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Proposed Additions to ASTM G 145 on Incident Study[2]

REFERENCE: Werley, B. L., **"Proposed Additions to ASTM G 145 on Incident Study"**, Self published paper, 2007, 12 pages.

ABSTRACT: ASTM G 145 was adopted in 1996 and has not been significantly altered since. Potential new material, elaboration and modifications are proposed for evaluation and possible inclusion in a next-generation document. New proposed items are additional factors, scenarios and analytical methods that do not alter existing material but rather append to it. They are not validated and are not intended to yield a comprehensive document but can provide a starting point for an expanded version. .

KEY WORDS: oxygen safety, oxygen incident, accident investigation.

ASTM G 145-96 Standard Guide for Studying Fire Incidents in Oxygen Systems was approved in October 1996. It was reapproved largely unchanged several times since on the basis that its content was still correct and applicable and that Committee G4 was not able at the time to launch an expansion of it. In 2002, the Committee had just launched a major effort to revise a much more dated standard *G 88 Designing Systems for Oxygen Service* (in addition to a challenging agenda of business already underway) which had not been changed greatly since its much earlier original publication, and the writer, who prepared the first draft of *G 145*, considered an updated *G 88* as desirable resource material for several items in the revision of *G 145*.

G 145 was an effort to portray a series of unique and uncommon insights and techniques that had been useful in the effort of seeking to identify the direct causes of oxygen system fire incidents. This included listing the mechanisms that had most frequently or most uniquely seemed to be involved in incidents as well as mechanisms and observations that have often been overlooked or proven misleading in past investigations. It did not seek to elaborate all of the failure mechanisms that might apply, nor claim to know all of them, just several which were known or referenced wherever others had already published. *G 145* was structured so that additional techniques and insights could be appended. At the same time (1996), G4 launched a reinvigoration of its seminar series with a specific effort to seek out

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[2] This paper was self-published for the writers oxygen safety-opinion web site.

papers applicable to incident study voids that existed, and several have been published in the intervening years, for example [*1-5*][3].

As of this writing, G4 has completed the major revision and expansion of its design Guide *G 88* in 2005. So as to not divert energies from other efforts underway, the writer is publishing the suggestions herein for future Committee consideration in a format that may facilitate editing and conversion into a ballot form. The reader needs to be careful that these are proposals only that have *not* been validated *nor* agreed upon by the Committee's consensus mechanism. It may require years before that procedure can be launched and possibly even further years before it can be completed. Therefore this material should only be viewed as opinion, speculation and sources of ideas. Indeed, some of this material may prove to be in error or may ultimately be adopted in a different fashion.

The items listed here are potentially new "Factors Affecting an Incident Study" in Section 9, "Common Incident Scenarios" in Section 10, or new "Analytical Techniques" in Section 11.

In addition, the writer has recently finished and posted a massive first draft analysis of adiabatic compression in real and ideal gases, some features of which bear mention in this standard. These items are listed below even though some of the data and analysis are not presented in other references and could not be confirmed. There have been no challenges to the methods or data thus far, but the paper has not experienced significant review.

Finally, this proposal is presented in this fashion because the development of a full consensus standard can delay the time when these data become available by years. And those performing incident study may benefit from access to the techniques reviewed even if the validity must be viewed as tenuous or suspect.

Note that text quoted from *G 145* is in black. Suggested text for deletion is in red. Proposed new text is blue (even if that new text is drawn in part from other G-4 standards). Proposed new figures from *G 88* are shown and would need renumbering. References and footnotes are also cited in normal ASTM style and would need inclusion and renumbering.

Section 5.0 Significance and Use

Section 5.0: Expand to adopt the Purpose, Role and Use format adopted with *G 88–05*. Specifically replace the existing section with:

5.0 Significance and Use

5.1 Purpose of Guide *G 145*—This guide helps those studying oxygen system incidents to select a direct-cause hypothesis and to avoid conclusions based on hypotheses, however plausible, that have proven faulty in the past.

5.2 Role of *G 145*—ASTM Committee G-4's abstract standard is *G 128*, and it introduces the overall subject of oxygen compatibility and the body of related work and related resources including standards, research reports and a video[4] G-4 has developed and adopted for use in coping with the oxygen hazard. The interrelationships among the standards is shown in Table. 1. *G-88* deals with hard-

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[3] Italic numbers in brackets refer to the reference list at the end of the paper.

[4] Available from ASTM Headquarters. Order ADJG0088.

Table 1—*Role of G 145*

G 128 Guide to Control of Hazards and Risks in Oxygen-Enriched Systems

- **G 88 Designing Systems for Oxygen Service**
  - **G 175 Evaluating the Ignition Sensitivity and Fault Tolerance of Oxygen Regulators**
  - **G4Math.exe**
- **G 63 Evaluating Nonmetallic Materials**
  - **D 2512 Compatibility of Materials With Liquid Oxygen (Mechanical Impact)**
  - **D 2863 Measuring the Minimum Oxygen Concentration to Support Candle-Like Combustion (Oxygen Index)**
  - **D 4809 Heat of Combustion of Liquid Hydrocarbon Fuels by Bomb Calorimeter (Precision Method**
  - **G 72 Autogenous Ignition Temperature of Liquids and Solids in High-Pressure Oxygen Enriched Atmospheres**
  - **G 74 Ignition Sensitivity of Materials to Gaseous Fluid Impact**
  - **G 86 Determining Ignition Sensitivity of Materials to Mechanical Impact in Pressurized Oxygen Environments**
  - **G 114 Aging Oxygen-Service Materials Prior to Flammability Testing**
  - **G 125 Measuring Liquid and Solid Material Fire Limits in Gaseous Oxidants.**
- **G 94 Evaluating Metals**
  - **G 124 Determining the Combustion Behavior of Metallic Materials in Oxygen Enriched Atmospheres**
    - **G4Math.exe**
- **G 93 Cleaning Methods for Material and Equipment**
  - **G 120 Determination of Soluble Residual Contamination in Materials and Components by Soxhlet Extraction**
  - **G 136 Determination of Soluble Residual Contaminants in Materials by Ultrasonic Extraction**
  - **G 144 Determination of Residual Contamination of Materials and Components by Total Carbon Analysis Using a High Temperature Combustion Analyzer**
  - **G 127 Guide to the Selection of Cleaning Agents for Oxygen Systems**
    - **G 122 Test Method for Evaluating the Effectiveness of Cleaning Agents**
      - **G 121 Preparation of Contaminated Test Coupons for the Evaluation of Cleaning Agents**
  - **G 131 Cleaning of Materials and Components by Ultrasonic Techniques**
- **G 145 Studying Fire Incidents in Oxygen Systems**
- **G 126 Terminology Related to the Compatibility and Sensitivity of Materials in Oxygen-Enriched Atmospheres**
- **G04 Video: Oxygen Safety**

ware design principles, and it is supported by a regulator test, and a computer algorithm[5]. Other standards cover: (1) the selection of materials (both metals and nonmetals) which are supported by a series of standards for testing materials of interest and for preparing materials for test; (2) the cleaning of oxygen hardware which is supported by a series of standards on cleaning procedures, cleanliness testing methods, and cleaning agent selection and evaluation; (3) this Standard *G 145* on the study of fire incidents in oxygen systems; and (4) related terminology.

5.3 Use of Guide *G 145*—*G 145* can be used as a rough guide in setting up an incident investigation or to supplement an existing procedure. In both cases, however, the principle investigation tools should employ the mechanical and other techniques from mechanical failure analysis disciplines adjusted for the unique properties of oxygen as indicated in *G 145*.

Section 9.0 *Factors Affecting an Incident Study*:

9.3 *Particle Impact:*

Add new 9.3.3:

9.3.3 Figure 1 (Fig. 10 from *G 88-05*) exhibits how certain installations of ball valves can accumulate debris and act as a particle sump.

Change title of 9.5 to "***Heat and Temperature of Compression***:"

Change 9.5.1 to:

"9.5.1 When a gas is rapidly compressed, its temperature rises. The pressurization of a system tends to produce the greatest temperatures within the gas initially in the system. The increase in temperature can cause autoignition of some system components This compression is can be nearly adiabatic and typically occurs at system end points or trapped volumes. In extreme cases, heat of compression has produced some of the most explosive (rupturing and fragmenting components) and most probable mechanisms of oxygen fires. In severe cases, a heat and temperature of compression fire may occur on the very first pressurization of a system. Every incident should be examined for a mechanism that may have enabled rapid gas compression and for where the compressed gas may have been located relative to the fire damage."

Cite three additional references [7-9] in ¶ 9.5.2.

Add new ¶ 9.5.3 to section on **Heat and Temperature of Compression**:

"9.5.3 Temperature of compression contributes to ignition by exposing materials to temperatures above their *in-situ* autoignition temperature. Peak compression temperatures for a given final pressure are greatest when the initial pressure is smallest

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[5] ASTM G4Math Utility software, available from ASTM International Technical & Professional Training Course Fire Hazards in Oxygen Systems.

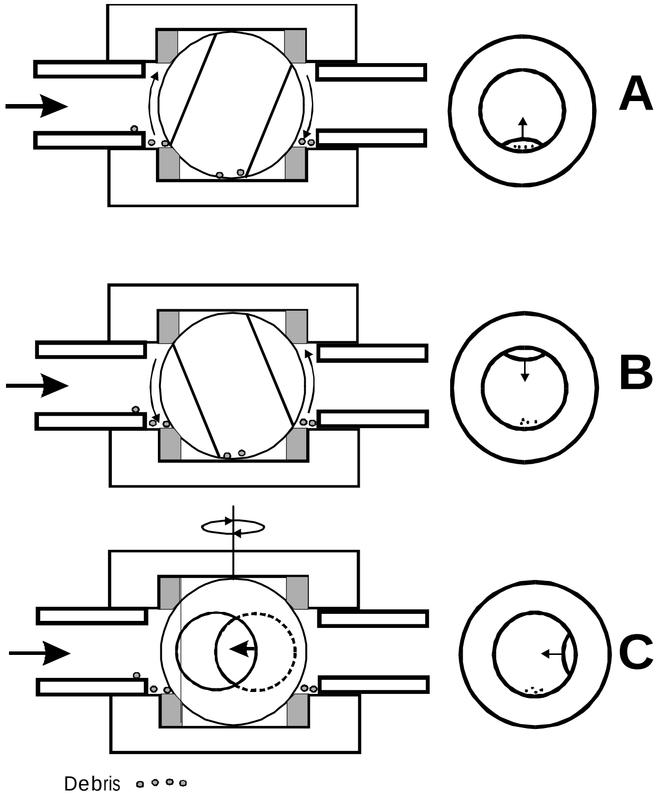


FIG. 1—Debris in ball valve installations.
(From ASTM G 88-05)

[7]. Oxygen mixed with gases of lower specific heat will produce higher final temperatures than oxygen alone during compression. Oxygen mixed with gases of higher specific heat will produce final temperatures [7] that are not as high as for oxygen alone.

Add new ¶ 9.5.4 to section on **Heat and Temperature of Compression**:

"9.5.4 Heat of compression contributes to ignition by exposing a material to a heat transfer greater then its minimum *in-situ* ignition energy. Heat transfer during compression is greatest when the initial pressure is at an optimum level [7] and may be more severe for a lower AIT materials at one pressure yet more severe for a higher AIT materials at a different pressure. Oxygen mixed with gases of lower specific heat will shift the worst case initial pressure and will increase the heat transfer possible in comparison to oxygen [7] and may increase the risk of ignition. Oxygen mixed with gases of higher specific heat will result in heat transfer less than for oxygen at all starting pressures.

Add new ¶ 9.5.5 to section on **Heat and Temperature of Compression**:

"9.5.5 Since heat of compression is most severe at an optimum pressure, one should always assess the range of potential starting pressures possible in any potential adiabatic compression-induced incident. Often it is easy to produce and overlook uncharacteristically elevated pressures that may have been present in hardware. For example, reference [7] describes how much more severe conditions may obtain if an oxygen gas regulator was *incompletely* vented when last shut down.

Addenda to “9.8 **Crevices”**

Add new ¶ 9.8.1 to section on 9.8 on **Crevices**:

9.8.1: *Seal Welds*. Where an internal component has been “seal welded” (welded along its perimeter to isolate any contained crevices), *ASTM G 88* recommends they be used with caution and properly applied. Crevices that show evidence of ignition or which were present in regions of a fire that have been destroyed, should be evaluated for mechanical integrity. Fig 2 exhibits two approaches to a seal-welded nozzle through a heavy vessel wall forming an annular crevice. Because the nozzle is lighter and more temperature responsive than the heavier wall, cold, cryogenic or even liquid oxygen that passes through the nozzle can produce greater contraction in the nozzle than in the adjacent wall leading to stress, fatigue, and failure at the weakest point, which in this case is the lower strength seal weld. Check to see if any open crevices were situated so as to serve as a sump (see 9.4), whether seal welds were adequately designed for the maximum likely stresses, and whether the contained crevice was vented to a safe area to prevent crevice pressurization in the event of weld failure.

Add new factor 9.15 on **Explosive/Mechanical Energy**:

9.15 *Explosive/Mechanical Energy*. When an oxygen fire occurs, it can produce pressure releases and shock waves that damage the area, and when damage is involved in an oxygen incident, it can often be related back to the size of the event that produced it. These two “faces’ of an analysis can allow important inference on causation. If area damage is consistent with a given TNT equivalency, and yet the vessel itself has not been consumed to yield at least that amount of damage, then one’s attention should focus on contamination. In one case, components were buckled and bent in a way for which the minimum energy needed to mechanically damage them could be calculated. This was related directly to the amount of metal that would have to burn and so a metal fire could be ruled out and the approximate amount of various contaminants that must have been present could be estimated. TNT-equivalency estimation techniques are reviewed variously [7,10-12]. Caution: the TNT equivalency of liquified gas systems is difficult to assess [7], and while there are many who would assume the TNT equivalency of venting liquid cryogens is small due to the low compressibility of liquids, this assumption can be seriously flawed. Liquid cryogens can release significant amounts of energy during a burst or rupture of a oxygen vessel [7].

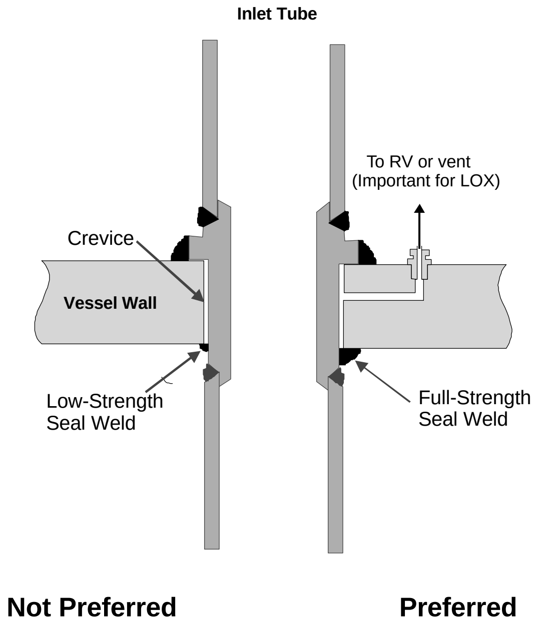


FIG. 2—*Seal welded crevices.*

Add new factor 9.16 on **Fluid Dynamic Effects**:

> 9.16 *Fluid Dynamic Effects*. Fluid dynamic effects can be difficult to assess in adequate detail. What paths will particles take? Where will they impact? When will they be fluidized or elutriated? Do their velocities differ from the gas velocity? All of these calculations can be daunting to perform. However, software use is emerging that will allow many of these questions to be answered in an incident study. To date, such software has been used to perform analysis is several G4 papers [6,8,13].

Add new factor 9.17 on: **Statistical Analysis**

> 9.17 *Statistical analysis*. Oftentimes incidents fit a pattern and a study involves sorting out common failure modes. Sometimes an incident can be extraordinary. When incidents appear so rare as to be unique, it can be worthwhile to examine the similar body of equipment that has *not* experienced fires. One of the most time-honored bases for proving the acceptability of hardware is a statistically significant history of safe use of similar equipment in similar service. Therefore when hardware previously considered safe experiences a fire, the statistical bases warrant consideration. Such a statistical analysis should seek to identify whether the hardware in the incident had changed in such a fashion as to render it of a characteristically different risk pattern, whether the statistical foundation was not adequate after all, or whether the incident was a true low-probability event that reflects the risk pattern of all similar

equipment in the future. In these cases, a single event is much less informative than multiple or even just two, events. When one event occurs it is difficult to calculate a meaningful failure rate probability. However when there have been two or more incidents, the reliability of the failure rate calculation is markedly improved and allows for much stronger conclusions and inference.

Add new factor 9.18 on **Unexpected Fire Limit**s:

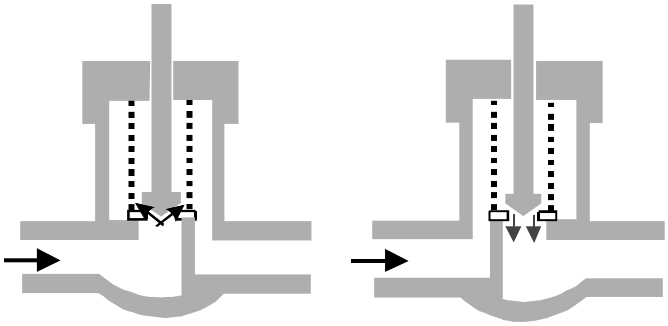
9.18 *Unexpected Fire Limits.* Often oxygen incidents have occurred in circumstances that might seem to be outside the necessary conditions for a fire to proceed even when ignition has occurred. However, Ball describes two fire events [14,15] in which oxygen concentrations were only 3.5 and five percent (far below published values of the minimum oxygen for combustion) but for which elevated temperatures widened the fire limits. Benning et al. [16] revealed how test results in which aluminum was nonflammable in oxygen containing just a few tenths of a percent of argon but which burned intensely at higher concentrations. Even today, much testing is being done and much more is needed to determine the threshold at which fires can and do occur in oxygen. Fire-limit estimation is still a field in which theory is to a large extent inadequate and empirical measurements are the main basis for predicting thresholds. When an incident occurs, it is proof that a fire *was* possible, and the possibility that conditions normally thought to be outside the fire limits may have actually allowed for fire must be carefully assessed.

Add new factor 9.19 on: **Paradoxical Diluent Behavior**

9.19 *Paradoxical Diluent Behavior*. In some cases, diluents, even inert gases, can act contrary to expectations. Adding argon to a system in certain ways can *cause* a fire. Some diluents (like argon and helium) can increase peak adiabatic compression temperature and heat transfer, can act (like helium) to increase the rates of material combustion, can act (like argon and helium) to widen fire limits. As a result the addition or presence of any gas, even inert gas, prior to any oxygen incident must be evaluated for any paradoxical tendency to facilitate or aggravate combustion.

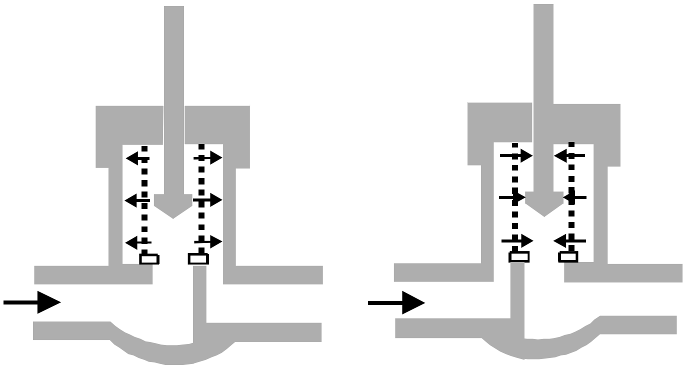
Add new factor 9.20 on **Flow Directionality**:

9.20 *Flow Directionality.* A component specifically designed for oxygen service can have its compatibility nullified if improperly installed. Fig 3 from ASTM *G 88-05* exhibits how particle impact risk can change when oxygen flow is reversed. Valves are usually marked with an arrow to indicate the forward flow direction. However often flow may be bi-directional and sometime the preferred flow direction is against the arrow to achieve quieter operation or other benefits. Flowing through a component in the opposite direction to that for which it is designed can produce mechanical impacts, adiabatic compression and particle impact among other mechanisms at locations that are vulnerable. Every component involved in an incident should be examined not only as to its basic design, materials of construction, and cleanness but also as to its specifics of installation and operation.



Normal Flow
Pressure Drop at Seat

Reverse Flow
Pressure drop at seat



Normal Flow
Pressure Drop at Cage

Reverse Flow
Pressure Drop at Cage

Fig. 3—Reversing flow through a common cage-type valve.
(From ASTM G 88-05)

Add new factor 9.21 on **Nonroutine Operation or Behavior:**

> 9.20 *Nonroutine Operation or Behavior*. A common observation during incident study is that they are most often seem to have been triggered. The fire occurs after a valve is operated, after a flow has been adjusted, after a system has been pressurized or upset, after a component has failed. Although not unheard of, it is far rarer for an incident to occur in a system that has been operating smoothly for a long period of time. For this reason it can be crucial to identify every deviation from "normal" operation. Was a valve opened more quickly? Were there any uncommon delays? Had the system been shutdown normally and completely in it last use? Had there been any maintenance or repairs? Any of these events may provide a clue to a "triggering" event.

10 Common Incident Scenarios

Add new incident scenario 10.11 on **Check Valve Hazards**:

10.11 *Check Valve Hazards.* Potential check valve behavior in oxygen incidents bears particular scrutiny. Check valves are often used for safety functions but can also be used for flow logic. However check valves can suffer from a series of common and frequent failure mechanisms that must all be considered and can in some cases be so frequent as to be considered probable. Check valve seats can corrode or be damaged by particle or mechanical impact or can accumulate material that prevents seating. Some flappers can be operate so rapidly as to produce mechanical impact, damaging or breaking components and creating loose debris in a system putting the downstream regions at risk. If the reverse pressure is not sufficiently high many check valve will not form a complete seal and will not isolate oxygen from entering forbidden regions of a system. For these reasons some system designers forego the use of check valves in safety roles and substitute PC-controlled isolation valves instead. But as a result, in any incident, the condition and potential operation of all check valves involved in the fire or upstream of it should be studied carefully.

Add new incident scenario 10.12 on **Spontaneous Palladium Oxide Reactions**:

10.12 *Spontaneous Palladium Oxide Reaction.* In a number of incidents, palladium oxide getter used in vacuum jacketed insulation had gettered trace hydrogen, which spontaneously ignited when mechanical failure introduced oxygen into the jacketing. In other cases, the palladium oxide migrated into the oxygen system through mechanical failure where it similarly was involved in ignition (through hydrogen reaction or other catalytic or alloying reaction-promoting effects of palladium) (See *G 88-05*, 7.15.3, 7.15.4). This mechanism must be considered in any incident in which palladium or its oxides may have been present.

11. Analytical Techniques

Add a new Analytical Technique 11.9 on **CFD Analysis**:

11.9 *Computational Fluid Dynamics Analysis.* Computer-based programs for performing finite element fluid dynamic analysis are being cited in the ASTM G-4 collegium [6,8,13]. These have included the commercial programs: CFX-5 [6], Fluent [13], and the proprietary program TOPAZ [8]. This software can help surmise flow, mixing, heating, particle impact and other dynamic patterns in an incident.

Add a new Analytical Technique 11.10 on: **Fluid Properties Analysis**:

11.10 *Fluid Properties Databases.* PC based thermodynamic properties are cited in several papers [7,17] being cited in the ASTM G-4 collegum, including databases from NIST [18,19], Outokumpu [17], and there are others available also. These databases can be used to calculate burn ratios [17], mechanical TNT equivalencies [7], maximum real-gas velocities [7], maximum total real-gas pressure [7], peak adiabatic compression temperatures and heat transfers [7] and much more.

Summary

A few additional investigation techniques common in oxygen incidents or even unique to oxygen incident study have been itemized. Most have been used at one time or another. All were presented in ASTM style for potential configuration and addition to *G 145*. However, none has been balloted and validated by ASTM G-4 and so all must be considered "as is" speculation, but may nonetheless suggest avenues of study until a consensus has been established.

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