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ANALYSIS OF PROPOSED SMOKE GENERATOR CONCEPTS FOR  
TRAINING SYSTEMS(U) NAVAL TRAINING EQUIPMENT CENTER  
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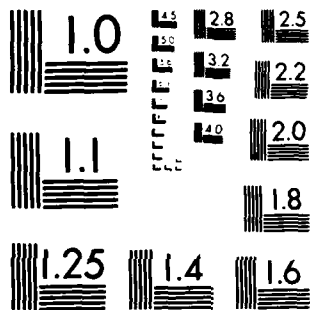
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TECHNICAL REPORT: NAVTRAEQUIPCEN IH-344

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CONCEPTS FOR TRAINING SYSTEMS

E. Swiatosz  
Simulation Concepts Laboratory  
Naval Training Equipment Center  
Orlando, Florida 32813

March 1983  
FINAL REPORT

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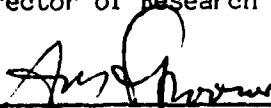
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to identify the efficiency of nucleate boiling phenomena in conjunction with new techniques for a high capacity electrical resistance-tube technique. Other techniques include small commercial off-the-shelf electric boilers and special flow/atomizing nozzles. Training and simulation applications utilizing these techniques are suggested for further research and development efforts. These applications include: shore based fire fighting training; on-board ship fire drills; extinguishment agent simulation; and other applications such as cockpit or evacuation trainers.



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SECTION I  
INTRODUCTION

Background and Purpose

For the past several years, there has been considerable interest in the generation and control of artificial smoke for the Navy's proposed 19F series fire fighter trainers.<sup>1,2</sup> Resulting studies revealed relatively few available smoke generating systems and only one system considered acceptable for the fire fighting trainer environment.<sup>3</sup>

The available methods for producing smoke generally involve the heating of the smoke agent material. In these cases, various heat transfer mechanisms are involved which can significantly affect the performance of the smoke generating unit. For example, available electrically powered smoke generators, as presently designed, are severely limited due to the high thermal resistance of the heating system. For this reason commercial high capacity electric smoke generators as yet have not been made available. Hence, high heat sources such as gas burners and jet pulse engines are generally used for this purpose. However, these high temperature systems present inherent potential hazards such as possible toxic decomposition products as well as danger due to fire.

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1. Swiatosz, Edmund, et al, New Developments in Navy Fire Fighter Trainers, Naval Training Equipment Center IH-316, Proceedings of the first NAVTRAEQUIPCEN Interservice/Industry Training Equipment Conference, November 1979, p. 217-227.

2. Swiatosz, E.; Grimmer, P.; NAVTRAEQUIPCEN Technical Report IH-303, Experimental Research for Advanced Firefighting Simulators, May 1978, p. 45-47, 102-104.

3. Fire Fighter Trainer Environmental Considerations Phase II, Booz, Allen and Hamilton, Inc., Contract N61339-79-C-0011, Mod. No. P00007, 31 July 1981.

This report considers the limitations of existing systems and proposes alternate methods of smoke generation intended to minimize the safety hazards normally associated with high capacity units. Particular emphasis is given to proposed electrically heated methods and boiling heat transfer analysis. Hence, the utilization of the nucleate boiling phenomena in conjunction with new techniques for potential high capacity are investigated. These techniques include: low electrical resistance-tubes as a source of distributed heat; small commercial, off-the-shelf electric boilers, and special divergent flow atomizing nozzles. Training and simulation applications utilizing these techniques are suggested for further research and development efforts.

#### Limitations of Existing Smoke Generators

The usual means of generating smoke is to vaporize an appropriate liquid smoke agent material for subsequent condensation into smoke particulates. Chemical or pyrotechnic methods are also used, particularly by the military, but these are not considered safe or cost effective for enclosed training applications.<sup>4</sup> Another method not as common utilizes an atomizing nozzle to shear the smoke agent liquid into ultra-fine particulates. In the first case (vaporization/condensation), high smoke capacities are available using heat sources such as gas burners<sup>5</sup> or jet pulse engines.<sup>6</sup> However, these systems can also have high temperature pyrolysis effects if they are not adequately designed or properly adjusted during operation. Hence, the pyrolysis or decomposition will depend on the residence heating time and on the properties of the smoke agent material.

In general, the application requirement will determine the choice of smoke agent material and the method of smoke generation. Simulators such as

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4. See page 102 of Reference 2.

5. See page 61 of Reference 3.

6. Operators and Organizational Maintenance Manual: Generator, Smoke, mechanical, pulse Jet, M3A3 (NSN 1040-587-3618), 12 December 1975.

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aircraft evacuation or cockpit trainers require a non-toxic and non-residue material such as propylene glycol. On the other hand, a more persistent smoke such as non-toxic and water soluble polyethylene glycol 200 (PEG 200) would probably be more suitable for some on-board ship fire drills.<sup>7</sup> In the case of the recently completed Navy prototype device 19F1 Advanced Fire Fighter Trainer, the enclosed flame environment dictated the need for combined non-toxic and non-flammable smoke properties.<sup>8</sup>

Commercially available electric foggers are presently being used for cockpit and aircraft evacuation trainers as well as in the entertainment field for visual effects. These units, however, are limited in capacity due to high heater temperature gradients and high thermal resistance. These latter characteristics are associated with a somewhat limited heating surface area which results in a relatively low heat flux (capacity).

The approach currently used for the device 19F1 utilizes an air/liquid mixing nozzle to produce ultra-fine, atomized smoke particulates. A high boiling point butylated triphenol phosphate (Chem Chex 220) material is used, with the air heated to about 1000°F for effective operation. Additional auxiliaries such as a gas heater, pump, and compressor are required resulting in a somewhat expensive system. The high temperature of operation can also be a fire hazard (i.e., smoke agent leakage at the nozzle) or cause chemical decomposition due to misadjustment or improper system design (i.e., smoke distribution system).

Additional limitations of existing smoke generating systems in conjunction with smoke agent material considerations are discussed in Appendix A.

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7. Crook, J. W., Acute Toxicity of Polyethylene Glycol 200 in Laboratory Animals. ARCFL-TR-81058, October 1981.

8. Sciascia, R. M., Advanced Fire Fighter Trainer, Device 19F1, NAVTRADEV P-1550-98.

SECTION II  
STATEMENT OF THE PROBLEM

Alternate Approaches

Alternate approaches to existing smoke generating systems are to be investigated and presented. These approaches will require consideration of the smoke generating constraints and limitations including the objections of low capacity electric smoke generators. These approaches will also require analysis of heat dissipation surface areas, reduction of thermal resistance for increasing smoke generating capacity, and utilization of boiling heat transfer. Approaches involving "bulk heating" or long "residence time" of contact with heated surfaces will require consideration of decomposition effects due to smoke agent material stability and catalytic effects of metal surfaces.

Thermal Analysis

This investigation will require a thermal analysis, including two-phase flow along a heated tube, and consideration of the various boiling heat transfer regimes including critical peak heat flux or "burnout" phenomena.

Application

Specific proposals for various applications using the alternate approaches are to be determined. These will involve utilization of electrical resistance-tube technique, small commercial electric boilers and special atomizing nozzles.

SECTION III  
METHOD OF APPROACHGeneral

The general approach will be to utilize an electrical powered heat source in conjunction with an efficient thermal process involving either of two basic smoke generating methods: vaporization/condensation; and control of smoke agent viscosity for atomization within a special nozzle. These will require consideration of smoke generator parameters associated with obscuration (e.g., visual range), operational requirements (e.g., frequency and duration of use) and heat transfer analysis of proposed techniques for heater design. These parameters also determine material usage and flow rates for nucleate boiling heat transfer computations as described later in this section. The types of heat transfer considered (i.e., pool boiling, free or forced convection boiling) involve various regimes which may include a two-phase flow condition. This involves the determination of a heat transfer film coefficient,  $h$ , which can be related to the heat flux,  $q/A$ , and the heater surface temperature. These relationships can then be used to determine a smoke generator design compatible with flow capacity and electrical power requirements.

Visual Range Parameters

The smoke agent usage or flow rate will depend on the concentration, volume, and other visual range parameters. The presence of particles in the air results in a reduction of visual range depending on the particle size, the number of particles, and the properties of the material. These effects on visual range for a homogeneous aerosol of spherical particles of unit density is given by Davies as:<sup>9</sup>

$$MV = \frac{5.2r}{E} \quad (1)$$

---

9. Davies, C. N., Visual Range and Size of Atmospheric Particles, J. Aerosol Science, p. 335-347, Vol. 6, 1975.

where  $M$  is the smoke concentration in g/m,  $V$  is the visual range in meters (m) and  $r$  is the particle radius in microns ( $\mu\text{m}$ ). The extinction efficiency  $E$  is a measure of the loss of light along the direction of illumination due to scattering and absorption. The extinction coefficient can be determined by theory (e.g., Mie's theory)<sup>10</sup> or by measurement with a narrow angle device to obtain an exponential decrease in beam intensity in accordance with the Bouger Law (also known later as the Lambert-Beer Law).

$$I = I_0 e^{-\sigma x} \quad (2)$$

where  $I/I_0$  is the transmittance and

$$\bar{\sigma} = N \pi r^2 E \quad (3)$$

where  $N$  is the Number of particles, and  $\sigma$  and  $E$  depend on particle radius  $r$ , the wave length of light  $\lambda$  and the refractive index  $n$  of the particle.

As indicated in previously mentioned references,<sup>11</sup> for transparent particles the value of  $E$  tends to increase to a maximum when the optical parameter:

$$\alpha = \frac{2\pi r}{\lambda} \approx \frac{2}{(n-1)} \quad (4)$$

With further increases in  $\alpha$ , the value of  $E$  decreases while oscillating, and becomes almost constant at 2 for  $\alpha > 100$ . (See Reference 11.) As a consequence, most effective smoke occurs when the particle radius is less than a micron. Hence, the average particle size in conjunction with equation (1) will determine the effectiveness of the smoke generator process, particularly in relation to its thermal performance.

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10. Green, H. L., Lane, W. R., Particulate Clouds: Dusts, Smokes and Mists, 2nd Edition, p. 108, London, E F.N. Spon LTD, 1964.

11. See page 337 of Reference 9.

Heat Transfer Relations

The boiling heat transfer<sup>12, 13, 14</sup> phenomena to be considered for the smoke generator approaches are described in Appendix B. These are classified into two general types of boiling heat transfer: Pool Boiling (free convection) such as with the proposed electric boiler; and Flow Boiling (forced convection) which is associated with the proposed resistance-tube approach. As indicated in Appendix B, the various boiling regimes will depend on the type and mode of operation of a specific smoke generator. A simplified approach for determination of the heat transfer is to sum the convective effect, either forced or natural convection without boiling, and the boiling effect. (See Glossary pp. 33-35 for definition of terms.)

$$q_{\text{Total}} = q_b + q_c \quad (5)$$

This approach would apply conventional heat transfer equations with equation (5) to investigate the tubular-resistance heating approach as follows:

For regimes a, b and c in Figure B-2 of Appendix B

$$\frac{q}{A}|_{\text{Total}} = \frac{q}{A}|_b + \frac{q}{A}|_c \quad (6)$$

where:

$$\frac{q}{A}|_c = \bar{h} (T_s - T_b) \quad (7)$$

12. Kreith, F. Principles of Heat Transfer, 2nd Edition, International Textbook Company, 1968.

13. Pitts, D. R., Leighton, E. S., Schaums Outline Series, Theory and Problems of Heat Transfer, McGraw-Hill Book Company, 1977.

14. Handbook of Heat Transfer, Edited by: Rohsenow, W. M., Hartnett, J. P., McGraw-Hill Book Company, 1973.

and  $\bar{h}$  is given by the appropriate convection relations.<sup>15</sup>

For boiling without convection, a commonly accepted general correlation is Rohsenow's equation for nucleate boiling<sup>16</sup> as follows:

$$\frac{q}{A}|_b = \mu_b h_{fg} \sqrt{\frac{g(\rho_l - \rho_v)}{g_c \sigma}} \left[ \frac{C_1 (T_s - T_{sat})}{h_{fg} Pr_l^{1.7} C_{sf}} \right]^3 \quad (8)$$

For regimes d, e, g for the transition to vapor and vapor flow the conventional gas heat transfer expression is used as follows:

$$\frac{q}{A}|_f = \bar{h}_f \Delta T_f \quad (9)$$

where  $\bar{h}_f$  for turbulent gas flow is obtained from the Nusselt relationship:<sup>17</sup>

$$\bar{Nu}_D = \frac{\bar{h}_f D}{k} = (.023) Re_D^{.8} Pr^{1/3} \left( \frac{\mu_b}{\mu_s} \right)^{.14} \quad (10)$$

where:

$$Re = \frac{VD\rho}{\mu} \quad (11)$$

$$Pr = \frac{Cp\mu}{k} \quad (12)$$

15. See page 206 of Reference 13.

16. See page 217 of Reference 13.

17. See page 170 of Reference 13.



The above relations can be used to estimate the approximate surface temperatures of the heater tube for various smoke generating capacities. In addition, however, where a superheated vapor phase is required, the critical heat flux and the minimum heat flux conditions must be considered.

Maximum heat flux (nucleate pool boiling) relationship by Rohsenow and Griffith<sup>18</sup> is:

$$\frac{q}{A}\Big|_{\max} = 143 \rho_v h_{fg} \left(\frac{g}{g_0}\right) \left(\frac{\rho_l - \rho_v}{\rho_v}\right)^{0.6} \quad (13)$$

Normally, heating systems would be designed to avoid the critical heat flux. However, where superheated vapors are required for smoke generation, the minimum heat transfer, as indicated in Figure 1, during transition from nucleate boiling to the gaseous phase must be considered. Expressions for minimum heat flux and the temperature at minimum heat flux in film boiling have been developed<sup>19</sup> and are given by the following equations.

$$\frac{q}{A}\Big|_{\min} = .09 \rho_{vf} h_{fg} \left[\frac{g(\rho_l - \rho_v)}{\rho_l - \rho_v}\right]^{1/2} \left[\frac{g_0 \sigma}{g(\rho_l - \rho_v)}\right]^{1/4} \quad (14)$$

$$\Delta T_{\min} = \frac{0.127 \rho_{vf}}{k_{vf}} \left[\frac{g(\rho_l - \rho_v)}{\rho_l - \rho_v}\right]^{2/3} \left[\frac{g_0 \sigma}{g(\rho_l - \rho_v)}\right]^{1/2} \left[\frac{\mu_f}{g_0(\rho_l - \rho_v)}\right]^{1/3} \quad (15)$$

18. See page 451 of Reference 12.

19. See pages 13-65 of Reference 14.

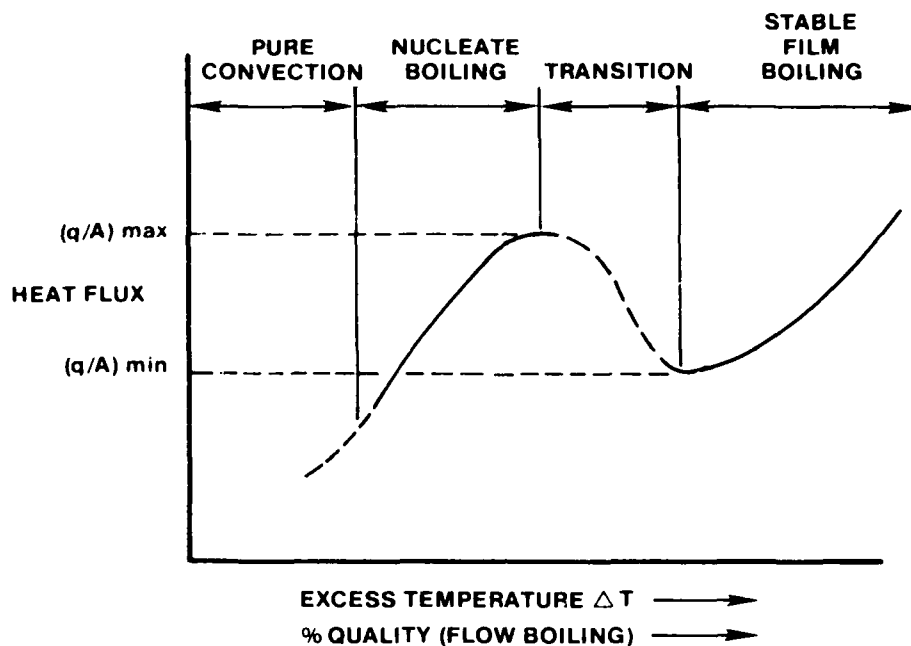


Figure 1. Critical Maximum and Minimum Heat Flux for Boiling.

For the case utilizing "pool boiling" for smoke generation (e.g., modified steam boiler), the nucleate boiling equation (8) could be superimposed with the natural convection equations involving the Nusselt number:<sup>20</sup>

$$Nu_D = \frac{\bar{h}_c D}{k_f} = 0.53 (Gr_D Pr)^{1/4} \quad (16)$$

where:

$$Gr_D = \frac{g\beta(T_s - T_\infty)D}{\nu^2} \quad (17)$$

is Grashof's number,<sup>21</sup> and Pr is defined by equation (12).

20. See page 206 of Reference 13.

21. See page 196 of Reference 13.

The equations (13), (14) and (15) for critical and minimum heat flux would also apply for "pool boiling" applications.

### Proposed Approaches

1. Resistance-tube. This method would utilize a long thin walled tube as a combined electrical heating element, heat exchanger surface area and fluid flow conduit. The tube could be coiled into a compact design for either a steady-state or transient operations. In the first case, as shown in Figure C-2, a small pump and reservoir system would provide the flow of smoke agent through the tube. The dissipated electrical power, which is distributed along the tube, is absorbed in accordance with the "flow boiling" heat transfer described in the previous subsection. For the transient short term operation (see Figures 4, 5 and C-4), the tube serves to store the smoke agent. In this case, the various regimes of "pool boiling" occur sequentially with respect to time. If heating is extended beyond the maximum and minimum heat flux (see Figure 1, Appendix B), then the final regime is film boiling into superheated vapor. This is subsequently released into the air where it condenses into smoke particulates to produce the obscuration effect in accordance with equation (2).

The resistance-tube design length will depend on the tube material resistivity ( $\rho_e$ ), the tube cross section ( $A_c$ ) and the power requirements (P). The power requirements are a function of the temperature limitations as determined by the heat transfer relations. Hence, tube size can be calculated by the following:

$$I = \frac{P}{E} = \frac{q}{A_s E} \quad (18)$$

$$R = \frac{P}{I^2} \quad (19)$$

$$L = \frac{R}{r_e} \quad (20)$$

$$r_e = \left( \frac{\rho_e}{L} \right) A_c \quad (21)$$

Practical considerations require that an alloy material be selected to provide a high ( $\rho_e/L$ ) ratio for a compact design, and for selecting the voltage (E) within the limitations of the available current (I).

2. Commercial boiler. Various approaches are possible using a small electric boiler,<sup>22</sup> as shown in Figure 2 for a smoke generating system. For example, a 4KW unit could be used for a "pool boiling" mode of operation to produce superheated vapors for flow through a valve and subsequent condensation into smoke particulates. However, this approach will require careful consideration of the pressure/temperature characteristics of the smoke agent material as well as consideration of heating stability of the smoke agent material for decomposition effects. Also, boiler and heater surface materials would have to be selected to minimize catalytic action with the smoke agent material. A second approach to avoid these problems is to lower the temperature sufficient for appropriate fluid viscosity for operation with an atomizing nozzle.<sup>23</sup> These nozzles would provide for mixing with injected air (or steam) in which a shearing process takes place to produce ultra-fine smoke particulates. Since superheated steam can be used in lieu of air, this suggests the possibility of using the boiler for both heating a smoke agent material and providing steam. In this case, the special properties of a particular smoke agent material such as butylated triphenol phosphate (Chem Chex 220) would be utilized. Thus, its high boiling point and high density would provide a means for interface heating of an upper layer of superheated steam for mixing with the heated smoke agent material in an atomizing nozzle.

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22. Steamaster Model No. HPJ-3, Steamaster, Inc., New York, New York.

23. Fluid Kinetics Inc., Fairfield, Ohio.

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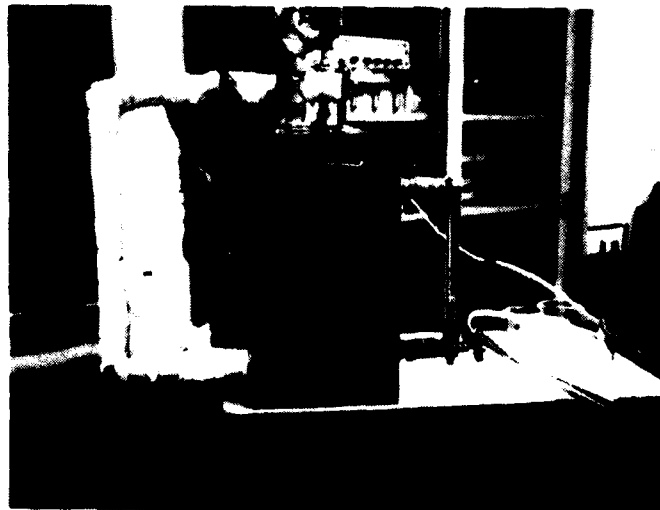


Figure 2. Proposed Boiler Smoke Generator Approach  
(4 KW Steamaster Boiler Apparatus)

SECTION IV  
RESULTS

Design Characteristics

1. Resistance-tube sizing. Utilizing equations (18) through (21) in Section III, the required tube lengths are determined as indicated in Figure 3. These are shown as a function of the power P, tube diameter and wall thickness for a specified alloy material. The corresponding flow capacity through the tube will depend on the extent of heating required of the fluid agent. For boiling beyond the transition regime and accounting for latent heat of vaporization, smoke generation of propylene glycol would be on the order of 1.0 gph/KW. As indicated in Figure 3, the tube length and capacity (KW) range from a practical minimum 30" length for a 4V system at .2 gph (test results indicated later in this section) to about a 100 foot length for a higher capacity system considered appropriate for training applications (i.e., fire fighting training). In general, as the voltage and tube length are reduced for a constant capacity (KW), the tube temperatures will increase. The design temperature limit will then be dependent on the fluid flow through the tube and the heat transfer relations discussed in Section III.

2. Heat transfer/resistance-tube. The temperature differential  $\Delta T$  and the maximum and minimum heat flux were calculated utilizing equations (5) through (17) as indicated in Table 1 for 100 feet of 1/4" x .015" wall material C-276 alloy tubing for propylene glycol smoke agent.

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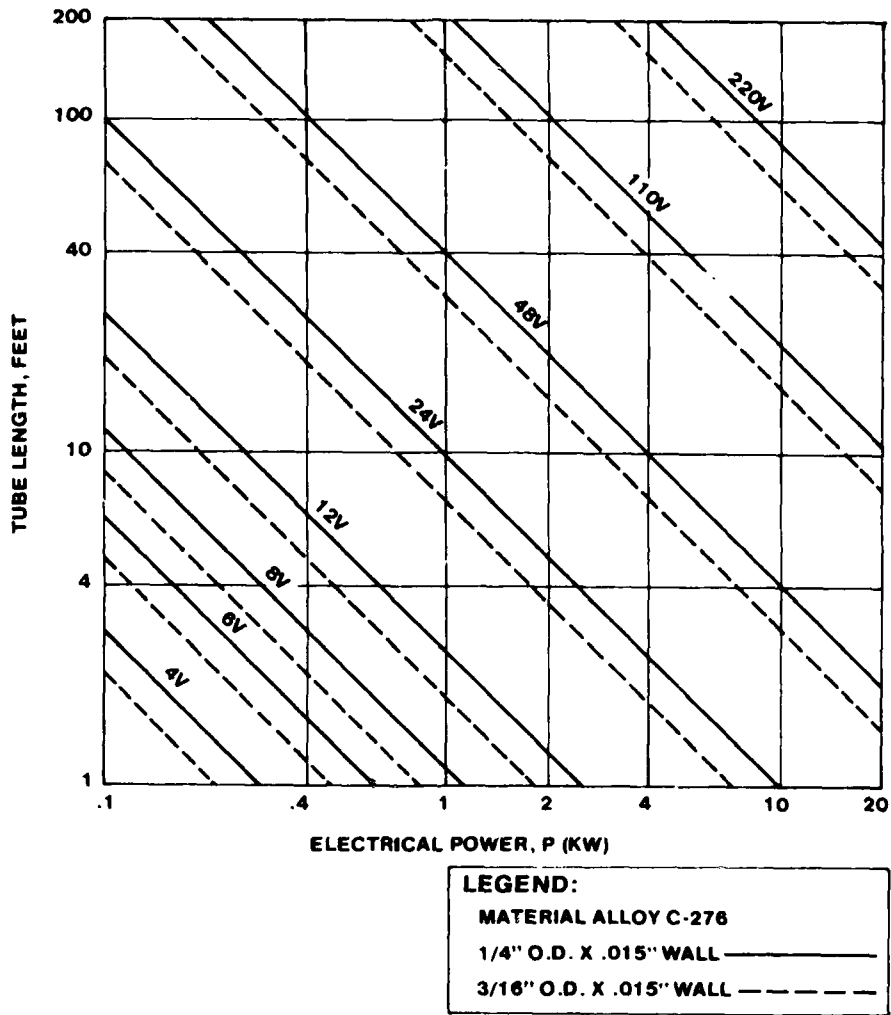


Figure 3. Tube Sizes for Resistance-Tube Heating.

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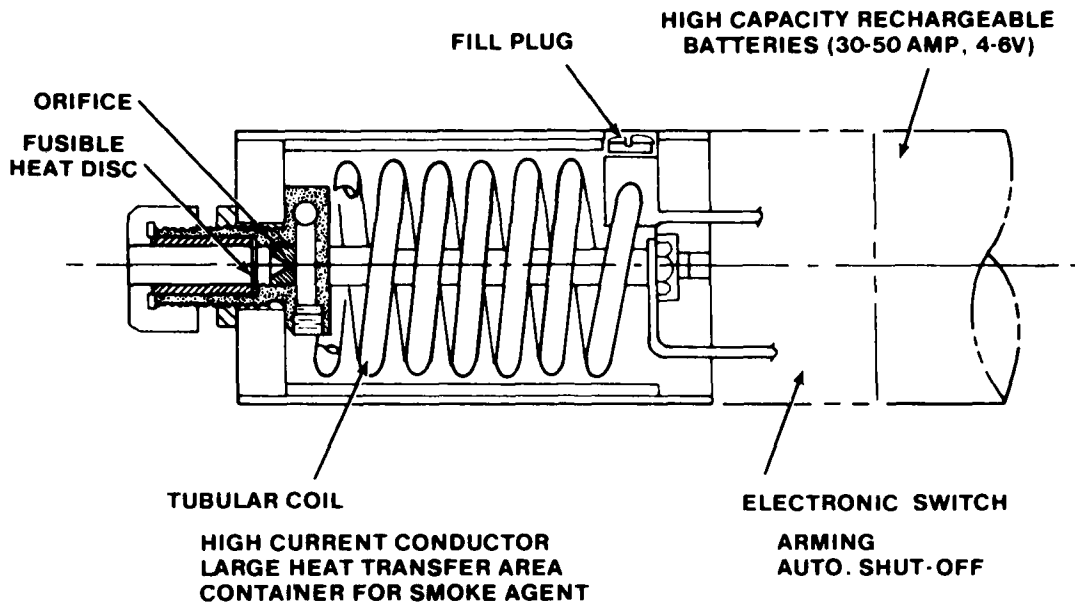


Figure 4. Schematic Battery Operated Smoke Generator.

TABLE 1. HEAT TRANSFER FOR 100 FEET OF 1/4" O.D. X .015" WALL TUBE

REGIME (See Appendix B Figure B-1)	G gph	$(q/A_s)$ Btu/hr- ft <sup>2</sup> - °F	$\Delta T$ °F	$(q/A)_{max}$ Btu/hr- ft <sup>2</sup> - °F	$(q/A)_{min}$ Btu/hr- ft <sup>2</sup> - °F
a, b, c	2.5	1800	43	458,000	-
eq. (7), (8), (13)	5.0 10.0	3600 7200	57 75	458,000 458,000	- -
d, e, f	2.5	1800	29	-	34,000
eq. (10), (14)	5.0 10.0	3600 7200	17 10	- -	34,000 34,000



Test Results

1. Tubular resistance coil. An experimental model shown schematically in Figure 4 was used to demonstrate feasibility. Three high capacity lead acid batteries, each two volt and five ampere-hour, were connected across the tube (3/16" O.D. X .015" Wall X 30" Long) containing 0.3 cubic inches of propylene glycol. About a one-minute power dissipation, as shown in Figure 5, was required to evaporate the material and rupture the fusible disc. Smoke was produced from the superheated vapor as indicated in Figure 6 for a period of about 12 seconds. The operation was repeated 15 times with batteries recharged each time and with consistently similar results. A similar test using PEG 200 material was conducted with a more persistent smoke result.

2. Commercial steam boiler. These tests utilized an off-the-shelf 4 KW electric boiler<sup>24</sup> with propylene glycol heated to a 420°F temperature and 40 psig pressure. Initial operation provided a transient smoke at about 30 to 50 gph rate for about 15 seconds, through a 1/4 inch diameter discharge tube. Subsequent tests as shown in Figure 7 utilized a .060 orifice to produce about a 3 gph smoke having about a 1.5 micron ( $\mu\text{m}$ ) average particle size. Rapid discoloration of the heated propylene glycol liquid occurred in the boiler tank almost immediately during the first heating period. This was due to the catalytic action of the copper clad heating elements and the carbon steel boiler tank on the heated propylene glycol.

3. Modified steam boiler. The steam boiler in Item 2 above was reworked and modified by nickel plating both the interior carbon steel boiler and the heating elements. Also, the carbon steel fittings and piping were replaced with stainless steel. Propylene glycol was heated to 420°F at 40 psig pressure and maintained for eight hours per day for three consecutive days. No discoloration was apparent the first day. Slight discoloration was noted the second day and a thin layer of black decomposition products accrued at the bottom of the boiler after the third day.

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24. See Reference 22.

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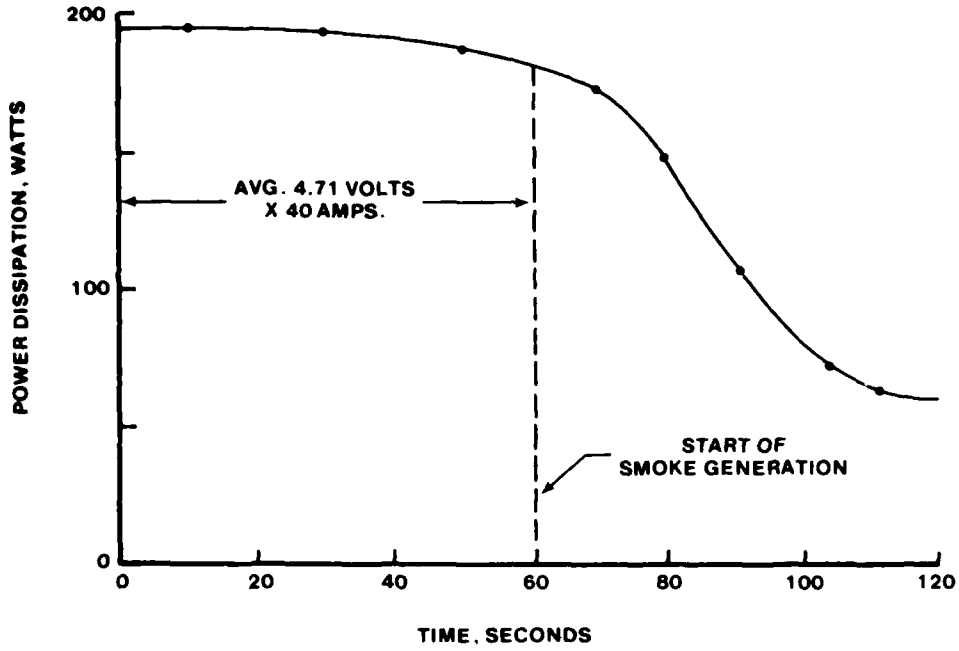


Figure 5. Power Dissipation Battery Operated Smoke Generator.

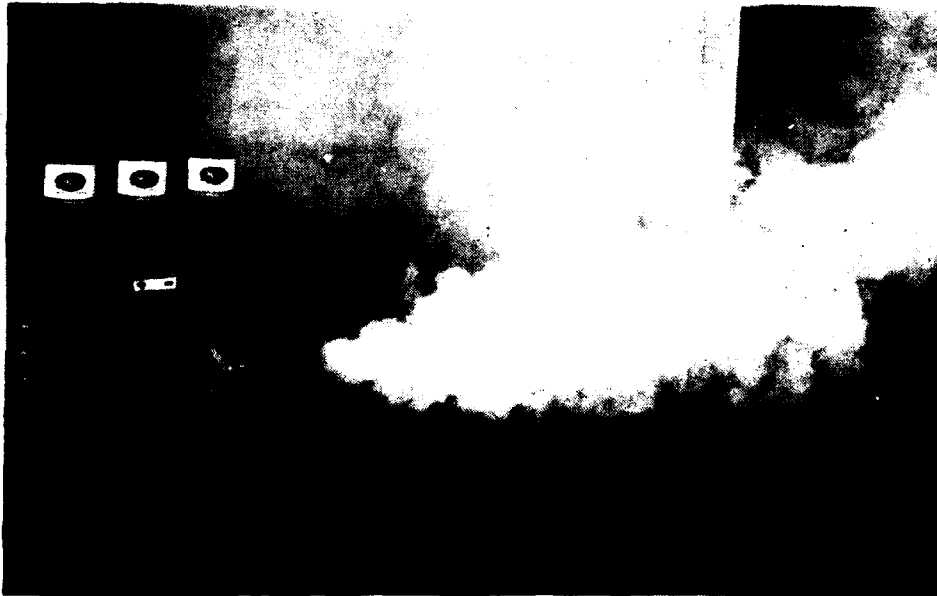


Figure 6. Tubular Coil Smoke Generator Test.



Figure 7. Boiler Smoke Generator Using Propylene Glycol.

4. Propylene glycol/water mixtures. Measurements of visual range for various propylene glycol/water mixtures were made using the steam boiler (Figure 7). Test results showing visual range as a function of time, and decreasing flow rate as a function of increasing water content are shown in Figure 8. The corresponding increase in particle size with increasing water content was calculated using equation (2) as shown in Table 2.

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TABLE 2. PARTICLE SIZES FOR PROPYLENE GLYCOL/WATER MIXTURE FOG GENERATOR

Test Run No.	Percent Water (Average)	Average particle diameter, ( $\mu\text{m}$ )
1	44	7.3
2	34	4.9
3	26	3.6
4	11	2.6
5	0	1.5

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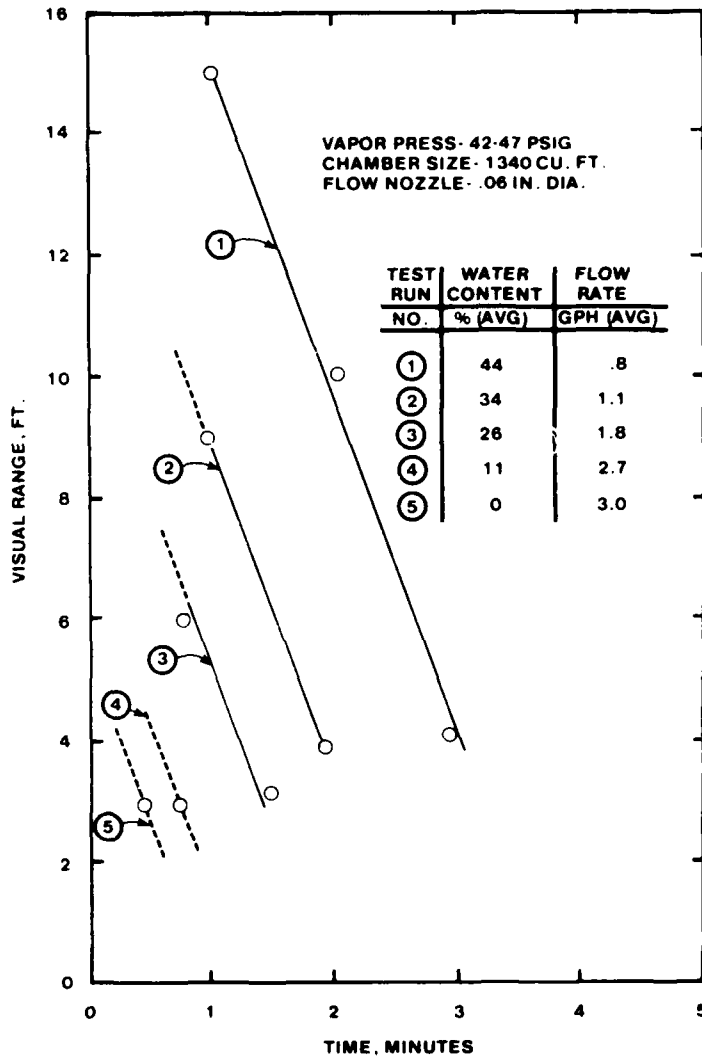


Figure 8. Fogging Characteristics for Propylene Glycol/Water Mixtures.

SECTION V  
DISCUSSION

Boiling Heat Transfer Criteria

A somewhat simplified heat transfer approach was formulated in Section III from complex boiling theory to determine:

- o The potential feasibility of a high capacity electric smoke generator (which to date has not been accomplished by industry).

- o The reduction of high temperatures normally associated with high capacity smoke generators.

- o The following rationale for the proposed smoke generator approach:

- a. *Flow boiling/resistance-tube.* The basis for this approach are the maximum and minimum heat flux indicated by Figure 1 and the various regimes described in Appendix B and by the heat transfer equations in Section III. These indicate limitations of the critical peak heat flux,  $(q/A)_{max}$ , for conditions when nucleate boiling dominate the heat transfer before vaporization (mist flow regime) take place. Normally the critical transition boiling regime is avoided to prevent possible "burnout." This could occur in some systems when the heat transfer coefficient is suddenly reduced to the  $(q/A)_{min}$  condition. In the case of an atomizing fogger nozzle, nucleate boiling would be useful as an efficient method to reduce fluid viscosity (and resistance to shear) as a method to produce smoke particulates. However, since the vaporization/condensation approach includes all the regimes of flow boiling, then flow capacity is limited by the minimum heat flux equation (14).

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The values of minimum and maximum heat flux and the temperature differential,  $\Delta T$ , for the corresponding flow capacities are given in Table 2. These indicate a relatively high flow rate for vaporizing propylene glycol within the minimum flux,  $(q/A)_{\min}$ , which would be more than appropriate for most training smoke applications.

The calculated low temperature differentials  $\Delta T$ , shown in Table 2 indicates the effectiveness of the resistance-tube technique. This is the result of distribution of  $I^2R$  power over a wide area, and the use of this area as a heat transfer surface to a relatively small amount of smoke agent material. Thus a low thermal resistance is provided in a radial direction resulting in a low thermal gradient ( $\Delta T$ ). Hence, the resistance-tube technique tends to match the high thermal efficiency associated with the flow boiling regime.

The critical peak heat flux, as well as the minimum heat flux, are independent of the heating element (e.g., depends on the smoke agent material properties and the type of metal surface). Therefore, the resistance-tube dimensions can be determined in accordance with parameters of Figure 3 to match the limitations of the minimum heat flux.

b. Pool boiling. The 4KW commercial steam boiler used for tests with propylene glycol, was limited by its relatively small heating surface area. Hence, the heat flux was about 18 watts/cm<sup>2</sup> for the boiler heater compared to about 1.5 watts/cm<sup>2</sup> for the same total output of the resistance-tube approach. This puts the heating range in approximately the same level as the minimum heat flux,  $(q/A)_{\min}$ , for propylene glycol with the commercial boiler. However, the 18 watts/cm<sup>2</sup> boiler heat flux is within the critical heat flux indicated in Table 1, therefore excess temperature burnout would not be expected.

The decomposition of propylene glycol noted in the long term heating tests was drastically reduced when the copper heater surfaces and carbon steel boiler materials were nickel clad. This identified the catalytic action of the former materials as a primary cause of decomposition of the heated propylene glycol. However, although  $(q/A)_{\min}$  was exceeded by a large factor, it would appear that a duty cycle type of operation utilizing the bulk heat storage of the boiler would be feasible. That is, a low level heating of the smoke agent (less than 1 KW) for long periods and short intermittent smoke usage at high capacity (4 KW).

The commercial boilers may be better suited in heating applications with an atomizing nozzle smoke generator. Hence, it can be operated in the nucleate boiling regime without exceeding the peak heat flux,  $(q/A)_{\max}$ . The resistance tube, on the other hand, can provide a distributed source of  $I^2R$  heating over a large area with a relatively small material contained in the tube. Then vaporization of propylene glycol in the stable film boiling regime would be possible without exceeding the minimum heat flux,  $(q/A)_{\min}$ , thereby providing higher capacity.

#### Residence Time/Decomposition

An important consideration is the "residence time" of heating. Smoke agent materials can decompose at high temperatures but this depends on the stability of the material and the time duration the smoke agent is in contact with a heated surface. In some cases this may be a matter of milliseconds. For example, if a smoke agent is injected into a hot gas stream or against a heated surface, vaporization may take place rapidly and tend to cool the heating medium quickly. If excess heat and temperature are applied then decomposition may take place. In the case of the relatively long resistance-tube, prolonged heating may vary from a fraction of a minute or longer. However, in this case the heating surface will be at a relatively low level due to its low thermal resistance characteristics. Also, the significant residence time will be a fraction of the total residence time since the temperature is near or beyond the boiling point will comprise of a



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partial section of the resistance tube. Since the resistance-tube tests of Section IV (Figure 6) were within the minimum heat flux  $(q/A)_{min}$ , this would explain the lack of decomposition residue after numerous operations.

The bulk heating with a commercial boiler approach will have a long duration heating of smoke agent material. The test results of Section IV with propylene glycol still indicated decomposition (although drastically reduced) after the catalytic effects for material surfaces were substituted. In this test, decomposition seems to occur after a relatively long period of time, but its final cause has not been determined (e.g., cycling of heater operation, or minimal catalytic effects). Hence, further testing for decomposition for this approach would still be required.

#### Non-Flammable Smoke Agent

As indicated in Appendix A, a non-flammable smoke is a desirable constraint. Although smoke concentrations for extreme obscurations (low visual ranges) are generally a small percentage of the lower explosive limit, a reportedly non-explosive smoke agent (butylated triphenol phosphate) was selected for the Navy's Device 19F1<sup>25</sup> fire fighter trainer. However, as noted in Section I and Appendix A, a high temperature system is required. This can cause problems of autoignition if a pressure leak occurs and a smoke agent liquid impinges on a hot surface in the open air and bursts into flame. A problem can also occur if the smoke distribution piping is maintained at high temperatures where the high concentrations of smoke particulates may be susceptible to decomposition.

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25. See page 134 and Appendixes of Reference 3.

Another possible non-explosive smoke agent considered was a mixture of propylene glycol and water. Results on testing this mixture for explosiveness in an oxygen atmosphere have been reported.<sup>26</sup> The fire protection code also lists a 30 to 60 percent propylene glycol and water mixture for non-freezing sprinkler systems for fire protection.<sup>27</sup> The limited test data on propylene glycol/water fog generation shown in Figure 8 indicate the feasibility of effective obscuration for this approach. The advantages would be an application where a non-residue and non-explosive smoke is warranted. Further testing would be required to determine mixture ranges for non-flammability and decomposition limits, particularly where hot surfaces and possible oncogenic effects are involved.

#### Experimental Nozzle Approach

Fluid particulates can be produced by three general types of atomizing nozzles. In order of decreasing particle size, these are: (a) liquid spray into ambient air, (b) air-atomizing by impact of a stream of gas or air, and (c) a sonic flow nozzle which mixes liquid and gas in a divergent expansion chamber internal to the nozzle. The sonic flow nozzle produces a water particle sizes spectrum to less than a few microns. Particle sizes down to 0.5 micron have been reported for some fuel atomization applications.<sup>28</sup> Smaller particle size generally result from: increases in air liquid pressure; smaller orifice-size; more dense liquid; less viscous liquid; and lower surface tension.

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26. Jamison, H. H., Determination of Water-Glycol, Coolant Flammability, NASA, June 1967.

27. National Fire Protection Association, National Fire Codes, Volume One, 1975, pages 13-94.

28. See Reference 23.

The proposed atomizing nozzle approach will require experimental testing to determine performance of particle size distribution for various smoke agent materials and heating conditions. This would include heating of the liquid material to facilitate the shearing process within the nozzle. In this report the oil-water interface/nozzle smoke generator described in Section III (Figure 2b) would be a viable approach. Further study and experiments are planned using this approach due to its simplicity of control, low temperature and potential low cost. The resistance-tube approach is also a viable method but would require an auxiliary air supply (plant air). However, heating would be well within the  $(q/A)_{\max}$  limit discussed previously. Consideration for utilizing the heating element as a temperature controller<sup>29</sup> for this application appears to be appropriate.

#### Limitations of the Analysis

The various technologies involved in smoke generation are extensive. These include physical and chemical behavior of materials under various phase conditions, in addition to the emphasis given to heat transfer in this report. A somewhat simplified approach was used for the heat transfer analysis along with a limited amount of testing sufficient only for preliminary investigation. This approach was necessary due to the complexity of the boiling phenomena which involves a large number of variables. Extensive testing for determining empirical relationships were considered beyond the scope of this report.

It is probable that better use could be made of the considerable progress that has been made in the past few years in gaining a physical understanding of the boiling mechanism. However, neither general equations describing the process nor general correlations of boiling heat transfer data are available to date.

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29. Series ADG Temperature Controllers, Reference 23.

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The proposed mechanism for the various two-phase flow or pool boiling regimes are useful but must be treated with caution. These are generally empirical equations obtained under specific conditions which may not be applicable to other configurations and fluids.

Other limitations are the determination of chemical decomposition effects of the combination of high temperature, catalytic action of the various materials and residence time of heating. This also would require empirical type testing involving a specific smoke generator application.

Most of the heat transfer analysis and tests were essentially limited to propylene glycol material. This is because propylene glycol was initially selected as the most probable candidate for training applications. Although this was sufficient for the scope of this investigation for the proposed smoke generating techniques, further research is required for demonstrating feasibility of these techniques with other materials including butylated triphenol phosphate and polyethylene glycol 200 (PEG 200).

#### Proposed Applications

Various types of applications of the proposed smoke generators utilizing resistance-tube and commercial boiler approach are suggested in Appendix C. These applications include: shore based fire fighting training; on-board ship fire drills; extinguishment agent simulation; and other applications such as cockpit or aircraft evacuation trainers.

The choice of smoke agent material for these applications is dependent on the restraint factors indicated previously in Section I and in Appendix A, such as flammability and residue. However, the choice of a smoke generator approach (i.e., vaporization or atomizing nozzle) will also depend on the type of smoke agent material.

SECTION VI  
CONCLUSIONS

The fundamental heat transfer analysis identifies the efficiency of the boiling thermal process and the heat flux distribution advantages of the electrical resistance-tube smoke generation technique.

These advantages include comparatively low temperature operation to minimize or eliminate decomposition or fire hazards associated with existing high heat source units.

In effect, this approach indicates a potential for a high capacity electric smoke generator which up to now has not been available.

The resistance-tube technique can be operated in the mist-flow regime below the minimum heat flux limit, whereas a commercial electric boiler may be limited to the nucleate boiling regime; i.e., critical peak heat flux for propylene glycol.

Various proposed systems utilizing atomizing or fogger nozzles are available that have not been fully explored for smoke generating systems. This includes an electric boiler technique which would utilize the unique properties of butylated triphenol phosphate (Chem Chex 220) which is presently used in the Navy's device 19F1 fire fighter trainer.

Several potential applications of the proposed techniques appear to justify further research due to inherent advantages of lower temperature, minimal fire and decomposition hazards, and simplified design approach.

Further feasibility study and testing will be required for specific applications of the proposed approaches.

SECTION VII  
RECOMMENDATIONS

The following actions are recommended:

1. The feasibility of high capacity electric smoke generators should be explored further for feasibility of practical application on the basis of (a) need and availability of specific applications and (b) the advantages of low temperature control for minimizing safety hazards and providing potential cost effectiveness.

2. Specific testing should be conducted in the areas of (a) resistance-tube technique and (b) low temperature atomizing nozzle technology.

3. After evaluation of the feasibility of the proposed approaches, a contract effort on selected prototype models should be procured for field testing.

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Sciascia, R. M.; Advanced Fire Fighter Trainer, Device 19F1, NAVTRADEV P-1550-98, 1982.

Steamaster Inc., New York, New York.

Swiatosz, E.; Guthrie, W. N.; Cadle, H. H.; New Developments in Navy Fire Fighter Trainers, Naval Training Equipment Center IH-316, Proceedings of the First NAVTRAEQUIPCEN Interservice/Industry Training Equipment Conference, November 1979, p. 217-227.

Swiatosz, E.; Grimmer, P.; NAVTRAEQUIPCEN Technical Report IH-303, Experimental Research for Advanced Firefighting Simulators, May 1978.



APPENDIX A  
SMOKE AGENT CONSIDERATIONS

The smoke agent material must meet health and safety requirements for training. In general, most smoke agents are eliminated from consideration by rationalizing all significant characteristics. These include toxic effects, flammability, corrosiveness, residue effects, cost and the training environment. Recent studies considered these factors to select an appropriate smoke from available candidates for the Device 19F1 Advanced Fire Fighter Trainer.<sup>1</sup> These included mineral oil, propylene glycol, polyethylene glycol 200 (PEG 200) and butylated triphenol phosphate (Chem Chex 220<sup>2</sup>). The latter material as a smoke is reportedly a non-toxic/non-flammable form of triaryl phosphate and was selected for the 19F1 for these reasons. However, Chem Chex 220 in liquid form is still susceptible to burning with the flash point, fire point and auto-ignition temperatures as indicated in Table A-1. The Chem Chex 220 and PEG 200 smoke particulates are persistent smokes and resistant to rapid evaporation in the high temperature environments encountered in some fire fighter trainers. This is unlike propylene glycol smoke which tends to evaporate rapidly when the ambient temperature reaches 140°F to 160°F. For this reason and the fact that propylene glycol will decompose at high temperatures, it has not been recommended for the Device 19F1.<sup>3</sup>

The flammability of smokes from materials such as propylene glycol or other hydrocarbons has been a serious consideration for the 19F1 trainer

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1. Fire Fighter Trainer Considerations Phase II Sooz, Allen and Hamilton, Inc. Contract No. N61339-79-C-0011, Mod. No. P00007, 31 July 1981.

2. TIFA (C.I.) Limited, Millington, New Jersey.

3. Boronson, M. L.; et al, "Propylene Glycol as a Fire Smoke Stimulant." NRL Report 8477, 29 June 1981.

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TABLE A-1. PHYSICAL AND CHEMICAL PROPERTIES OF SMOKE AGENT MATERIALS FOR TRAINING APPLICATIONS

	<u>PEG 200</u>	<u>PROPYLENE GLYCOL</u>	<u>CHEM CHEX 220</u>
Chemical Name	Polyethylene Glycol 200	Propylene Glycol	Butylated Triphenol Phosphate
Other Name	Carbowax 200	-	Triaryl Phosphate
Physical State, at 77°F, 1 atm	Liquid	Liquid	Liquid
Specific Gravity	1.127	1.038	1.12-1.21
Viscosity	4.3 Centistokes at 210°F	.581 Poise at 20°C	90-1000 SUS at 100°F
Average Specific Heat, Cal/qm/°C	.52	.59	-
Vapor Pressure, at 20°C, mm Hg	<.01	.07	-
Boiling Point, °C	315	188	391
Pour Point/ Freezing Point	-	(-60°C)	-30° to 30°F
Flash Point, °F	>350	214	450
Fire Point, °F	-	-	650
Autoignition, °F	-	790	1050

environment.<sup>4</sup> For these materials however, the danger is somewhat minimized considering the extreme obscuration obtained (visual range 1 to 3 feet) for relatively low smoke concentrations which are generally less than 2 percent of the explosive limit. It should be noted however that materials in the invisible or transparent vapor state could add to this concentration. However, unlike a "natural" fire which may have a large source of volatile material to produce a dense smoke, an artificial smoke generator needs only a limited amount of material. Since an extremely large amount of material is generally required to produce a flammable smoke concentration, then the control of usage rate would tend to preclude a flammability hazard.

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4. Swiatosz, E.; Grimmer, P.; NAVTRAEQUIPCEN Technical Report IH-303, Experimental Research for Advanced Firefighting Training Simulators, May 1978, p. 45-47, 102-104.

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APPENDIX B  
BOILING HEAT TRANSFER CHARACTERISTICS

Boiling heat transfer<sup>1,2,3</sup> involves vaporization (and its inverse condensation) which is one of the most common phase-change processes. A simple expression relates the heat transfer film coefficient,  $h$ , with the heat flux,  $q$ , to the temperature differential between the heating surface area and the saturated smoke agent liquid as:

$$q = hA (T_s - T_{sat})$$

However, a phase-change process involves changes in variables (i.e., density, viscosity, specific heat, thermal conductivity and thermal expansions) while the fluid's latent heat is being absorbed (vaporization). Hence the heat transfer coefficient is much more complicated than for a single-phased convective process and will generally require empirical correlations in making calculations.

The behavior of a fluid during boiling involves various regimes that are highly dependent upon the "excess temperature"  $\Delta T = T_s - T_{sat}$ . The essential features of boiling heat transfer are the extremely high rate of heat transfer compared with the normal convective processes and the conditions of peak heat flux, called the "burnout point." This occurs when the bubble columns or vapor steam is retarded by the downward replacement liquid resulting in an increased thermal resistance vapor blanket. In some

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1. Kreith, F., Principles of Heat Transfer, 2nd Edition, International Textbook Company, 1968.

2. Pitts, D. R., Leighton, E. S., Schaums Outline Series, Theory and Problems of Heat Transfer, McGraw-Hill Book Company, 1977.

3. Handbook of Heat Transfer, Edited by: Rohsenow, W. M., Hartnett, J. P., McGraw-Hill Book Company, 1973.

instances, the temperature at this point is above the melting point of most heater materials, and the failure of the heater occurs before reaching it.

Two general types of boiling heat transfer are considered for the various vaporization type smoke generators: Pool Boiling (free convection); and Flow Boiling (forced convection). The various boiling regimes for these are shown in Figures 1 and 2 respectively. Pool boiling involves the relations of five regimes: free convection (Regime 1); nucleate boiling (Regimes 2 and 3); and film boiling (Regimes 4 and 5). Flow boiling occurs when a liquid flows through a tube which is maintained at a higher temperature than the saturation of the liquid. The flow is a two-phase mixture of liquid and its vapor as shown in Figure 2. This indicates a subcooled liquid entering a tube (evaporator) and passing over the hotter wall where nucleate boiling occurs. The flow is considered bubbly for 10 percent vapor quality with increases in heat transfer coefficient. At higher qualities it becomes "slug-flow," then "annular" with a thin liquid layer on the wall and a vapor core, with the velocity of the vapor much higher than the liquid. In the transition from annular to vapor flow the heat transfer coefficient drops sharply and burnout can sometimes occur at this point. Vapor flow continues until 100 percent quality is reached when conventional forced convection is then the mode of heat transfer.

The point of maximum heat transfer or the critical heat flux is independent of the heating element. If the temperature of the heating element at this point is not excessive to cause burnout, the boiling curves of Figures B-1 and B-2 continue to rise to beyond the boiling regime. Most applications do not go beyond the critical heat flux and use average heat flux in designs. Since heat flux is a local quantity for a given regime in the proposed application, then the local temperature value should be considered as conservative for the design.

In general, the analytical expressions of the various modes and regimes of boiling heat transfer are quite complicated. Superposition techniques are generally used and simplified approaches for the heat transfer relations in Section III are utilized.

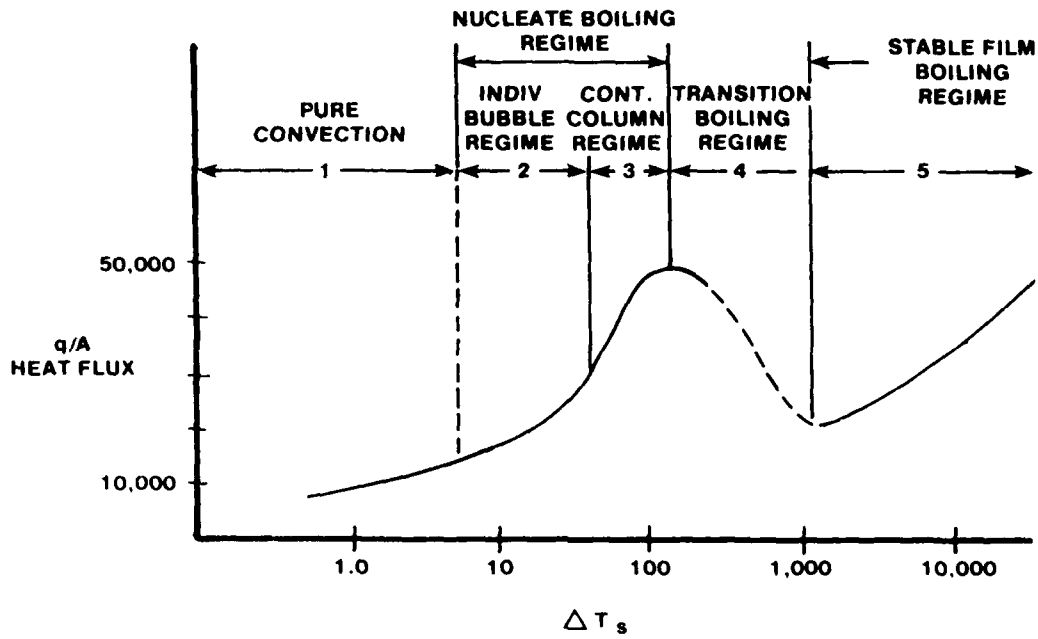


Figure B-1. Typical Pool Boiling Curve.

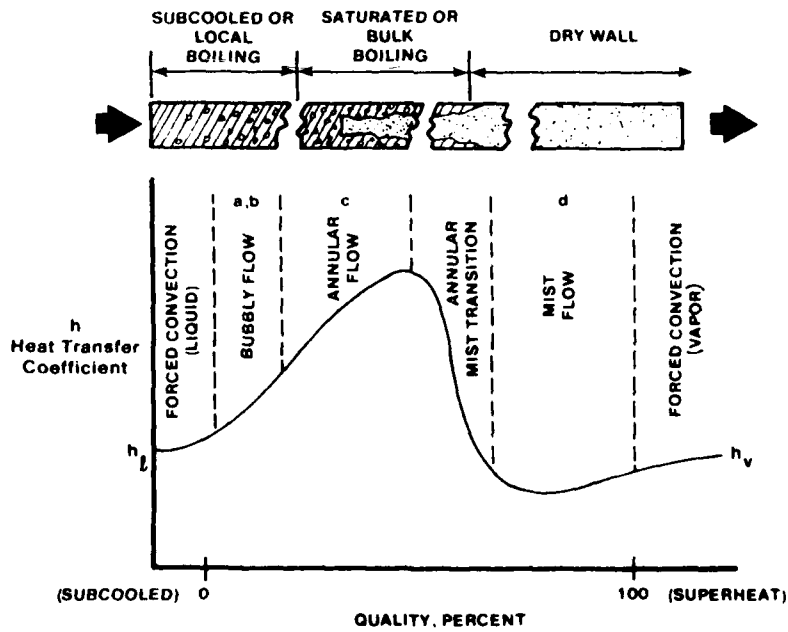


Figure B-2. Flow Boiling Regimes.

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APPENDIX C  
PROPOSED APPLICATION OF NEW SMOKE GENERATOR TECHNIQUES

The new techniques for smoke generation such as resistance-tube and commercial boilers have yet to be fully developed and tested. The advantages of these systems, however, indicate potential applications in the following areas:

- a. On-board ship fire fighting drills.
- b. Shore-based fire fighting training.
- c. Extinguishment agent simulation.
- d. Other applications (such as aircraft evacuation, cockpit training, theatrical affects).

(1) On-board ship fire fighting drills. The general purpose for this application is a means for providing training smoke aboard a Navy vessel for fire fighting training purposes. A requirement has been stated for a small self-contained but inexpensive smoke cartridge that can be easily applied for short periods of smoke generation.

The background for this application indicated that the Navy has in the past been interested in smoke generators for fire drills. Commercial smoke bombs or grenades are available, but these are pyrotechnic in nature and some produce highly toxic smoke such as zinc chloride and hence, cannot be used indoors. The Army has many smoke devices but they do not fall in the present category. The Naval Weapon Supply Center has recently studied a pyrotechnic smoke bomb using non-toxic propylene glycol as a smoke agent. However, their study has been discontinued since their projected development costs per unit were estimated about \$6 to \$8 each.

Description and operation of a proposed portable smoke generator. Smoke can be produced by supplying heat to a material such as oil or propylene glycol and thus vaporizing it. The vapor is then condensed in air to produce a cloud of small particulates to produce the smoke. One proposed method is to

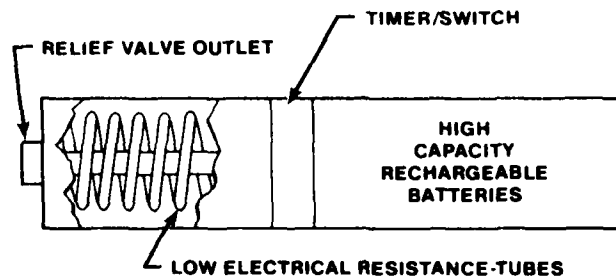
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use the electric current from a small, but high capacity, battery as a source of heat energy. A battery such as a Gates Model PN0800-004 (5 ampere-hour) or equivalent would have a high density energy and could provide 20 to 50 amperes for a short period of time. The battery is rechargeable and can be used many times (200-500 for complete discharge). A relatively small amount of propylene glycol (or carbo wax 200 for a more persistent smoke) is required, from .5 to 3.0 cubic inches, depending on the rate or duration of smoke. The smoke device is illustrated by Figure C-1.

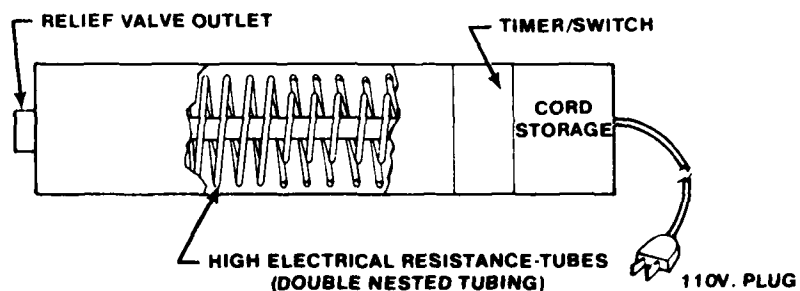
The device is actuated by closing an arming switch which permits flow of current through a tubular resistance coil. The coil is designed to contain the smoke agent, carry sufficient current, and have appropriate surface area to dissipate heat to vaporize the liquid smoke agent. When the temperature reaches a set level above the vaporization temperature, the pressure will rise to a point to open the relief valve (or fusible disc). The vaporized liquid will flash through the relief valve discharge and out the control orifice to produce the smoke. The battery can be selected so it can be expended at a preselected time period depending on the selected resistance heating element. The quantity of liquid and smoke generated can be preselected to match the output of the battery. A timing device can be utilized in lieu of the arming switch which could limit the battery operating time and hence can be used consecutively before recharging both the battery and the liquid smoke agent. As an alternate, a plug-in operation for 110V outlet can be provided in lieu of batteries. This would provide 4 to 10 times the smoke generating capacity while still maintaining some portability, but not to the degree of a battery system.

The advantages of this system are indicated in Figure C-1. These indicate a low unit cost of operation as a reusable smoke generating unit as compared with existing disposable pyrotechnic smoke bombs. Other advantages are its safety and minimized storage requirements.

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**LOW VOLTAGE/RESISTANCE-TUBE CONCEPT**



**HIGH VOLTAGE/RESISTANCE-TUBE CONCEPT**

	NEW CONCEPT RESISTANCE- TUBE	NAVY PYROTECHNIC PROPOSAL	CURRENT COMMERCIAL PYROTECHNIC
TRAINING EFFECTIVENESS	HIGH	LOW	LOW
TOXICITY	NO	NO	YES
FIRE HAZARD	NO	YES	YES
UNIT COST PER ACTIVATION	LOW (REUSABLE)	HIGH (DISPOSABLE)	HIGH (DISPOSABLE)
DEVELOPMENT COST	LOW	HIGH	EXISTING

**COMPARISON ON-BOARD SHIP FIRE FIGHTING  
TRAINING ALTERNATIVES**

Figure C-1. Portable Smoke Generator Concept  
For On-Board Ship Fire Fighting Drills.

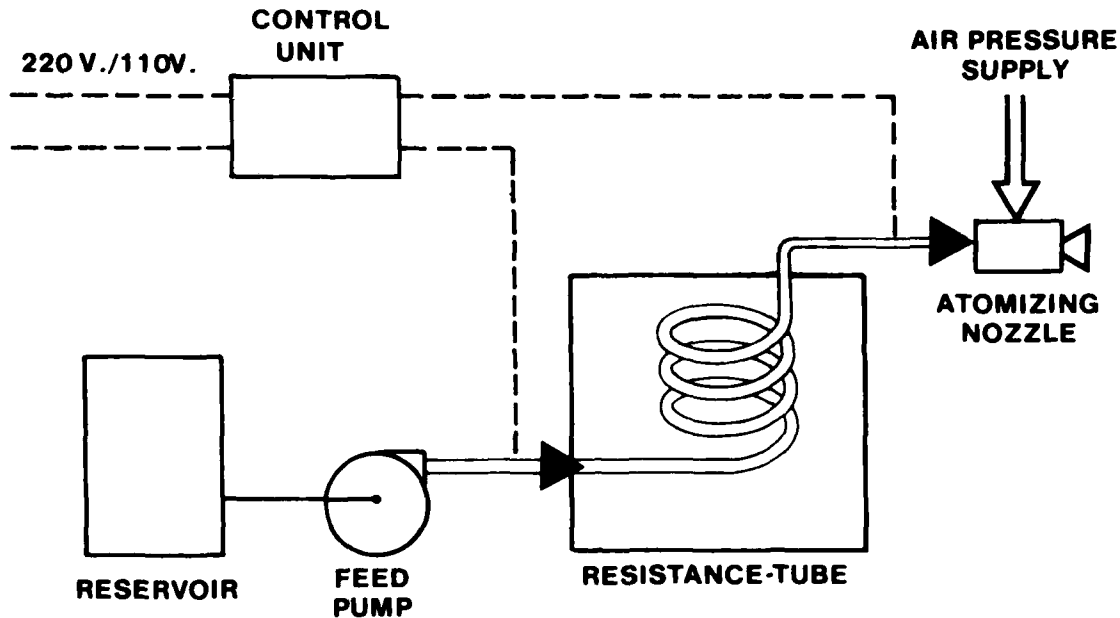


Figure C-2. Resistance-tube Heater/Nozzle Smoke Generator Concept.

(2) Shore-based fire fighting training. The Device 19F1 Advanced Fire Fighter Trainer utilizes a clean burning propane flame environment, hence the introduction of a non-toxic training smoke would be limited to a non-flammable material smoke such as butylated triphenol phosphate (Chem Chex 220). However, this material would generally require a high temperature smoke generating system due to its high boiling point. Another approach is to utilize the material in conjunction with an atomizing nozzle as described previously in this report. This suggests the possibility of preheating the smoke agent material prior to injecting it with pressurized air (or superheated steam) through a special atomizing nozzle using the resistance-tube technique as illustrated in Figure C-2.

A variation of this approach is shown in Figure C-3 which utilizes the unique properties of Chem Chex 220. These properties are its high boiling point (735°F) and specific gravity (1.1 to 1.2) greater than water, and the

fact that it is not miscible with water. Hence combined heating of the two materials in a boiler would provide both superheated steam and heated smoke agent material for subsequent injection of both fluids into a similar type atomizing nozzle as referenced in this report (see reference 23). This atomizer would be designed to mix pressurized air (or steam) with heated smoke agent fluid in a chamber within the nozzle. Air flow from this chamber at sonic velocity would accelerate a liquid film on an annular surface. The liquid film is thus reduced and sheared as the compressed air expands within a divergent nozzle. Supersonic velocities are attained resulting in pressure fluctuation and shock waves which vibrate the liquid layer causing further shearing and break-up of the material for complete atomization. Any significant percentage of large droplets which may be present would be filtered out of the resulting smoke.

The advantages of this approach is that it avoids a more complicated high temperature air heater and the possible decomposition of smoke agent substance is minimized or eliminated.

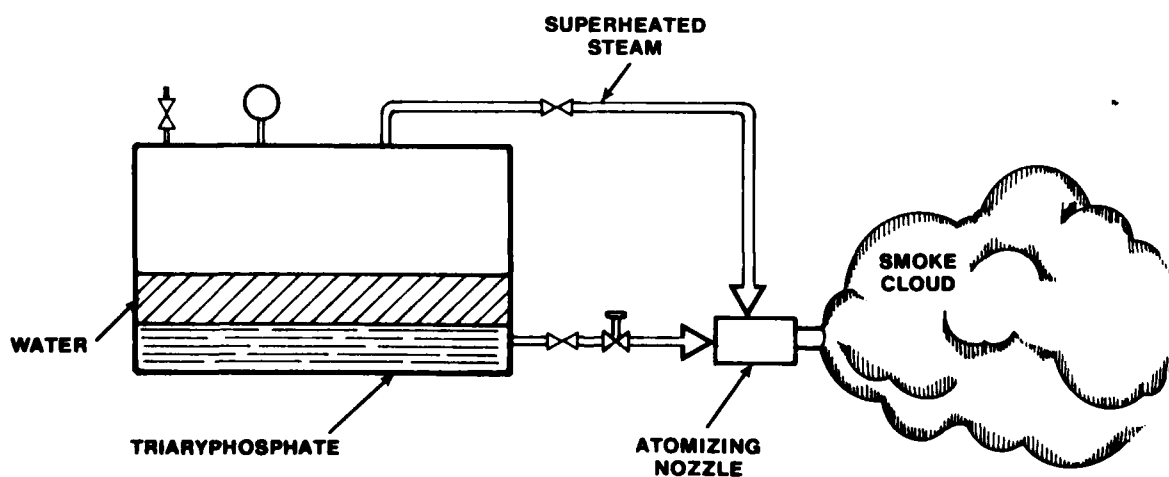


Figure C-3. Oil Water Interface/Nozzle Smoke Generator.

(3) Extinguishment agent simulation. Another application utilizing the resistive-tube technique is described by Figure C-4. The basic idea would be to produce a dense cloud of smoke from a portable container to simulate the Navy's PKP extinguisher. Optical type sensors would be required to sense the smoke and provide a control signal for flame control (i.e., oil spray fire) or extinguishment via valve closure. For a real fire trainer, a non-flammable smoke such as butylated triphenol phosphate or a mixture of propylene glycol and water may be feasible. The latter case would require extensive tests for possible decomposition of a dense cloud in a flame environment. Evidence of non-flammability of propylene glycol/water mixtures have been reported (see reference 26) and is also used as a low freezing method in fire sprinkling systems (see reference 27). The test data shown in Figure 8 on smoke performance of water/propylene mixtures indicate significant increases in material usage and particle size, both of which would greatly increase energy requirements for vaporization. For non-fire or visual simulated fire, such as Ansul's<sup>1</sup> fire fighting trainer, propylene glycol would provide a residue free smoke cloud with minimal material usage.

(4) Other applications. Propylene glycol would be a prime choice for enclosed, non-flame environment such as for cockpit or commercial aircraft evacuation trainers where minimum or non-residue is a requirement. At present, some of these trainers utilize a modification of inexpensive, low capacity electric foggers. However, for higher capacity smoke generation where large smoke volumes are required, then the resistance-tube or commercial boiler approach as described in this report would be applicable.

1. Ansul Corp., Marinette, Wisconsin.

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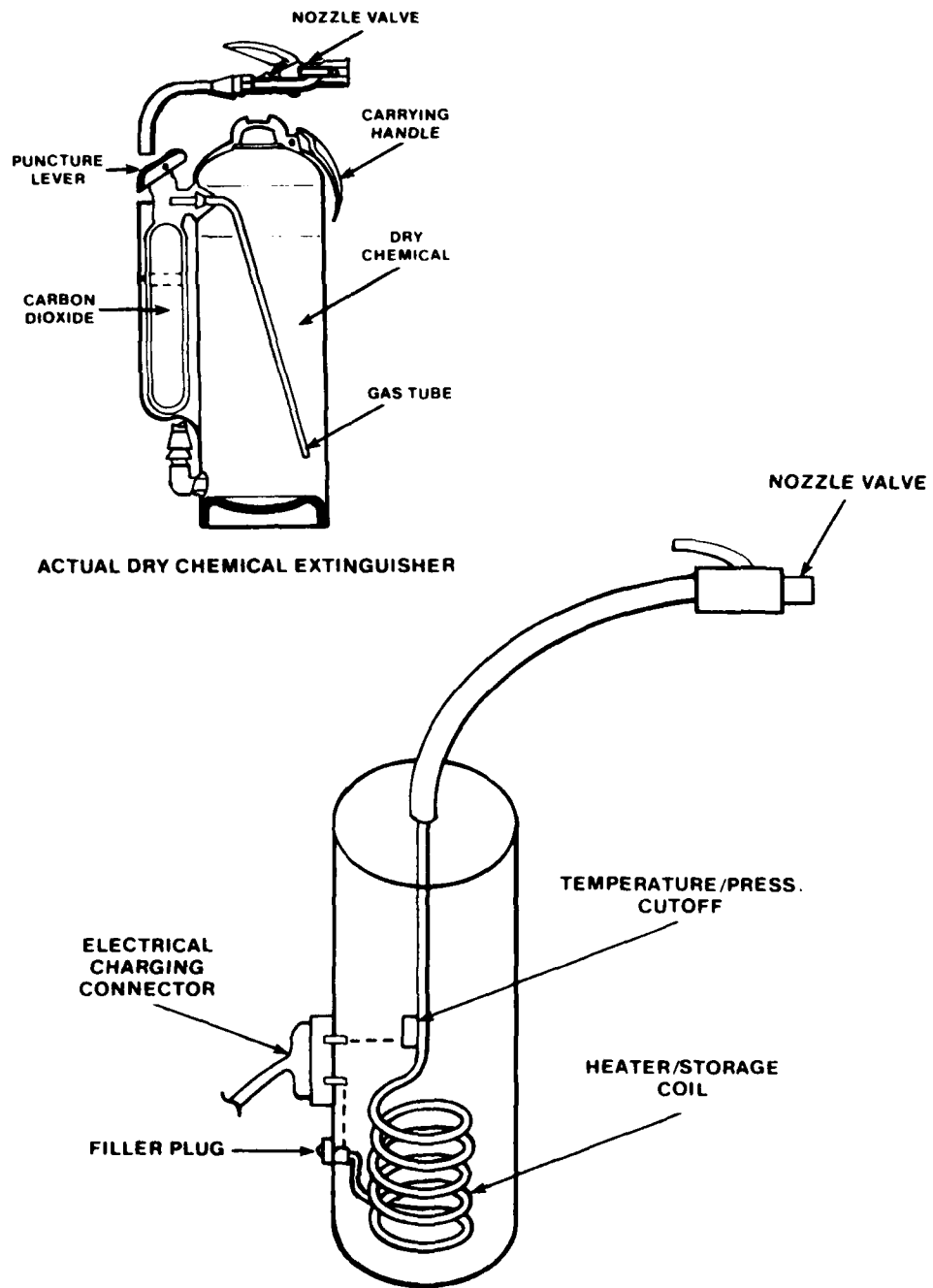


Figure C-4. Simulation PKP Extinguisher.

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## GLOSSARY

Letters

A,As	Area of heating surface
Ac	Cross sectional area
Cp	Specific heat
Cp <sub>vf</sub>	Specific heat of vapor at T <sub>f</sub>
C <sub>sf</sub>	Empirical constant for pool boiling
C <sub>l</sub>	Specific heat of saturated liquid
D	Tube diameter
E	Extinction coefficient, or voltage
G	Flow rate gallons per minute
g	Local acceleration of gravity
g <sub>c</sub>	Dimensional conversion factor (32.17 ft lbf/lbm sec <sup>2</sup> )
g <sub>o</sub>	Earth's standard gravitation (32.17 ft/sec <sup>2</sup> )
$\bar{h}$	Average combined unit-surface conductance, $\bar{h} = \bar{h}_c + \bar{h}_r$
h <sub>c</sub>	Convective heat transfer coefficient
h <sub>r</sub>	Unit conductance for radiation
h <sub>fg</sub>	Latent heat of condensation or evaporation
$\bar{h}_f$	Gas film coefficient
h <sub>f</sub>	Enthalpy fluid
I	Current or Intensity of light
k	Thermal conductivity
k <sub>l</sub> , k <sub>f</sub>	Thermal conductivity of fluid
k <sub>m</sub>	Mean thermal conductivity
k <sub>vf</sub>	Thermal conductivity of vapor at T <sub>f</sub>
l	Length of heat flow path
L	Tube length
n	Refractive index
N	Number of particles
P	Electrical power
q	Rate of heat flow
q <sub>b</sub>	Rate of heat flow by boiling

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$q_c$	Rate of heat flow by convection
$(q/A)_{\max}$	Maximum or critical heat flux for boiling
$(q/A)_{\min}$	Minimum heat flux for boiling
$q_{\text{Total}}$	Combined rate of heat flow
$R$	Total electrical resistance
$r$	Particle radius
$r_e$	Unit electrical resistance
$T$	Temperature
$T_b$	Temperature of bulk fluid
$T_f$	Mean fluid temperature
$T_s$	Surface temperature
$T_{\text{sat}}$	Saturation temperature
$T_{\infty}$	Temperature far from heat source
$\Delta T$	Temperature difference
$\Delta T_s$	$=T_s - T_{\text{sat}}$ , Excess temperature
$\Delta T_f$	Temperature difference between surface and fluid
$\Delta T_{\min}$	Excess temperature at point of minimum heat flux
$V$	Average velocity
$V_e, E$	Voltage

Greek Letters

$\alpha$	Optical parameter
$\beta$	Temperature coefficient of volume expansion
$\Delta$	Difference between values
$\lambda$	Wave length
$\mu$	Absolute viscosity
$\mu_m$	Mean viscosity
$\mu_b$	Bulk viscosity
$\mu_l$	Liquid viscosity
$\mu_s$	Viscosity of saturated liquid
$\mu_f$	Viscosity of vapor at $T_f$

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$\mu m$	Micron ( $10^{-6} m$ )
$\nu$	Kinematic viscosity, $\mu/\rho$
$\rho$	Mass Density
$\rho_e$	Resistivity
$\rho_l$	Density of liquid
$\rho_v$	Density of vapor
$\rho_{vf}$	Density of vapor at $T_f$
$\sigma$	Surface tension
$X$	Quality of vapor

Dimensionless Groups

Gr	Grashof number = $\beta g L^3 \Delta T / \nu^2$
$Gr_D$	Diameter Grashof number = $\beta g D^3 \Delta T / \nu^2$
Nu	Nusselt number = $h_c L / k_f$
$Nu_x$	Local value of Nu at point x
$\bar{Nu}$	Average value of Nu over surface = $\bar{h}_c L / k_f$
$\bar{Nu}_D$	Diameter Nusselt number = $\bar{h}_c D / k_f$
Pr	Prandtl number = $c_p \mu / k_f$ or $\nu / a$
Re	Reynolds number = $V \rho L / \mu$
$Re_D$	Diameter Reynolds number = $V \rho D / \mu$

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