



Flammability and Sensitivity of Materials in Oxygen-Enriched Atmospheres

11th Edition

D. B. Hirsch
R. Zawierucha
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Editors

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*Flammability and Sensitivity of
Materials in Oxygen-Enriched
Atmospheres: Eleventh Volume*

D. Hirsch, R. Zawierucha, T. Steinberg,
and H. Barthelemy, editors

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The quality of the papers in this publication reflects not only the obvious efforts of the authors and the technical editor(s), but also the work of the peer reviewers. In keeping with long-standing publication practices, ASTM International maintains the anonymity of the peer reviewers. The ASTM International Committee on Publications acknowledges with appreciation their dedication and contribution of time and effort on behalf of ASTM International.

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Foreword

This is the Eleventh Volume in a series of Special Technical Publications produced by ASTM Committee G4 on Flammability and Sensitivity of Materials in Oxygen-Enriched Atmospheres. The Eleventh Volume consists of a group of peer-reviewed publications from the Journal of ASTM International of work that was also presented at Committee G4s Eleventh International Symposium on Flammability and Sensitivity of Materials in Oxygen-Enriched Atmospheres held in Washington, DC in October 2006. This volume was edited by David B. Hirsch, Jacobs Sverdrup Engineering, Inc., NASA White Sands Test Facility, Las Cruces, New Mexico, USA; Robert Zawierucha, Materials Consultant, East Aurora, New York, USA; Theodore A. Steinberg, School of Engineering Systems, Faculty of Built Environment and Engineering, Queensland University of Technology, Brisbane, Queensland, Australia; and Herve Barthelemy, LAir Liquide Group, Paris, France.

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Overview

This is the eleventh Special Technical Publication (STP) originating from ASTM Committee G4 focusing on Flammability and Sensitivity of Materials in Oxygen-Enriched Environments. As in the past STPs, the eleventh volume expands upon the objectives that have been carried forward since the first STP was published in 1983. These objectives include:

- Review the current research on polymers and metals ignition and combustion;
- Overview principles of oxygen systems design and issues related to materials compatibility with oxygen; contribute to the knowledge on the most current risk management concepts, practices, approaches, and procedures used by individuals and organizations involved in the design, use, retrofitting, maintenance, and cleaning of oxygen systems;
- Review accident/incident case studies related to oxygen systems and oxygen handling procedures;
- Provide the most current data related to the flammability and sensitivity of materials in oxygen-enriched atmospheres to designers, users, manufacturers, and maintainers of oxygen components and systems and to support the Committee G4's Technical and Professional Training Course on Fire Hazards in Oxygen Systems and Oxygen Systems Operation and Maintenance standards;
- Discuss enhancement, development, and use of standards sponsored by ASTM Committee G04 on Compatibility and Sensitivity of Materials in Oxygen Enriched Atmospheres;
- Provide a readily accessible reference addressing oxygen compatibility.

The Eleventh Volume consists of a group of peer-reviewed publications from the *Journal of ASTM International* of work that was also presented at Committee G4's Eleventh International Symposium held in Washington, DC, USA in October 2006. The volume contains 32 papers on topics related to ignition and combustion of non-metals, ignition and combustion of metals, oxygen compatibility of components and systems, analysis of ignition and combustion, failure analysis and safety, and aerospace applications.

The keynote address was presented by Robert Zawierucha, Materials Consultant, East Aurora, New York. He retired in 2006 as Praxair's Materials Engineering Manager after 37 years of service in the industrial gas area. Mr. Zawierucha has been an active contributor to the ASTM Committee G4 publications since 1986 and was actively involved in testing engineering alloys for compatibility in oxygen-enriched atmospheres for over 30 years. In addition, he has been a member of key CGA technical committees dealing with issues of significance to the industrial business such as aluminum-structured packing for oxygen distillation columns, hydrogen, carbon monoxide and Syngas. His presentation provides a review of materials testing techniques and criteria for selecting engineering alloys for oxygen service. In addition, potential advanced oxygen applications and materials and future test requirements for these applications are discussed.

Four papers focus on ignition and combustion of non-metals. A study conducted at the University of California at Berkeley presents results from an experimental study on the ignition of fire retarded polyurethane foam in oxygen concentrations from 30 % to 60 %. The experiments show that the foam undergoes a weak smoldering reaction that requires significant assistance in the form of external heat input in order to propagate. Furthermore, given sufficient oxygen and radiant heat flux, the smoldering reaction can produce enough volatile fuel and heat to trigger gas phase ignition. The NASA Johnson Space Center White Sands Test Facility (WSTF) presents

two papers, one of which is on frictional ignition testing of composite materials. The paper describes the test system, approach, data results, and findings of the reciprocal friction performed on composite sample materials being considered for propellant tanks for aerospace applications. The second paper investigates the rapid pressurization ignition of sebum contaminant in high-pressure oxygen. The level of sebum contaminant that can be expected to be deposited by handling oxygen system components and the threshold levels of sebum contaminant required for rapid pressurization ignition in a high-pressure oxygen system are presented. A fourth paper on ignition of non-metals is a study conducted to characterize the flammability of commonly used surgical drapes by their oxygen index. The paper indicates that materials commonly used for surgical draping have an oxygen index less than or near the oxygen content of ambient air, making them particularly susceptible to fire.

Five papers address ignition and combustion of metals. NASA Marshall Space Flight Center (MSFC) presents a study on promoted combustion of metals in ambient and elevated temperatures. The focus of this work is on examining the transitional region and the quasi-steady burning region of metals. Experimental data obtained on a new heated promoted combustion facility at the MSFC is presented. The pressure boundaries of acceptable, non-burning usage are found to be lowered at elevated temperatures. Interest in the effects of increasing pressure and temperature on the flammability of metals led to an industry-sponsored program for heated combustion testing of metals. WSTF provides a paper summarizing the results of heated promoted combustion tests from the industry-sponsored 98-1 program. Promoted combustion testing of coated metal rods in high pressure oxygen by the Federal Institute for Materials Research and Testing (BAM) are presented from the new promoted ignition test apparatus allowing investigations with pure oxygen or oxygen mixtures at pressures up to 500 bar and at temperatures up to 400 °C under static or flowing conditions. A study on surface ignition of aluminum in oxygen is provided by Wendell Hall and Associates (WHA) who developed a test method to evaluate the ignitability of various aluminum surfaces. An alternative concept of threshold pressure is suggested and the influence of surface treatments on aluminum is evaluated. The Queensland University of Technology presents a study on the effect of sample geometry on flammability of carbon steel in oxygen. Promoted-ignition testing on carbon steel rods of varying cross-sectional area and shape was performed in high pressure oxygen to assess the effect of sample geometry on the regression rate of the melting interface.

Four papers focus on issues related to oxygen compatibility of components and systems. A BAM study indicates that transfer of test results on materials to valves and fittings in real life situations is complex. Consequently, BAM developed a metallic disc ignition test; a commonly used nonmetallic sealing ring is placed in front of this disc and serves as an igniter after which the test array is exposed to high pressure gaseous oxygen impacts. A WSTF paper on oxygen compatibility assessment on components and systems indicates that a systematic approach to identify and address fire hazards in oxygen systems is essential to protecting personnel and equipment. The oxygen compatibility assessment process designed by WSTF can be used to determine the presence of fire hazards in oxygen systems and the likelihood of a fire; this process may be used as both a design guide and an approval process. WHA provides a study on mechanical impact of aluminum cylinders pressurized with oxygen. There are reported fires involving aluminum medical oxygen cylinders that have ignited after experiencing mechanical impacts. A mechanical impact test was developed by WHA to investigate the conditions required to cause ignition of a cylinder and valve assembly by this ignition mechanism. Cylinder assemblies were tested with various orientation and impact points including the cylinder valves. A paper provided by L'air Liquide explains why the adiabatic compression test was proposed for the qualification of

oxygen-compatible equipment such as valves, regulators, and flexhoses and addresses how this test method was developed and improved over the years and how harmonization was reached in various related standards.

In the analysis of ignition and combustion section, WSTF provides a review on a relatively little investigated ignition mechanism - flow friction. The paper indicates that there have been fires in oxygen systems that could not be attributed to most common ignition mechanisms, some of which have been attributed to a poorly understood ignition mechanism for polymers, called flow friction. A brief history of fires attributed to flow friction is presented.

Six papers relate to failure analysis and safety. Two papers on this subject were provided by L'air Liquide, both involving oxygen cylinders. The first describes two accidents involving aluminum cylinders, while the second paper describes an accident involving composite cylinders. The composite cylinder accident was attributed to the violent reaction of the oxygen (contained in the compressed air) with the plastic liner. Recommendations to avoid repetition of such accidents are proposed. A WSTF paper discusses a failure analysis conducted by the WSTF Oxygen Hazards and Testing Team on the 2003 U.S. Navy VP-62 fire. The study indicates that the fire started due to heat generated by an oxygen leak past a silicone check valve seal (flow friction) or possibly by the particle impact near the seat of one of the aluminum manifold and check valve (MCV) assembly. To prevent future fires of this nature, the U.S. and Canadian fleets of P-3 aircraft have been retrofitted with MCV with an upgraded design and more burn-resistant materials. To ensure the ongoing safe operation of the Royal Australian Air Force (RAAF) P-3 Orion life-support oxygen system, a system review was completed that included a failure modes and effects analysis combined with an oxygen hazards and fire risk analysis. A paper provides a brief summary of the analyses performed and the results obtained. Risk tables were generated; their use lead to the recommendations for changes incorporated onto RAAF P-3 Orion aircraft. A common concern in the welding industry is the development of conditions where oxygen acetylene flashback reactions can propagate into a welding hose causing it to burst due to the rapid localized pressurization associated with an oxygen-acetylene deflagration-to-detonation transition. A WHA investigation of a recent welding hose fire resulted in testing to evaluate the conditions under which detonations could be generated within welding hoses and the conditions in which welding hoses would burst when exposed to these events. This paper reports on elements of the welding hose fire investigation, the conditions for flashback reactions to develop, and the analytical work performed during the accident reconstruction to characterize deflagration-to-detonation transition within typical welding hoses. Performing analyses of the fire hazards in oxygen systems is critical to avoiding fires. Oxygen Safety Consultants (OSC) and WHA have applied new engineering technologies and materials test data to better understand, discern, and characterize oxygen fire hazards. Their paper describes some of the new technologies and materials test data used and how they can be applied to evaluating the compatibility of metals in oxygen service, including three-dimensional component analysis, computational fluid dynamics flow modeling, metals flammability test data in static, flowing, and high-temperature oxygen, and metals ignition test data.

Six papers relate to aerospace applications. A frayed wire was found inside the extravehicular mobility unit (EMU) spacesuit, which led to concerns that it may be possible to ignite materials in the EMU by electrical arcing. As a result, WSTF developed three arc-ignition test methods; the most severe method was used to characterize the materials presently used in the EMU by determining the minimum level of current necessary to initiate combustion at a given voltage. The inherent problems identified with the mechanical and pneumatic impact testing per ASTM

G86 and G74 would not allow precise identification or the magnitude of problems related to running the tests, such as lack of consistency of systems performance, lack of adherence to procedures, etc. Excessive variability leads to increasing instances of accepting the null hypothesis erroneously, and so to the false logical deduction that problems are nonexistent when they do really exist. A WSTF paper attempts to develop and recommend an approach that could lead to increased accuracy in problems diagnostics. The approach presented could also be used to evaluate variable effects with increased confidence and tolerance optimization. University of Southern California at Los Angeles conducted a study on the rates of flame spread and minimum oxygen concentrations supporting flame spread over thermally-thick fuel beds at earth gravity and microgravity for varying concentrations of a gaseous extinguishing agent (N_2 , CO_2 , or He) added to O_2-N_2 atmospheres. At earth gravity, CO_2 was the most effective on a molar basis at reducing spread rate whereas at microgravity, He was the most effective at reducing spread rate and causing flame extinction. These results are particularly noteworthy considering that the International Space Station employs CO_2 as fire extinguishers; the results suggest that helium may be a better suppressant agent on both mass and mole basis in microgravity. A Queensland University of Technology study investigates the causes of increasing regression rates of the melting interface for metals burning in reduced-gravity. The sudden increase in regression rate of the melting interface indicates that it is due to a change in the geometry of the molten ball, rather than higher temperatures. A one-dimensional, steady state heat transfer model was developed, correlating regression rate of the melting interface to surface area of the solid/liquid interface. Revelations of dimensional instability in polychlorotrifluoroethylene (PCTFE) semifinished articles and finished parts raised concerns that leaks or part failure could occur during service, leading to catastrophic component or system failure especially in high-pressure gaseous oxygen systems. WSTF lead and effort to evaluate the factors contributing to property variation in PCTFE; the effects of molding method, resin grade, process route, annealing method, and machining on dimensional stability, molecular weight, and crystallinity were determined. A voluntary consensus material specification was then implemented to control properties in finished PCTFE parts used in aerospace applications. In a related paper, representative PCTFE replacement parts used in at risk high pressure oxygen and air systems at KSC were removed from inventory and tested. Tests included determination of dimensional stability by thermo mechanical analysis and metrology, percent crystallinity by specific gravity, and the effect of annealing. Dimensional instability was determined not to be a major issue in existing inventories; however, annealing was found to lead, on occasion, to out-of-tolerance parts.

Five papers address miscellaneous subjects. The importance of proper filtration, recommendations for filters design, installation, and maintenance are presented in an L'air Liquide paper. Experience shows that accidents with gaseous oxygen filters are often extremely severe and can have catastrophic consequences, and therefore there is a serious risk for fire spreading which should not be ignored. ASTM G175 is a standard test method for evaluating the ignition sensitivity and fault tolerance of oxygen regulators used for medical and emergency applications. To assess the reproducibility of ASTM G175, a series of interlaboratory tests were performed; the results are presented and discussed in a WSTF paper. Mechanical impact is a real ignition mechanism which must be considered and understood in the design of oxygen systems. ASTM G86 is a commonly used test method used to evaluate ignition sensitivity of materials to mechanical impact in GOX or LOX environments. The use of test data from this method has been questioned because of the lack of a clear method of application of the data and variability found between tests, material batches, and facilities. A MSFC paper explores a large database, which has been accumulated over many years. A recent test program was sponsored by seven companies that are involved in the worldwide distribution and use of NF_3 to develop several test

systems and materials compatibility data for the most common metals and non-metals utilized in NF_3 transfer systems. A WHA paper presents the data developed by the industry steering group on the compatibility of 12 metallic materials and 15 non-metallic materials with NF_3 . In a related paper, WHA presents a new test approach developed to ignite a non-metallic seat of a cylinder valve pressurized with NF_3 to investigate whether the ignition of the seat would kindle the surrounding sub-components of the valve and ultimately whether a kindling reaction would develop that could breach the valve body. The new test provides an approach for evaluating the propagation propensity of NF_3 components containing non-metallic materials.

The *Eleventh Volume on Flammability and Sensitivity of Materials in Oxygen-Enriched Atmospheres* provides a diverse source of new information to air separation industry, oxygen manufacturers, manufacturers of components for oxygen and other industrial gases service, manufacturers of materials intended for oxygen and other industrial gases service, and users of oxygen and oxygen-enriched atmospheres aerospace, medical, industrial gases, chemical processing, steel and metals refining, as well as to military-commercial-recreational diving.

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