REVISED NFPA CUP-BURNER TEST METHOD: IMPROVING REPRODUCIBILITY

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Abstract. NPFA 2001 *Standard on Clean Agent Fire Extinguishing Systems* requires that flame extinguishing concentrations of gaseous agents for flammable liquid fuels be determined using the cup-burner test method. Other national and international standards have the same requirement. Critical examination of extinguishing concentration data published in various standards indicates significant inconsistencies. Accurate and reproducible determinations of flame extinguishing concentration values are important in establishing a consistent level of design safety for total flooding fire extinguishing systems. In November 2003 the NFPA 2001 technical committee formed a Task Group to develop an improved version of the cup-burner test method with the objective of achieving a high degree in reproducibility among investigators. This paper summarizes (a) the theoretical and experimental basis for a highly reproducible test method, (b) the work of the Task Group in development of a revised test method and apparatus, and (c) preliminary findings from an inter-laboratory study.

Introduction. Fire extinguishing systems using gaseous agents are in very wide use. The array of hazard types protected is broad but hazards are classified as either Class A or Class B. NFPA 2001, and other national and international standards, base the determination of the minimum agent design concentration on the results of specific test protocols. The Class A fire test protocols among the several standards involve similar, but not identical, large scale tests usually conducted in an enclosure of at least 100 m^3 volume. These several standards call for Class B fire test protocols that involve determination of minimum flame extinguishing concentrations, MEC, on both large scale tests (pan sizes vary slightly) and but the cup-burner test. Heptane is used as a reference fuel on both large scale and cup-burner tests. MEC values of Class B fuels vary depending on fuel properties. The standards make the provision that for fuels other than heptane the MEC as determined by the cup-burner method shall be used.[1] The cup-burner test method, however, has not

[1] NFPA 2001 (2004): "5.4.2.1 The flame extinguishing concentration for Class B fuels shall be determined by the cup burner method described in Annex B." ISO 14520-1 (2006): "7.5.1.2 The minimum Class B design concentration for each extinguishant shall be a demonstrated extinguishing concentration for each Class B fuel plus a safety factor of 1,3. The extinguishing concentration used shall be that demonstrated by the cup burner test, carried out in accordance with the method set out in Annex B, that has been verified with the heptane pan tests detailed in C.5.2. For hazards involving multiple fuels, the value for the fuel requiring the greatest design concentration shall be used. The extinguishing concentration shall be taken as the cup burner value or the heptane pan test value (see Annex C), whichever is greater.

been standardized in a manner consistent with its important role in standards making. It has been shown that MEC values reported in various standards are not consistent, a state that can lead to variability in specification of minimum design concentrations (MDC) in otherwise identical applications. An analysis has been made of the dependency of inert gas MEC values to show that (a) inert gas MEC values depend solely on heat capacity effects, (b) MEC values reported by investigators show a similar high degree of self-consistency and agreement with the capacity model but do show some inconsistency among investigators, and (c) MEC values reported in standards show greater inconsistency with expected behavior (Senecal). The root cause of inconsistencies in the inert gas agent MEC database is very likely due to variability in the application of the cup-burner method. There is no reason to expect that MEC data for fluorochemical agents is free from similar inconsistencies. Establishing an accurate and consistent MEC database is most important with respect establishing a consistent minimum level of performance of gaseous fire extinguishing systems in Class B applications. This paper describes a work in progress to revise the cup-burner test method with the goal of improving the reproducibility of test results reported by various laboratories.

Theoretical and experimental basis for consistent MEC measurement. A reasonable question is whether or not the cup-burner test method has the potential to have the high degree of reproducibility necessary to support the fire protection industry's needs. The first step in addressing this question is to establish a theoretical basis for MEC values and then to validate that extinguishing data obtained in a self-consistent manner, i.e., within a single laboratory, conforms closely to the model.

Inert gas extinguishing agents lend themselves to a simple theoretical analysis as the extinguishing function is based on agent physical properties only, namely heat capacity. The relationship between extinguishing concentration, expressed as a mole fraction of agent in air, and the properties of both inert gas agent and a given fuel are as follows:

$$X_G = \frac{\dfrac{Q - \Delta H_P}{\Delta h_G}}{4.76\left(n + \dfrac{m}{4} - \dfrac{y}{2}\right) + \dfrac{Q - \Delta H_P}{\Delta h_G}} \qquad \text{Eq. 1}$$

and where Q is the fuel heat of combustion, ΔH_P and Δh_G are the enthalpy changes of the normal combustion products and inert gas agent, respectively, when heated from initial conditions to the extinction limit temperature (Senecal). These terms are defines\d as follows:

$$\Delta H_P = \sum_{i=1}^{I} \nu_i \int_{298}^{T_{Ex}} C_{P,i}\, dT \qquad \text{Eq. 2}$$

where the summation is over all normal combustion product species, i.

$$\Delta h_G = \int_{298}^{T_{Ex}} C_{P,G}\, dT \qquad \text{Eq. 3}$$

Equation 1 indicates that, for a given fuel for which an MEC (MEC, vol.% = 100X_G) is known for any one inert gas agent, the MEC of any other inert gas agent is completely predicable. The validity of Eq. 1 was firmly established by examination of a set of cup-burner MEC data obtained in one lab using six different inert gases. A measured value of MEC for nitrogen for n-heptane flames served as the benchmark to predict the MEC values for the five other gases. These results and the measured MEC values are given in Table 1.

Table 1
Predicted and Measured Inert Gas Extinguishing Concentrations. Fuel: n-Heptane

Agent[2]	MEC Pred. mol %	MEC Meas. mol %	Rel. Diff. %	$C_{P,\,298}$ J/mol-K
IG-01	42.4	42.5	0.2	20.8
IG-55	36.4	36.4	0.1	24.6
IG-541	34.2	34.3	0.4	26.1
IG-100	Ref.	31.9	-	28.5
N_2/CO_2:92/8	30.7	30.2	1.5	29.2
CO_2	22.0	20.9	5.2	37.5

$C_{P,\,298}$ values are given for reference.

As is evident from Table 1, the predicted and measured values of MEC are in very close agreement thus (a) validating the model as represented by Eq. 1, and (b) establishing the ability to obtain highly consistent cup-burner measurements, at least within one lab.

NFPA Task Group on the Cup-Burner method. The NFPA technical committee recognized that the guidance given in *NFPA 2001 Standard on Clean Agent Fire Extinguishing Systems* required that the cup-burner test method be used to determine flame extinguishing concentrations of gaseous agents was not consistent with the apparent ability of the test method, as currently practiced, to yield consistent results from different laboratories. A Task Group was appointed in November 2003 with the charge to:

> "… review the NFPA 2001 Appendix B cup burner method for determination of flame extinguishing concentrations of Class B fuels with the goal of recommending revisions to Annex B which would improve the test method with respect to (1) inter-laboratory reproducibility, and (2) consistency of results with best available theory;"

[2] Agent compositions: IG-01: argon; IG-55: 50% argon, 50% nitrogen; IG-541: 52% nitrogen, 40% argon, 8% carbon dioxide; IG-100: nitrogen; N_2/CO_2:92/8, 92% nitrogen, 8% carbon dioxide.

The Task Group appointees were:

- Joe Senecal, Kidde-Fenwal, Manufacturer, Task Group Chair
- John Owens, 3M, Manufacturer
- Ingeborg Schlosser, VDS, Insurer
- Soonil Nam, FM Global, Insurer
- Ron Scheinson, U.S. Navy, User
- Mark Robin, Hughes Associates, Special Expert
- Mitch Hubert, Tyco, Manufacturer
- Howard Hammel, DuPont, Manufacturer

The TG composition of four manufacturers, two insurers, one user, and one special expert provided a balance of interests. Additionally, the TG chairman asked three additional special experts to act as consultants to the project. These were Dr. Richard G. Gann and Dr. Greg Linteris of NIST and Dr. Fumiaki Takahashi of the NASA Glenn Research Center. Dr. Gann has an extensive history related to fire and extinguishing science. Dr. Linteris also has extensive experimental and modeling experience in combustion processes. Dr. Fumiaki is an expert on modeling of flames and extinction with recent publications on cup-burner flames in particular.

Approach to developing a revised test method. The cup-burner test method as described in NFPA 2001 Annex B (2004) provides a general framework for testing. As written it lacks several features that are common similar types test standards in wide use. Preece et al, among others, have shown that cup-burner results can be affected by several factors in the test method that must be carefully controlled. The ASTM style of standard test method was used as a model to frame a revised cup-burner method. In particular features of the new standard were incorporated to address calibration, standardization, interferences, safety precautions, details related to apparatus, air and fuel supply, procedural details for both liquid and gaseous fuels, determination of agent minimum extinguishing concentration (MEC), minimum number of replicate tests, statistics on reporting of the MEC, and elements of a test report.

Test procedure development. An initial draft, Rev 0, of a revised test method was prepared by the chairman and distributed to the TG members in early April 2004. The TG met in Albuquerque on May 3, 2004 and reviewed the approximately 120 comments on the Rev 0 draft. Nearly all comments and recommendations were adopted in preparation of a Rev 1 version of the test method which was again sent to the TG members for review in October of 2004. Approximately 20 additional recommendations were received which were incorporated into a final draft, Rev 2, that was submitted to the NFPA 2001 technical committee as a public comment in July of 2005.

Standardized cup-burner apparatus. At the Rev 2 stage the revised cup-burner test method still had not addressed standardization of the actual cup-burner apparatus itself. Differences in test apparatus might well be expected to have an influence on lab-to-lab reproducibility. Each laboratory has its own cup-burner which may have design and fabrication differences among them. In particular, one cup-burner system was know to have a cup diameter only 5/8 that of the design recommended in NFPA 2001 Annex B[3]. Certain considerations were viewed as very important in

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[3] The 5/8-scale cup had, therefore, an exposed liquid surface area of about 0.39 that of the standard size cup.

developing a new standard cup-burner design. A new standard apparatus should be able to be assembled from readily available components to the extent possible; replacement parts must be obtainable; assemble and disassemble for cleaning should be simple. A new cup-burner design was developed and proposed to the TG in August 2005. A prototype cup-burner assemble was constructed and displayed at the September 2005 meeting of the newly formed NFPA GFE-AAA technical committee on Gaseous Fire Extinguishing Agent Systems responsible for NFPA standards 12, 12a, and 2001. The consensus of the technical committee was that the design appeared to be reasonable and should be adopted into the revised standard. The engineering details of the revised cup-burner design were submitted as a public comment to the NFPA GFE committee which was formally adopted at the committee's meeting in April 2006. The public comment submitted to NFPA GFE-AAA committee is given in Annex A.

In October of 2005 the availability of the new standard NFPA cup-burner apparatus was advertised to an array of likely interested parties. As of May 2006 a total of 13 identical NFPA standard cup-burner systems were constructed and distributed to interested laboratories. This level of interest in the new standardized apparatus has to be viewed as gratifying given that historically only a few laboratories have been active in making and reporting cup-burner extinguishing data.

Standardization and calibration. The efforts to date by the cup-burner Task Group have delivered a highly specified test method and test apparatus. This progress is not in itself sufficient, however, to assure meeting the original goal which is to improve inter-laboratory reproducibility to a level comparable to intra-laboratory repeatability in making measurements of flame extinguishing concentrations of gaseous agents. What remains is the design and execution of an inter-laboratory study, or "round robin" test program, for the purpose of determining the reproducibility of the new test protocol. To that end a Cup-burner Users Group has been formed that will continue to support the mission of the NFPA Task Group. An initial draft of a round robin test program was prepared and submitted to the Task Group for comment. Feedback was incorporated into a revised test program which is shown in Annex B. The essential elements of the inter-laboratory study are to assess an inert gas agent (nitrogen) and a fluorocarbon gas agent (HFC-227ea) against three flammable liquids (n-heptane, 2-propanol and toluene) .

An important element of the round robin test program will be objective analysis and reporting of the data submitted by participating parties. Kathleen Almand has offered the offices of the Fire Protection Research Foundation to serve the role of an unbiased party to receive analyze and report on the work of the inter-laboratory study. The schedule of the inter-laboratory study is expected to be set at a meeting of the members of the Task Group and the Users Group on May 15th.

Open issues. Upon completion of the inter-laboratory study a number of questions remain.

1. When there is consensus on the extinguishing concentrations of the reference agents for the reference fuels how are these results used to assess data from a single laboratory for a non-reference agent on a reference fuel, or, more importantly, the extinguishing concentration of a non-reference agent on a non reference fuel?
2. Exactly haw are the benchmark data to be used to as a basis of calibration for cup-burner measurement of any agent with any fuel?
3. How should extinguishing data be reported from a statistical perspective?

4. If an MEC value is reported with a tolerance, e.g., 7.0 ± 0.3%, how do the user and standards communities interpret that value with respect to specifying an agent minimum design concentration?

Summary. National and international standards reference the cup-burner test method as a basis for setting the minimum design concentration of a gaseous agent for flammable and combustible liquid fuels. Examination of extinguishing data published in standards indicated that extinguishing data exhibit inconsistencies with respect to theoretical expectations. Inert gas extinguishing data obtained in a consistent manner is shown to agree exactly with theory. That history served as a basis for the NFPA GFE-AAA committee to appoint a Task Group to investigate development of a revised cup-burner test method that would be sufficiently reproducible to serve the interests of the standards making community. The Task Group produced a highly specified test procedure and re-designed cup-burner apparatus that has been adopted into the current draft revision of NFPA 2001 through the ROC stage of the revision process. An inter-laboratory study has been designed. The number of participants and schedule for completion are undetermined at this writing. Additionally, several matters relating to implementation of new extinguishing data remain to be addressed.

Nomenclature.

C_P	Heat capacity at constant pressure, J/mol-K
Δh_G	Enthalpy change of inert gas agent, kJ/mol inert gas
ΔH_P	Enthalpy change of normal combustion products, kJ/mol fuel
MEC	Minimum extinguishing concentration
Q	Heat of combustion, kJ/mol fuel
T_{Ex}	Extinction limit temperature, K
X_G	Mole fraction in air of added inert gas agent at the MEC
m, n, y	Atom coefficients for a $C_mH_nN_xO_y$ type fuel

References

ISO 14520-Part 1, "Gaseous fire-extinguishing systems - Physical properties and system design," International Organization for Standardization (2005).

NFPA 2001, "Standard for Clean Agent Fire Extinguishing Systems," National Fire Protection Association, Quincy, MA (2004).

Preece, S.; Mackey, P.; Chattaway, A, "Cup Burner Method: A Parametric Analysis of the Factors Influencing the Reported Extinguishing Concentrations of Inert Gases," HOTWC Proceedings (2003).

Senecal, Joseph A., "Flame extinguishing in the cup-burner by inert gases," *Fire Safety Journal*, Volume 40, Issue 6, pp. 579-591 (September 2005).

Annex A

Public Comment to NFPA GFE-AAA Committee on the NFPA Standard Cup Burner Apparatus

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Document title: Standard on Clean Agent Systems

NFPA No. & edition: 2001 (2004)

Section / paragraph: Fall 2005 ROP Log #4 – Annex B figures

Comment. The Technical Committee accepted the proposal of Log #4 to substitute a revised cup-burner procedure for the existing Annex B procedure. The revised cup-burner method did not include a recommendation for a revised cup-burner apparatus design Subsequent to the submittal of Log #4 a sub-Task Group prepared a revised design for a standard cup-burner apparatus. A prototype of the new design was displayed at the Burlington meeting. Attached are figures and a parts list of critical parts for use in fabricating a standard cup-burner system. By the time of the ROC meeting several labs will have acquired the cup-burner system shown.

Substantiation. Completion of apparatus section of Annex B as proposed in Log #4.

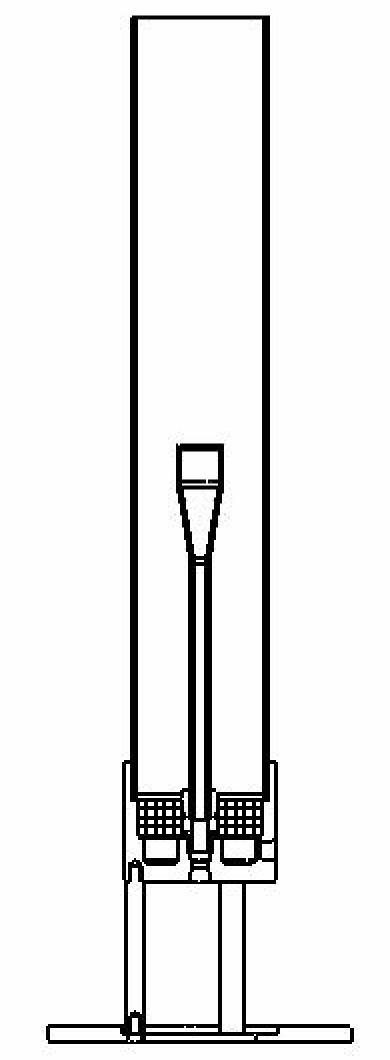

Figure A1. Cup-burner assembly.

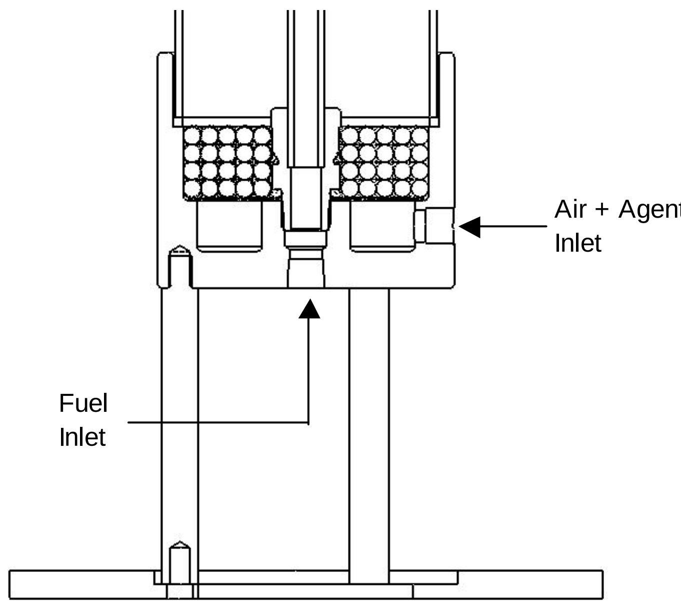

Figure A2. Base assembly, enlarged.

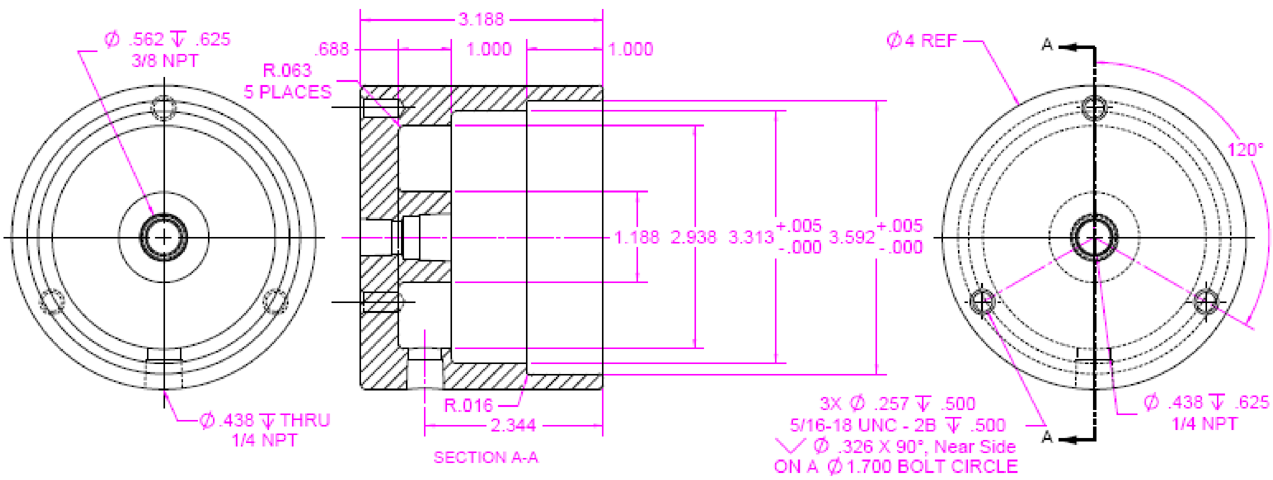

Figure A3. Cup-burner base. Material: Brass

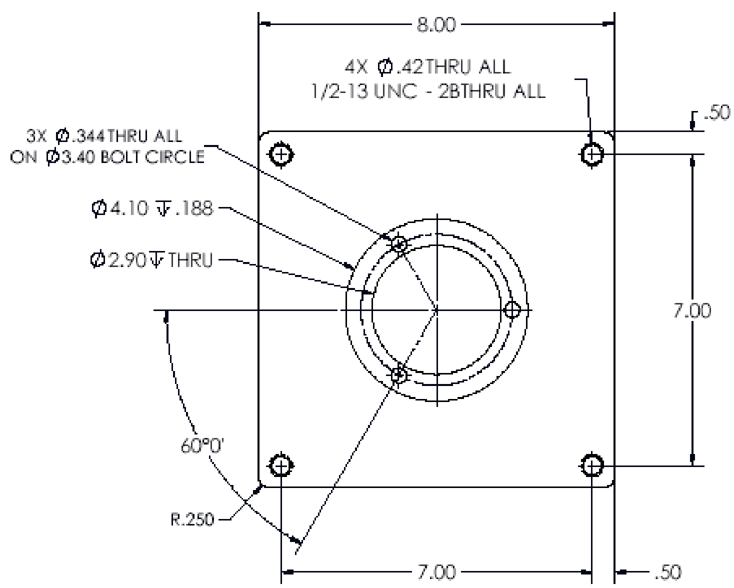

Figure A4. Cup-burner base support plate. Material: Brass, 0.38” thick

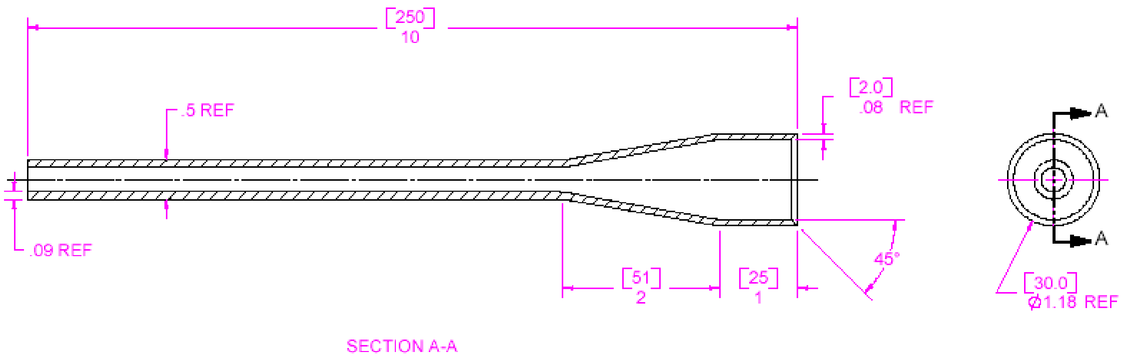

Figure A5. Cup. Material: Quartz

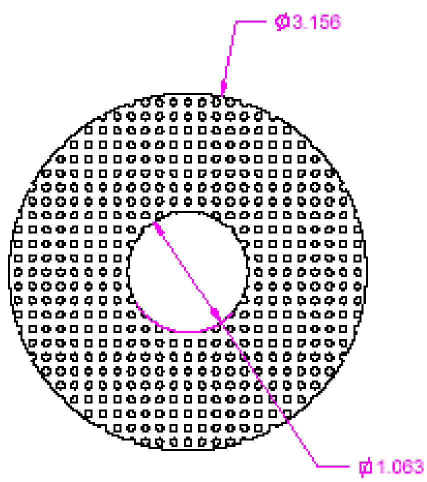

Figure A6. Diffuser bead support screen. Material: 304 SS. 0.030” thick.

Table A1. Cup-burner system major components

Component	**Specification**	**Supplier**
Cup-burner base	Design: per figure 2 Material: Brass	Custom fabrication
Cup-burner base support plate	Design: per figure 3 Material: Brass	Custom fabrication
Chimney	90 mm OD x 85 mm ID x 520 mm (nominal) Material: Quartz.	National Scientific Company, Inc. 205 East Paletown Road P.O. Box 498 Quakertown, PA 18951 USA
Cup	Design per figure 4 Material: Quartz	G. Finkenbeiner Inc,. 33 Rumford Ave., Waltham, MA 02453 or other laboratory glass fabricator
Adapter, NPT to glass tube	Swagelock p/n SS-8-UT-1-6, SS Ultra-Torr Male Connector, 1/2 inch Female Vacuum Seal Fitting - 3/8 in. MNPT	Cambridge Valve & Fitting, Inc. 50 Manning Road, Billerica, MA 01821.
Diffuser bead support screen	Design per figure 5 Material: McMaster-Carr p/n 9358T131. Type 304 Stainless Steel Perforated Sheet 36" X 40", .0625" Hole Dia, 23% Open Area, 22 Ga.	Custom fabrication
Diffuser bed beads	Diameter: 3 mm Material: glass	Fisher Scientific p/n 11-312A
Gasket, chimney-base	Buna-N Square O-Ring Cord Stock, 1/8" Fractional Size	McMaster-Carr p/n 9700K121
Support plate legs	Hex cap bolt, 1-1/4” 1/2-13 UNC , 4 ea.	Common
Connector screws, support plate-to-base	5/16-18 x 4" hex cap bolts, 3 ea.	Common
Support plate-to-base spacer sleeves	p/n M37 9mm OD x 89mm Material: Brass Custom cut to finish	K&S ENGINEERING 6917 West 59th Street Chicago, Illinois 60638

Annex B

NFPA Cup-burner Inter Laboratory Study – Rev 1, 31 March 2006

Procedure	NFPA 2001 Annex B ROP (Sep 2005) Draft cup-burner method	
Fuel No. 1	n-Heptane	Fisher Cat. No. O3008-1
Fuel No. 2	2-Propanol	Fisher Cat. No. A416-1
Fuel No. 3	Toluene	Fisher Cat. No. T324-1
Agent No. 1	Nitrogen	99.9% min
Agent No. 2	HFC-227ea	from agent manufacturer
No. data points per trial	Report each result of 5 consecutive determinations per trial	
No. trials per fuel	3, each on separate day, same operator	

Report results to:

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