RESOURCES AVAILABLE FOR HAZARDS ANALYSIS OF AEROSPACE FLUIDS*

Stephen S. Woods
Honeywell Technology Solutions Inc.
P.O. Box 20
Las Cruces, NM 88004
(505) 524-5607
swoods@wstf.nasa.gov

Walter F. Stewart
L & M Technologies
Las Cruces, NM

David L. Baker
Harold D. Beeson
NASA Johnson Space Center White Sands Test Facility
Las Cruces, NM

INTRODUCTION

In recent years, the legislative and executive branches of the federal government have pushed to make government more efficient and responsive to the needs of the marketplace. One of these initiatives, Public Law 104-113, also known as the National Technology Transfer and Advancement Act of 1995 (NTTAA), is designed to accelerate technology transfer to industry and promote government-industry partnership. Summarized, NTTAA states that "… all Federal agencies and departments shall use technical standards that are developed or adopted by voluntary consensus standards bodies, using such technical standards as a means to carry out policy objectives or activities determined by the agencies and departments."[1] Government agencies must now determine if their in-house requirement-setting activities are sufficiently unique that no public interest is served by having them adopted by a voluntary consensus organization (VCO), or if not, to use or develop voluntary consensus standards. The Office of Management and Budget (OMB) is chartered by the law to monitor federal agency progress and report the results to Congress.

In response to NTTAA, agency-wide oxygen[2] and hydrogen[3] safety standards sponsored by the NASA Headquarters (HQ) Office of Safety and Mission Assurance (OSMA) were obvious choices for early adoption by VCOs. In 1996, HQ sought assistance from the Johnson Space Center (JSC) White Sands Test Facility (WSTF), the technical lead for development of these safety standards, to evaluate their adoption by VCOs. At that time, WSTF-developed propellant hazards manuals were likewise identified for possible VCO adoption. Subsequently, WSTF was asked to represent NASA for development of an international ISO safety standard for hydrogen use. Concurrent with these WSTF standards activities are related efforts to develop and publish propellant hazards analysis protocols and safety courses for the industrial, propellant use of oxygen, hydrogen, and hypergols.

This paper reports on these efforts and describes WSTF's overall voluntary consensus standards program to coordinate the interchange of NASA's propellant hazards and safety information with industry.

WSTF VOLUNTARY CONSENSUS STANDARDS DEVELOPMENT AND TECHNOLOGY TRANSFER PROGRAM

WSTF has been involved with testing of hazardous fluids, components, and materials for over 30 years and with the development of hazards manuals during the last 15 years. With this new emphasis in direction prompted by NTTAA, the relationship among research and development, hazards analysis

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protocols, safety course development, voluntary consensus standards activities, and industry communications has become apparent.

A New Environment for Cooperation

The rapid pace of transfer of government activities to the aerospace industry, along with the increasing incidence of aerospace corporate mergers, have the potential for disrupting coordination and flow of vital propellant safety and hazards information among personnel involved in design, operations, and safety. Within this milieu exist the risks associated with employees' potential exposure to hazardous chemicals in governmental and industrial work environments. The latter has led to detailed regulations that specify a highly trained work force, the use of hazards review methodologies, hazards communications with employees and the surrounding community, and adequate emergency preparedness. How can the effects of these potentially opposed forces be countered?

One response is for government and industry to cooperate within the framework provided by a VCO, which acts as a clearing house for critical information, helps identify top expertise, and offers training. The democratic structure of VCOs enables them to develop voluntary consensus standards that meet the needs of both government and industry.

By design, NTTAA has prompted a new, more cooperative environment between government and industry that accelerates technology transfer to industry and promotes government-industry partnership. But technology transfer from government to industry involves more than simply relaying scientific data and technology development. It also involves sharing hazards review and training expertise and making the information and techniques used by government laboratories more accessible to industry and the public. Technology transfer activities also drive government efforts to be more attuned to industry needs.

An Engine for Focused Technological Advancement

One of WSTF's primary goals is to support NASA's propellant safety efforts, which involve testing, research and development, and hazards analysis of cryogenic and hypergolic propellants. These activities are organized to support queries from industry and the public, to provide training to those who need it, and to collaborate with VCOs to develop voluntary consensus standards. Important insights into the role hazards analyses can play in the overall direction and planning of safety research have become apparent. WSTF is recognized throughout NASA and by the aerospace community for its formalized approach to oxygen hazards analysis and has designed protocols for application to hydrogen, hydrazine fuels, and nitrogen tetroxide.

WSTF Hazards Analysis Protocol

The protocol works by examining in detail all components exposed to a particular propellant, analyzing likely failure modes, determining the consequence(s) of a particular failure to the system, and qualitatively assessing the risk for the system owners. The general hazards analysis procedure is depicted in Figure 1. Protocols for oxygen and hydrogen have been established, and protocols for hypergols are near completion. The protocols address primarily combustion hazards.

Preliminary activities are to adequately define the application and the scope of the investigation. Once defined, an analysis team with expertise in mechanical design, materials, ignition and combustion, safety, and component testing as it pertains to the propellant is assembled. Before convening for the analysis, detailed information on the components and the system in question is compiled as a skeleton report draft that the team fleshes out during the analysis. Thorough preparation at this point cannot be overemphasized, for it directly influences the productivity of the analysis.

The team begins by reviewing the hazards analysis protocol objectives and methodology. An overview of system design and operation is then established through review of system and component drawings, materials lists, and a failure modes and effects analysis. Operating and worst-case conditions are then identified. Component design and function are examined to see if grouping them by failure type, failure effect, or subsystem can streamline the analysis. The analysis proceeds for each component or subsystem in a given operational mode by identifying the nature of the failure, type of combustible mixture formed, potential ignition mechanisms, and whether a flash, fire, or explosion can occur. Also considered are design features and administrative controls that may be used. Occurrence probabilities are assessed for each of these categories. The scenario posed by a given failure and its potential to result in combustion are evaluated to see what secondary effects may result. Assessing the overall risk to the actual system or to its intended purpose completes the analysis at this level. The results are documented in a summary chart for each component. When necessary, supporting rationale is noted. An example summary chart from the hydrogen hazards analysis procedures is shown in Figure 2.

Analysis scores are determined by team consensus and are tallied through a qualitative rating scheme that relies heavily on existing databases. Where data are insufficient to define the hazards, then a recommendation for testing is made. Quantitative analysis, personal experience, and intuition are also a vital part of the decision-making process.

The rating scheme, used in the assessment of the probability of failure, formation of combustible mixtures, potential for ignition, and the resulting consequences, is based on a qualitative probability rating of 0 through 4, with the following identification:

- Almost impossible (0),
- Remotely possible (1),
- Possible (2),
- Probable (3), or
- Highly probable (4).

The secondary effects category is assigned an “R” when additional analysis is required; otherwise “N” for “No further analysis required” is noted. To describe the overall risk arising from component failure, the reaction effects category is scored as:

- Negligible (A),
- Marginal (B),
- Critical (C), or
- Catastrophic (D).

The results tabulated in each step are read as independent assessments of probability rather than as interrelated. Analysis places failure of an individual component not only in the context of its function in the subsystem or system but also its functional environment. When necessary, the interaction among components may be evaluated in a matrix fashion. Analysis may also be driven by fault-level requirements. The final risk assessment given for reaction effects is not read as a result derived by “multiplying” the probabilities assessed in Steps 2 through 5 of Figure 2. Rather, it is an assessment of the overall effect on personnel, the system, or its mission caused by the particular failure mode of the component under consideration, regardless of the probability.

The analysis proceeds through all the components. Recommendations are recorded as they become apparent from the analysis. During team deliberations the analysis, supporting rationale, and recommendations are recorded into the skeleton draft report by a team member acting as “secretary,” with the objective of having a draft report when the team is finished. After review of this draft report, a final report is prepared for the system owners. Where needed, the report provides recommendations for testing, component redesign, materials replacement, and the identification of procedural controls. The risks identified in the hazards analysis are then available for appropriate upper management review teams.

The Hazards Analysis Protocol as the Engine for Technology Transfer

Successful technology transfer requires placing critical information where it is needed. While this sounds obvious, the challenge is in identifying what information is critical and then knowing how to get it to those who need it.

In its traditional role, the hazards analysis protocol is used by project- and program-oriented groups as a means of identifying and remediating potential component and system inadequacies. But sometimes during the course of an analysis, a need arises for data that do not exist. For example, in the assessment of propellant hazards, this may involve the need for combustion or materials data that are not currently available but can be gained through testing. But if the team determines that testing is too difficult or expensive, the analysis might prompt a system redesign, the acceptance of greater risk, or a new method for assessing the hazards.

Unfortunately, the information obtained from the hazards analysis and how to apply it is often perceived as so specialized that little is done other than basic documentation of the analysis. End-users perceive that only those involved could promote further use of the data, which may or may not be true. Given this, how can hazards analysis protocols figure both in the promotion of technology transfer and technology development?

The hazards analysis process is by nature dynamic and points out what is known and what is not. The results of this process can be used to identify new research, problem areas, operational issues, or training requirements and should be considered prime information for technology transfer. When this knowledge is acted upon, perhaps by obtaining new data through testing, the results are state-of-the-art information. Typically the information is efficiently obtained because it results from the already-funded process of the hazards analysis. In a proactive environment, hazards analysis information can be used to propose new research to cover the deficits of data uncovered by the process. This information can prompt a refinement of hazards analysis techniques, which can then point toward improvements of the protocols. Another benefit is that the information is developed by industry expertise and can be applied directly to industry development as specific solutions and recommendations. Finally, publishing the information in the open literature makes it accessible to a wide audience that may be able to take advantage of it without “reinventing the wheel” and incurring the cost of unnecessary testing.

There are implications for use of this information beyond immediate aerospace applications. Such information is not only important in the technical development of a system; it can also be critical in the acceptance of the technology. For example, systems developed by the commercial sector that will be used by the public must be perceived as safe before investors can obtain the insurance to cover venture capital. One area of current development in which this is true is the application of hydrogen fuel cells to everyday applications. Also, it is acknowledged that the use and protection of proprietary information will always be a sensitive issue.

How might hazards analysis information be gathered and distributed? There are “lessons learned” databases and compilations of data on accident investigations currently available, but they appear to be static compilations that are periodically updated. It is hoped that the information gathered through hazards analyses would be the focus of an established group. WSTF currently serves that function, but given the current emphasis on VCOs, the activity could be managed by a VCO as well, with appropriate input from industry and government. The VCO’s objective would be to compile and analyze the findings of recently completed hazards analyses, then help distribute the results.

Consensus as a Means of Communication

Easily leveled criticisms of standards efforts conducted within government agencies are that the results are inadequate, one-sided, and inaccessible. The NTTAA has forced government to reevaluate its standards efforts. But for NASA, an agency that has always been proactive with regard to public outreach and technology transfer, NTTAA provides the basis for even greater interaction with industry and the public.

Aside from the primary goal of managing standards through a VCO, other positive attributes should arise from pursuit of the law. These include improved communication within government agencies and between industrial entities as well as interagency/interindustry connections. This has the potential to bring different interests together and lead to the establishment of a common ground in which research and development can take root. But it is likely that VCOs will continue to be a focal point for general information related to voluntary consensus standards, such as identifying where particular expertise can be found.

NASA's interest in participation with VCOs in the safety arena includes transfer of hazards manuals and the development of voluntary consensus standards. In theory, hazards information is better distributed by VCOs, with the cost being covered by the program interests that need the information rather than subsidized by the government. One goal is to promote the creation of general safety standards for propellant use that can be applied in government-industry contract negotiations.

For agencies that are not proactive in response to NTTAA, it will be interesting to see how the law will work in the future. The OMB requires federal agencies to report on the status of their efforts to meet the law. Already the mobile home construction industry has brought a legal challenge[4] against legislation pending in Congress, the American Homeownership and Opportunity Act, H.R. 1776, citing conflicts with NTTAA. Here industry is claiming that preexisting law directs them through VCOs to keep standards for manufactured homes up-to-date and the new law is not needed.

Interrelationship Among Hazards Analysis, Consensus Communications, and Research

The hazards analysis process is depicted at the center of the technology transfer process shown in Figure 3. The information gained by hazards analyses can serve as input to VCOs, for research, and for training. Conversely, VCO committees, research groups, and trainers can have influence on hazards analysis protocols. For this scheme to function effectively, some group in industry or government must have a vested interest in tracking, documenting, and communicating key information obtained from the use of hazards analysis protocols. At present WSTF is funded to do this work. A logical extension of who performs this sort of work would include the VCOs themselves.

SPECIFIC ACHIEVEMENTS

WSTF's parallel efforts to promote safety research and safety standards development are a vital part of its mission. The next section outlines the specific achievements by these efforts.

Propellant Oxygen

Research into propellant oxygen hazards has been ongoing at WSTF since the mid-1970s and is its most mature expression of the interrelationship among research, hazards analysis, and VCO participation. Technical communications and technology transfer with industry are achieved through a long-standing participation with ASTM Committee G4 on Compatibility and Sensitivity of Materials in Oxygen Enriched Atmospheres and the National Fire Protection Association's committees on Health Standards and Hyperbaric Standards. The oxygen hazards analysis protocol has been in use for over a decade. WSTF researchers have developed an oxygen safety training course, "Fire Hazards in Oxygen Systems,"[5] that is offered through ASTM. At the request of the NASA HQ/OSMA, WSTF developed a safety standard for oxygen and subsequently collaborated with ASTM to publish it as Manual 36, "Safe Use of Oxygen and Oxygen Systems."[6] WSTF's progress in the oxygen arena serves as a model for its development of hydrogen and hypergol propellant programs. The following documents and courses are available for oxygen safety assessment:

- NASA Safety Standard 1740.15, "Safety Standard for Oxygen and Oxygen Systems"
- ASTM MNL36, "Safe Use of Oxygen and Oxygen Systems"
- NASA Technical Memorandum 104823,[7] Guide for Oxygen Hazards Analyses on Components and Systems"
- ASTM G63, "Guide for Evaluating Nonmetallic Materials for Oxygen"[8]
- ASTM G88, "Guide for Designing Systems for Oxygen Service"[9]

- ASTM G94, "Guide for Evaluating Metals for Oxygen Service"[10]
- NFPA 53, "Recommended Practice in Oxygen-Enriched Atmospheres"[11]
- ASTM Technical and Professional Training Course, "Fire Hazards in Oxygen Systems" (several versions exist that are tailored to particular audiences, such as design engineers, technicians, and the scuba community)
- ASTM Technical and Professional Training Course, "Oxygen Systems: Operation and Maintenance"

Propellant Hydrogen

Progress in the hydrogen safety arena includes development of the NASA Safety Standard for Hydrogen and Hydrogen Systems and collaboration with the American Institute of Aeronautics and Astronautics (AIAA) toward the formation of an aerospace hydrogen safety committee. This hydrogen safety committee will oversee the development of a consensus guide based on the NASA hydrogen safety standard and ultimately the development of a national standard. NASA has been invited to help represent U.S. interests in the international hydrogen safety community. In parallel with the AIAA effort, WSTF supports ISO Technical Committee 197, Working Group 7 on general hydrogen safety. Following the model of oxygen activities, a hydrogen hazards analysis protocol and a hydrogen safety training course have been developed. The hydrogen safety training course is available through the NASA Safety Training Center. The hydrogen hazards analysis protocol is available from WSTF. The following documents and courses are available for hydrogen safety assessment:

- NASA Safety Standard 1740.16, "Safety Standard for Hydrogen and Hydrogen Systems"
- TP-WSTF-937,[12] "Guide for Hydrogen Hazards Analysis on Components and Systems"
- RD-WSTF-0001,[13] "Ignition and Thermal Hazards of Selected Aerospace Fluids"
- NASA Safety Training Center, Course 037, "Hydrogen Safety"

Hypergolic Fuels and Oxidizers

Progress in the hypergol safety arena parallels WSTF's oxygen and hydrogen efforts in that several manuals covering the hazards of hypergolic propellants have been developed. This is just the kind of information that could better serve the aerospace community if it was managed by a VCO. In collaboration with AIAA, WSTF has promoted the formation of the recently initiated AIAA Liquid Propellant Committee on Standards to serve as a forum for discussion of hypergolic and related propellant safety issues. This committee has an agenda to oversee the development of voluntary consensus standards covering hydrazine, monomethylhydrazine, dinitrogen tetroxide, and other aerospace fluids of interest. WSTF hypergolic hazards manuals have been transferred to AIAA for distribution as AIAA Special Projects. The agreement stipulates that needed updates of hypergolic hazards information will be published through AIAA Special Projects or Guides. In addition to the AIAA committee work, JSC has funded development of a hazards analysis protocol for hypergolic propellants. Also, NASA HQ/OSMA has funded WSTF for development of a hypergol safety training course. Both these efforts are in progress and the results will be available in fiscal year 2001. The following documents and courses are available for hypergolic safety assessment:

- RD-WSTF-0001, "Ignition and Thermal Hazards of Selected Aerospace Fluids"
- RD-WSTF-0002,[14] "Fire, Explosion, Compatibility, and Safety Hazards of Hydrazine"
- RD-WSTF-0003,[15] "Fire, Explosion, Compatibility, and Safety Hazards of Monomethylhydrazine"
- RD-WSTF-0017,[16] "Fire, Explosion, Compatibility, and Safety Hazards of Nitrogen Tetroxide"
- AIAA SP-084-1999,[17] "Fire, Explosion, Compatibility, and Safety Hazards of Hypergols – Hydrazine"
- AIAA SP-085-1999,[18] "Fire, Explosion, Compatibility, and Safety Hazards of Hypergols – Monomethylhydrazine"
- TP-WSTF-953,[19] "Guide for Hydrazine Hazards Analysis on Components and Systems"
- TP-WSTF-959,[20] "Guide for Nitrogen Tetroxide Hazards Analysis on Components and Systems"

- NASA Safety Training Center, Course 040, “Hypergolic Propellant Safety”

SUMMARY AND CONCLUSIONS

The goal of the paper has been to inform aerospace researchers and engineers of new resources and an improved way of approaching and communicating propellant safety concerns and to raise awareness regarding NTTAA. The nexus of propellant activities for oxygen, hydrogen, and hypergol safety underway at WSTF can aid researchers with locating critical information, expertise, testing services, and training. The authors encourage those who have a stake in making this kind of information available to their own organization to participate in VCO activities, such as the ASTM Committee G4 and the AIAA Liquid Propellant Committee on Standards. For hydrogen, readers are encouraged to contact AIAA and/or the WSTF propellant hazards program for further information.

Another goal of this paper is to recommend that the aerospace community reevaluate how the results of hazards analyses are conveyed beyond an immediate project or program. It is important that a mechanism exist to organize and convey this information. Specific recommendations for oxygen, hydrogen, and hypergol safety are:

- Examine how your own organization treats the results of hazards analyses after specific project or program needs have been satisfied.
- Consult the WSTF propellant hazards programs, which have a strong history as contact points for coordinating and organizing hazards information.
- Seek participation in an appropriate VCO to organize and disseminate hazards analysis results.

The NTTAA has pointed the way for a reconsideration in the way government and industry interact. For the maximum benefit to accrue in the propellant safety arena, industry and government representatives must participate through the technical committees of the VCOs chartered to manage this information.

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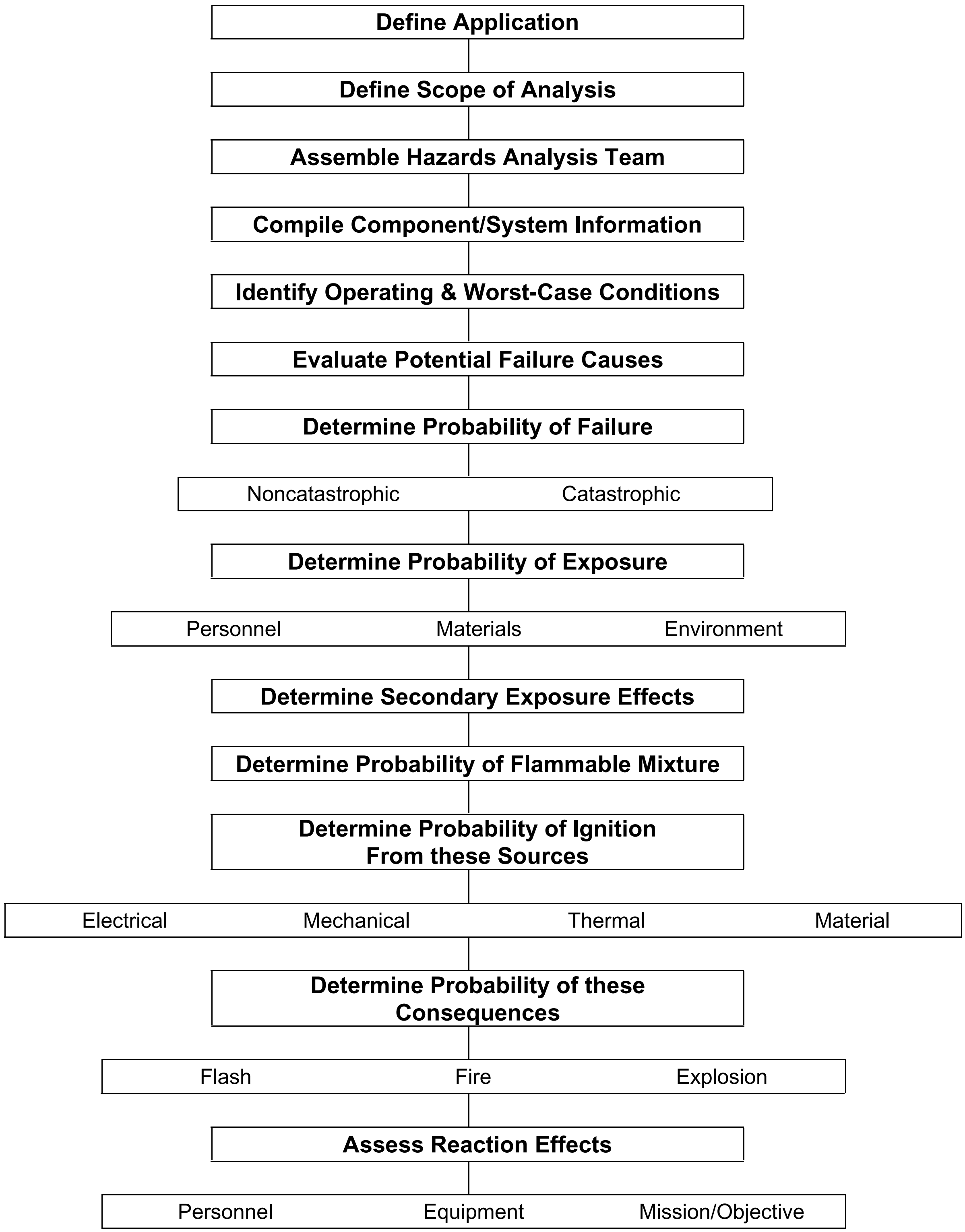

Figure 1. Procedure for General Hazards Analysis