Applying Flammability Limit Probabilities and the Normoxic Upward Limiting Pressure Concept to NASA STD-6001 Test 1

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Repeated Test 1 extinction tests near the upward flammability limit are expected to follow a Poisson process trend. This Poisson process trend suggests that rather than define a ULOI and MOC (which requires two limits to be determined), it might be better to define a single upward limit as being where 1/e (where e (=~2.7183) is the characteristic time of the normalized Poisson process) of the materials burn, or, rounding, where approximately 1/3 of the samples fail the test (and burn). Recognizing that spacecraft atmospheres will not bound the entire oxygen-pressure parameter space, but actually lie along the normoxic atmosphere control band, we can focus the materials flammability testing along this normoxic band. A Normoxic Upward Limiting Pressure (NULP) is defined that determines the minimum safe total pressure for a material within the constant partial pressure control band. Then, increasing this pressure limit by a factor of safety, we can define the material as being safe to use at the NULP + SF (where SF is on the order of 10 kPa, based on existing flammability data). It is recommended that the thickest material to be tested with the current Test 1 igniter should be 3 mm thick (1/8") to avoid the problem of differentiating between an ignition limit and a true flammability limit.

Nomenclature

α_s	= thermal diffusivity of the solid
l	= burn length, cm
L	= burn length non-dimensionalized with 15.2 cm, Test 1 length criterion
ℓ	= characteristic thickness of the solid
MOC	= maximum oxygen concentration where all samples tested (at least five) pass the Test 1 criteria
N	= *integer* number of Test 1 tests
NULP	= Normoxic Upward Limiting Pressure
μNULP	= NULP + SF, the microgravity normoxic upward limiting pressure
O2	= Oxygen percentage by volume
p	= average probability of observing a burn in a Test 1 test (material fails test)
$\hat{p}$	= maximum likelihood estimate of p from a set of data.
q	= probability of not observing a burn in Test 1 = 1-p
SF	= safety factor to account for enhanced flammability in spacecraft
t	= time
ULOI	= upward limiting oxygen concentration where ~ 50 % of samples fail the Test 1 criteria
V_f	= flame spread rate
x	= integer number of actual observed burns
λ	= mean number of burns observed in a given number of tests. = Np, also the variance of the distribution
$\hat{\lambda}$	= maximum likelihood estimate of λ from a set of data. = N $\hat{p}$
σ	= standard deviation for number of burns observed = $(Npq)^{1/2}$
τ	= characteristic time of process

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I: Introduction

TEST 1 of STD-6001[1] is an upward flame spread test to determine if a material is safe to use in a particular environment. It is pass-fail and is only valid at the atmosphere tested. NASA tests materials for flammability using NASA STD-6001 Test 1, which is an upward burning test at the worst-case atmospheric conditions in which the material will be used. A similar Test 4 [1] is done with wire samples. A modified Test 1 has been proposed [1-3] and evaluated to provide additional information about the flammability limits of the material and not just a pass/fail statement regarding its use in the worst-case atmosphere. In the modified test procedure, the oxygen concentration in Test 1 is successively reduced to identify the Upward Limiting Oxygen Index (1g ULOI) and the Maximum Oxygen Concentration (1g MOC) that consistently results in self-extinguishment of the material. The 1g ULOI is defined as the oxygen concentration at which a material passes the NASA STD 6001 Test 1 burn length criterion 50% of the time. The 1g MOC is defined as the oxygen concentration where five samples passed the burning criterion [2, 3] and where at least one sample in five failed in the environment that contained 1 percent more oxygen by volume.

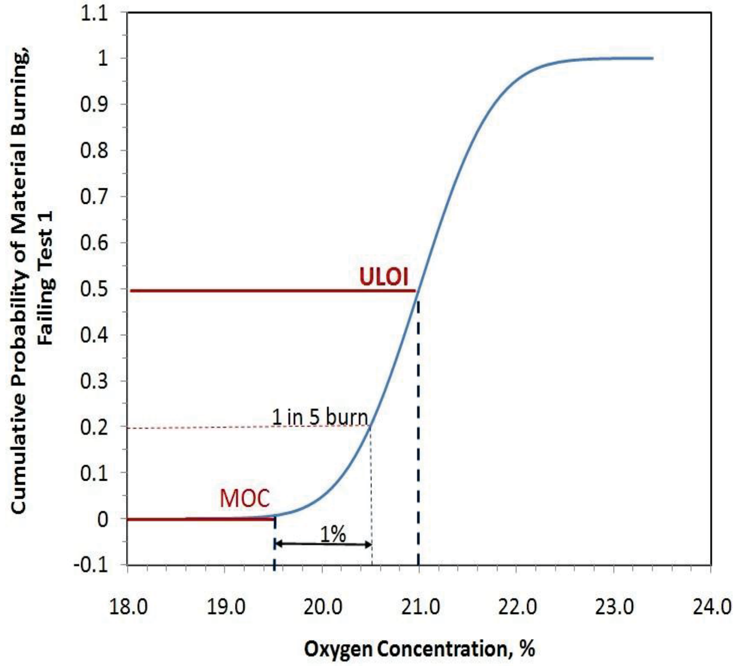

Figure 1. Near limit probability that a material will burn or not, with the ULOI and MOC indicated. [4]

This is depicted conceptually in Figure 1 [3]. The curve in Figure 1 was approximated with a cumulative normal distribution. According to T'ien [5], the closer a flame is to extinction, the more likely a small disturbance will extinguish it. At any given oxygen concentration near enough to the limit, there will be a normal distribution of random perturbations, and a fraction of those will be adequate to extinguish the flame. Far from the limit, no perturbations will extinguish the flame, and none would extinguish the flame. As the oxygen is reduced, the flame is easier to extinguish, and more of the perturbations would extinguish the flame, so the probability of extinction increases (material would pass the test). Eventually, even the smallest perturbation will extinguish the flame, so no flame will survive.

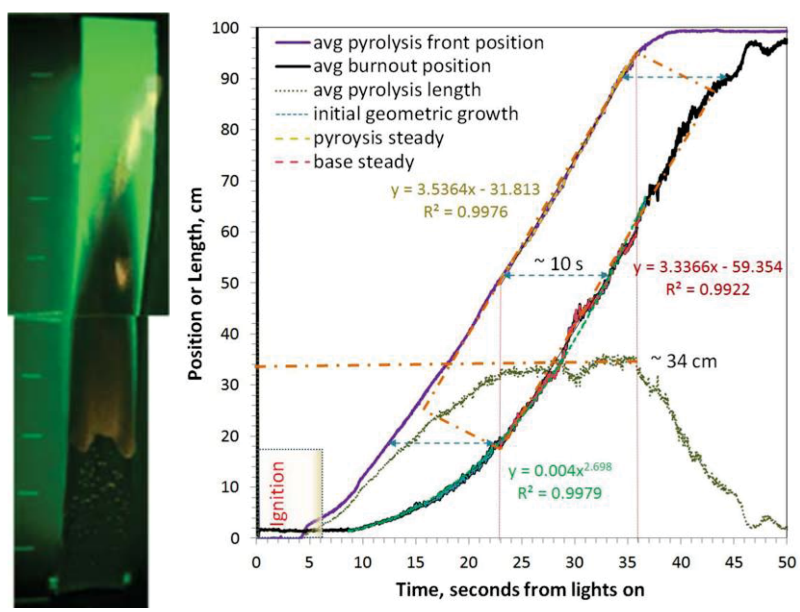

Figure 2. Flame tracking of the pyrolysis front (green-black border) and flame burnout position (bottom of flame) as a function of time for the steady-state flame case at 6.5 psia air with SIBAL fuel. The flame is shown on the left after the flame has reached a steady size. This growth to steady state flame size history is in very good agreement with [7,8]. Ref: [6].

The ULOI in 1g is defined as the oxygen concentration where 50% of the samples burn less than 6". For upward flame spread, the initial flame growth is acceleratory. Test 1 has been criticized for being an ignition limit test rather than a flammability limit test. Indeed, for many materials, the 6" pass/fail burn length criteria is too short for a 1g steady flame size. For thick fuels, the 25 second chemical ignition time may sustain a brief flame, but solid-phase conductive losses will be too large, and the flame will extinguish after the igniter burns out.

Ignition at the bottom of a vertical fuel sample results in a rapid acceleratory upward flame spread, as shown in Figure 2. For these conditions, (6.5-psia air test with 12.5 cm wide, 1 m tall SIBAL cotton-fiberglass fuel), a steady-state flame size was reached [6]. This was a near-limit atmosphere. Similar steady flame length trends for 5 cm wide samples were reported recently by Johnston et al. [7].

In theory [8], after the initial acceleratory flame spread, there is a stable flame length for upward spread for thin fuels, but it is difficult to attain for most practical fuel dimensions. In the work of Ref. [5] this stable flame spread was tracked and the flame image and tracking results are shown in Figure 2. Some interesting observations from this include that even for this relatively wide sample, the pyrolysis front is clearly parabolic in shape. The flame pyrolysis front rapidly achieves a steady-state spread rate of 3.44 cm/s. The flame base accelerates more slowly, but reaches the same spread rate by about 25 seconds (well beyond a 6" (15.2 cm) spread). The flame reaches a steady size of ~ 34 cm at this time, and maintains it until the pyrolysis front reaches the end of the sample. The flame base continues until burnout. At any point on the fuel surface, the time between the onset of pyrolysis and burnout remains constant ($L_f/V_f \sim 10$ s), also in good agreement with theory.

For a thick fuel [9] the flame spread rate V_f is proportional to the pyrolysis length, which accelerates at $x_p \sim t^2$. So for both thin and thick fuels, the initial growth phase is acceleratory. Test 1 achieves a blowoff extinction during this acceleratory growth phase of the flame, which occurs when the residence time of the premixed gases in the hot zone becomes too short for the reactions to occur, and the flame can no longer stabilize in the hot zone, but blows off the surface of the material. As the flammability boundary is approached, small perturbations can blow off the flame.

II: Extinction as a Poisson Process

Finding a flammability limit is not an easy task. The extinction process is stochastic, and the actual time to extinction will vary considerably with repeated tests under the exact same conditions due to the random timing of an encounter with a perturbation of adequate size to extinguish the flame. It is hypothesized here that the extinction process can be modeled as a Poisson process, which is a stochastic branching process where the spacing (in time or length) between consecutive independent events has an exponential distribution. This model is commonly used to describe exponential decay, and other processes. It is the simplest birth-death model, and we can apply it to an ignition-extinction process in a similar manner.

A Poisson probability is calculated as $$P(x,\lambda)=\frac{e^{-\lambda}\lambda^{x}}{x!}=\frac{e^{-Np}(Np)^{x}}{x!} \qquad (1)$$

In Equation 1, λ=Np is the mean number (and variance) of burns observed for N number of tests with a mean rate of burns of p. The mean rate of burns, p, is *selected* to achieve the desired determination of the flammability boundary. For example, if p is selected to be a mean rate of one burn per three tests (i.e. material fails Test 1), one would expect to find through repeated triplets of tests at decreasing oxygen concentrations, a flammability limit between the ULOI and MOC of Figure 1, which is deemed to be an acceptable intermediate limit between the two and is actually close to the 1/5 rate that is the basis of the MOC.

Also in Equation 1, x is the actual number of burns observed (since burns are undesirable, they can be considered a rare event when trying to determine the limit).

A cumulative Poisson probability, given in Equation 2, refers to the probability that the Poisson random variable x is greater than some specified lower limit and less than some specified upper limit.

$$P(x_{low} < x < x_{high}, \lambda) = \sum_{x=xlow}^{x=xhigh} \frac{e^{-\lambda} \lambda^x}{x!} \qquad (2)$$

Assume that for Test 1, we would like to define the flammability limit to be where the mean probability of observing a burn is p=1/5 (one in five tests on average), based on [1-3]. N=5 tests can be conducted, so that λ =Np. Figure 3 show the probability of observing one burn (one Test 1 failure), i.e. x=1, as a function of the value of this λ=Np. If we want to reduce the number N of tests needed to achieve the limit, we want to maximize the probability of finding the limit. Figure 3 shows that the maximum probability occurs at λ =Np= 1.

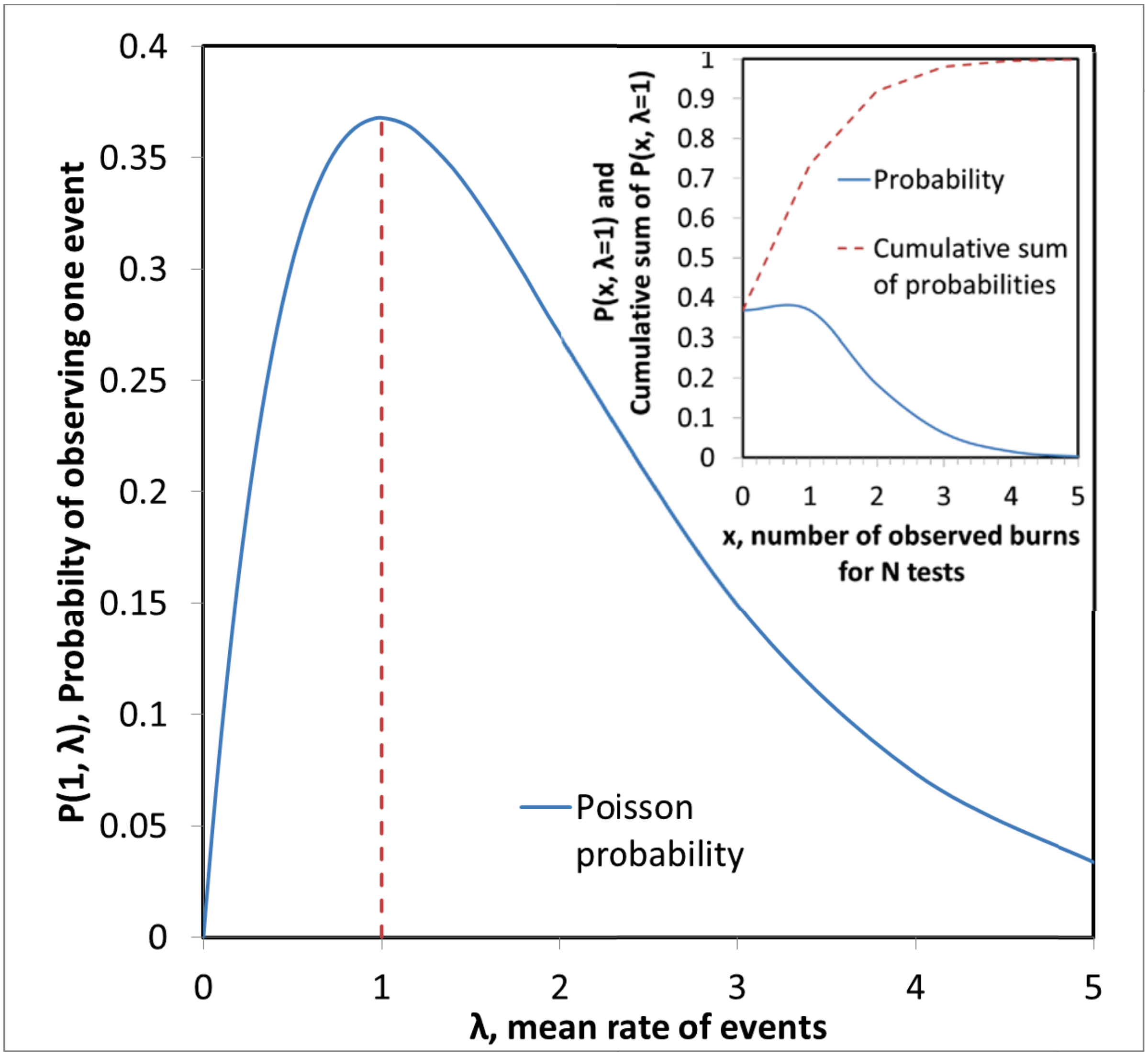

Figure 3: The Poisson probability of observing one event as a function of the mean rate, showing that the maximum probability is at λ=1. The inset shows the probability and cumulative probability of observing x burns for N tests if λ=1.

The inset to Figure 3 gives the probability and cumulative probability of observing x burns in N tests for λ=1. If p=1/5, and N=5, and the probability of observing x=0 burns in 5 tests is 0.3679 at this limit, and the probability of observing x=1 burn in 5 tests is also 0.3679, which is the maximum possible probability for Figure 3. It is a property of Equation 1 that the maximum probability occurs at both x=λ and x=λ-1. This 36.79% probability is simply 100/e where e is the Euler transcendental number (=~2.7183) characteristic of the normalized Poisson process. Thus p=1/5 and N=5 seem to be good choices for the mean rate of burns for defining a Test 1 limit to maximize the probability in a reasonable number of tests. The probability of observing one or fewer burns in Test 1 testing at the limit (i.e. the rate required to pass Test 1) is the sum of the probability of observing one burn plus the probability of observing no burns, for a cumulative probability of 73.6% via Eq.2.

We can estimate the maximum likelihood for the value of p for λ=Np, from a set N tests with measured values x_i where i=1…N. We can take the natural logarithm of Eq. 2 and then partially differentiate the distribution with respect to p,

$$\ln P(x_1.....x_N, Np) = -Np - NN + \ln(p)\sum_1^N x_i + \ln(N)\sum_1^N x_i - \sum_1^N \ln(x_i!) \qquad (3)$$

and set the derivative to zero to find the maximum likelihood estimate $\hat{p}$, which is simply

$$\frac{d(\ln P)}{dp} = -N + \frac{\sum_1^N x_i}{p} = 0 \qquad (4) \qquad\qquad \hat{p} = \frac{\sum_1^N x_i}{N} \qquad (5)$$

This maximum likelihood estimate $\hat{p}$ is also statistically the minimum variance unbiased estimator of p.

III: Poisson Distribution example: Test 1 and Test 4 Round Robin results

As part of the effort to evaluate the consistency of Test 1 and Test 4 [1] upward flame spread test results between different labs for flat and wire samples, six materials were tested and the burn length results compared [10, 11]. This data set provides a useful example for how to use the Poisson distribution to determine how close to the limit a material is under a given set of test conditions (O2, pressure). Three to five labs conducted the tests, each performing the test per the test protocol (N=5). The test conditions were standard test conditions, and not specifically near the ULOI or MOC for the materials.

If the desired failure rate at the limit is p=0.2 (i.e. 1/5 of tests so λ=1), we can compare that to the estimate value of $\hat{p}$ from Eq. 5. The closer the two p values, the closer to the desired limit. We can also estimate the probability of observing the actual failed tests (x) for the N tests reported (i.e. burn length > 15.2 cm) using Eq. 1. The higher the probability, the nearer to the desired flammability limit the material is at the test conditions. Table 1 shows that the highest probability was for the cotton fabric, which also had the closest to desired p values. The lowest probability was for Wire M22759 (Test 4), where 16 of 30 tests failed Test 4 standards (15.2 cm criteria also). The $\hat{p}$ was close to the ULOI of 0.5 for this wire.

Table 1: Test 1 and Test 4 Statistics, using data from [10, 11][4]

Poisson model parameter	Kydex 100 25.9% O2 14.3	Kydex 100, 30% O2, 10.2 psia	Silicone, 20.9% O2, 14.7 psia	Wire M22759 30% O2, 10.2 psia	Wire M81044 20.9% O2 14.7 psia	Royal Blue Cotton, Flame Resistant 30% O2 10.p psia
x, # failed Test 1	0	1	1	16	0	1
N, # Test 1 tests	20	35	45	30	35	20
p, mean failure rate	0.2	0.2	0.2	0.2	0.2	0.2
$\hat{p}$ estimate	0	0.029	0.022	0.533	0	0.05
P(x, λ=1)	0.018316	0.006383	0.001111	0.000334	0.000912	0.073262556

[4] Trade names or manufacturer's names are used in this paper for identification only. This usage does not constitute an official endorsement, either expressed or implied, by the National Aeronautics and Space Administration.

We can also use the burn lengths (l) reported [10, 11] as a measure of how close to the limit a material was at a given condition. We can graph the sorted normalized length (L=l/15.2 cm) against number of tests to compare the length distribution to a cumulative probability distribution like that shown in the inset to Figure 3. The sorted normalized length (L) is shown in Figure 4. The M22759 clearly fails the test and is above the flammability limit at the conditions (O2, pressure) listed in Table 1. Silicone, Kydex at 30%, and the cotton all have one failure. All the tests show a nice distribution of lengths. Based on these length distributions, all but the Wire M22759 appear to be below the flammability boundary. It is interesting that Wire M22759 still exhibits finite burn lengths well beyond the 15.2 cm and the average burn length is only 16 cm, which calls into question the appropriateness of that length as a criterion for flammability. This material may be very close to the ULOI. The length criterion does err on the conservative side, though, which is acceptable.

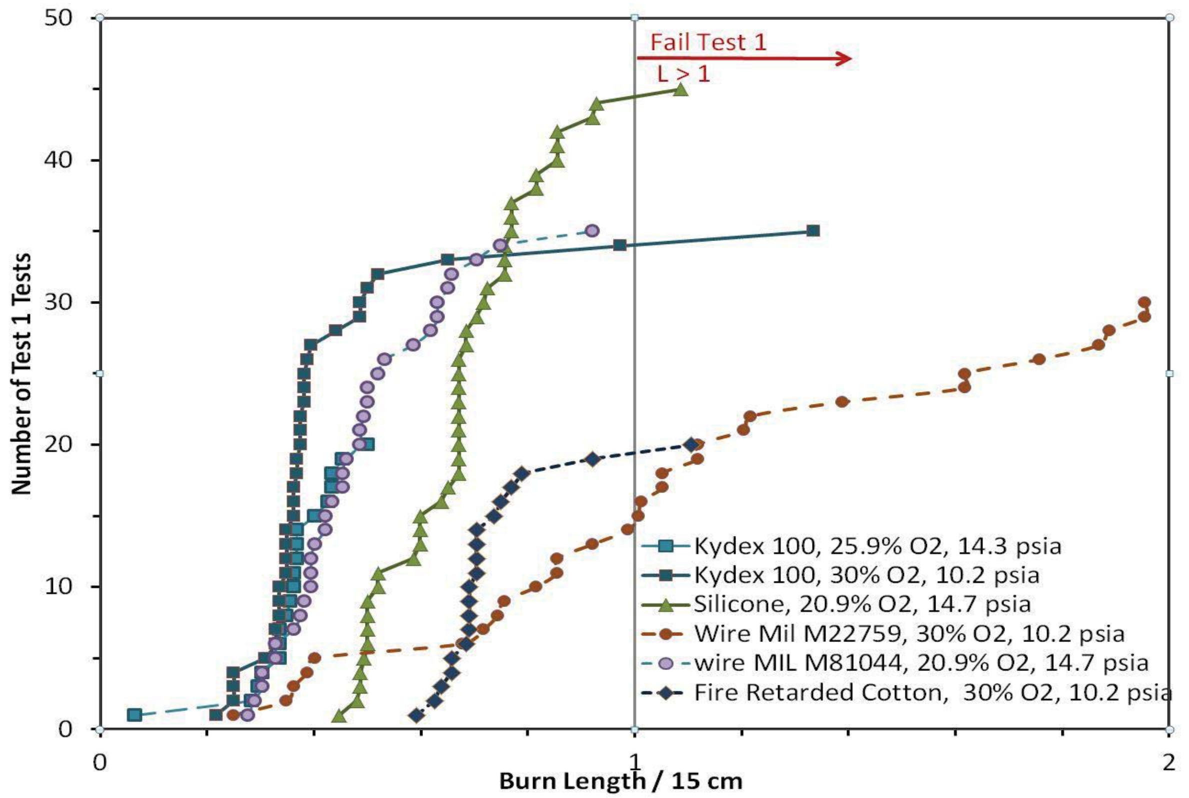

Figure 4: Round Robin burn length results [10, 11], sorted from low to high, to show the Poisson distribution character of the length data.

For each set of 5 tests (at a give atmospheric condition), the maximum likelihood estimate of $\hat{p}$ can be calculated to determine how close to the desired limit p that atmospheric condition is. The current recommended test protocol [2] has incremental changes in oxygen concentration of 1%. It is noted [12] however, that with very few exceptions, the MOC occurrs at an oxygen concentration of less than or equal to 3% below the ULOI. Using the maximum likelihood estimates, intelligently chosen larger increments of oxygen concentration can be made to approach the limit more efficiently.

In addition to the Round Robin data [10, 11], the effect of oxygen on the probability of failing Test 1 was published in [13]. In that paper, the ambient oxygen concentration was reduced in 1% increments and the probability of failing Test 1 was reported for Kydex 100 and Nomex materials. This data is plotted in Figure 5. It is interesting that for each material, the ΔO_2 is 5% from zero probability to unity, or approximately 2.5 from zero to 50% probability, corresponding to the ULOI-MOC difference. Figure 6 replots this data by normalizing the oxygen concentration with the oxygen concentration where the reported probability of failure is 0.2. The two materials overlap fairly well. Similar trends as Figures 4 and 5 for burn length and oxygen concentration for Kydex 100, Conathane, silicone rubber, and Lexan are found in [14].

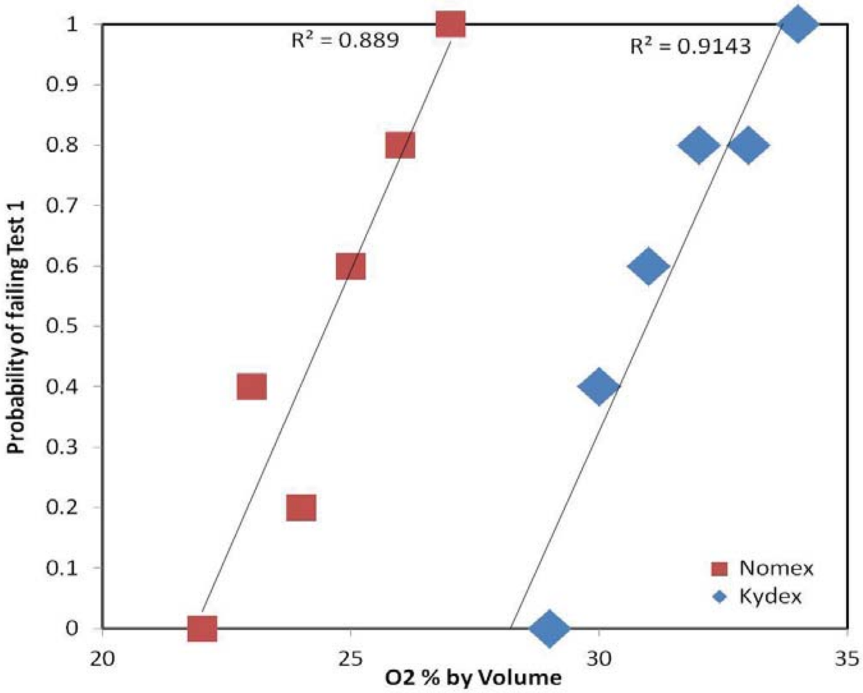

Figure 5: Probability of failing Test 1 for two materials as a function of ambient oxygen concentration by volume. [13].

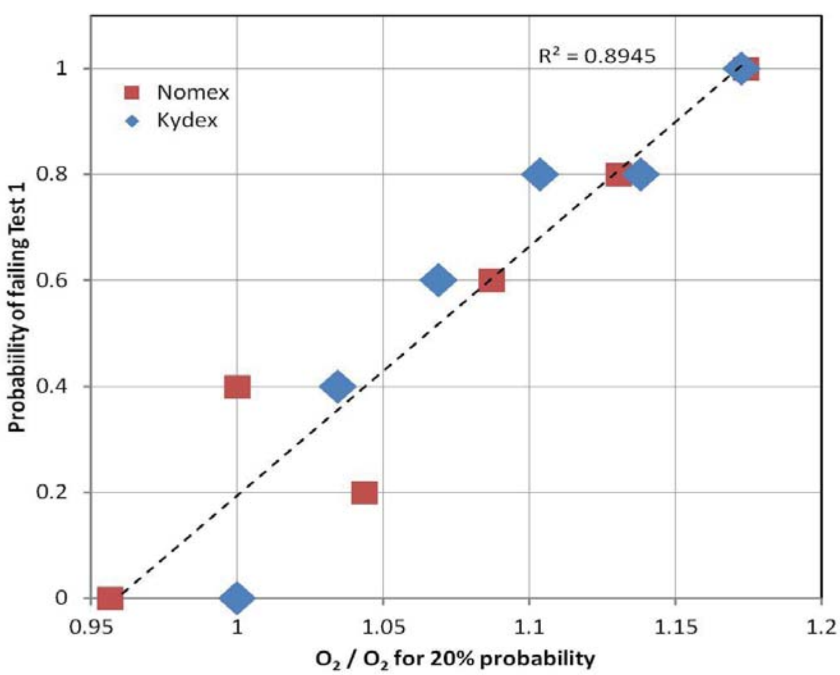

Figure 6: Replotting Figure 5 data by normalizing the oxygen with the oxygen concentration where the probability is 0.2, the desired failure rate to determine a flammability limit for a material.

IV: Proposed Normoxic Upward Limiting Pressure (NULP)

Typical NASA Test 1 test conditions are selected at a fixed pressure, and oxygen concentration is decreased for each set of five tests until the desired failure rate is observed (one in five tests burns more than 15.2 cm) [1, 3, 15]. However, we can utilize the fact that except for EVA suits (which are a special case), all spacecraft will operate in a band around the normoxic atmosphere condition. The normoxic atmosphere is where the partial pressure of oxygen is held constant at Earth normal (ppO_2=21 kPa), and the total pressure is varied by changing the relative amount of diluent. Human lungs require an adequate partial pressure of oxygen to provide an adequate concentration gradient to support diffusion of oxygen across the alveoli into the capillary blood flow. Material flammability, on the other hand, is a function of both pressure and oxygen.

If we can limit the flammability test parameter space to the control band around the normoxic condition, this makes the evaluation of material flammability limits simpler since they don't need to be evaluated over the entire classic pressure-O_2% range, but just in the narrow normoxic band of conditions.

This is shown in Figure 7 for 11 different spacecraft materials MOC limits [16]. As is clear from this figure two materials, PTFE and PCTFE (yellow lines), are not flammable in any spacecraft normoxic atmospheres and 6 materials are flammable under all normoxic atmospheres (grey lines). Only 3 materials

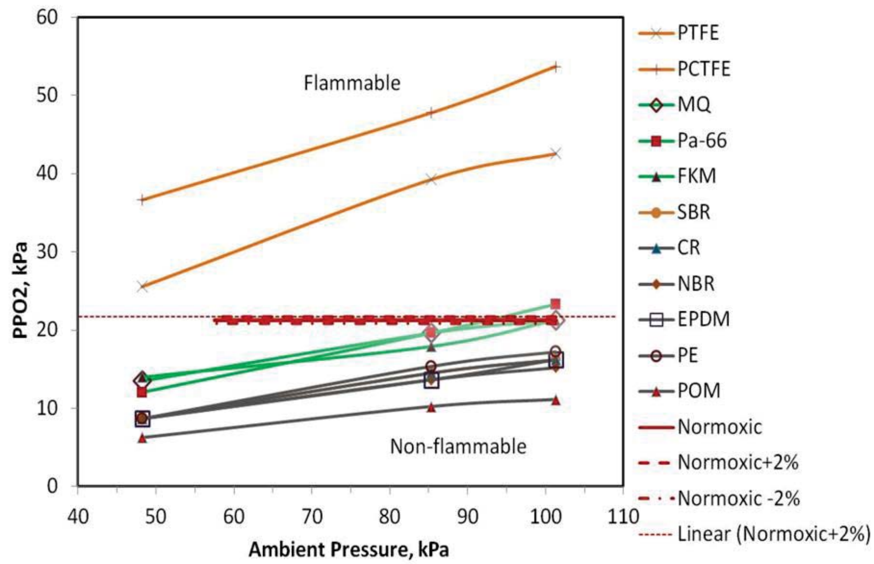

Figure 7: Material MOC flammability limits plotted with pressure and partial pressure of oxygen. A second x axis reflects the oxygen concentration at each pressure. The spacecraft normoxic atmosphere control band is shown in red shading. Data from [16].

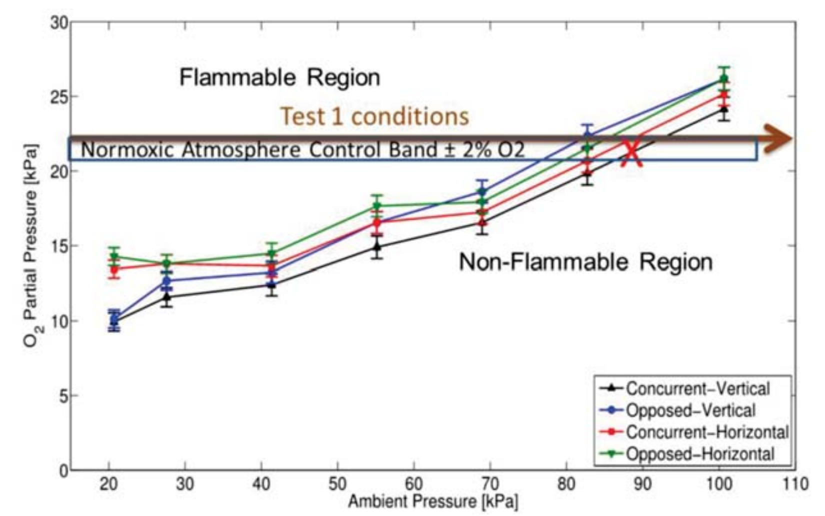

Figure 8: Figure from [17] for Nomex HT-9040 in a flow duct. Normal gravity flammability boundaries as a function of partial pressure of oxygen and ambient total pressure. The normoxic atmosphere control band for exploration spacecraft atmospheres is shown by the rectangle. The red X marks the upward (concurrent) flame spread limit conditions for the material. The arrow indicates the direction of Test 1 conditions to determine this limit.

(green lines) cross over from the non-flammable or marginally flammable at higher ambient pressures to flammable at lower ambient pressures relative to the normoxic control band.

Where the material crosses the upper limit of the spacecraft normoxic control band (±2% on the fixed partial pressure of oxygen) can be considered the Normoxic Upward Limiting Pressure (NULP). At pressures above this, the material is not flammable. In Figure 7, all three green line materials (MQ, PA-66, FKM) have NULP values of up to 101.3 kPa. Notice a second x axis provides the ambient oxygen concentration by volume for each pressure.

Published data [17] for Nomex HT-90-40 indicates that the NULP in 1g is approximately 90 kPa for the concurrent vertical worst case test geometry, most similar to NASA's Test 1. This data is shown in Figure 8 with the normoxic atmosphere control band added.

The general trend for all these materials shown in Figures 7-8 is for flammability to be worst at the lower total pressures for fixed partial pressure of O_2, which corresponds to the highest % O_2. So it makes sense to start at the lowest expected total pressure for a spacecraft (8.2 psia exploration atmosphere, excluding EVA environments which are a special case), and run constant partial pressure of oxygen Test 1 tests there. If the material passes at that atmosphere, it is safe for all higher pressure atmospheres as well. If it burns at that atmosphere, increase the total pressure along the high normoxic control band until the material passes Test 1, thus defining the NULP for the material in a much smaller test parameter space. For each pressure tested, evaluate the $\hat{p}$ to determine how close to the desired p limit the pressure is. The same ≤ 3% oxygen guide can be used to inform the increments in pressure to optimize the test matrix.

Once the NULP is determined, then, a safety factor (SF) can be incorporated to define under what normoxic atmospheres the material is safe for use in space. This is the μNULP = NULP + SF (where SF is on the order of 10 kPa, based on existing flammability data).

V: Ignition Limits versus Flammability Limits

For flame spread over solid fuels, the characteristic time for extinction is often dictated by the solid-phase response time, since gas-phase reaction times are typically much faster than solid phase response times. For a thin fuel, the characteristic response time is $\tau \sim L_f/V_f$.

For thick fuels, the characteristic time is a solid phase conduction time, estimated using ℓ^2/α_s where ℓ is the characteristic thickness of the material (a half-thickness, a solid-phase conduction length), and α_s is the solid phase thermal diffusivity. It should be noted that the ignition time should exceed this characteristic time so that the sample is adequately heated to sustain a flame without undue heat losses to the cold solid. Depending on the thickness of the solid this time can become quite long, and the existing Test 1 igniter, which only lasts for 25 seconds, may not be adequate.

Using the thermal diffusivity of PMMA (1.2×10^{-3} cm^2/s) as representative of plastic materials, the critical thickness for a Test 1 ignition is ~ 3 mm (1/8'). The thicker the sample, the longer it takes to heat it to a sustained ignition. A flame may appear while the igniter is on, but extinguish as soon as the igniter is off, due to excessive heat losses to cold material. It is thus possible to pass Test 1 with a material that is thick enough so that the observed limit is actually an ignition limit, and not a flammability limit. There have been cases where if the test is run and the material fails at the worst case thickness [1], they then run the test at the use thickness to support the Materials Usage Agreement. The material must be reasonably close to the flammability limit to pass at the use thickness while fail at the worst case thickness.

On the other hand, if the igniter is on long enough, it preheats the material which will sustain a too-weak flame for some time after the igniter is turned off until the material cools back down, or the flame moves out of the preheated region. It is be possible for the flame to exceed the 15.2 cm in the 25 s ignition time, resulting in a failure due to an overdriven ignition. The best practice for evaluating materials for flammability rather than ignitability is matching the ignition time to the solid phase response time, which for the current chemical igniter is estimated to be ~3 mm thick material to evaluate the intrinsic flammability of the material.

VI: Conclusions

A material's flammability boundary is shown here to be a fuzzy boundary due to the stochastic nature of the flame spread and burning processes near extinction. The probability of a near-limit flame extinguishing within a characteristic length is shown to follow a Poisson distribution that can be used to understand the variation in reproducibility found for near-limit tests.

This Poisson process trend suggests that rather than define a ULOI and MOC for Test 1 (which requires two limits to be determined), it might be better to define a single upward limit as being where one sample out of five tests fail the test (and burn). The limit is approached from the flammable side, so that statistics on the burns at each test condition can be used to evaluate the proximity of the limit. This is shown to optimize the probability of achieving the desired low average burn rate in the fewest number of tests.

To further reduce the number of Test 1 tests required to screen a material, it is recognized that spacecraft atmospheres will not bound the entire oxygen-pressure parameter space, but actually lie along the normoxic atmosphere control band. Test 1 tests can thus focus the materials flammability testing along this normoxic band. A Normoxic Upward Limiting Pressure (NULP) is defined that determines the minimum safe total pressure for a material within the constant partial pressure control band. Then, increasing this pressure limit by a factor of safety, we can define the material as being safe to use at the μNULP= NULP + SF.

Lastly, it is recommended while evaluating materials for flammability that the ignition time should be matched to the solid phase response time. It is estimated that the thickest material to be tested with the current Test 1 igniter should be 3 mm thick (1/8") to avoid the problem of differentiating between an ignition limit and a true flammability limit.

VII: Acknowledgements

The authors would like to acknowledge support from NASA as part of the international JAXA AO to support the International Fire Safety Standard Experiment "FLARE".

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