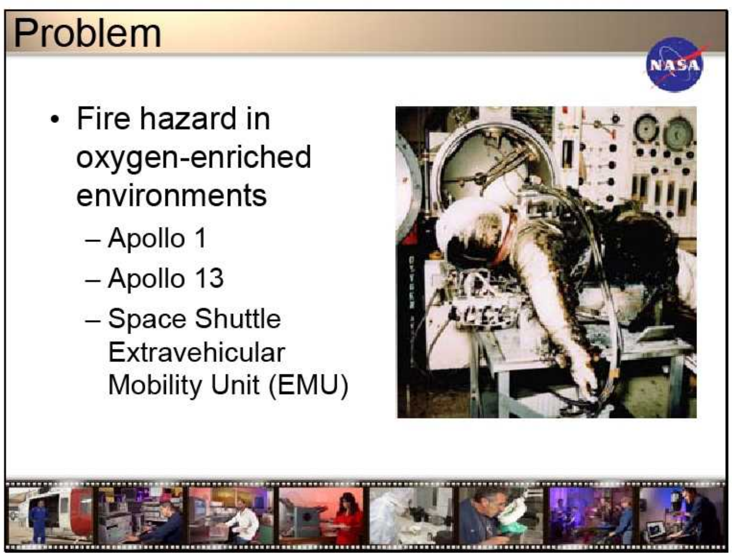
Slide 1

Slide 2



Slide 3

Problem

- Fire hazard in oxygen-enriched environments
  - Space Shuttle Main Engine (SSME) development
    - Cataldo documents 12 fire events
    - Biggs documents several events in first 10 years of SSME development
    - “LOX pump explosions are nightmarish events in rocket engine development programs”
  - Shuttle GOX flow control valve

Slide 4

Problem

- Fire hazard in oxygen-enriched environments
  - Personnel have perished
  - Missions have been lost
  - Equipment has been destroyed

Slide 5

Solution

- Understand hazard and apply knowledge
- Oxygen Compatibility Assessments (OCA) required NASA-wide
  - Performed per NASA-TM-2007-213740, Guide for Oxygen Compatibility Assessments on Oxygen Components and Systems
- Available nationwide

Slide 6

OCA Process

- Determine the worst-case operating conditions
- Assess the flammability of oxygen-wetted materials
- Evaluate the presence and probability of ignition mechanisms
- Determine the kindling chain
- Analyze the reaction effect
- Identify the history of use
- Report the results of the analysis

Slide 7

Worst-Case Operating Conditions

- Analysis must be done using worst-case conditions
- Ignition hazards and fire severity increase:
  - Oxygen concentration
  - Temperatures
  - Pressures
  - Flow rates
  - Contamination level

Slide 8

Assess Flammability

- If a material is not flammable
  - Ignition evaluation simplified
- If a material is flammable
  - Can only be used if ignition mechanisms known and controlled
- Standard test
  - Configuration dependent
  - Must know final configuration so configurational effects can be incorporated into analysis
- Test data available

Slide 9

Evaluate Ignition Mechanisms

- Particle Impact
- Rapid Pressurization
- Flow Friction
- Resonance
- Mechanical Impact
- Galling and Friction
- Fresh Metal exposure
- Static Discharge
- Electrical Arc
- Chemical Reaction
- Explosive Charges
- Personnel Smoking and Open Flames
- Fragments from Bursting Vessels
- Lightning
- Welding
- Engine Exhaust
- Fresh Metal Exposure
- Chemical Reaction
- Thermal Runaway

Slide 10

Evaluate Ignition Mechanisms

- Particle Impact
  - Heat generated when small particles strike a material with sufficient velocity to ignite the particle and/or the material
- Rapid Pressurization
  - Heat generated when a gas is rapidly compressed from a low pressure to a high pressure
- Flow Friction
  - Heat generated when oxygen flows across a polymer and produces erosion, friction, and/or vibration
- Galling and Friction
  - Heat generated by the rubbing of two or more parts together

Slide 11

Evaluate Ignition Mechanisms

- Characteristic elements (Example)
  - Galling and Friction — Heat generated by the rubbing of two or more parts together. The characteristic elements for frictional ignition are:
    - Two or more rubbing surfaces, generally metal-to-metal
    - Rapid relative motion
    - High loads pressing the rubbing parts together
- If one characteristic element is eliminated or demonstrated not to be present, then the ignition mechanism is not possible
- If all are present, then ignition is possible to probable
- If all are strongly present, then ignition is highly probable

Slide 12

Determine Kindling Chain

- Ability of a fire to propagate and burn through a component
  - Significantly impacts Reaction Effect Assessment

Slide 13

Assess Reaction Effect

- Effects of a fire on personnel, mission, and system objectives
  - Most severe effect controls analysis

Slide 14

Identify History of Use

- Component has experienced routine operation/cycling in similar or more severe conditions over an extended period of time

Slide 15

Report Results

- Enables communication to interested parties
- Must contain record of configuration
  - Pictures
  - Drawings
  - Schematics
  - Cross-sectional view showing oxygen-wetted materials
- Provides record of recommendations
- Assists in risk review
- Assists in anomaly resolution

Slide 16

Applications of OCA Process

- Over 400 OCAs conducted for ISS, Space Shuttle, Ground Support Equipment (GSE), and rocket engine components and test systems
- Resolution of SSME contamination anomalies
- Guide to failure analyses
  - NK-33 event in Russia
  - IPD fuel-rich preburner fire event

Slide 17

Summary

- Real problem exists
- Real solution available
- Oxygen Compatibility Assessment
  - Design and testing
  - System integration
  - Anomaly resolution

Slide 18

Future Work

- Web-based OCA tool being deployed within NASA community
  - Eventually to contractor partners
- WSTF available for:
  - Standard tests
  - Special materials and component tests
  - Oxygen compatibility assessments
  - Design process assistance

OXYGEN COMPATIBILITY ASSESSMENT OF COMPONENTS AND SYSTEMS†

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ABSTRACT

Fire hazards are inherent in oxygen systems and a storied history of fires in rocket engine propulsion components exists. To detect and mitigate these fire hazards requires careful, detailed, and thorough analyses applied during the design process. The oxygen compatibility assessment (OCA) process designed by NASA Johnson Space Center (JSC) White Sands Test Facility (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 during the approval process to ensure proper design features and material selection. The procedure for performing an OCA is a structured step-by-step process to determine the most severe operating conditions; assess the flammability of the system materials at the use conditions; evaluate the presence and efficacy of ignition mechanisms; assess the potential for a fire to breach the system; and determine the reaction effect (the potential loss of life, mission, and system functionality as the result of a fire). This process should be performed for each component in a system. The results of each component assessment, and the overall system assessment, should be recorded in a report that can be used in the short term to communicate hazards and their mitigation and to aid in system/component development and, in the long term, to solve anomalies that occur during engine testing and operation.

INTRODUCTION

During the development of the Space Shuttle Main Engine (SSME), liquid and gaseous oxygen related failures destroyed equipment and hindered development. C. E. Cataldo lists 12 events that occurred in test facilities and SSME hardware in the late 1970s.[1] Robert E. Biggs chronicles the first 10 years of the SSME development and describes high-pressure oxidizer turbopump explosions saying, “LOX pump explosions are nightmarish events in rocket engine development programs”.[2] For example, on March 24, 1977 a major fire occurred in the general area of the high-pressure oxygen turbopump (HPOTP) primary liquid oxygen (LOX) seal drain cavity producing a fire that severely damaged the pump (Figure 1).

Fires in oxygen-enriched environments have occurred through the duration of the U.S. space program costing human lives, causing mission failure, and destroying costly equipment. In the Apollo 1 (Apollo 204 Command Module) incident, astronauts Chaffee, Grissom, and White perished in a fire in a 16.5 psia, 100% oxygen environment. The Apollo 13 mission failure, which was turned into a great success by the heroic efforts of all involved, was caused by an electrical arc in a stirring motor switch in a LOX tank. In 1980, a fire occurred in the 6000 psi secondary oxygen pack (SOP) isolation-valve/regulator assembly of the extravehicular mobility unit (EMU), destroying the suit and backpack and injuring the worker who was standing next to the suit (Figure 2). No one was in the suit at the time of the fire.

† Approved for public release; distribution is unlimited.

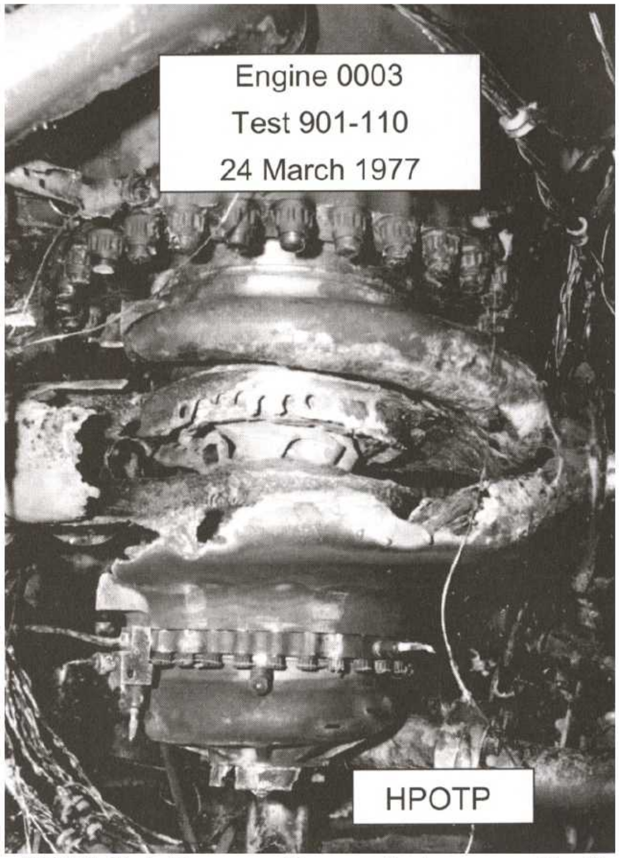

Figure 1. SSME High-Pressure Oxygen Turbopump after fire event.[2]

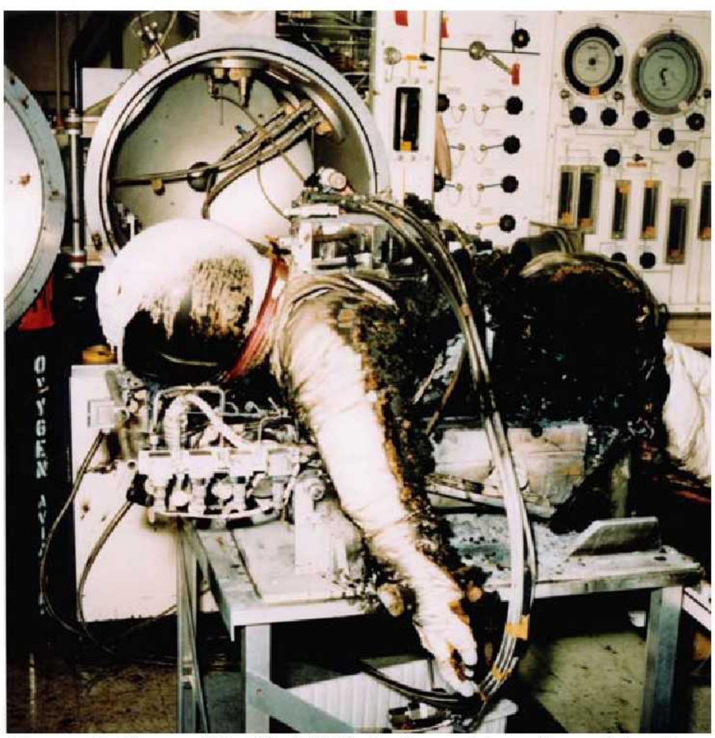
Figure 2. Space Shuttle EMU destroyed in a fire originating in the SOP isolation-valve/regulator assembly.

Because of the fire hazard in oxygen-enriched atmospheres, especially at elevated pressures, the WSTF Oxygen Group developed an oxygen compatibility assessment (OCA) process to evaluate the flammability and vulnerability to ignition of the materials used in the construction of oxygen systems. This evaluation procedure[3] has been adopted by NASA, ASTM, and ISO as a standardized analysis procedure to evaluate the fire hazard in oxygen-enriched environments. It has been successfully employed since the early 1990s by the WSTF Oxygen Group to evaluate oxygen systems, identify fire hazards, and make recommendations to avoid fires in oxygen-enriched environments. This paper presents the OCA process and suggests its application to oxygen systems in rocket engines.

OXYGEN COMPATIBILITY ASSESSMENT PROCEDURES

The OCA process provides a systematic approach for identifying and addressing the fire hazards in any oxygen system. The primary goal is to reduce the likelihood of a fire occurring in an oxygen system or component. The necessity for conducting an OCA is directly tied to minimizing the risk of fire and the potential effects of a fire on personnel and system. The OCA process may be used as either a design guide, to aid in the approval process for components and systems, or in the conduct of a failure analysis to identify the flammability of materials and possible ignition mechanisms. Having a thorough analysis can also aid in the solution of anomalies that occur during testing or operational use of rocket engine related oxygen components and systems. The OCA procedure is to:

1. Determine the worst-case operating conditions;
2. Assess the flammability of oxygen-wetted materials;
3. Evaluate the presence and probability of ignition mechanisms;
4. Determine the kindling chain, which is the potential for a fire to breach the system;
5. Analyze the reaction effect, which is the potential loss of life, mission, and system functionality as the result of a fire;
6. Identify the history of use;
7. Report the results of the analysis.

DETERMINE WORST-CASE OPERATING CONDITIONS

The worst-case operating environment should be determined to facilitate the evaluation of the ignition and flammability risks for a component or system. Increased oxygen concentration, temperatures, pressures, flow rates, and contamination can intensify flammability and ignition risks. Therefore, quantifying each of these conditions is a prerequisite of analyzing a system or component. Reliance on procedural controls to regulate the conditions within the oxygen systems should be minimized. A failure modes and effects analysis may be used to determine the worst-case operating conditions. In addition, the analyst should determine the worst-case cleanliness level of each component.

ASSESS THE MATERIAL FLAMMABILITY

The flammability of the materials of construction should be determined. The configuration of a system or component significantly influences the ignitability and flammability of the materials of construction. For instance, metals, including those that normally exhibit high resistance to ignition, are more flammable in oxygen when they have thin cross-sections (e.g. thin-walled tubing) or when they are finely divided (e.g. wire mesh or sintered filters). Therefore when assessing flammability, a system flow schematic and a cross-sectional diagram (e.g. machined cut-away) of each component that shows the configuration and materials of construction should be used. The flow schematic of the system and cross-sectional diagrams of each component should be included in the report.

With few exceptions, materials become more flammable in oxygen as pressures increase. This includes metals, plastics, elastomers, lubricants, and contaminants. In fact, nearly all polymer materials are flammable in 100 percent oxygen at atmospheric pressure. Several test methods, such as promoted ignition[4] and oxygen index,[5] have been developed to determine the relative flammability of metals and nonmetals. The latest versions of ASTM Manual 36,[6] Standard G63[7] and Standard G94[8] provide test data for determining material flammability.

Unfortunately, material flammability is affected by many factors and, therefore, absolute flammability thresholds are difficult to establish without testing the actual use configuration. Much of the OCA process focuses on the presence and probability of ignition mechanisms.

EVALUATE PRESENCE AND PROBABILITY OF IGNITION MECHANISMS

The presence and relative probability of ignition mechanisms should be determined**.** An ignition mechanism is simply a source of heat that under the right conditions can lead to ignition of the materials of construction or contaminants in a system. The most effective way to analyze the ignition risks in a system is to methodically analyze the system for known ignition mechanisms (Table 1).

Table 1
Ignition Mechanisms

Particle Impact	Lightning
Rapid Pressurization	Explosive Charges
Flow Friction [a]	Personnel Smoking and Open Flames
Resonance	Fragments from Bursting Vessels
Mechanical Impact	Welding
Galling and Friction	Engine Exhaust
Fresh Metal exposure	Static Discharge
Electrical Arc	Chemical Reaction
Thermal Runaway	Other

[a] Theoretical only: No current test method exists to duplicate flow friction in the laboratory.

For ignition mechanisms to be effective, certain elements must be present. These characteristic elements are unique for each ignition mechanism, and each element is necessary for an ignition to occur. Conversely, if all the characteristic elements are present, ignition is possible. Ignition mechanisms are rated using the ignition mechanism rating logic in ASTM Manual 36, Table 2.[6] This logic takes into consideration both the presence of a mechanism's characteristic elements and flammability of materials. If the flammability of a material is unknown, or the materials of construction have not been selected, then the material should be considered flammable for the purposes of assessing the ignition mechanisms.

IGNITION MECHANISMS

Particle Impact — Heat generated when small particles strike a material with sufficient velocity to ignite the particle and/or the material.

Particle impact is a very effective ignition mechanism for metals, but less likely to ignite nonmetals unless they are very hard. The characteristic elements necessary for ignition by particle impact are:

- particles that can be entrained in the flowing oxygen;
- gas velocities, typically greater than approximately 30 m/s (100 ft/s);[9] and

- an impact point ranging from 45 degrees to perpendicular to the path of the particle.[‡,§]

Test data show that, in most cases, the particulate must be flammable to produce ignition of the target material. However, some highly reactive materials, such as aluminum and titanium, can be ignited when impacted by inert particles.

Data: Particle impact data for metals and nonmetals are located in the latest versions of ASTM Manual 36[6] and Standard G94.[8] In general, copper and nickel-based alloys are resistant to ignition by particle impact. Hard polymers have been ignited in particle impact tests, but limited data exist.

Rapid Pressurization — Heat generated when a gas is rapidly compressed from a low pressure to a high pressure. This ignition mechanism is also known as heat of compression or adiabatic compression. Rapid pressurization ignition is the most effective igniter of nonmetals, but does not ignite bulk metals. The characteristic elements for rapid pressurization ignition are:

- rapid pressurization, generally occurring in less than 1 s;
- an exposed nonmetal close to the rapidly pressurized dead-end; and
- a pressure ratio that causes the maximum temperature from compression to exceed the situational auto-ignition temperature of the nonmetal.

The maximum theoretical temperature from compression can be calculated using the following equation:

$$\frac{T_f}{T_i} = \left(\frac{P_f}{P_i}\right)^{\frac{(n-1)}{n}} \quad \textbf{(1)}$$

Where:

T_f = final temperature (absolute),
T_i = initial temperature (absolute),
P_f = final pressure (absolute),
P_i = initial pressure (absolute),
N = ratio of specific heats (1.4 for oxygen).

The actual maximum temperature is inevitably appreciably lower than the maximum theoretical temperature.

Data: Auto-ignition temperature data for nonmetals are found in the latest versions of ASTM Manual 36[6] and Standard G63.[7] Extensive testing in a system consistent with ASTM G74[10] has demonstrated that for initial upstream pressures less than 275 psia and an initial downstream pressure of ambient or above, the actual temperature rise (with real heat loss) is too small for ignition to occur.

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‡ This was concluded from tests conducted using test fixtures that simulated the configuration of the Space Shuttle Type II MPS oxygen flow control valve. The Type II test fixtures were fabricated from Inconel 718 with drill points downstream the flow control orifice similar to the actual valve and with drill points removed. The tests were performed at the same conditions and using the same particle mixture that ignited and burned the Type II oxygen flow control valve during certification testing. The test conditions were as follows: 600 K oxygen temperature, 4600 psig oxygen pressure, and 10 mg of a particle mixture consisting of 26 percent Inconel 718, 29 percent 21-6-9 stainless steel, and 45 percent aluminum 2219 by weight. The Type II Inconel 718 test fixture that contained the drill point ignited and burned on the second test. The Type II Inconel 718 test fixture in which the drill points were removed resulting in an impact angle of 45° did not ignite or burn when subjected to 40 tests. [The Space Shuttle flow control valve was subsequently redesigned.]

§ Benz, F. *Summary of Testing on Metals and Alloys in Oxygen at the NASA White Sands Test Facility (WSTF) During the Last 6 Months.* In RF/DLPippen:kp:09/14/88:5722, *WSTF Metals Work Memo,* from David Pippen to Director of Materials and Processes Laboratory at George C. Marshall Space Flight Center, September 15, 1988.

Flow Friction — Heat generated when oxygen flows across a polymer and produces erosion, friction, and/or vibration. Flow friction is a theoretical ignition mechanism, but current theory suggests that the characteristic elements for flow friction ignition include:

- nonmetal exposed to flow; and
- flow that produces a vibration in the nonmetal.

Surfaces of nonmetals that are highly fibrous from being chafed, abraded, eroded, or plastically deformed may render flow friction heating affects more severe. Although this ignition mechanism is poorly understood, it has caused a significant number of real-life fires.

Resonance — Acoustic oscillations within resonant cavities that cause rapid temperature rise. The characteristic elements for resonance ignition include:

- a favorable system geometry, which includes a throttling device (e.g. nozzle, orifice, regulator, or valve) directing a sonic gas jet into a cavity or closed-end tube;
- acoustic resonance (often audible) and
- flammable materials in the area of the resonance.

The distance between the throttling device and the closed end affects the frequency of acoustic oscillations in the cavity due to the interference of incident and reflecting sound waves.[11] The distance also affects the temperature produced in the cavity. Higher harmonic frequencies have been shown to produce higher system temperatures. The resonant frequency has been shown to be a function of pipe diameter and pressure ratio.

Flammable materials residing at or near the closed end of the cavity can self-ignite due to the high gas temperatures produced by resonance heating. Alternatively particulate or debris can vibrate, causing collisions that generate sufficient heat to self-ignite.

Mechanical Impact — Heat generated due to single or repeated impacts on a material with sufficient energy to ignite it. Most metals cannot be ignited by mechanical impact; however, nonmetals are susceptible to ignition by mechanical impact. The characteristic elements for mechanical impact ignition are:

- a single, large impact or repeated impacts; and
- a nonmetal or reactive metal at the point of impact.

Some components, such as check valves, regulators and relief valves, may become unstable and “chatter” during use. Chattering can result in multiple impacts in rapid succession on polymer poppets or seats within these components, creating a mechanical impact ignition hazard. The presence of LOX (instead of gaseous oxygen) may cause some porous materials to become dramatically more sensitive to mechanical impact.

Data: Most metals are not susceptible to ignition by mechanical impact. However, data has shown that aluminum, magnesium, titanium, and lithium-based alloys, as well as some lead-containing solders, can be ignited by mechanical impact. Mechanical impact ignition data for nonmetals are found in the latest versions of ASTM Manual 36[6] and Standard G63.[7]

Galling and Friction — Heat generated by the rubbing of two or more parts together. The characteristic elements for frictional ignition are:

- two or more rubbing surfaces, generally metal-to-metal;
- rapid relative motion; and
- high loads pressing the rubbing parts together.

Data from ASTM Manual 36[6] indicate that metals, not polymers, are most susceptible to ignition by friction in the frictional heating tests currently available. Research indicates that polymers may also be susceptible to ignition in certain conditions. Some components, such as check valves, regulators, and relief valves, may become unstable and "chatter" during use. Chattering can result in rapid oscillation of the moving parts within these components, creating a frictional ignition hazard.
Data: Frictional heating data for various pairings of materials is located in the latest versions of ASTM Manual 36[6] and Standard G94[8]

Fresh Metal Exposure — the heat of oxidation released when unoxidized metal is exposed to an oxidizing atmosphere.

This ignition mechanism usually acts in conjunction with other ignition mechanisms, such as frictional heating or particle impact, which damage metal surfaces. This ignition mechanism may also be present with a fracture or tensile failure of an oxygen-wetted pressure vessel. The characteristic elements for fresh metal exposure ignition are:

- metal that oxidizes quickly and has a high heat of formation for its oxides, such as aluminum and titanium alloys;
- destruction or rapid removal of oxide layer; and
- configuration that minimizes heat loss.

Static Discharge — Discharge of accumulated static charge with enough energy to ignite the material receiving the charge. The characteristic elements for static discharge are:

- static charge buildup from flow or rubbing accumulated on an electrically isolated surface; and
- discharge point between materials, generally with differing electrical potentials.

Generally, two charged surfaces are not as likely to arc unless one material is conductive. Static discharge ignition is most likely to occur in dry gas environments.

Electrical Arc — Sufficient electrical current arcing from a power source with enough energy to ignite the material receiving the arc. The characteristic elements necessary for ignition by electrical arc are:

- an electrical power source;
- an arc with sufficient energy to melt or vaporize materials; and
- flammable material exposed to heating from the arc.

Chemical Reaction — A reaction of a combination of chemicals that could release sufficient heat energy to ignite the surrounding materials.

The characteristic elements for chemical reaction ignition depend on the reactants involved. For example, some mixtures may be self-igniting while others need an external heat source. In oxygen-hydrogen mixtures, the ignition energy is so low that it is assumed that energies released from mixing will ignite the mixture.
Thermal Runaway — some materials, notably certain accumulations of fines, porous materials, or liquids, may undergo self-sustained reactions that generate heat.

If the rate of heating compared to the rate of dissipation is unfavorable, the material will increase in temperature. In some cases, a thermal runaway may be attained and later the material may spontaneously ignite. Ignition and fire may occur after short time periods (seconds or minutes) or over long time periods (hours, days, or months). In the most extreme cases, the thermal runaway temperature may be near or below normal room temperature. The characteristic elements for thermal runaway ignition include:

- a material with a high surface-area-to-volume ratio (e.g., dusts, particles, foams, chars, etc.) that reacts exothermically (e.g. oxidation or decomposition) at temperatures significantly below its ignition temperature and
- an environment that does not adequately dissipate heat (e.g., an insulated or large volume vessel or an accumulation of fines).

Other—Potential ignition sources to consider should initially include any external heat sources. Many of the potential sources of heat are self-explanatory and include: lightning, explosive charges, personnel smoking and open flames, fragments from bursting vessels, welding, and exhaust from combustion engines.

DETERMINE THE KINDLING CHAIN

The ability of a fire to propagate and burn through a component, i.e., the kindling chain, should be evaluated. A kindling chain begins when a material is ignited, and the material's heat of combustion is sufficient to heat and ignite the surrounding materials leading to a burn-through of the component. A burn-through is considered unlikely when the materials are nonflammable or an unfavorable fire propagation configuration is present. A burn-through is considered likely when most materials (including the body) are flammable and a favorable fire propagation configuration is present.

An example of a component with a possible kindling chain could be a manual valve with a polysulfone seat and a stainless steel stem and body. In this configuration and at high pressures, the seat, stem, and body are flammable. If the polysulfone seat were ignited (e.g., by flow friction or rapid pressurization), enough energy could be released to ignite and burn the stem, which could then ignite the body and result in a burn-through of the manual valve. The analyst should assess the kindling chain based on the presence of ignition mechanisms and the ability of the materials of construction to contain a fire. If a component could be breached, a kindling chain is present.

ANALYZE THE REACTION EFFECT

The reaction effect should be determined. The effects of a fire on personnel, mission, and system objectives are assessed by determining the reaction effect. This value is primarily assigned based on the presence of a kindling chain and the potential consequences of a fire. The potential consequences of a fire are based on the extent of fire propagation in the materials that surround the component. Because it is difficult to conceive all possible fire scenarios resulting in injury, reaction effect ratings are often applied conservatively, which means the worst-case scenario drives the reaction effect assessment.

IDENTIFY THE HISTORY OF USE

The relevant history of use should be evaluated. The history of use is determined by whether the component has experienced routine operation/cycling in similar or more severe conditions over an extended period of time. For example, if an engine component has been used in similar or more severe conditions over a period of time, then the component may be considered to have a successful history of use.

REPORT RESULTS OF THE ANALYSIS

The results of the compatibility assessment should be documented. An OCA can facilitate the communication and dissemination of the results to interested parties and record the findings for future reference. The OCA may also recommend changes to design, materials, and procedures in order to mitigate the fire hazards identified.

A complete and thorough record of information is extremely beneficial in communicating the findings of the assessment. Whenever possible, references to the data used in determining the various ratings should be included. Pictures, drawings, and schematics of the component should also be referenced and included in the final report.

A system-level OCA should contain the compatibility assessment charts and drawings for each component in the system. A system description and flow schematic should also be included in the final report.

Once prepared, the report should be reviewed by other analysts to obtain consensus. Comments and feedback should be considered when finalizing the report.

APPLICATIONS OF OCA PROCESS

WSTF has successfully applied the OCA process to oxygen systems for the Space Shuttle and International Space Station programs, ground support equipment at KSC and JSC, and test systems at WSTF and throughout NASA. Over 400 analyses have been performed since the mid-1990s resulting in recommendations that have significantly improved the ignition and burn resistance of oxygen systems and hardware. The process has been applied to the J-2X Rocket Engine and the oxygen turbopump seal test rig in support of Marshall Space Flight Center (MSFC) (WSTF/MSFC, 2008).[12]

In addition, the OCA process has been used to guide the resolution of anomalies that have occurred in the SSME throughout the space shuttle program. On several occasions, post-flight inspection has revealed the presence of metal particles and debris in various SSME components. The question was always raised regarding the possible ignition of the contaminant and propagation of a fire to the surrounding components. The OCA process was used to identify the vulnerable ignition and burning sites and to prescribe the data necessary to determine the SSME system vulnerability. In some cases, test data already existed and in some cases tests were performed to obtain the needed ignition and burn data. In all cases, once the data were obtained, decisions were made to either fly as is or to take other appropriate action to mitigate the risks identified by the OCA process.

Finally, the procedure can and has been used to guide failure analyses of oxygen system fires in general, and for high-pressure turbomachinery, in particular. Using the OCA process as a guide, WSTF has consulted with Aerojet to investigate a turbopump fire for the NK-33 event occurring in Russia and for a fire in the fuel-rich, pre-burner LOX diffuser screen in the Air Force Research Laboratory's Integrated Powerhead Development Program. By using the OCA process to identify flammable materials and credible ignition mechanisms, analysts can eliminate unlikely ignition scenarios and focus on those for which all the characteristic elements are present. Often, this process leads to a reasonable understanding of the possible ignition scenarios.

SUMMARY AND CONCLUSIONS

There is a real problem with fires in oxygen-enriched atmospheres, specifically, within rocket engine oxygen systems. An analysis protocol has been developed which, when aggressively applied, will result in increased fire resistance and fewer destructive fire events. This process, codified as NASA-TM-2007-213740, *Guide for Oxygen Compatibility Assessments on Oxygen Components and Systems*,[3] has been successfully applied to reduce fires in oxygen-enriched environments and as a failure analysis tool during the investigation of fires.

REFERENCES

1 Cataldo, C. E. ***LOX/GOX Related Failures During Space Shuttle Main Engine Development***. Technical Memorandum NASA TM-82424, Marshall Space Flight Center, Alabama (May 1981).

2 Biggs, R. E. "Space Shuttle Main Engine, The First Ten Years." ***American Astronautical Society History Series***, S. E. Doyle, Ed., Vol. 13, pp. 69-122, (1992).

3 Rosales, K. S. ***Guide for Oxygen Compatibility Assessments on Components and Systems***. Technical Memorandum NASA-TM-2007-213740, NASA Johnson Space Center White Sands Test Facility, Las Cruces, New Mexico (March 2007).

4 ASTM G124. ***Standard Test Method for Determining the Combustion Behavior of Metallic Materials in Oxygen-Enriched Atmospheres***. American Society for Testing and Materials, West Conshohocken, Pennsylvania (2003).

5 ASTM G125-00. Measuring Liquid and solid Material Fire Limits in Gaseous Oxidants. American Society for Testing and Materials, West Conshohocken, Pennsylvania (2008).

6 ASTM. ***Safe Use of Oxygen and Oxygen Systems: Guidelines for Oxygen System Design, Materials Selection, Operations, Storage, and Transportation, ASTM Manual 36***," H.D. Beeson, W. F. Stewart, and S. S. Woods, Editors, American Society for Testing and Materials, Philadelphia, Pennsylvania (2000).

7 ASTM G63-95. ***Standard Guide for Evaluating Nonmetallic Materials for Oxygen Service. American Society for Testing and Materials***. American Society for Testing and Materials, West Conshohocken, Pennsylvania (1999).

8 ASTM G94-92. ***Standard Guide for Evaluating Metals for Oxygen Service***. American Society for Testing and Materials, West Conshohocken, Pennsylvania, 2005.

9 Williams, R. E., F. J. Benz, and K. McIlroy. "Ignition of Steel Alloys by Impact of Low-Velocity Iron/Inert Particles in Gaseous Oxygen," ***Flammability and Sensitivity of Materials in Oxygen-Enriched Atmospheres, ASTM STP 986***, D. W. Schroll, Ed., American Society for Testing and Materials, West Conshohocken, Pennsylvania, 1988, pp. 72-84.

10 ASTM G74. ***Standard Test Method for Ignition Sensitivity of Materials to Gaseous Fluid Impact***. American Society for Testing and Materials, West Conshohocken, Pennsylvania (2008).

11 Phillips, B. R., ***Resonance Tube Ignitions Metals***, Ph.D. Thesis, University of Toledo, Toledo, Ohio (1975).

12 Davis, E., Eidson, A., Herald, S., Lambdin, R., Peralta, S., S. Smith, K. Sparks, and J. Stoltzfus. ***Oxygen Compatibility Assessment Report J-2X Rocket Engine***. OXHAZ/FAIL.0399, NASA Marshall Space Center, Alabama (August 28, 2008). ***This document is ITAR controlled; approved for U.S. Citizens only.***