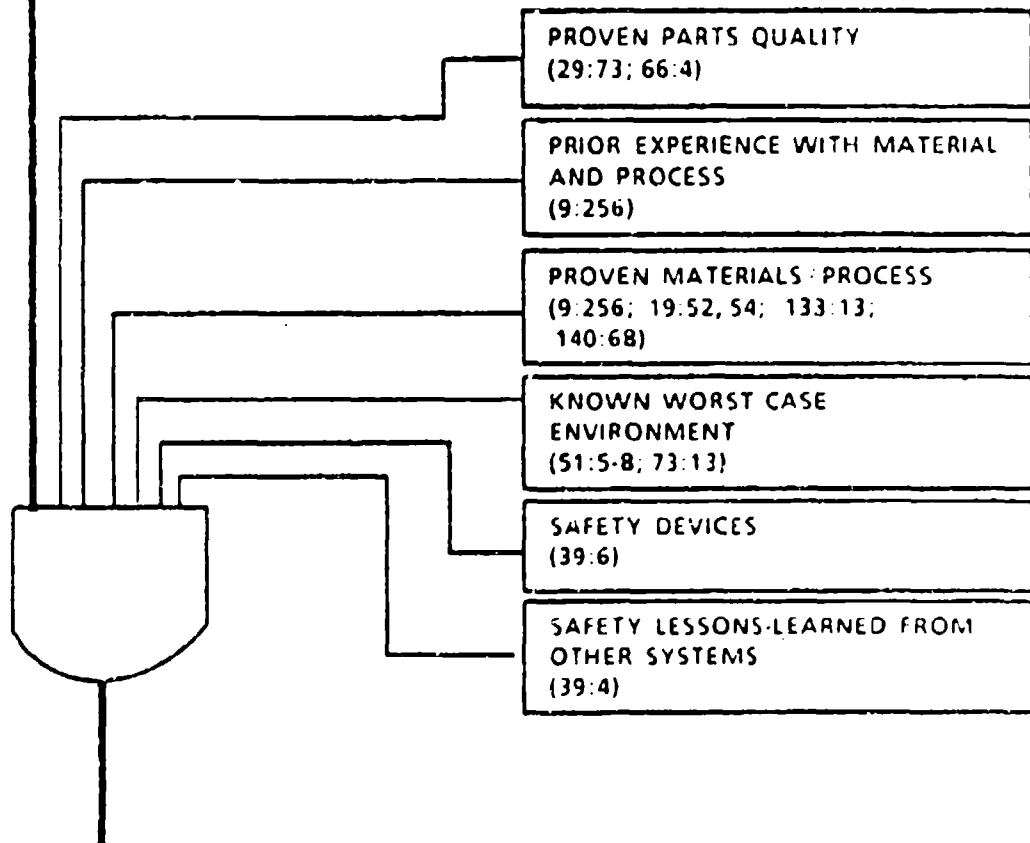


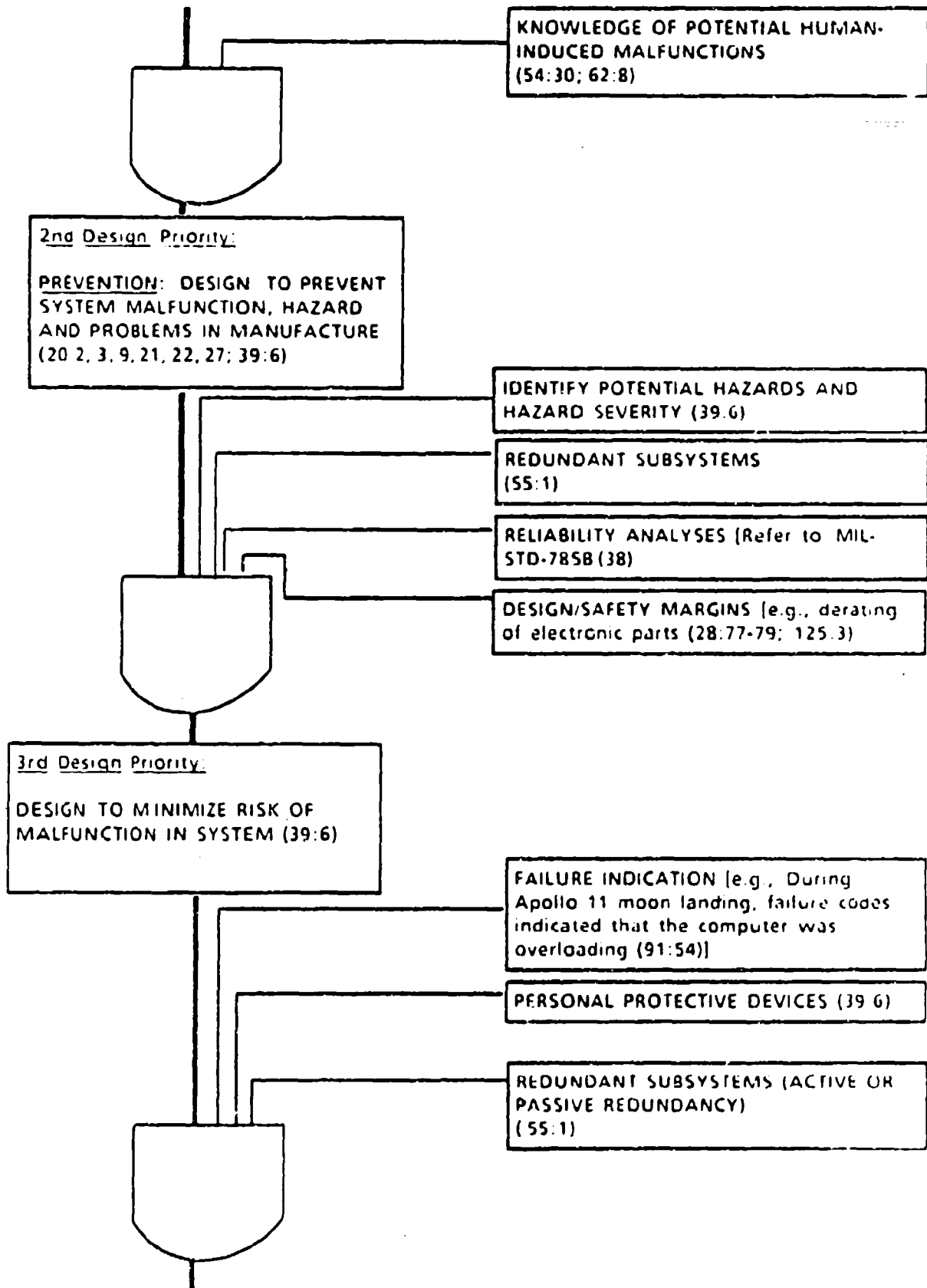


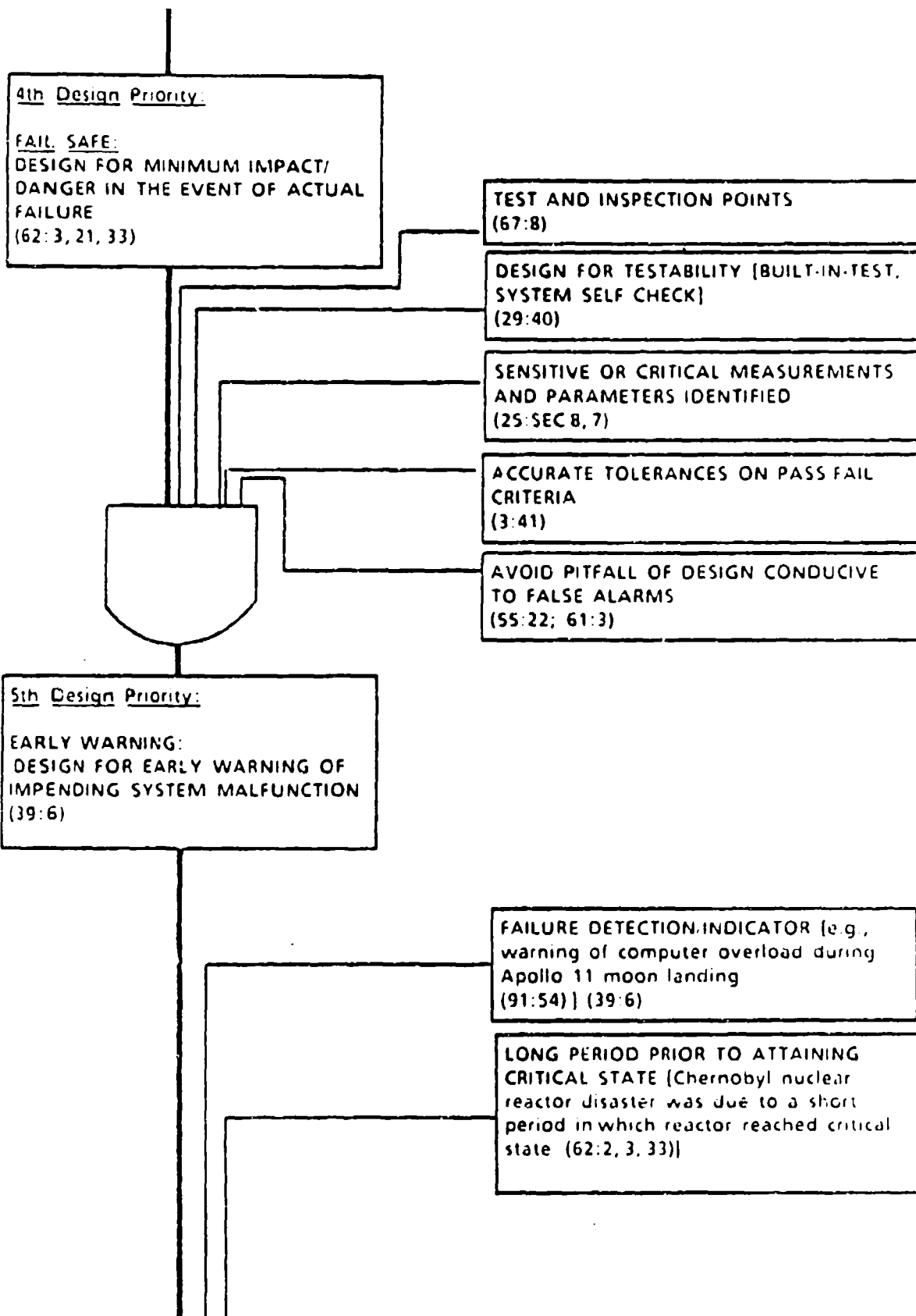


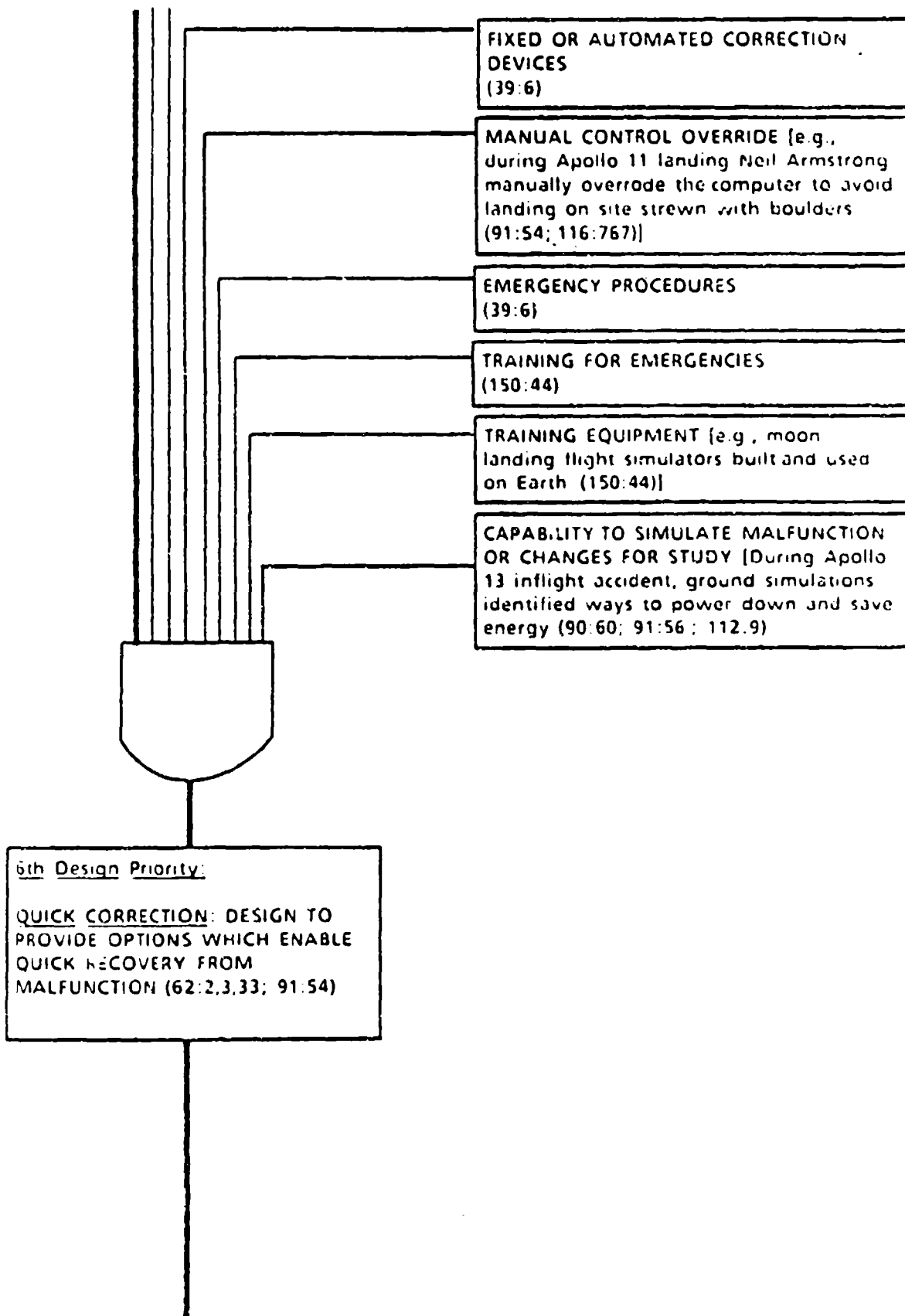
STAGE 8: DESIGN OF PROTOTYPE

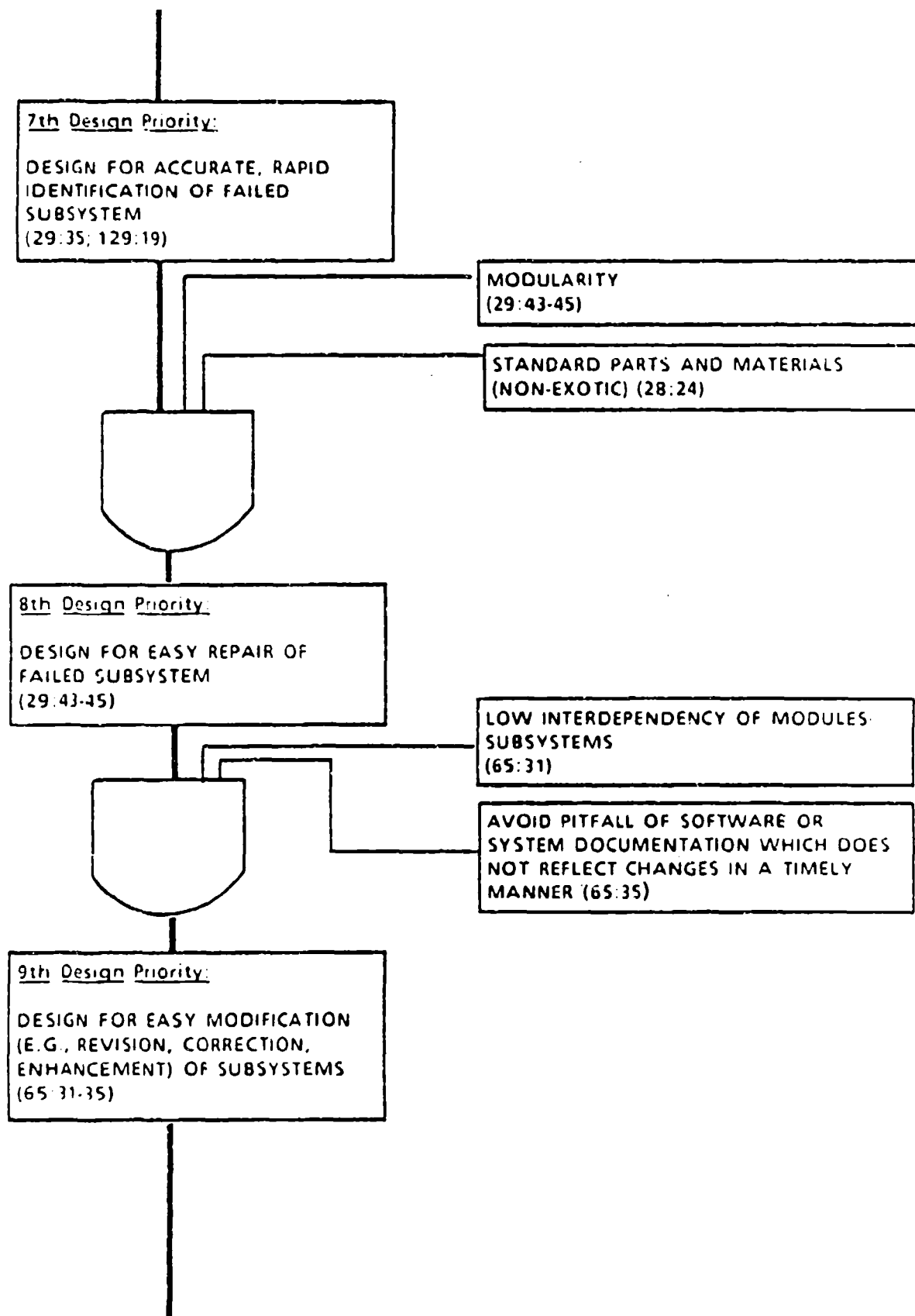
1st Design Priority:
DESIGN TO MEET OR EXCEED PRIMARY
PERFORMANCE OBJECTIVES (13)



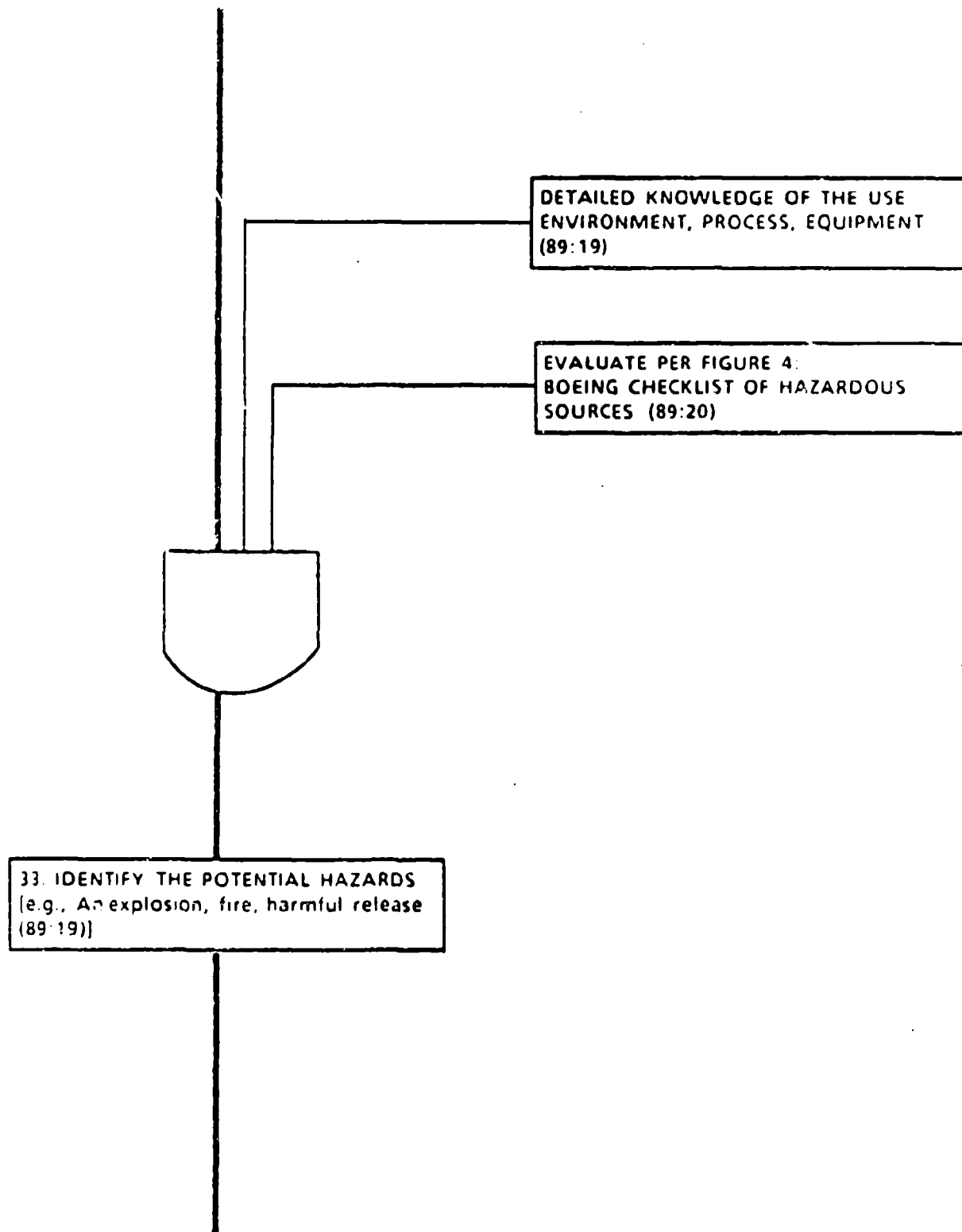


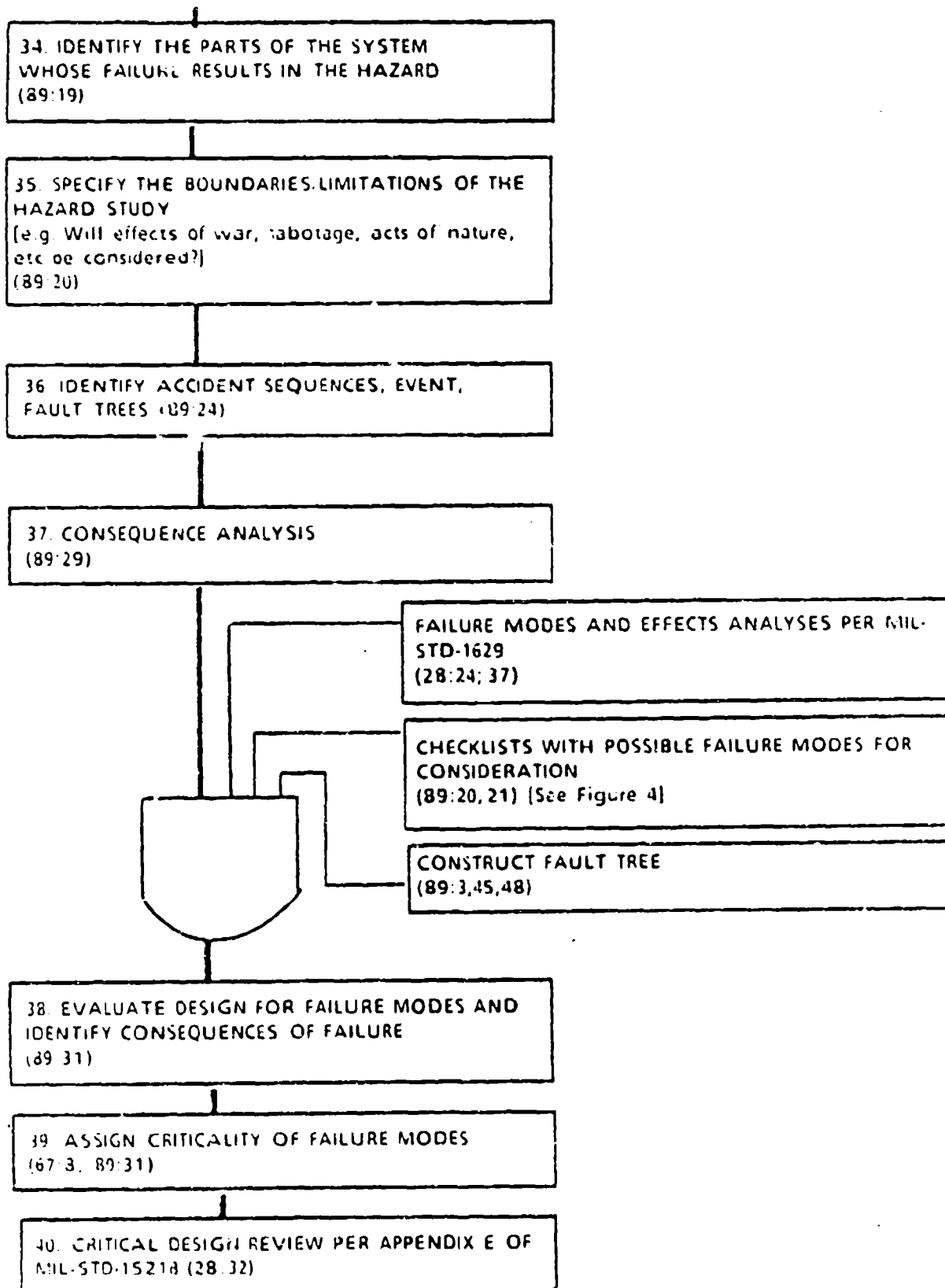




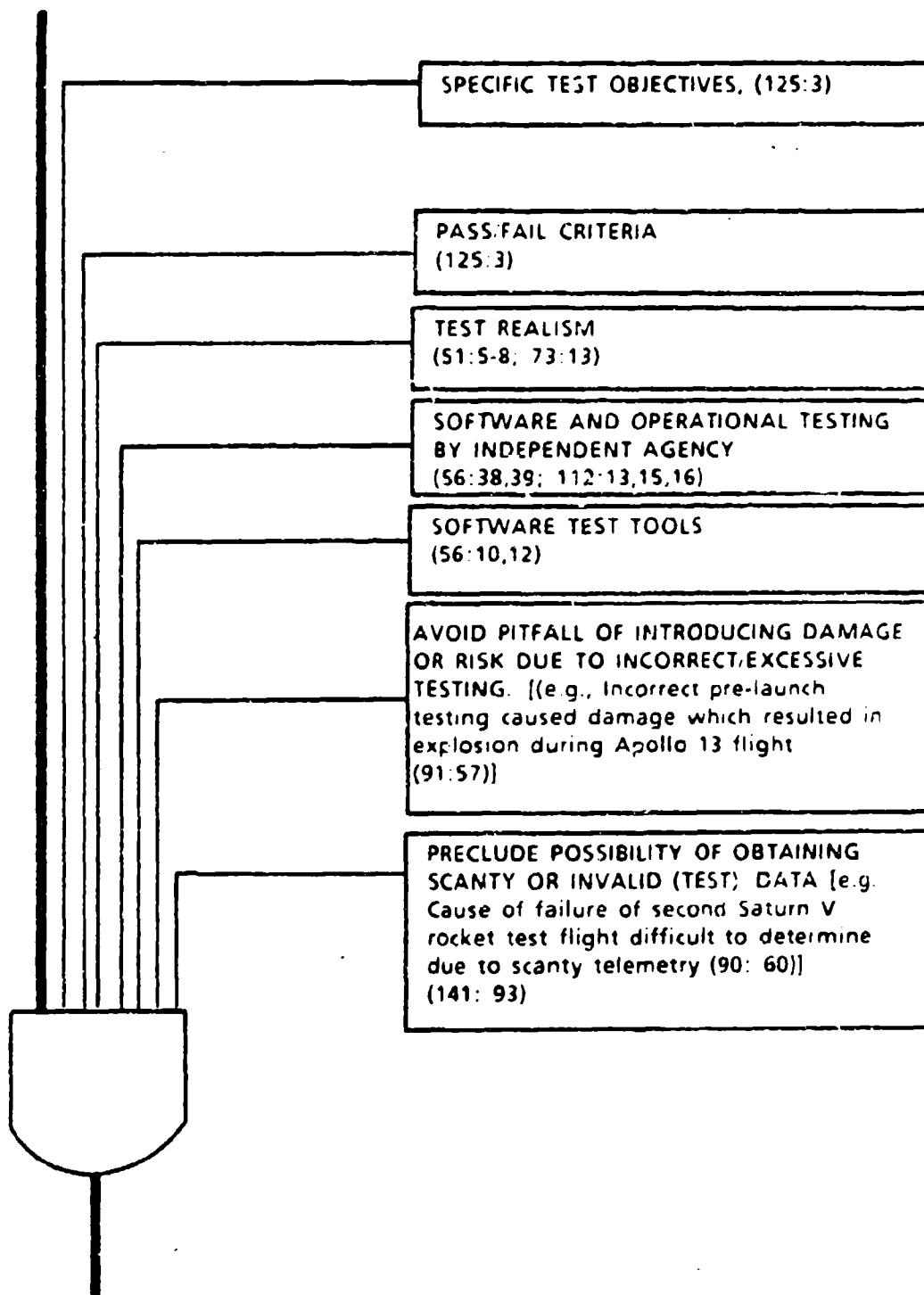


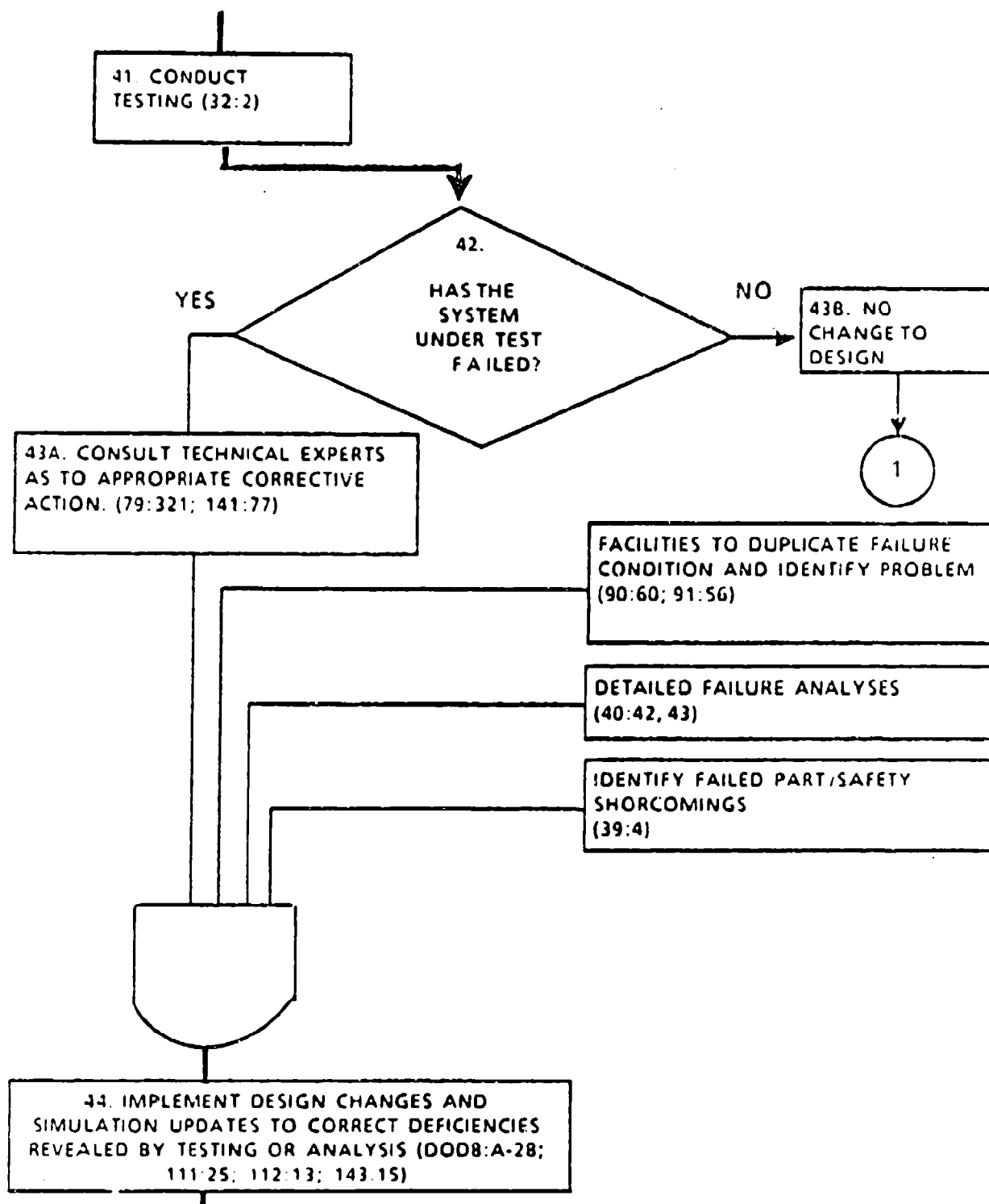
STAGE 9: POST-DESIGN RISK ANALYSES

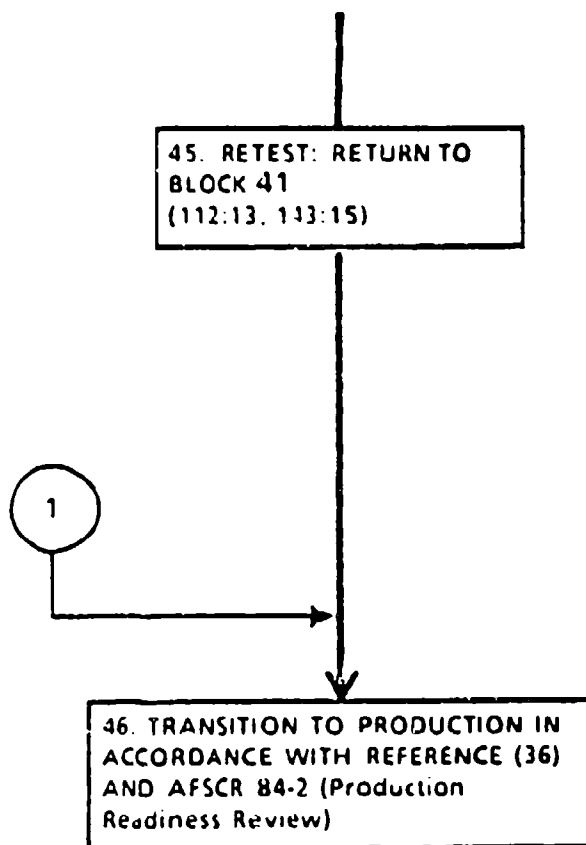




STAGE 10: TEST







V. Conclusions and Recommendations

Overview

Inadequately managed technical risks have resulted in setbacks, failures and operational disasters in Department of Defense programs. Therefore, the purpose of this research was to synthesize a model that epitomizes a strategy for the management of technical risk. The model was synthesized using the three-pronged effort of: (1) a literature search and review to determine what previous work was done in risk assessment and risk management, (2) case studies of historical, contemporary and prospective new technology development programs, and (3) interviews predominately with Chief Scientists at the Wright Research and Development Center (WRDC) at Wright-Patterson Air Force Base. The model validation was via reviews of the model that were made by the stated interviewees. If the model is used as a technical management guide and decision aid by individual program or project managers at all levels, collective marked improvement in the technical risk management throughout the Department of Defense may be achieved.

Conclusions

The research reveals that the management of technical risk is essentially a sequential, cumulative, repercussive and iterative activity. Technical risk management is

basically sequential because the start of one particular task often requires the successful completion of one or more preceding tasks; one task often requires inputs from one or more previous tasks. Technical risk is cumulative because failure to adequately fulfill the prerequisite tasks contributes to the technical risk for all succeeding tasks. For example, the act of selecting an inferior or uncertain design approach may thereafter incur significant risk to successful system development regardless of whether or not all succeeding tasks are performed in exemplary fashion. Technical risk management is repercussive because changes to a particular component in a system may cause undesirable, or even unanticipated, technical ripples throughout the entire system. Therefore, to minimize system complexity and risk, it is important to understand, and if possible, limit the interdependence of modules and subsystems within a system.

Finally, technical risk management is iterative because as the technical effort continues, knowledge gained about system deficiencies or potential for improvement results in changes to the system. Since changes occur during the development of virtually all systems, the technical approach must be flexible enough to accommodate system revisions indicated by analysis, test, production, and operation.

According to Mr. C. J. Cosenza, Chief of the Advanced Development Division of WRDC's Technology Exploitation

Directorate, technical risk is usually managed in stages so that the risk is systematically less in successive stages (22). However, he emphasized that where time is the major factor, such as when a system is urgently needed to counter a known threat, then multiple tasks must proceed in parallel since technical risk considerations and cost become secondary to the schedule in that case (22).

Model Value/Validation

The technical risk model has been reviewed by cognizant technical experts of WRDC. Appendix J contains written comments that were provided, on the preliminary model. Mr. Jack Cannon, Technical Director of the Development Planning in the ASD Office of Plans, said that the risk management model is valuable to the program manager who skips some of the intermediate steps to show him the "management risk he is taking . . . by treating as unnecessary certain steps" (Appendix J). That is, the model prevents the program manager from unknowingly skipping steps or being unmindful of the potential technical future risks he may be incurring to the development of a system by doing so. Dr. Jim Olsen, Chief Scientist of the WRDC Flight Dynamics Laboratory wrote that "the logic [in the model] is impeccable." He stated that the important technical "question/answers are not frequently addressed, or are addressed in an uncoordinated way" during systems development. Therefore, the technical

risk management model may ensure that the crucial questions and answers have been systematically asked and obtained, respectively, prior to each important system decision to achieve technical risk reduction. The model was developed based upon inputs revised from an exclusive literature review, case analyses, and interviews with experts. Information was then synthesized into a realistic and workable output for the model.

After his second review of the evolving model, Dr. Brown remarked that the model is "an interesting piece of work" and that it is in accord with his experience in the area of technical risk assessment/management. Mr. Cannon's comment that "unknown unknowns" (i.e., unanticipated events that cause technical risk) cannot actually be evaluated. Therefore, the prerequisite regarding "unknown unknowns" (near Block 13) was clarified to mean the "potential unknown unknowns" that were derived from the case histories.

Recommendations for Further Research

Although the technical risk management model has been validated by a group of technical experts, it now requires formal testing in System Program Offices.

DSMC Evaluation. The model should be provided to the Defense System Management College (DSMC) for their evaluation and possible incorporation into acquisition risk management strategy. Specifically, the model may be very

beneficial when used in conjunction with MIL-STD-1521B-- essentially an effective technical checklist. Recently, the Willoughby templates (36) have been drafted as part of a strategy to attempt to decrease the Department of Defense risks in transitioning programs from development to production. The model herein encompasses technical risk in general and references the Willoughby templates via reference (36). The model may therefore provide a strong foundation for a general comprehensive technical risk management strategy.

Subjective Evaluation. One method of doing this would be to provide the model as a technical risk management strategy and decision aid to ten (10) Department of Defense program managers (at the Captain to Lieutenant Colonel levels and civilian equivalents). This group will be designated as the "model group." After a definite time interval (e.g., 18 months) the group with the technical risk model should be asked to provide specific comments as to the utility benefit or shortcomings of the model.

Testing. For actual testing, a control group of program managers, that will not receive the model, will be identified. The objective of the trial would be to determine whether the programs being managed by individuals in the model group achieve a superior technical status--an indication of better technical risk management--than the control group. Realistically, since the required period over which to evaluate technical progress could be long,

the comparison can be made by evaluating whether the model the control group are practicing a better technical risk assessment and management based on predetermined criteria.

Specifically, at the end of the trial, participants would complete a survey questionnaire (Likert scale) which would attempt to evaluate to what extent they are following effective technical risk management techniques. For instance, they would be asked to respond on a Likert scale to what extent they have ensured or are personally aware that the following have been (or are being done) in their program:

1. Specific laboratory experts that could help their program in a consulting capacity in the event of technical problems, have been identified.

2. Technical program risks have been identified.

3. Technical program risks have been prioritized.

4. Interface requirements have been (are being) specifically defined.

5. Technical personnel connected with the program attend professional seminars and obtain suitable training.

6. There is a capability to simulate or reproduce system malfunctions for study.

7. Personnel from the using organization who can provide more information or details on the use environment and the specific employment of the system have been specifically identified.

8. Exotic materials, parts and processes of the system have been specifically identified.

9. Backup options for exotic materials, parts and processes have been identified.

10. The specific worst case locales where the system can be used (e.g., sandy, dusty, cold, hot, at altitude or a combination) have been specifically identified.

The ten criteria just stated are a partial list of the criteria that could be used as indicators of how well the technical risks of a program are being managed. Although the responses to the questionnaire would not guarantee that a particular program manager is in fact managing technical risk as indicated by his/her responses, the responses should generally be a good measure of risk management. If the model is of high utility then theoretically the model group should score higher.

Given the variation in program type, maturity, and external influences (e.g., budget, schedule changes) in the Department of Defense it may be necessary to select programs which are at or near the same Department of Defense acquisition milestone, or to ensure that the model and control groups have the same mix of programs at the various milestones.

Management Implications to DOD

To successfully achieve the objectives of a particular Department of Defense weapon development program, the

program manager must effectively manage the program's risk. Since technical risk often has a direct bearing on the risk of failing to achieve both a target cost and schedule, it is essential that an effective strategy be formulated and implemented for managing risk. The importance of strategy has been previously discussed in Chapter I (Justification). However, a particularly noteworthy example of the potential advances that can be achieved by implementing an effective strategy is the emergence of Japan as a dominant of Japan's defeat in World War II. The Japanese have "attributed much of their success to the teachings of such Americans as [Dr. W. Edwards] Deming" (136:541) in the areas of quality and industrial management. The nation that can more ably manage technical risk is likely to have decided defense and industrial advantages over nations with lesser technical risk management skills. With a superior technical management strategy, a greater percentage of defense programs may be done correctly "the first time," and within budget and schedule. Further, a period of diminishing Department of Defense resources and a public that is increasingly intolerant of even minor defense acquisition fiascos, may require that an improved technical management strategy be implemented.

It is likely that no general officer would propose that a war be fought without a potentially effective combat strategy which pervades even the lowest echelons. By analogy, defense weapons development and acquisition could

benefit from a pervasive technical risk management strategy that is available even to lower level program and project managers. Such a deliberate strategy could supplant marginally effective--and perhaps impromptu--technical risk management approaches that may be in use by some Department of Defense program managers in the day-to-day management at the lower and middle level (officer) echelons. A codified technical risk management model is likely to enhance communication and synchronize the efforts of managers and engineers at all levels since that model would provide a common reference point.

Ideally then, the model that resulted from this research could be provided as a reference to every program manager at almost all levels. The technical risk management improvements which the model may facilitate for each individual program manager could result, collectively, in a quantum improvement of technical risk management in weapons acquisition throughout the Department of Defense.

Appendix A: Einstein's Letter to President F. D. Roosevelt

(41:397)

August 2nd, 1939

F.D. Roosevelt,
President of the United States,
White House
Washington, D.C.

Sir:

Some recent work by E. Fermi and L. Szilard, which has been communicated to me in manuscript, leads me to expect that the element uranium may be turned into a new and important source of energy in the immediate future. Certain aspects of the situation which has arisen seem to call for watchfulness and, if necessary, quick action on the part of the Administration. I believe therefore that it is my duty to bring to your attention the following facts and recommendations:

In the course of the last four months it has been made probable - through the work of Joliot in France as well as Fermi and Szilard in America - that it may become possible to set up a nuclear chain reaction in a large mass of uranium, by which vast amounts of power and large quantities of new radium-like elements would be generated. Now it appears almost certain that this could be achieved in the immediate future.

This new phenomenon would also lead to the construction of bombs, and it is conceivable - though much less certain - that extremely powerful bombs of a new type may thus be constructed. A single bomb of this type, carried by boat and exploded in a port, might very well destroy the whole port together with some of the surrounding territory. However,

I understand that Germany has actually stopped the sale of uranium from the Czechoslovakian mines which she has taken over. That she should have taken such early action might perhaps be understood on the ground that the son of the German Under-Secretary of State, von Weizsäcker, is attached to the Kaiser-Wilhelm-Institut in Berlin where some of the American work on uranium is now being repeated.

Yours very truly,

A. Einstein
(Albert Einstein)

From Franklin D. Roosevelt Library

Appendix B: Interview Questions

1. What are your technical qualifications: Specifically what technical degrees do you hold?
2. What is your technical experience? [What technical jobs have you held?]
3. What is the mission of the organization of which you are a part?
4. What is your present job?
5. In your opinion, what are the most important techniques for managing technical risk?
6. Based on your experience, what is the most important technique for managing technical risk?
7. Does your organization have a specific written strategy or policy for assessing and managing technical risk (e.g., document, statement of policy, operating instruction)?
8. Can I have a copy?

After each interview had a copy of the preliminary model for at least six working days the following questions were asked:

1. Have you reviewed and marked up the technical risk management model to indicate deficiencies or the model?
2. What did you think of the model?

Appendix C: Letters Regarding "Tin Whisker"
Failure Mode

THE OFFICE OF THE SECRETARY OF THE AIR FORCE
ATTENTION: THE SECRETARY OF THE AIR FORCE
DEPARTMENT OF THE AIR FORCE
THE PENTAGON
WASHINGTON, D.C. 20330-1000
TELEPHONE: (202) 697-2000
FACSIMILE: (202) 697-2000
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INSPECTOR GENERAL: (202) 697-2000
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United States Senate
COMMITTEE ON
GOVERNMENTAL AFFAIRS
- SUBCOMMITTEE ON
OVERSIGHT OF GOVERNMENT MANAGEMENT
WASHINGTON, DC 20510

December 4, 1986

The Honorable Edward C. Aldridge
Secretary
Department of the Air Force
The Pentagon
Washington, D.C. 20330-1000

Dear Mr. Secretary:

It has come to my attention that some electronic parts in weapons systems may have failed, or be subject to failure, due to the growth of crystals or "tin whiskers". This phenomenon appears to result from the use of pure tin in close proximity to electronic parts. An example is the use of tin cases for housing electronic hybrids. While several months may be required for the tin whiskers to develop, they eventually grow to a length sufficient to bridge circuits. I understand that at least two major weapon systems require retrofitting as a result of the discovery of tin whiskers. This raises several questions I would like answered by December 19, 1986.

Are tin cases for electronic parts used in Air Force weapon systems. If so, do these parts use current of approximately 20 micro amperes at approximately 10 volts?

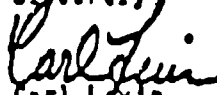
Have any of these parts failed? If so, was a failure analysis performed, including an analysis to determine whether tin whiskers were at fault? If so, what was the result of the failure analysis?

-2-

In addition to electronics housed in tin cases, are there other instances of failed electronic parts attributable to the existence of tin whiskers? If so, please describe these instances.

- Thank you for your cooperation in this matter. If you have any questions regarding this request please direct your staff to contact Brad Vans of my staff at 202-224-3682.

Sincerely


Carl Levin

CL:ljj



DEPARTMENT OF THE AIR FORCE
HEADQUARTERS AERONAUTICAL SYSTEMS DIVISION (AFSC)
WRIGHT-PATTERSON AIR FORCE BASE, OHIO 45433-3303

19 JAN 1987

REPLY TO
ATTN OF: EN

SUBJECT: Congressional Inquiry Regarding the Growth of Crystals or "Tin Whiskers" in
Electronic Parts (Sen Carl Levin's ltr, 4 Dec 86)

TO: HQ USAF/LEYY

1. The generic phenomena, growth of metallic whiskers, was identified during World War II with the growth of cadmium whiskers on variable plate capacitors used in communication radios. Since that time, cadmium, zinc, or tin whiskers have been found in crystal oscillators, capacitors, relays, connectors, tin-plated copper conductors in printed wiring boards, and tin-plated part leads. Limited occurrences are documented in the Government/Industry Data Exchange Program (GIDEP) data bank and the technical literature. Mil specs such as MIL-M-38510 have addressed the latter issue for several years. These metal whiskers are undesirable as they have the potential to cause electrical disturbances within electronic components/ systems.

2. We have also experienced some limited experiences with this issue within a few components used in the F-15 radar and the AGM-65D IR Maverick Missile. These occurrences came to light as a result of ours and of our contractor's internally generated activities. The specifics are outlined in paragraph 3, for the F-15 radar; and in paragraph 4, for the AGM-65.

3. Gould Corporation was given a contract by ASD (the PRAM office) to demonstrate the effectiveness of Combined Environmental Stress Screening (ESS) and Destructive Physical Analysis (DPA) program for the surveillance of electronic parts returned from the field. The DPA identified tin whiskers in selected microchip packages. Subsequent inquiries indicated that Hughes, El Segundo CA, altered their original production process specification after one of their vendors had a fire in the vendor's production facility. The F-15 radar uses a solder seal process for providing a hermetic seal for their hybrids using a pure tin plate on the hybrid lids to facilitate the solder process. Originally these lids had a fused tin coating (heated in an oil bath to 240-260°C to relieve stress within the material). After the change, the fusing process was deleted. The unfused tin lids have a high probability of growing tin whiskers while the fused lids are stable. Tin whiskers have been found in a number of lids that have been removed from fielded units or from spares inventory. A small number of these units have evidence which indicates that tin whiskers have shorted between circuit conductors and part of the whisker has vaporized. This could cause an intermittent in the operation of the radar. In the event a tin whisker resists between two unprotected conductors within the hybrid, and if the hybrid at that location is unable to deliver the current necessary to fuse the whisker, a hard failure could result. However, there is no evidence of whisker generated hard failures in F-15 radar hybrids. Hughes has modified their manufacturing processes to preclude the growth in tin whiskers.

BIRTHPLACE OF INNOVATION

4. The AGM-65 IR Maverick Missile has experienced one problem during factory acceptance testing of a Rate of Acceleration Meter (RCAM) provided by Systron-Donner. This device contains a moving coil mounted around a fixed permanent magnet which senses movements of the IR gimbal platform and provides correction signals to the gimbal drive motors. Failure analysis of inoperative ROAMs found during missile assembly showed tin whiskers to be growing from a tin-plated solder pad on the movable coil which were shorting the outer case. This design has been modified to replace the tin-plated solder pad with one plated with beryllium copper which has eliminated the problem. Current production incorporates this change. The approximately 300 missiles delivered to the field are being retrofitted at the contractor's expense. This retrofit is expected to be completed by the summer of 1987. There is no indication this problem has caused any failures in over 40 launches by operational units.

5. As a result of this experience the following observations are made:

a. We are able to respond to these questions because our disciplines have been effective in identifying and correcting potential causes of field failure in electronic equipment.

b. We have reminded our program offices of the potential for metallic whisker growth in electronic parts and the appropriate control procedures.

c. We have asked our Air Force laboratories to identify/develop suitable, cost effective, alternatives to tin plating for the solder sealing of hermetic packages.

d. We recommend that the ALCs adopt an electronic piece part surveillance program utilizing the DPA and ESS process, as appropriate. Prompt identification of the causes of field failures and the feed back of this information to the appropriate equipment and part manufacturers will have a significant impact on the operational capabilities of our weapon systems.

6. We are pleased that our efforts were instrumental in bringing this issue to a successful conclusion.

8. T. Roll, Jr.
ROBERTSON T. ROLL, JR.
Technical Director
Deputy for Engineering

1 Atch
Sen Levin's ltr, 4 Dec 86

cc: HQ AFEC/SD
HQ AFEC/PL
AFVAL/MLS
ASD/EX/PA)
ASD/TLS
ASD/X:

Appendix D: A Brief Chronology of the Development
of the Rocket

- AD 1232 Rocket-propelled arrows (somewhat like firecrackers) used in battle in China (145:26).
- 1903 Konstantin Eduardovitch Tsiolkovsky's first article on rocketry appears in a Russian journal; Tsiolokovsky conceives of a rocket with a combination of a liquid oxygen and liquid hydrogen (145:41,42).
- 1914 Robert H. Goddard, American, granted patents covering "combustion chambers, propellant feed systems, and multistage rockets" (145:45).
- 1915 "Robert H. Goddard proved validity of rocket propulsion principles in a vacuum, at Clark University, Worcester, Mass" (42:4).
- 1920-1922 "Goddard developed and unsuccessfully tested first liquid propellant engine, using liquid oxygen, and devised small high-pressure pumps to force fuel into the chamber" (42:16).
- Nov 1923 "Robert H. Goddard successfully operated a liquid oxygen and gasoline rocket motor on a testing frame, both fuel components being supplied by pumps installed on the rocket" (42:17).
- Late 1923 "Die Rakete zu den Planetenaumen (The Rocket into Planetary Space) by Hermann Oberth was published in Germany, and was the genesis for considerable discussion of rocket propulsion" (42:18).
- Mar 1926 "Robert H. Goddard launched the world's first liquid-fueled rocket at Auburn, Mass., which traveled 184 feet in 2 1/2 [two-and-a-half] seconds. This event was the "Kitty Hawk" of rocketry" (42:21).

Nov 1929 Famed aviator Colonel Charles A. Lindbergh visited Goddard. Through Lindbergh's effort Goddard was awarded a \$50,000 grant from the Guggenheim Fund and another grant from the Carnegie Institution (145:46).

Dec 1930 "Robert H. Goddard fired 11-foot liquid fuel rocket to a height of 2,000 feet and a speed of near 500 mph over Roswell, New Mexico" (42:26).

Apr 1932 "First flight of Goddard rocket with gyroscopically controlled vanes for automatically controlled flight" (42:29).

Mar 1935 "Goddard rocket attained altitude of 7,500 feet in New Mexico" (42:33).

Mar 1936 "Robert H. Goddard's classic report on "Liquid Propellant Rocket Development" reviewing his liquid-fuel rocket research and flight testing since 1919, was published by the Smithsonian Institution" (42:34).

Oct 1936 "Lt. John Sessums (AAC) visited Robert H. Goddard to officially assess military value of Goddard's work. He reported that there was little military value, but that rockets would appear useful to drive turbines" (42:43).

Dec 1941 First test of the German V-1 rocket at Peenmunade (145:105).

Jun 1942 "First test of the German A-4 (V-2) rocket unsuccessful at Peenemunde, Germany" (42:43).

Oct 1942 "First successful launch and flight of 5 1/2 [five-and-a-half] ton German A-4 rocket (V-2) at Peenemunde, which traveled 120 miles" (42:44).

Appendix E: Chronology of Some Major Events Regarding
Atomic Bomb Development

- 1905 Albert Einstein publishes the Special Theory of Relativity that states the equivalence between energy and mass (46:829).
- Dec 1938 Enrico Fermi receives Nobel Prize for experiments involving low velocity neutron bombardment of elements (45:324).
- Jan 1939 Refugee Austrian scientists Lise Meitner and Otto Frisch explain (via Niels Bohr) that German scientists discovered "low-velocity neutrons cause the uranium nucleus to fission, [break apart]". . . much energy was released in the process" (46:324); numerous laboratory experiments begun (46:324).
- Aug 1939 Albert Einstein's letter (dated 2 August 1939) addressed to President Roosevelt, warns that the Germans may be developing the first atomic bomb, and that recent work by L. Szilard and Enrico Fermi has established technical feasibility (41).
- 1939 Alfred A. O. Nier achieves the first separation of the uranium isotopes U-235 and U-238 at the University of Minnesota (47:517).
- 1940 First funds for atomic research given to United States scientists (46:831).
- 1941 "The Columbia chain-reaction experiment with natural uranium and carbon yielded negative results" (45:325).
- Dec 1941 The U.S. enters World War II (45:325).
- May 1942 "The decision is made to proceed on all promising production methods [for obtaining fissionable materials]" (45:325).
- 1942 Army Corps of Engineers opens an office in New York City called the Manhattan Engineer District office (45:325).

Dec 1942 "First nuclear chain reaction successfully accomplished at the University of Chicago" (42:44).

Jun 1942 J. Robert Oppenheimer appointed "director of Project Y, the group that was to design the actual weapon" (45:325).

July 1942 Experimental data reveals "plutonium does give off neutrons in fission, more than Uranium-235" (45:325).

Apr 1943 Seth Neddermeyer proposes an "implosion" method of attaining supercritical mass (45:325).

1943 John von Neumann and Edward Teller support the implosion approach (45:325). Summer/Fall "Gun" Method of attaining supercritical mass of 1943 being pursued (45:325).

Jul 1943 "It [becomes] clear that the plutonium gun could not be built" (45:325), therefore, the implosion approach is pursued.

Sep 1944 "First reactor at Hanford, Washington, turned on but . . . promptly turned itself off" (45:325).

Apr 1945 Harry Truman briefed on the Manhattan Project, after just two weeks as president (45:325).

Jul 1945 "First test atomic device exploded in New Mexico" (42:50).

6 Aug 1945 An atomic bomb (using gun approach) is dropped on Hiroshima, Japan (42:51; 47:830).

9 Aug 1945 An atomic bomb (using implosion method) is dropped on Nagasaki, Japan (42:51; 47:830).

16 Aug 1945 "World War II ended with Japanese surrender" (42:51).

Aug 1946 The Soviet Union tests their first atomic device (47:831).

Apr 1956 "Dr. John von Neumann was awarded the Enrico Fermi Award for anticipating the importance of the high speed computer in nuclear development programs. . . ." (42:82).

Appendix F: A Brief Chronology of the Development
of the Laser

- 1917 The principles of spontaneous and stimulated emission of radiation recognized by Albert Einstein (44:686; 101:23).
- 1954 A working maser device is built by Townes, James P. Gordon and H. J. Zeiger using ammonia gas; subsequent improved models are built by Bell Laboratories. MASER is the acronym for Microwave Amplification by Stimulated Emission of Radiation (135:234).
- 1958 Arthur L. Schawlow and Charles H. Townes proposed a technique to obtain an optical MASER. Such a device would be based on Light Amplification by Stimulated Emission of Radiation (LASER) (134:234).
- 1959 A helium-neon gas laser is proposed by Ali Javan of Bell Telephone Laboratories (135:230).
- 1960 A successful prototype helium-neon gas laser built and demonstrated by Ali Javan, W. R. Bennett, Jr., and D. R. Herriott (135:230).
- Jul 1960 The first successful construction and operation of a laser achieved by T. H. Maiman of the Hughes Aircraft Company using a synthetic ruby crystal (134:234; 135:227).
- 1961 The first gas laser is operated (Bell Laboratories) (135:266).
- 1961 Ivan P. Kaminow of Bell Laboratories demonstrates a high-frequency laser modulator that uses a potassium dihydrogen phosphate (KDP) crystal (117:333).
- 1961 Other lasers are constructed using: (1) different crystals, and (2) "a mixture of hydrogen and helium gas" (23:495).
- 1963 First liquid laser successfully operated by General Telephone and electronics (101:259).

Appendix G: A Brief Chronology for Achievement of Man on the Moon

Sept 1955 President Eisenhower assigns "highest national priority" (42:79) to the research and development of the Intercontinental Ballistic Missile (ICBM).

4 Oct 1957 The Soviets launch Sputnik I--the world's first man-made satellite--into Earth orbit (11:32; 42:91; 145:164).

31 Jan 1958 United States launches Explorer I satellite into Earth orbit (11:32; 42:91; 145:164).

2 Apr 1958 Eisenhower creates the National Aeronautics and Space Agency (NASA) (11:32; 145:165).

12 Apr 1961 Soviet Cosmonaut Yuri Gagarin "orbited earth in a five-ton capsule becoming the first man in space" (1 32).

5 May 1961 United States President John F. Kennedy, in a speech to the Congress, announces the goal of a manned rocket mission the moon (116:736; 145:170).

25 Jan 1962 Congress approves a development program for the three-stage Saturn V launch vehicle; program given the highest priority (145:170).

1962 U.S. Ranger 3 probe missed the moon entirely. Ranger 4 lands on moon but due to malfunction sends back no data. Ranger 5 misses moon and loses power due to solar cell malfunction (145:191).

1964 U.S. Ranger 6 probe launched; unsuccessful due to burned-out electrical system. Ranger 7 appropriately redesigned and successfully transmitted pictures of the moon (145:19).

1965 Soviet space probes Luna 5, 7, and 8 crash onto the moon. Luna 6 misses the moon entirely (145:191).

9 Nov 1966 First launch of a Saturn V vehicle successful (90:60; 145:171).

3 Feb 1966 Soviet space probe Luna 9 achieves first soft landing on the Moon's surface (145:191-192).

30 May 1966 U.S. Surveyor probe launched; makes successful soft landing on moon and transmits pictures (145:193).

Apr 1968 Second launch of a Saturn V vehicle--part of the unmanned Apollo 6--is unsuccessful due to failures of three J-2 engines on the vehicle (90:60; 145:171).

27 Jan 1967 Apollo 1. Three astronauts killed by fire during full launch rehearsal (91:53).

Oct 1968 Apollo 7. First manned flight of Apollo Command and Service vehicles conducted in Earth orbit; test fired Service Module's engine by firing it (while in orbit) automatically as well as manually; heat shield performance checked during reentry (91:53).

Dec 1968 Apollo 8. Man's first flight around the moon; 147-hour mission. Twenty hours spent circling the moon. Photos of potential landing areas taken (91:53).

Mar 1969 Apollo 9. First manned flight with the Lunar Module; ten-day flight confined to earth orbit; separation, rendezvous and docking practiced between the Lunar Module (LM) and the Command Module (CM) (91:53).

May 1969 Apollo 10. "Successful dress rehearsal for the actual moon landing [which occurred] two months later . . . first time complete Apollo spacecraft had orbited the moon" (91:53). This was an 8-day mission (91:53).

Jul 1969 Apollo 11. First man on the moon; crew of Neil Armstrong, Edwin Aldrin, Mike Collins (91:54).

Appendix H: A Brief Chronology of the Development
of the Jet Aircraft

Nov 1917 "Committee on Light Alloys established within NACA to develop new metals for aeronautical use, constructor Jerome C. Hunsaker was Navy member" (42:7).

Dec 1919 "The Aeronautical Engineering Society was organized at MIT" (42:11).

Mar 1922 "NASA report No. 159 on Jet Propulsion for Airplanes, by Edgar Buckingham of the Bureau of Standards, pointed out that jet fuel consumption would be four times that of propeller engine at 250 mph, but that efficiency of jet increased at higher speeds" (42:14,15).

Jun 1920 "Initial flight of all-metal airplane (Gallaudet) designed by Engineering Division at Wright Field" (42:17).

Sep 1928 "Frank Whittle, RAF officer and engineer, obtained British patents for turbojet engine" (42:27).

During 1929 "NACA annual report indicated that aerodynamic efficiency may be increased by applying the principle of boundary layer control to the wings and possibly other parts of the airplane" (42:26).

During 1931 "Bureau of Standards made a number of experiments to determine whether the thrust reaction of a jet could be increased, and tested combinations of jets" (42:28).

During 1932 "German engineer, Paul Schmidt, working from design of Loran tube, developed and patented a ramjet engine later modified and used in the B-1 Flying Bomb" (42:29,30).

Apr 1937 "Frank Whittle's first gas turbine engine, the U-type, was static tested" (42:35).

1940 "Committee of the National Academy of Sciences reported that operation of turbine wheels at temperatures up to 1,500 [degrees] F might soon be possible because of U.S. and foreign development of high-temperature alloys" (42:40).

Mar 1941 "NACA established Special Committee on Jet Propulsion to review early British reports on the Whittle engine, which subsequently aided development of TG-100 turboprop engine by GE and the 19-B turbojet by Westinghouse. Dr. W. F. Durand was called out of retirement to head this committee" (42:41).

Nov 1941 "Italian jet-propelled Caproni-Campini airplane flown 475 kilometers in 2 hours 11 minutes from Turin to Rome, by Mario de Bernardini" (42:42).

Jul 1942 "German ME-262 turbojet fighter flown on spectacular flight test, concluding a series begun in May" (42:44).

Jul 1942 "First U.S.-designed jet engine successfully demonstrated at Langley Laboratory, the NACA Jeep, which was never flown but proved invaluable for continued NACA research on gas-turbine jet propulsion" (42:44).

Oct 1942 "First U.S. jet-propelled aircraft flight, by an Airacomet Bell XP-59A (powered by two I-16 engines developed by General Electric from the British Whittle prototype), made at Muroc Dry Lake, CA, with Robert Stanley as pilot" (42:44).

Jul 1943 "First turbojet engine completed for the Navy, the Westinghouse 19A, completed its 100-hour endurance test" (42:45).

Aug 1943 "German turbojet fighter, a Messerschmitt ME-262, demonstrated before Adolph Hitler in East Prussia" (42:45).

Appendix I: Letter Regarding Electrostatic Discharge Damage



DEPARTMENT OF THE AIR FORCE
HEADQUARTERS AERONAUTICAL SYSTEMS DIVISION (AFSC)
WRIGHT-PATTERSON AIR FORCE BASE, OHIO 45433

7 AUG 1985

REPLY TO
ATTN OF EN(PA)

SUBJECT: Product Assurance Policy, Electrostatic Discharge (ESD)

TO: ASD/AE ASD/AF ASD/B1 ASD/RW ASD/TA
ASD/YP ASD/YS ASD/YW ASD/YY ASD/YZ
(for Assistant for Product Assurance)

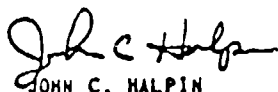
1. Electrostatic discharge has become well recognized as a source of failure, delay and cost in electronics assembly as well as of incipient failures affecting system reliability and durability in operational service. Parts such as microcircuits, discrete semiconductors, thick and thin film resistors, hybrids and chips are known to be sensitive to this phenomenon. In conjunction with our general workmanship and quality program requirements, we have come to expect that our contractors dealing with such devices will have adopted effective ESD protection practices.

2. In a recent special survey conducted by AFSCMD, they not only found deficiencies in contractor ESD protection efforts, but also experienced a lack of contractual leverage on some programs with which to secure contractor improvements in the ESD area. DOD-STD-1686 (1980), "Electrostatic Discharge Control Program for Protection of Electronic Parts, Assemblies and Equipment," is the preferred contractual vehicle for specifying the need for ESD controls and should be cited in the product specification for all systems containing ESD sensitive devices.

3. In a review conducted for Gen McMullen, we found that DOD-STD-1686 is generally cited as a requirement on the newer ASD programs; but since product specifications on several current programs predate the existence of this standard, it has not always been made contractually applicable. In such cases, we advise looking into the adequacy of your contractor's ESD control practices in conjunction with the AFPRO to be sure that there are no misunderstandings of our contractual intent. It is our opinion that the MIL-Q-9858A quality program specification should suffice as the governing requirement in such instances.

4. Our near term policy is that DOD-STD-1686 be referenced in all new product specifications for systems containing static-sensitive devices. This standard will be added to the listing of workmanship standards on the ASD Form 45, Quality Assurance Memorandum. In the long term, the Avionics Integrity Program MIL-PRIME standard, now under development, will encompass the DOD-STD-1686 provisions and will be the primary means for contractually invoking ESD and other integrity-related requirements in avionics systems acquisition.

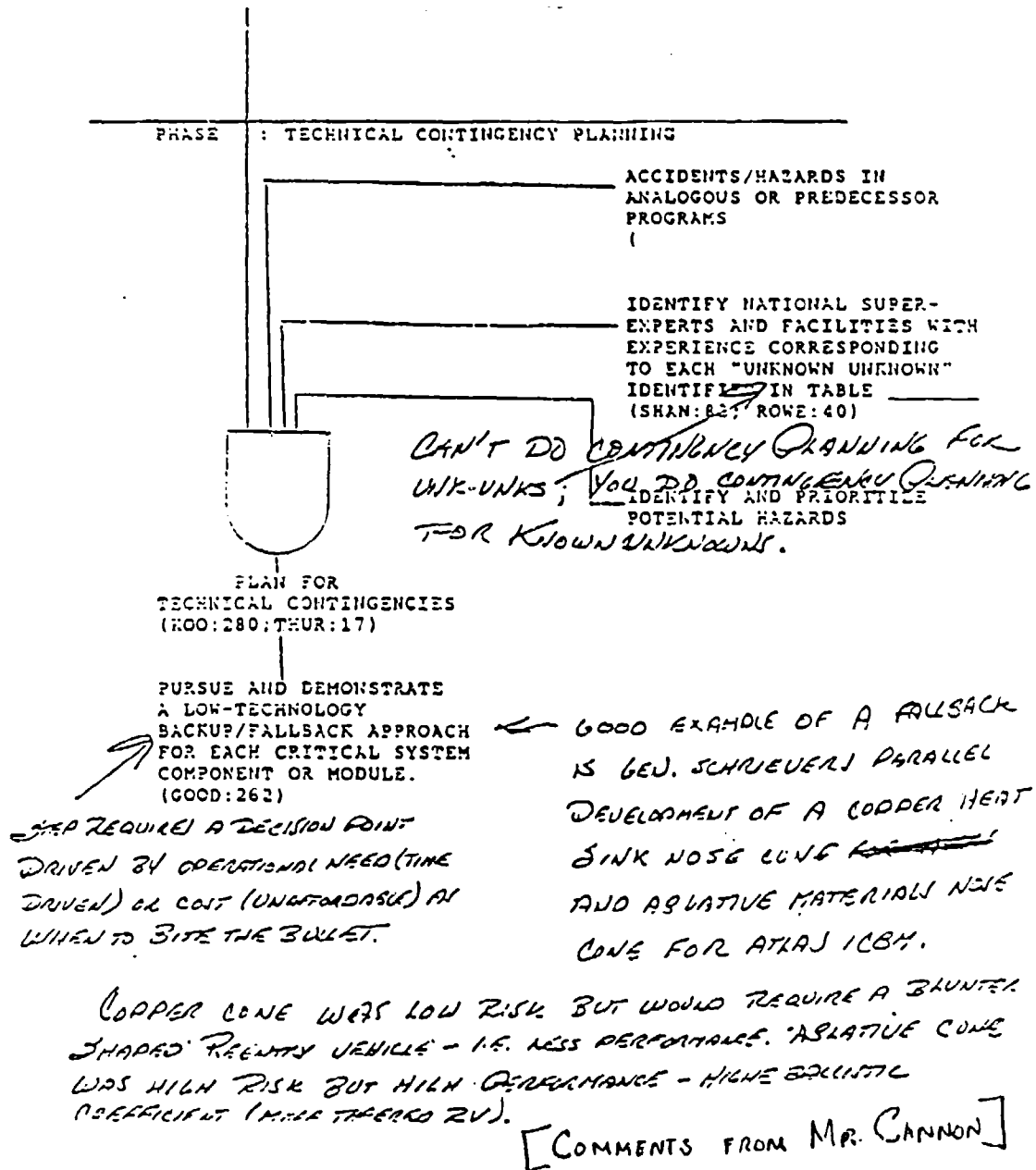
5. Should you have any questions about this policy or its implementation, please contact the undersigned or Mr George Thielen, ASD/ENSI, extension 53460.

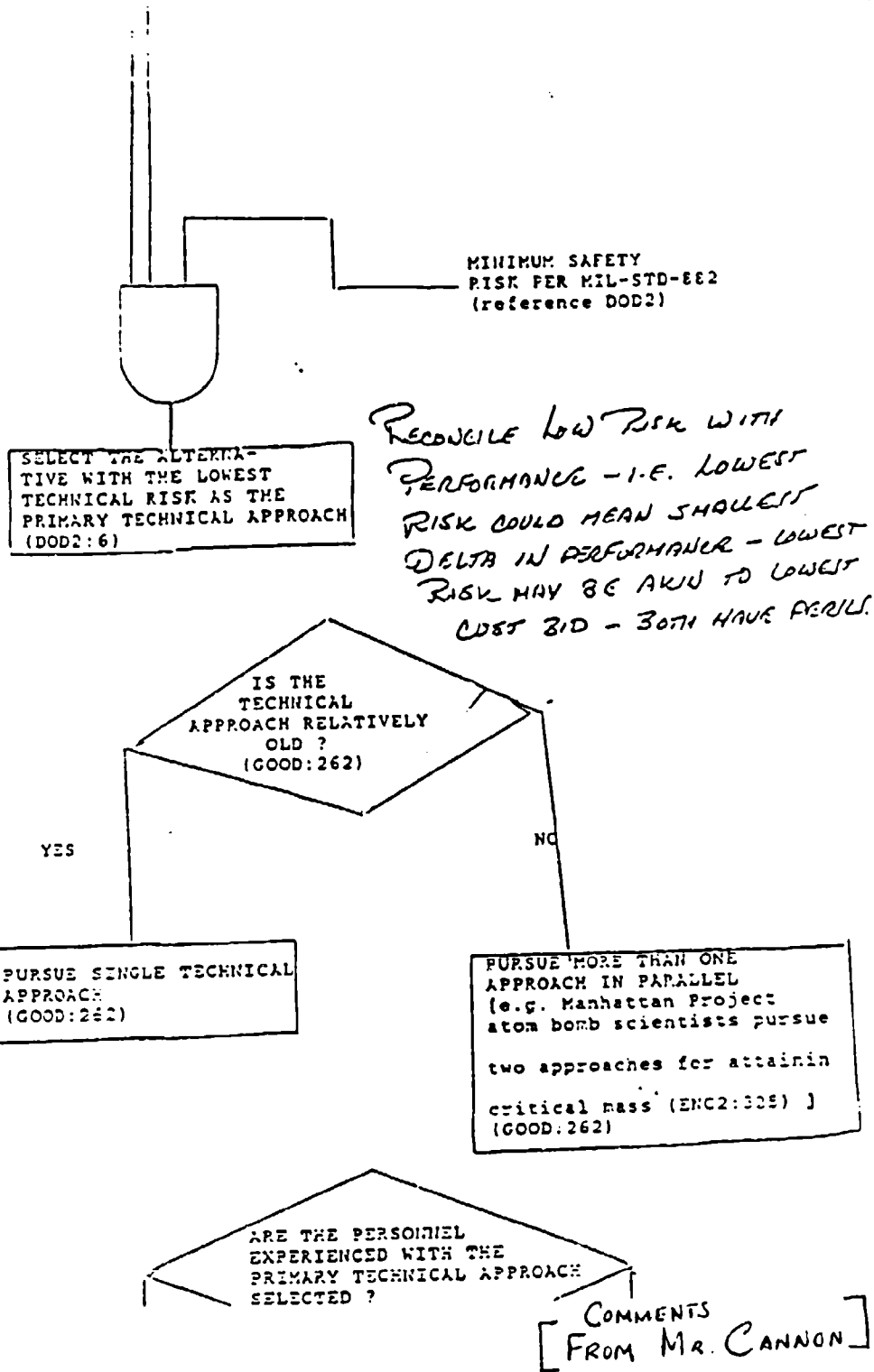


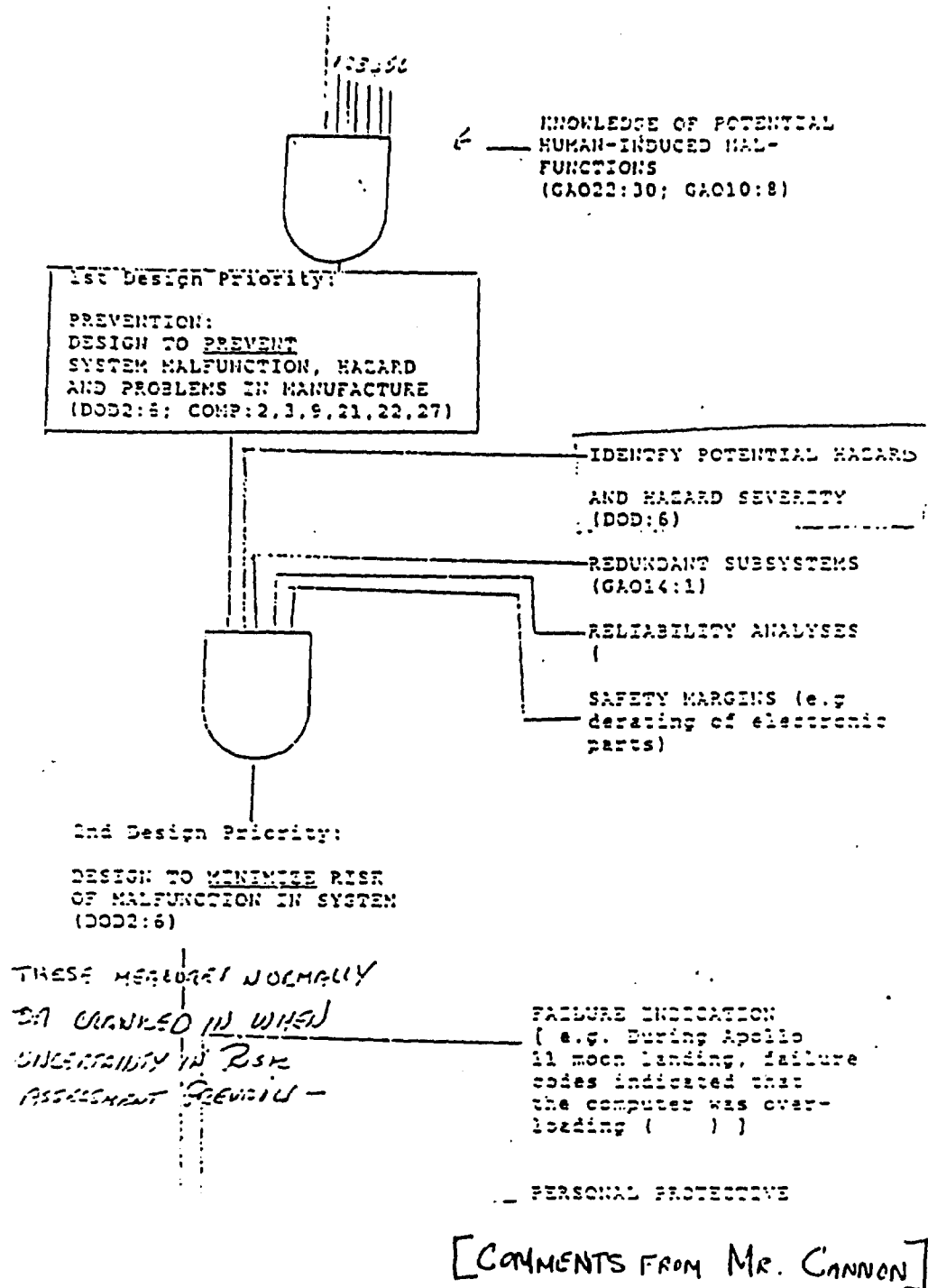
JOHN C. HALPIN
Assistant for Product Assurance
Deputy for Engineering

cc: ASD/ENSI
ENAS
PMOQ

Appendix J: Model Review Comments from WRDC







CONDUCT FEASIBILITY/CONCEPT
STUDIES
(THUR:15)

OBTAIN RELEVANT
PREVIOUS RESEARCH
(ANDE:3,6-10,12)

AVOID PITFALL OF
TECHNICAL OVER-OPTIM-
ISM REGARDING THE EASE
OF APPLYING NEW OR MODIFY-
ING ESTABLISHED TECHNOLOGY
(FOX:128; GAO:12:51
DAF1:24)

AVOID PITFALL OF PROCEEDING
WITH NEW TECHNOLOGY WHEN
EXISTING OR MODIFIED OFF-
THE-SHELF EQUIPMENT WILL
SATISFY REQUIREMENTS.
()

*USING EXISTING EQUIPMENT
SHOULD NOT FORECLOSE
ON GROWTH POTENTIAL OF THE
SYSTEM*

EVALUATE LEVEL OF
TECHNICAL EXPERTISE
REQUIRED VS AVAILABLE
(ROWE:40; THUR:12)

DEFICIENCIES/LIMITATIONS
OF EXISTING TEST FACILI-
TIES AND EQUIPMENT
(PENT:14)

DESIGN OR FABRICATION
ITEMS NOT REDUCED TO PRAC-
TICE
(RNO:1:5,7; BAU:1:254)

EVALUATE STATE-OF-THE-
ART PER TABLE
(ROWE:40; GAO:1:261
DAF1:27)

01 AUG 1983

Dear Peter King -

I MADE SOME PASS THROUGH YOUR
MODEL AFTER OUR MEETING ON TUES. 1 AUG.
I MADE SOME SPECIAL COMMENTS WHICH
MAY BE OF ASSISTANCE TO YOU. IN MY ORIGINAL
REACTION IS I THOUGHT (AS I MENTIONED TO
YOU) THAT THE MODEL WAS VERY DETAILED.
UPON GOING BACK OVER IT, I WOULD TEMPER
THAT STATEMENT TO RECOGNIZE THAT YOU'VE
COVERED ALL ASPECTS IN A PROCESS THAT
GOES FROM PRE-MILESTONE ZERO TO
WELL INTO FULL SCALE DEVELOPMENT. EXPERIENCE
WOULD PROBABLY SHOW THAT ^{IN THE FUTURE} SOME OF
THE STEPS ARE LESS EXPLICITLY ADDRESSED
THAN THE MODEL REFLECTS AND ARE ASSESSED
MORE IMPLICITLY/LESS THOROUGHLY. ~~THE~~
AS A ~~CLASSICAL~~ MODEL IS STILL OF VALUE
TO THE MANAGER, WHO SKIPS SOME OF
THE INTER-MEDIATE STEPS, TO SHOW HIM
THE "MANAGEMENT RISK" HE IS TAKING BY
~~SKIPPING~~ ~~SOME~~ OR IN HIS EYES
TREATING AS UNNECESSARY CERTAIN STEPS. IF HE
SKIPS STEPS WITH A CONSCIOUS DECISION
HE IS ACCEPTING THE MANAGEMENT RISK BUT
IF HE DOES SO UNCONSCIOUSLY HIS FEARFUL
BEGINNING AND FUTURE HEARTBURNS.

[FROM MR. CANNON]

HEADQUARTERS
AERONAUTICAL SYSTEMS DIVISION
WRIGHT-PATTERSON AIR FORCE BASE, OH 45433-0043

DATE: 20 Feb 89

MEMORANDUM FOR: Capt. King
SUBJECT: Risk Report

I had to rush through your model so probably missed something but have two observations:

1. Where does cost enter into model? Technical feasibility may be demonstrated but may not be affordable.

2. How manage risk of new technologies. Transistor had no requirement when invented. Many things in the model don't have answers. User can't help because too far removed from technology.

3. Perhaps this model is more representative of "Risk Report" - the feasibility (over)

demonstration [FROM DR. RILES]



CHIEF SCIENTIST
AVIONICS LABORATORY

25 JUL 1963

To: BRT/LSG (Capt. King)

I'm afraid I didn't do you much good - there are some detailed comments in the text.

By way of general comments:

(a) "System Requirements" - formal ones - frequently come late - sometimes not at all.

(b) Many revolutionary systems/capabilities did not have agreed "requirements" - in fact they were resisted by the ~~or~~ then-current military establishment (e.g.: Tank, Submarine, Stirrups for horses, Flying Wing, ...)

(c) The logic is impeccable, but I see a lack of an institution which works itself through the questions. The questions/answers are not frequently addressed or are addressed in an uncoordinated way.

Jim Olson, WRECK-F
57329

Appendix K: Interview with Dr. Keith Richey,
Technical Director of WRDC, 28 July 1989

Interviewer: Sir, what are your technical qualifications?

Dr. Richey: The highest degree is a PhD in Aerospace Engineering from the University of Michigan.

Interviewer: What is your technical experience?

Dr. Richey: I'll give you a biographical sketch, then I'll fill in some details. I have 28 years of experience in the government laboratory systems. In fact, all in Flight Dynamics laboratories of AFWAL now [reorganized into] WRDC. And for the last 2 years in WRDC front office. So, all of my experience except for 2 years I've gone to school full-time with a PhD level with the flight dynamics laboratory, and with WRDC.

Interviewer: What is the mission of the organization of which you are a part?

Dr. Richey: Basically research and development. Technology development for the Air Force. So, its a focused application of all technologies. Aerospace, electrical--any technologies that we deal with, focused toward Air Force applications. The basic research through advanced development.

Interviewer: What is your present job?

Dr. Richey: Technical Director of WRDC. (Chief Scientist of the Chief Scientists, if you will).

Interviewer: In your opinion, what are the most important techniques for managing technical risk?

Dr. Richey: Well, first of all I think you have to understand the problem. And understand as much as you can about the technical characteristics of a problem. Try to be as analytical as you can. I guess the engineer in me is coming out. You try to be as analytical as you can but to recognize a lot of things that you can't be analytical about. But I think you need to sit back and try to understand the problem as much as you can. Then try to understand the various facets of the problem. I'll try to break it down into some elements. Try to understand how the elements interact. And then try to get a feel for the degree of risk--whether its achieving an objective, or schedule or cost, or anything else. A degree of risk that

might be associated with each element and the interaction among the key elements, and then try to construct a critical path function that shows you where the highest risk elements are and their importance to the outcome of the system. Something might be very high risk but not very important. So you wouldn't care about managing it at all. Let it be high risk. So what. It doesn't affect the outcome. Something else could be of lower risk but extremely critical. So, that a little bit of risk in a critical element could have a large affect on the outcome of the system. Try to identify those elements or most likely combination of elements because things don't usually happen singularly. They usually happen in multiples. Those combination of elements which are the highest risk to achieving the desired outcome. This assumes that you have a pretty good idea of what the outcome is, which is not a good assumption in all cases. But, let's say you have a good idea of the desired outcome; so having gone through this analysis it could be qualitative or quantitative. But you have some idea of the elements and the degrees of risk, and the importance. Now we have identified the elements or combination of elements that have the largest impact on the desired outcome. And as I said before some of those elements might be high risk factor; others might be the low risk factors. But the criteria is the effect on the outcome. So, having identified the elements of the problem that have the largest effect on the outcome, now we would be in the position where we'd try to manage the risk of the elements. To me managing the risk means to identify what the risk is at the beginning of the process, then taking positive action to reduce the risk to an acceptable level at the conclusion of the process--recognizing that you can't wait until everything is at zero risk to complete. Most R and D [Research and Development] projects will be completed without having risk equal to zero in all factors. There is going to be some risk at the end. But it has been managed to be by the process. It has been managed to be reduced by the many factors to an acceptable level. Now a case in point in the Air Force labs WRDC particular, is reducing risk to an acceptable level so that the next stage of technology development can begin or follow on. Which would be engineer development. Category 6.4 budget, which is not done by the laboratory but is done by the system program offices. Whoever is applying the technology would take our product. Our product is technology developed to such a point that there is enough confidence in a low enough risk, but I wouldn't say zero risk. Enough confidence and low enough risk, so that they can apply the technology with confidence in the next step of development. Which is 6.4 engineering development. And that is the way it is in the Air Force. That is the way it is in the evolution of the technology. Now my perception would be that in any given project there will still be risk, when we

hand it off from 6.3 to 6.4. The risk will be further reduced and managed in the 6.4 and beyond. But the laboratories wouldn't have much to do with that--with the risk management 6.4 and beyond. Only on consultation basis. Because our job is to develop the technology to a point and then hand off. We very seldom stay with a technology all the way through to its final application. It's just the way the Air Force is organized. We have laboratories, SPOs, users. We have Logistics Command and so forth and, so on. If we took the attitude in the laboratories, that we have to reduce risk to an absolute zero level before we transition it, number one: we'll keep the technologies too long and they wouldn't transition to the Air Force as fast as they should. Two, it would be prohibitively expensive because the last 10 percent of a project, in terms of a full risk reduction, is very expensive. And you want to only do that in given applications. Because if we would say that we had to reduce the risk to zero for any and all applications since we don't know what the applications will be, we'll have to reduce it for any possible application, and that would take many more resources, in terms of dollars and people, than we have available. So, we make a conscious decision as to when to turn it loose. To use a reasoned judgment on what that hand off is. We sometimes learn after we hand it off that we didn't do enough. There is a major surprise somewhere in the application of our technology. And if we were real honest with ourselves, we'd say we should have caught that. We should have known that would happen. The users of our technologies, in that case, give us a poor mark. The user comes back and says: you guys gave me foreign technology, and we say: well we probably did. We usually make an excuse that we didn't have enough money or didn't have enough time. And there is always the unknown unknowns. Once in awhile a technology goes sour in a big way after it leaves the laboratory. So we try to minimize that by lessons learned and by understanding the application of our technology to the field after they leave the laboratories. We try to learn as we go, and minimize our cases but, they can still happen.

Interviewer: Based upon your experience, what is the most important technique for managing technical risk?

Dr. Richey: It's hardly a technique, but I would say the answer to your question would be knowledge; as much knowledge as you can possibly have on the physical and non-physical phenomenon that you're dealing with. We don't have perfect knowledge of any perimeters, but I would say that the single most important to know to manage risk is to understand the physical and nonphysical driver.

Interviewer: Does your organization have a specific written strategy or policy for assessing and managing technical risk?

Dr. Richey: Not specifically. There are no documents that you can pick out--that I am aware of at least for the center level--that's called risk management or even the risk assessment. On the other hand it goes through everything we do. You know we manage risk every day. It's part and parcel to the management of technology. And knowledgeable people, scientist and engineers, and managers, and project managers, and technical development are--whether they recognize are managing risk every day. But to my knowledge there's not a written policy. Now there have been some studies done on risk assessment by the laboratories; risk assessment and perhaps risk management. And the most knowledgeable guy I would know of that has done this in WRDC is Dr. Squire Brown [Interviewed].

Appendix L: Interview with Dr. Harris Burte,
Chief Scientist of WRDC Materials Lab,
17 August 1989

Dr. Burte: I understand better what you are driving at as we look at this outline [Preliminary Risk Management Model]--it's a rather thorough and complete outline of many things. I have two comments. One has to do with the idea that risk reduction means different things depending upon whether you're in the process of developing a system to meet a stated operational deficiency--at one extreme or at the other extreme exploring or doing what you can to foster the transition into use of new technological possibilities. Those are quite different things. In the middle between those [extremes] you might have the question of pursuing a national goal that's less well defined than a required operational deficiency that you have to pursue or pursuing the possibilities of meeting some national vision or goal that somebody such as the President enunciates. Examples of these might be "put a man on the moon" or the SDI project where the President or some other decision making authority has a vision of something and says "I want to get there." Those are three different levels. In one case you have a required operational need and [you want to solve] "What's the best way to meet it at this time?" That's akin to the systems development process. In the other case you have a vision of something in the future and you are exploring possibilities. In the third case you're developing the capability to meet these possibilities. In the final case, you have a technological possibility which might be applied to a wide variety of operational needs, or perhaps only a small number of operational needs and you are exploring what you have to do to transfer laboratory concepts or demonstrations into something that can actually be used. I have the feeling that you treat all of these a bit the same in this [model] and I think that you might want to explore the extent to which they are different. When we're working against a potential threat or a statement of operational deficiency, to use your words [in the model], the ways of doing it tend to fall into many of the things that you're talking about here [in the model]. That's what a SPO does when it tries to organize of analyze: What are the best ways of meeting this? What are the cheapest ways? What will give me the most bang for the buck? How do I cope with the risk? In these ways, balance the risks against the payoff and make sure that I'm not taking undue risks for the time and the budget I have to do my system. In the "mandated national priority" sort of thing, such as "put a man on put a man on the moon or do an SDI, there has to be some guidance as to timeline. At

different stages you can take a lot of risk, you can explore a lot of possibilities, or, in something as simple as SDI--"let's provide a defensive shield for the country"--risk isn't much applicable there in the initial stages. The question is to explore what the possibilities are more at that stage. And then when you have the possibilities, to assess the question of what it takes to get them into use. Risk becomes a factor as a function of time and budget available to put it into use. In the exploration stage, risk is considered differently. Risk is: Which things are most likely to be promising in the long range? That's different than: How much time and money will it take me to get all the bugs out of an actual operational system? Those are quite different questions. Finally, in the case of taking something where some degree of laboratory feasibility has been demonstrated--I talked about this to some extent last time [earlier interview]--and transitioning it. The question is now: you've got a laboratory thing, but if somebody is building a system, he has a certain time and budget and he's got to meet that time and budget so he has to know that the things he chooses for his system are compatible with his kind of budget. An industrial analogue to that is: if somebody wants to bring a new product to the market, he does a return on investment calculation. But to do the return on investment calculation in the commercial world often requires a great deal of information about the new product, and he requires the knowledge that he will be able to do these things [that] strange things won't pop up and hit him in the face and destroy him.

Therefore, the decision to go ahead with a new product--the capitalizing, build the factory, do all the advertising and everything to get a new product to the market--is a big multi-buck decision. If there is a lot of risk in terms of the new product--we're not really going to be able to do it or strange things are going to happen, or it's going to take us a lot more money or a lot more time to bring it to the market place--then the decision takers are likely not to go with the new product. We may go with it foolishly as Rolls Royce did [mentioned earlier interview] and go bankrupt first. So, those are different elements of risk reduction. In some cases it is a case of risk assessment. In the case of a system developer, it's more a case of risk assessment. You don't have that much time to reduce risk once you decide that you want to go to a system. In the case of pushing new technology forward, then there is the question of learning what the strange things are or: How can I scale it up? Or making sure there are no gaps in it or learning more about the behavior of the new product so that you can really assess what the new benefits will be versus the cost of it. In the case of exploring new possibilities, like in the SDI example, that's a totally different question. There one has to

[ask], which possibilities are most likely to give me the biggest payoff? Now at a much later stage, somebody might decide now I want to set up an SDI system. Of the different possibilities available, in which one is the risk adequate for my purpose? That becomes a risk assessment issue.

Interviewer: So, risk assessment doesn't start until you completely or comprehensively explore the possibilities?

Dr. Burte: Well, you can always do risk assessment at any time. People in the military in particular--you're spending money to take chances. But at any given time you may say I have got to use this technology [or] I won't be able to do what I want to do. But you can take an assessment of what the risk is and ask yourself then: Are you willing to do that? You shouldn't just go ahead without thinking about it. So those are the main points as I see it. And I think those are a bit different and I think you have a bit of all of those confused. In other words for the three things of mandated major possibility like SDI or the Orient Express [National Aero-Space Plane] at the present--that's for the question of the early stage. For each of them [the three sources of risk shown in the model] the question of risk is considered differently. If it is a requirement, I want to do this in a finite time--like put a man on the moon. That can be like a system requirement and you can say, well, for that time and budget I have, is the risk tolerable or can I overcome the thing? If it is a mandated national thing that says: I will build an Orient Express that's a different thing. There we're exploring the possibilities--or SDI as initially put forth. And if in fact you're restricting yourself to where the President says I want a definitive capability at such a time at such a budget, then it is a risk assessment issue. But there may be time in that to do the development of new technology. Much of what I was talking about wasn't in the risk assessment aspect it had to do with the question of converting new technology to a point where somebody could do a credible risk assessment. If it's too early, you're making too many assumptions about the risk; you don't have the knowledge of what the risks are. Part of risk reduction is just getting the information so that you can make a risk assessment. Okay, those are the main things that I want to say and that may or may not apply very much to this [risk management model]. If you're sticking very much to [the case where] the technology is essentially there to do the job or to do something like the job that I want, within the time and budget that I have, trying to pick the technologies that will best work for the purpose, what you've written tends to apply considerably. If you're getting into other things like an SDI system, or finding uses for new technology such as VHSIC--that's much of what

I was talking about beforehand [in the earlier interview] and you may not be getting into that. You may want to look over what you're saying from the viewpoint of it [the model] creeping into that. Because that's risk reduction. Here you're talking about risk assessment and assuring that the risk in the first case where you've got a definitive set of requirements and now you want to make sure that the approaches that you take fit that. That's not really risk reduction. That's risk assessment and risk selection--unless you have some time to explore different possibilities. If you have time to explore different possibilities, that becomes something like risk reduction. But many of these [projects] don't give you much time to explore different possibilities. . . . Risk management gets to be not so much risk reduction as risk assessment--choosing the right things--when you're in the systems world. You should have a lot of that done before you go into the system selection. Essentially, risk management is different than concept exploration.

The other thing I want to talk about is what is the role of a government lab in this. There I feel strongly that a government lab such as our lab or any other government lab--one of their highest callings is to play a major leadership role in doing any of the things I have talked about. A government lab hopefully is wedded only to the Air Force--in the case of an Air Force Lab. It's a neutral ground; it has no ax to grind. Hopefully it has within itself excellence which is the peer of anybody in the country, not just bureaucratic smart buyers. Really competent people who know the technology and are on the forefront of leading the development of new technology. People such as this should be deeply involved in any of the things I've talked about: risk assessment for giving a clear-minded unbiased viewpoint of what we know and what we don't know. And an assessment of how serious is what we don't know and how long it will take us to fill in the gaps and is that commensurate with the budget and time available for the project that you've set up. In the case of exploring a spectrum of new possibilities, the excellence involved here is that which can exercise leadership in the nation as a whole. To have very good people explore new possibilities in other than a wish-is-the-father-to-the-conclusion mode. Exploring them enthusiastically but always asking: What do we know and what don't we know and what might the pitfalls be? The government lab can again exercise tremendous leadership here and act as a governor on that process because the people who are advocates for a given activity tend to enthusiastically look at the potential for success. As [the late Nobel prize winning physicist Richard P.] Feynman said--I think his words were something like in the Challenger [Space Shuttle disaster review] committee--I think his words were something like "you can't fool Mother Nature." That's the point. People

who really understand the science and the technology and, by being wedded to the Air Force, make sure we ask the right questions. The other point which is the business of assessing and understanding what it takes to reduce the risk. That's all the work that takes place as you go between the typical 6.2 work and the introduction of something into a system. It is that work--when I talked to you last--that I was saying is deficient in many areas of the country.

Appendix M: Interview with Dr. Jim Olsen, Chief Scientist
of WRDC Flight Dynamics Laboratory and Dr. Arnold Mayer,
Assistant for Research and Technology, 25 July 1989

Interviewer: Sirs, what are your technical qualifications?

Dr. Olsen: I hold a bachelors, masters, and PhD all in Aerospace Engineering.

Dr. Mayer: I have a bachelors in Mechanical Engineering, a masters in Engineering Mechanics, and a PhD in Mechanical Engineering.

Interviewer: What is your technical experience?

Dr. Olsen: I've done aircraft performance, instability and control and then went into structures, vibrations, flutter unsteady aerodynamics.

Dr. Mayer: I was a mechanical engineer with Bell Telephone laboratory supporting the mechanical and thermal development of electronic devices, electron tubes, and integrated circuitry, and also principal engineer. I was also Cryogenic Engineer with Grumman Aerospace, also I was the principal engineer with Cornell Aeronautical labs, SCAD Missile project. With the Air Force worked on R&D into aircraft environmental control systems, Electronics coolant, a little bit of windshield impact research. I have to get into a lot of diversified things because of the position I hold as Chief Engineer of Mechanical Division where we cover landing gear, escape systems and environmental control, and ballistics research.

Interviewer: What is the mission of the organization of which you are a part?

Dr. Olsen: Our mission is to do the research and the development that gives the Air Force the capability to develop a better airplane and to improve the ones they have or to give them a range of options of what they might want to choose for the next aircraft. We do a research and development and aero dynamics, structure, flight control, system and all the subsystems.

Interviewer: What are each of your present jobs?

Dr. Olsen: I'm the Chief Scientist of the [Flight Dynamics] the laboratory.

Dr. Mayer: For the Vehicle Subsystem Division, I'm the division's Chief Assistant for Research and Technology.

Interviewer: In each of your opinions, what are the most important techniques for managing technical risk?

Dr. Olsen: Risk is something I don't think we manage that much. We generally working on trying to prove something is feasible or something can be done. How about assessment? I guess explicitly I don't think we practically speaking really evaluate the risk. We talk about risk. But we generally determine if the idea is possible. In a very general way if it's practical. At least I don't know of any way really quantify risk in deciding to go with higher risk or lower risk.

Dr. Mayer: We compare various alternative concepts and do payoff analyst. We try to establish the feasibility and the process of establishing feasibility. I think we discover that some things are not feasible therefore too risky and other things are more feasible. And those that survive these various levels of investigation, they eventually get developed. And our contractors evaluated alternative approaches. They propose approaches and if we think they're credible by virtue of having checked the concepts versus the physical laws of nature then we just keep going as long as it remains feasible. If we run against an obstacle. Because we've in the business of eliminating risk or sorting out risky things from impossible things, just by continuing to develop them. If we hit a stone wall then the project stops, or some other alternative attack is pursued.

Dr. Olsen: I guess if you're developing an airplane you want to look at several different approaches of doing a particular part of the mission or building part of the airplane. You look at the risk there. But I guess in my experience in the 61XX and 62XX areas really risk is not something you evaluate very much Maybe in 63XX development there might be some efforts they pursue or don't pursue because of risks.

Interviewer: What is the most important technique for managing technical risk?

Dr. Olsen: I'll go back and say that I don't think that we really have some kind of graduated scale of risk that we manage against. We try to put our resources where they pay off the most and we try to do things that we can prove are feasible and will have high payoff.

Interviewer: How do you improve that feasibility?

Dr. Olsen: Well, I guess you come up with the possible design or application or implementation you can have. But, again the feasibility is sort of either it is or it isn't. It's like, it works or it doesn't work. For instance we developed something called a active control system to aircraft flutter the vibrations of the wings. And we demonstrated to our satisfaction that the 61XX and 62XX level that we could make it work. We went into the wind pile and built it. Yes, this thing works. And we know how to do it. When the question about risk comes that sort of moves up into another ball game. That question is: can we get the F-16 program office to use this method to improve their airplane? At this point they're saying either it is too expensive, or it doesn't come at the right time or is a too high of a risk. But again its a "go" or "no go" decision. So I don't know what the best method is of managing risk.

Interviewer: Does your organization have a specific written strategy or policy for assessing and managing technical risk?

Dr. Olsen: Not that I'm aware of. We have one set of programs that we pursue called the laboratory independent programs where the director tells us that he wants us to go in to very risky areas. Because of the perception that sometimes we get too conservative. So there is a whole pot of funds set aside to go into those high risk areas to see what you can do.

Dr. Mayer: We make use of analysis to see if our concept is feasible. Using mathematical, physical models of things to the extent we can anticipate that. Another step is to actually do development testing to do tests to determine some phenomenon performs. Or we can get the performance out of the phenomenon that we look for in magnitude. And we eventually try to develop a demonstration. And there is a lot of iterative steps between analysis and testing until it's clear the right combination of the attributes and performance characteristics have been achieved. We also worry about cost, weight. Is the thing too heavy? is it palatable? It can't weigh too much, it can't cost too much, and it has to be energy efficient. So, it is a balancing act, and sometime we switch concept in order to alleviate some of the objectionable characteristics.

Dr. Olsen: I think that you're going to find risk in the laboratories is not the same as risk in the SPO. He's got a plane to build and a time to build it in, and a cost to build it in. He's definitely looking for the lowest risk way of getting done what he has to get done.

Dr. Mayer: We though provide him with the information on which concepts are feasible, because they have been tried in the laboratory previously. I think a SPO director would be foolish not to require that something have been demonstrated previously in an advanced development program where we spend a lot of money just trying to do something for the first time to prove that it can be done. And its done in a quasi generic fashion so, that when the SPOs want to build a particular aircraft, they derive some confidence measure from our having done a generic version of that previously.

Dr. Olsen: We demonstrate whether it works at all, or whether if it can be done at all.

Interviewer: Can I have a copy of any strategy for minimizing technical risk?

Dr. Olsen: I don't know of any.

Dr. Mayer: Well, I suppose that you could consider the way we categorize the levels of research as basic research where natural phenomenon are investigated basically to understand, the exploratory research, where we try to apply these phenomena and configure them to work and perform some useful function on an aircraft or Air Force contracts. Then there is advance development, where some form of realistic full scale demonstrations of the subsystem or product is conducted. And then there is the 64XX, the engineering development, for a particular weapon system. That is what ASD and the SPOs is exposed to.

These also correspond to budget categories. The "appropriate money set aside are kind of inversely with the risk. The further stages really get more expensive, because you have to pay attention to more realistic details. You have to make it look like an airplane, make it look like a wing, a landing gear, or a tire. Whereas at the early stages, we can just play with the materials, rubber or what ever.

Dr. Olsen: I think that is a good point, because I guess when you move up to basic research, exploratory. Are you familiar with the 61XX, 62XX, 63XX? The 61XX is basic research, 62XX is exploratory development. And as you move into the other categories like 63XX and 64XX then risk. . . . In the 63XX program they do look for different options to achieving the goal and evaluating the risk. [Is 61xx, 62XX, 63XX, part of the labs?] Yes, even some 64XX.

Dr. Mayer: We actually build some windshields through retrofits. But we primarily use 61XX, 62XX, 63XX.

Dr. Olsen: The programs are 61XX for basic, 62XX for exploratory, 63XX for advanced, and 64XX is for engineering development. I guess there is other [budget categories] categories 65XX but I don't know what they are. Maybe you should talk to some 63XX people. I was trying to think of the guys who does the 63XX programs for structures. There's a guy you should talk to named Vern Johnson. Johnson's phone number is X55664. And I know that they look at part of their 63XX program, and they look at several different approaches to get a particular improvement in an airplane. And one of the things they evaluate is the risk. Risk versus cost performance. They try to avoid risk because they're now in the exploratory and basic. We're more "blue sky" and willing to be more daring, and try different things. As it gets closer to something that goes on an airplane people begin to manage the risk as you say by eliminating risky things and pursuing less risky design options.

Dr. Olsen: I think we just didn't really get into it [risk reduction] until we start talking about the 63XX that Arnold [Dr. Mayer] brought up.

Dr. Mayer: That's where the aircraft or aerospace aircraft manufacturers get into it. They are usually the performers of those contracts. And they force them to do things the way they already know how to do them. To some extent that minimizes risk too.

Dr. Olsen: I don't know if you would want to minimize the risk. I think its just an all out effort. Maybe later on when you got to the point of where, you've got a bomb built and you're going to put it on an airplane to drop it, then minimizing risk might become an issue.

Dr. Mayer: Well, they had to work out a lot of problems. How do you make sufficient quantities of these radioactive materials for the bomb. And I guess they have to develop some of the factories. Some of the uranium purifications centrifuge and whatever is involved.

Dr. Olsen: And then there were a couple of different process. I remember that General Groves was forcing the people to pursue at least two different manufacturing methods. The manufacturing methods and minimizing risks. And giving himself at least an option.

Dr. Mayer: Now we use that too, we call it fly offs. We usually try to have two different teams go and build something. Then they fly off the best result so you'll at least have the better of two approaches.

Dr. Olsen: Of course the engineers wanted to keep the parallel path going as long as possible [for the atom bomb]. Eventually General Groves forced them into a decision to go one way or the other. Whether the way they do the enclosure or how they manufacture the stuff. That's a good history to look at. I always thought that he was just the civil engineer that built the things and put them together. The last book I read, he really played a very strong management role. He wasn't just someone that was standing on the side lines waiting on for results, but he was really driving those guys.

Dr. Mayer: Well, I don't know whether putting the man on the moon is one of your cases [it is]. I recall that one way they minimize risk is that they had, one engineer on every piece of hardware. There was one engineer that did nothing but one particular valve for three years. And he was 100 percent responsible for that valve. The design and performance. I guess if you put a lot of people on something and dedicate them you can reduce risk.

Appendix N: Interview with Dr. Jess Riles, Chief Scientist
of the Avionics Laboratory, Wright Research and
Development Center, 25 July 1989

Interviewer: Sir, what are your technical qualifications?

Dr. Riles: I hold a bachelor in Mechanical Engineering, bachelors in Aeronautical Engineering, and a masters and PhD in Electrical Engineering.

Interviewer: What is your technical experience?

Dr. Riles: At one time I was the program manager for NASP [National Aero-Space Plane] National back in the 60s' when it was called the Aero-Space Plane, now it is the National Aero-Space Plane. I have worked in research and development. I have worked in the acquisition business in Aeronautical Systems Division. When I was in the service I was a Maintenance and Communication Officer. So I kind of had the full spectrum of creating the idea to how you keep it working on the flight line.

Interviewer: What is the mission of the organization of which you are a part?

Dr. Riles: Research and development, and Aerospace Avionics.

Interviewer: What is your present job?

Dr. Riles: Chief Scientist of the Avionics Laboratory, Wright Research and Development Center.

Interviewer: In your opinion, what are the most important techniques for managing technical risk?

Dr. Riles: So you're saying that the first elements of feasibility have been assessed?

Interviewer: Yes.

Dr. Riles: Well, I think probably the most used technique here at ASD [Aeronautical System Division] is to put people on it with systems engineering experience, that have developed similar kind of things in the past. To try as much as possible to support at least a couple of competing approaches. These days with the funding we have its a little difficult to fund competing approaches. So sometimes you prematurely have to decide on, if you will, "one horse to ride." And after you have gone a year or two

downstream, you find you're on the high risk horse. If you could, you could fund the beginning approaches. The other is to solicit the opinion of many people in the other services and other national agencies, to help you in establishing their course of engineering development of whatever you're talking about, and we do a lot of that. We bring in expert committees, scientific advisory boards. We bring in expert consultants from industry and from other sources other national labs to help us.

Interviewer: Based on your experience, what is the most important technique for managing technical risk?

Dr. Riles: I think that probably the one that seems to have worked most often is make sure you use people that have experience. What's the old saying? "When you don't know what direction you're going, almost any direction will do".

Interviewer: Does your organization have a specific written strategy or policy for assessing and managing technical risk?

Dr. Riles: Well, see the way you justified the risk, you've almost taken the problem out of the laboratory. Because what we do is come up with some new ideas and we carry them through to some kind of feasibility demonstration. Then we try to encourage users. "Users" is a rather broad term to us it can be people in the operating commands. It could be people in the intelligence agencies, it could be the engineering people in ASD who support SPO's in going out and acquiring weapon systems. So, once you take it out of that "demonstrate the feasibility" it's a kind with technical viability of a concept for use of the Air Force or other services. Its then something that's outside the laboratory to manage to get into a weapon system.

Interviewer: Let's say that you have a lot of feasible options, how does the lab decide which one has the least technical risk?

Dr. Riles: Well, you're kind of getting into the philosophy of how do we prioritize the work we do. What you're talking about is an investment strategy. And what we do is that in the various disciplines that we're responsible for like electronic warfare, offensive avionics, developing things to go out and find targets, identify them and provide the weapons capability to strike them. We build programs. First of all, we provide some top down guidance, and how much money we have, what does front office think we should be in what kind of businesses, which ones look like we should invest in the heavier, and

then from the bottom they build the program. They put together the various ideal that we want to pursue. Now some of them are way out. Some of them are closer in. Then we have what we call kind of a rack. It's a period of time, usually the early part of the given year where we develop the next year program. And during that time we have to evaluate the maturity of the concept, and how much risk there is involved in doing this and is it absolutely frivolous to go out and do something or is there some possibility it's going to pay off. Usually we take expert opinion inside, in doing our first ranking of these ideal. If we have questions about the liability of some particular piece of technology, we have experts that we can go to: scientific advisory boards, defense science boards. We all have people in the industry we can talk to or technical compatriots in universities that we can go access and get their opinions to help us decide whether or not we have ranked or prioritized or agree to fund this idea in the appropriate fashion. Or is there too much risk in it? It's just not worth investing in now. So I would have to say that expert opinion is probably the most used.

Interviewer: Is there any policy within the organization for managing technical risk?

Dr. Riles: A policy document?

Interviewer: Yes.

Dr. Riles: No.

Dr. Riles: One thing that I didn't mention is that we have a voting process, which involves risk in it and its essentially a Delphi method of choosing things to fund. We typically take a vote after we make sure that everybody understands the particular things that we want to fund. And by the way you talked about it. We have about 700 different things going on at once, and about 100 new items are added each year and about 100 die. So we typically have a steady state of about 700 programs, about 100 new ones starting, and 100 old ones completing. So, what we do is rank the continuing ones with the new ideas, and we use Delphi to do that. And a part of Delphi involves consideration and risk. We will fund things that have high risk if it has high pay off.

Appendix O: Interview with Dr. Squire Brown, Chief
of the Technology Assessment Division, Wright
Research Development Center, 28 July 1989

Interviewer: Sir, what are your technical qualifications?

Dr. Brown: I have a bachelor of science and a PhD in Aerospace Engineering, some 22 years of professional experience mostly related to aircraft technology, aircraft design, development of aircraft related technologies.

Interviewer: What is your technical experience?

Dr. Brown: I primarily worked in aerodynamics and flight vehicle design and analysis, from aerodynamics research to configuration development, analysis of operational effectiveness.

Interviewer: What is the mission of the organization of which you are a part?

Dr. Brown: The Technology Assessment responsibility is to examine and create systems concepts for future mission requirements for the Air Force, and to examine the technologies that are essential for the development or employment of that system. What are the technologies that are needed to be effective in the future scenarios?

Interviewer: What is your present job?

Dr. Brown: I'm Chief of the Technology Assessment Division [Wright Research and Development Center (WRDC)].

Interviewer: In your opinion, what are the most important techniques for managing technical risk?

Dr. Brown: Deal a little bit with the term risk. Can we? Would you like to help me out with what you mean by risk?

Interviewer: Assuming that technical feasibility has been established, how do we go from the establishment of feasibility to minimizing the risk of actually achieving that project. I guess a contemporary example would be the Space Defense Initiative or the contemplated X-ray laser. .

Dr. Brown: the accepted approach, and I believe one that works well, is one that would lead through a series of hardware demonstration programs. It might be peculiar to the technologies, but it might be a combination of

component bench testing, simulation flight demonstration, either on a test bed or perhaps as part of a new prototype system. An X-vehicle [Experimental vehicle] or some suitable modification of a flight vehicle. But ultimately risk in the sense that we're talking about here almost need verification of the article. That would go into a deployed system.

Interviewer: Based on your experience, what is the most important technique for managing risk?

Dr. Brown: It's a loaded question. Let me try to break it apart a little bit. We approach the demonstration in terms of getting the risk out as an accepted way of doing business. We recognize that technologies come along and show promise in the feasibility demonstrations, and we know that they're going to be critical to some capacity in the future system. And you've got to simply understand that you got to go ahead and do the flight demonstration part, or a suitable demonstration. Much of our energy is consumed, I wouldn't say so much as with management as with the advocacy and developing the programs to carry out this demonstration. The management would only occur in so far as our management of programs themselves. We are very much captive of the institutional way that we do business of the POM [Program Objective Memorandum] cycle. Are you familiar with the 61XX, 62XX, 63XX programs? [Yes].

As we come out of 61XX is a basic research, much of the in-house work; much of the feasibility work is the 62XX arena limited amount of dollars. As we come out of 62XX saying this is the technology that we really need to flight demonstrate as for an example. Much of our energy is devoted to getting the dollars to get the program put in place to do that flight demonstration. A very excellent example at the moment is the 2-D [two-dimensional] vectoring nozzles that are flying on the F-15. Would you like me to go through that example for? [I think that I would prefer you to go through it.]

It is probably as good an example as we have at the moment. It's relevant to your questions about how we manage risk. Because the idea several years ago looking into advanced systems, or advanced concepts. We thought that airplanes like the ATF should have a 2-D vectoring nozzle. Having decided that, then we had to look at what was the real capability to produce the flying article within weight, specs, and if it would be reliable. The chief engineer would incorporate that in the system. A lot of features: improved take-off performance--up and away maneuverability. In some cases considerations are embedded in that. Generally, a lot of added capability. There's clearly some risk embedded in that and part of that risk had to be with cost and weight issues. The management of that risk took the form of saying ground test alone is not

adequate. And subsequently, that has proven out. In fact, Pratt and Whitney did boiler plate--almost feasibility study--and test cell, put in a new engine and now you can see the thing move and all of that. But as they tried to transition that into a flight weight article they encountered a lot of difficulties in manufacturing and performance. Now, we eventually got there; the thing is flying. But it is still not [without problems] but it will establish a database for production people on the ATF [Advanced Tactical Fighter Aircraft] to use. Even the ones that are flying right now are not suitable for putting on a production airplane. We're going to have to go one stage more. So our management of the risk took the form of saying, first in the paper studies: this will help to expand the flight of the envelope of the airplane. The ground test itself was recognized through recognize through professional judgement. The ground test itself is not adequate. When we built some flight articles, that those were still not suitable because of the problems we encounter. They were still not suitable as a production article. So there will be one more stage to go through this for the ATF program. All they do is the production at the very end of that. There is still some risk to that program office, that they may not meet all their goals in terms of cost, or weight or features in the long run. But our risk management took the form of assessing at each stage what we thought we'd do, what was positive, efficient, what was good to know, what critical issues did we have to address at the next stage. That's largely embedded for 2-D nozzles or anything. It's largely embedded in the programmatic of the cycle of POM submittals and annual budget reviews of program advocacies. Now generally its not called risk. Risk is a term that is not used very much. It is usually described more in traditional things like: does this thing weight too much, or does it function as well as it should, or took too long to manufacture. That is kind of our way of saying, well at the stage of that we have risk embedded there because we didn't [meet our goals], but I'm quite sure we can meet our goals. The lab rarely describes things in terms of risk as the management schools teach this king of favorite subject of mine. But it's not something that is a conscious part of the way we do business.

Interviewer. Does you organization have specific written strategy or policy for assessing and managing technical risk?

Dr. Brown: First of all, the mission statements recognize the need to go through the sequence that I just described. In order to eliminate risk. They don't necessarily look at a program. They very seldom look at risk typically. I'll show you this chart, and say for instance, this is a very

systematic way we do studies. And we start with a kind of a classical process for each program. We come out at the bottom at the end having come out of a technology assessment. And talk about technology goals and notice that risk is in there. If you look at our formal mission statements and the way we tell people we do business we hope to achieve what's in the risk. Survivability constitutes the one-on-one engagement process. If I'm looking at a penetration system, first I get the concept of it, then I look at the concept of one-on-one situation. And get the piece of this. Then I go into a more aggregated effectiveness analysis in which I may look at the total mission problem. And perhaps the number of airplanes dealing with the number of threat sites, or the number of supporting systems. Then begin to understand what the total mission problem. And perhaps the number of airplanes dealing with the number of threat sites, or the number of supporting systems. Then begin to understand what the total effectiveness is in an aggregated sense. Survivability may mean, as it flies along at a particular speed at an altitude at a particular flight path, maybe stable, maybe maneuvering and has a certain signature, runs across a certain encounter. What is the probability survival there? One airplane against one threat site. Then I may have the total mission of reaching the target and dropping the bomb or whatever. Maybe it is composed of a number of sequential elements that I have at the end. And the next step, I'll have to kind of total all of those up. And try to decide if the system in aggregate was reasonably effective.

We has a request some years ago by Military Airlift Command to look at what might be done for C-130 replacement. Our designers started sketching out what they know about the mission. We begin to look at how the airplane would be used to begin to refine the designs. We looked at some one-on-ones: engagements with triple A sites. Also, we looked at how we might vary the performance of the airplane. Did it need to go faster? Have a lower signature? and begin to establish those tradeoffs. And we begin to compare this airplane with perhaps a more traditional variant of the transport. All through this there are clearly technologies that are required to make the airplane feasible. Once we satisfy ourselves that this airplane is a good candidate versus that. Suppose we decided that this is really better than that one way or the other. We'd then say the reason that this was successful is that it had the advance materials, and this advance gear box, and this advanced crew station. In order to survive an engagement like this, crew is going to have to have the following information and be able to act on it expeditiously. And that may require a few displays of evaluating those in a simulator or ultimately perhaps a flight article. If you can go back and look at

technology assessment, if you went to a functional division for example, if you went to a mechanics division and talk to them about technology assessment they have figures of merit that are uniquely associated with what they do with their science. You might need a life to drag [ratio of] and airfoil. And if they can improve a lift to drag of the airfoil, they've had a success. We try to look at technology in terms of the whole system and it may be that the new airfoil does make some contribution. It may turn out, in fact, that the real key to success is a redesigned inlet--that is the most important thing that can be done. The total system picture we would come back out with the recommendation with the program and inlets. Then the guys down in XR [ASD Office of Plans] and other places may take a look at the whole scenario of the war, and say, what we really need is airplanes that will fly faster or something. They don't really care if this kind of thing needs a better inlet or something. So, that is kind of how we put technology into perspective.

Appendix P: Interview with Mr. Jack Cannon, Technical
Director of Development Planning, ASD Office
of Plans, ASD/XR, 25 July 1989

Interviewer: Sir, what are your technical qualifications? Specifically, what technical degrees do you hold?

Mr. Cannon: I simply hold a bachelor in science with a major in physics with considerable graduate work above the level.

Interviewer: What is your technical experience? What technical jobs have you held?

Mr. Cannon: I worked as a physicist in the materials laboratory for about five years and the rest of my career has been at the staff levels: a director of research of Wright Air Development Center, and later at ASD. I've been in systems planning since about 1963.

Interviewer: What is your present job?

Mr. Cannon: My position here is Technical Director of Development Planning [ASD/XR].

Interviewer: What is the mission of the organization of which you are a part?

Mr. Cannon: The mission of the organization basically is to essentially develop new system starts--and when I say new system starts it's not only totally new systems but major modification to existing systems--to solve major command deficiencies. Virtually all of the systems you will find today came through this kind of a process--through XR [the Office of Development Planning]. Things like the F-15, the A-10, the C-5, the B-1, the ATF [Advanced Tactical Fighter] the NASP [National Aero-Space Plane]. All of those programs started in XR and we take them up to the point of having done the concept exploration studies and then transition them to an acquisition agency, to a SPO [Systems Program Office] or to a deputy for acquisition.

Interviewer: In your opinion, what are the most important techniques for managing technical risk? The is assuming that [a system] has been demonstrated feasible in the laboratory.

Mr. Cannon: You're saying breadboard feasibility?

Interviewer: Yes. So from that point what is necessary to manage the technical risk?

Mr. Cannon: Well, generally, my feeling would be that you would have to go into an advanced development program which we generally speak of as being a, so that it's prototype hardware to demonstrate the concept. It could be demonstrated on a ground test level in some cases to satisfy your concerns about risk or it might have to be flight demonstrated. But generally, you would not develop flight qualified hardware, you would build prototype hardware that would be flown in a prototype system before you would go the full nine yards of fully developing the system to prove out the concept. You would prototype it using as much existing technology that you can to demonstrate it before we get into new technology at the same time.

Interviewer: Based on your experience, what is the most important technique for managing technical risk?

Mr. Cannon: Well, you know if you had to select one I think that certainly the prototype testing is the way you reduce the risk.

Interviewer: Does your organization have a specific written strategy or policy for assessing and managing technical risk?

Mr. Cannon: Well, what is used in ASD is first of all, is whenever a 63XX [budget designation] program is started, it goes through what is called the SENTAR process. The deputy of engineering of ASD is really responsible for the SENTAR process. What they do is review at the start of the 63XX-program. I'm talking about a advanced development hardware demonstration program. They will review that proposed advanced development plan, and particularly concentrate on setting some criteria that they felt should be met through this demonstration. Some performance that would be demonstrated in the hardware demonstration. Then once the laboratories and the engineering people have signed up to that, and say that this is what we're going to do, and this is what the lab plans to do, and this is what is going to be necessary to do in order to satisfy the engineers that the technology is mature and is documented in a transition plan. The old twist was basically that at the same time you involve a customer. The customer could be an existing SPO or an existing system organization, if there is no existing system organization it then becomes XR as the customer for that technology. You will have a three prong agreement: a customer agreeing that it is useful technology in terms of the future, a laboratory which is developing the technology, and an engineering organization

which is geared to look over the results of the laboratory program to make sure that it has satisfied the predetermined criteria. And therefore, the technology would be considered mature at that time. You will probably want to look into the SENTAR process, which stands for Senior Engineering Technology Assessment Review. It is a group of tech directors out of the deputy for engineering, that form the SENTAR group, and they review all laboratory 63XX-programs. The 63XX-program stands for advanced development. The programs that are used in the Air Force, 61XX program is basic research, 62XX program is exploratory development, and 63XX program is advanced development. The 63XX program is broken down into A&B. 63XXA is advanced technology, and 63XXB is systems oriented development. If you we're going to build a flying prototype, for example prototype it would be built under 63XXB. Electronic components would be built under 63A in that sort of broad technology area. Then the 64XX program is engineering development. Ideally something would flow from basic research to exploratory development to advanced development to engineering development. I say ideally because you'd probably find that many things don't always go in that nice classical fashion.

Interviewer: Anything else you would like to say about technical risk?

Mr. Cannon: Well, when we do advanced studies here in XR, I'm talking about things that are going to be operational in [the year] 2010. Our first look-see at technical risk-- we would be in our laboratories and ask for technical risk analysis. In other words, did the lab see technologies that would make this system possible in the year 2010? We've been able to describe the system in terms of its performance: for example, its speed, range, altitude, maneuver and so forth. Then we ask the laboratories basically to give us a technology assessment in things like, materials, structures, avionics, propulsion which make up the system, and they give us an initial technical risk assessment. And then they begin to show that they have technology that they feel is going to satisfy that requirement or they will show that no they don't have and here is what will have to be done in the years you got as lead time for the system to begin to develop some technology. So I think that the key to us in this business is that we get that initial tech assessment done by the laboratory folks, who understand what technologies they really have in hand and what they really have to do yet in order to satisfy a given system requirement. As they imitate things, then the SENTAR process begins to be involved in terms of following, tracking what is happening on that advanced development type effort.

Interviewer: Thank you a lot for your time. I appreciate it.

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SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED			1b. RESTRICTIVE MARKINGS		
2a. SECURITY CLASSIFICATION AUTHORITY			3. DISTRIBUTION / AVAILABILITY OF REPORT Approved for public release; distribution unlimited		
2b. DECLASSIFICATION / DOWNGRADING SCHEDULE					
4. PERFORMING ORGANIZATION REPORT NUMBER(S) AFIT/GSM/LSR/89S-22			5. MONITORING ORGANIZATION REPORT NUMBER(S)		
6a. NAME OF PERFORMING ORGANIZATION School of Systems and Logistics		6b. OFFICE SYMBOL (If applicable) AFIT/LSY		7a. NAME OF MONITORING ORGANIZATION	
6c. ADDRESS (City, State, and ZIP Code) Air Force Institute of Technology Wright-Patterson AFB OH 45433-6583				7b. ADDRESS (City, State, and ZIP Code)	
8a. NAME OF FUNDING / SPONSORING ORGANIZATION		8b. OFFICE SYMBOL (If applicable)		9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER	
8c. ADDRESS (City, State, and ZIP Code)				10. SOURCE OF FUNDING NUMBERS	
				PROGRAM ELEMENT NO.	SUBJECT NO.
11. TITLE (Include Security Classification) A MODEL FOR THE MANAGEMENT OF TECHNICAL RISK IN NEW TECHNOLOGY DEVELOPMENT PROGRAMS					
12. PERSONAL AUTHOR(S) Peter B. King, B.S., Capt, USAF					
13a. TYPE OF REPORT MS Thesis		13b. TIME COVERED FROM _____ TO _____		14. DATE OF REPORT (Year, Month, Day) 1989 September	
15. PAGE COUNT 237					
16. SUPPLEMENTARY NOTATION					
17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)		
FIELD	GROUP	SUB-GROUP	Risk Program Management Program Risk		
12	04		Technical Risk New Technology		
05	01				
19. ABSTRACT (Continue on reverse if necessary and identify by block number)					
Thesis Advisor: Captain Carl L. Davis Associate Professor Research Methods Department of Communication and Organizational Sciences Approved for public release: 1AW AFR 190-1. <i>Larry W. Emmelhainz</i> LARRY W. EMMELHAINZ, Lt Col, USAF 14 Oct 89 Director of Research and Consultation Air Force Institute of Technology (AU) Wright-Patterson AFB OH 45433-6583					
20. DISTRIBUTION / AVAILABILITY OF ABSTRACT ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS			21. ABSTRACT SECURITY CLASSIFICATION UNCLASSIFIED		
22a. NAME OF RESPONSIBLE INDIVIDUAL Captain Carl L. Davis, Assoc. Professor			22b. TELEPHONE (Include Area Code) (513)255-2254		22c. OFFICE SYMBOL AFIT/LSR

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Inadequately managed technical risks have resulted in setbacks, failures and operational disasters in Department of Defense programs. Therefore, the purpose of this research was to synthesize a model that epitomizes a strategy for the management of technical risk. The model was synthesized using the three-pronged effort of: (1) a literature search and review to determine what previous work was done in risk assessment and risk management, (2) case studies of historical, contemporary and prospective new technology development programs, and (3) interviews predominately with Chief Scientists at the Wright Research and Development Center (WRDC) at Wright-Patterson Air Force Base. The model validation was via reviews of the model that were made by the stated interviewees. If the model is used as a technical management guide and decision aid by individual program or project managers at all levels, collective marked improvement in the technical risk management throughout the Department of Defense may be achieved.

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