

DEVELOPMENT OF A STANDARD PROCEDURE FOR THE EVALUATION OF THE PERFORMANCE OF CLEAN AGENTS IN THE SUPPRESSION OF CLASS C FIRES

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ABSTRACT

At a recent meeting of the NFPA 2001 Technical Committee, Comment ROC 2001-61a (log #CC7) was proposed, and after much debate, accepted by the Committee. Comment ROC 2001-61a would require that the minimum design concentration for a Class C hazard be increased from the current level of 1.2 times the Class A minimum extinguishing concentration to 1.6 times the Class A minimum extinguishing concentration for scenarios in which the power dissipation from an electrical circuit failure is not likely to exceed 1500 W continuous. Higher concentrations would be required to be specified for scenarios in which the power dissipation from an electrical circuit failure exceeds 1500 W continuous.

In this paper we discuss the implications of ROC 2001-61a, and discuss in detail the tests which have been cited as justification for ROC 2001-61a. It is concluded that neither field experience over the past 15 years, nor the cited tests justify the far-reaching changes that would result from the acceptance of ROC 2001-61a. The cited tests suffer from numerous shortcomings, e.g., poor reproducibility, questionable relationship of test configurations to real world fire scenarios, etc., and these shortcomings are discussed in detail.

Following this review of past efforts, we present the results of our recent suppression testing of clean agents on electrically energized components. These tests employ configurations believed to be representative of real world hazards, and avoid the shortcomings of the previously reported studies. There is currently no standard test method available for the evaluation of the performance of suppression agents on fires involving electrically energized equipment, and it is anticipated that these tests can serve as the basis for the development of such a standard test method.

CLASS C FIRES

INTRODUCTION

Section 3.3.4.3 of *NFPA 10 Standard for Portable Fire Extinguishers* defines Class C fires as "Fires that involve energized electrical equipment." Class C fires are of concern due to the fact that in some applications power disconnection is highly undesirable due the magnitude of the financial impact associated with system downtime.

As discussed by Robin and McKenna¹, service interruptions are a major concern in telecommunication facilities due to the unique nature of the information processing performed in such facilities. Telecommunication systems are on-line information exchange systems: the system does not store or process customer data, but merely transfers the data from one point to another. When a service disruption occurs, all information in transit is lost. This contrasts to the case of data processing centers, where data is stored in the systems memory, and during an interruption only that data which has not yet been placed in permanent memory (i.e., disks, tapes) is lost.

The financial impact of service disruptions can be significant in both telecommunications facilities and in data processing centers². The estimated downtime impact per minute for various business applications is shown in Table 1. The downtime impact for a typical computing infrastructure is estimated at \$42,000 per hour. Downtime impacts for companies relying entirely on telecommunications technology, such as online brokerages or e-commerce sites can reach \$1 million per hour or more^{3,4}, as shown in Table 2. On June 14, 1999 the popular Internet auction site e-bay saw its stock value plummet by \$4 billion dollars due to a 22 hour outage, every hour of downtime resulting in an estimated \$200,000 loss in sales. A 75 minute outage at e*trade resulted in its stock dropping by \$6.50 per share (\$1.5 billion total value) and a 19 hour outage at America on Line (AOL) resulted in its stock dropping by \$4.50 per share (\$4.8 billion total value).

Table 1: Downtime Impact per Minute for Various Business Applications

Business Application	Estimated Outage Cost per Minute
Supply Chain Management	\$11,000
Electronic Commerce	\$10,000
Customer Service Center	\$3,700
ATM	\$3,500
Financial Management	\$1,500
Messaging	\$1,000
Infrastructure	\$700

Source: Alinenan ROI Report, January 2004 (Reference 2).

Table 2. Service Disruption and Stock Value

Company	Service Disruption, hours	Stock Value
e-bay	22	down \$4.0 billion

¹Robin, M.L. and McKenna, L., *Fire Protection Considerations for Telecommunication Central Offices*, International Fire Protection Magazine, Issue 22, May 2005.

²Alinenan ROI Report, January 2004; <http://www.alinean.com/Newsletters/2004-1-Jan.asp>

³Robin, M.L., *Fire Protection in Telecommunication Facilities*, Process Safety Progress, 19, 107 (2000).

⁴Freedman, R.E., *It Wasn't a Hurricane or an Earthquake, But For Some E-Commerce Businesses It Might As Well Have Been*, Disaster Recovery, Summer 1999, p. 26. ; <http://www.drj.com/articles/sum99/free.htm>

AOL	19	down \$4.8 billion
e*trade	1	down \$1.5 billion

Source: Reference 4.

PROTECTION OF CLASS C HAZARDS

NFPA 2001 (2004 edition)

As discussed above, in applications such as telecommunication facilities and data processing facilities, power disconnection is highly undesirable due the magnitude of the financial impact associated with system downtime. As a result, the possibility exists for the occurrence of Class C fires in these facilities, i.e, fires involving energized electrical equipment. Such fires could involve both energized electronic equipment and energized wiring.

Due to their unique combination of properties, clean agents are often employed for the protection of telecommunication facilities and data processing centers. In fact, telecommunication and electronic data processing applications represent the major use of the clean agents, corresponding to approximately 80 percent of clean agent applications. The clean agents are low in toxicity, provide efficient extinguishment of combustibles found in such facilities, are electrically nonconducting, and leave no corrosive or acidic residues following their use.

The minimum requirements for total flooding clean agent fire extinguishing systems are contained in *NFPA Standard 2001 Standard on Clean Agent Fire Extinguishing systems*. For Class C hazards, Section 5.4.2.5 of the current (2004) edition of NFPA 2001 requires that the "minimum design concentration for Class C hazards shall be at least that for Class A surface. fire" The minimum Class A design concentration is defined in Section 5.4.2.4 of NFPA 2001 to be the Class A extinguishing concentration times a safety factor of 1.2. The extinguishing concentration for Class A fuels is defined in Section 5.4.2.2 of NFPA 2001, and must be determined by test as part of a listing program; as a minimum the listing program must conform to UL 2127, Standard for Inert Gas Clean Agent Fire Extinguishing System Units, or UL 2166, Standard for Halocarbon Clean Agent Fire Extinguishing System Units, or equivalent. UL 2127 and UL 2166 require agent testing on Class A hazards including wood cribs and a selection of plastic materials. These standards were developed by Underwriters Laboratories in cooperation with members from the various facets of the fire suppression industry, including agent manufacturers, system installers, independent test laboratories, environmental regulatory bodies (U.S. EPA), and representatives from the insurance industry.

REPORT ON COMMENTS A2007 ROC

At a recent meeting of the NFPA 2001 Technical Committee, Comment ROC 2001-61a (log #CC7) was proposed, and after much debate, accepted by the Committee⁵. Comment ROC 2001-61a would require that the minimum design concentration for a Class C hazard be increased from the current level of 1.2 times the Class A minimum extinguishing concentration to 1.6 times the Class A minimum extinguishing concentration for scenarios in which the power dissipation from an electrical circuit failure is not likely to exceed 1500 W continuous. Higher concentrations would be required to be

⁵ Report on Comments A2007, NFPA 2001, published as 2001-A2007-ROC.pdf on the NFPA website at <http://www.nfpa.org/Assets/Files/PDF/ROP/2001-A2207-ROC.pdf>

specified for scenarios in which the power dissipation from an electrical circuit failure exceeds 1500 W continuous.

Table 3 indicates the changes in the minimum design concentration that would result from the adoption of Comment ROC 2001-61a for a selection of clean agents. In Table 3, the NOAEL is the no observed adverse effect level and the LOAEL is the lowest observed adverse effect level for cardiac sensitization.

Table 3. Effects of ROC 2001-61a on Minimum Class C Design Concentrations

Agent	Minimum Class C Design Concentration Current (% v/v)	Minimum Class C Design Concentration Comment ROC 2001-61a (% v/v)	NOAEL (%)	LOAEL (%)	Max. Allowable Conc. In Normally Occupied Areas (%)
HFC-227ea	6.25	8.3	9.0	10.5	10.5
HFC-125	8.0	10.7	7.5	10.0	11.5
HCFC Blend A	12.9	15.8	10	>10	10
FIC-13I1	4.2	5.1	0.2	0.4	0.3
IG-541	40	53.3	42	53	52
FK-5-1-12	4.2	5.6	10	10	10

The implications of Comment 2001-61a are far-reaching, and its adoption would have a major impact on the clean agent fire suppression market:

- For Class C hazards, the minimum design concentrations for all clean agents would be increased by 33 percent
- As a result, clean agent system costs would increase by at least 33 percent
- Several agents could be essentially removed from the marketplace
- Increased system costs and reduced safety levels could render the entire clean agent marketplace unattractive, resulting in a move towards other types of suppression systems providing lessened and potentially inadequate levels of protection

ROC Comment 2001-61a could essentially result in the removal of IG-541 from the clean agent marketplace as NFPA 2001 does not allow inert gas agents to be employed at concentrations in excess of 52% v/v. HFC-125 is currently employed at concentrations below its LOAEL of 10.0% v/v, but would be required under ROC 2001-61a to employ a Class C design concentration of 10.7% v/v, which, although allowed under NFPA 2001, exceeds its LOAEL.

A 33 percent increase in the design concentration for clean agent systems would lead to an increase in system costs of at least 33 percent; taking into consideration increased packaging and shipping costs,

the increased number of system cylinders required and the increased storage space required to house these additional cylinders, a projected total increase in clean agent system costs of 50 percent is not unreasonable. Clean agent system costs are already significantly higher than those for alternative suppression systems (e.g., pre-action sprinkler systems) and such an increase could result in a significant portion of the fire suppression market abandoning the clean agents for less effective, and possibly inappropriate, alternative technologies, resulting in potentially dangerous reductions in the safety levels currently provided by the clean fire suppression agents.

JUSTIFICATION OF ROC COMMENT 2001-61a

FIELD EXPERIENCE

The field experience gained with clean agent systems does not justify the drastic changes called for in Comment ROC 2001-61a. During the past 15 year period in which clean agent fire suppression agents have been employed, there is not a single documented report of the failure of any clean agent system to extinguish a fire involving energized electrical equipment.

LABORATORY STUDIES CITED

In its acceptance of ROC 2001-61a, the NFPA 2001 Technical Committee provided the substantiation that "Laboratory testing indicates that the agent concentration required to extinguish a fire in energized electrical equipment typically increases with increased electrical power input." The laboratory testing employed as a basis for this substantiation is described in a series of reports⁶⁻²³ and can be categorized as follows:

- Tests involving electrically energized metals in flames
- Tests lacking the presence of electrically energized equipment
- Conductive heating, ohmic heating and PC board failure (arcing) tests
- Modified conductive heating
- Tests involving nichrome wire as a conductor and polymethylmethacrylate

These tests are discussed in detail below.

Tests Involving Electrically Energized Metals in Flames

Hamins and Borthwick⁶ examined the impact of a series of fire suppression agents on the possible ignition of reactants flowing over a hot metal surface by measuring the changes in ignition temperature of stoichiometric mixtures of methane/air, ethane/air, and ethylene/air as a function of agent concentration. In these experiments the gaseous fuel/air mixtures were passed over a thin nickel foil heated to a temperature of approximately 1200 °C (2192 °F). It is difficult to envision the relationship between this experimental setup and real world configurations, which do not involve electrically energized nickel foils or hydrocarbon flames. Furthermore, as discussed in greater detail below, copper wire, the electrical conductor found in almost all real world circuits, fails rapidly at temperatures above approximately 538 °C (1000 °F). Hence the nickel foil/hydrocarbon flame tests

⁶ Hamins, A. and Bothwick, P., *Suppression of Ignition Over a Heated Metal Surface*, Combust. Flame, 112(1/2), 161 (1998).

differ from real world hazards in both the materials involved and in the conditions employed. Braun, et. al.⁷ later extended the method of Hamins and Borthwick to include the examination of additional suppression agents, retaining the energized nickel foil/hydrocarbon flame configuration, and hence retaining the nonrepresentative materials and conditions of the Hamins and Borthwick studies.

Driscoll and Rivers⁸ reported the results of tests in which an electrically energized piece of nichrome wire was exposed to the flame from a cup burner. Again, it is difficult to envision the relationship between this experimental setup and real world configurations, which do not involve electrically energized nichrome wires exposed to flames of Class B fuels, and we again have a series of tests which are nonrepresentative of the real world hazard with respect to both the materials involved and the conditions employed.

It is interesting to note, however, the performance of the clean agents as a function of the temperature of the nichrome wire in these tests. As seen in Table 4, for wire temperatures as high as 800 °F, the extinguishing concentration of HFC-227ea required for extinguishment showed no increase over the concentration required at 70 °F. A wire temperature of 800 °F is very close to the upper temperature limit at which copper wire can be maintained without fusing, and hence the results here suggest that no increase in agent concentration is required for copper wires heated almost to their practical upper use temperature. At temperatures in excess of 1200 °F, additional agent was required for extinguishment, but as discussed in detail below, copper wire would not survive these elevated temperatures longer than a few seconds before breaking and interrupting the flow of current.

Table 4. Extinguishing Concentration and Nichrome Wire Temperature [8]

NiCr Wire Temperature (°F)	Extinguishing Concentration, % v/v			
	PFC-3-1-10	PFC-2-1-8	HFC-227ea	HFC-23
70	6.0	7.1	7.4	13.4
800	6.3	7.5	7.4	13.9
1200	7.8	8.7	8.6	14.8
1600	10.0	10.5	11.2	18.5

Tests Lacking the Presence of Electrically Energized Equipment

Four of the studies cited by the NFPA 2001 Technical Committee involve test configurations in which no electrically energized components are present. Kelly and Rivers⁹, Steckler and Grosshandler,¹⁰ Smith and Rivers¹¹ and Smith, et.al.¹², reported the suppression by several clean agents of PMMA fires exposed to an external radiant flux produced by the Radiantly Enhanced

⁷ Braun, E., et. al., *Determination of Suppression Concentration for Clean Agents Exposed to a Continuously Energized Heated Metal Surface*, 1997 Halon Options Technical Working Conference, Albuquerque, NM, May 6-9, 1997.

⁸ Driscoll, M. and Rivers, P., *Clean Extinguishing Agents and Continuously Energized Circuits*, October 1996.

⁹ Kelly, A. and Rivers, P., *Clean Agents Concentration Requirements for Continuously Energized Fires*, August 1997.

¹⁰ Steckler, K. and Grosshandler, W., *Clean Agent Performance in Fires Exposed to an External Energy Source*, November 1998.

¹¹ Smith, D. and Rivers, P., *Effectiveness of Clean Agents on Burning Polymeric Materials Subjected to an External Energy Source*, 1999 Halon Options Technical Working Conference, Albuquerque, NM, April 27-29, 1999.

¹² Smith, D., et. al., *Energized Fire Performance of Clean Agents: Recent Developments*, November 1997.

Extinguishing Device (REED). These tests employ a cone heater to direct a continuous heat flux towards a burning cylindrical piece of PMMA. As the imposed heat flux is increased, the amount of agent required for extinguishment increases.

Based upon the differences between the REED test configuration and an energized cable, it is difficult if not impossible to relate these test results to actual Class C fires. For example, the test material is not representative of real world hazards - PMMA is rarely if ever found as a component of electrical cable. In addition, it is questionable whether or not the heat fluxes employed in these tests are representative of heat fluxes possible in real world applications. These studies basically demonstrate the well known fact that extinguishing requirements increase as the radiative feedback to a fuel increases.

Conductive Heating, Ohmic Heating, and PC Board Failure (Arcing) Tests

McKenna, et. al.^{13,14} have reported the results of fire testing of HFC-227ea on continuously energized Class C fires, employing configurations designed to replicate hazards encountered in power conduction applications. McKenna, et. al. point out that, to reflect actual field conditions as closely as possible, it is important to select materials as test fuels that are in widespread use, and to ensure this a survey of telecommunication providers was conducted to determine the types of materials encountered in real world installations. Hence, in contrast to the studies described above, these studies employed materials which can be related to real world applications, i.e., copper wire conductors, common insulation materials (PVC, Hypalon, polyethylene), printed circuit boards, etc. Furthermore, the test fires were developed to replicate the physical phenomena found during overheated cable, overheated connection, and printed wire board (PWB) failure scenarios.

Three types of tests were conducted:

- Ohmic heating (overheated cable) tests
- Conductive heating (overheated connection) tests
- Printed Wire Board (PWB) failure tests

Ohmic Heating Tests. Electrically overheated wire and cable are a well-documented phenomena. An electrical fault or the failure of an overload protective device can result in the development of an overcurrent in a wire or cable. When sufficient current flows through the conductor, it will overheat due to resistance in the conductor (i.e., ohmic heating). Heating is proportional to the current flow and hence higher current flows result in higher temperatures. A "dead" short in an electrical circuit can result in a nearly instantaneous overheating of an entire cable and ignition of the cable insulation.

This scenario was modeled by creating a controlled overcurrent condition in a sample of wire or cable. A wire bundle sample was positioned in the center of a test enclosure and the wires mounted between two copper busses which extended through the enclosure wall. The copper busses themselves were connected to a 600 A arc welder which supplied current to the conductors of the wire bundle. Following a preheat period, a butane pilot flame was applied at the midpoint of the underside of the

¹³ McKenna, L.A., et. al., *Extinguishment Tests of Continuously Energized Class C Fires Using HFC-227ea (FM-200)*, Hughes Associates Inc., February 1998.

¹⁴ McKenna, L.A., et. al., *Extinguishment Tests of Continuously Energized Class C Fires*, Proc. 1998 Halon Options Technical Working Conference, Albuquerque, NM, May 12-14, 1998.

sample to ignite the cable insulation, and after a suitable preburn period the suppression system was activated. Five commonly encountered cable types were examined: crosslinked polyethylene (XLPE), polyvinyl chloride (PVC), chrome PVC jacket over polyethylene, neoprene jacket over rubber insulation and SJTW-A (thermoplastic jacket over thermoplastic insulation). All test samples were effectively extinguished at HFC-227ea concentrations of 5.8% v/v (note that the minimum Class A design concentration for HFC-227ea is 6.25 % v/v).

Conductive Heating Tests. Overheated electrical connections are a well-documented phenomena. In these scenarios, the connection at one end of a wire or cable becomes loose due to one or more causes (mechanical stress, vibration, etc.). When the connection becomes sufficiently loose, a resistance to electrical flow develops in the connection and the connection will begin to heat. As the connection heats, the copper conductor of the cable acts as a heat sink, conducting heat away from the connection, and at some point the insulation of the cable can reach its ignition temperature.

This scenario was modeled by clamping one end of a copper cable inside a 1000 Watt ring heater. Three typical 350 MCM cables, currently in common use, were employed: Lucent Technologies type KS 5482-L28FR (Hypalon insulation covered by cotton braid sheathing), Lucent Technologies type KS 20921 (unsheathed Hypalon insulation) and Lucent Technologies type KS 20747 (PVC insulation). The sample cable was heated until the top of the cable sample reached 590 °F (750 °F for PVC cables) and a small pilot flame applied. The enclosure was then sealed, and the suppression agent discharged into the enclosure following a one minute preburn period. All test samples were effectively extinguished at HFC-227ea concentrations of 5.8% v/v (note that the minimum Class A design concentration for HFC-227ea is 6.25 % v/v).

Printed Wire Board Failures (Arcing). Internal printed wire board (PWB) failures are a common event in electronics equipment, generally caused by contaminants within the PWB, and can also be induced by component failures. If an overheating component is located above the power tracks on a PWB, pyrolysis of the insulating material between the tracks can lead to the development of an arc between the power tracks. In this scenario, an electrical fault allows excess current to flow through the power tracks on the board, overheating the tracks. The overheated power tracks pyrolyze the substrate material between them and after a time the insulating properties of the material are sufficiently degraded such that an arc develops between the two tracks, igniting the gaseous pyrolysis products. The arc travels along the tracks starting at the point of ignition and moves towards the power supply.

This scenario was modeled with a specially designed PWB failure board; when overloaded, an arcing short could be created between two tracks on an FR-4 board substrate. At the point at which the arc had traveled 130 mm, the fire was judged to be well established and the suppression agent was discharged. All test samples were effectively extinguished at HFC-227ea concentrations of 5.8% v/v (note that the minimum Class A design concentration for HFC-227ea is 6.25 % v/v).

Based on the results of their ohmic heating, conductive heating, and PWB failure tests, McKenna, et. al., concluded that "fires initiated by, and involving, energized electrical circuits can be controlled by HFC-227ea at concentrations below 7%."

It is important to note that of the reports cited as substantiation for Comment ROC 2001-61a, only the McKenna, et. al. studies employed materials and conditions representative of those actually encountered in real world Class C configurations. The results of the McKenna, et. al. study indicate that for HFC-227ea, the minimum Class A design concentration is sufficient for the protection of Class C hazards, i.e., the results of the McKenna, et. al. studies do not justify Comment ROC 2001-61a.

Modified Conductive Heating Tests

Smith, et. al.¹⁵ have reported the results of testing of Novec™ 1230 and HFC-227ea in a "modified" conductive heating test, Bengtson, et. al.¹⁶ have reported updated test results for Novec™ 1230 in the modified conductive heating test, and Flamm, et. al.¹⁷ have reported the results of testing of HFC-125 and HFC-236fa in the modified conductive heating tests.

A conductive heating test was originally developed by Larry McKenna of Hughes Associates, Inc. to simulate an overheated connection (see previous discussion). The "modified" conductive heating test is based on the original conductive heating test, with the modification of the introduction of a continuous arc source.

Several aspects of the modified conductive heating test are problematic. The results obtained in the modified conductive heating tests suffer from poor reproducibility. In the modified tests the entire surface of the cable does not burn as was the case in the original procedure; in the modified test, which employs an arc as the flame initiator, a "small" flame appears at the top of the cable. This small flame "sometimes" ignites the vapors rising up the sides of the cable, according to the authors, who offer no further detail. Furthermore, the authors indicate that because the flame is small, it "sometimes" disappears while the enclosure is being sealed. Determining the point of extinguishment in these tests is difficult, as acknowledged by the authors who indicate that this is due in part to obscuration from the discharge.

A lack of reproducibility is also seen in the test results. For example, it was concluded in one of the reports that for KS-5482L28F cable, a concentration of 11.0% HFC-227ea was required to both extinguish the fire and prevent reignition, yet test results are presented where 8.0% HFC-227ea extinguished the fire and in which reignition was not observed. For tests involving KS-20921L2 cable, three different results were obtained at a concentration of 8.0% HFC-227ea: in one test the fire was not extinguished, in a second test the fire was extinguished but reignition occurred, and in a third test the fire was extinguished and no reignition observed.

The criteria employed by the authors in these tests, shown in Table 5, are also problematic. The authors use the fourth criteria shown in Table 1 to define agent concentrations capable of extinguishing the flame and preventing reignition. However, the fourth criteria actually represents a condition in which both the flame *and the arc itself* are extinguished and no reignition occurs. In reality, the concentration required to extinguish the flame and prevent reignition corresponds to the second criteria shown in Table 5. Unfortunately, the concentration requirements to satisfy criteria number two are not reported.

¹⁵ Smith, D.M., et. al., *Examination and Comparison of Existing Halon Alternatives and New Sustainable Clean Agent Technology in Suppressing Continuously Energized Fires*, Proc. 2001 Halon Options Technical Working Conference

¹⁶ Bengtson, G., et. al., *Update on the Examination and Comparison of Existing Halon Alternatives and New Sustainable Clean Agent Technology in Suppressing Continuously Energized Fires*.

¹⁷ Flamm, J., et. al., *Continuing the Examination and Comparison of Existing Halon Alternatives in Preventing Reignition on Continuously Energized Fires*, Proc. 2005 Halon Options Technical Working Conference, Albuquerque, NM, 2005.

Table 5. Criteria for Extinguishment and Inertion in Modified Conductive Heater Tests

	Criteria	Interpretation
1	Flame remains or is diminished AND is localized around arc source	The fire did not extinguish (DNE)
2	Flame is extinguished AND only a blue arc is visible	The fire was extinguished but the arc source remained
3	Flame is extinguished AND small localized flames are visible around arc shortly thereafter	The fire was extinguished, but reignition occurred
4	Flame and arc are no longer visible AND both remain nonexistent over hold period	The concentration employed is capable of providing extinguishment and preventing reignition

Tests Involving Nichrome Wire and PMMA

Six of the cited reports involve the testing of configurations consisting of nichrome wire and PMMA. The first of these studies was reported by Niemann, et. al.¹⁸ In these tests, a sample of PMMA was heated with a nichrome wire which was either wrapped around the PMMA sample or "sandwiched" between a pair of PMMA sheets, and it was observed that increased power levels led to greater quantities of clean agent required to extinguish the PMMA fires. Wire temperatures employed in these tests were in all cases in excess of 1800 °F. The lack of reproducibility in these tests is evident from the authors indication that from out of over 100 tests conducted, "sixteen (16) tests were selected to be representative of the overall net effort." The exact details as to the logic behind rejecting more than 84 percent of the tests conducted was not provided.

Driscoll and Rivers^{19,20} provided updates to the original nichrome/PMMA work in 1996 and in 1997, as did Niemann and Bayless²¹ in 1998, Bengston, et. al.,²² in 2002, and Bengston and Niemann²³ in 2005.

The relationship of the test configuration in these studies to real world Class C hazards is highly questionable. Typical Class C hazards encountered in telecommunications or electronic data processing facilities consist of cables and electronic equipment. Power conduction in these types of facilities almost always involves the use of copper wire; aluminum wire is rarely encountered, and nichrome wire is never encountered as a power conductor. Power cable insulation is typically comprised of polyvinyl chloride (PVC) or polyethylene (PE), with smaller amounts of polymers such

¹⁸ Niemann, R., et. al., *Evaluation of Selected NFPA 2001 Agents for Suppressing Class C Energized Fires*, Proc 1996 Halon Options Technical Working Conference, Albuquerque, NM, 1996.

¹⁹ Driscoll, M. and Rivers, P., *Clean Extinguishing Agents and Continuously Energized Circuits*, October 1996.

²⁰ Driscoll, M. and Rivers, P., *Clean Extinguishing Agents and Continuously Energized Circuits: Recent Findings*, Proc 1997 Halon Options Technical Working Conference, Albuquerque, NM, May 6-8, 1997.

²¹ Niemann, R. and Bayless, H., *Update on the Evaluation of Selected NFPA 2001 Agents for Suppressing Class C Energized Fires*, Proc. 1998 Halon Options Technical Working Conference, Albuquerque, NM, May 12-14, 1998.

²² Bengston, B., et. al., *Update on the Evaluation of Selected NFPA 2001 Agents for Suppressing Class C Energized Fires Featuring C6 F-Ketone*, NIST Special Publication 984, 2002.

²³ Bengston, G. and Niemann, R., *Update in the Evaluation of Selected NFPA 2001 Agents for Suppressing Class "C" Energized Fires*, 2005 Halon Options Technical Working Conference, Albuquerque, NM, 2005.

as Hypalon or cross-linked polyolefin (XLPO) also being employed. PMMA is characterized by its excellent optical properties and shatterproof nature, and is employed in hockey rink barriers, lenses, optical instruments, stop lights and exterior automobile lights; it is not employed as electrical insulation.

The nichrome wire/PMMA tests are nonrepresentative of real world hazards with respect to both the materials employed (nichrome wire and PMMA) and the conditions employed. Nichrome wire is an alloy of nickel and chromium, and due to its high electrical resistance, high resistance to corrosion, and its high mechanical strength at elevated temperatures, nichrome is widely employed for resistive heating. For example, nichrome wire is employed as the heating element in items such as hair driers, coffee makers, toasters, and radiant heaters. Nichrome is never employed for power or data conduction. Table 5 compares the properties of nichrome and copper wire, and it can be seen that the two materials are characterized by vastly different properties.

Table 5. Comparison of Nichrome and Copper

Nichrome	Copper
Ni/Cr alloy	Cu
High mechanical strength	Low mechanical strength
Highly resistant to corrosion	Low resistance to corrosion
High electrical resistance	Low electrical resistance
Use: Resistive Heating	Use: Power and data conduction
Maximum Use T = 2000 °F	Maximum Use T = 1000 °F

Temperature Behavior of Copper Wire

In order to better understand the characteristics of copper wire, we carried out a series of simple laboratory scale tests involving electrically energized copper wires. In these tests samples of copper wire were energized via connecting the ends of a length of wire to a power supply and examining the behavior of the wire when subjected to various conditions.

The behavior of copper wire subjected to elevated temperatures was examined by connecting the ends of a ten inch length of 24 AWG bare copper wire to Electronics Measurements, Inc. Model TCR power supplies rated up to 40 volts @ 100 amps. The current was then adjusted to a constant level and the temperature of the wire monitored using unsheathed, bare, thermocouple wires and Fluke thermocouple meters. The results of these tests are shown in Table 6, where it can be seen that for wire temperatures below approximately 950 °F, the copper wire remained intact for a time period of at least 10 minutes. Wire temperatures above approximately 1000 °F could not be maintained for 10 minutes as the wire would break; higher wire temperatures could be tolerated for shorter time periods before the wire was observed to break.

Table 7 shows the results of the same test, but conducted with jacketed copper wire. In this case the wire was observed to fail at average temperatures in excess of approximately 725 °F. Compared to bare wire, less heat is dissipated away from the copper wire when it is surrounded by the insulator, leading to an increased corrosion rate due the higher localized wire temperatures.

Table 6. Overloaded Copper Wire; 24 AWG Bare Copper Wire

Current (A)	Temperature (°F)	Duration (time to wire failure)
21	700	> 10 min
23	800-825	> 10 min
25	925-950	> 10 min
26	1000	8 min
27	1050	3:23 ; 5:13 ; 6:02

Table 7. Overloaded Copper Wire; 24 AWG Jacketed Copper Wire

Current (A)	Temperature (°F)	Duration (time to wire failure)
20.5	700	> 10 min
21.5	725	24 s
23.5	850	28 s
27	1050	10 s

Additional tests were conducted to examine the temperature limitations of braided copper wire compared to stranded wire, and no significant differences were observed.

A number of important conclusions can be drawn from these tests:

- Bare copper wire can withstand a 10 minute overcurrent only when the wire temperature is limited to 1000 °F
- Insulated copper wire can withstand a 10 minute overcurrent only when the wire temperature is limited to 700 °F
- Larger gauge wires require more current to attain a given temperature but behave similarly to smaller gauge wires at similar temperatures
- Wire gauge makes little difference in the ability of copper wire to withstand high temperatures:
- the maximum temperature which can be tolerated for 10 minutes is approximately 900 to 1000 °F
- Stranded cables and single conductor cables behave similarly
- Copper wire heated to 750-1000 °F is sustainable for 10 minutes only if these temperatures are not exceeded anywhere along the length of the wire

- When copper wire is heated to above 700 °F, corrosion is accelerated and this corrosion is the primary reason for failure at these temperatures

It will be recalled that the studies discussed above involving nichrome wire and PMMA were conducted at current levels corresponding to wire temperatures in excess of 1800 °F. At this temperature, bare copper wire is sustainable for less than 10 seconds, and at 1800 °F insulated copper wire is sustainable for even lessened time periods. Hence, these tests involving a nichrome wire and PMMA would be impossible to conduct if one were to employ, instead of nichrome, the conductor used in 99.9% of all power transmission cables. The conditions employed in the nichrome wire/PMMA tests are clearly not representative of the real world hazard, and as previously discussed, neither are the materials employed.

Class C Hazards and Power Levels

Comment ROC 2001-61a would require that the minimum design concentration for a Class C hazard be increased from the current level of 1.2 times the Class A minimum extinguishing concentration to 1.6 times the Class A minimum extinguishing concentration for scenarios in which the power dissipation from an electrical circuit failure is not likely to exceed 1500 W continuous. Higher concentrations would be required to be specified for scenarios in which the power dissipation from an electrical circuit failure exceeds 1500 W continuous.

A major misunderstanding associated with ROC 2001-61a, and with a large number of the studies cited as justification for ROC 2001-61a, is the association of the severity of a Class C hazard with the power level involved. First, there is no known technical basis for the division of Class C hazards into those with power levels below 1500 W and those above 1500 W.

Second, the power level involved is not the appropriate factor of concern in Class C hazards. The threat involved in a Class C scenario is related to heat transfer issues, i.e., to the elevated *temperature* of a component or a wire. Basic thermodynamics of heat transfer teaches that the temperature of an object is a balance between heat-in and heat-out. For this reason, any amount of heat-in in excess of heat-out results in a temperature increase until again the object achieves equilibrium. A large quantity of heat-in (units of watts) that is properly balanced with a large heat-out (usually called power dissipation and measured in watts) does not in itself result in rising or elevated temperatures. Hence, for a high wattage (high power) scenario in which heat is efficiently dissipated, there will be little or no increase in temperature, and hence no threat due to elevated component temperatures. Conversely, for the scenario in which low power levels are involved but heat dissipation is poor, dangerously high temperatures could potentially be developed. It is the *temperature* of the component that determines whether or not an ignition threat exists, not the power level involved, and hence the linking of Class C design concentrations to power levels is technically unfounded.

DEVELOPMENT OF A STANDARD CLASS C TEST

There is currently no standard test method available for the evaluation of the performance of suppression agents on fires involving electrically energized equipment. As discussed above, past investigations of clean agent performance on Class C fires, with the exception of the work reported by

McKenna, et. al.,^{24,25} employed materials and conditions that are not representative of real world Class C hazards in telecommunication and electronic data processing facilities. As a result, such tests are inappropriate as a basis for the development of a standard Class C test.

In developing a standardized Class C test, a critical objective is to replicate the real world scenario with respect to both the materials (fuels) tested and the test conditions employed. An acceptable test should be challenging, but not to such a degree that the challenge represents a scenario never encountered in real world Class C scenarios. Additional critical requirements include a test procedure that is simple to perform and which provides reproducible results.

In order to replicate real world materials, the power conductor employed in any Class C standard test should be copper wire or cable, which is employed almost exclusively throughout the industry. PVC dominates as the material of choice for electrical insulation, followed by polyethylene (PE), which is typically employed as an insulation when cables are located outside. Additional insulation materials include Hypalon, cross-linked polyolefin (XLPO), high density polyethylene (HDPE), and Neoprene.

With respect to test conditions, it is critical to keep in mind the limitations of copper wire/cable. As discussed above, copper wire can withstand temperatures of up to only approximately 1000 °F for extended periods, and at higher temperatures will quickly fuse, breaking the electrical circuit. Tests carried out at wire temperatures of approximately 1200 °F would therefore represent a reasonable worst case scenario, but cannot be performed with copper wire, which will fuse in seconds at such wire temperatures. However, by employing nichrome wire at 1200 °F, we can simulate an overcurrent scenario that is very challenging in nature since such a wire temperature is 20% higher than what could be withstood by copper wire.

Ignition of plastic samples as a function of wire temperature was evaluated and it was determined that a wire temperature of 1800 °F was sufficient to cause the ignition of a wide range of plastic materials.

Based on the above considerations, the following test protocol was proposed:

- Employ nichrome wire at 1800 °F for sample ignition
- At 30 s after ignition, reduce the wire temperature to 1200 °F and maintain at 1200 °F throughout the remainder of test
- At 60 s after ignition, activate suppression system
- Examine test material for reignition during a 10 minute hold period

Several configurations of plastic sample and ignition/heating wire were examined before deciding on the final configuration. The configuration ultimately adopted is shown in Figures 1 through 3. The test frame is constructed from aluminum and contains two electrical standoffs with ceramic insulators for connection of the test frame to a power supply. The test specimen is shown in Figure 2. It was

²⁴ McKenna, L.A., et. al., *Extinguishment Tests of Continuously Energized Class C Fires Using HFC-227ea (FM-200)*, Hughes Associates Inc., February 1998.

²⁵ McKenna, L.A., et. al., *Extinguishment Tests of Continuously Energized Class C Fires*, Proc. 1998 Halon Options Technical Working Conference, Albuquerque, NM, May 12-14, 1998.

found that shorter specimens presented a more challenging scenario than taller specimens; when testing PMMA samples, small "finger" flames developed on the top edge of the PMMA sample, which

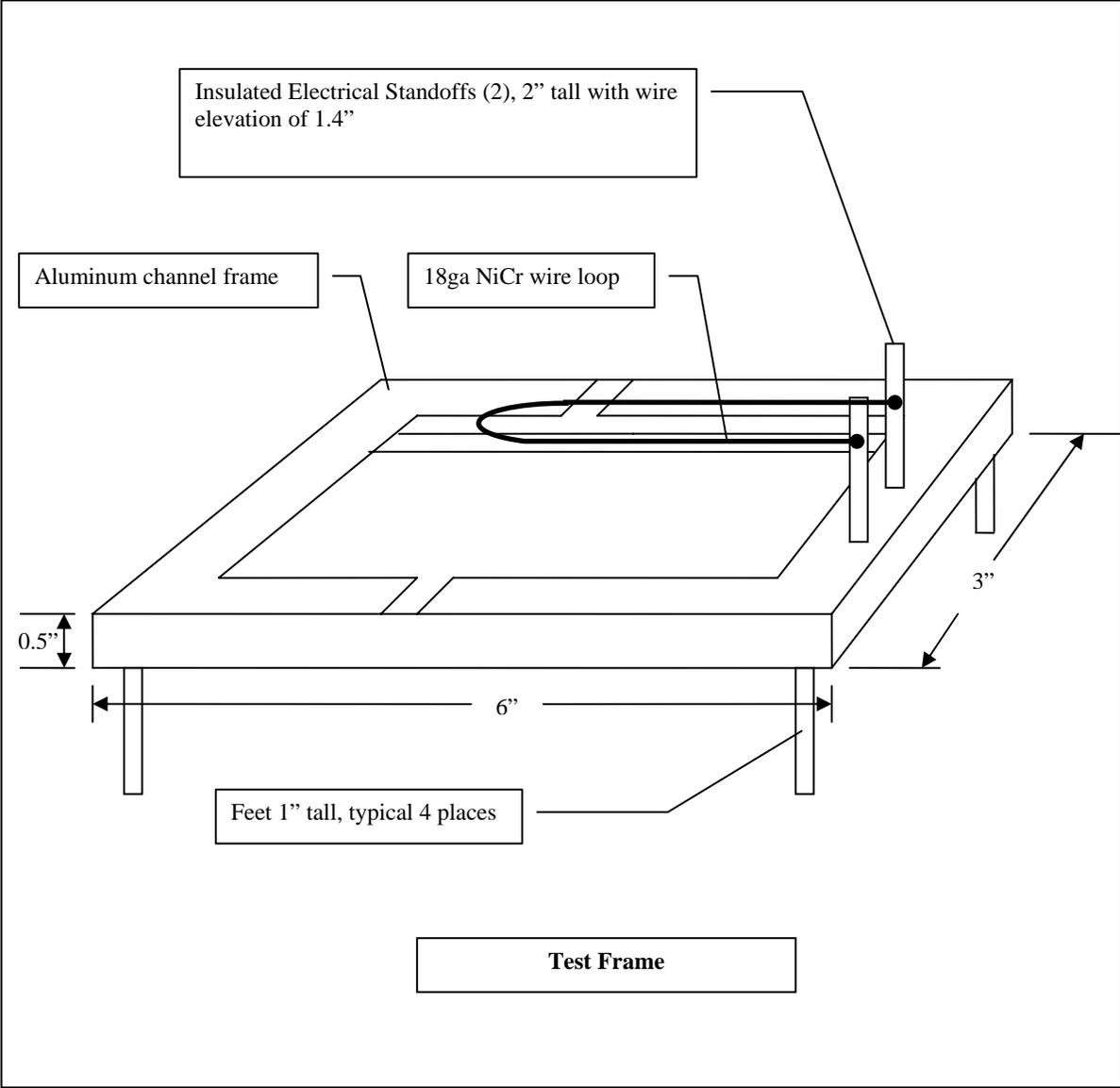


Figure 1. Test Frame

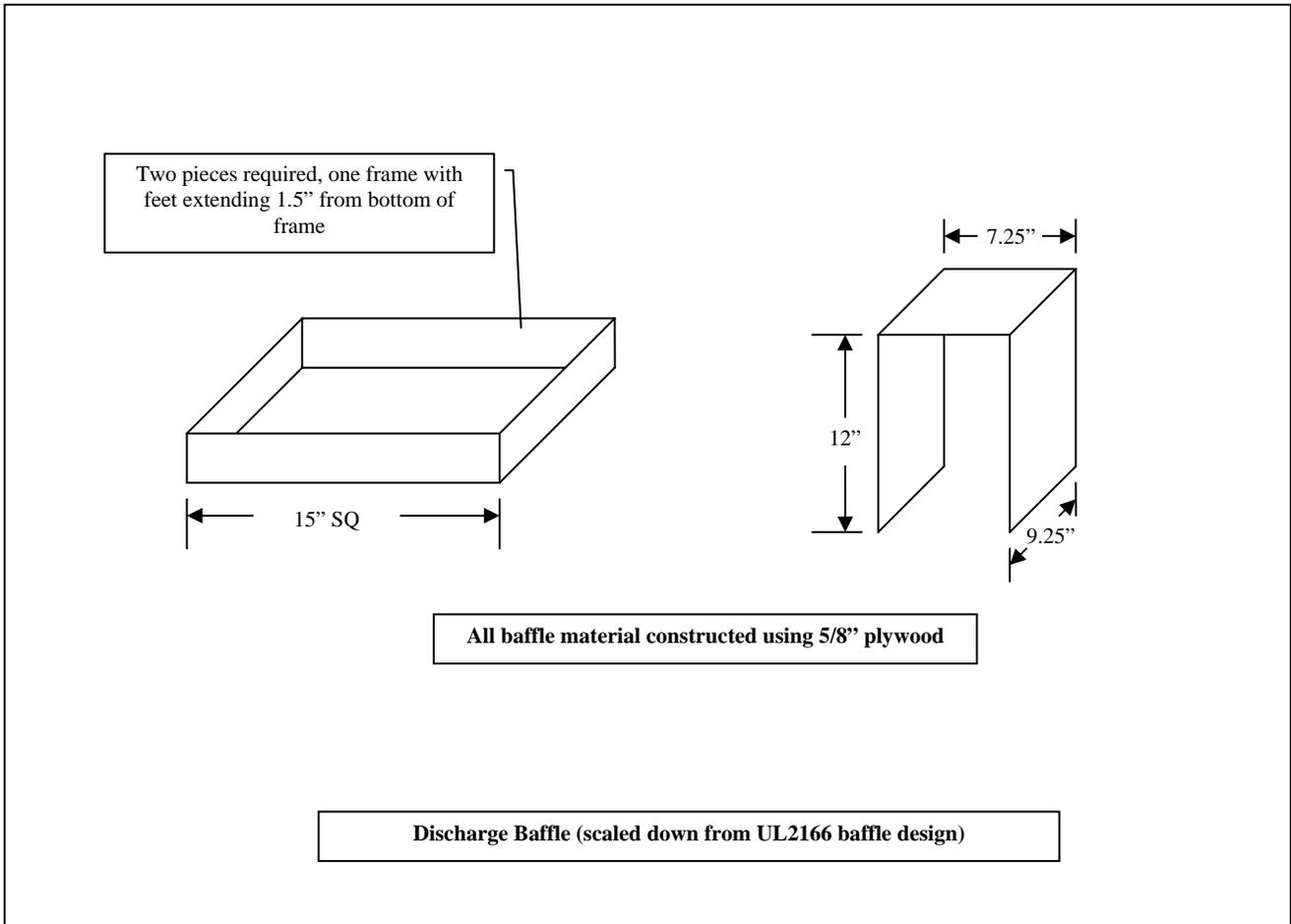


Figure 2. Baffling System

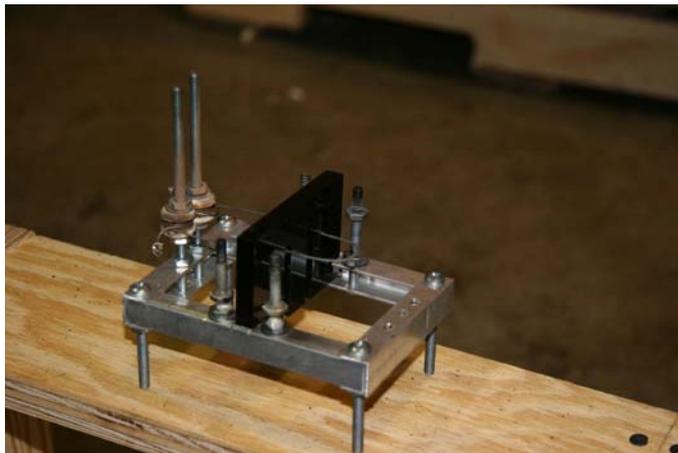


Figure 3. Test Frame and Test Specimen

did not develop when taller specimens were employed. Figures 3 and 4 shown the plastic specimen in place within the specimen holder.

Suppression tests were conducted in a 200ft³ box constructed from plywood and measuring approximately 3.3 feet wide, 7.6 feet deep and 8 feet tall. A walk-in door is on one end of the enclosure, a 12 inch square viewing window and two ventilation ports are used to purge the enclosure between tests. Electronics Measurements, Inc. Model TCR power supplies were used heat the Ni-Cr wire to the desired temperature. Temperatures are determined using unsheathed, bare, thermocouple wires and Fluke thermocouple meters. Agent was discharged into the test cell using an inverted container to ensure that all contents were discharged into the test cell. A single nozzle was installed centrally in the test cell; the nozzle discharges in a 360° pattern. All tests employed scaled baffling modeled after the UL 2166 polymer fire.

Plastic samples investigated included PVC, HDPE, PMMA, ABS, and PP. PMMA, ABS and PP were investigated due to their inclusion in UL 2166 Class A listing tests.

Tests were conducted with HFC-227ea at its minimum Class A design concentration of 6.25% v/v. A current corresponding to a wire temperature of 1800 °F was applied to the nichrome wire to afford ignition of the sample. At 30 seconds after ignition, the current was reduced to a level corresponding to a wire temperature of 1200 °F, and maintained at this level throughout the entire test. At 60 seconds from ignition the suppression system was activated. The system was then observed for any reignition during a 10 minute soak period.

The test results are shown in Table 9. In all cases, the Class A minimum extinguishing of HFC-227ea (6.25% v/v) was found to be capable of extinguishing the fires and preventing reignition over a 10 minute hold period during which the nichrome wire remained energized at a current level corresponding to a wire temperature of 1200 °F, well above the upper use limit of copper wire. The tests also demonstrated the "self-extinguishing" nature of PVC. Although small intermittent flames were observed with PVC, a self-sustaining flame could not be generated under the test conditions.

CONCLUSIONS

A detailed analysis of field experience, past testing and the results of the present study result in the following conclusions with respect to Comment ROC 2001-61a:

- Field results do not justify ROC 2001-61a
- The cited studies do not justify ROC 2001-61a
- The McKenna, et. al., studies do not justify ROC 2001-61a
- The results of the present study do not justify ROC 2001-61a

Table 9. Test Results

Run	Plastic	Ignition (s)	Ext Time from EOD (s)	Reignition during Soak?
A1	ABS	10	10	NO
A2	PP	25	10	NO
A3	PP	30	12	NO
A4	PMMA	5	20	NO
A5	PVC	NA	NA	NO
A6	PVC	NA	NA	NO
A7	PVC	NA	NA	NO
A8	HDPE	30	10	NO
A9	PMMA	20	40	NO
A10	ABS	3	11	NO
A11	PP	4	10	NO
A12	HDPE	30	10	NO
A13	ABS	4	12	NO
A14	PMMA	9	41	NO
A15	HDPE	9	6	NO

Field experience does not justify the changes that would be required following acceptance of Comment ROC 2001-61a. Clean agent systems have been installed in hundreds of thousands of facilities over the past 15 years, and there is *not a single* documented piece of evidence indicating the failure of these systems in fire scenarios involving electrically energized equipment.

The studies cited as justification for ROC 2201-61a are characterized by serious flaws with regard to the materials and test conditions employed, and in several cases are also plagued by a lack of reproducibility. As a result, they do not justify the far-reaching changes that acceptance of ROC 2001-61a would require.

Both the McKenna study and the present study, both of which employed materials and conditions representative of the real world Class C hazards indicate that current Class A minimum design concentrations are sufficient for the protection of Class C hazards.

The test procedure developed in the present study is simple, challenging and reproducible, and it is suggested that it be employed as a starting point for the development of a standard Class C fire test.

